6

Switching Comets

During the mid-1990s, when the details of the Rosetta rendezvous mission were still being refined, mission planners were considering several possible comets as targets. The favored candidate was periodic comet 46P/Wirtanen, but potential back-ups included periodic comets 73P/Schwassmann-Wachmann 3 and 15P/Finlay.

As time went by, Wirtanen was confirmed as the ideal objective for Rosetta and the mission was planned with it in mind. The baseline plan targeted launching on a European Ariane 5 in January 2003. In order to rendezvous with the comet in November 2011, the spacecraft would require a gravity assist from Mars in August 2005 and two assists from Earth in November 2005 and November 2007. Wirtanen was selected because of its fairly active nature, modest size, and orbital path, which meant that it would be in the right place at the right time for a rendezvous with Rosetta. Upon arrival, the spacecraft would fly alongside the nucleus. Full payload operations would start at a heliocentric (solar) distance of 3.25 AU (488 million km) in August 2012 and continue to July 2013, when the comet was at perihelion (closest point to the Sun).[1]

6.1 COMET 46P/WIRTANEN

Comet Wirtanen was discovered by chance on 15 January 1948 by Carl Wirtanen while he was examining photographic plates at the Lick Observatory in California.

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[1] One astronomical unit (AU) represents the average radius of Earth's orbit around the Sun; some 150 million km or 93 million miles.

P. Bond, *Rosetta: The Remarkable Story of Europe's Comet Explorer*,
Springer Praxis Books, https://doi.org/10.1007/978-3-030-60720-3_6

Like many periodic comets that have been captured or influenced by the powerful gravity of the largest planet in the Solar System, collectively known as the 'Jupiter family', Wirtanen commutes between the orbits of Jupiter and Earth.

Wirtanen's elliptical orbit is susceptible to change by gravitational interactions with the planets. In particular, close approaches to Jupiter in 1972 (at a distance of 0.28 AU or 41.9 million km) and 1984 (0.46 AU or 68.8 million km) shortened its orbital period from 6.71 years to 5.46 years.

By the close of the 20th century, Wirtanen's perihelion was just outside Earth's orbit, so the amount of heating during its inward passage was quite modest. At perihelion its heliocentric distance was 159 million km (1.06 AU) and when farthest from the Sun (aphelion) it was 768 million km (5.13 AU, near the orbit of Jupiter). The inclination between the orbit of the comet and that of Earth was moderate, at less than 12 degrees.

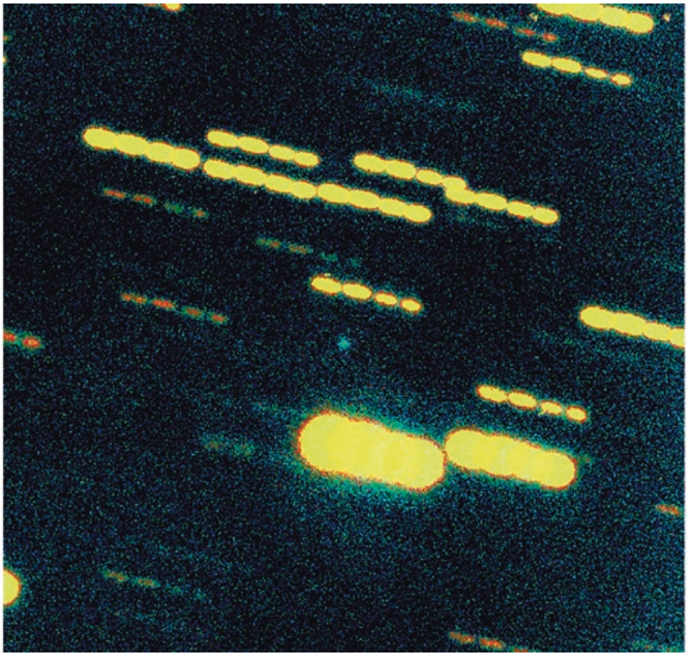

Fig. 6.1: A false-color composite image of Comet 46P/Wirtanen, based on four exposures recorded on 9 December 2001 by the 8.2 meter VLT YEPUN telescope. The telescope was tracking the motion of the comet, so stars are seen as four consecutive trails. The star-like image of the comet's nucleus shows no surrounding gas or dust. The brightness indicates a diameter of roughly 1 km. The comet's distance from Earth at that time was approximately 534 million km. (ESO)

With the exception of 1980, Wirtanen had been observed during every approach to the Sun since its discovery. It was particularly closely monitored during a coordinated observational campaign in 1996-1997, and again following its selection as the primary target for Rosetta.

Despite such intensive observations, little was known about the comet's size, shape, mass or rotation period. Usually, its faint image was drowned in a sea of stars, making ground-based studies extremely difficult. Although it released little dust or gas near aphelion, it was too far away to study in detail. During its brief ventures into the inner Solar System, the warmth of the Sun prompted ices on its surface to sublimate and jets of gas to blast dust grains into the surrounding space – characteristics that led scientists to favor it as the target for the Rosetta mission. Unfortunately, although this enveloping coma increased its brightness, it also hid the nucleus from view.

Assuming Wirtanen's nucleus to be very dark, reflecting 3% of incoming sunlight, as was the case for most other comets, its brightness implied a diameter of approximately 1.1 km. If the reflectivity were higher, then of course the nucleus would be smaller. Ground-based studies identified water, oxygen, carbon dioxide, and various compounds of nitrogen, hydrogen and carbon.

6.2 ASTEROID FLY-BY OPPORTUNITIES

Since opportunities to investigate asteroids at close quarters were few and far between, ESA planners wanted Rosetta to visit two rocky objects on the way to Comet Wirtanen.

In 1995, ESA announced that Rosetta's baseline mission would have opportunities to fly past main belt asteroids (3840) Mimistrobell and (2530) Shipka, after the spacecraft had made its first and second fly-bys of Earth, respectively.

Although Wirtanen remained as Rosetta's prime target, further studies of possible candidates resulted in changes to the asteroid fly-bys. By 1997, the planners were considering whether to visit a different S-class asteroid, (2703) Rodari, instead of Shipka (see Table 6.1).

Table 6.1: Summary of Planned Major Events for Rosetta's Mission to Comet Wirtanen with Fly-bys of Asteroids Mimistrobell and Rodari

Event	Date	Days	Object Distance (km)	Earth Distance (km or AU)
Launch from Earth	21 Jan 2003	0	0	0 km
Mars gravity assist	26 Aug 2005	948	200	0.69 AU
First Earth gravity assist	26 Nov 2005	1,040	3,332	3,332 km
Mimistrobell fly-by	15 Sep 2005	1,333	600	2.34 AU
Second Earth gravity assist	26 Nov 2007	1,770	2,315	2,315 km
Rodari fly-by	4 May 2008	1,930	1,580	1.46 AU
Orbiting Wirtanen	24 Aug 2011	3,136	4-18	4.81 AU
Delivery of RoLand	22 Aug 2012	3,443	1	2.60 AU
Shutdown of systems	10 July 2013	3,768	0	1.06 AU

As the launch came closer, the fly-by targets were changed to another pair of contrasting objects: (140) Siwa, which would be the largest asteroid yet encountered by a spacecraft, and (4979) Otawara, the smallest apart from Dactyl, the tiny satellite discovered by the Galileo spacecraft during a fly-by of (243) Ida.

