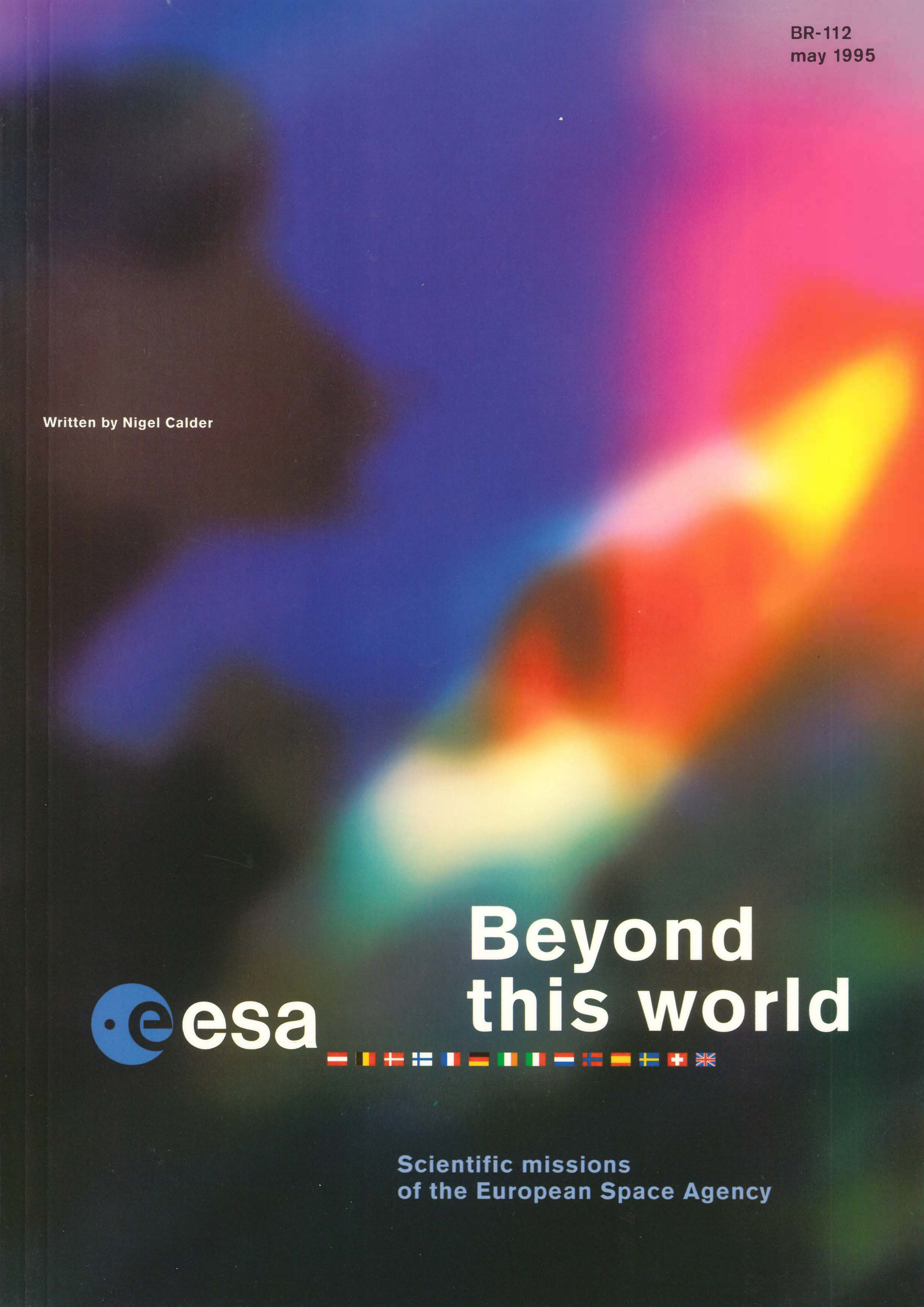


BR-112
may 1995

Written by Nigel Calder

esa

Beyond this world

Scientific missions
of the European Space Agency

Published by
ESA Publications Division
c/o ESTEC
PO Box 299
2200 AG Noordwijk
The Netherlands
Tel.(31) 1719 83400
Fax (31) 1719 85433

Editor
Bruce Battrick

Text
Nigel Calder, London

Design
Total Design, Amsterdam
Hans P Brandt
Gonnie Hengelmolen

Coordinator
Simon Vermeer, ESA, Paris

Typesetting and lithography
Boxem, Amsterdam

Price
Dfl 35

ISBN 92-9092-388-1

The teams of scientists who participate in a mission are highly motivated. They have to be. They spend years winning a consensus for the project they want. They compete for the right to put a few kilograms of experiments on the spacecraft.

They construct exquisite instruments and test them to destruction, to make sure they're fit to go into space. When the launching rocket ignites they pray that their efforts won't end up on the seabed. After that they may have to wait several more years for the results. Why do they do it? To learn things no one ever knew before.

Contents

Roger Bonnet, ESA's Director of Science
Image: S. Brunnier/Ciel & Espace

A menu for discoverers

Beyond the blue sky created by the Earth's air, the Universe appears as a black void dotted with planets, stars and galaxies. This is the realm of the space scientists. They despatch missions to explore the Solar System and put telescopes in orbit for the richer view of the wide Universe that becomes available out of this world.

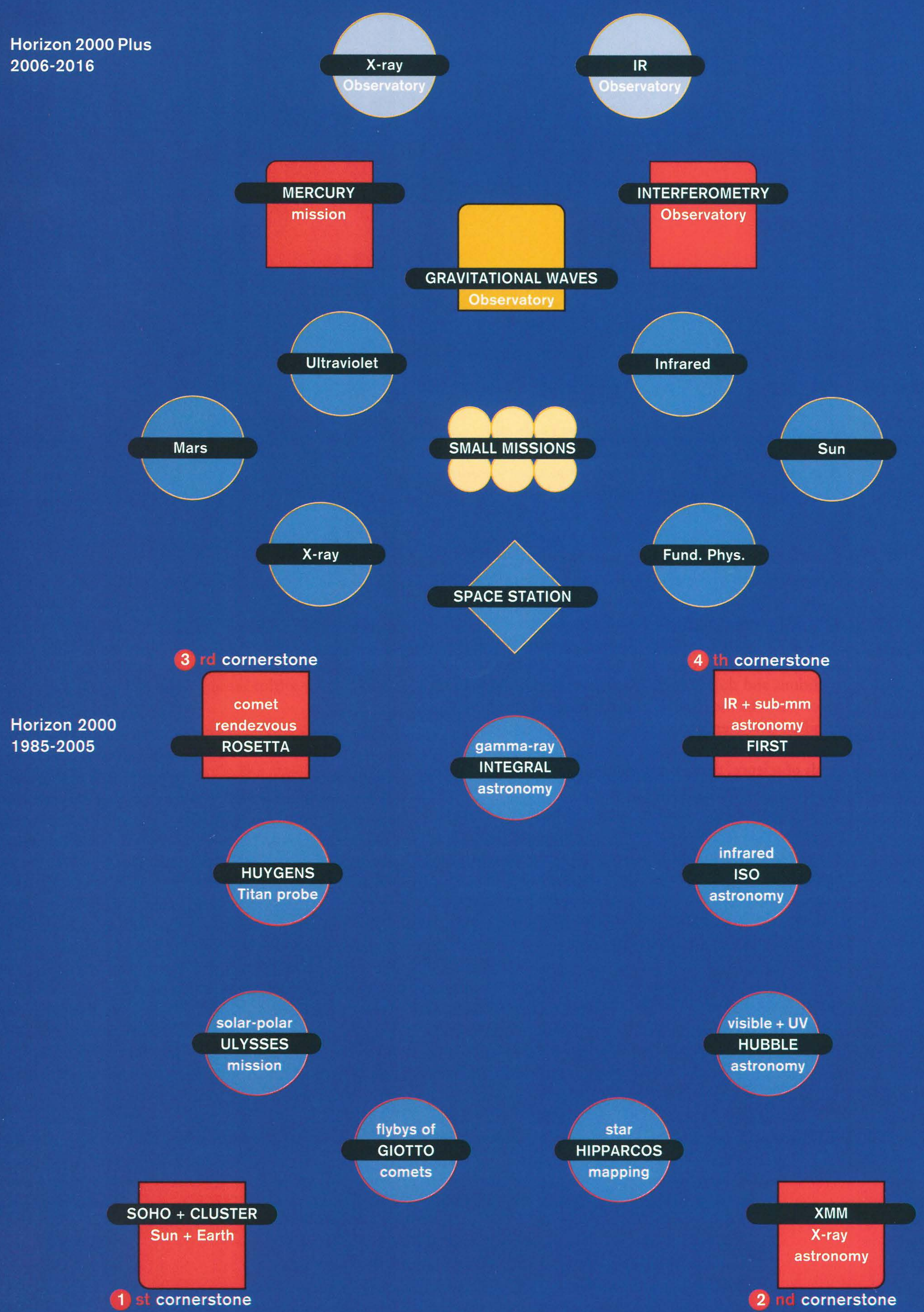
The menu in these pages starts with surprising discoveries over the Sun's poles. It ends for the time being with preliminary plans to search for waves of gravity that are thought to pervade space.

Take fourteen countries, the member states of the European Space Agency, each with its own scientific traditions and skills. Let their scientists propose any space missions they like. ESA has recently been sifting a hundred new suggestions. Give to groups of active researchers from a variety of countries, and from assorted fields of science, direct responsibility for recommending which spacecraft should fly.

At first wide differences of opinion will prompt detailed technical studies of a shortlist of competing possibilities. But gradually a consensus will emerge, and eventually a unanimous conviction that this is the right mission.

The national delegates who formally authorize each mission seldom dispute the scientists' judgments. They know that ESA's recipe produces space science of the highest quality.

"We're not kind to people's favourite ideas," admits Roger Bonnet, ESA's Director of Science. "By the time a mission is approved, sceptics will have questioned its scientific and technical merits, and its costs, again and again. But amid all the jargon, any proposal must pass one supreme test. To win acceptance as an ESA science mission, it must be a remarkable adventure of the human spirit."


Horizon 2000 Plus
2006-2016
X-ray
Observatory
IR
Observatory
MERCURY
mission
INTERFEROMETRY
Observatory
GRAVITATIONAL WAVES
Observatory
Ultraviolet
Infrared
Mars
SMALL MISSIONS
Sun
X-ray
Fund. Phys.
SPACE STATION
3 rd cornerstone
comet
rendezvous
ROSETTA
4 th cornerstone
IR + sub-mm
astronomy
FIRST
Horizon 2000
1985-2005
gamma-ray
INTEGRAL
astronomy
HUYGENS
Titan probe
infrared
ISO
astronomy
solar-polar
ULYSSES
mission
visible + UV
HUBBLE
astronomy
flybys of
GIOTTO
comets
star
HIPPARCOS
mapping
SOHO + CLUSTER
Sun + Earth
1 st cornerstone
XMM
X-ray
astronomy
2 nd cornerstone

"We initated our first long-term plan in space science ten years ago," Roger Bonnet observes. "This was Horizon 2000. ESA now pursues the imaginative ideas of European scientists. It also executes major missions that are second to none and have no equivalent in any of the other space agencies' programmes. We work on several missions with NASA, now as an equal partner, while we cultivate new collaborations with Russia and Japan."

Horizon 2000 and Horizon 2000 Plus

Before Europe found its self-confidence in the 1980s, researchers in the USA and the former USSR took advantage of Cold War rivalries to concoct ever-more ambitious science missions. Their opposite numbers in Western Europe usually had to rely on the superpowers condescending to launch their ingenious but small satellites.

Then NASA fumbled a once-in-a-lifetime opportunity to fly a spacecraft to Halley's Comet. ESA moved in to fill the gap for Western science, and in 1985 Europe's own Ariane rocket sent the Giotto spacecraft on its way. In the following year it plunged deeper into the dusty head of Halley's Comet than its Soviet and Japanese companions chose to go. As a result Giotto obtained pictures and data that remain the best available until ESA's Rosetta mission makes its rendezvous with Comet Wirtanen in the 21st Century.

New assurance infused the long-term science programme developed in the 1980s by the European scientists advising ESA. Horizon 2000 aimed to use a modest but predictable science budget as boldly as possible, by defining objectives for four major cornerstone projects that would be affordable over a period of time. Here an à la carte policy of choosing missions one by one gave way to a table d'hôte. A provision to interpolate less expensive missions on shorter timescales preserves flexibility. And while the Americans and Russians find ambitious ideas harder to fund in the post-Cold War era, Europe continues steadily with its projects.

Now Horizon 2000 Plus extends ESA's science programme to the years 2006-16. Major missions proposed for that period are to send a spacecraft to the planet Mercury, and to fly a satellite using the technique called interferometry to pinpoint the stars and perhaps even their planets. Subject to the available budget, Europe's scientists also call for a six-satellite mission to look for gravitational waves. This would extend the scope of ESA's research beyond its traditional commitments to Solar System science and space astronomy, into a third domain: fundamental physics.

In relation to the long-term programmes, five of the missions detailed in this book were approved before Horizon 2000 and have been included in it. Seven new projects have now been added and two or more will be selected before the end of the century. These extend from the SOHO and Cluster missions, ready for launch in 1995 to investigate the Sun's behaviour and its effects on the Earth, to FIRST, due to fly in 2005 and open up new realms of astronomy at submillimetre wavelengths.

ESA's "roll-forward" science programme. In 1994 the existing Horizon 2000 programme was extended into the second decade of the 21st Century, by proposals for Horizon 2000 Plus. They include three major "Cornerstone" missions in addition to the four cornerstones of Horizon 2000. Each cornerstone mission costs about 640 million ECU (800 million US dollars) at 1995 prices. Evolving on shorter timescales are medium-scale missions costing about half as much, and even cheaper small missions. Two medium missions of Horizon 2000 have still to be selected, and a further four are envisaged in Horizon 2000 Plus. International ventures concerning Mars and the Sun are likely to attract ESA participation, among the medium missions.

Scientific motives

The missions divide naturally into groups. Part 1 deals with spacecraft targeted on the Earth's environs, the Sun and other destinations in the Solar System. Part 2 covers telescopes deployed in Earth orbit for astronomical purposes. In each case an Overview puts these European missions into a broader perspective. Part 3 gives a foretaste of Horizon 2000 Plus.

Not included here is the scrutiny from space of the Sun's third planet, and of its lands, oceans, ice sheets, atmosphere, vegetation and human settlements. Remote sensing has revolutionized geography and the monitoring of environmental changes. ESA is prominent in Earth observation, with its Meteosat weather watchers, its ERS remote-sensing satellites, and a big new Envisat in preparation. But the domain of space science proper begins a little further out, beyond the Earth's atmosphere.

The descriptions of individual spacecraft provide some technical details in illustrations and tables, but the text stresses the purposes of each mission. This approach reflects the scientific and human factors that sustain the immense effort that is always involved.

The missions often call for engineering at the margins of feasibility, and so they help to foster high technology in ESA's member states. Some projects are directly linked to concerns about human well-being, notably in three current missions that explore links between the fickle behaviour of the Sun and climate changes on the Earth. All of the projects enlarge fundamental human knowledge about where our species belongs in spacetime, and how we come to be living on a comfortable planet in a generally hostile Universe.

Our curiosity and our intelligence, and those of our children, are challenged by these missions.

The teams of scientists who participate in a mission are highly motivated. They have to be. They spend years winning a consensus for the project they want. They compete for the right to put a few kilograms of experiments on the spacecraft. They construct exquisite instruments and test them to destruction, to make sure they're fit to go into space. When the launching rocket ignites they pray that their efforts won't end up on the seabed. After that they may have to wait several more years for the results.

Why do they do it? To learn things no one ever knew before. Why do we pay for it? To discover the unknown, to challenge our skills and ultimately to establish the grounds for peaceful exploratory endeavours with our fellow man.

SOHO:
ESA's Solar and Heliospheric
Observatory (1995)

esa

PART 1

The Sun and its family

Overview: exploring the Solar System

Before the Space Age many people thought the Earth was an island, touched only by the steady light from the Sun and the Moon-engendered tides. Now scientists know that our planet swims in the effusions of a variable Sun. It is vulnerable to impacts of the kind that have left their craters on the face of the Moon and every other rigid surface in the Solar System. And the Earth's unique environment for supporting life will be properly understood only by comparisons with the quite different worlds that orbit around the mother star.

Laurels for the initial exploration of the Solar System rest with NASA, and to a lesser extent the former Soviet Union. Europe's scientists were at first cautious about considering distant missions. Now the European Space Agency finds itself at the forefront of the two branches of space research in the Solar System that bear most closely on human existence and the Earth's environment.

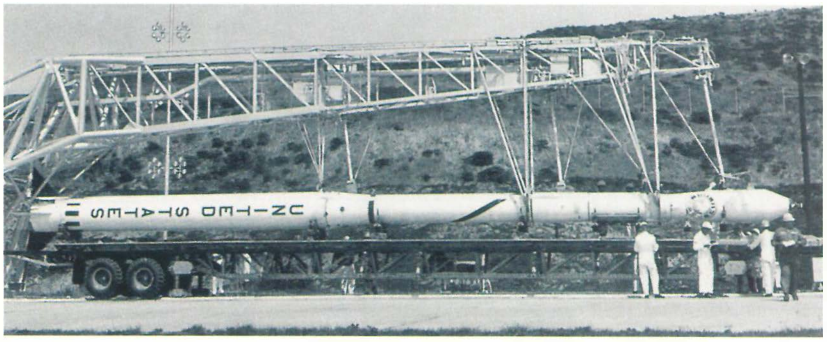
One concerns the Sun. Changes in the solar output of energy could affect the climate on the Earth, and new anxiety on this score has exposed the scientists' ignorance about fundamental aspects of solar and solar-terrestrial physics. A succession of ESA missions, Ulysses, SOHO and Cluster, now provides a timely opportunity to make sense of the Sun's behaviour and its effects on the Earth.

Another area where ESA exercises leadership is in comet research. Its Giotto spacecraft confirmed that comets carry vital clues to the origin of the planets and their atmospheres, and to the chemical antecedents of life. Europe now plans to continue the enquiry into comets with the Rosetta mission. The interest in primeval chemistry also inspires ESA's Huygens probe, which will analyse the atmosphere of Titan, a moon of Saturn.

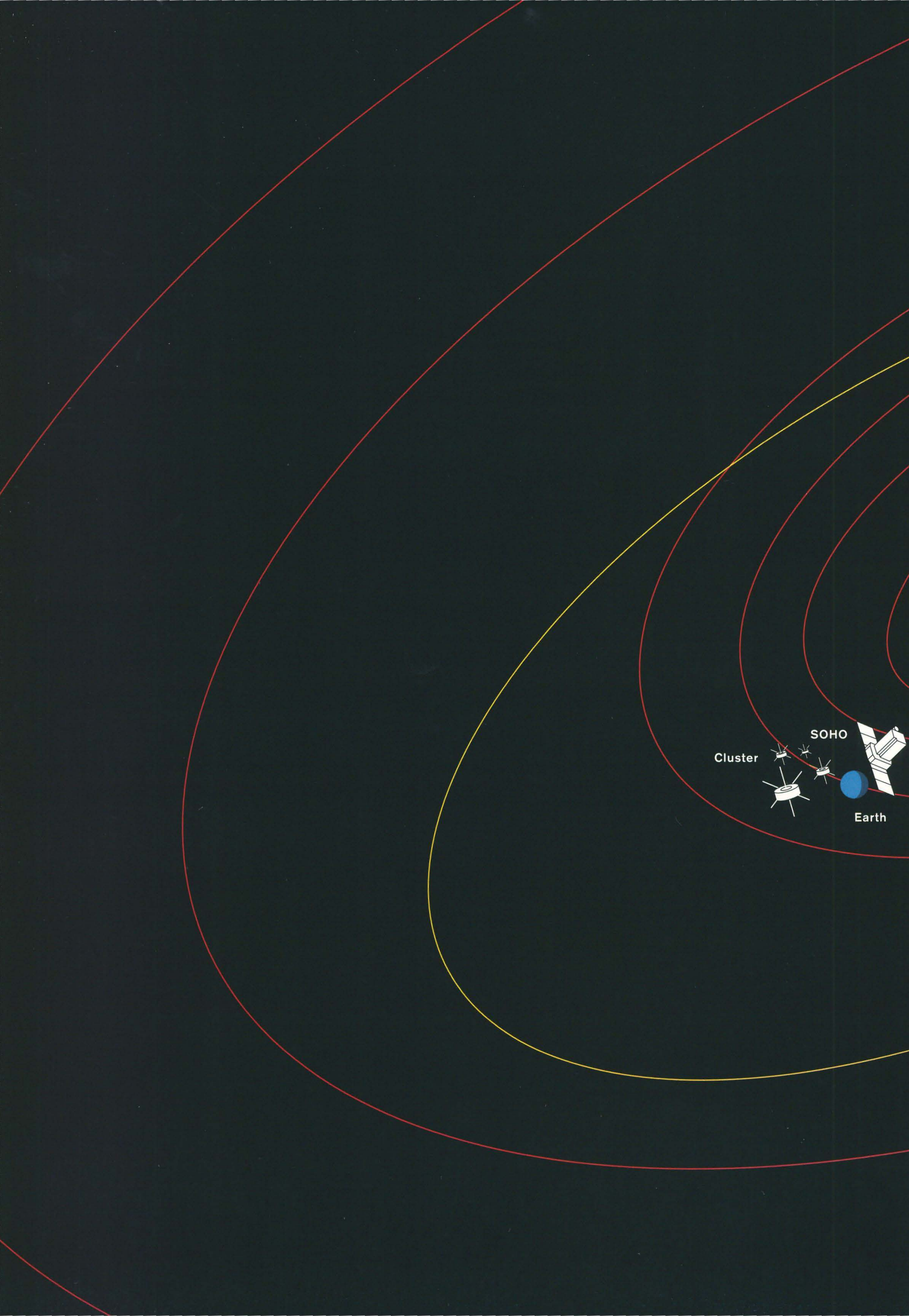
A growing capability. Europe's first joint space mission was the European Space Research Organisation's little ESRO 2 which operated 1968-71. It weighed 85 kilograms. By contrast, the four satellites of ESA's Cluster mission (1995) have a combined mass at launch of 4800 kilograms.
Image: Dornier

"Space science in Europe is always an extension of our ground-based research, in which we have the longest traditions," comments Martin Huber, who heads ESA's Space Science Department at Noordwijk in the Netherlands. "Even when we had no launchers, we were strong in ideas and techniques."

"Europe's watch on the Sun goes back as far as Galileo. Other predecessors began research on the chemistry of the Solar System by recognising meteorites as stones from outer space. And the 19th-Century discovery of the link between sunspots and magnetic storms led, through an unbroken line of teachers and students, to space missions investigating the Earth's magnetosphere."



Self-sufficiency in launchers. In the early days Europe relied heavily on NASA rockets, as with the Scout vehicle that put ESRO-2 into orbit in 1968 (right). By 1995, the development of Europe's own launchers has culminated in Ariane 5 (above), capable of lifting large spacecraft. Missions earmarked for Ariane 5 launches include Cluster (1995) and Rosetta (2003), as well as the astronomical projects XMM (1999) and FIRST (2005).


SOHO
Cluster
Earth

ESA's ventures in the Solar System range from Titan, near distant Saturn, to Mercury, close to the Sun.

A battle around the Earth

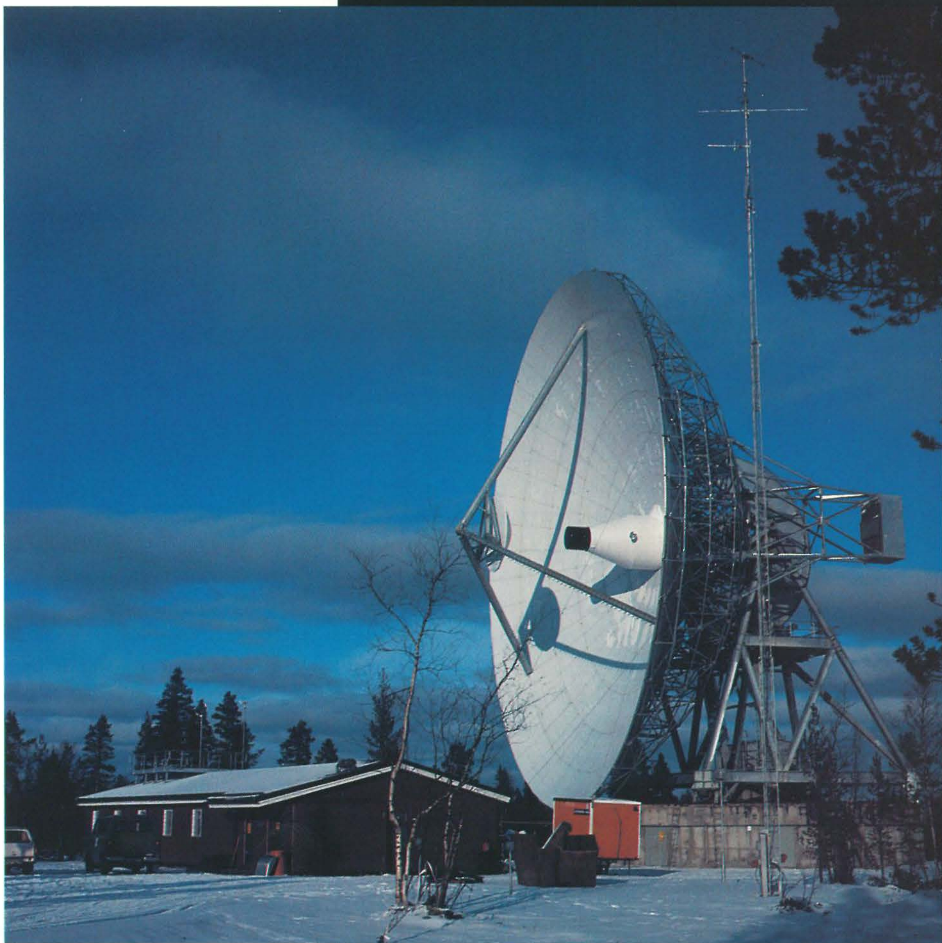
Early in the 20th Century a Norwegian physicist, Kristian Birkeland, reasoned that auroras lighting the Arctic air were due to electrons from the Sun. In 1951 the German astrophysicist Ludwig Biermann, who was studying comet tails, predicted the existence of a non-stop wind of electrons and charged atoms blowing from the Sun through the whole Solar System.
Unexpected radiation belts girdling the Earth showed up as energetic particles in a Geiger counter flown in the very first US satellite, Explorer-1 (1958). The Sun was their most likely source. Four years later NASA's Mariner 2 flew through an invisible barrier in the sky and found the solar wind. Other US and Soviet missions then investigated the barrier, some 60,000 kilometres out in space, where the Earth's magnetism fights the solar wind and forces it aside. Conversely, the wind confines the Earth's magnetism in a magnetosphere which is rounded on the sunny side and stretches away downwind like a comet's tail. Some solar particles break through the barrier to stock the radiation belts and light the auroras.

