3

The Birth of Rosetta

3.1 DEFINING THE FUTURE

Even before the exciting new data came flooding back from the pioneering missions to various comets (see Chapter 2), scientists on both sides of the Atlantic were starting to consider their next steps. This process of crystal-ball gazing came at a time when knowledge of the origin, physical properties and composition of these 'cosmic icebergs' was distinctly sketchy. Innumerable comets had been studied by ground-based observatories, but, as yet, none had been visited by spacecraft and inspected at close quarters.

In 1985, ESA was putting together its long-term science program, named 'Horizon 2000'. There was still a year to go before Giotto would encounter Comet Halley but the planetary science community was already looking beyond that, and the Solar System Working Group recommended a Comet Nucleus Sample Return (CNSR) mission as a cornerstone of the new program. This was seen as the next logical step in improving our knowledge of these familiar, yet mysterious, objects. The proposed mission would involve sending an advanced spacecraft to land on a comet's nucleus, collect material, and return it to Earth for laboratory analysis.

In September 1985, a joint Science Definition Team (SDT) was created by Reimar Lüst, the European Space Agency's Director General, and Geoffrey Briggs, Director of Solar System Exploration at NASA, to identify the scientific goals for such a mission. It comprised thirteen European experts, many of whom were involved in the Giotto mission, and seven American researchers (see Table 3.1). They worked in parallel with another joint ESA-NASA panel, the Primitive Bodies Science Steering Group, whose task was to investigate possible missions to primitive bodies, namely asteroids and comets.

P. Bond, *Rosetta: The Remarkable Story of Europe's Comet Explorer*,
Springer Praxis Books, https://doi.org/10.1007/978-3-030-60720-3_3

Table 3.1: The Members of the CNSR Science Definition Team

European delegation:	
E. Grün (Co-Chairman)	Max-Planck-Institut fur Kernphysik, Heidelberg, West Germany
F. Begemann	Max-Planck-Institut fur Chemie, Mainz, West Germany
P. Eberhardt	Physikalisches Institut, Universitat Bern, Switzerland
A. Coradini	Istituto Astrofisica Spaziale – CNR, Rome, Italy
M. C. Festou	Institut d'Astrophysique, Paris, France
Y. Langevin	University Paris-Sud, Paris, France
J. A. M. McDonnell	University of Kent, Canterbury, UK
C. T. Pillinger	Open University, Milton Keynes, UK
G. Schwehm	ESA/ESTEC, Noordwijk, Netherlands
D. Stöffler	Universitat Munster, Munster, West Germany
H. Wänke	Max-Planck-Institut fur Chemie, Mainz, West Germany
R. M. West	European Southern Observatory, Garching, West Germany
U.S. Delegation:	
T. J. Ahrens (Co-Chairman)	California Institute of Technology, Pasadena, California
H. Campins	Planetary Science Institute, Tucson, Arizona
D. E. Brownlee	University of Washington, Seattle, Washington
S. Chang	NASA Ames Research Center, Moffett Field, California
A. W. Harris	Jet Propulsion Laboratory, Pasadena, California
G. J. Wasserburg	California Institute of Technology, Pasadena, California
J. A. Wood	Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts

The SDT held five meetings between 1985 and 1987, and then released a report. Meanwhile, NASA's Solar System Exploration Committee's Augmented Program rated such a mission as having high scientific merit.

3.2 HORIZON 2000

1985 also saw a major innovation in Europe's approach to space science, when ESA Member States approved Horizon 2000 as a long-term program of scientific research. This ambitious program was to ensure that Europe continued to play a key role in space science over the next 15 years, and beyond. It was also the starting point for a ground-breaking space mission that would soon become known as Rosetta.

- The primary objectives of Horizon 2000 were:
- To contribute to the advancement of fundamental scientific knowledge.
- To establish Europe as a major participant in the worldwide development of space science.
- To offer a balanced distribution of opportunities for frontline research to the European scientific community.
- To provide major technological challenges for innovative industrial development.

This new mandatory program would necessitate an increased financial commitment from the ESA Member States during the period of implementation.

Specifically, the realization of the Horizon 2000 plan would be critically dependent on an annual increase in expenditure of 5% until at least 1994, which was an unprecedented requirement at the time. The 5% growth rate for 1985-1989 was unanimously accepted at the ESA Council Meeting at Ministerial Level in 1985. However, the abstention by the UK at another vote at the next meeting in The Hague in 1987 effectively blocked the increase for the time being.

The Horizon 2000 missions would be separate from, but complementary to, the space science programs of ESA Member States. The countries that made the largest financial contributions to the Agency's science program would receive the largest industrial contracts – a procedure known as *juste retour* (fair return). The scientific payloads would be developed and provided by the Member States, under the leadership of principal investigators from the lead countries.

Although it was seen as a key means of promoting European space science, the program also allowed for the possibility of cooperation with agencies outside Europe, such as the United States and the Soviet Union, particularly for projects which were prohibitively expensive and required the development of new, advanced technologies.

Horizon 2000 was to include a balanced sequence of large and medium/small projects in all of the traditional science disciplines. In particular, it would include four major Cornerstone missions that would be developed over the next 15 years.

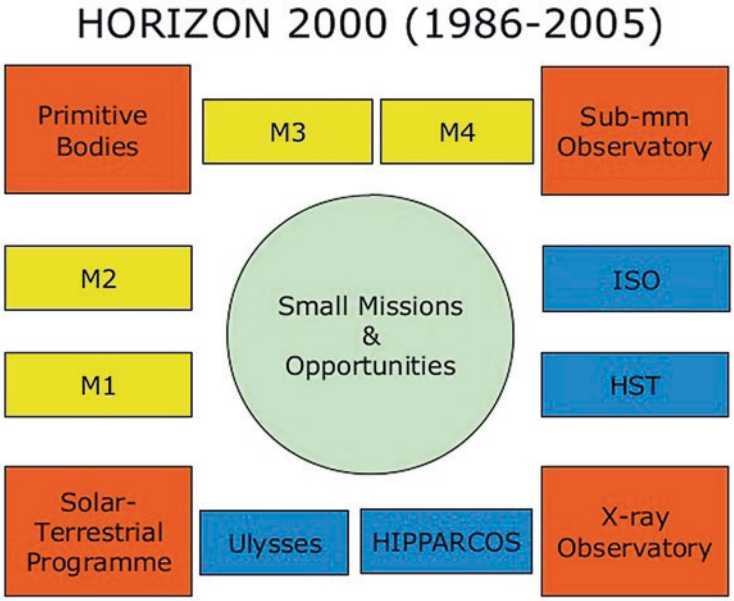

Fig. 3.1: ESA's Horizon 2000 long-term science program included four major Cornerstone space missions. The Primitive Bodies Cornerstone became the Rosetta mission. (ESA/Alvaro-Gimenez)

Cornerstone 1 was the Solar-Terrestrial Science Program (STSP). It comprised two medium-sized missions that were to investigate the complex interactions between the Sun and Earth. The Solar and Heliospheric Observatory (SOHO) was to be placed in a stable orbit between the Sun and Earth, a location known as the L1 Lagrangian point, from which it could observe continuously our nearest star, its corona and the solar wind.