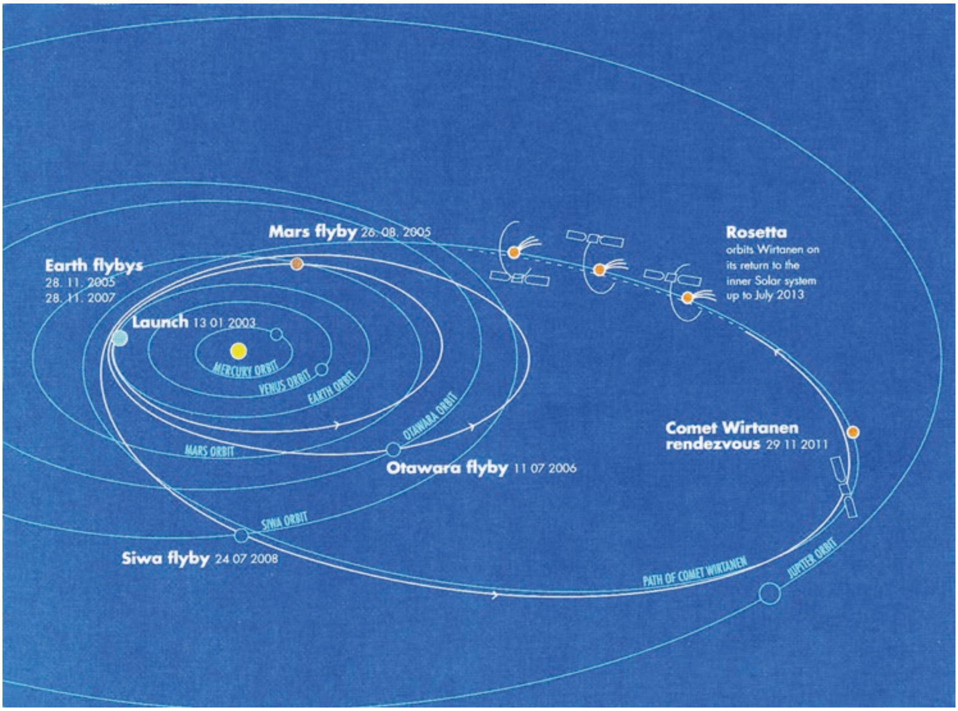

Fig. 6.2: The mission plan for the Rosetta mission with one Mars fly-by, two Earth fly-bys, and encounters with main belt asteroids Otawara and Siwa on the way to Comet Wirtanen. (ESA)

The Otawara fly-by (see Fig. 6.2) was to occur 1.89 AU from the Sun, on 11 July 2006. The spacecraft would pass its sunlit side at a range of about 1,595 km and a relative velocity of 10.63 km/s.

Apart from its orbit, little was known about Otawara until it became the subject of a ground-based program of studies undertaken by telescopes in France, Chile and the USA.

Otawara was believed to be a stony object rich in the minerals pyroxene and/or olivine, but it was also possible it belonged to an asteroid family named after its largest member, (4) Vesta. Presuming Otawara to be dark, its diameter was likely 2.6-4 km. Its density was estimated at 2-2.5 times greater than water, suggesting a substantial rocky component. A study of changes in its reflected light (its light curve) indicated that it rotated once every 2.7 hours, which was faster than any asteroid visited by spacecraft to that time. This would be an advantage during a fly-by, as it would enable the spacecraft's instruments to image the surface and measure its characteristics at high resolution during one complete rotation.

In contrast, with a diameter of 110 km, Siwa was much larger than any asteroid previously examined by spacecraft. Spectral studies indicated that it was a primitive, very black, carbon-rich object. Estimates for its rotation period varied between 18.5 hours and 22 hours. Rosetta was to obtain images and high-resolution data as it flew within 3,000 km of Siwa on 24 July 2008. It would approach the sunlit side at 17.04 km/s and see a crescent phase as it withdrew. Siwa would be 2.75 AU from the Sun and 3.11 AU from Earth, so signals from the spacecraft would take 26 minutes to reach ground stations.

Table 6.2: Vital Statistics of Rosetta's Asteroid Targets (pre-2003)

	Otawara	Siwa
Average distance from Sun (million km)	324	409
Orbital period (years)	3.19	4.51
Estimated size (km)	2.6-4	110
Estimated rotation period (hours)	2.7	18.5
Orbital inclination (degrees)	0.91	3.19
Orbital eccentricity	0.144	0.215
Asteroid type	V or SV	C
Date of discovery	2 August 1949	13 October 1874
Name of discoverer	K. Reinmuth	J. Palisa

6.3 A DRASTIC CHANGE OF PLAN

After years of planning for a launch to Comet Wirtanen in 2003, a major spanner was thrown in the schedule on 11 December 2002, when the Ariane 5 ECA rocket exploded during its maiden flight, with the loss of its payload of two communication satellites.

An Inquiry Board appointed by Arianespace, ESA and CNES (the French Space Agency) was established to investigate the cause of the "anomaly". Meanwhile, Arianespace, the operator of the Ariane 5, decided to create a Review Board to offer advice regarding the launch date of the next payload on the manifest: the Rosetta mission.

On 5 January 2003, the key participants announced that all irreversible operations involved in the Rosetta launch must be suspended. This would result in a launch postponement of at least several days beyond the targeted date of Sunday, 12 January (Kourou time).

On 7 January, the Board announced that the cause of the explosion early in the flight was a fault in the main rocket motor. The investigation blamed a leak in the cooling system of the nozzle of the Vulcain 2 engine. The overheating and deterioration of the nozzle produced an imbalance in the thrust of the engine which resulted in loss of control over the trajectory.

Although Rosetta was to be launched on a basic Ariane 5G – which differed from the ECA version by using tried-and-tested Vulcain 1 engines – the Review Board decided to play safe and recommended postponing the ground-breaking comet mission. Arianespace, ESA, and all of the other interested parties accepted this recommendation, and began a long consultation to decide arrangements for the earliest possible launch of Rosetta, and how it might differ from the planned mission.

Meanwhile, there was a thorough re-examination of the system qualification procedures for the Ariane 5 program to prevent the recurrence of such a mishap.

As for the spacecraft, it had to be moved and stored in flight-ready condition in a clean room at Kourou while its next launch campaign was decided. Long term storage involved removing its batteries, removing the harpoons from the lander, and draining the propellant tanks.

"The same care that went into building the spacecraft will now be applied to storing it and making sure it will be in perfect shape for us to launch it when the date comes," said John Ellwood, the project manager.

After the initial shock and disappointment of the last minute postponement, the Rosetta team set about redefining the entire mission profile. The overall sentiment was one of defiance and a determination to succeed, despite the significant setback.

As Rosetta's project scientist, Gerhard Schwehm, put it, "During the decade it has taken us to develop and build Rosetta, we have faced many challenges and overcome them all. This new challenge will be met with the same energy, enthusiasm and, ultimately, success."

6.4 THE PROJECT MANAGER'S VIEW

In November 2019, John Ellwood, Rosetta project manager at the time of the Ariane 5 ECA disaster, commented in an email about its impact on the comet mission:

> I was actually in Paris in mid-December when we heard of the problems with the Ariane launch. The spacecraft was in Kourou being filled with fuel and oxidizer, which we planned to do before the Christmas break to be ready for launch in January 2003.
>
> We took no immediate action until Arianespace could assess the problem. I went out to Kourou just after Christmas and had many discussions with Jean

Jacques Dordain, who was in Europe during this time. He was Director of Launchers, just about to become DG (ESA Director General). I remember the actual call – when we decided to postpone the mission – was when I had taken the day off with my family to go to visit Devil's Island. I was sitting on the side deck of a large catamaran in the hot sun, difficult to hear my mobile due to the gentle breeze, taking part in this decision-making process!

There was no real choice in this decision – Arianespace/ESA/Europe could not risk another failure and there was not really enough time to demonstrate what had gone wrong and how to make the Rosetta launch safe.

At first the team were pretty devastated – we had had a pretty long and hard launch campaign and were almost at the climax. We also did not know what were the back-up scenarios. The scientists had continuously told us that this was the unique opportunity.