When the fledgling European Space Research Organisation, ESRO, came into existence, six out of the first seven European spacecraft were devoted to the magnetosphere. ESRO-2 (1968) showed that solar particles could reach the polar atmosphere via the tail of the magnetosphere. ESRO-1A and 1B tracked the auroral particles arriving at different latitudes according to the time of day and the occurrences of solar storms. ESRO-4 found a mysterious pool of helium gas over the magnetic poles in winter.
Meanwhile HEOS-1 (1968) had ranged two-thirds of the distance to the Moon. It explored the bow shock, where the solar wind falters as its approaches the magnetosphere. HEOS-1 also logged variations in the solar wind over a period of seven years. HEOS-2 orbited high over the Arctic and charted streams of solar particles crowding around a dent in the magnetosphere, called the polar cusp, over the magnetic pole.

In the 1970s, after the European Space Agency evolved from ESRO, magnetospheric studies continued with Geos-1 and 2 (1977-78). They investigated fields and waves that accelerate particles, to try to establish why those inside the magnetosphere are more energetic than the ordinary particles of the solar wind. All of this research by the world's space scientists was hampered by ambiguities in the data coming from individual spacecraft. Each had only a limited view of very complex events in the Earth's space environment. The launch in 1977 of twin satellites with similar instruments, NASA's ISEE-1 and ESA's ISEE-2, was an attempt to cure the problem. They operated together until 1988, but even this combination was not enough.

An adequate analysis of the battle around the Earth, and of how solar particles penetrate the magnetosphere, requires four satellites in company. That is the minimum number needed to build up a fully interpretable 3-D picture of events. To meet this requirement, ESA will launch the four satellites of the Cluster mission, in 1995. Its new Ariane 5 launcher, one of the most powerful in the world, will carry them into space on its maiden flight. Cluster will explore the particles, fields and waves in the magnetosphere and its surroundings. Powerful computers will analyse the very detailed results radioed from the four satellites. The mission scientists believe that Cluster will provide definitive answers to fundamental questions that have teased them and their colleagues around the world since 1958.

Image: Torbjörn Lövgren;
European Incoherent
Scatter Scientific Association



Intellectual ground support. From upper-air radars in the Arctic to the towers of sun-gazing telescopes on the Spanish island of Tenerife off the African coast, Europe's scientific community has both the facilities and the expertise in the science of the Solar System to underpin ESA's space missions - in conception as well as execution.

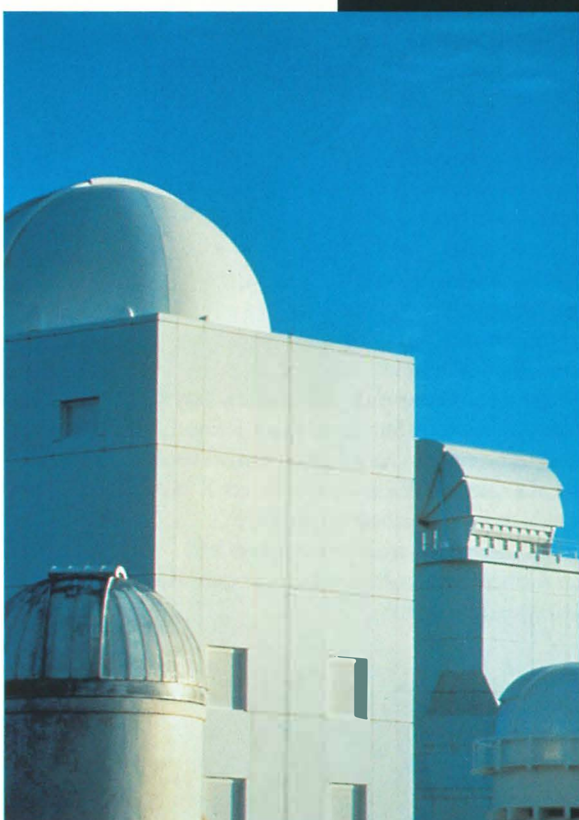
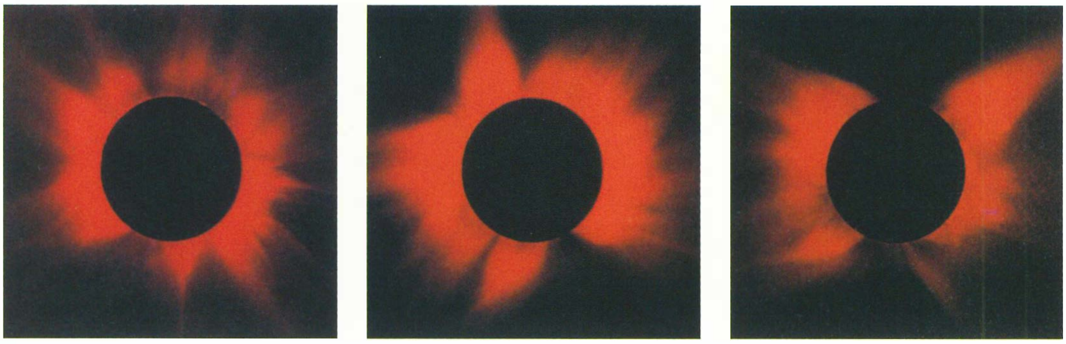


Image: Instituto de Astrofisica de Canarias, Spain



The moody Sun. The corona at different phases of the sunspot cycle shows great variability and lack of symmetry. Images: D.G. Sime (HAO, Boulder)

The Sun from space

American spacecraft en route to other planets built up a vivid picture of solar windstreams, imbued with magnetism from the Sun, racing through the zone where the planets orbit. NASA's Pioneer and Voyager missions followed the solar wind and its storms into the outer Solar System. The German-US Helios-1 and 2 spacecraft operated closer to the Sun, from 1974 to 1984.

The results raised more questions than answers. More than thirty years after its discovery, the solar wind remains an enigma. No one can say exactly what drives it, or why its speed varies according to its region of origin on the Sun. One weakness in solar-wind research was that all observations were made in the equatorial zone of the Sun. In 1977 ESA and NASA agreed to join forces for an exceptional project to explore the solar wind over the poles of the Sun.

The mission had a chequered history but eventually ESA's spacecraft Ulysses was sent on its way by NASA's space shuttle, the only launcher with the required power. It passed under the Sun's south pole in 1994. On its way, Ulysses had established chemical differences between the sources of fast and slow solar windstreams, and found shock waves passing through interplanetary space by unexpected routes. In the Sun's south polar region it discovered magnetic conditions quite different from what the scientists had expected. Ulysses continues its long journey by visiting the north polar region in 1995, and returning to the south pole in the year 2000, when the Sun will be much stormier.

Telescopic observation of the Sun from space is another long-established task. In 1948 American scientists used the short flight of a German V2 rocket to detect X-rays from the Sun, which do not penetrate the Earth's atmosphere. They confirmed what astronomers had suspected, that the Sun's outer atmosphere, or corona, is far hotter than its visible surface.

NASA flew the orbiting solar observatory OSO-1 in 1962. Thereafter a succession of missions examined the Sun, including the European satellites ESRO-2 (1968) and TD-1 (1972) which studied X-rays from solar flares. The pioneering phase came to a climax in 1973-74 when solar X-ray and ultraviolet telescopes aboard the US manned space station Skylab obtained classic pictures of the Sun's outer atmosphere.

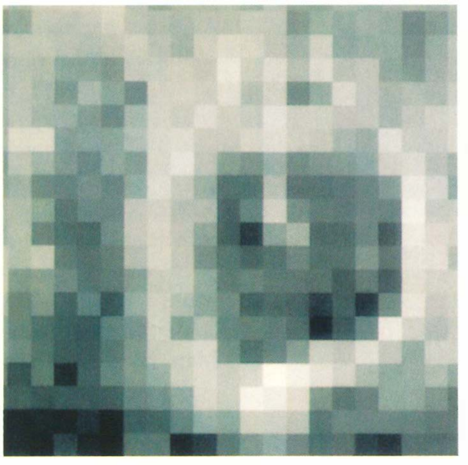
Skylab's X-ray pictures of the Sun have been surpassed by images and data streaming from Japan's Yohkoh satellite (1991). A set of advanced ultraviolet telescopes will fly in ESA's SOHO spacecraft (1995), which will be launched by a NASA rocket under a cooperative agreement. The scientists advising ESA have selected ultraviolet observations of the solar atmosphere as the best way to investigate the processes that heat the corona and let loose the solar wind.

SOHO is remarkable for the variety of its instruments. The spacecraft will hover on the sunward side of the Earth, immersed in the solar wind, so particle detectors will enable the scientists to relate the effusions from the Sun to events seen in its atmosphere. And SOHO will carry special telescopes designed to detect oscillations in the Sun's surface that will tell astronomers what is going on inside the Sun.

SOHO will investigate the Sun's output of radiant energy, which governs the Earth's climate. Natural and manmade dust veils in the atmosphere make accurate measurements of the Sun's true brightness impossible from the ground. NASA's SMM satellite (1980) established that the Sun is slightly brighter overall when there is a lot of sunspot activity. American weather satellites now monitor the Sun routinely. SOHO will link the fluctuations in output to external and internal events on the Sun.

Sensors of solar emissions in the ultraviolet, visible and infrared have also flown in ESA's retrievable carrier Eureca. This 4.5-tonne spacecraft accommodates a wide variety of technological and scientific experiments and it is launched and later returned to the Earth by US shuttle flights. The first Eureca mission flew for eleven months after a launch in 1992. Similar European solar instruments are carried in US shuttle-borne environmental missions.

A return to the Moon?



Orbiting very close by interplanetary standards, the Earth's Moon was the first target for extraterrestrial exploration. After a succession of Soviet and American unmanned probes, NASA's Apollo programme achieved six separate landings by astronauts, 1969-72.

They deployed various experiments on the Moon, including a foil nicknamed "the Swiss flag" to collect solar-wind particles for analysis by scientists in Bern. Seismometers detected small earthquakes caused by tidal stresses and the impact of meteorites. These revealed a crust 60 kilometres thick, and possibly a semi-molten core.

The astronauts made geological observations, and brought home 380 kilograms of rock from different locations for analysis. Soviet unmanned probes recovered smaller quantities. Analyses and dating of Moon rock, in which European scientists played a notable part, revealed a history of the cratering on the Moon caused by impacts of giant meteorites. The Moon is like a frozen, scaled-down image of the infant Earth, which was afflicted by many impacts of even greater violence.

After a lull of two decades in lunar exploration, NASA's Clementine (1994) went into orbit over the Moon's poles. It imaged the entire surface at eleven wavelengths, using modern remote-sensing techniques. A forthcoming Japanese mission, Lunar-A, is expected to drop a fresh set of seismometers onto the Moon.

ESA is evaluating a possible successor to Clementine, called MORO. It could obtain more detailed images, and use infrared and gamma-ray sensors for a mineralogical survey. A radar altimeter would trace the Moon's topography, while the tracking of a small subsidiary satellite, on another orbit, would reveal variations in the Moon's gravity from region to region.

An international lunar mission to test soft-landing techniques called LEDA is proposed by ESA. This might be a prelude to a concerted lunar programme by the world's space agencies in the 21st Century. European scientists have reviewed proposals for a lunar programme, including further work on lunar geology, the erection of arrays of astronomical telescopes on the Moon, and research on ecological life-support systems. In Europe as elsewhere, there are differences of opinion about the roles of astronauts versus mobile robots, in any return to the Moon.

It is easier to agree on the chief unanswered question about the Moon itself. Where did it come from? Some scientists believe that it assembled itself from debris flung from the Earth in a collision with an asteroid as large as Mars. Settling this question is therefore essential for understanding the early history of the Earth.

The scientific survey committee for ESA's Horizon 2000 Plus programme has considered solar missions for the 21st Century. It recommends that special attention be paid to the advent of instruments able to see fine details on the Sun, and to the possibility of observing it from more than one direction to achieve stereoscopic views of events on and above the stormy surface. Another proposal is for a spacecraft to dive into the atmosphere of the Sun, and into the Sun itself. Undertaken in collaboration with other agencies, the new solar mission will rank as a medium-scale project for ESA.

A sharper Moon. The vague impression of a kilometre-size crater in previous lunar missions is illustrated in the upper image. In the lower image the same feature appears at the higher resolution envisaged for MORO, a lunar mission proposed to ESA.

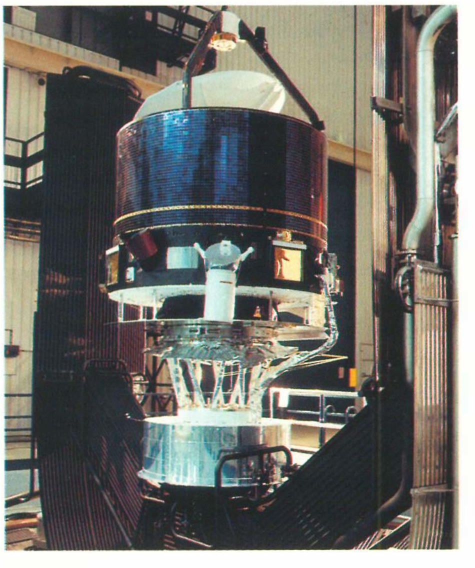
Halley's Comet in 1986
Image: European Southern Observatory

Other worlds

Collisions haunt the study of the planets and their moons. In the standard scenario, these objects arose in their astonishing variety by accretions of ever-larger lumps of material present in the solar nebula, the cloud of gas and dust that collapsed under its own gravity to build the Sun. So when NASA's Magellan mission mapped cloudy Venus by radar (1991-94) and revealed its geology to be quite unlike the Earth's, the researchers had to envisage different collisional histories for the twin planets.
The raw materials of the solar nebula were gas (mostly hydrogen and helium) and dust of icy, stony and tarry compositions. The best information about the solids comes from Europe's Giotto mission and the Soviet Vega spacecraft that accompanied it to Halley's Comet in 1986. Comets are left-over bricks from the building of the planets, and they contain almost pristine samples of the primeval dust at an early stage of accretion.
In all other bodies heat and pressure have altered the materials. This is so even in the small asteroids that resemble the bricks of the rocky planets. They and their planetary products inhabit the innermost zone of the Solar System, where the Sun's heat evaporates the ice of comets and leaves a refractory residue. Comet ice probably supplied abundant material to the more massive cores of the giant outer planets, as well as building icy moons and decorating Saturn with icy rings.

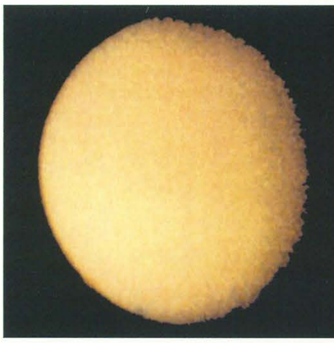
As a comet is a Rosetta Stone for unravelling the mysteries of the planets, Rosetta is the name of ESA's next comet mission. Unlike Giotto, which spent only minutes near Halley's nucleus, Rosetta will spend many months observing a comet at close quarters, and drop instruments on to its surface. There will be special interest in carbon compounds in the tar, of the kind that may have helped to fertilize the young Earth.
Meanwhile, an escape from the dusty traffic-lanes of the planets allows ESA's Ulysses mission to identify dust grains wafting into the Solar System from interstellar space. They include grains larger than expected. Stone, tar and ice seem to accumulate in the grains, long before star-making and planet-making start in earnest.

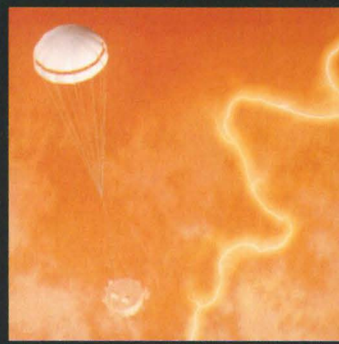
American and Russian explorations of the planets continue. NASA's pioneering flybys of all the major planets began with Mariner 2 to Venus in 1962 and ended with Voyager 2 at Neptune in 1989. The impacts of asteroids and comets, which continued after the completion of the planets, enabled the planetary scientists to estimate the geological ages of regions on planets and moons with rigid surfaces. They simply counted the impact craters.
More detailed studies of the planets, with orbiters and landers, have been already accomplished on Venus and Mars. By general consent Mars remains very interesting as the only planet where human beings, if properly dressed and supplied with oxygen, might exist in reasonable comfort. A mission to Mars, to complement other space agencies' efforts, is now under study among the medium-budget proposals for ESA's Horizon 2000. Horizon 2000 Plus, which starts in 2006, also recommends a Mars mission as a priority. Under a plan called Intermarsnet, ESA might scatter a network of four to six automatic geophysical observatories on the planet. A chain of giant volcanoes, the Tharsis mountains, straddles the Martian equator. This is the most promising region for detecting earthquakes and so exploring the internal structure of Mars.



Comet interceptor. When Halley's Comet made one of its visits to the inner Solar System in 1986, ESA's Giotto flew through its dusty head. Although damaged by the comet dust the spacecraft survived to intercept a second comet, Grigg-Skjellerup, in 1992. Giotto is still not dead, only hibernating, and will return to the Earth's vicinity in 1999, fourteen years after its launch.

Distant target. Titan is a moon of Saturn wreathed in haze, which ESA's probe Huygens will penetrate in an adventurous descent by parachute.





Titan from Voyager 1
Image: NASA

Other atmospheres

Mercury, closest to the Sun, is the least studied of the inner planets. Three fast flybys by NASA's Mariner 10 in 1974-75 showed Mercury to be pockmarked with craters, like the Moon. But that reconnaissance raised questions fundamental to planetary science which remain unanswered after twenty years. Why does Mercury have a magnetic field, when similar objects like the Moon and Mars do not? And is it the case, as the Mariner 10 images suggest, that an impact on one side has shocked the crust all around the planet, even to the antipodes?

A major ESA mission should set off for Mercury at some time in the period 2006-16, according to the scientists of the survey committee for the Horizon 2000 Plus programme. The Mercury spacecraft will go into orbit around the planet, in order to make far more detailed observations. Planetary scientists have wanted such a mission for a long time, but it poses formidable difficulties.

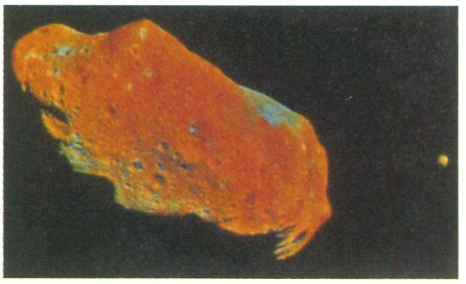
The problem of catching up with the fast-moving Mercury can be solved by a series of planetary swingbys. Designing a spacecraft capable of withstanding the intense heat, close to the Sun, will tax the skills of Europe's space engineers. The two German-built Helios spacecraft of 1974-84 currently hold the record for long endurance in orbits passing as close to the Sun as Mercury goes.

Detailed examination of the giant outer planets and their attendant moons begins with NASA's current Galileo mission to Jupiter. In 1997 NASA will despatch Cassini, for a prolonged exploration of Saturn, its rings, and its moons. Cassini will also carry ESA's probe Huygens, which will plunge into the atmosphere of Saturn's moon Titan, to make the most distant landing ever attempted on another celestial object.

The Huygens mission relates to the planetary histories that fascinate the scientists advising ESA. Most bodies in the Solar System have no atmospheres worth mentioning. The giant planets, at the other extreme, were massive enough to suck in large quantities of primeval gas from the solar nebula. Intermediate are bodies like Venus, Earth, Mars and Titan, which possess an atmospheric veneer on a solid surface.

Only on the Earth and Titan is nitrogen the main constituent of the atmosphere. Only the Earth and (by inference) Titan have abundant liquids at their surface. And only on these two bodies have elaborate carbon compounds evolved and survived in large amounts. Huygens may find on Titan a refrigerated version of the chemistry that preceded the origin of life on the Earth.

Questions of collisional history reappear when scientists try to explain contrasts in the atmospheres of Venus, Earth, Mars and Titan. American experts participating in Huygens have proposed that deliveries of volatile materials by impacting comets created the atmospheres. As some impacts would blast the volatiles away, different histories could give very different outcomes. Atomic fingerprints in Titan's atmosphere will test this theory.



A ruddy asteroid. Ida is 60 kilometres long, and when NASA's Galileo mission imaged the asteroid in 1994 scientists discovered a 1-kilometre moon, visible on the right. Here the red colouring of Ida is exaggerated to show that its moon is greyer.
Image: JPL/NASA

The asteroids

Many of the small planets called asteroids are similar in size to comets, although some are bigger. They all lack the comets' effusions of gas and dust. Asteroids are the last ingredient of the Solar System to win attention from space probes, beginning with flyby pictures of Gaspra and Ida from NASA's Galileo spacecraft. These objects are among thousands of stony and iron-rich asteroids that orbit as pieces of a failed planet, in the Asteroid Belt between Mars and Jupiter. ESA's Rosetta will also observe objects during its passages through the Asteroid Belt, en route for its rendezvous with a comet.

Astronomers know many kinds of asteroids. Analysis of meteorites falling to the Earth, as fragments produced in collisions between asteroids, may give a better impression of the constitution of asteroids in general than detailed examinations of one or two objects by dedicated space probes. On the other hand it is important to discover the origins of those asteroids that follow orbits that bring them close to Earth. Are they mostly rocky objects displaced from the Asteroid Belt, or burnt-out comets that have exhausted their surface ice? A NASA spacecraft called NEAR is expected to rendezvous with a near-Earth asteroid.

A future catastrophic collision with the Earth is a possibility that exercises the asteroid hunters. This concern is likely to provoke more intensive space activity in the 21st Century. Meanwhile NASA has proposed a global network of ground-based observatories dedicated to discovering and monitoring the asteroids and comets that could threaten the Earth. Dramatic images from the NASA-ESA Hubble Space Telescope showing the impact sites of the fragmented Comet Shoemaker-Levy 9 in Jupiter's atmosphere, in July 1994, confirm that interplanetary traffic accidents are not a figment of scientific imaginations.

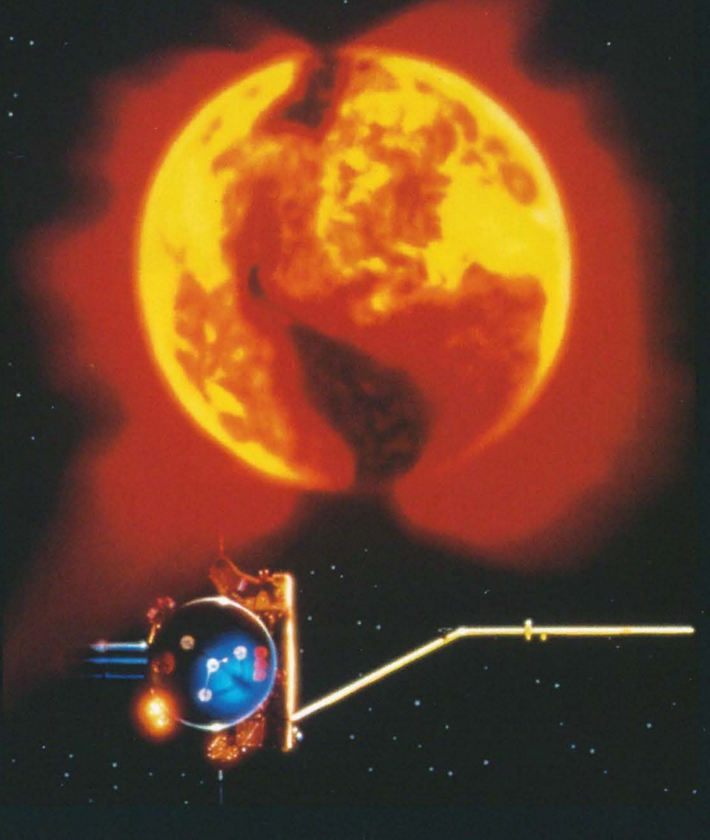
The Hubble pictures are also a reminder that telescopes on or near the Earth complement the deep-space probes in exploring the Solar System. Besides existing US-European astronomical satellites, IUE and Hubble, ESA's forthcoming ISO and FIRST missions operating at infrared and submillimetre wavelengths will make intensive observations of the planets, moons, comets, asteroids and interplanetary dust.

Ulysses: over the Sun's poles

"We went to the south magnetic pole of the Sun and it wasn't there," says André Balogh of London. He is in charge of the magnetometers aboard the European Space Agency's spacecraft Ulysses. When it made the first-ever flight through polar regions of the Sun's windy empire, in September 1994, Balogh's instruments found no concentration of magnetism such as exists near the poles of the Earth. Ulysses had gone to the right place, but the Sun chose not to behave as scientists had expected.

On the other hand, Ulysses encountered strong magnetic waves coming from the polar regions. "It is as if there is a man in the Sun hitting the field-lines with a hammer," says Balogh. "When we can work out how the waves are really produced, we may understand better what drives the solar wind."

ULYSSES



Into unknown space. In this impression of Ulysses, the radio dish remains locked on the distant Earth. The black cylinder projecting on the left contains a radioactive source that powers the spacecraft. The boom on the right carries the magnetometers that made salient discoveries about the Sun.

The textbooks will have to be rewritten in the light of Ulysses' findings, which is the sure sign of progress in science. They will also describe the effect of the polar magnetic waves on the cosmic rays approaching the Sun from the depths of space. According to predictions, Ulysses should have seen intensified cosmic rays in the polar regions. Instead, the magnetic waves caused the incoming particles to disperse, even when the Sun was relatively calm, as in 1994. These are headline results from the south solar-polar pass of Ulysses. They rank with the great enlightenments of earlier Solar System exploration, like the lifelessness of Mars and the sulphur volcanoes of Io. But compared with the planets and moons, the nebulous and every-varying Sun requires quite different methods of observation.

Ulysses detects electric particles and magnetism, carried by the wind that blows nonstop from the Sun. It also looks outwards, at the energetic particles of the cosmic rays, which serve as probes of distant parts of the Sun's empire not visited by the spacecraft. Other sensors detect gas and dust arriving from interstellar space beyond the heliosphere, or radio waves and other disturbances created by eruptions on the Sun.

The solar wind blows a huge bubble in space called the heliosphere, which extends far beyond the realm of the planets. The task of Ulysses was to observe the Sun and its heliosphere from new angles. But compared with the explorations of the planets, getting to the polar regions of the heliosphere was much more difficult.