The second STSP mission, named Cluster, involved the deployment of four identical, drum-shaped spacecraft into elliptical Earth orbits, to study the response of the near-Earth magnetic and particle environment to variations in solar activity.

The STSP was to be a co-operative venture by ESA and NASA, with its investigations led by scientists from both sides of the Atlantic.

The second Cornerstone to be authorized was an astrophysical observatory that would be a follow-on to Europe's successful Exosat mission. It would be devoted to the investigation of extremely hot, energetic objects that emit much of their energy in X-rays. Examples of such cosmic X-ray sources include supernova remnants and active galaxies. Originally called the High-Throughput X-Ray Spectroscopy Mission, it would be flown as the X-ray Multimirror Mission (XMM).

Bringing up the rear were the two remaining Cornerstones. One of these was to be a mission devoted to submillimeter astronomy. By providing the first space-based observations of the Universe at submillimeter wavelengths, the observatory would break new ground in the study of interstellar dust clouds and the formation of stars and planets. It was initially known as the Far Infra-Red Spectroscopy Mission, and then the Far Infrared and Submillimeter Telescope (FIRST), but in 2000 it was named the Herschel Space Observatory in honor of the famous discoverer of the planet Uranus and also the existence of infrared light.

The fourth Cornerstone was to be an international venture that was identified as a "mission to primordial bodies, including return of pristine material". This Cornerstone would build on the technological and scientific knowledge gained from the fly-by missions to Comet Halley, in particular the Giotto mission (see Chapter 2). This would require an advanced spacecraft that could return samples of material from either an asteroid or a comet. However, this ambitious next step was soon refined to become the first space mission designed to collect a sample of a comet's icy nucleus and return it to Earth.

This program introduced an unprecedented degree of complexity and sophistication to Solar System exploration, including long-term reconnaissance of a comet, soft landing on a comet's nucleus, drilling into its surface, collecting a sample, and safely returning it to Earth for study using the most advanced laboratory techniques.

To ensure that the new technologies and techniques required for a successful implementation of this pioneering enterprise would be available, ESA initiated a special Preparatory Program in 1986, with an anticipated completion date of 1991. This would define the mission scenario and system design, with the participation of European industry and the international scientific community. NASA would be involved as the likely provider of support in areas such as the carrier spacecraft, the launcher and deep space communications.

Following the formation of a joint ESA-NASA Science Definition Team in late 1985 (see Defining the Future above), the University of Kent at Canterbury, UK, held a workshop to inform the wider scientific community of this work. After the completion of major industrial studies, there were follow-up workshops in Granada (1990) and in Cagliari (1991).

Meanwhile, ESA's Technology Research Program studied most of the enabling technologies required for a sample return mission, confirming the feasibility of the ambitious project, now known as Rosetta.

3.3 WHY ROSETTA?

The ESA comet chaser was named after the Rosetta Stone, a famous, ancient slab of basalt (a dark volcanic rock) that is on display in the British Museum in London. It was unearthed in 1799 by French soldiers near the town of Rashid (in English, Rosetta) on the Nile Delta. Two years later, after the surrender of Napoleon's army in Egypt, the 762 kg slab was handed over to the British.

The carved inscription on the stone was unique because, for the first time, it included the same text in different languages – ancient Greek, which was readily understood, and ancient Egyptian. Furthermore, the latter was present in two forms – the common Demotic script and the pictorial hieroglyphs that were famous from their presence in the tombs of the pharaohs of ancient Egypt.

By comparing the inscriptions, scholars were able to painstakingly decipher the meaning of the mysterious hieroglyphs. Most of the pioneering work was done by an English physician and physicist, Thomas Young, and by French scholar Jean François Champollion. As a result of their breakthroughs, it became possible, for the first time, to piece together the language and literature of a long-lost civilization that dominated the Nile valley a thousand years.

Almost 200 years later, European scientists were seeking an appropriate name for the newly proposed Cornerstone mission to explore a comet in unprecedented detail. At the time, this international venture was simply the 'Comet Nucleus Sample Return' mission, but the Solar System Working Group was eager to come up with a more memorable name.

Eberhard Grün at the Max-Planck-Institute for Nuclear Physics in Heidelberg, Germany, was the chairman of the joint ESA-NASA Science Definition Team created to specify the science goals (see Defining the Future above), and he suggested the name 'Rosetta'.