The immediate decisions were what to do with the spacecraft and what were our future options. We managed to defuel the spacecraft but could not take the oxidizer out for fear of potential technical problems – this had never been done before. We therefore decided to leave the spacecraft in Kourou and the immediate tasks were to organize the logistics of this.

We then started to have discussions with the scientists and ESOC about what other possible target comet opportunities there were. There were none with comets around the same size and with the same journey time with a launch in the near future.

Someone proposed that there could be a possibility to launch to Wirtanen later in the year, using the slightly more powerful Proton launcher. I then embarked on a crash action with the Russians to address this possibility. There were all sorts of political and financial implications with it, but we started with looking at the technical possibilities. Although it was technically possible from an interface and orbit viewpoint, the main problem was moving the spacecraft from Kourou to Baikonur – we could not this do with oxidizer on board, and eventually we judged it too risky to the reaction control system to try and take it out.

We were back to looking at other opportunities and then the scientists hit on 67P/C-G, which was larger than Wirtanen and would take, I think, another two years' journey time.

The mission team had quite a frustrating 2003, but there were many things to do. After the business with the Russians, we had to prepare the new scenario. It also gave us a bit of time to sort out other issues. (See Chapter 4.)

6.5 A NEW DESTINATION

One obvious issue was that Rosetta could no longer reach its original target, Comet Wirtanen, in the planned time frame. The mission team was tasked to identify any suitable comets that it could reach if launched within the next two-and-a-half years.

There were three overriding criteria: the potential for maximum scientific return, minimizing the technical risks to the spacecraft, and minimizing the additional expenses, estimated at that time as likely to be in the range €50-100 million.

Fortunately, the Rosetta team was able to start with the list of potential targets for the Comet Nucleus Sample Return mission developed by the ESOC mission analysis team, headed by Martin Hechler (see Chapter 3). During the early study phase for CNSR they had developed extended lists of launch date and comet target combinations, along with calculations of the spacecraft mass that could be delivered to each target by an Ariane launcher.

Nevertheless, the search for Rosetta's new destination proved problematic, and the shortlist presented to ESA's Science Program Committee (SPC) on 25-26 February 2003 provided no easy answers.

The options included:

- Keeping Comet Wirtanen as the target. The spacecraft, and especially its lander, were designed to explore this comet with its small nucleus. However, waiting for the next easy launch window to Wirtanen was undesirable because that would require keeping Rosetta in storage until the comet returned to the inner Solar System after completing another 5.5 year orbit.
- A fly-by of Venus that could sling the spacecraft to a 2012 rendezvous with Wirtanen after launches in October 2003 or April 2004. However, sending Rosetta to Wirtanen by utilizing a Venus gravity assist was impossible because Rosetta's design was only qualified to go within 0.9 AU of the Sun. The greater intensity of solar radiation near Venus would potentially damage many spacecraft systems – unless a major redesign was undertaken, which was undesirable.
- Comets Tempel 2 or Howell could be reached without a fly-by of Venus. However, Rosetta would still require an approach within 0.8 AU of the Sun. Furthermore, the nucleus of Tempel 2 was far too large at 16 × 8 km. In the stronger gravity field the lander would crash onto the surface.
- A launch to Wirtanen in January 2004, using a more powerful rocket than the Ariane 5G. This might be done using an Ariane 5 ECA, but there was a doubt over whether this version would be ready in time. The only qualified rocket that was suitable was Russia's Proton DM, but Rosetta was 40 cm too

big for the Proton's payload fairing, which would have to be modified and qualified within the next 10 months.

- A launch to another familiar periodic comet – 67P/Churyumov-Gerasimenko. This seemed to be the easiest solution. Using an Ariane 5G+ rocket to launch in February 2004 and taking advantage of fly-bys of Earth and Mars, the mission could reach the comet in 2014. On the down side, the nucleus was thought to measure about 5 km in diameter, which was somewhat larger and more massive than the lander's designers had envisaged.

Of the nine mission scenarios studied by the Rosetta Science Working Team, three survived and were presented to the delegations of the ESA Member States during the Science Program Committee meeting on 25-26 February 2003. Two of the scenarios would see Rosetta launch to 67P/Churyumov-Gerasimenko in February 2004 or 2005 using either an Ariane 5 hybrid or a Proton. The alternative was to use a Proton to launch it to Comet Wirtanen in January 2004.

To better inform the comet selection process, intensive efforts were made to learn as much as possible about the potential targets using facilities that included the Hubble Space Telescope and the Very Large Telescope of the European Southern Observatory in Chile.

Having discussed the suitability and viability of the options, the SPC announced its decision on Rosetta's new baseline mission at its meeting on 13-14 May 2003.

The revamped mission was to be launched in February-March 2004 by an Ariane 5G+ for a rendezvous with Comet 67P/Churyumov-Gerasimenko in November 2014. Mission planners were to study a launch to the same target one year later as a back-up.

Even then, the revamped mission did not immediately receive the all-clear, owing to financial constraints. The cost of the proposed postponement was estimated at €80 million.

In January 2003, ESA's Director of Science, Professor David Southwood, had been confident that the additional commitment could be absorbed by the existing science budget. However, since then a number of other unexpected financial challenges had arisen – notably the need to inject €70 million into the development of instruments for two other high profile astronomy missions: Herschel and Planck.

"I am not asking for more money overall, but for help in cash flow," explained Southwood. "We in ESA are sure that we will find the necessary sensitivity, understanding and, ultimately, solidarity from the [ESA] Council. Europe paved the way to comet science with Giotto and it is a matter of great pride that the ultimate comet explorer will be European."

He gained a sympathetic hearing at the June meeting of the ESA Council, which decided the money to save Rosetta would be found through some immediate "financial flexibility" at Agency level.

6.6 COMET 67P/CHURYUMOV-GERASIMENKO

Like Comet Wirtanen, Rosetta's new target was a regular visitor to the inner Solar System. 67P/Churyumov-Gerasimenko – hereafter abbreviated to 67P – was a member of the Jupiter family of comets whose orbits were modified by close approaches to the giant planet. Both of these comets were thought to have originated in the Kuiper Belt (see Chapter 1) and been deflected into the inner Solar System.

Comet 67P was discovered in 1969, when several astronomers from Kiev were visiting the Alma-Ata Astrophysical Institute to undertake a survey of comets. On 20 September, while studying photographs of 32P/Comas Solá taken by Svetlana Gerasimenko, Klim Churyumov found a comet-like object near the edge of one plate. He assumed that the faint object was the expected comet, but further analysis established it to be a new one.

Table 6.3: Comet 67P/Churyumov-Gerasimenko (2003 data)

Diameter of nucleus (km)	5 × 3
Orbital period (years)	6.57
Perihelion distance from Sun	194 million km (1.29 AU)
Aphelion distance from Sun	858 million km (5.74 AU)
Orbital eccentricity	0.632
Orbital inclination (degrees)	7.12
Year of discovery	1969
Discoverers	Klim Churyumov, Svetlana Gerasimenko

The comet's orbital history is particularly interesting. Until 1840, it never approached the Sun closer than 4 AU and was thus completely unobservable from Earth.

That year, a fairly close encounter with Jupiter caused the orbit to move inward, producing a perihelion of 3 AU. Over the next century, this was gradually decreased to 2.77 AU. Then, in 1959, another Jupiter encounter reduced it to a mere 1.28 AU. The orbit continued to evolve and, after another perturbation from Jupiter in 2007, the perihelion at the time of the Rosetta encounter in 2014 was expected to be 1.24 AU.