Data on Ulysses

Purpose
to observe the Sun's effusions from new angles

Responsible agencies
ESA and NASA (equal partners)

Name
from the classical sailor-hero (Odysseus in Greek, Ulysses in Latin)

Prime contractor
Dornier, Friedrichshafen, Germany

Mass
370 kg

Scientific payload
55 kg, 9 experiments

Power supply
radio-isotope

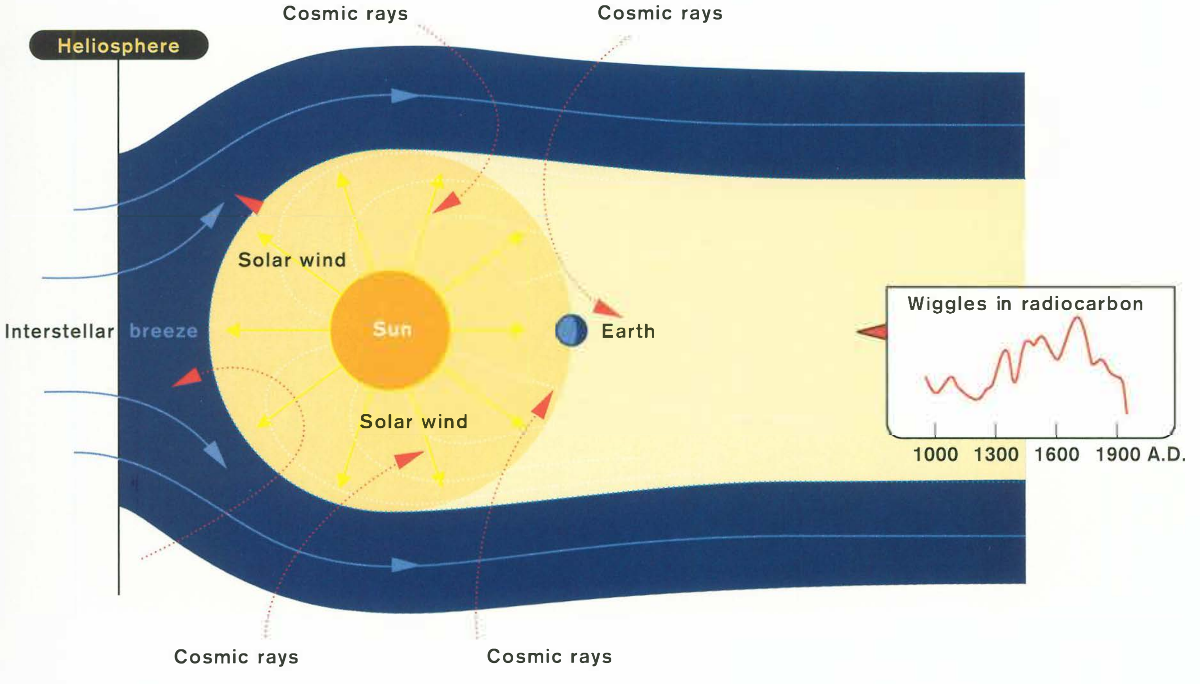
Ground stations
NASA Deep Space Network

Launch vehicles
Space Shuttle Discovery and 3-stage solid-fuel interplanetary injector (NASA)

Launch
6 October 1990
Swingby of Jupiter
8 February 1992
Highest south solar latitude (80.2 deg.)
13 September 1994
Highest north solar latitude (80.2 deg.)
31 July 1995
Return to solar-polar regions:
south 2000, north 2001

How did the Sun vary in past centuries?

The biggest experiment in Ulysses reports on the battle between the Sun and the cosmic rays, in the immense heliosphere that surrounds the Sun and envelops its planets. Cosmic rays are very energetic atomic particles flung from exploding stars far away in cosmic space. They reach the Earth, in a modified and weakened state, only after passing through obstacles created by the Sun.



Magnetic waves and shocks in the solar wind scatter the cosmic-ray particles. When the Sun is stormiest, at the peak of its 11-year sunspot cycle, the cosmic rays are reduced. But in frequent episodes in the past the cosmic rays reaching the Earth have been, on average, significantly more numerous than today. Old wood, accurately dated by its tree-rings, shows enhancements in radiocarbon, caused when cosmic-ray particles hit nitrogen atoms in the air.

Some tree-ring records of cosmic-ray "wiggles" now go back thousands of years.

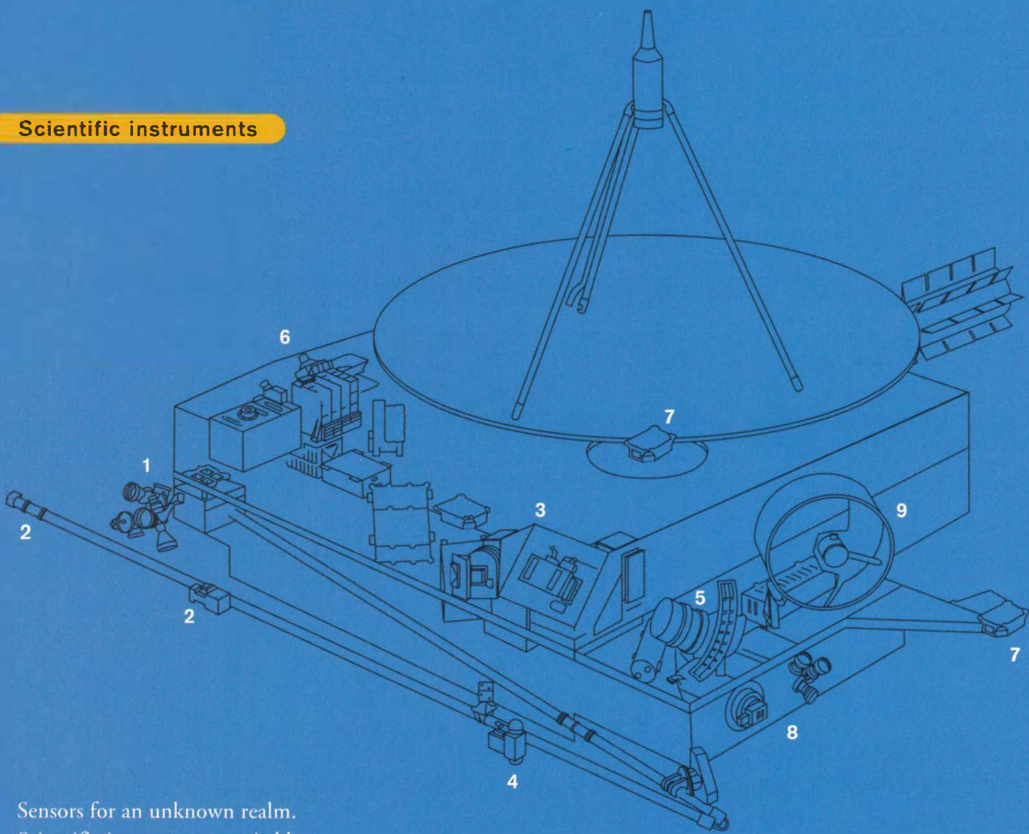
The last cosmic-ray peak coincided with a Little Ice Age on the Earth, at the end of the 17th Century, when the climate was unusually cold. It was also a period when astronomers were complaining about an almost total lack of sunspots.

While cosmic rays have no effect on the weather themselves, they report changing behaviour by the Sun which may also alter its output of energy from century to century.

Ulysses has confirmed and discovered various ways in which the present-day Sun hampers the cosmic rays. At the sunspot maximum in 2000-01, when the spacecraft revisits the solar poles, the battle with the cosmic rays will be at its height.

If the scientists can decipher the connection between cosmic rays and solar behaviour they will make a vital contribution to understanding past and present climate changes on the Earth.

Scientific instruments



Sensors for an unknown realm. Scientific instruments carried by Ulysses sample many kinds of particles that haunt the previously unexplored regions of the Sun's environment. Only the Principal Investigators of the onboard experiments are named, but more than 100 scientists from twelve countries are involved in the mission.

1 HI-SCALE
Low-energy ions and electrons
L.J. Lanzerotti
Bell Laboratories

2 VHM AND FGM
Magnetic field
A. Balogh
Imperial College
London

3 SWOOPS
Solar wind plasma
J.L. Philips
Los Alamos

4 GRB
Solar X-rays and cosmic gamma-ray bursts
K. Hurley
UC Berkeley
M. Sommer
MPE Garching

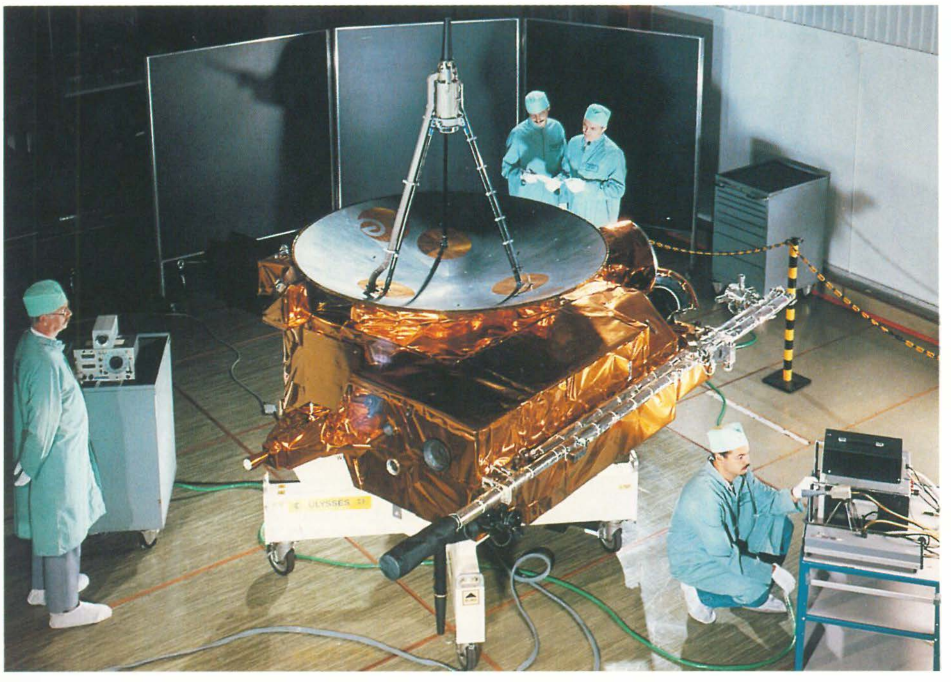
5 SWICS
Solar wind ion composition
J. Geiss
Bern
G. Gloecker
U. Maryland

6 COSPIN
Cosmic rays and solar particles
J.A. Simpson
Chicago

7 URAP
Radio and plasma waves
R.G. Stone
NASA Goddard

8 EPAC, GAS
Energetic particles and interstellar neutral gas
E. Keppler
MPAe Lindau

9 DUST
Cosmic Dust
E. Grün
MPK Heidelberg



Ready for the new odyssey. A gold-coloured thermal blanket makes the Ulysses spacecraft look a gift-wrapped parcel. The dish antenna on top must always remain pointed at the Earth, for communication with ground stations and mission control.

A boost from Jupiter

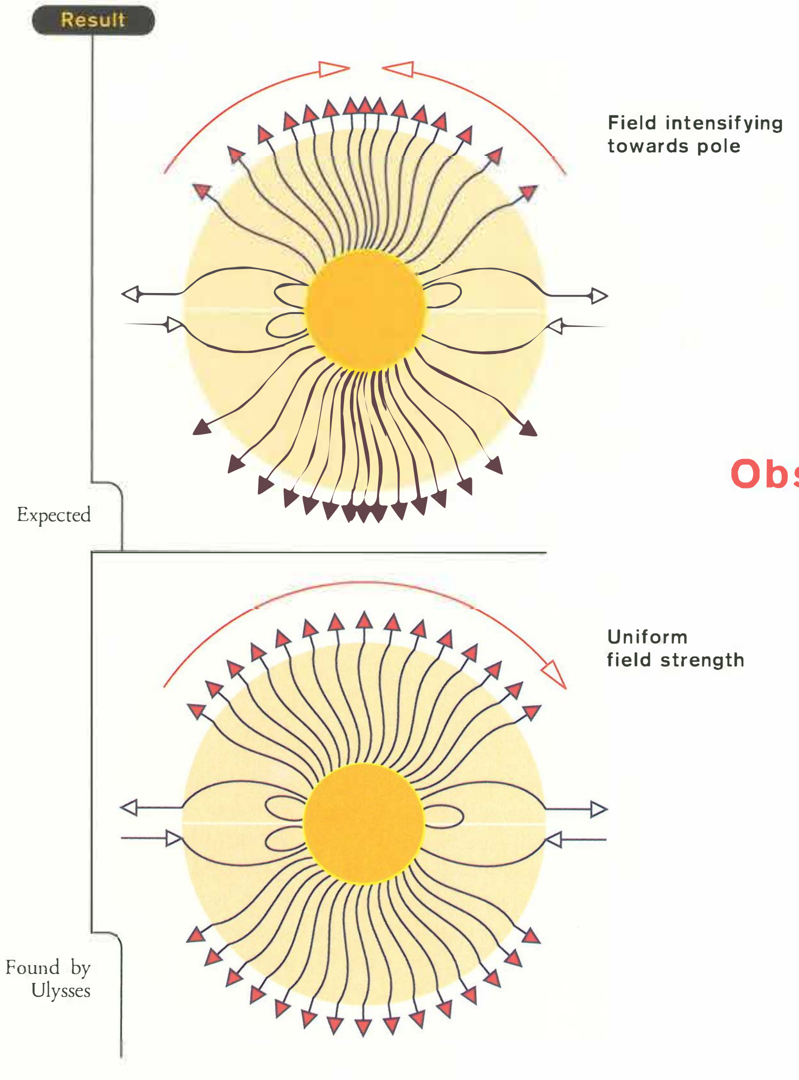
"How could you expect to understand the Earth's weather if you lived at the Equator and were never quite sure about the climate in other latitudes?" asks Richard Marsden, ESA's project scientist for the mission. "It's the same with the Sun. Yet astronomers and space scientists always had to make do with an equatorial view of the Sun, until Ulysses."

The Earth orbits in a flatland called the ecliptic plane, which slants at only 7 degrees to Sun's equator. The other major planets remain very close to the same plane. Existing rockets are too feeble to send a probe out of the ecliptic and over the Sun's poles. The rockets can only subtract or add a little velocity to the Earth's own speed of 30 kilometres per second in orbit around the Sun.

Ulysses attained 41 kilometres per second, relative to the Sun, at its launch in October 1990, making it the fastest interplanetary spacecraft ever despatched. But it still needed to cancel the Earth's motion and build up speed in a new direction. Sixteen months later the spacecraft's navigators achieved this result by making Ulysses pass close to the north of the massive planet Jupiter. The strong gravity deflected it southward, out of the ecliptic, on the new orbit that would carry it over the polar regions of the Sun in 1994-95.

The four-year voyage via Jupiter was not long compared with the timescale of building the Ulysses spacecraft and then waiting seven years for its launch. The delay was partly due to the accident with the space shuttle Challenger in 1986.

The solar-polar mission was conceived in the 1970s as a joint ESA-NASA mission, and so it remains. NASA cancelled a second spacecraft intended to round the Sun in the opposite direction to Ulysses, but fulfilled promises to launch the European spacecraft, to provide a radioactive power source, and to make available the ground stations needed to communicate with Ulysses across vast distances. ESA developed the spacecraft and now operates it. Half the experiments aboard Ulysses are allotted to US-led teams of scientists and half to European principal investigators.



The outward behaviour and variability of the Sun are wholly bound up with its magnetism, which remains deeply puzzling.
Before Ulysses, scientists knew that the solar wind drags out the equatorial magnetism into a sheet, but they imagined that conditions near the Sun's poles of rotation would be more like those on the Earth, with the magnetism focused toward well-defined magnetic poles. Ulysses found the magnetism evenly spread so the experts will have to re-cast their theories.

Observations en route

On its way towards Jupiter, Ulysses was in the familiar solar weather of the equatorial heliosphere. This is dominated by a relatively slow solar wind, travelling at about 400 kilometres per second. Windstreams from the northern and southern hemisphere contend for possession of the equatorial zone, and finish up travelling side by side.
The windstreams drag with them the solar magnetism of the hemisphere from which they originate. They are separated only by the skirt-like "current sheet" which waves and swirls with the rotating Sun, like a ballerina's skirt. Ulysses felt many abrupt reversals of the magnetic field as the skirt swept past it. It also experienced shock waves, when outbursts on the Sun sent out swift gusts that overtook the slow-moving solar wind.

When the solar wind runs up against the strong magnetism of Jupiter, a tussle ensues. Essentially, the planet holds the solar wind at bay, excluding it from a large region called the magnetosphere. In February 1992, the Ulysses scientists took advantage of the spacecraft's close encounter with Jupiter to observe the magnetosphere. It swelled and shrank as the solar wind-strength varied, and its interior was thick with effusions from Jupiter's volcanic moon Io.

After its encounter with Jupiter, Ulysses gradually worked its way southwards, out of the equatorial zone of the heliosphere and towards higher solar latitudes. The heliospheric weather began to alter. The Sun itself helped with the changes by calming down, after the stormy period associated with a maximum in the count of sunspots on its surface, which occurred in 1990.
From August 1992 onward, Ulysses experienced spells of a much faster solar wind. Blowing at up to twice the speed of the slow wind, at 800 kilometres per second, the fast wind comes from relatively cool parts of the solar atmosphere called coronal holes. By the latter part of 1993, the spacecraft was fully immersed in the fast wind from a south coronal hole. In the meantime, the scientists had compared the composition of the two kinds of solar wind.

"Our instrument sensed a striking difference," says Johannes Geiss of Bern. "At the source of the slow wind the temperature of the solar atmosphere is about 1.8 million degrees. It is hundreds of thousands of degrees lower in the coronal holes. Although the slow wind comes from the hotter source, it is poor in elements such as nitrogen that are hard to ionize. These elements must be depleted."

Shock waves from outbursts on the Sun continued to wash over Ulysses, at much higher latitudes than expected. They arrived by circuitous routes. And in February 1994, energetic particles from a solar flare at 20 degrees north latitude reached the spacecraft at 55 degrees south latitude. Richard Marsden says, "Ulysses tells us that the regions of the heliosphere are interconnected in ways we had not imagined."

More tranquil solar weather made easier the observation of events obscured in turbulent conditions. Strange magnetic nulls occurred, with the all-pervading magnetism of the solar wind disappearing for up to a minute. They were interpreted as a spray from the Sun, of material sufficiently hot and dense to repel the magnetism.

As the Sun travels among the stars, a thin interstellar gas creates a breeze that shapes the heliosphere. One instrument in Ulysses detected its atoms directly, and showed the breeze to be a little faster than expected.

A high-tech dustbin collected dust particles from interstellar space, representing raw material of the kind from which the planets were built.

In their search for the Sun's south magnetic pole, Ulysses scientists expected it to be offset from the axis of rotation, which defines the true pole. They thought that the rotation would swing the magnetic pole directly into line with Ulysses, around the time in mid-September 1994 when the spacecraft reached its furthest south, 80.2 degrees below the Sun's equator.

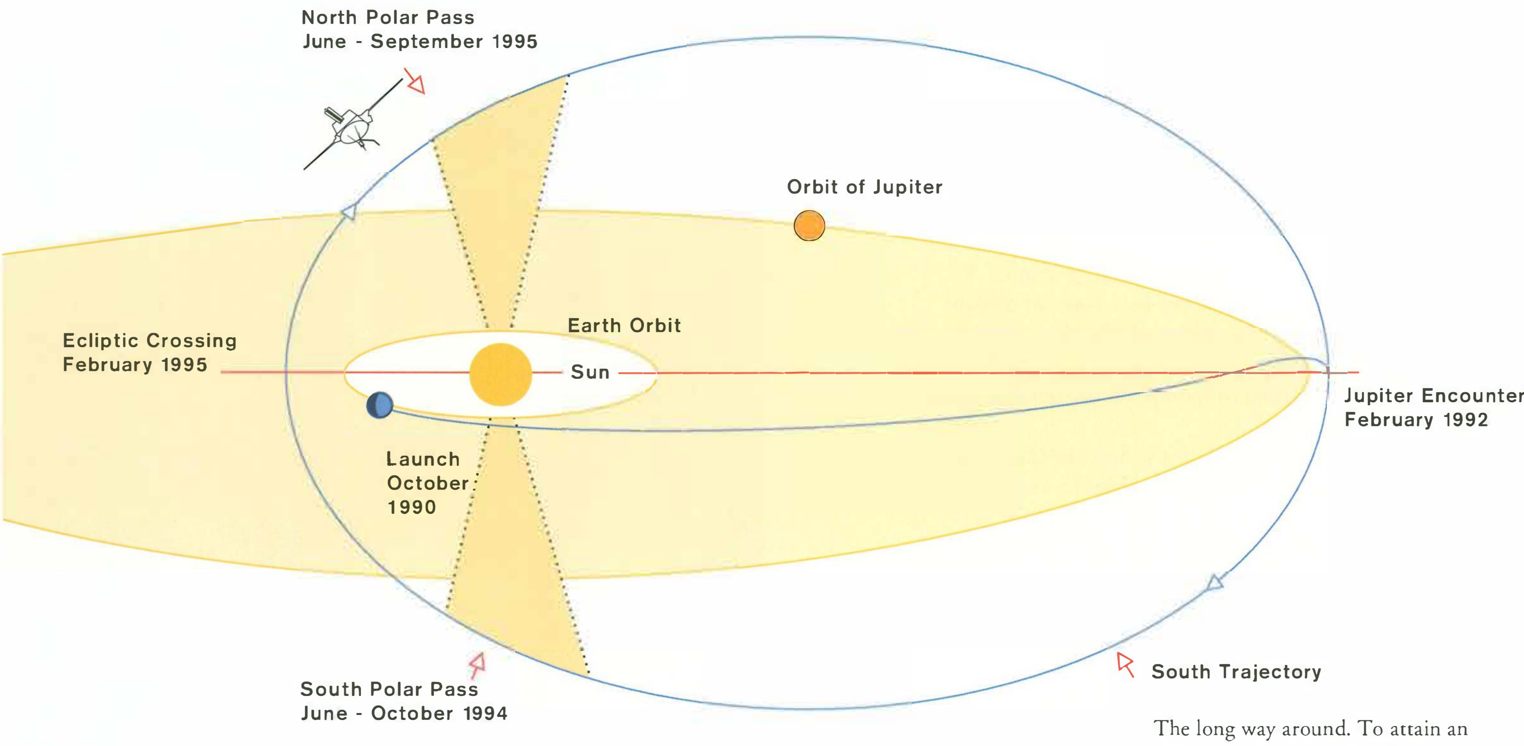
Even in August there was no sign of intensifying magnetism and cosmic rays, which might have marked an approach to the magnetic pole. The Ulysses scientists met at ESTEC in Noordwijk at furthest-south time. Some were rueful and others mystified, but all were excited as the data coming from the spacecraft compelled them to agree that the Sun conceals from the outside world any ordinary magnetic pole that it may possess.

October 1991

March 1994

The calming Sun. While Ulysses was on its long journey, the Japanese satellite Yohkoh in orbit around the Earth observed X-rays from the Sun's atmosphere. Between 1991, near sunspot maximum, and 1994, approaching sunspot minimum, the Sun became calmer and more orderly. The dark coronal holes, which are sources of a fast solar wind, are plain to see in the second image.

Image: R.D. Bentley (MSSL, UK) and Yohkoh SXT team



The long way around. To attain an orbit over the poles of the Sun, Ulysses used the gravity of Jupiter to hurl it southwards out of the "flatland" in which the planets orbit.

The odyssey continues

Ulysses has already rewarded the years of effort that went into preparing and flying the mission, but there is much more to come. The solar-polar orbit carries the spacecraft rapidly across the Sun's equator and then onwards to an overflight of the north polar region in July 1995.

Meanwhile the dust experiment aboard Ulysses comes to a culmination of its own. It has detected interstellar dust heavier than expected, and the German team imagines them encrusted with ice. If so, the ice should evaporate near the Sun and the dust should become lighter during Ulysses' closest approach. A positive answer would sustain a growing belief that ice was a crucial ingredient in planet-making.

Over the north pole the scientists will be able to confirm or vary their impressions from the south. The mission was due to end after the north-polar pass in 1995, after which the orbit will carry Ulysses away from the Sun. But their successes have helped the scientists to win the argument for continuing the odyssey until the spacecraft returns to the Sun in the years 2000-01.

This will multiply the value of the mission. The polar observations 1994-95 coincide with a quiet time on the Sun, marked by a scarcity of sunspots. At the end of the decade, the Sun will be highly active and close to its sunspot maximum, creating completely different weather in the high-latitude heliosphere explored by Ulysses.

SOHO: making sense of the moody Sun

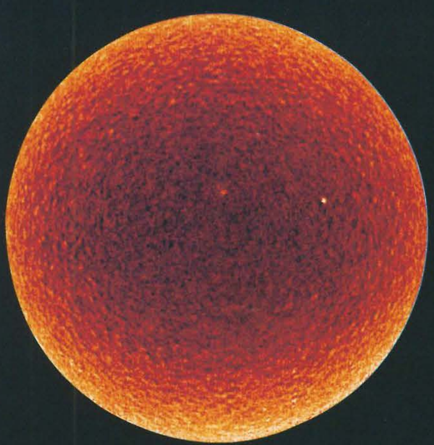
One of the most surprising discoveries about the Sun in the past few decades is that it sings to itself. The notes are too low for human hearing, and cannot cross the near-vacuum of interplanetary space. Solar physicists can nevertheless detect rhythmic motions in the solar surface, produced by sound waves reverberating inside the Sun. The resulting oscillations have precisely defined frequencies, like musical notes and overtones, and on analysis they give novel information about the way the Sun is built.

In 1995, the European Space Agency's SOHO spacecraft will station itself 1.5 million kilometres out, on the sunward side of the Earth, where the gravity of the Earth and the Sun are in balance.