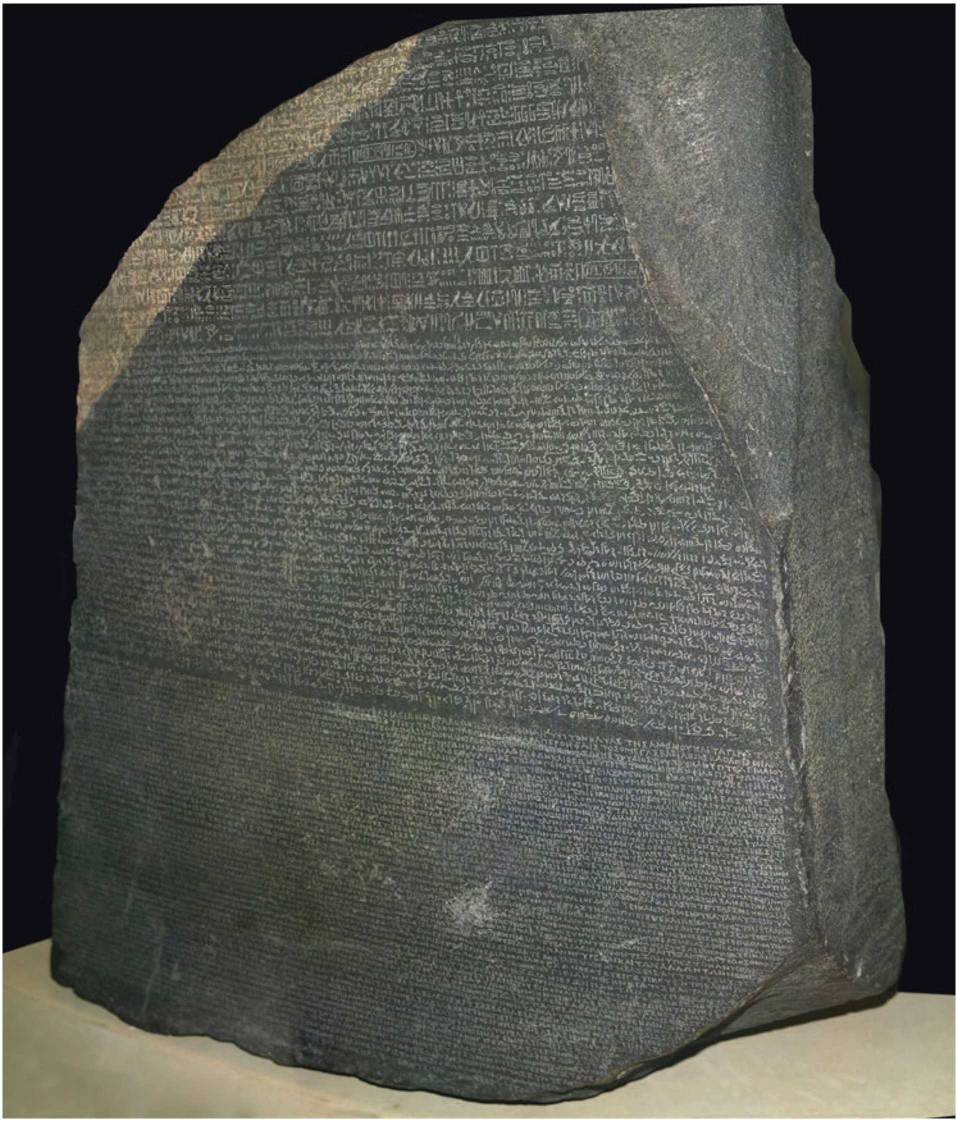

Fig. 3.2: The Rosetta Stone, now located in the British Museum, London, has three different carved inscriptions showing the same text in ancient Greek and two different forms of ancient Egyptian. This permitted scholars such as Thomas Young and Jean François Champollion to reveal the meaning of the mysterious hieroglyphics. (Wikimedia https://en.wikipedia.org/wiki/Rosetta_Stone#/media/File:Rosetta_Stone.JPG)

As Grün later explained:

Meteorites are debris from (mainly) asteroids that make it to the surface of Earth, and their study helped us piece together the chemical composition of

> the Solar System today. But if we want to study the primordial Solar System, comets are the objects to explore. While asteroids formed between Mars and Jupiter, comets formed much farther away from the Sun, so comet material has been much less processed and is much closer to the pristine composition of the Solar System.
>
> With a space mission to visit a comet and collect samples from its nucleus, we could gather brand new information to decipher the history of our Solar System. And it was then that it occurred to me that this is the same story as the Rosetta Stone!
>
> When this idea first crossed my mind, towards the end of 1986, I went to the library at the University of Heidelberg to learn more about the Rosetta Stone and how it revolutionized the study of Ancient Egypt. There was clearly a parallel with comets and their role to interpret the history of the Solar System, and besides, the name 'Rosetta' was much more powerful than what we had before. I phoned Gerhard Schwehm, the mission study scientist at ESA, and he liked the idea. The entire Science Definition Team thought it was a great name and also Roger Bonnet, ESA's Science Director at the time, so it stuck pretty quickly.
>
> By the end of 1987, we referred to the mission as 'Rosetta – Comet Nucleus Sample Return' in the first study report from the Science Definition Team.

As Grün would later observe during the mission, "Every new day with Rosetta at the comet, we are gathering more clues on how a comet works and how to decipher the Solar System hieroglyphs and piece together our cosmic origins."

3.4 COMET RENDEZVOUS OR SAMPLE RETURN?

Although the return of pristine material from a comet's nucleus was ESA's preference as the planetary Cornerstone in its Horizon 2000 program, it was recognized that such an ambitious enterprise would be difficult to achieve.

An acceptable alternative would be a mission that returned to Earth samples of dust and gas from a cometary 'atmosphere'. Accordingly, in response to ESA's Call for Mission Proposals in July 1985, a group of scientists led by J.A.M. (Tony) McDonnell of the University of Kent at Canterbury put forward a plan to develop a mission named CAESAR (Comet Atmosphere and Earth Sample Return) and a detailed Assessment Study was undertaken between July and November 1986.

CAESAR would carry nine scientific experiments to investigate a comet's nucleus and its surroundings. However, the most notable objective was to be the first mission to return to Earth samples of comet dust and gas. Unlike dust particles of extraterrestrial origin that are collected as they penetrate our planet's atmosphere, these samples of volatile and non-volatile materials would come from a known source and have a well-defined history.

As it passed through the comet's coma, the spacecraft would collect this pristine, unprocessed material and later return it to Earth for analysis in advanced laboratories. Protected by a nose cone made of ablative material, the return capsule would parachute to a fairly soft landing at a designated site.

It was anticipated that the mission would, for the first time, enable scientists to look back to the earliest stages in the history of our Solar System, and thus obtain important data on the composition of the solar nebula, including the composition of individual interstellar grains and the processes that resulted in the condensation of material in the solar nebula.

The Assessment Study recognized that the scientific objectives of the mission could be more easily fulfilled if the fly-by velocity was very small. This would mean that the number of dust motes obtained, and the percentage of those that would survive the collection process intact, would increase as the impact hazard to the spacecraft diminished. The optimum case would be a "zero velocity fly-by", meaning a rendezvous in which the spacecraft flew alongside the comet.

Although the CAESAR team was unable to find an international partner that was willing and able to conduct a slow fly-by, they did suggest that a "truly exciting" scientific mission could be achieved if CAESAR could be carried out as part of NASA's CRAF (Comet Rendezvous and Asteroid Fly-by) mission (see Section 3.5 below).

The CAESAR team envisaged their small craft piggybacking on the much larger CRAF as it rendezvoused with and flew alongside Comet Temple 2. This would enable a sizeable sample of material to be collected when the comet became most active around its closest approach to the Sun, known as perihelion. Later, CAESAR could return to Earth with its precious payload of perhaps 10-100 g of cometary dust.

Although CAESAR never got off the ground, these preliminary studies would prove valuable when the Rosetta comet rendezvous mission became the Agency's priority a few years later. Interestingly, the baseline comet for the CAESAR proposal, 67P/Churyumov-Gerasimenko, was eventually visited by Rosetta.

3.5 CRAF – COMET RENDEZVOUS AND ASTEROID FLY-BY

In the late 1980s, as ESA was refining its plan to develop the international Rosetta Comet Nucleus Sample Return mission, NASA was preparing a complementary mission, known as CRAF (Comet Rendezvous and Asteroid Fly-by), which it intended to design in parallel with a mission to the outer Solar System (the Cassini Saturn orbiter) in order to make cost savings by having commonality of systems.