At the time that 67P was selected as Rosetta's target, the comet was making one circuit of the Sun every 6.57 years. It had been observed from Earth on six apparitions – 1969 (discovery), 1976, 1982, 1989, 1996 and 2002 – and was unusually active for a short period object, with a diffuse coma of dust and gas surrounding the solid nucleus and often producing a tail when at perihelion. At the 2002-2003 apparition, the tail was up to 10 arcminutes long, with a bright central condensation in a faint extended coma. Even seven months after perihelion its tail was very well developed, although it then rapidly faded.

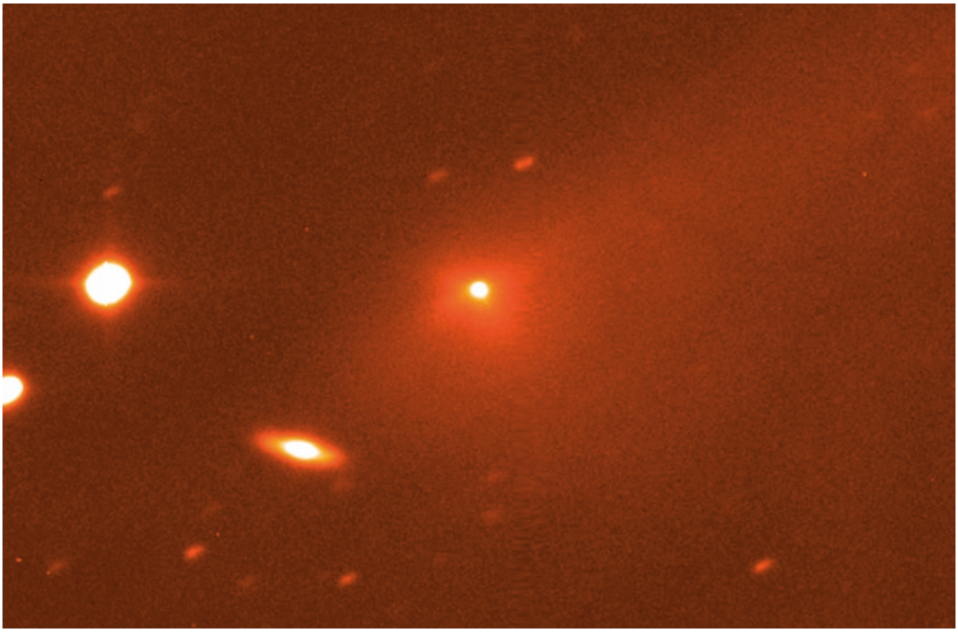

Fig. 6.3: A composite of 15 images of the nucleus of Comet 67P (the central point of light), taken on 26 February 2004 using the 3.5 meter New Technology Telescope of the European Southern Observatory. The telescope was tracking the comet, so the stars appear as streaks. The comet's nucleus appears almost star-like, indicating it to be surrounded by a very small amount of gas or dust. The comet was approximately 600 million km from Earth. (ESO)

The comet typically reached a magnitude of 12, with outbursts around perihelion on its 1982-1983, 1996-1997 and 2002-2003 apparitions. Despite being a relatively active object, even at the peak of outburst the rate of dust production was estimated to be some 40 times lower than for Halley's Comet. Nevertheless, 67P was classed as a dusty comet. In 2002-2003, the peak dust production rate was approximately 60 kg/s, and values as high as 220 kg/s were reported in 1982-1983. The gas to dust emission ratio was approximately two.

The Wide Field Planetary Camera 2 on the Hubble Space Telescope (HST) took 61 images of Comet 67P on 11-12 March 2003. The HST's sharp vision enabled astronomers to isolate the comet's nucleus from the surrounding coma. The images showed that the nucleus measured 5 × 3 km and had an ellipsoidal (rugby ball) shape. It rotated once in approximately 12 hours.

"Although 67P is roughly three times larger than the original Rosetta target, its elongated shape should make landing on its nucleus feasible – now that measures are in place to adapt the lander package to the new configuration before next year's launch," said Philippe Lamy of the Laboratoire d'Astronomie Spatiale in France.

6.7 LANDING ON A LARGER COMET

In May 2003, engineers were presented with a new challenge when ESA's SPC announced that 67P would replace Wirtanen as Rosetta's objective.

The most obvious challenges were the different orbits and dates of arrival in the inner Solar System. However, the team from ESA, industry and academia would also have to prepare the Rosetta lander for a hazardous descent onto a much larger cosmic iceberg than was initially envisaged.

With time of the essence, the team began to study the implications of exploring 67P and the modifications that the fragile lander might require. After months of studies and simulations, engineers were confident that everything possible had been done to ensure the success of the first soft touchdown on such a pristine surface.

As Philippe Kletzkine, ESA's manager for the Rosetta lander, explained:

> Churyumov-Gerasimenko is a much bigger comet than Wirtanen. It is about four times the diameter and its gravity could be at least 30 times greater. This means that the landing speed will increase from 0.2-0.5 meters per second to 0.7-1.5 meters per second.
>
> In the case of Wirtanen, our biggest problem was avoiding a rebound – the spacecraft only had to bounce slightly and the momentum would overcome the weak gravitational hold of the comet.
>
> Now, we also have to worry about absorbing the shock from a faster landing and the stability of the lander upon touchdown. In the worst case scenario of a 'hard' comet surface, rough terrain and relatively high gravity, it was possible that the lander could topple over. In order to prevent this, we decided to modify the landing gear.

Reluctant to remove the landing gear or eliminate the entire lander from the Rosetta orbiter, the team considered options for something that would be small, light, and easy to fit. Their solution was a bracket, called a tilt limiter, that could be attached to the bottom of the lander.

Jean-Christophe Salvignol, the Rosetta lander mechanical engineer, explained the issue:

> By restricting the angle at which the landing gear can flex on touchdown to only 3-5 degrees, we improve the damping effect on touchdown and reduce the possibility of a rebound.
>
> The limiter was designed by Astrium GmbH in collaboration with ourselves and the Max-Planck-Institute in Lindau. During pendulum tests with a model of the landing gear, we simulated landing on a wall at different angles of

approach, and verified that the spacecraft could successfully touch down at speeds of up to 1.5 meters per second on a 10 degree slope, or up to 1.2 meters per second on a 30 degree slope.

In parallel, computerized simulations of landings were run by the Max-Planck-Institute to better determine the landing performances for various surface characteristics, impact velocities and lander attitudes.

On 30 September 2003 the tilt limiter was delivered to Kourou and installed on the Rosetta lander.

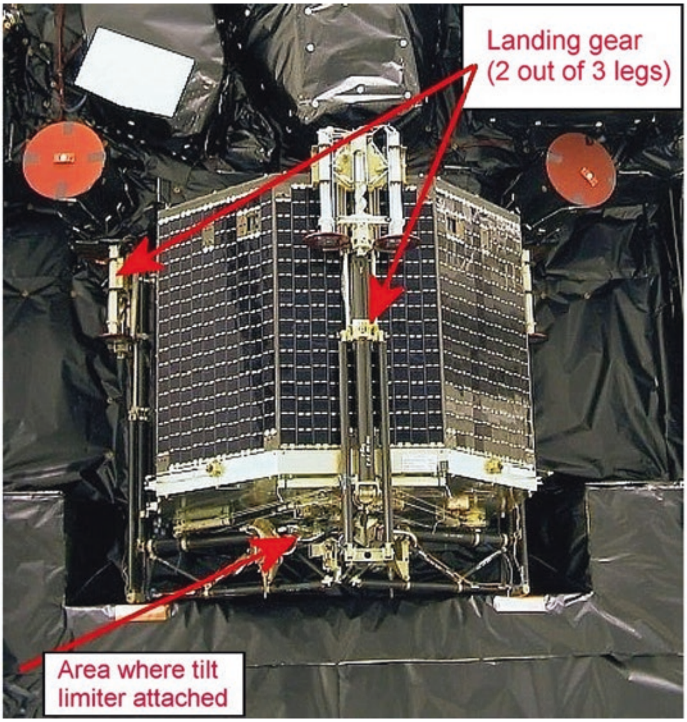

Fig. 6.4: The location of the tilt limiter on the Rosetta lander. (Max-Planck-Institute/ESA)

"This excellent collaboration between ESA, industry and MPAe has enabled us to adapt to the new mission very quickly and efficiently," said Salvignol.