Raw Data

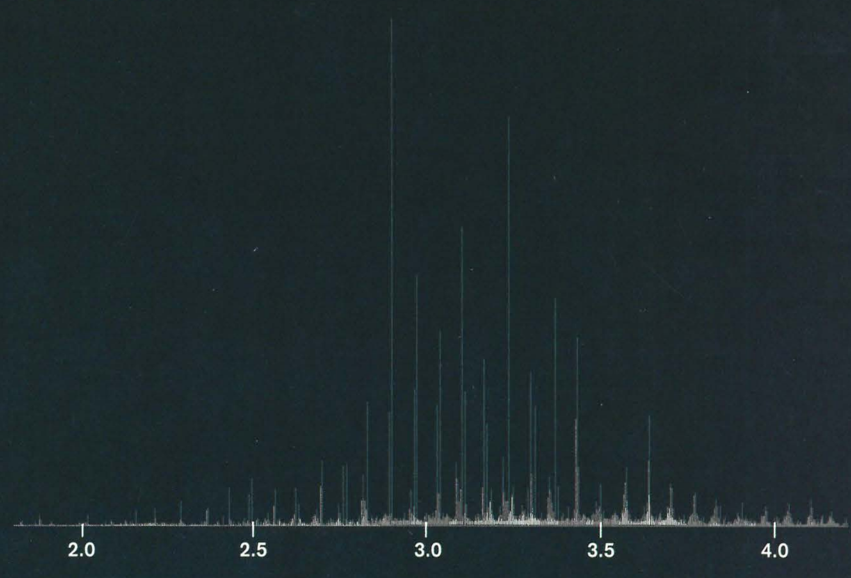
SOHO

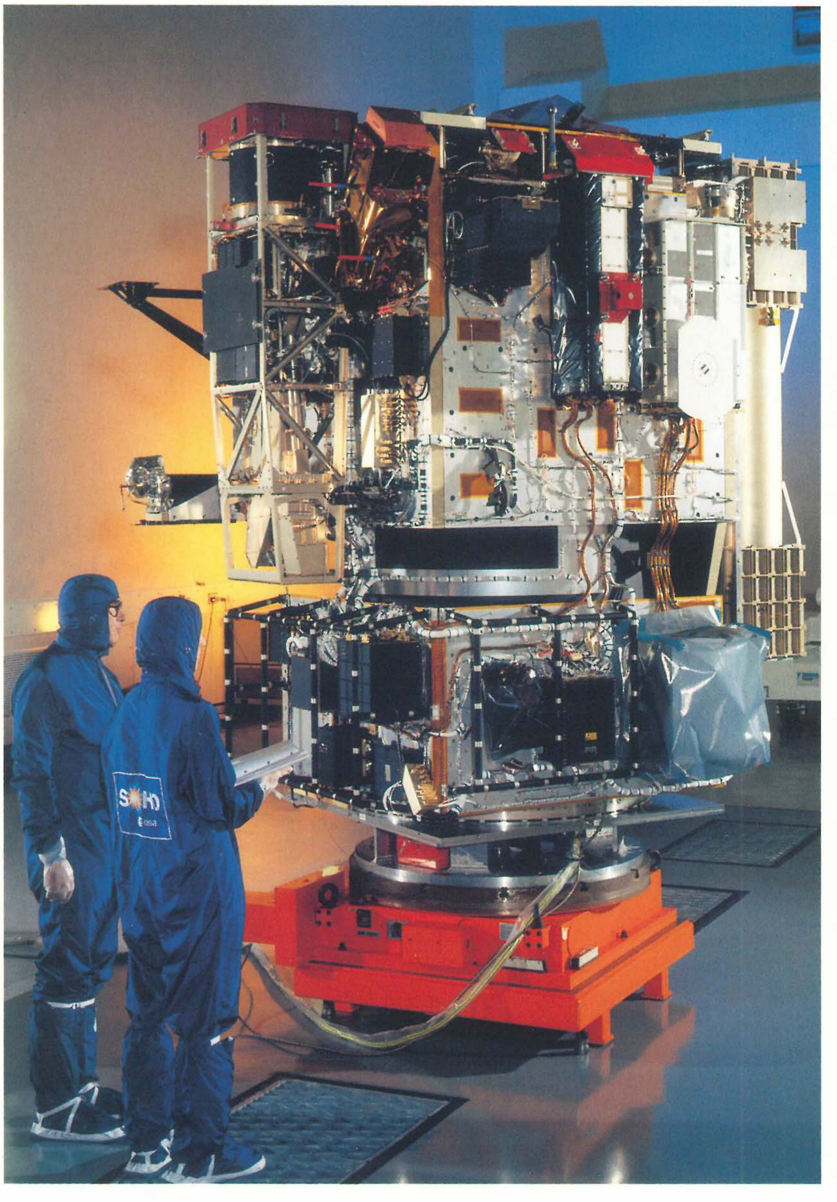
SOHO stands for Solar and Heliospheric Observatory, and one of its tasks will be to make a hi-fi recording of the Sun's song. Other instruments in the spacecraft will make a coordinated study of the processes that heat the outer atmosphere of the Sun to millions of degrees, and propel the solar wind. SOHO will also sample the solar wind as it blows towards the Earth, where it influences our planet's space environment.



Dopplergram Residuals

Solar sound. SOHO's MDI instrument shows parts of the surface approaching (yellow) and receding (red). The Sun's rotation dominates the raw data. When this effect is subtracted (lower image) complex surface motions due to internal sound waves become apparent. A scale (right) shows distinct "notes" registered by Birmingham University's ground-based global network. These are whole-Sun oscillations taking about 5 minutes, and the scale is in millihertz.
Images: P.H. Scherrer (Stanford) and Lockheed Palo Alto Research Lab.
Oscillations spectrum: G.R. Isaak (Birmingham)





Intricate enginering. The complexity of SOHO's instrumentation was evident during the spacecraft's construction.
Less obvious in this photograph is the fact that every component and sensor is designed to withstand the rigours of the launch and a hostile space environment.

Data on SOHO

Purpose
to observe the Sun from its deep interior to its outer regious and the solar wind

Responsible agencies
ESA and NASA
(SOHO/Cluster joint STSP programme: ESA 70%, NASA 30%)

Name
from Solar and Heliospheric Observatory
also a medieval Anglo-French hunting cry

Prime contractor
Matra Marconi Space, Toulouse, France

Mass
1610 kg plus 240 kg propellant

Scientific payload
650 kg, 12 experiments

Length
3.8 metres

Launch
1995

Launch vehicle
Atlas-IIAS (NASA)

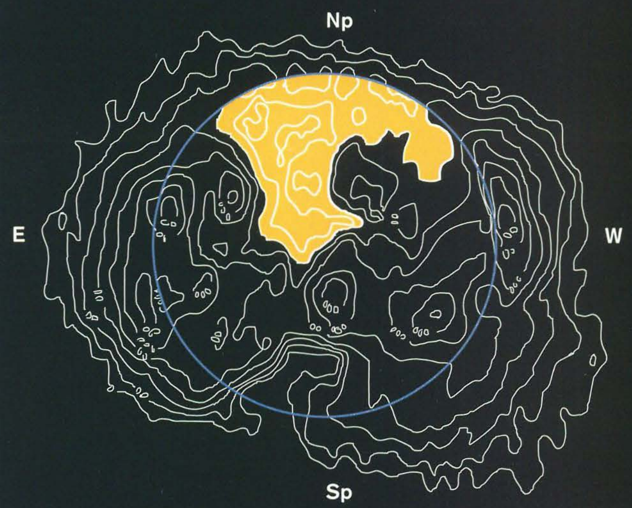
Orbit
around L1, 1.5 million km sunward of Earth

Control centre
NASA Goddard

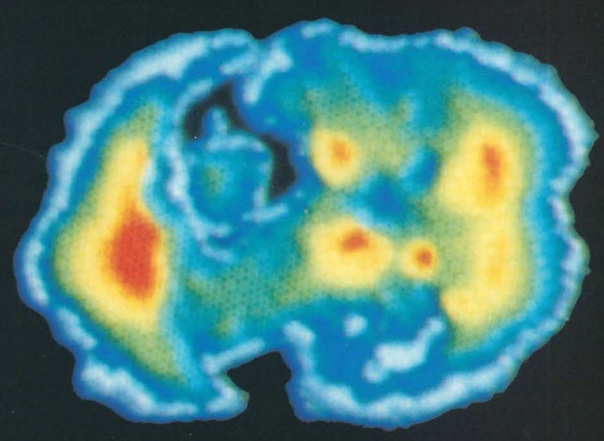
Ground stations
Deep Space Network (NASA)

Lifetime
two to six years

Power supply
solar cells



At short wavelengths. Impressions of the Sun's atmosphere as observable by SOHO's EIT instrument come in data from NASA's OSO-7 satellite in 1972: intensity contours above, and a colour-coded image below. Highly ionized iron atoms emit very short ultraviolet waves. Emissions are strongest (red) in regions near the equator. Besides giving daily pictures of overall solar weather, EIT can examine chosen regions in detail.
Image: W. Neupert; EUV Spectroheliograph



The ultraviolet Sun

The Sun's atmosphere seethes above its bright surface, as hot, electrified gas fights the Sun's magnetism.

The symptoms include arching prominences, hairlike features, and masses of gas welling up like thunderclouds.

End results of this activity are well known. The Sun's atmosphere, or corona, becomes hot enough to radiate X-rays. Some electric particles win their fights and break out as the solar wind, which drags the Sun's magnetism into space in the distorted patterns investigated by ESA's Ulysses mission. But the intervening processes remain mysterious.

That's why the largest group of instruments in SOHO will observe them by ultraviolet light. It is selected from the wide range of emissions from the Sun as the waveband most likely to reveal what happens in the outer atmosphere. The ultraviolet in question is not the long-wavelength kind that penetrates the Earth's air and causes sunburn, but much shorter wavelengths detectable only in space.

"We want to know how the Sun makes its atmosphere surprisingly hot," says Klaus Wilhelm of Lindau, Germany, "and how pieces break loose to become the solar wind." He is principal investigator for the SUMER experiment, which will repeatedly scan active and quiet regions of the Sun at selected ultraviolet wavelengths.

"Short-wave ultraviolet," Wilhelm explains, "picks out precisely those parts of the Sun's lower atmosphere where the temperature begins to soar, from 10,000 degrees to more than a million. We suspect that the heating events are small and quick, so we need an instrument to match. SUMER will see features smaller than 1000 kilometres, and will scan an 80,000-kilometre strip of the Sun forty times in an hour."

CDS, an instrument conceived in the UK, will scan regions of the Sun at shorter ultraviolet wavelengths. Comparisons of intensities at different wavelengths will enable the observers to identify dense patches of the atmosphere. Shifts in the wavelengths will measure their speeds.

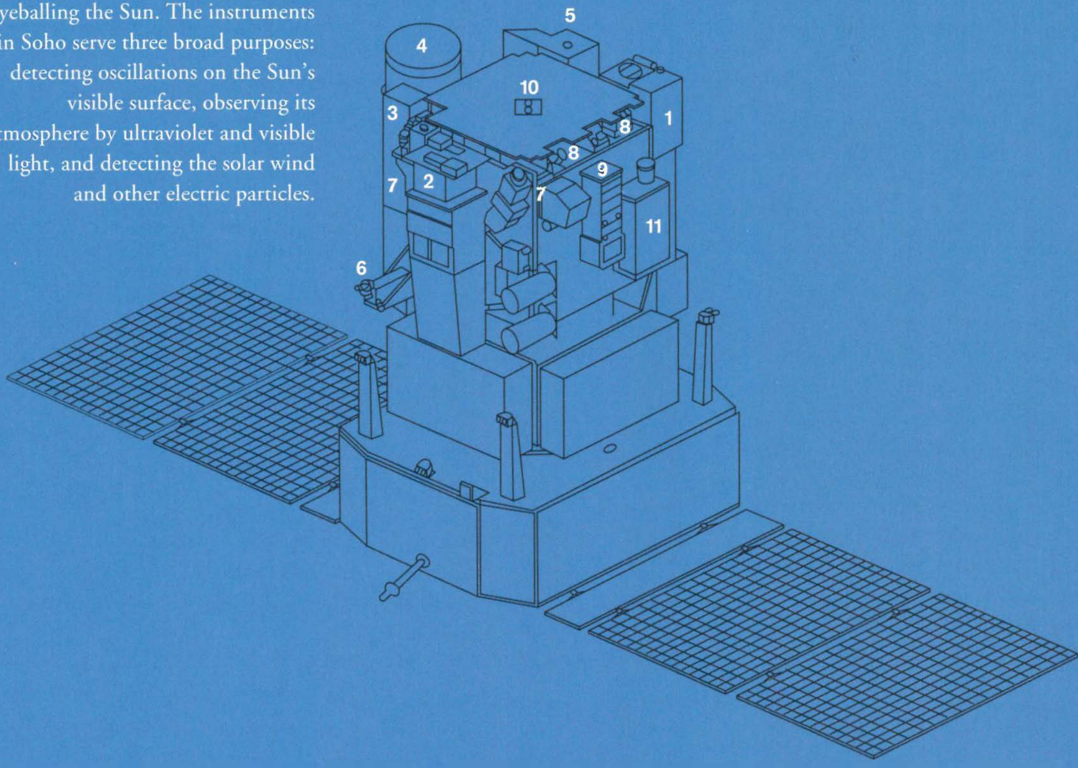
Samples of the Sun's atmosphere

Both of these scanning spectrometers will be guided to the most promising sites by a telescope devised by a French, Belgian and US team. It will provide daily images of the whole Sun and its inner atmosphere at four different ultraviolet wavelengths selected by filters.
It will also survey the Sun sector by sector in greater detail, and support the other instruments in close observation of the selected areas.
An American-Italian instrument will look further afield, scanning the corona out to a distance of 7 million kilometres, or five times the Sun's diameter. It will observe selected chemical elements by ultraviolet light, including typical ultraviolet coming from the hydrogen atoms of the Sun. As the atoms accelerate into the solar wind, the streams will appear dimmer because of the shift in their apparent wavelength. The dimming effect will be a measure of their speed.
A second American coronograph, working by visible light, will image the corona out to a record-breaking 21 million kilometres, where it is extremely faint. Related French-British and German instruments will give more detailed views of the corona closer in.

SOHO's extraordinary powers to observe the events in the Sun's atmosphere by both ultraviolet and visible light come partly from the quality of the individual instruments. But the simultaneous observations by five instruments on different scales, and at various wavelengths, will enable the scientists to trace events from the lowest parts of the atmosphere to its windy fringes.
"We worked out the best combination of telescopes," Wilhelm comments. "We shall operate them together and use one another's results to help interpret what we see."
One ultraviolet instrument aboard SOHO will look not at the Sun but at an ultraviolet glow of hydrogen atoms pervading the Solar System. Scanning the whole sky, this French-led experiment will try to discover whether or not the heliosphere, the giant bag in space that contains the Sun's magnetism and the solar wind, is flattened on the poleward sides.

The solar wind will sweep past the spacecraft at hundreds of kilometres a second. A joint German, Swiss and American experiment will identify the chemical elements and measure their electric charges. It will also count rarer and faster particles accelerated in solar outbursts and the consequent shocks. These last arrive at an angle, coming along the magnetic field.
For even more energetic particles, travelling almost as fast as light, devices made in Germany and Ireland will distinguish electrons and the nuclei of various elements by tracking them through sandwiches of semiconductors. Sensors from Finland will extend the search to lower and higher energies.
The atoms and electrons in interplanetary space are samples of the Sun's atmosphere. SOHO will enable scientists to trace chemical packets back to their origins on the Sun. Comparisons with what the telescopes show will help to check the theories about what propels the particles.
The solar wind will continue on its way, past SOHO, to arrive near the Earth an hour or so later. There, the four satellites of ESA's Cluster will observe effects of the solar wind in the Earth's vicinity. SOHO and Cluster are related projects, and scientists from the two missions will exchange both data and theoretical ideas. They will all be striving to understand the Sun better, and to learn how it rules interplanetary space and the Earth's environment.
And by observing the Sun in many different ways, with its own instruments, SOHO will link events in the Sun's atmosphere and solar wind to activity beneath the visible surface and the Sun's strange song.

Eyeballing the Sun. The instruments in Soho serve three broad purposes: detecting oscillations on the Sun's visible surface, observing its atmosphere by ultraviolet and visible light, and detecting the solar wind and other electric particles.



Scientific instruments

1 SUMER
Scanning ultraviolet spectrometer
(50-160 nanometres)
PI: K. Wilhelm
MPAe, Lindau, Germany
Co-Is: D, CH, F, USA

2 CDS
Extreme ultraviolet spectrometer
(15-79 nanometres)
PI: R.A. Harrison
DRAL, Chilton, UK
Co-Is: UK, CH, D, I, N, USA

3 EIT
Extreme ultraviolet imaging telescope
(17-30 nanometres)
PI: J.P. Delaboudinière
IAS, Orsay, France
Co-Is: F, B, USA

4 UVCS
Ultraviolet coronograph spectrometer
(50-130 nanometres)
PI: J.L. Kohl
SAO, Cambridge, USA
Co-Is: USA, CH, D, I

5 LASCO
Large-angle coronograph for visible light
PI: G.E. Brueckner
NRL, Washington DC, USA
Co-Is: USA, D, F, UK

6 SWAN
Whole-sky Lyman alpha mapper
PI: J.L. Bertaux
CNRS, Verrières le Buisson, France
Co-Is: F, SF, USA

7 CELIAS
Solar wind composition and extreme UV flux
PI: D. Hovestadt
MPE, Garching, Germany
Co-Is: D, CH, Russia, USA

8 COSTEP
Energetic particles (low range)
PI: H. Kunow
University of Kiel, Germany
Co-Is: D, E, ESA, F, IRE, J, USA

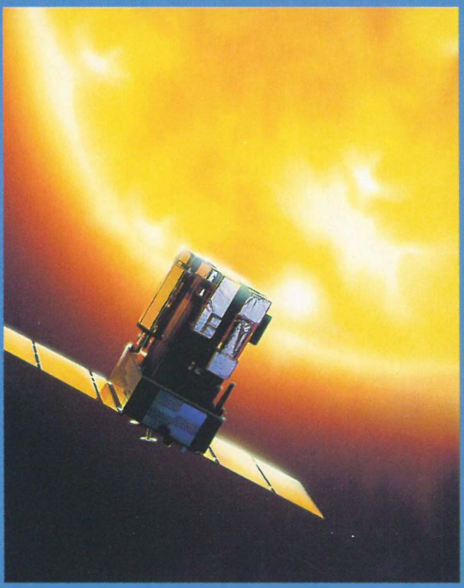
8 ERNE
Energetic particles (high range)
PI: J. Torsti
University of Turku, Finland
Co-Is: SF, UK

9 GOLF
Global low-degree velocity oscillations
PI: A. Gabriel
IAS, Orsay, France
Co-Is: F, CH, D, DK, E, ESA, NL, UK, USA

10 VIRGO
Solar irradiance and luminosity oscillations
PI: C. Fröhlich
PMOD, Davos, Switzerland
Co-Is: CH, B, E, ESA, F, N

11 SOI
Oscillations by Michelsen Doppler Imaging (MDI)
PI: P.H. Scherrer
CSSA, Stanford University, USA
Co-Is: USA, DK, UK

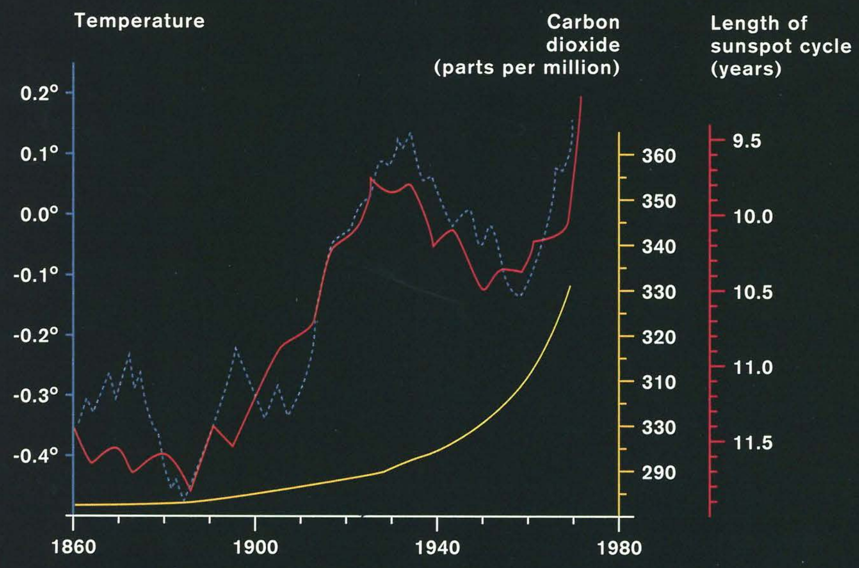
PI = Principal Investigator
Co-Is = countries of Co-Investigators



In a gentle orbit. SOHO will hover on the sunny side of the Earth, in the vicinity of Lagrange Point No. 1, or L1, where the Sun's gravity and the Earth's are in balance. It will follow a slow-motion orbit around L1. This location provides ideal conditions for continuous observation of the Sun, undisturbed by sunsets or by the spacecraft's motion.

Why is the Sun manic-depressive?

Earth's climate



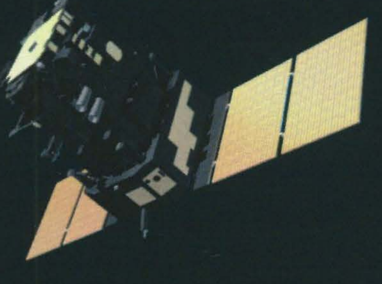
Many climatologists believe that carbon dioxide added to the air by human activity is warming the Earth. Controversially, solar-terrestrial physicists in Copenhagen account for global warming by a speed-up in the sunspot cycle. They suggest that fast cycles spell warmth, while slow cycles mean a chillier Earth. Solar experts can't confirm or deny this Danish proposition, even though a verdict on the relative importance of natural and manmade changes is crucial for environmental policymaking.

Every eleven years or so, the Sun reverses its magnetism, swapping its north and south magnetic zones around amid a frenzy of sunspots and upheavals on its visible surface. The sunspot activity is then depressed again until the next reversal is due. The duration of the sunspot cycle can vary from nine to fourteen years, and has been known to stop completely.

Textbooks explain the Sun's manic-depressive moods by a dynamo, driven by different rotation rates inside the Sun. Electric currents supposedly generate the magnetism, and the rotations wind it up like a rope on a winch. The winch becomes overloaded and the magnetism bursts through the Sun's surface in sunspots. The rope breaks and the magnetism flips over. But the theory is shaky. SOHO will probe the inner layers where a dynamo may exist, by mapping surface oscillations.

Meanwhile the questions remain, whether and how the changes in the Sun could have climatic consequences on the Earth. Pulses of particles from a stormy solar atmosphere may affect the Earth's atmosphere directly. Observations of the solar wind by SOHO may shed light on that possible connection. SOHO also tackles the question of the Sun's radiant energy, which may vary from decade to decade and century to century.

The VIRGO experiment is climate-oriented. Its six instruments will record minute-by-minute fluctuations in the Sun's radiant output, and oscillations in the Sun revealed by rhythmic changes in its surface brightness. Claus Fröhlich of Davos, Switzerland, leads the VIRGO team.



"Our measurements will directly help the scientists who make computer models of the Earth's climate," Fröhlich says. "And we'll analyse the data in many other ways. We can link changes in the Sun's output to visible activity.

The oscillations will tell us about mechanisms hidden below the surface. When SOHO has helped us to grasp the details of solar variability, we'll be better able to judge the long-term climatic issues."

Helioseismology: learning from the Sun's song

"The oscillations of the visible surface allow us to look behind the mask of Sun's visible face, " says Vicente Domingo, ESA's project scientist for SOHO. "The technique is like seismology, which uses earthquake waves to discover layers and structures inside the Earth. So we call it helioseismology. It is astonishingly accurate. In fact it gives solar physicists their most precise numbers to work with. And SOHO provides the helioseismologists with the exceptionally steady observing platform, never interrupted by sunsets, that they need."

Already solar oscillations detected at observatories on the ground have confirmed that the deep interior is much as the theorists predicted. But they reveal that the turbulent outer layer, the convective zone, is thicker than expected.

The oscillations also indicate that rotation speeds at the surface, which decline from the equator to the poles, are shared by deeper parts of the convective zone. Mid-latitude rotation rates vary during the sunspot cycle.

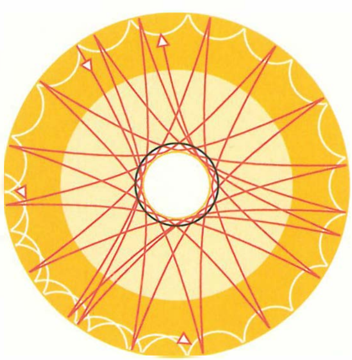
Among new prizes that helioseismologists seek is the dynamo inside the Sun which, they think, generates its external magnetic field. Another is a kind of oscillation caused not by sound waves but a rise and fall under gravity, like a deep-seated sea-wave. Unlike the sound waves, which passively convey information, gravity waves could affect the Sun's behaviour, by mixing the core.

The GOLF instrument prepared for SOHO by a French-led team will record the oscillations of the whole Sun, which probe the deep structure towards the hot nuclear core.

An American instrument, MDI, divides the Sun's face into a million segments, to register more intricate modes of oscillation that convey information about the outer layers of the Sun, as well as the deep structure.

Both of these experiments will spot the oscillations by small shifts in the frequency of light that occur as the Sun's surface rises and falls. A third oscillation detector, part of the Swiss-led VIRGO experiment, looks for rhythmic changes of brightness in the whole Sun and in segments of its surface.

Solar sound waves probe the Sun's interior. Sound waves penetrating deepest into the Sun give rise to the whole-Sun oscillations to be observed by GOLF. These convey the best information on the Sun's overall structure. MDI will analyse more complex oscillations associated with shallower sound paths and the behaviour of the turbulent convective zone. LOI (part of VIRGO) will detect oscillations of low to intermediate complexity.



Cluster: holes in Earth's windscreen

The Sun's flames lick the surroundings of our planet. A hot wind of electric particles rushing past the Earth comes straight from the atmosphere of the mother star. About 60,000 kilometres out, on the sunny side, an invisible windscreen ten times wider than the Earth pushes the solar wind aside. It excludes most of the solar particles from a volume of space called the magnetosphere, created by the Earth's magnetism. But some solar particles penetrate into the magnetosphere and reach the Earth's upper air. Then the flames of the Sun flicker visibly, as auroras in the Arctic and Antarctic skies.

The European Space Agency's Cluster mission will report in unprecedented detail on the Earth's battle with the effusions from the Sun. At the end of 1995 Europe's Ariane 5 rocket

CLUSTER

will, in one throw, put four identical satellites into an elongated orbit. The satellites' own thrusters will tilt the orbit so that it passes over the Earth's polar regions, and stretch it a third of the way towards the Moon.

Then Cluster will tour the magnetosphere and the solar windstreams that envelop it, operating in the cluster that gives the mission its name. The Sun will play its part, by varying its behaviour. At the time of the launch, a scarcity of sunspots on its visible face will signify relative calm, giving Cluster a baseline of quiet conditions. In subsequent years the number of sunspots will grow, and the Sun will be stormier.

Space quadruplets. The four identical satellites of the Cluster mission will travel in company, at up to 140,000 kilometres from the Earth, to report on our planet's battle with the solar wind.

When strong gusts in the solar wind stress the magnetosphere, auroras may be visible in southern parts of Europe and the United States. Associated magnetic storms deflect compass needles and sometimes trigger blackouts in electric-power systems. Swarms of solar particles hitting the upper atmosphere heat it and make it swell, so that it arrests low-flying satellites and destroys them.