The motivation for CRAF was to address the major gaps in our knowledge of the origin and nature of small Solar System bodies. Specifically, it was to conduct a close fly-by of a main belt asteroid and then rendezvous with a short period comet (Kopff or Tempel 2) out near the orbit of Jupiter. It would fly alongside the nucleus for up to three years to study its changing surface activity at varying distances from the Sun.

Unlike Rosetta, CRAF was not intended to collect and bring back samples from the nucleus itself. Instead, its priority was to remotely study the nucleus and its environment, including onboard analysis of captured dust particles. It would also fire an instrumented penetrator into the nucleus.

The principal objectives were to:

- Determine the composition and character of a cometary nucleus, and characterize changes that occur as functions of time and orbital position.
- Characterize the comet's atmosphere and ionosphere and study the development of the coma as a function of time and orbital position.
- Determine comet tail formation processes and characterize the interaction of comets with the solar wind and radiation.
- Characterize the physical and geological structure of an asteroid.
- Determine the major mineralogical phases and their distribution on the surface of an asteroid.

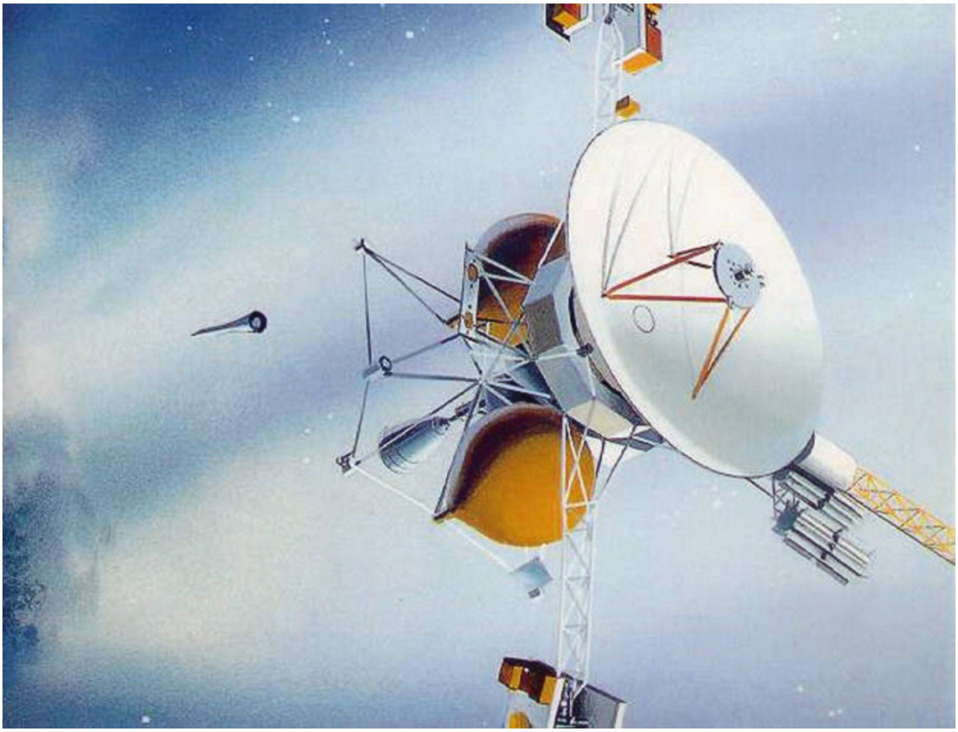

Fig. 3.3: NASA's Comet Rendezvous and Asteroid Fly-by (CRAF) mission was to be based on a new, nuclear-powered, Mariner Mark II spacecraft. It would make an asteroid fly-by *en route* to Comet Tempel 2, then fire an instrumented penetrator (left) into the nucleus and fly alongside the comet for three years, examining the formation of its coma and tails. (NASA)

Selected in 1986, the scientific payload for CRAF included:

- Cameras to photograph the nucleus, the coma and tail, and changes that occurred as the comet moved around its orbit. The images would also help to determine the size and structure of the nucleus, the location of its poles, its rotation rate and geological make-up.
- A surface penetrator would be fired into the nucleus and travel perhaps 1 meter into the icy crust. Its instrumentation would measure the abundances of up to 20 chemical elements. A gamma ray spectrometer would measure the elemental composition of both ice and non-volatile material; an accelerometer would measure the strength and structure of the surface; thermometers would measure the temperatures beneath the surface; a calorimeter would detect phase changes as an ice sample was heated and vaporized; and a gas chromatograph would determine types and amounts of gaseous molecules released from the ice sample. The data would be radioed to the spacecraft and relayed to Earth.
- Various mass spectrometers to study the composition of gases released by the nucleus and cloud of plasma (ionized gas) surrounding the nucleus.
- A visual and infrared mapping spectrometer to study the chemical composition of the coma and the surface of the nucleus as they changed over time.
- Dust counters, collectors and analyzers to capture samples of the comet's dust and to study them on board. This would help scientists to determine the chemical elements that make up the dust and ice. At the same, the mass, size, shape and composition of individual dust grains would be measured.
- A magnetometer and a plasma wave analyzer to measure interactions between the coma and electrically charged particles of the solar wind. The magnetometer would also measure any intrinsic magnetic field associated with the comet.

CRAF and Cassini were to be based on a new spacecraft platform, called Mariner Mark II, which was intended for flights to the outer planets and primitive bodies such as comets. The same platform was proposed during design studies for ESA's Rosetta Comet Nucleus Sample Return spacecraft.

Mariner Mark II comprised a central, 10-sided bus to hold most of the electronics; a large propulsion subsystem (fuel tanks, rocket engine and structure) beneath the bus; a high-gain antenna and radio feeds on top of the bus; two nuclear-powered radioisotope thermoelectric generators on a boom behind the bus; and booms on which to mount experiments. There was considerable international involvement, most notably for the spacecraft's chemical propulsion system, whose development was entrusted to the German Federal Ministry for Science and Technology (BMFT). While the spacecraft flew with its high-gain antenna pointing at Earth, two instrument-laden platforms would ensure its telescopes and other sensors trained on the target.

CRAF was initially penciled in for launch by a Titan IV/Centaur-G rocket in February 1993. On its way to Tempel 2, it would gain gravitational boosts using fly-bys of Venus and Earth. After an asteroid fly-by in January 1995, the spacecraft would reach the comet in November 1996, just inside Jupiter's orbit. It would fly alongside the nucleus for more than three years as it approached the Sun and reached perihelion. The warming of the icy nucleus would lead to the growth of a coma and tail, increased jet activity and expulsion of dust and gases. As the comet became more active, the spacecraft would recede to a safe distance of several thousand kilometers.