No major changes were envisaged for the lander's descent profile. However, under the new mission scenario, there would be more time available for the orbiter's instruments to map the nucleus in detail, in order to facilitate the selection of a safe touchdown location for the 100 kg lander.

The historic touchdown on the icy nucleus of Comet 67P was expected to occur sometime in November 2014.

6.8 THE NEW FLIGHT PLAN

During the decade-long journey to reach 67P – two years longer than the planned mission to Comet Wirtanen – Rosetta would have to travel as far from the Sun as Jupiter's orbit. Since no launch vehicle was capable of sending it there directly, the plan required the spacecraft to gain energy from gravitational assists during one fly-by of Mars in 2007 and three fly-bys of Earth in 2005, 2007 and 2009.

It was anticipated that the amount of science that could be conducted during this deep space cruising would be similar to that expected in the original flight plan. The Wirtanen flight plan had included observations of Mars and two very unusual asteroids. However, with the revised mission scenario, Rosetta would experience an eclipse during the Mars fly-by, and this would restrict the science activities that could be performed there.

As before, Rosetta would pass twice through the asteroid belt – where it was hoped to make close-up observations of at least one of these primitive objects. A number of candidate targets were identified, but the final selection would not be made until after launch, once the amount of fuel that was available had been verified by mission engineers.

Since Rosetta would be launching to 67P with the same amount of oxidizer and fuel that was available for the Wirtanen target, the mission team had to examine the spacecraft's propellant margins very carefully. Of particular concern was the extended thruster firing that would be required to rendezvous with the comet.

"We do not have too much fuel to spare," explained John Ellwood, Rosetta project manager. "Our capability to target one or more asteroids will depend on the efficiency of the launch and how much fuel we will need to conduct orbital maneuvers and course corrections, so no decision will be made until after lift-off."

Despite the modifications and unknowns mentioned above, many aspects of the expedition to explore some of the most primitive objects in the Solar System remained very similar to those originally planned.

The Ariane 5 launch from Kourou in February-March 2004 would put the upper stage into a 4,000 × 200 km orbit of Earth. About two hours later, the rocket's upper stage would ignite once more to send the comet chaser on its way.

The first gravitational 'slingshot' was to take place in March 2005, when Rosetta returned to the vicinity of Earth. Three years into the mission, it would pass Mars. The second encounter with Earth would occur in November 2007. With its orbit now more elliptical, Rosetta would penetrate the asteroid belt for the first time, prior to its third and final visit home in November 2009. Only then would it have sufficient velocity to set course for the comet. After its second passage through the asteroid belt it was to be placed in a state of hibernation.

Finally, after more than seven years of interplanetary travel, Rosetta was to cross the orbit of Jupiter, some 800 million km from the Sun, and fire its thrusters to alter course and intercept 67P. Handicapped by the reduced sunlight (25 times

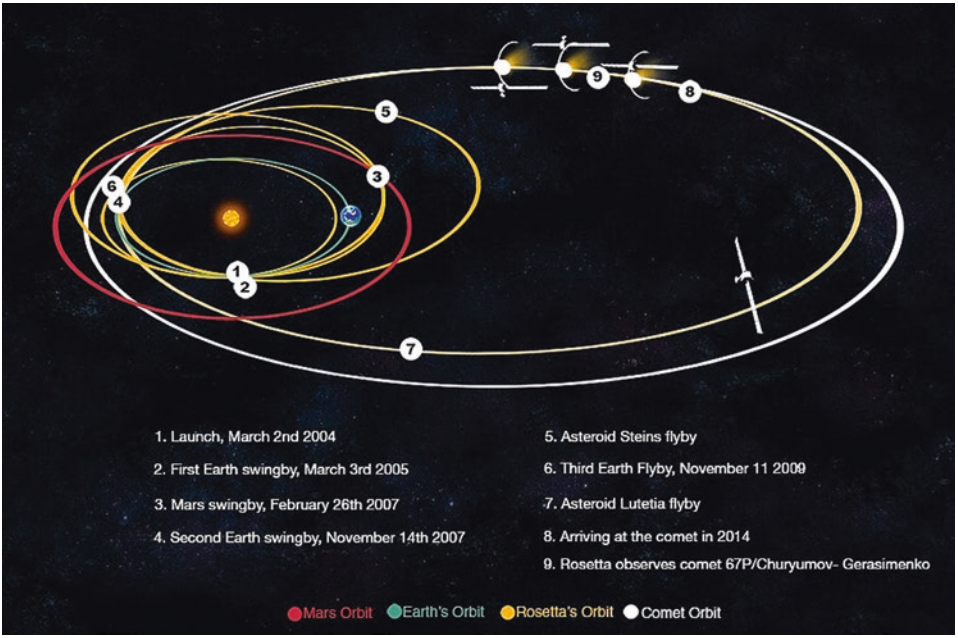

Fig. 6.5: Launching in March 2004, Rosetta would take 10 years to rendezvous with Comet 67P using gravitational assists from three Earth fly-bys and a Mars fly-by. Along the way, it would twice cross the main asteroid belt, where there would be opportunities to conduct two asteroid fly-bys. (NASA-JPL)

less intense than on Earth) the spacecraft would be running on minimal electrical power and relying heavily on its huge solar panels to capture every photon. But the power levels would gradually rise as it started to head sunward and close in on 67P. By the second rendezvous maneuver in May 2014, the electricity supply would be adequate to enable operation of the suite of 10 scientific instruments.

When the target's position was pin-pointed, Rosetta would edge towards the speeding comet and, in August 2014, maneuver into orbit around it. Once the nucleus had been surveyed, and a safe landing site selected, the spacecraft would release its lander to slowly fall toward the black, pristine surface.

"We may separate at a lower altitude, since this means less acceleration," explained Philippe Kletzkine. "We anticipate a maximum separation speed of just half a meter per second, so the overall descent time is likely to be between 30 minutes and one hour. We anticipate a landing on the 'summer' side of the nucleus, where there is maximum illumination."

Over a period of several weeks, a treasure trove of data from the lander's nine instruments would be sent back to Earth via the orbiter.

Meanwhile, the orbiter would continue to watch the dramatic changes in the nucleus during its headlong plunge toward the inner Solar System.

Despite its generally more active nature, scientists reckoned that the dust environment close to the nucleus of 67P would be only marginally more hazardous to the spacecraft than would have been so for Wirtanen. This was because 67P's larger perihelion distance meant that its nucleus was heated less strongly by the Sun, potentially limiting the output of dust that could threaten the orbiter.

Rosetta's unique odyssey of exploration was expected to end in December 2015, six months after the comet passed perihelion and was retreating to the frigid regions of deep space. After a saga lasting almost 12 years, the curtain would finally fall on the most ambitious European scientific mission ever launched.

Table 6.4: The Revised Mission Plan – The Voyage to Comet 67P

Launch from Kourou	2 March 2004 (UT)
1st Earth gravity assist	4 March 2005
Mars gravity assist	25 February 2007
2nd Earth gravity assist	13 November 2007
Asteroid Steins fly-by	5 September 2008
3rd Earth gravity assist	13 November 2009
Asteroid Lutetia fly-by	10 July 2010
Enter deep space hibernation	8 June 2011
Exit deep space hibernation	20 January 2014
Major comet rendezvous maneuver	May 2014
Arrive at comet	August 2014
Philae lander delivery	11 November 2014
Perihelion passage	13 August 2015
Mission end	31 December 2015

6.9 PREPARING FOR LAUNCH, ROUND 2

After deciding to ground Rosetta in January 2003, weeks before its launch campaign was due to complete, the priority was to ensure that the orbiter and its attached lander could be stored in a completely safe, clean environment until a new launch date could be agreed.