Some climatologists wonder if these high-altitude heating events affect wind patterns at the surface, so providing a link between solar variations and the Earth's weather and climate. NASA's Sampex satellite has confirmed that energetic electrons from the Sun can damage the ozone layer.

And uncertainty remains about the source of the energetic particles that form radiation belts in space, girdling the equator. So there are many reasons for needing to know the Earth's space environment better.

Each satellite in Cluster is a highly-equipped electrical laboratory in its own right, sensitive to electric and magnetic fields, to electrical and magnetic waves of various kinds, and to electrons and charged atoms. Electric sensors whirl on wires 50 metres long, as the spacecraft spins. Radio pulses and electron beams sent out from the satellite probe the surrounding regions of space. And metal ions squirted into space cancel any electric charge building up on the spacecraft, which could hinder Cluster's most delicate observations.

The four spacecraft will fly in formation at the points of a triangular pyramid, or tetrahedron. Until now, spacecraft have explored the magnetosphere alone, or at best in pairs. And their signals about the writhing swarms of electric particles have often left scientists unable to tell whether a change reported by a satellite comes from the passing of time, or movement in space.

"Cluster will eliminate the ambiguities of previous missions," says Rudolf Schmidt, ESA's project scientist for Cluster. "With the data from four satellites our computers will build up a 3-D action picture of the physical processes at work in the Earth's space environment."

Data on Cluster

Purpose
to explore the Earth's magnetic and electric surroundings

Responsible agencies
ESA and NASA
(SOHO/Cluster joint STSP programme: ESA 70%, NASA 30%)

Name
four satellites will operate in a cluster

Prime contractor
Dornier, Friedrichshafen, Germany

Per satellite
mass 550 kg plus 650 kg propellant

Scientific payload
72 kg, 11 experiments

Diameter
2.9 metres

Launch
November 1995

Launch vehicle
Ariane 5

Earth orbit
near-polar, 26,000-140,000 km, 57 hours

Mission control
ESOC, Darmstadt, Germany

Joint Science Operations Centre
DRAL, Chilton, UK

Ground stations
Redu and Odenwald (ESA)
Deep Space Network (NASA)

Intended lifetime
2 years

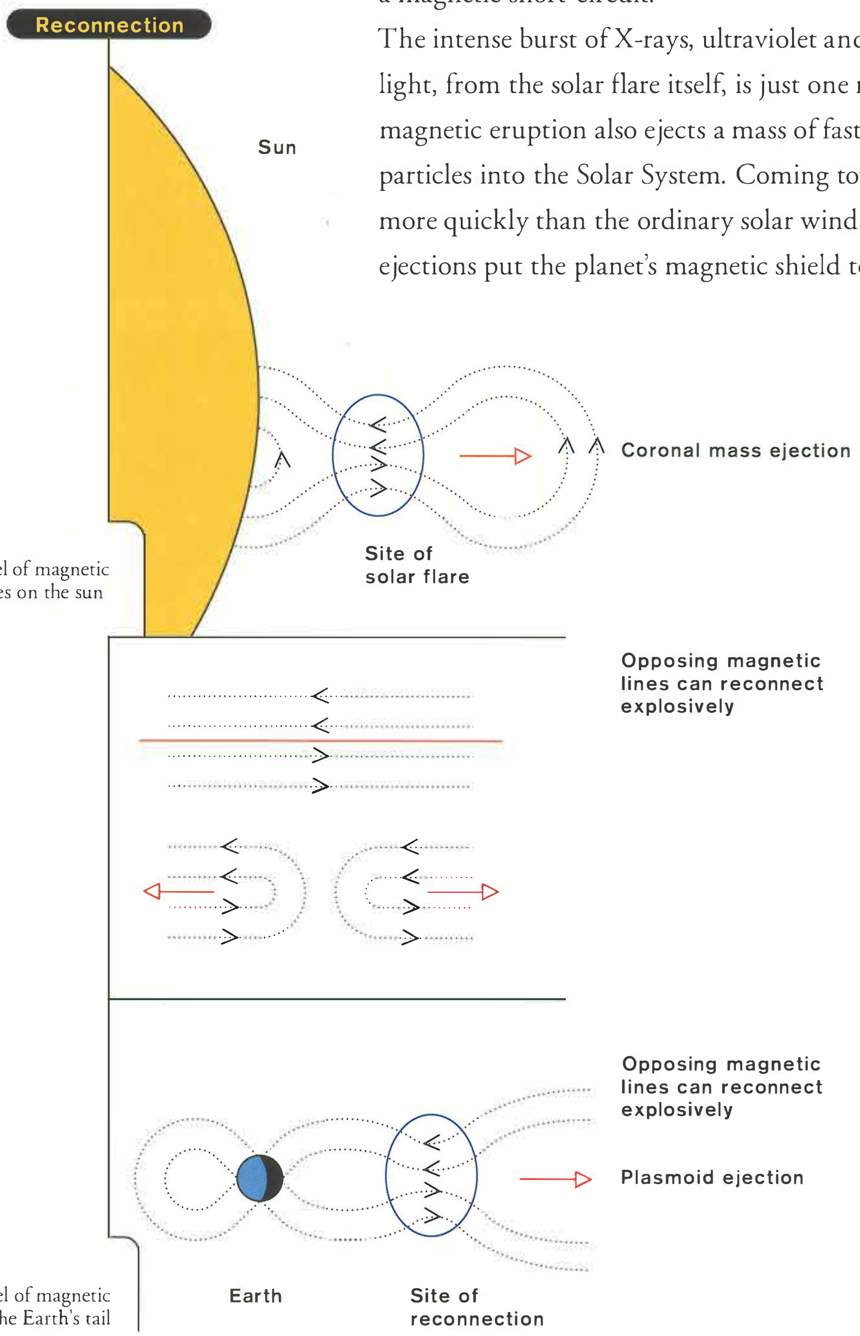
Power supply
solar cells

How does Nature stage a magnetic explosion?

Solar flares are stupendous eruptions on the Sun's visible face, with the force of billions of H-bombs. The explosions are produced not by nuclear reactions, but by magnetism.

The hot electrified gas, or plasma, of the Sun wrestles with ropes of magnetism that arch high over the visible surface. Different masses of plasma, with built-in magnetism, usually repel one another. But when the magnetic ropes become tangled or pinched, concentrated energy can break loose in a magnetic short-circuit.

The intense burst of X-rays, ultraviolet and sometimes visible light, from the solar flare itself, is just one result. The magnetic eruption also ejects a mass of fast-moving electric particles into the Solar System. Coming towards the Earth more quickly than the ordinary solar wind, the mass ejections put the planet's magnetic shield to its severest test.



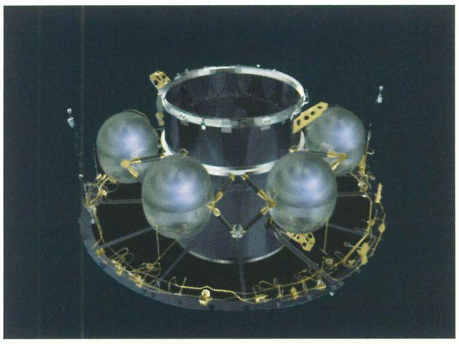
A quarrel of magnetic lines on the sun

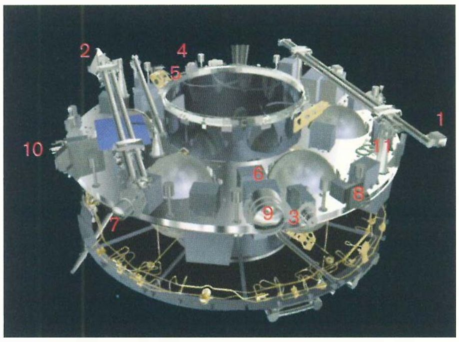
A quarrel of magnetic lines in the Earth's tail

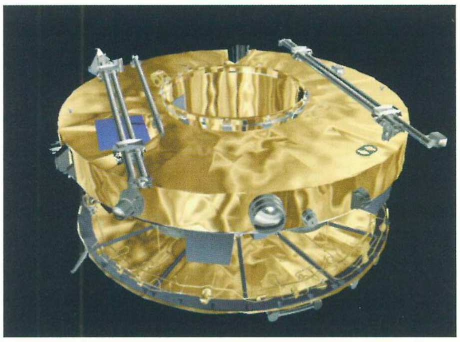
Scientists of the Cluster mission have two quite different interests in solar flares. As space environmentalists, they want to know how the mass ejections affect the planet. But as plasma physicists they investigate processes in electrified gases near the Earth, which may help to explain the magnetic explosions on the Sun. They share this interest with the scientists of ESA's related SOHO mission, which examines the Sun directly.

The Earth's own magnetism is drawn out and compressed by the solar wind, in the geotail, so that the magnetic lines finish up running in contradictory directions. Magnetic explosions can result, much milder than those on the Sun but possibly working in the same way, by a magnetic short-circuit or "reconnection". Besides shooting solar particles back into the Earth's magnetosphere, the explosion in the tail also propels a mass of particles down the tail as a "plasmoid", less massive but perhaps similar in kind to the mass ejections from Sun. Cluster will be the first space mission to examine such events in sufficient detail to be sure of what happens.

Unpredictable tricks of plasmas and magnetic fields tease the astrophysicists. Besides the still-mysterious magnetic processes in the Sun and the solar wind, the wider Universe is full of plasma events. They range from broken comet tails to natural particle accelerators powered by giant black holes in the hearts of galaxies, and the Big Bang itself was a plasma. On the Earth, the variable behaviour of the radio-reflecting ionosphere is a problem in plasma physics. So are the wriggling plasmas that for half a century have frustrated the physicists who try to control thermonuclear fusion reactions for power generation. "Turbulent events in the Earth's surroundings reveal many different kinds of plasma behaviour, including dramatic rearrangements of the magnetic field," says Alain Roux of Velizy, France, who is a former coordinator of experiments in Cluster. "As the electric particles almost never collide, the turbulence must be due to electric and magnetic waves. We understand these waves only vaguely at present. When Cluster characterizes them clearly, in this laboratory provided by Nature, it will make a remarkable contribution to fundamental plasma physics."







One out of four. Each of the four Cluster satellites is equipped with the same state-of-the-art electric and magnetic instruments, and particle detectors. The design of the spacecraft and instruments has paid special attention to curbing stray magnetic fields, and electric charges on the spacecraft will be actively suppressed by the ASPOC system.

Scientific instruments

1 FGM
Magnetometers
PI: A. Balogh
Imperial College London, UK
Co-Is: UK, A, D, DK, F, USA

2 STAFF
Magnetic field fluctuations
PI: N. Cornilleau-Wehrlin
CNET, Paris, France
Co-Is: F, DK, ESA, S, UK, USA

3 EFW
Electric fields and waves
PI: G. Gustafson
IRF, Uppsala, Sweden
Co-Is: S, ESA, F, N, Russia, SF, UK, USA

4 DWP
Wave processor
PI: L.J.C. Woolliscroft
Univ. Sheffield, UK
Co-Is: UK, DK, F, N, Russia, S, USA

5 WHISPER
Electron density and plasma waves
PI: P.M.E. Décréau
CRPE, Orléans, France
Co-Is: F, DK, S, UK, USA

6 WBD
Waveforms from EFW sensors
PI: D.A. Gurnett
Univ. Iowa, USA
Co-Is: USA, D, DK, F, S, UK

7 EDI
Electron emitters and detectors
PI: G. Paschmann
MPI Garching, Germany
Co-Is: D, ESA, I, J, USA

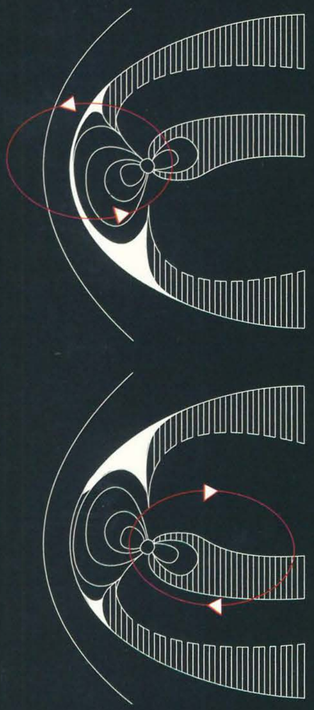
8 PEACE
Electrons and currents
PI: A.D. Johnstone
MSSL, Holmbury St Mary, UK
Co-Is: UK, China, F, India, N, USA

9 CIS
Ion composition
PI: H. Rème
CESR, Toulouse, France
Co-Is: F, Canada, CH, D, ESA, G, I, S, USA

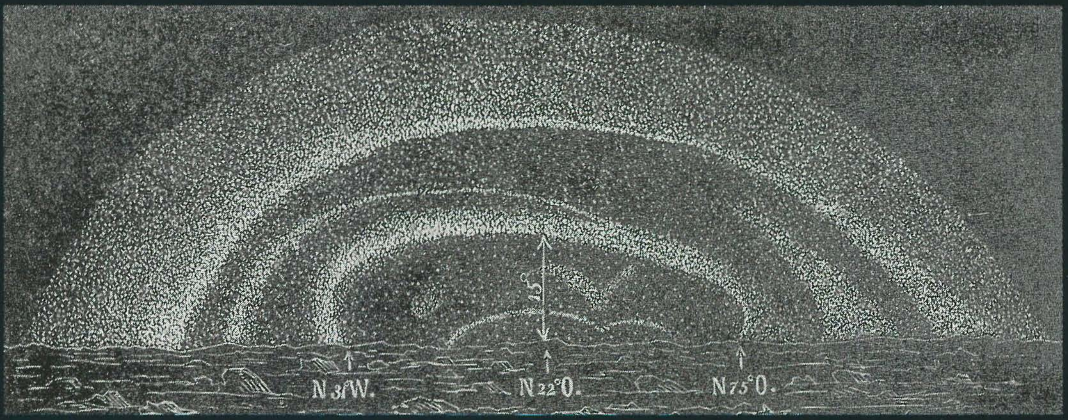
10 RAPID
Particle imaging detectors
PI: B. Wilken
MPI Lindau, Germany
Co-Is: D, G, H, IRL, N, S, SF, UK, USA

11 ASPOC
Spacecraft potential control
PI: W. Riedler
IWF, Graz, Austria
Co-Is: A, ESA, N, USA

PI = Principal Investigator
Co-Is = countries of Co-Investigators



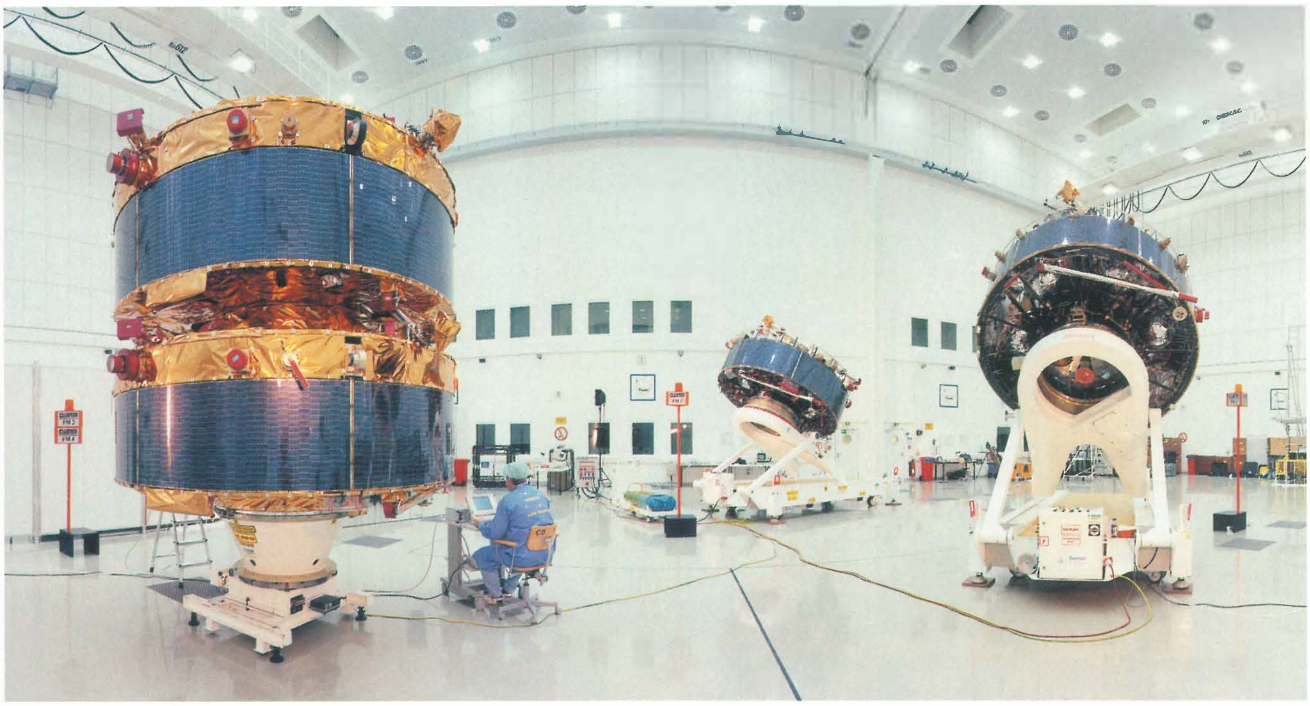
The Cluster orbit and the magnetosphere. The orbit will pass over the polar regions and carry the spacecraft to a distance of 11 times the diameter of the Earth at its farthest point, or 140,000 kilometres. As the seasons pass the far point will sometimes be upwind, sometimes downwind, allowing Cluster to explore different parts of the magnetosphere. The separations of the four spacecraft will vary from a few hundred kilometres to 20,000 kilometres, depending on the task in hand.



The auroral oval stretches beyond the horizon. Adolf Erik Nordenskiöld made this very realistic drawing of auroras in March 1879, from a research ship icebound from Siberia during the Arctic winter.
Image: R. Pellinen (Helsinki) and K. Kaila (Oulu)

Nature's disco lights. Auroras occur when incoming beams of particles hit the upper air. How they get there is a question that still mystifies the experts.

The four Cluster spacecraft. Two are nested together as if for the launch.



Searching for the entry points

Physicists can explain why the Earth's magnetism keeps most solar particles out, more easily than they can say how some of them sneak in. The solar wind is itself a magnetized, electrified gas, or plasma, and a good conductor of electric currents. The Earth's magnetism creates currents that oppose any mixing of the Sun's realm and the Earth's realm. The windscreen of the Earth's magnetosphere, called the magnetopause, marks the surface where the pressure of the solar wind plasma is matched by an equal repulsion due to the Earth's magnetism.

While the solar wind is kept out, the Earth's magnetism is kept in. The wind confines it within the magnetosphere, which is rounded on the sunny side but extends on the night side of the Earth in the manner of a comet's tail. There are also dents in the magnetosphere, called polar cusps, over the north and south magnetic poles.

To let its particles break in and light the auroras, the solar wind has to tear a hole in the magnetopause.

Once inside, the solar particles will find their way to the auroral zones by following the magnetic field-lines, which converge on the magnetic poles. So the entry points can be anywhere. The theorists favour three main possibilities.

Short cuts to the auroral zones may exist in the polar cusps, which will also attract special attention from Cluster. Some scientists think that there is an open gate for solar particles in each polar cusp. More probably, the gate is closed.

If so, solar particles will crowd there like football fans without tickets, waiting for some electric or magnetic wave to bounce them through the magnetic barrier.

Or the solar particles may enter like burglars through the back door. The solar wind can squeeze the Earth's magnetic tail and briefly break it. When that happens, particles are catapulted back towards the Earth.

The common green auroras of the polar night sky may be nourished by particles coming that way. Cluster will examine that route in detail.

A third possibility is the frontal assault. The solar wind may sometimes rip open the magnetopause on the sunny side and let its particles pour in. Some scientists think that particles entering that way cause the red auroras, which are easily visible only in midwinter because they occur on the sunward side of the magnetic pole.

A frontal breach may occur when the magnetism carried by the solar wind runs in a direction contrary to the Earth's field.

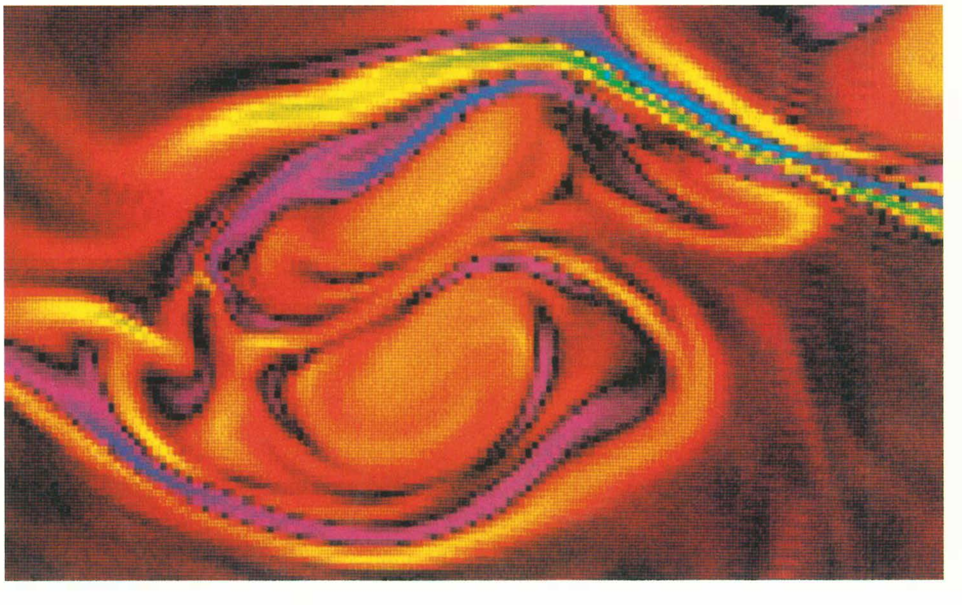
Again, Cluster will test this version of events, while it also checks the integrity of the magnetosphere on all sides. The aim is not merely to find the holes in the windscreen, but to specify how the breaches occur, how many particles enter by each route, and what the consequences are within the magnetosphere.

Global connections

Two hundred scientists from seventeen countries play a direct role in Cluster. Leaders of the experiment teams will receive the data by computer links, and without leaving their home laboratories they will be able to command their instruments via a science operations centre in the UK. Data centres in several other European countries, and in the USA and China, will receive results and help to process them. But the Cluster connections are more extensive than that.
Cluster is part of ESA's current campaign of solar research, which includes Ulysses' far-flung exploration of the solar wind over the Sun's poles, and the SOHO observatory. While Cluster examines effects of solar wind on the Earth's environs, SOHO will monitor oscillations in the Sun and its emissions of ultraviolet light and energetic particles. The mission scientists will exchange information about events and ideas about processes.

NASA participates in Ulysses, Cluster and SOHO, and has related missions of its own. These include the long-lived IMP-8 satellite, and a new spacecraft called Wind which will spend most of its time on the sunward of the Earth observing the incoming solar wind. In the other direction, the Japanese are operating the Geotail satellite, farther out than Cluster. The Russians have planned two pairs of satellites to investigate the tail and the polar regions of the magnetosphere, in a mission named Interball. The world's space agencies are coordinating all their relevant missions, to maximize the scientific return. There are connections also with networks of ground stations, notably in the Arctic and Antarctic.

Cluster scientists will interact with their colleagues who monitor magnetic and upper-air activity from the ground. For example, the EISCAT system in northern Scandinavia observes the upper air by radar. As Bengt Hultqvist of Kiruna, Sweden, remarks:
"Here in Lappland we have a ringside view of solar-terrestrial effects. The auroras are part of our everyday scenery. Some people thought that our ground-based instruments would become superfluous in the Space Age. But we observe continuously, while spacecraft can visit our region only intermittently. Three times a week in the case of Cluster. So space missions and ground stations need each other.
After our years of effort, including the recent Viking and Freja satellites which imaged the aurora from space, some fundamental questions remain unsettled. We look forward to collaborating with the Cluster mission, hoping that the detailed perspectives from four satellites in company will give us the answers we need."



Wriggling plasma. An impression of the electric weather awaiting Cluster in the Earth's vicinity is illustrated by a computer simulation. It calculates the vorticity generated by interactions between a stream of electric particles and the magnetic fields associated with them. Translating the data from the four Cluster satellites into accurate and detailed three-dimensional pictures of events requires the power of modern supercomputers. Image: M.L. Goldstein (NASA Goddard)

Huygens: to the strangest world

If you parachuted on to Titan you could enjoy a fine view of the rings of Saturn before you disappeared into the orange haze that shrouds that unusual world. Colleagues would be curious to know whether you landed on natural tarmac or splashed into a sea of hydrocarbon, but that would be your last message. You would either freeze to death, or run out of oxygen and suffocate in an atmosphere smelling like an oil refinery. For such a mission a robot is better. To clear up one of the last great mysteries remaining after the reconnaissance of the Solar System by spacecraft, the European Space Agency is preparing a robot probe called Huygens to unmask Titan, which is Saturn's largest moon. It is part of Cassini/Huygens, a collaborative mission to Saturn and Titan by NASA and ESA.

HUYGENS

Enigmatic moon. Titan's atmosphere, imaged by NASA's Voyager 1 in 1980, is rich in hydrocarbons and mystery. ESA's probe Huygens will enter the atmosphere and descend to the hidden surface of the moon. Image: NASA/JPL

When NASA's Voyager 1 spacecraft flew past Titan in 1980, the pictures showed only a hazy orange atmosphere with a bluish tinge on the horizon. But the spacecraft's instruments revealed that Titan has an atmosphere of nitrogen thick with carbon compounds. Although Titan is unlike any other planet or moon in the Solar System, it may in important respects resemble the Earth as it was before life began.

Daniel Gautier of Paris was one of the Voyager scientists. "I was very excited about the results from Voyager 1," he recalls. "It immediately came into my mind that the next mission should be to Titan. After in-depth discussions with American and European colleagues, Wing Ip from Lindau and I proposed the Titan probe to ESA in November 1982 as an ESA-NASA cooperative mission."

Voyager 1 also confirmed the presence of methane, the lightest hydrocarbon. This puzzles the chemists. The Sun's rays remorselessly convert methane into ethane, so Titan must resupply its atmosphere. Contradictory theories talk of oceans of methane or underground reservoirs.

ESA's Huygens should settle the argument. It will ride on another spacecraft, a Saturn Orbiter, which NASA is developing with Italian help. The name of the whole mission is Cassini, and its launch is due in 1997. In 2004 the mother spacecraft will deliver Huygens to Titan, and relay the probe's signals to the Earth. Then the Orbiter will spend four years examining the Saturn and its rings and moons, including thirty passes over Titan.