The flight plan was modified as time went by. When the mission was approved as a new start in NASA's Fiscal Year 1990 budget, it was scheduled for launch to Comet Kopff in February 1996, with arrival at its target in January 2003 and the nominal end of mission in June 2005, after the comet had passed perihelion. However, the overall flight plan remained very similar to the original.

Unfortunately, the Mariner Mark II program ran into financial and technological headwinds. In particular, CRAF was squeezed on two fronts. The projected cost of a key instrument, the comet nucleus penetrator, was increased from an initial estimate of $22 million to a projected $120 million. The soaring cost obliged NASA to cancel the instrument in 1990, undercutting a major part of the scientific justification for the mission. Furthermore, the Scanning Electron Microscope and Particle Analyzer (SEMPA) instrument was also eliminated.

With the proposed Freedom space station seen as NASA's top priority by Congress, funding for the Agency's space science program was put under extreme pressure. In autumn 1991 the launch date was put back from February 1996 to April 1997, a decision that would spread out the mission's cost but delay the comet rendezvous by three years, from 2003 to 2006. Despite these setbacks, a 1992 National Research Council report stated that "the CRAF mission had great scientific merit even without the penetrator experiment."

However, the final stumbling block was the continuing congressional budget restrictions on mission expenditures. In the 1992 NASA budget, the money allocated to CRAF and Cassini was slashed by a whopping 36%. After the comet rendezvous program was deleted from the President's 1993 budget request, NASA abandoned CRAF and redesigned Cassini to make it cheaper.

3.6 ROSETTA COMET NUCLEUS SAMPLE RETURN

As already mentioned, Rosetta was originally envisaged to be the first mission to land on a comet, drill into its nucleus, and return a sample of material to Earth for analysis. Alongside NASA's CRAF, the ESA-NASA Comet Nucleus Sample Return (CNSR) would complete an ambitious double-header to reveal the secrets of comets.

Analysis of the cometary samples would be a huge advance over the knowledge gained from ground-based observations and fly-bys, yielding insights into the chemical, mineralogical and physical properties of comet material. It was expected that the Rosetta CNSR mission would revolutionize scientists' ideas about comets and their role in the formation of stellar nebulae – the birthplaces of stars and planetary systems.

In order to achieve these objectives, there were to be four phases of science investigations in the vicinity of the comet:

- Target acquisition, characterization of the nucleus, precise orbit determination and definition of gas and dust emission patterns.
- Coma transit, assessment of nucleus activity, mapping of active areas of dust and gas jets and evaluation of hazards to the spacecraft, determination of the rotational state of the nucleus.
- Landing/sampling site selection, and definition of the approach strategy.
- Sample acquisition and surface characterization.

Rosetta CNSR would carry a suite of remote sensing and in-situ experiments to investigate the nucleus and the coma (see Table 3.2).

An imaging system and radar sounder would support spacecraft navigation and landing, in addition to carrying out detailed mapping of the nucleus. A thermal infrared radiometer was to provide information on the distribution of surface temperatures on the nucleus to support the selection of the landing site. A neutral mass spectrometer and dust monitor would study the cometary environment. Other instruments would measure the temperature in the borehole and the temperatures of the samples, and high-resolution images of the sampling would be provided by a stereoscopic camera.

Table 3.2: The Rosetta CNSR Model Payload

Site Selection	Imaging system
	Infrared/thermal mapper
	Radar altimeter/sounder
	Laser altimeter
Environment Monitoring	Neutral/ion mass spectrometer
	Dust counter
Surface Drilling and Sampling	In-situ stereo imaging system
	Sample thermal logger
	Temperature profiler in drill hole
	Thermal logger for surface temperature
	Borehole stratigraphic (layer) recorder

There was also the possibility of depositing a surface science package on the nucleus which would remain active after the completion of the sample mission, to monitor the changes there as the comet traveled a considerable fraction of its orbit.

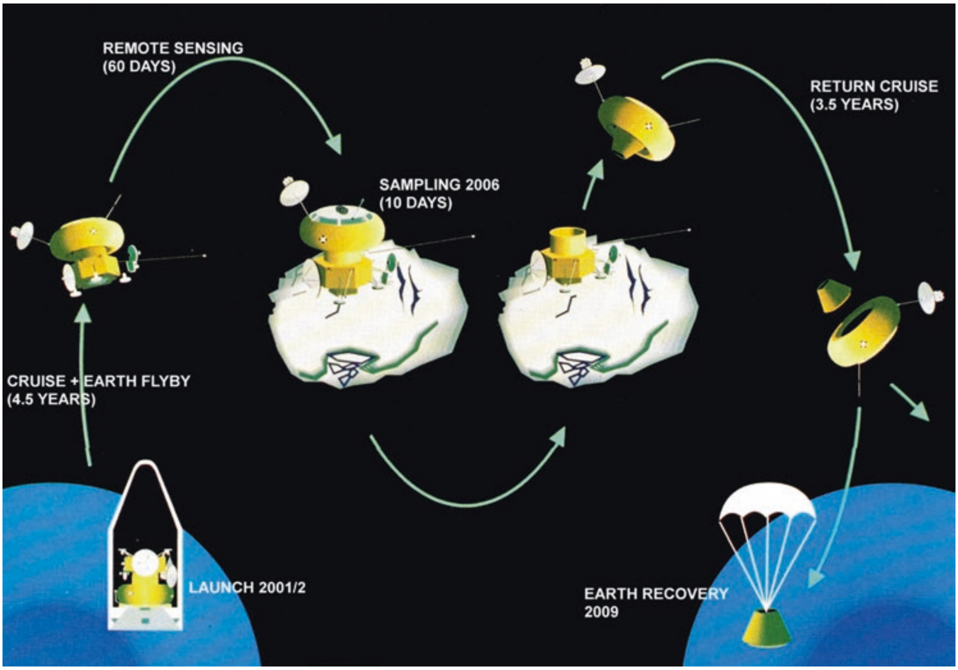

Fig. 3.4: An early artist's impression of the key stages in the Rosetta CNSR mission. From left to right: the spacecraft is launched from Earth; after a comet rendezvous, it makes a soft landing on the nucleus; the landing module remains behind as the return spacecraft lifts off with the Earth-Return Capsule; the capsule separates from the spacecraft and parachutes to Earth for recovery and analysis of its precious samples. (ESA)

The spacecraft was to comprise three modules: the Cruise module, the Lander, and the Earth-Return Capsule. The entire spacecraft would touch down on the nucleus of a short period comet such as 103P/Hartley. The Lander would remain on the nucleus after the sampling was finished and the sample had been stowed in the Earth-Return Capsule. After returning to the vicinity of Earth, the spacecraft would release the capsule on a trajectory that would enable its recovery.