Once the spacecraft was carefully moved to the empty S3B clean room at Kourou, a number of safety precautions were undertaken, including the removal of the needle-sharp explosive harpoons, the high-gain antenna, and the huge solar arrays. The mission team also decided to exploit the delay by removing and refurbishing five of the orbiter's instruments.

One of the main questions was how to deal with the fully fueled spacecraft. Eventually, it was decided to offload the 660 kg of toxic, corrosive, monomethylhydrazine (MMH) fuel. This dangerous and time-consuming procedure was eventually completed on 7 May. However, it was decided to leave the nitrogen tetroxide oxidizer on board, with the system pressurized. Experience with other spacecraft had indicated that, after offloading this oxidizer, the residual nitric oxide acid had the potential to corrode the titanium tank.

After the mission was retargeted to explore 67P, the Rosetta ground team was able to begin preparations. One of their first tasks was to update the software to satisfy the requirements of the revised mission.

As Jan van Casteren, Rosetta's systems engineering manager, explained, "We had already prepared some software for uplink to Rosetta in May, four months after its planned launch, so we decided to take advantage of the delay to include additional functionality and put the new software on board the spacecraft while it is on the ground."

Other modifications were made to allow for the fact that Rosetta would at various times move closer to the Sun, or farther away from it, than previously planned during its prolonged trek to its target.

"We put reflective surfaces on the exterior of some thermal blankets to prevent overheating," explained van Casteren. "We also had to analyze the potential impact of spending longer in space during a period of maximum solar activity. By accumulating a larger overall dose of radiation, there was a likelihood that the solar arrays would be degraded more quickly, so we carefully investigated the power situation to ensure that we would have a sufficient margin throughout the mission. This gave us confidence that Rosetta will have enough power at all stages of its mission, even when it is beyond the orbit of Jupiter."

John Ellwood, Rosetta's project manager, said, "Although we were all disappointed by the delay, we've been able to take advantage of the additional time on the ground to ensure that Rosetta is in perfect health for its exciting new mission."

The Second Launch Campaign

After verifying system functionality in August-September, the Launch Preparation Readiness Review Board gave the go-ahead to initiate Rosetta's second launch campaign. Once the new flight profile and fly-by targets had been identified, the way was clear for the Center Spatiale Guyanais (CSG) in Kourou to formally start the new campaign on 24 October 2003.

After the postponement of the original launch, some pieces of hardware were removed from the Rosetta orbiter, prior to its storage so the first steps on the road to mission recovery were to reinstall these appendages.

By 3 November, the Alenia assembly, integration and verification (AIV) team had successfully reattached the high-gain antenna to the spacecraft. On 28 November, it passed its deployment test and was then returned to the stowed position required for launch.

In parallel, experts from Dutch Space were carefully inspecting the solar arrays whilst they were still dismounted and suspended beneath the solar array rig. Once this was finished, the electrical and mechanical connections for the arrays were undertaken by a joint Dutch Space and Alenia team.

When the solar arrays were reinstalled, a final deployment test was carried out on each wing. This involved six sequential firings of the thermal knives on each wing, enabling each panel to open, supported by the deployment rig. Then the wings were restowed in readiness for the launch.

Another task included finalization of the multi-layer insulation. In November, personnel from Austrian Aerospace, assisted by staff from Alenia, Astrium and ESA, carefully sowed these blankets back into position.

By late November, the two PROM (Programmable Read-Only Memory) cassettes had been successfully integrated and verified, including tests that were made remotely from ESOC in Germany. The final activities for the GIADA instrument were also undertaken, including the cleaning of internal optical surfaces and laser system health checks.

Rosetta activities in Kourou were closed down for the rest of the year on 3 December, after which the spacecraft was “baby-sat” by a small team of engineers.

The next major pre-launch milestone in Kourou took place on 27-28 January 2004, when the orbiter was refueled with MMH propellant and then pressurized by a team from Astrium Ltd.

Fig. 6.6: MMH propellant being loaded into the Rosetta orbiter by a team from Astrium Ltd., on 27-28 January 2004. (ESA-CNES-Arianespace)

January also saw the completion of the ground checkout activities of the Rosetta lander. The flawless Cruise Abbreviated Functional Test demonstrated that all subsystems and payloads were fully operative. To round off these tests, the electrical configuration was finalized for launch, the primary battery was checked, and the secondary battery was charged. Finally, the harpoons to anchor the lander to the surface of the comet were reinstalled, still fitted with tip protectors.

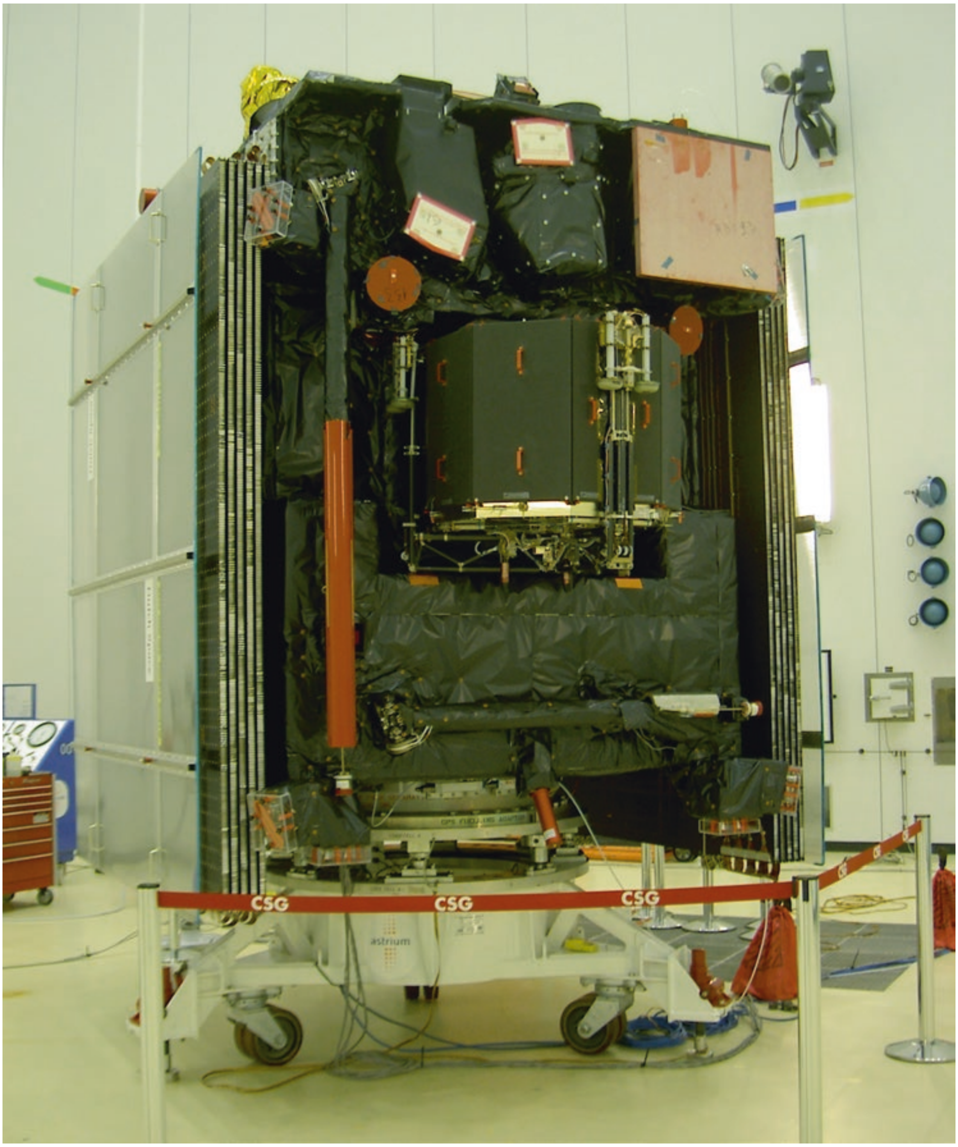

Fig. 6.7: The Rosetta orbiter and its lander (center) in the clean room at Kourou in January 2004. Note the folded solar arrays on either side of the orbiter. (ESA)

On 5 February, the DLR-led team and ESA announced that the pioneering comet lander had been named ‘Philae’.