Two of the Saturn Orbiter's sets of instruments, measuring magnetism and dust, are masterminded by European scientists. US colleagues participate in them. The rest, with US leaders, involve European partners. Conversely, two experiments in Huygens are allotted to US principal investigators, with European co-investigators. American scientists take part in all the others, which are built under European leadership. Scientifically, too, the operations mesh. On-the-spot information from Huygens will help in interpreting the Orbiter's observations of Titan, to be made with five different remote-sensing instruments using visible, ultraviolet and infrared light, and radar.

Data on Huygens probe

Purpose
to descend through the atmosphere of Titan

Responsible agency
ESA; part of NASA's Cassini Mission

Role in Horizon 2000 programme
medium-size mission M1

Name
from Christiaan Huygens
(Dutch discoverer of Titan in 1655)

Prime contractor
Aerospatiale, Cannes, France

Mass
343 kg (+ 30 kg in Orbiter)

Scientific payload
48 kg, 6 experiments

Diameter (shield)
2.7 metres

Launch
6 October 1997 (nominal)

Delivery to Titan
by NASA's Saturn Orbiter

Arrival at Titan
27 November 2004 (nominal)

Duration of parachute descent
120-150 minutes

Operations on surface of Titan
3-30 minutes

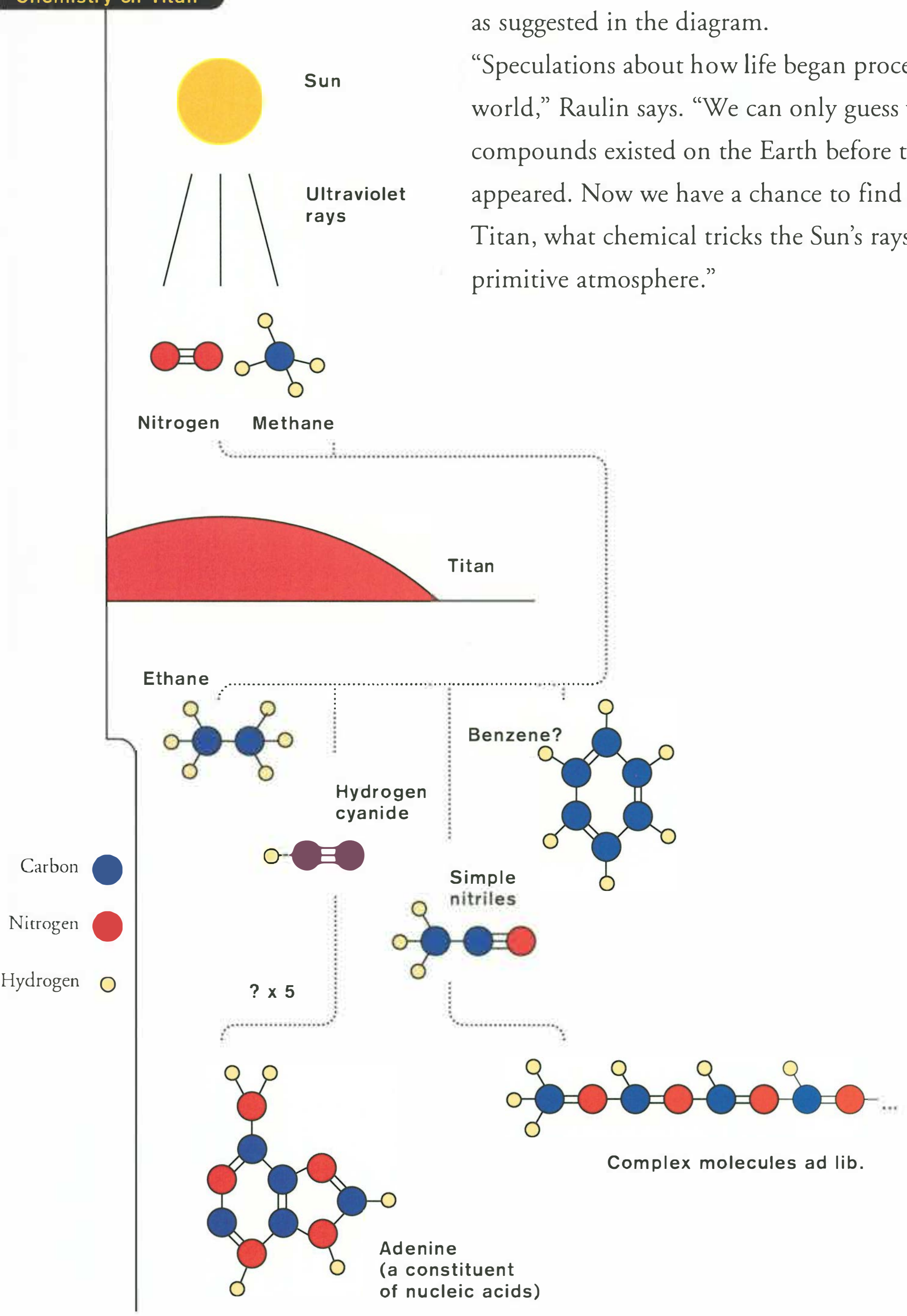
Power supply
batteries (153 minutes)

What does primeval soup taste like?

A powerful motive behind the Huygens space probe to Titan is the scientists' wish to see what carbon molecules Nature makes from simple gases. Titan is far too cold for life, and water is scarce. The atmosphere and surface of Saturn's peculiar moon may nevertheless contain many chemicals of the kind that existed on the young Earth, and stocked the primeval soup in which the first living organisms appeared. François Raulin of Paris coordinates the exobiological aspects of the mission. He has conducted laboratory experiments to predict the carbon compounds that may be found on Titan, as suggested in the diagram.

"Speculations about how life began proceed in an imaginary world," Raulin says. "We can only guess what chemical compounds existed on the Earth before the first bacteria appeared. Now we have a chance to find out in a real world, Titan, what chemical tricks the Sun's rays can perform in a primitive atmosphere."

Chemistry on Titan



Comet tails may have strewn such materials on the young Earth. But ultraviolet light from the Sun, cosmic rays and lightning strokes could also manufacture carbon compounds from simple materials available at the Earth's surface.

The Huygens probe will investigate this "home cooking" on Titan. An American instrument will identify the complex molecules by their masses, and by their speeds of transfer through various filters. A French/Austrian instrument will collect particles from Titan's atmosphere and use an oven to vaporize them for identification.

Speculations and experiments concerning the origin of life have led to no clear conclusions, despite a hundred years of effort by eminent scientists. How self-sustaining assemblies of nucleic acids, proteins and fats came into existence remains as inexplicable as ever. Space research may break through a log-jam of ideas by identifying the likely chemical precursors that flavoured the primeval soup.

The examination of comets, as in ESA's Giotto and Rosetta missions, reveals quite complicated carbon molecules available in cosmic space.

"The results from Huygens will give a fresh impetus to the theories of the origin of life on the Earth," Raulin concludes. "Perhaps they will lead us in unexpected directions."

Data on Titan

Distance from Saturn
1,226,000 km

Period of orbit (Titanic day)
15.95 days

Mean distance from Sun
1,427,000,000 km
(9.54 times Earth-Sun distance)

Diameter to the surface
5150 km
(Ganymede 5262 km, Mercury 4878 km, Earth's Moon 3476 km)

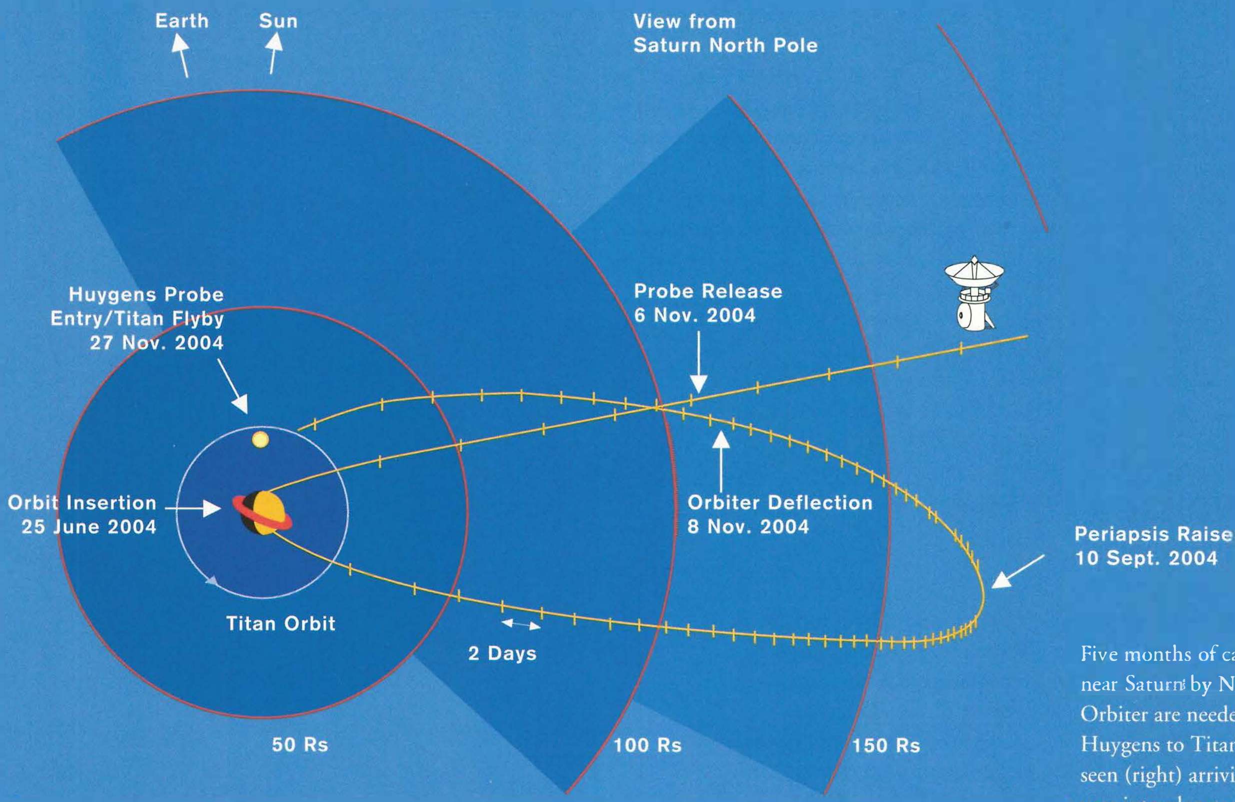
Diameter to upper atmosphere (1 mbar)
5550 km

Mass
1/45 of Earth's mass

Density compared with ordinary water
1.881

Surface temperature
- 179 deg. C (+94 K)

Atmospheric pressure at surface
1500 mbar (1.5 times Earth's)



Five months of careful manoeuvring near Saturn by NASA's Saturn Orbiter are needed to deliver Huygens to Titan. The Orbiter is seen (right) arriving after a seven-year interplanetary journey, wearing Huygens like a shield. It slows down to go into orbit around Saturn, and then alters course ("periapsis raise") to widen its orbit and aim at Titan. After the Orbiter has released the Huygens probe, an orbit deflection enables it to miss Titan and position itself to receive the probe's transmissions. When the Huygens mission is complete, the Orbiter will tour the Saturnian system for four years, studying the planet, its rings and its moons in unprecedented detail. (The scale unit Rs is the radius of Saturn, 60,000 km.)

Data on Cassini mission and Orbiter

Purpose
to explore the Saturnian system

Responsible agency
NASA

Name
from Jean-Dominique Cassini (French-Italian investigator of Saturn in 1671-85)

Launch mass of Orbiter + Huygens
5.82 tonnes

Orbiter scientific payload
300 kg, 12 experiments

Launch vehicle
Titan-IV/Centaur (NASA)

Launch
6 October 1997 (nominal)

Swingbys
Venus, Venus, Earth, Jupiter

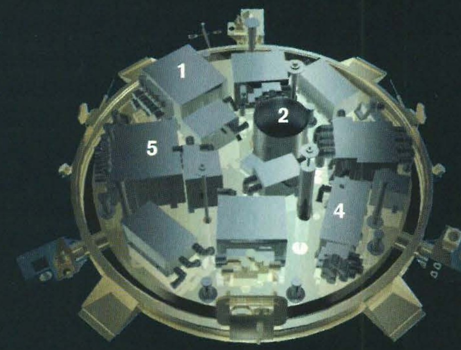
Arrival at Saturn
25 June 2004 (nominal)

Orbiter operations in Saturn's vicinity
4 years

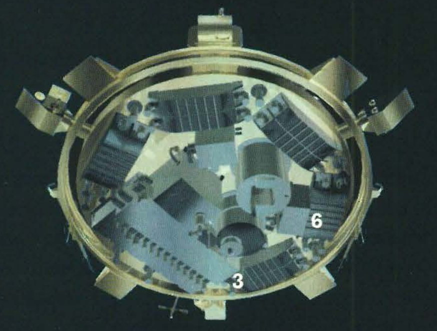
Power supply
radio-isotope

Scientific instruments

Six experiments packed into Huygens are designed to extract as much new knowledge as possible from a descent of 120-150 minutes through the atmosphere of Titan, and perhaps from several minutes on the surface.



Upper side



Bottom side

Fierce minutes of the entry phase

Huygens will sleep all the way from the Earth to Saturn, except for occasional reveilles to check its readiness. The Orbiter will manoeuvre around Saturn and release Huygens on a collision course for Titan. Then the Orbiter will swerve to receive the probe's signals at a safe distance. The robot will still be slumbering, because it has battery power for less than three hours of full operation.

Alarm clocks will wake Huygens just a quarter of an hour before it reaches the outer fringe of Titan's atmosphere. Then the robot must be smart enough to look after itself. The distance from the Earth is too great for exchanges of signals and commands.

More than 1000 kilometres above Titan's surface, accelerometers will sense the first faltering in probe's headlong speed of 20,000 kilometres per hour. From the rates of slowdown recorded in this entry phase, scientists will deduce the changing density of Titan's outer layers.

Every structure and joint will be severely stressed at an altitude of about 300 kilometres, when the deceleration peaks at perhaps 16 g.

Huygens is built like a shellfish, with hard protection for a delicate interior. The shell will act as a brake and a thermal shield, as the gas temperature in front of it soars to 12,000 degrees. During three fierce minutes Huygens will plunge to within 180 kilometres of the surface, while its speed drops to 1400 kilometres per hour.

The robotic controls will then fire a pilot parachute to pull out the main parachute. Within a minute, the speed will ease to less than 300 kilometres per hour. The shell will fall away and expose the scientific instruments to Titan's atmosphere, at a height of about 160 kilometres. The atmospheric temperature may be about minus 120 degrees C.

The use of 300 watts of power, in the robot's brain, sensors and transmitters, will help to combat the insidious cold. But the probe must reach the surface before the batteries run out. The main parachute used for braking at high altitude will be cut away after just 15 minutes, and replaced by a smaller one. The probe will then be at about 120 kilometres altitude. It should complete its descent in two more hours, plus or minus 15 minutes, while the robot follows a schedule of activities keyed to the altitude measured by a radar altimeter.

Protective shell. Heat-resistant tiles cover Huygens' curved front shield, to withstand the braking and heating when it first enters Titan's atmosphere. The probe then discards the shield and the foil-wrapped back cover, revealing the instrumented section here seen nested in the shield.
Image: DASA, Germany

1 **HASI**
Physical profile of Titan's atmosphere
PI: M. Fulchignoni
University of Rome, Italy
Co-Is: I, A, D, E, ESA/SSD, F, N, SF, USA, UK

2 **GCMS**
Chemical profile of Titan's atmosphere
PI: H.B. Niemann
NASA Goddard, USA
Co-Is: USA, A, F

3 **ACP**
Aerosol sampler and oven
PI: G.M Israel
Service d'Aéronomie
Verrières-le-Buisson, France
Co-Is: F, A

4 **DISR**
Images and spectra
PI: M.G. Tomasko
University of Arizona
Tucson, USA
Co-Is: USA, D, F

5 **DWE**
Zonal winds
(by tracking from Saturn Orbiter)
PI: M.K. Bird
University of Bonn, Germany
Co-Is: D, I, USA

6 **SSP**
State of Titan's surface
PI: J.C. Zarnecki
University of Kent
Canterbury, UK
Co-Is: UK, ESA/SSD, I, USA

PI = Principal Investigator
Co-Is = countries of Co-Investigators

Weather and chemistry in the haze

Winds of 250 kilometres per hour are expected to propel Huygens sideways. They will diminish during the descent. A German radio system will measure the wind speeds by frequency-shifts in the signals received by the watchful Saturn Orbiter. As the probe sidles over the still-hidden surface, the radar altimeter should begin to show whether Titan is smooth or rough.

Detailed weather information will come from atmospheric instruments provided by a multinational team under Italian leadership. Besides the accelerometer measurements, thermometer and barometer readings will be reported all the way to the surface. Other instruments will measure electrical properties of the atmosphere and register radio pulses from lightning strokes, if they occur. A microphone will listen for thunderclaps.

"Most studies of planetary meteorology rely on images and other methods of remote sensing," says Marcello Fulchignoni of Rome. "Huygens gives us a rare chance to record the weather of another world directly, and we have to be prepared for surprises."

Small vanes around the probe's rim will make it rotate as it drops, so letting the imagers of an American-led experiment scan the scene. They may not see much at first, within the layer of orange haze that gives Titan its deadpan appearance. The Sun, though, will be plainly visible, and yellow and infra-red light imaged in the halo around it will reveal the physical size and abundance of the haze particles. Visible and infra-red spectrometers will measure the heat flows inwards from the Sun and outwards from Titan into space.

A chemical analyser from the USA will sort and count molecules and atoms by weight, in a mass spectrometer. Gas chromatographs will help, by separating the molecules by their speeds in worming through columns of adsorbent material. The mass number 28 for nitrogen molecules will provide the dominant background, with 16 for methane as the chief vapour at a few percent. But many other materials will be detectable, even in minute traces.

Primordial argon atoms with masses of 36 and 38 will fingerprint the origin of Titan's atmosphere. If it came from comet-like icy bodies that built the Saturnian moon, the argon count should be high. That would encourage those who argue that the Earth acquired its own nitrogen atmosphere, and its water too, from impacting comets. A low abundance of argon would match an alternative scenario, in which Titan was formed from ices rich in methane and ammonia, existing in a cloud around Saturn. In that case, the gases supposedly leaked from Titan's interior into its atmosphere, and the Sun's rays decomposed the ammonia to make nitrogen.

Chemists will expect much more complex compounds, up to a mass of 146, the limit of the mass spectrometer's range. The large molecules will show how far the lifeless chemistry of Titan has proceeded in making materials that, in other settings, would be useful for initiating life. Many of the largest molecules may be detected drifting down from the bluish outer layers of Titan's atmosphere, 200-500 kilometres out.

They will exist in aerosol particles sampled by an instrument devised in France and Austria. At an altitude of 45 kilometres, this aerosol collector will process the harvest so far. A filter will retract into an oven that heats the collected material by stages, up to 650 degrees C. The products from each stage will go to the mass spectrometer and a special gas chromatograph for analysis. The filter will then be purged, and returned to the probe's exterior to gather more aerosol samples in the cloud layer.

Huygens in the atmosphere of Titan. Two other parachutes, a pilot and a main chute, will help to slow down the probe on its arrival, and the one illustrated in this artist's impression will let it descend at the right rate for scientific observations.

Into the unknown

The atmospheric temperature will drop from minus 120 to perhaps minus 200 degrees C, horribly cold for Huygens. At the base of Titan's stratosphere, perhaps 50 kilometres above the surface, the temperature should begin to recover a little. Here the haze may clear and give Huygens' imagers their first glimpse of the surface of Titan, between fluffy cloud-tops.
Meteorologists will be fascinated by parallels and contrasts with the weather on the Earth, in a world where clouds and raindrops are made of methane and nitrogen. The imagers will build up panoramas of the clouds and the scene below, as Huygens turns.

The further down you go, in imagining the probe's descent, the more the uncertainty and the greater the adventure. Will Huygens find an ocean of mixed methane and ethane, perhaps decorated with luridly coloured organic icebergs? A dry landscape with geysers spouting methane from underground reservoirs? Volcanoes throwing out ammonia and water? For the last few hundred metres of the descent, a landing light will help the spectrographs to look for methane in the surface. An acoustic sounder will listen for echoes.

If Huygens survives the thud or splash, as it hits the surface at a speed of about 20 kilometres per hour, the radar, chemical and imaging experiments may continue to operate usefully after the landing. And a special surface science package, developed under British leadership, will come fully into its own for the last few minutes of the mission. For a landing on a dry surface, a penetrometer will gauge its hardness, and a tiltmeter will show whether or not the surface is flat locally.

The tiltmeter may detect sea-waves, if the touchdown is in a liquid. The acoustic sounder will probe the depth of the ocean or lake, while other instruments measure its density and the speeds of sound and light in the liquid. The proportion of methane to ethane, indicated by the density, will give an impression of how long Titan has spent converting the one into the other. That may enable scientists to judge whether the ocean is as old as Titan, or a later addition.

The time available on the surface may be anything from 3 minutes to half an hour or more. That assumes Huygens will survive the cold and the impact. But expire it must, when the batteries run out. Huygens will remain on Titan as the first human token there, and the first European spacecraft to land on another world.
Out in space, the Saturn Orbiter will pick up Huygens' last signals, then fly beyond the horizon. Turning its antenna towards the Earth, it will relay the recorded messages from all of Huygens instruments. Then the waiting scientists will see Titan's veil of secrecy dissolve.

Rosetta: waltzing with a comet

For thousands of years people gazed in awe at apparitions with luminous heads and tails that sprawled across the starry sky. The nucleus of a comet is nowadays known to be only a few kilometres wide. It creates its eyecatching display by throwing dust and gas into space.

Comets fascinate scientists because they preserve ingredients gathered from interstellar space at the birth of the Solar System. Comets like those seen today went into building the planets and took part, in hazily understood ways, in the origin of life on the Earth. And comet-strikes still occur in the Solar System, as the impacts on Jupiter in 1994 confirmed. The European Space Agency's next comet mission takes its name from the Rosetta Stone, which deciphered the hieroglyphics of ancient Egypt. Its full title is the International Rosetta Mission.

ROSETTA

A quick glimpse of a comet nucleus. The best picture so far, of a comet seen in close up and emitting jets of gas and dust from its sunlit side, comes from ESA's Giotto spacecraft. Giotto flew at a very high speed through the dusty head of Halley's Comet. Rosetta will obtain much more leisurely and detailed views of another comet, by travelling in company with it.

Image: MPI für Aeronomie (Lindau) and ESA

The Rosetta spacecraft will decode the messages of atoms and molecules and help to make sense of our cosmic origins. Rosetta will accompany the nucleus of a comet as it makes one of its periodic visits to the Sun. The spacecraft will map the comet's surface in fine detail and drop instruments on to it. Waltzing around the comet for many months, Rosetta will watch the surface erupting in the warmth of the Sun. On-board instruments will analyse the effusions of dust and gas. This culmination will not occur until the year 2013 or thereabouts, but in laboratories across Europe the countdown for the International Rosetta Mission has already begun. ESA will select the scientific instruments in 1996, from competing proposals by multinational teams.
The winners must then perfect them, and submit them for rigorous testing, before incorporation in the spacecraft for a launch in 2003.

Data on Rosetta

Purpose
to rendezvous with a comet and make observations

Responsible agency
ESA, with surface probes from CNES/NASA and a German-led consortium

Role in Horizon 2000 programme
3rd cornerstone mission

Name
from the Rosetta Stone

Mass
1.3 tonnes (+ about 1.4 tonnes propellant)

Scientific payload
about 100 kg plus 2 surface probes each of 45 kg

Max. dimension (excluding solar panels)
3 metres

Launch vehicle
Ariane 5

Launch
22 January 2003 (nominal)

Swingbys
Mars, Earth, Earth

Arrival at comet
28 August 2011 (nominal)

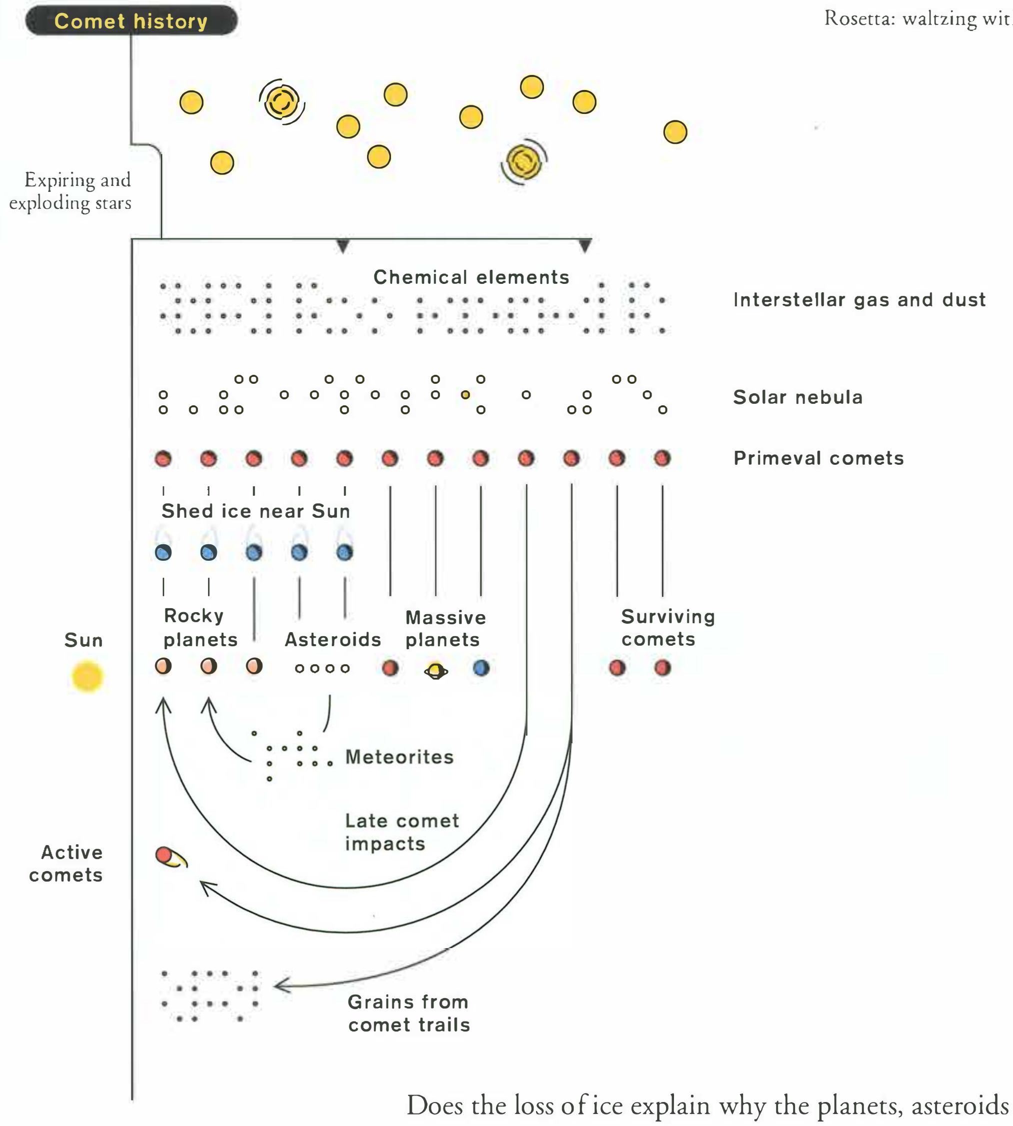
Termination of mission
21 October 2013 (nominal)

Duration of active observations
18 months

Power supply
solar panels (batteries for surface probe)

What were the planets made from?