Such a complex plan was beyond the financial and technological resources of ESA alone, so major U.S. involvement was deemed essential to the success of the mission.

As defined in 1991, the mission would be launched on a Titan/Centaur provided by NASA, and the spacecraft would be derived from the Mariner Mark II that was being developed by NASA. The Lander and Earth-Return Capsule would be supplied by ESA, thus allowing that Agency to focus on the cometary science. In flight, the mission would be primarily controlled by NASA's Deep Space Network of ground stations.

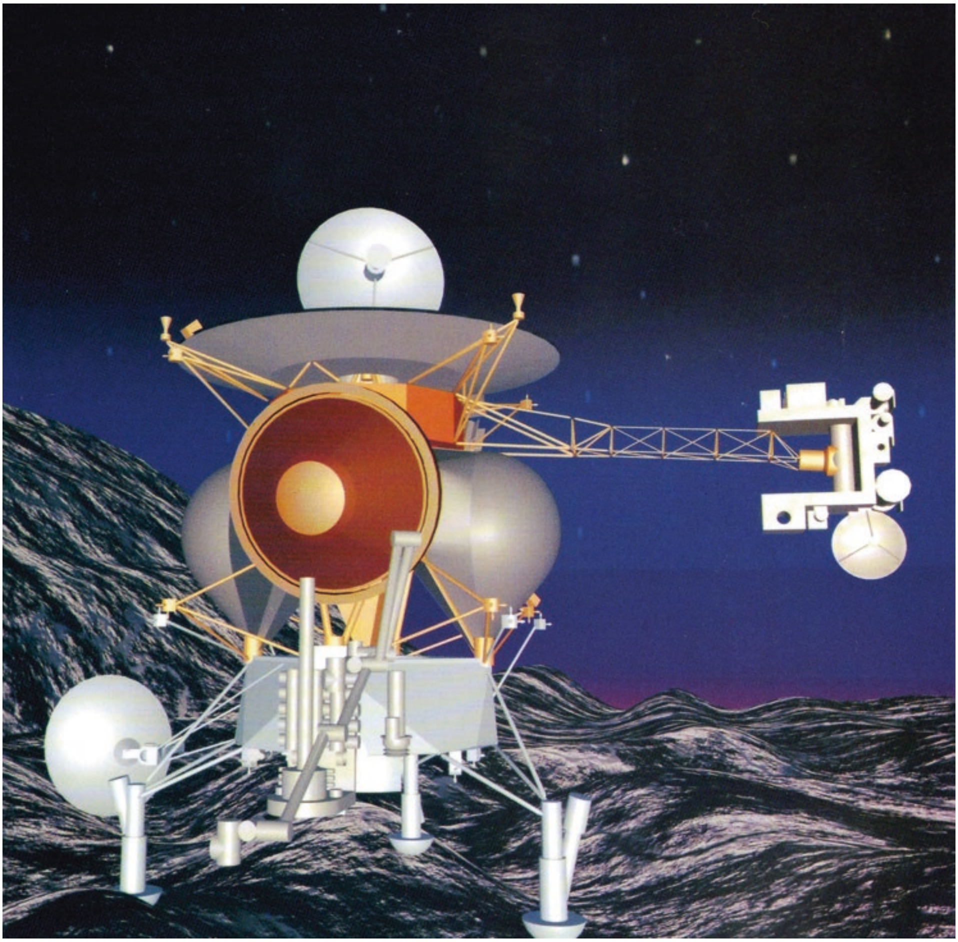

Fig. 3.5: An artist's impression of the Rosetta CNSR spacecraft on the surface of a comet. In the center is the Earth-Return Capsule (the red-brown conical module), with the drilling unit beneath it. The boom on the right carries the High-Precision Scan Platform, with its suite of scientific instruments. (ESA)

According to the 1991 mission definition document, the overall dry mass of Rosetta CNSR would be 2,447 kg, of which the main spacecraft, referred to as the Cruiser, would account for 1,523 kg. The Lander would account for 474 kg, with the Earth-Return Capsule weighing in at 297 kg and the launcher adapter at 153 kg. In addition, the spacecraft would carry 3,611 kg of fluids, primarily propellants for its main engine.

The three-axis stabilized Cruiser would be carried on top of the Lander module, and was to provide attitude control, navigation, propulsion, power generation, telecommunications, and the overall mission management. The science and engineering instruments that required high pointing accuracies, notably the cameras, laser range finder and radar altimeter, would be on a High Precision Scan Platform that could be moved in elevation and azimuth with respect to the main body.

The propulsion subsystem included a 400 Newton bi-propellant main engine for large orbital maneuvers that would use around 3,500 kg of monomethylhydrazine and nitrogen tetroxide. There was a mono-propellant system with 24 × 10 Newton thrusters for attitude control and small trajectory changes. These thrusters would also be used for the initial landing operations, and for lift-off after the sample was safely aboard. These maneuvers would use about 70 kg of hydrazine. The final stages of the descent to the comet's surface would be performed using 24 × 20 Newton cold gas thrusters with a supply of 39 kg of nitrogen.