Philae is an island in the river Nile where an obelisk was found with a bilingual inscription which included the names of Cleopatra and Ptolemy in Egyptian hieroglyphs. This gave the French researcher Jean-François Champollion the final clues that he required to decipher the hieroglyphs of the Rosetta Stone, and thereby unlock the secrets of the civilization of ancient Egypt (see Chapter 3).

On 10 February, the Ariane 5G+ (V158) launcher, minus its payload, was transferred on its mobile table from the Launcher Integration Building (Batiment d'Integration des Lanceurs, BIL) to the Final Assembly Building (Batiment d'Assemblage Final, BAF) with a temporary dome in place to protect the EPS upper stage and vehicle equipment bay.

That same day, the finely choreographed campaign continued with the transfer of the Rosetta spacecraft from the fueling hall, followed by its integration with the mechanical and electrical launcher interfaces on the cone-shaped launch adapter (Adapteur de Charge Utile, ACU) that would attach it to the top of the launcher.

Whilst the spacecraft underwent a day of electrical health tests, the power supply rack for the spacecraft was installed in the bottom of the rocket's launch table. This would supply power to Rosetta until several minutes before launch.

After its transfer from the S3B building to the Final Integration Building, Rosetta was placed on top of its launcher on 16 February. This maneuver required it to be lifted about 40 meters to the top of the BAF, then moved sideways, lowered onto the Ariane 5, and secured in place by nearly 200 bolts.

Fig. 6.8: On 16 February 2014, Rosetta and its payload adapter were lifted about 40 meters in the Final Assembly Building, ready for mating with its Ariane 5 launch vehicle. (ESA)

Fig. 6.9: Rosetta was secured on top of the Ariane 5 launch vehicle by almost 200 bolts. The upper stage is visible, as is one of its side boosters on the right, beneath the platform. (ESA)

The next day, the orbiter's batteries were connected and charged to full capacity. At the same time, its protective covers were removed. This cleared the way for the aerodynamic fairing to be installed that would protect the spacecraft on its final days on the launch pad and the early part of the ascent.

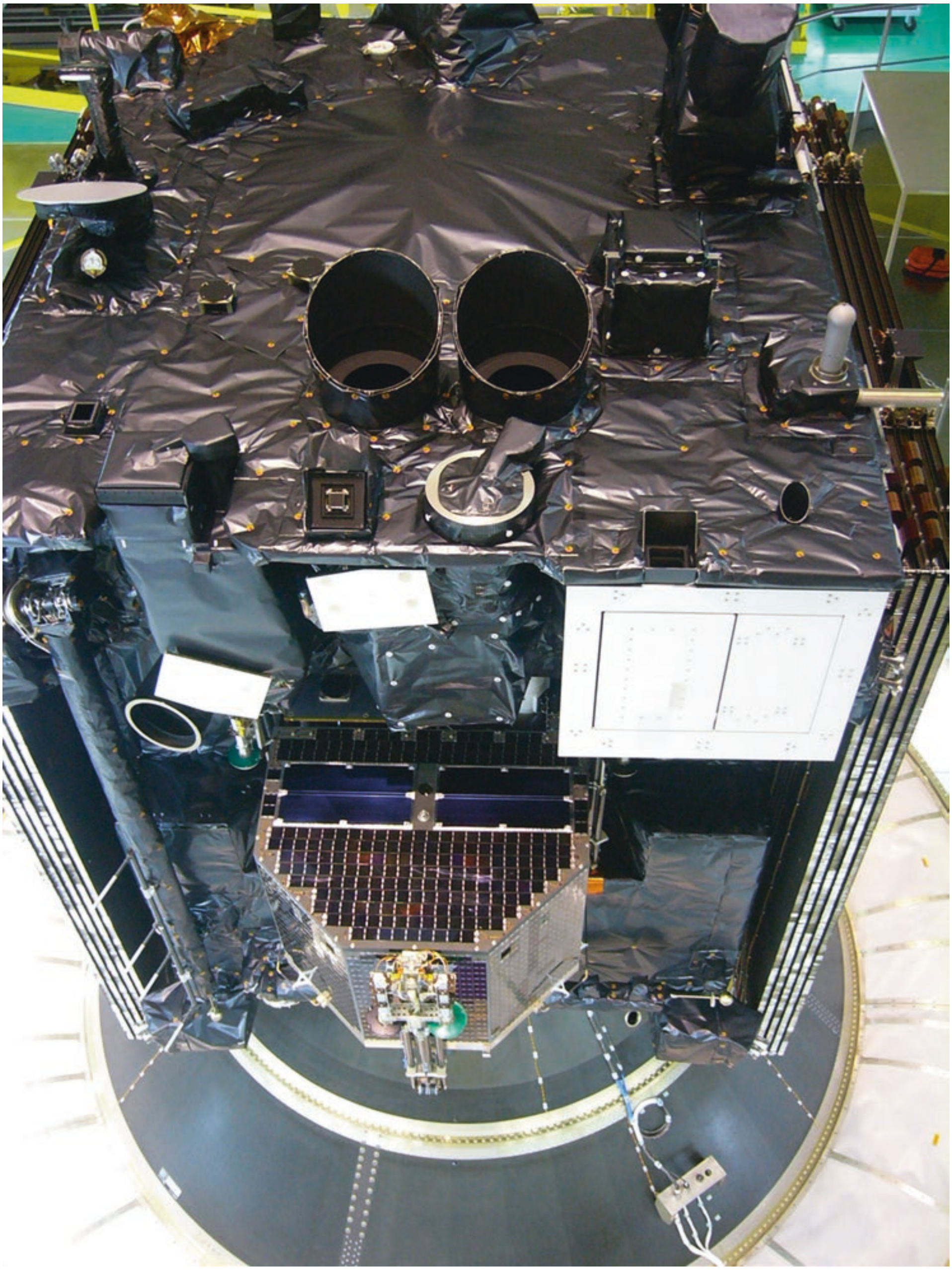

Fig. 6.10: Rosetta with all of its protective covers removed, shortly before the aerodynamic fairing was attached to the launcher on 17 February. The lander is visible in the foreground. (ESA)

A large hose connected to the fairing provided a continuous airflow of 3,400 cubic meters per hour in order to keep the satellite in a clean, temperature controlled environment until launch.

The final activity involving the spacecraft took place on the evening of 23 February, when the lander's harpoons were armed and their protective covers removed – a delicate operation that involved a team member entering the fairing with what was referred to as a "diving board".

Fig. 6.11: A technician working inside the payload fairing to arm the lander's harpoons and remove their protective covers. (ESA)

At 15:30 local time on 24 February the Ariane 5G+ rocket moved along the 2.8 km rail line from the Final Assembly Building to the ELA-3 launch zone.