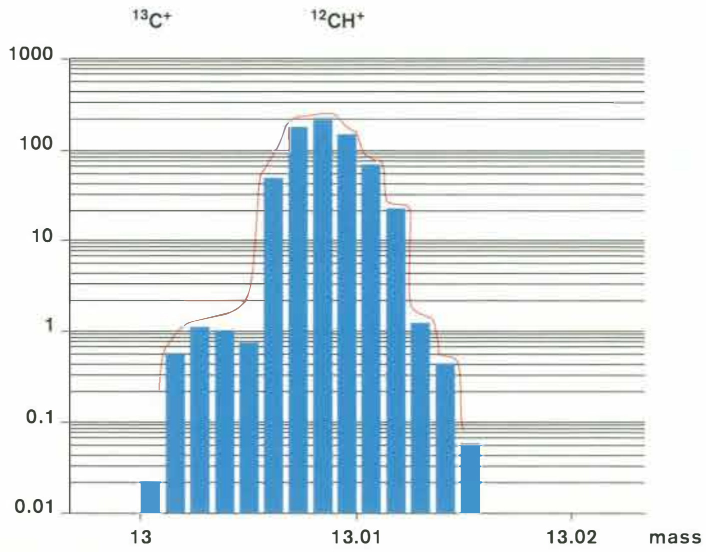
The solar nebula around the newly forming Sun built the Earth and other planets 4600 million years ago. But the raw materials are now unrecognizable. Gravity has crushed and churned the primeval ingredients, heat has cooked them, and chemical, geological and biological processes have rearranged them.
Comets are the great exception. As small, cool objects they preserve the raw materials in a nearly pristine form.
They must have grown in the collapsing cloud of interstellar gas and dust that formed the solar nebula. Most of them were then consumed in building planets.
The comets observed today are survivors that have only recently ventured close to the Sun, where ice vaporizes and blasts the stony and tarry material into space, as dust grains.
The same thing must have happened to the far more numerous comets that swarmed around the newborn Sun.



Does the loss of ice explain why the planets, asteroids and meteorites near the Sun are small and stony? Did the far bigger outer planets grow on icy cores? Were the Earth's ocean and atmosphere an afterthought, added by impacts of fresh comets? And did chemicals needed for life come in a gentle rain of carbon-rich grains from comet tails? Scientists will seek answers to all these questions when the ESA-led International Rosetta Mission analyses the composition of a comet more comprehensively than was ever possible before.

Rosetta will also carry a microprobe to examine the smallest dust grains, looking for our starry origins at the start of the process shown in the diagram. Some grains survive intact since they formed in the vicinity of dying stars, long before the Sun and the planets came into existence. The microprobe will find atomic signatures in the grains, which distinguish one ancestral star from another. There may be hundreds of them.

How to savour comet dust. The Cometary Matter Analyser (below), developed in Germany for a defunct US-German comet mission, may be adapted for Rosetta. It is designed to identify the chemical constituents of dust grains from the comet, by their molecular mass. A simulated mass spectrum shows how an optimized performance could distinguish two materials with almost identical masses.
Image: J. Kissel (MPK Heidelberg)



Giotto's legacy

Somewhat to their surprise, Europe's space scientists find they lead the world in one of the most exciting and exacting fields of deep-space exploration. Their American colleagues twice believed that NASA would grant them a major comet mission. Twice they were disappointed and ESA has plugged the scientific gap.

Rosetta is the successor to ESA's Giotto, the gallant little robot that braved the dust-storms of the most famous comet. In 1986, in company with two Soviet and two Japanese spacecraft, Giotto intercepted Halley's Comet. Guided by observations from the Soviet Vegas, Giotto plunged deepest into Halley's dusty head and passed within 600 kilometres of the nucleus.

In a high-speed encounter, dust grains damaged Giotto. Its camera was blinded, but not before it obtained pictures of the nucleus of Halley's Comet. Shaped like a peanut 15 kilometres long, and sombre in colour, Halley was seen firing jets of vapour and dust into space from small active regions.

Chemical instruments aboard Giotto and the Vegas radioed data about the gas and dust. They established that the main ingredients of a comet are small stony grains, tarry carbon compounds, and frozen water and carbon monoxide. These form a crumbly, meringue-like structure. In the warm sunshine of the inner Solar System, ice near the comet's surface turns to vapour and drives dust particles into space.

In 1992, by a navigational tour de force unforeseen at the start of the mission, Giotto flew within 200 kilometres of the nucleus of a second comet, Grigg-Skjellerup. Plasma instruments detailed the interaction of the wind of particles from the Sun with the comet's atmosphere and found contrasts with more turbulent effects near Halley. The comet's dust cloud was visible to ground-based optical experiments, but Giotto's dust-impact detectors registered only a few counts.

Comet Grigg-Skjellerup is smaller and much less active than Halley, and resembles the likely target for Rosetta. Comet Wirtanen and other candidate comets are on relatively tight orbits that return them to the Sun's vicinity every six years or so. Frequent exposure to solar heat has all but exhausted the near-surface ice that drives their emissions.

As the third cornerstone mission of ESA's Horizon 2000 programme, Rosetta was originally meant to scoop up samples from such a comet and bring them back to the Earth for analysis. It would have been a gamble for the engineers, and it required a major contribution from NASA. The cancellation of the US-German CRAF mission in 1992 changed the scene in international comet science.

Scientists advising ESA rethought Rosetta as an essentially European project. They dispensed with the sample return, and instead asked for a CRAF-like mission to operate a well-equipped analytical laboratory for many months in the comet's vicinity. Experiments conceived for CRAF provided a starting point for planning Rosetta.

"Instruments for doing chemistry in space are improving all the time," says Jochen Kissel of Heidelberg, who flew key experiments in the Giotto and Vega missions to Halley's Comet in 1986. "And Rosetta will see the comet's molecules in a relatively undamaged state, because of the low speed of the spacecraft and its proximity to the comet. Even so, the results will have to be interpreted with care, and with the aid of parallel experiments in the laboratory."

The long wait

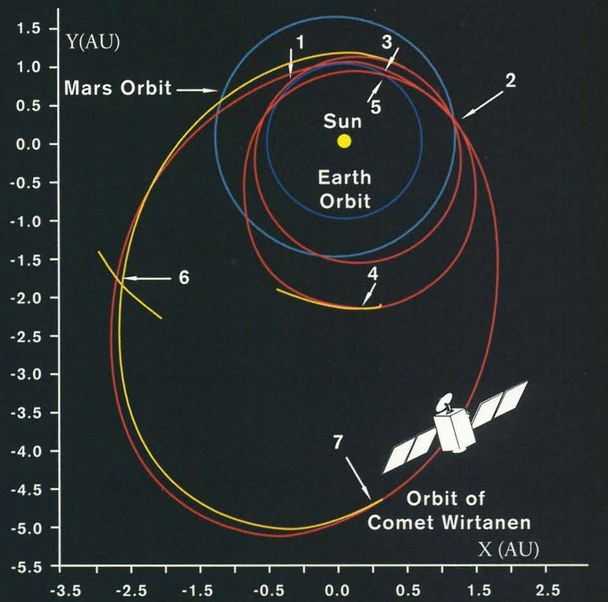
Rosetta's timetable will be taxing, less because of the frantic work associated with some other missions than because of the demand for patience. After the Ariane 5 launcher sends Rosetta on its way, nominally in January 2003, close encounters with the gravity of planets will boost the spacecraft into an orbit resembling the target comet's. Only thus can Rosetta rendezvous with it at a low relative speed, and nine years will pass before useful observations can begin.

The long wait will be relieved for some of the scientists when the spacecraft passes through the Asteroid Belt, beyond the planet Mars. Here the pieces of a failed planet orbit around the Sun as objects large and small. Rosetta will probably inspect two asteroids at close quarters. Likely targets are called Mimistrobell and Shipka. The aim will be to add to the knowledge of asteroids of different types, taking account of earlier US observations of various objects.

The asteroid operations will rehearse the remote-sensing instruments carried by Rosetta. From 1000 kilometres, a camera will see details on the asteroid down to 15 metres. A scanning spectrometer will break up the incoming light into its visible and infrared wavelengths, looking for the signatures of various minerals and mapping their distribution in patches about 500 metres wide.

When the planetary swingbys and asteroid encounters are finished, Rosetta will be on an orbit similar to that of the target comet, and it will go into hibernation for about three years. The spacecraft will cruise away from the Sun, without communicating with the Earth, until mission control rouses it for its rendezvous with the comet.

Rosetta will close to about 100 kilometres, feel the comet's feeble gravity, and go into orbit around it. From then on Rosetta and the comet will approach the Sun together, while mission control varies the leisurely orbit as required.



1 Spacecraft departs from Earth
2 Mars swingby for energy gain
3 Earth swingby for energy gain
4 Flyby of asteroid Mimistrobell
5 Second Earth swingby
6 Flyby of asteroid Shipka
7 Rendezvous with the comet

Chasing Comet Wirtanen. The Rosetta spacecraft's orbit (red) has to evolve with the aid of planetary swingbys until it matches the orbit of the target comet (yellow). In the scheme illustrated here, Rosetta leaves the Earth early in 2003 and achieves its rendezvous with Comet Wirtanen in 2011, having inspected two asteroids on the way. After the rendezvous, Rosetta travels in company with the comet for two years. The mission ends when the comet makes its closest approach to the Sun, in October 2013, nearly eleven years after the launch.

Simulated comet grains. On a small scale, comets may be built as shown in this conceptual model. Grains about a thousandth of a millimetre long may possess hidden stony cores wrapped in a carbon-rich material (orange). Coats of ice supposedly trap some much smaller grains (black). Loose packing leaves empty space between the larger grains. Image: J.M. Greenberg (Leiden)

Scientific instruments

RIS
Remote Imaging System
Surface appearance and activity, in wide and narrow camera fields

VIMS
Visual and Infrared Spectral and Thermal Mapper
Surface composition and temperature

GIMS
Gas and Ion Mass Spectrometer
Composition of gas and ionized gas from the comet

COMA
Cometary Matter Analyser
Composition of dust grains from the comet

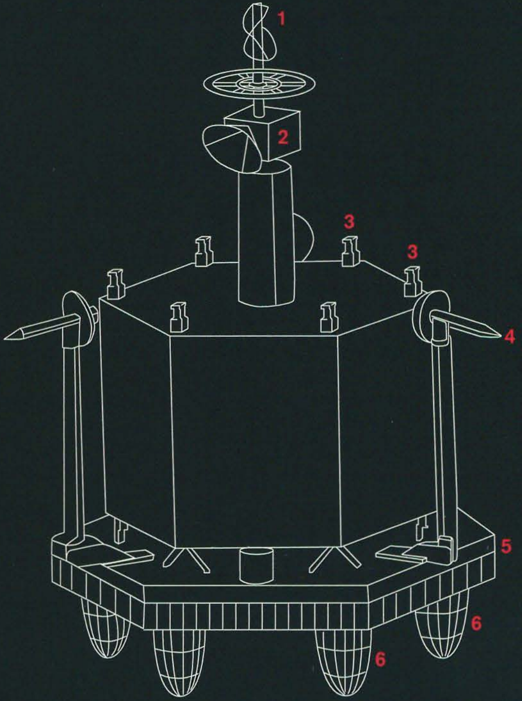
SEMPA
Scanning Electron Microprobe and Particle Analyser
Elemental composition and physical form of dust grains

DA
Dust Production Rate and Velocity Analyser
Comet's emission rate for dust

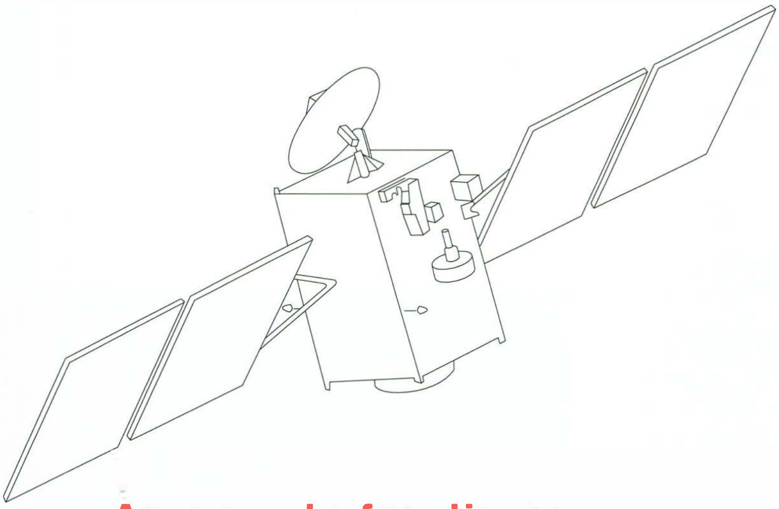
PP
Plasma Package
Solar wind and comet interactions (secondary objective)

SP
Surface Probes
Multiple instruments for dropping on to the comet

Preliminary concept for a comet lander. Rosetta drops it on the comet's surface. Small thrusters prevent it bouncing in the weak gravity, and bed it firmly. Spikes then anchor the lander. While its camera scans the scene, a drill probes into the surface and instruments in the lander analyse the material recovered. Operations could last for 84 hours. This possible contribution to the Rosetta mission is proposed by NASA/JPL (USA) and CNES (France). They call it Champollion, after the Frenchman who deciphered the Rosetta Stone early in the 19th Century.



1 Antenna
2 Camera
3 Hold-down thrusters
4 Anchor
5 Baseplate
6 Crushable honeycomb and feet



An early impression of the Rosetta spacecraft. It may look like a telecommunications satellite. Here the dish antenna provides the radio link with the Earth across interplanetary space. The onboard scientific instruments and the surface probes can fit on other sides of the box.

An agenda for discovery

The first task of the International Rosetta Mission will be to map the comet in its inactive state. Camera close-ups showing details down to a metre will be accurately located on the whole comet observed with wide-angle optics. The scanning spectrometer may detect localized occurrences of ice or organic compounds.

The scientific team will look for potentially active regions like those seen by Giotto on Halley's Comet, and inspect them in even more detail as possible landing sites for the two surface probes. When Rosetta releases each probe from a height of about one kilometre, the weak gravity will cause an impact like a drop of a few centimetres on the Earth.

"It is likely that national space agencies or institutes will take overall responsibility for the surface probes," says Gerhard Schwehm, ESA's project scientist. "So we are not too specific at this stage, except to say that the total mass of each probe should not exceed 45 kilograms."

Within the 45-kilogram limit, a joint US-French proposal called Champollion would put a drill on the surface of the comet. It would penetrate about 20 centimetres below the surface, in search of fresh material that had not been exposed to the Sun's rays. Robotic mechanisms would transfer the recovered samples to a set of analytical instruments. Another lander is mooted by a German-led consortium, RoLand. Although many conceivable instruments could explore the physical nature of the comet, chemical analysis is likely to have the highest priority, in the landers as well as Rosetta in orbit.

Weak effusions of gas and dust from the comet may already be detectable by Rosetta by the time the probes are dropped. Observations by instruments aboard Rosetta will then enter their main phase, as emissions multiply more than a billionfold in the months that follow.

The camera and remote-sensing spectrograph will watch for changes on the comet's surface. Dust grains arriving at Rosetta will register in a sensor as they pass through curtains of light. To prevent too much dirt accumulating on the spacecraft and its instruments, the mission controllers may withdraw Rosetta to the outer regions of the dusty coma, as the comet nears the Sun in 2013.

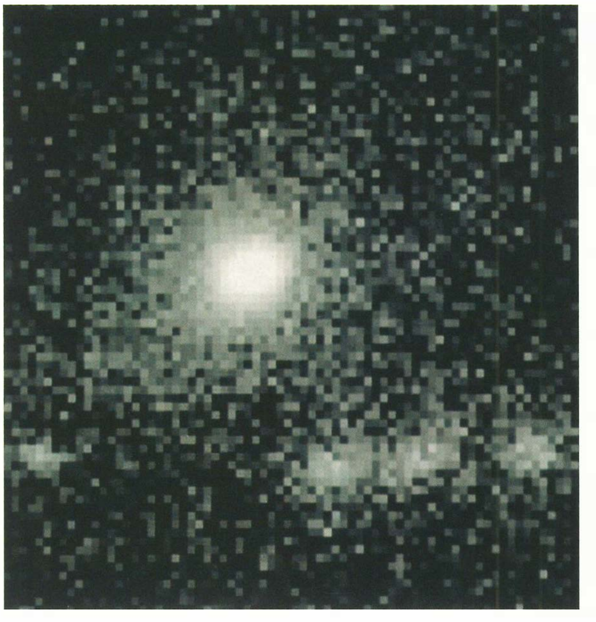
Chemical analysis will start with instruments that weigh the atoms, molecules and ions in the comet's atmosphere. The results should reveal how the ice is stored in the comet, and whether it has trapped other gases from interstellar space. Relative abundances of common and rare atoms will enable scientists to finger-print cometary contributions to the volatile atmospheres of the planets. Separate observations of charged particles in the solar wind will help the chemists to take account of their effects on the comet's atmosphere.

Many thousands of individual dust grains will be analysed, with a liquid-metal ion source breaking up the dust grains and energizing the materials for analysis. Mineral components will show whether or not the comets possess the constituents of the Earth and other rocky planets. And fuller knowledge of the carbon compounds in the grains, which provoked intense interest in the Giotto and Vega results, will show to what extent materials useful for starting life existed at the origin of the Solar System.

"I suspect," Jochen Kissel says, "that Rosetta will find a soup powder containing every combination of hydrogen, carbon, nitrogen and oxygen atoms that is stable at the temperature and pressure inside the comet. Molecular overkill, in fact. If so, scientists will learn more about the physical conditions in the dust than about any special chemical traits. My own view is that the raw materials for life were widely available in the young Solar System, and it was the physical environment, perhaps on a microscopic scale, that determined what happened to them."

To learn about the cosmic sources of the dusty material in a comet, a scanning electron microprobe in Rosetta will examine individual dust grains. It will discover variations in their form and composition, and gauge the abundances of elements by X-rays generated when the electron beam strikes the surface. Examination of fluffy comet grains, of a kind collectable today in the Earth's upper atmosphere, will test the idea that the dust thrown out in comets' tails scattered carbon compounds on the young Earth.

In the light of the Giotto results, the scientists advising ESA about Rosetta can set a logical agenda for discovery and give reasons why more detailed knowledge will be well worth acquiring. "But we expect surprises," says Gerhard Schwehm. "Not everything can be anticipated in a mission as adventurous as Rosetta's."



Comet Grigg-Skjellerup. It is like Comet Wirtanen and other small, aged comets considered for Rosetta. ESA's spacecraft Giotto went to Grigg-Skjellerup in July 1992, six years after Halley's Comet. This picture came from a ground-based telescope on the day of Giotto's arrival. The dust cloud, or coma, was 20,000 kilometres wide, with a faint tail extending to the left and downwards.
Image: K. Jockers (MPAe Lindau) and European Southern Observatory

ISO:
ESA's Infrared Space Observatory (1995)

esa

PART 2

The Universe from space

Overview: telescopes in orbit

The stars have colours that we cannot see. Human eyes are tuned to the narrow waveband of light that happens to reach the Earth's surface, but other light-like messengers make long journeys across the chasms of spacetime only to die in the upper air. By rising above the air, satellites carrying telescopes and detectors tuned to the various wavebands open new windows on the Universe.

That may sound easy. In practice it requires scientists to gamble with important years of their lives in developing astronomical instruments for spacecraft. They often have to put up with disappointments and delays that would tax a saint, in the hope that one day they can say, "Wow! Look at that!"

Europe's scientists have played a distinguished role in the adventure of space astronomy. Indeed ESA's role can be fully appreciated only by taking into account the efforts of teams in the member states. These have contributed telescopes, sensors and observational projects to many astronomical missions originating in the USA, Russia and Japan, as well as in Europe. Their expertise guides ESA's selection of future missions.

The story really begins in the days of horse-drawn carriages. Around the year 1800 a German-born astronomer working in England, William Herschel, measured the heating power of the different colours of sunlight spread out in a spectrum.

He found that even when he moved his thermometers beyond the red end of the spectrum, heating occurred. He had discovered infrared rays.

Before the 19th Century was over, ultraviolet rays, radio waves and X-rays extended the list of invisible forms of radiation. Meanwhile, in the 1860s, James Clerk Maxwell developed the electromagnetic theory of light. It authorizes a rainbow of rays, all travelling at the speed of light, with wavelengths ranging from the very short (X-rays, for example) to the very long (radio). Visible light is confined to a narrow waveband in the middle. Puzzles about the dual character of the rays of Maxwell's rainbow, which sometimes behave like particles and sometimes like waves, were not settled until the quantum theory matured in the 20th Century.

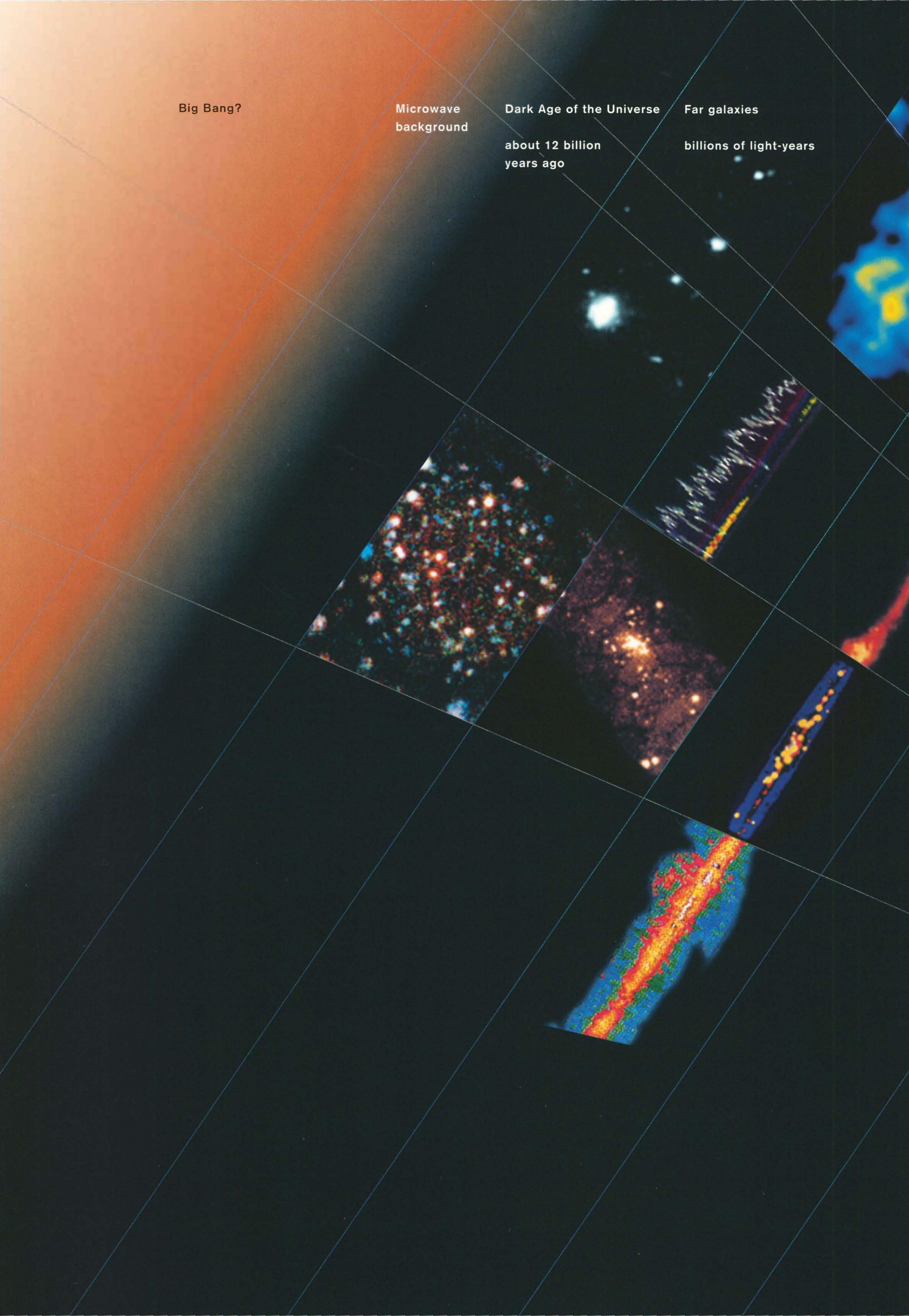
To theorists it was obvious that stars and other objects in the sky should emit a wide range of wavelengths. The impact on astronomy was nevertheless slow to come.