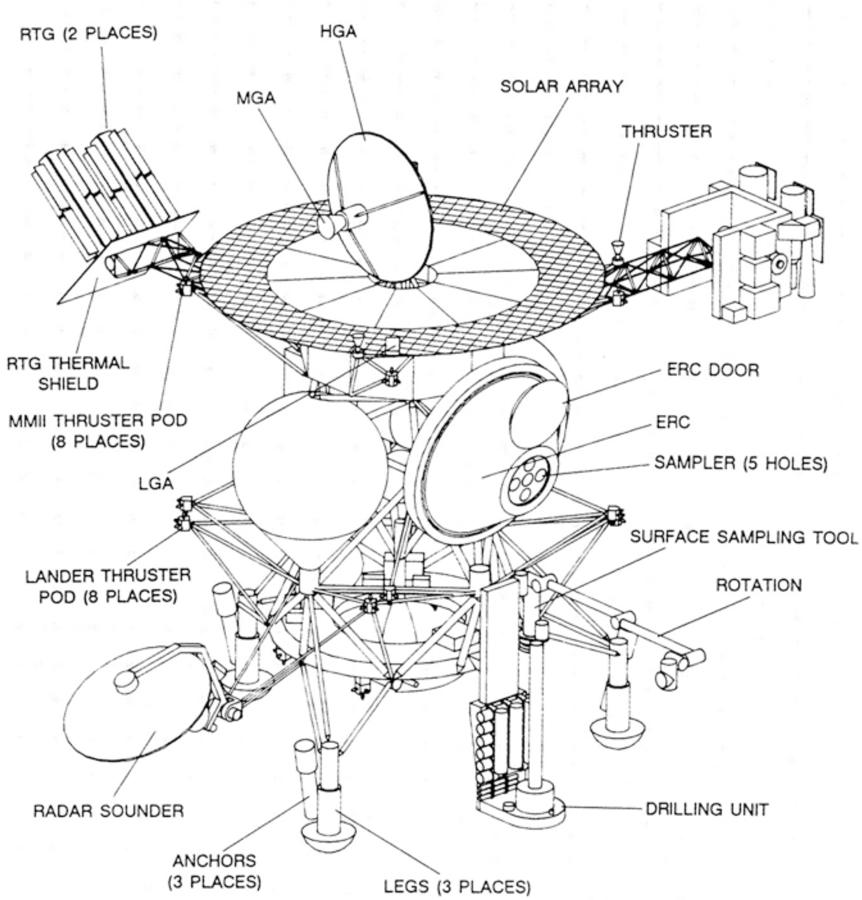

Fig. 3.6: The main features of the Rosetta CNSR spacecraft. The Lander is below the Cruiser and the Earth-Return Capsule is mounted on the side of the Cruise module. (ESA)

One technology that was not available in Europe was the pair of radioisotope thermoelectric generators (RTG) on a deployable boom. These would provide electrical power from the heat generated by the radioactive decay of plutonium-238, in the form of plutonium dioxide. The large difference in temperature between this hot fuel and the cold environment of space was applied across solid-state metallic junctions known as thermocouples to generate an electrical current without moving parts. If the mission were to proceed without RTGs, it would have to rely upon solar power, and, at the distance from the Sun at which the comet rendezvous was to occur, the solar arrays would have to be extremely large. Solar power became a requirement after NASA reduced its role in the Rosetta mission in 1993.

On top of the Cruiser was a ring-shaped Sun shield with an annular solar array on its exterior to provide 350 W/h after the RTGs were jettisoned prior to Earth-return – a safety precaution to eliminate the possibility of radioactive contamination of our planet's environment.

In the center of the sunshield was a steerable, 1.47 meter diameter high-gain antenna that was based on a design used by the Viking Orbiters that were sent to Mars. The boom-and-gimbal design ensured a clear field of view to Earth for data downlinking during comet approach and operations. The primary system operated in X-band, but a medium-gain antenna and a pair of low-gain antennas were available for back-up, including emergency commands and low-rate telemetry.

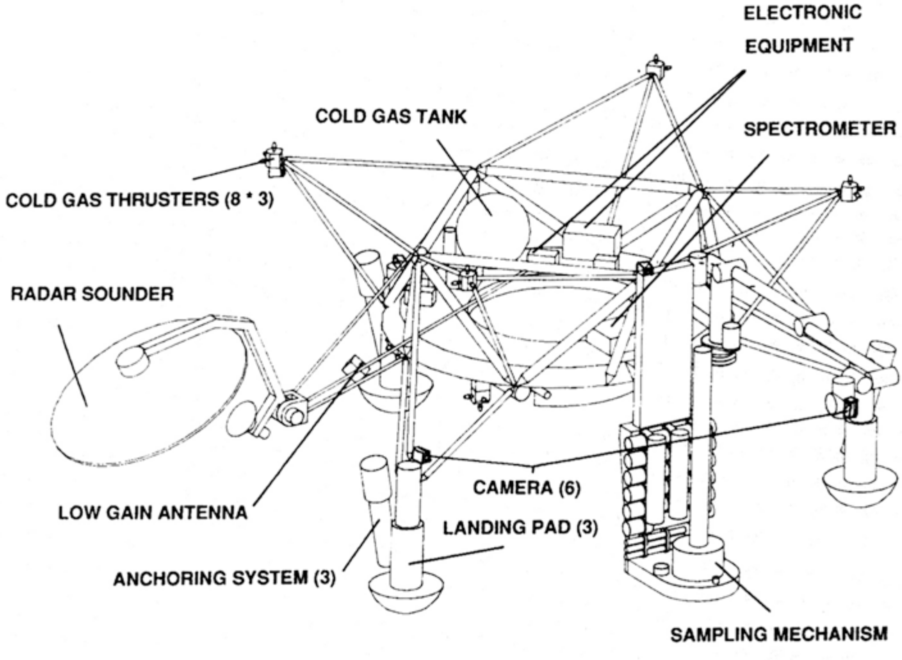

Fig. 3.7: The main features of the Rosetta CNSR Lander module. The three-legged module was to be anchored securely to the surface of the nucleus before drilling operations began. The module formed the lower part of the spacecraft that landed on a comet, and acted as a launch platform for the Cruiser once the surface sample had been collected and loaded into the Earth-Return Capsule. (ESA)

The Lander module – a tubular truss construction – would be attached beneath the Cruiser by four explosive bolts. It formed the basic load-carrying structure for the Cruise module during launch from Earth, and was attached at its base to the launch vehicle's adapter. It would carry the remaining science instruments, and have three legs with foot pads and anchors to secure it to the nucleus in the comet's low gravity. It also carried the surface sample acquisition unit. It would enable the entire Rosetta CNSR spacecraft to approach the nucleus and touch down.

For the last few hundred meters of the descent, control would be switched from the hydrazine thrusters to a set of cold gas thrusters to avoid contamination of the sample area.

The fixed legs were equally spaced around the periphery of the Lander for optimum stability, and devices were incorporated into each leg to reduce the shock of touchdown impact.

The anchoring system that would stabilize the spacecraft during the touchdown and sampling phases comprised a pyrotechnic (explosive) device on the pad of each leg. The design of the anchor had to accommodate a broad range of possible soil materials, hardness and strength. A telescoping system involving two aluminum or titanium tubes was proposed. In very soft soil, both tubes would be deployed. The minimum desired penetration in the hardest of soils was 50 cm. If both telescopic tubes were fully extended the maximum depth would be 1.2 meters.

In the event of the anchoring system failing, a back-up system comprising two 70 Newton bi-propellant thrusters mounted on the edge of the Cruiser's Sun shield would push the vehicle against the comet's surface and also provide the necessary resistance to the drilling forces and rotational torques.

3.7 SURFACE SAMPLING

The Sample Acquisition System (SAS) was to consist of a core sampler, a surface sampler, and a handling arm. The SAS and the Earth-Return Capsule were designed to collect and store five sample tubes, consisting of three core tubes, one volatile sample and one surface sample tube.

Surface sampling of non-volatile material (i.e. organic and inorganic compounds) would be the first task, using a dedicated tool that would be placed in selected locations by a robot arm. The device consisted of a rotary shovel head at the bottom and an attached sample container tube. Fluffy or coarse material with a mass of 1-5 kg could be collected to a depth of 10 cm, possibly containing solid fragments up to 5 cm in diameter.