Although the available launch window lasted from 26 February until 17 March, the launch time was unusually precise due to Rosetta's unique mission profile, with the lift-off of Ariane Flight 158 scheduled for 07:36:49 UT on 26 February.[2]

All seemed to be going as planned, but with only 20 minutes to go the launch was postponed due to strong winds at high altitude above the launch site. Both the Ariane launch vehicle and its payload were put in a safe mode. Arianespace Chief Executive Officer Jean-Yves Le Gall announced that the next opportunity would occur at the same time on the following day.

However, unexpected problems arose once again on 27 February, causing the countdown to be stopped for a second time. On this occasion, the launch vehicle was the cause. Prior to the start of the cryogenic stage's fueling, a visual inspection of the core stage's exterior revealed that a 10 × 15 cm piece of insulation was missing. The thermal protection was necessary to insulate the cryogenic oxygen/hydrogen in the core stage from the environment at the tropical launch site.

Arianespace and ESA announced that the lift-off would be delayed by several days while the insulation was repaired. To the frustration of all concerned, the rocket had to be moved back to the Final Assembly Building, where a new block of thermal protection would be installed. The adhesive would require some 36 hours to dry and cure.

Resumption of the countdown was postponed until the beginning of the following week. In the meantime, the 'safed' spacecraft remained inside the fairing.

The third attempt to launch Rosetta was scheduled for 07:16 UT on 2 March, at the start of that day's window, with an opportunity at 07:36 UT if the weather intervened again.

Lift-off!

After the postponement of the two previous launch attempts, it proved to be third time lucky. The final countdown resumed at 19:47 UT on 1 March. At 23:47 UT the ground team carried out a check of all electrical systems. Early the next morning, the filling of the main cryogenic stage with liquid oxygen and hydrogen took place, followed by the chill-down of the Vulcain engine.

At 06:07 UT on 2 March, checks of the communication links between the launcher and the telemetry, tracking, and command systems were successfully completed, and 63 minutes later mission control announced "all systems go" and initiated the synchronized launch sequence.

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[2] Flight 158 had two precise launch slots on 26 February: one at 7:16:49 UT and the other at 7:36:49 UT. These times would change a little if the actual launch date were to be changed. The actual launch time on 2 March was 07:17:44 UT. The overall launch window began on 26 February and lasted for 21 days. If this window had been missed, the mission would have been postponed.

Fig. 6.12: The Ariane 5G+ rocket lifts off from the ELA-3 launch site at 07:17:44 UT on 2 March 2004 carrying the 3 tonne Rosetta spacecraft. (Arianespace)

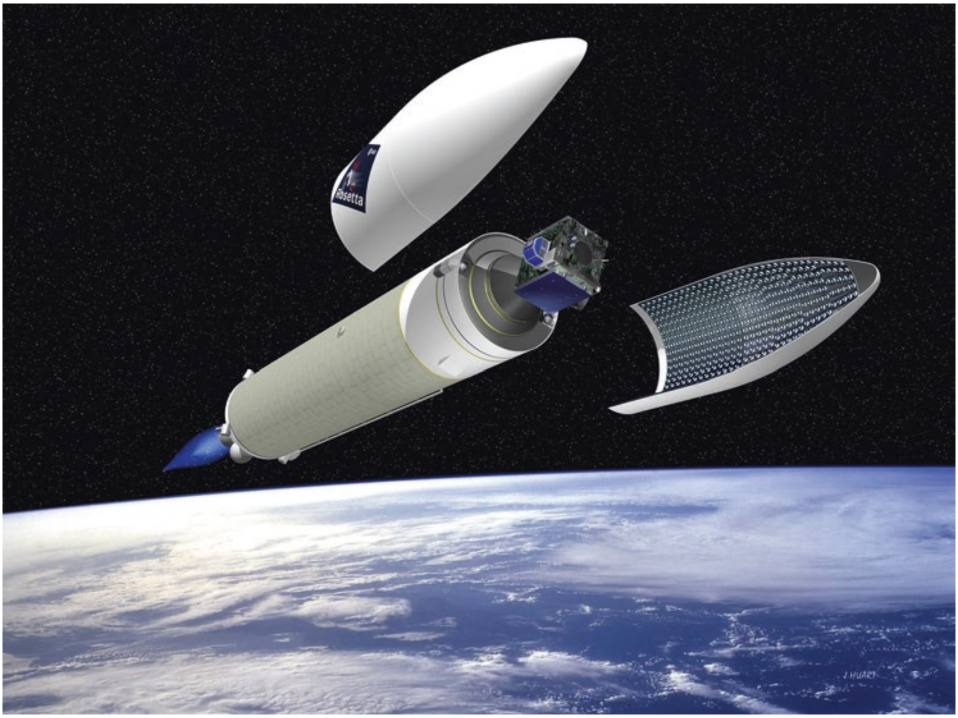

Fig. 6.13: The spent boosters jettisoned, the core stage of the Ariane 5 discards the fairing on its way to Earth orbit. (ESA/J. Huart)

At 07:17:44 UT, Ariane 5 Flight 158 roared off the ELA-3 launch pad at Kourou, its core stage and solid rocket boosters leaving a trail of fire as it rose into the black sky and headed east across the Atlantic Ocean. Three minutes later, the side booster rockets were successfully jettisoned, followed 50 seconds later by the fairing. At 07:29 UT the core stage exhausted its fuel and was discarded. The upper stage and its Rosetta payload were placed in an elliptical parking orbit that ranged between 250 km and 4,000 km.

Regular checks on the spacecraft's status were provided by ground tracking stations in Natal, Dongara (Australia) and Hawaii.

As this was the first time an Ariane 5 was being used to put a spacecraft on an Earth escape trajectory, involving a long delay prior to the final ignition of the upper stage, the European Space Operations Center (ESOC) in Darmstadt, Germany, monitored progress with mounting tension.

At 09:16 UT, the rocket's upper stage was ignited at an altitude of around 550 km. About 17 minutes later, the upper stage motor shut down on schedule, at an altitude of around 1,200 km. By the end of the burn, Rosetta's velocity had been boosted from 7,500 m/s to around 10,250 m/s. The tracking station at Kourou

Table 6.5: The Planned Sequence of Key Launch Activities

07:17:44 UT – Lift-off.
07:20 UT – The two solid rocket booster stages are successfully jettisoned, followed by the fairing.
07:25 UT – Acquisition by tracking station at Natal, Brazil.
07:29 UT – Ariane 5 has moved into a ballistic phase. Having burnt all its fuel, the main cryogenic stage was jettisoned. Rosetta and the Ariane 5 upper stage entered an elliptical parking orbit around Earth ranging between 250 km and 4,000 km.
08:05 UT – Acquisition of signal at the Dongara tracking station in Australia.
09:04 UT – Acquisition of signal at the South Point Tracking Station in Hawaii.
09:16 UT – Ignition of the EPS upper stage at an altitude of around 550 km and a velocity of 7,500 m/s. By the end of the 17 minute engine burn Rosetta is traveling at over 10,000 m/s (36,000 km/h).
09:28 UT – Signal acquisition at Kourou tracking station confirms an altitude of 750 km and a velocity of 10,180 m/s.
09:32 UT – Shut down of the EPS stage on schedule at an altitude of around 1,200 km and a velocity of around 10,250 m/s.
09:33 UT – Successful separation of the spacecraft. Rosetta is now on an escape trajectory and traveling out into the Solar System at a speed of about 3.4 km/s.
09:37 UT – ESOC in Germany takes over control of the mission and begins communicating with the spacecraft.
13:30 UT – The solar panels have been deployed successfully and the spacecraft is receiving power through them.

confirmed that Rosetta was looking good for separation and soon afterward the spacecraft set off at the start of its independent voyage into deep space.

After many years of trials and tribulations, Europe's comet chaser was finally escaping the grip of Earth's gravity and starting its 10-year trek to Comet 67P. The adventure had begun.

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