The core sampler would consist of a rotary table equipped for independent axial and rotary articulation, a set of two outer core tubes that had a diamond-tipped drill head at the bottom, and six inner core sample containers.

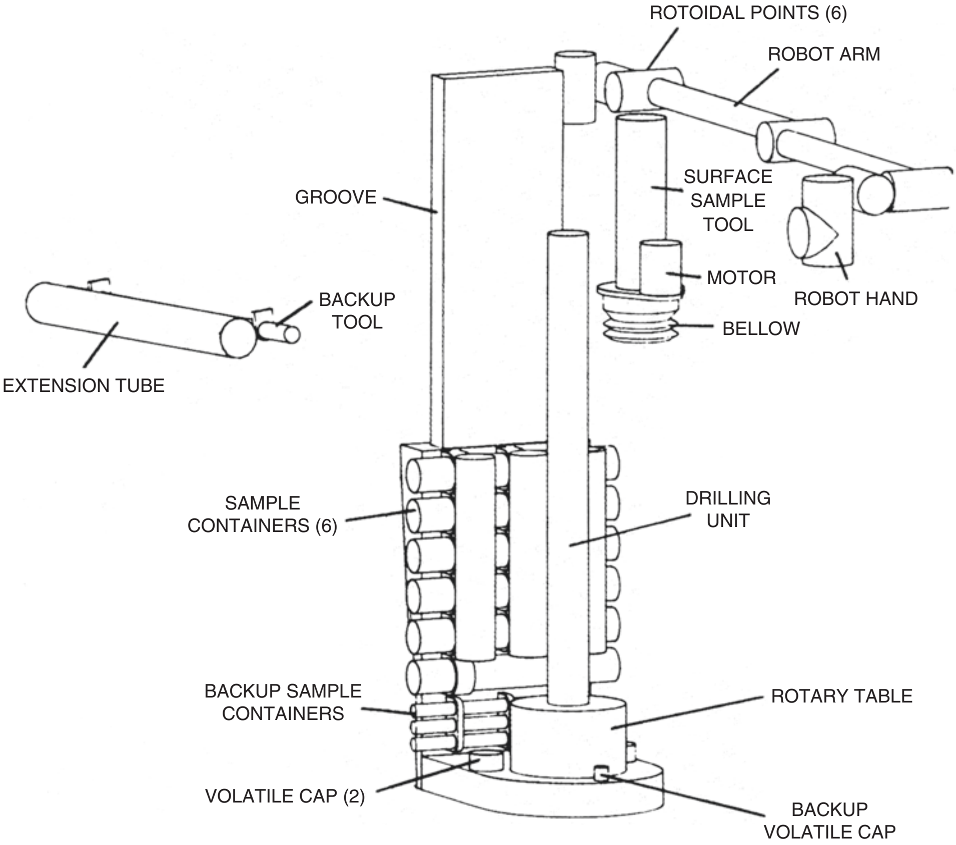

Fig. 3.8: The CNSR comet core sampler consisted of a vertical slide bar, a rotary table, two outer coring tubes with a drill head at the bottom, and six inner core sample containers. The drilling operations were to begin when the rotary table was lowered to the surface. The unit could extract material from a depth of 1-3 meters. (ESA)

The rotary table would be lowered to the surface by a vertical slide bar. Drilling would take place with a rotation rate in the range 10-100 rpm, and depth progression would be actively controlled in terms of the allowable temperature increase on the sample and the resistance of the surface material.

One coring tube would be installed on the rotary table prior to launch from Earth, to permit coring operations to start as soon as the spacecraft was safely anchored to the nucleus. The tube was 1.6 meters long, and could reach a depth of 1-1.3 meters, depending on the surface roughness beneath the rotary table. At that depth, the first volatile sample would be collected and retrieved. With extra core tubes, it might be possible to achieve a total sampling depth of 2.3-2.6 meters.

The core samples, having an overall mass of up to 10 kg, would form a continuous record of subsurface layering, although some compression of the core could be applied in a controlled manner. In addition, a small (10-100 g) sample of volatile material would be loaded into a sealed container capable of preserving it intact during the return to Earth.

The surface samples would be picked up by a manipulator arm and stored inside the ERC for delivery to Earth. An onboard camera would enable ground control to watch operations, and intervene if necessary.

The capsule would be a spinning, unguided, ballistic aeroshell with a sphere- or cone-shaped forward heat shield and a blunt rear end. Its baseline dimensions were 1.8 meters in diameter and just over 1 meter in height. At its heart was the container capable of holding five sample compartments, each with a length of 650 mm and a diameter of 130 mm. The passive thermal control regime involved the use of multiple layers of insulation, with low-power heaters for the battery, transmitter, parachute, and other mechanisms.

The samples would all be sealed independently. Their conditions would have to be carefully controlled during the return journey, with the core sample maintained below –110°C for the entire return trek, until recovery. In addition, the samples would have to avoid extreme levels of acceleration or vibration.

Sometime after the largely autonomous sampling operations were completed, the Cruiser and its piggybacking ERC would lift off, using the Lander as a launch platform. On approaching Earth after a 2 year cruise, the RTG power pack would be jettisoned in order to comply with safety regulations. Several days later, the ERC would be released for a ballistic entry into the atmosphere. After a parachute assisted descent, it would splash into the Pacific Ocean. It was to be recovered by helicopter within 30 minutes. Then the priceless comet samples would be delivered to the sample receiving laboratory.

3.8 CANCELLATION

This imaginative and ambitious endeavor never came to fruition. By late 1991, it was clear that the CRAF mission was not the only NASA space science project in dire jeopardy. The Rosetta CNSR program was threatened by the rising cost of the Mariner Mark II spacecraft and other hardware, combined with financial cutbacks for NASA and difficulties associated with program planning and implementation timing.

ESA officials wisely began to initiate parallel studies for a smaller, all-European mission to investigate the primitive bodies of the Solar System. This revamped Rosetta mission would have to adhere to the budgetary constraints of a Horizon 2000 Cornerstone mission and rely on technologies and launch capabilities available in Europe.

The new studies looked at two mission alternatives:

- Multiple asteroid fly-bys *en route* to a near-Earth asteroid rendezvous and a possible landing on the asteroid at the end of the mission.

- A comet rendezvous with payload operations starting when both the spacecraft and the comet were within 2.5 AU of the Sun.

When NASA said in 1993 that it could no longer be a major participant in the Rosetta CNSR mission, ESA pursued a cheaper and less technologically challenging European project in the form of a comet rendezvous which was remarkably similar to the canceled CRAF proposal.

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