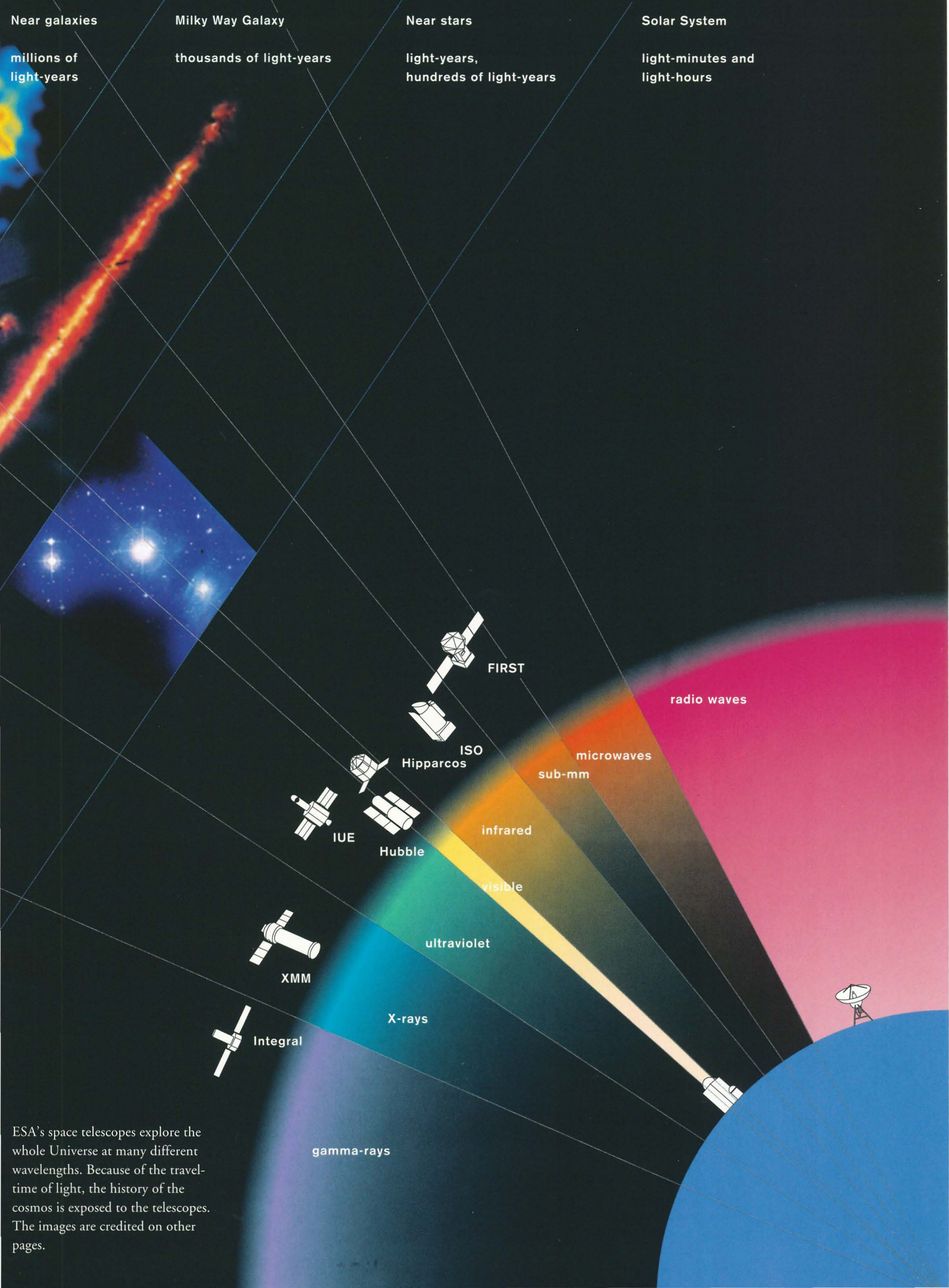
In 1931, the American radio engineer Karl Jansky detected interference coming from the Milky Way. But astronomers went on working with the visible waveband and slivers of infrared and ultraviolet close to it.

Their visible Universe looked serene and unchanging, except when comets cruised across the sky or distant stars exploded. To be sure, some of the other galaxies, great congregations of stars like the Milky Way Galaxy where we live, seemed curiously misshapen. And an odd idea of the Belgian astronomer Georges Lemaître, that the Universe began in an immense explosion, apparently fitted with the observations of the American astronomer Edwin Hubble, who found that the galaxies were flying apart. But there was little else to see that disturbed a deep sense of tranquillity.

A revolution in human perceptions of the cosmos began after 1945. Physicists in the UK, the Netherlands and Australia made radio telescopes that picked out scenes of ferocious change: exploding stars and exploding galaxies. In 1965 American radio engineers unwittingly found the microwave background predicted as a relic of a primordial explosion. Dense aggregations of nuclear matter, the neutron stars, showed up as pulsating radio sources, or pulsars. Among the galaxies, quasi-stellar radio sources, or quasars, turned out to be so distant and therefore so immensely powerful that they seemed to need giant black holes to energize them.

Visible light and some infrared and radio wavebands are the only parts of Maxwell's rainbow that penetrate the Earth's atmosphere to reach telescopes on the ground. Instruments on high mountain-tops, balloons and high-flying aircraft can catch other invisible rays, but only telescopes in space have a clear view.

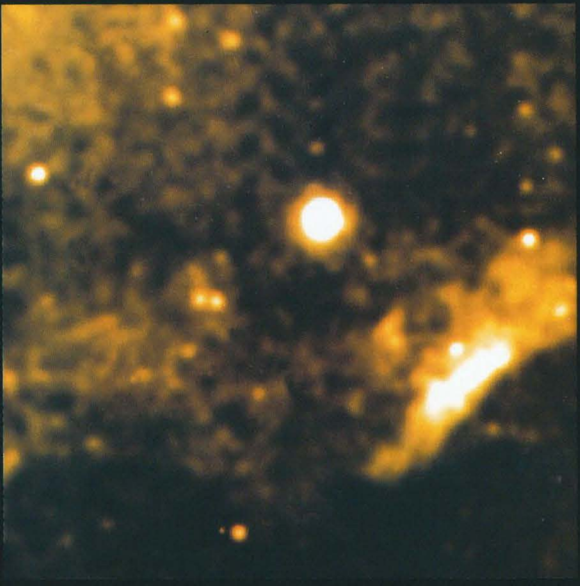

Big Bang?
Microwave background
Dark Age of the Universe
about 12 billion years ago
Far galaxies
billions of light-years



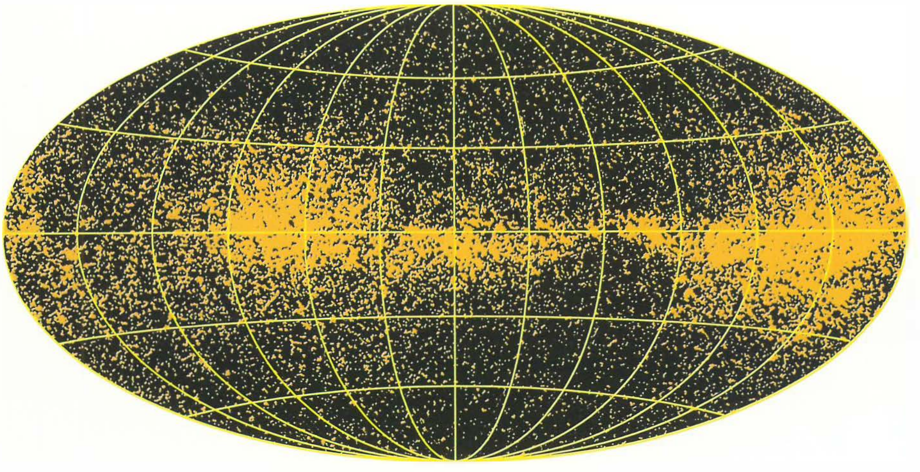
ESA's space telescopes explore the whole Universe at many different wavelengths. Because of the travel-time of light, the history of the cosmos is exposed to the telescopes. The images are credited on other pages.

Confirmation that there was something out there to see came during a quick peep by an American rocket in 1962. Unexpectedly it found an intense X-ray star in the Scorpius constellation, Sco X-1. A few years later, another salient discovery involved gamma-rays, which are like X-rays but even more energetic. US military satellites, designed to watch for manmade nuclear explosions, detected cosmic explosions called gamma-ray bursts. They remain mystifying to this day. Dedicated astronomical satellites began to appear in the late 1960s, but there was an unhappy period of total or partial failures. It fell to NASA's Uhuru, launched in 1970, to prove that you could do serious astronomy in space. Although its detectors were rudimentary by present standards it mapped hundreds of X-ray sources across the sky.

Uhuru established that in sources like Sco X-1 a small and dense white dwarf or neutron star sucked gas from a nearby companion, in vampire fashion. One source, Cyg X-1, varied in intensity so rapidly that astronomers suspected that the vampire in this case was a black hole. Uhuru also found X-rays coming from other galaxies and from quasars and, more surprisingly, from clouds of hot gas associated with clusters of galaxies.



A suspected stellar black hole. Cygnus X-1 is a bright and variable X-ray source interpreted as a black hole about ten times the mass of the Sun. It is supposedly consuming matter dragged from a nearby companion star by the intense gravity of the black hole. The theory is that the black hole was made by the collapsing core of a star far larger than the Sun, at the end of its life. Cygnus X-1 was one of the earliest discoveries in X-ray astronomy, but here it is seen in a recent image from the German-built Rosat X-ray satellite.
Image: J. Trümper (MPE Garching)



Concentrations of ultraviolet stars. Twenty years ago, the European Space Research Organisation's satellite TD-1 mapped ultraviolet sources in the Universe. The whole-sky chart shows hot stars crowded in the directions of the Cygnus and Orion constellations.

Europe joins in

Just fifteen months after Uhuru's launch, the European Space Research Organisation (ESRO) made a debut in space astronomy with a mission memorable for its difficulties. The satellite's name, TD-1, came from NASA's Thor-Delta rocket, which put it into orbit in 1972.

The aim was to scan the whole sky with gamma-ray, X-ray and ultraviolet instruments. But TD-1's cosmic-ray detectors were swamped by particles in the Earth's radiation belt, and were able to pinpoint emissions only from the centre of the Milky Way Galaxy. An X-ray counter upset the spacecraft's telemetry, and anyway its results were overshadowed by Uhuru's. The tape recorders failed, so that ESRO had to recruit or create forty ground stations beneath TD-1's orbit, even in Antarctica and on a ship wallowing in the Southern Ocean. In this frenzy of improvisation, TD-1's ultraviolet instruments catalogued 30,000 hot stars and provided the first copious supply of spectra analysing the emissions from ultraviolet sources.

NASA's next satellite for the ultraviolet, Copernicus, was also launched in 1972. At 2.2 tonnes it was very large for its time. It transformed the astronomers' perceptions of interstellar space by detecting fierce winds from hot stars. And by lasting for nine years Copernicus demonstrated that a telescope in space could be a trustworthy tool for the astronomers.

Soviet efforts in space astronomy date back to Cosmos 215 launched in 1968, with instruments for X-rays, ultraviolet and visible light. Like the Americans, the Russians have also been able to put telescopes into manned spacecraft. Until Europe's space scientists had access to their own Ariane launcher in the 1980s they flew their experiments by courtesy of the superpowers of the day.

Gamma-ray and ultraviolet instruments developed by French scientists operated in Soviet spacecraft from 1972 onwards, and France launched its own ultraviolet satellite in 1975. The Netherlands and the UK both built astronomical satellites for NASA launches in 1974.

The Dutch ANS satellite discovered X-ray bursters, in which vampire stars create nuclear explosions.

The British Ariel-5 registered more powerful outbursts that suggested the presence of black holes.

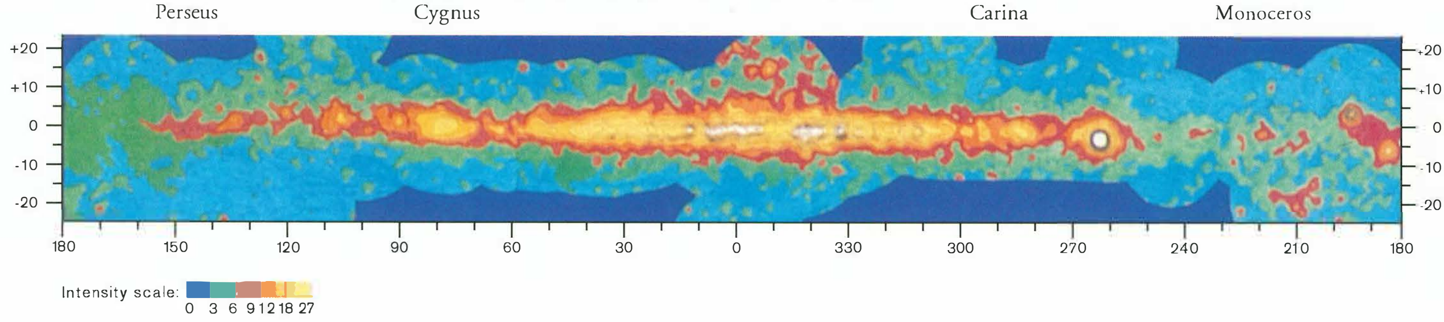
Experts advising the European Space Agency (successor to ESRO) sought to balance these national initiatives, and ESA participation in NASA's own missions, with further astronomical spacecraft built and instrumented by Europe-wide collaboration. ESA gained its credentials as a pioneer in space astronomy with COS-B, launched in 1975.

COS-B mapped the sky by gamma-rays. A similar US gamma-ray satellite, SAS-2, had discovered point sources of gamma-rays corresponding with two known and one unknown neutron stars, and a ridge-like source near the centre of the Milky Way. But SAS-2 suffered a power failure with its work scarcely begun and left the field clear for COS-B. During its five-year lifetime, the European satellite pinpointed two dozen gamma-ray sources, including a distant quasar, and extended the ridge of intense gamma-rays on either side of the Galactic Centre.

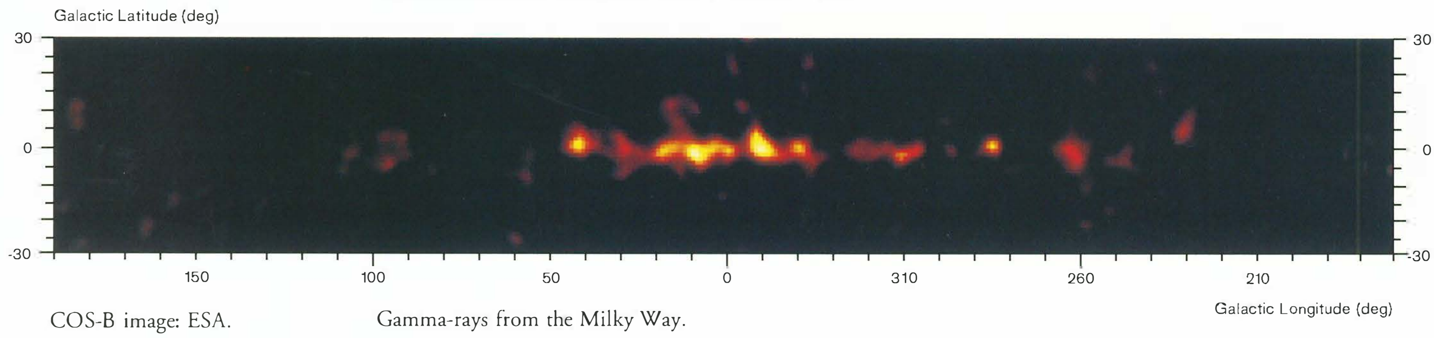
In 1977, ESA agreed to contribute to NASA's space telescope for the visible and ultraviolet wavebands, which was later named Hubble. The reasons for putting visible-light telescopes into space are somewhat different from those for spacecraft capturing wavebands blocked by the atmosphere. In Hubble's case, it was to escape from the distortions caused by the air's turbulence. ESA provided one of two main cameras for Hubble, the solar panels for powering the spacecraft, and European staff for the associated science institute.

As Hubble became fully functional only in 1994 it belongs to a later part of the story. So does Hipparcos, a highly unusual and all-European visible-light project inspired by French astronomers and authorized as an ESA mission in 1980.

COS-B Galactic Gamma-Ray Emission 70 MeV - 5GeV



CGRO/Comptel 1.8 MeV MEM Map of Galactic Plane



COS-B image: ESA.
Compton image: V. Schönfelder (MPE Garching) and COMPTEL team/NASA Compton Gamma-Ray Observatory; image created by J. Knoedlseder and R. Diehl.

Gamma-rays from the Milky Way. These representations of our Galaxy correspond to the disk of densely-packed stars which makes the band of light around the sky, here flattened out. The upper chart shows gamma-rays observed by ESA's pioneering COS-B satellite (1975-81). In the lower chart, a German instrument in NASA's Compton gamma-ray observatory (1991) uses emissions from radioactive aluminium to map the locations of recent element-making by exploding stars. Volker Schönfelder of the Max-Planck-Institut für Extraterrestrische Physik, at Garching in Germany, runs the COMPTEL instrument which generated this image. "We expected a much more even picture," Schönfelder says. "The bright spots were a big surprise."

Space astronomy matures

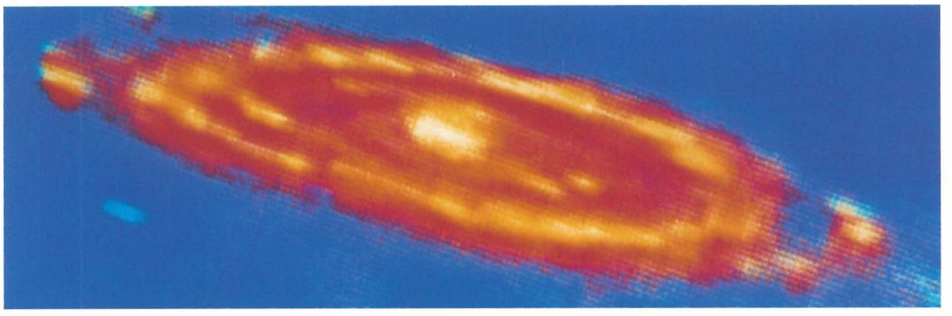
It is one thing to scan the sky at exotic wavelengths and plot the locations of a variety of objects emitting them. To interpret the objects properly is a more exacting task. Besides imaging and positioning them accurately, astronomers have to find out how the energy varies at different wavelengths. They look for telltale signatures of particular atoms and for continuous emissions that reveal physical conditions in the sources. In a word, they do the spectroscopy.

Ultraviolet astronomy reached maturity first, with the launch in 1978 of IUE, the International Ultraviolet Explorer. Promoted by British space astronomers as a mission to analyse the spectra of ultraviolet sources, IUE became a joint project of NASA, ESA and the UK.

It proved an amazing success, and is still operating in the mid-1990s. Astronomers love IUE because they can go to ESA's ground station near Madrid, or NASA's near Washington, and use it just as they would an important ground-based telescope.

IUE was the first professional telescope turned on the Large Magellanic Cloud in 1987, when a star exploded in that nearby galaxy. Comparisons with previous IUE data identified the star that blew up. Most of what astronomers now know about ultraviolet emissions from quasars, galaxies, stars, planets and comets comes from IUE. Only recently has the Hubble Space Telescope challenged its mastery of the ultraviolet sky.

In the year when IUE went into orbit, 1978, NASA flew an X-ray focusing telescope in the Einstein satellite.



Andromeda Galaxy by infrared rays. It is the nearest spiral galaxy beyond the Milky Way, but instead of the crowds of bright stars seen in visible light, the IRAS infrared space telescope (1983) highlighted dust encircling the galaxy.
Image: IRAS/NASA/JPL

Previous X-ray missions had used blinkers called collimators, in front of the detectors, which merely excluded X-rays from all but a chosen part of the sky. Leading space astronomers in the USA adopted a German invention for focusing X-rays, first in a solar X-ray telescope for the Skylab space station and then in the instrument for Einstein. Unlike previous sky-scanning X-ray missions, Einstein operated in an observatory mode, picking out objects at will for intensive examination.

The remnants of supernovae, exploded stars, took shape as shells of X-ray emitting gas. The Andromeda galaxy had looked previously like a single source, but Einstein located within it about a hundred different X-ray stars. The spacecraft also saw small, rapidly varying sources in the hearts of more distant galaxies, where giant black holes are thought to operate. By the time Einstein expired in 1981, an impending X-ray mission for Europe had being hurriedly re-engineered to match the new norms for X-ray astronomy.

Although much smaller than Einstein, with one-sixth of the mass, ESA's Exosat carried small focusing telescopes and state-of-the-art detectors. After its launch in 1983, Exosat was able to continue where Einstein left off, notably in close study of X-ray stars, supernova remnants and suspected giant black holes in other galaxies. Astronomers clamoured for an extension of the mission beyond its intended two years, and Exosat continued operating until attitude-control problems terminated the mission in 1986.

A satellite built in the Netherlands opened another window on the Universe in 1983, by mapping the sky by infrared light. IRAS was a joint US-Dutch-British venture, and it ranks with IUE as one of the most successful of astronomical space missions. This is despite the fact that IRAS operated for only 300 days.

Its life was limited by the need to cool the telescope and its instruments severely, so that their own emissions of heat rays did not mask the small packets of infrared energy arriving from the cosmos. The helium used to cool IRAS ran out when its all-sky survey was about 98 per cent complete. But by then it had charted no fewer than 250,000 distinct sources of infrared emissions in the Universe.

By observing at four different infrared wavelengths, IRAS enabled the astronomers to distinguish dust clouds, cool stars and distant galaxies. Immediate findings included dust orbiting around stars, strange dust-clouds in the Milky Way Galaxy called infrared cirrus, and extremely dusty and energetic infrared galaxies. More than a decade after the spacecraft fell silent, astronomers still quarry the IRAS catalogues for new discoveries.

The cosmic objects detected by IRAS deserved closer individual scrutiny, and a more sensitive telescope would find many objects too faint for the pioneering mission. ESA therefore authorized work to begin in 1986 on ISO, the Infrared Space Observatory. It is now due to fly in 1995.

ISO will give images ten times sharper than IRAS's and will detect rays 100 to 1000 times fainter. Instead of being confined to four preselected wavelengths, ISO will analyse spectroscopically the entire range of wavelengths across a wider waveband. And it will operate in an observatory mode. Like IRAS, ISO will be cooled by a finite supply of liquid helium, but its operational lifetime should be about twice as long.

With this ESA spacecraft, infrared space astronomy matures too. The target list for ISO spans the Universe, from nearby comets to the most distant galaxies. Among many interesting topics for investigation are the formation of planets and the evolution of the galaxies. ISO may also help to solve a cosmological conundrum. If it can detect cool brown dwarf stars in the vicinity of the Milky Way, these may account for the invisible Dark Matter that causes outlying stars in the Galaxy to travel faster than expected.

Towards a coherent policy

When ISO was authorized in 1983, ESA was preparing Horizon 2000. This long-term programme takes a balanced view of the competing claims of Europe's space scientists and astronomers for limited resources, as well as the opportunities for making distinctive contributions. By the time Horizon 2000 was initiated telescopes in space had proved their worth in mainstream astronomy, and European scientists had found leading roles on the world stage. IRAS had triumphed, Exosat was in orbit, and ESA's Faint Object Camera was ready to fly in the Hubble Space Telescope. Laboratories all over Europe were busy with new tasks.

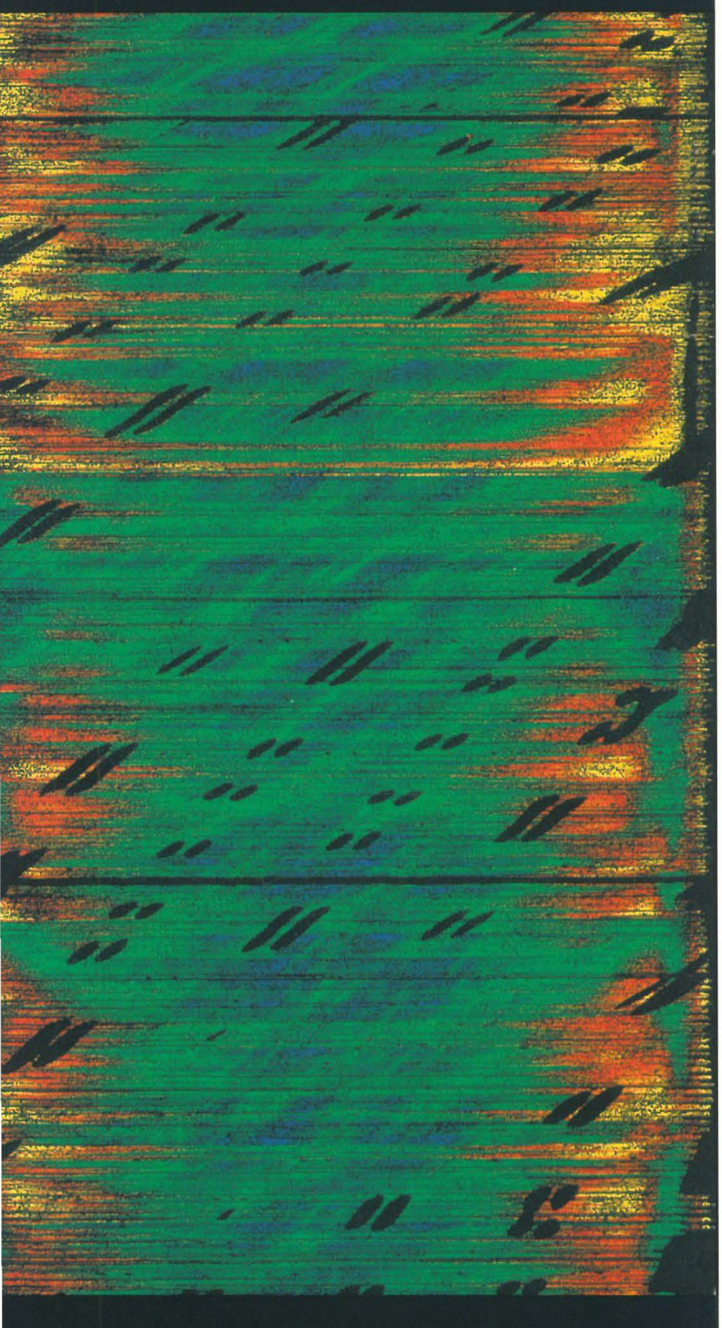
The Germans were developing Rosat as a major X-ray satellite in collaboration with NASA, and preparing a telescope for a US gamma-ray mission. The British were supplying the main instrument for a forthcoming Japanese X-ray mission. Among the telescopes tested in ESA's Spacelab aboard a NASA shuttle was a British X-ray telescope using a coded mask. In this technique, cosmic sources are pinpointed by the shadows they cast on an array of detectors, through a mathematically configured mask. A coded mask was to figure in a French gamma-ray telescope aboard a Soviet spacecraft, Granat.

The Danes were planning instruments to detect gamma-ray bursts, which would fly in Granat and also in ESA's recoverable carrier Eureca, deployed and retrieved by the US shuttle. An Italian X-ray satellite SAX, with strong Dutch participation, was in contemplation. And a suite of astronomical instruments from ESA, Germany, the Netherlands and the UK was to go aboard the Soviet Mir space station.

Besides all this activity in space, Europe was pursuing its programmes of ground-based astronomy. The scientists advising ESA could therefore comment authoritatively and judiciously on new priorities.

"We want our space telescopes to be the best in the world for their stated purposes," says Martin Huber, head of ESA's Space Science Department. "As part of a global research community we are always juggling the benefits of cooperation versus friendly competition. So we pay close attention to what other space agencies are planning, and they watch what ESA intends to do. Following the advice of Europe's space astronomers, we announced that Horizon 2000 would include daring cornerstone missions in the X-ray and submillimetre wavebands. To these major projects we have already added a medium-scale gamma-ray mission."

The remainder of this Overview puts these forthcoming ESA astronomical spacecraft in perspective, in relation to other people's missions and to the scientific opportunities. This is most conveniently done in a quick scan across Maxwell's rainbow. Modern astronomy is, though, a "multispectral" science in which observations of the same object at many different wavelengths promise the deepest insights. Preferably the observations are simultaneous, but that can be timeconsuming to arrange unless a single spacecraft carries its own range of instruments. Multispectral spacecraft, of which ESA's new missions provide examples, may show the way ahead.



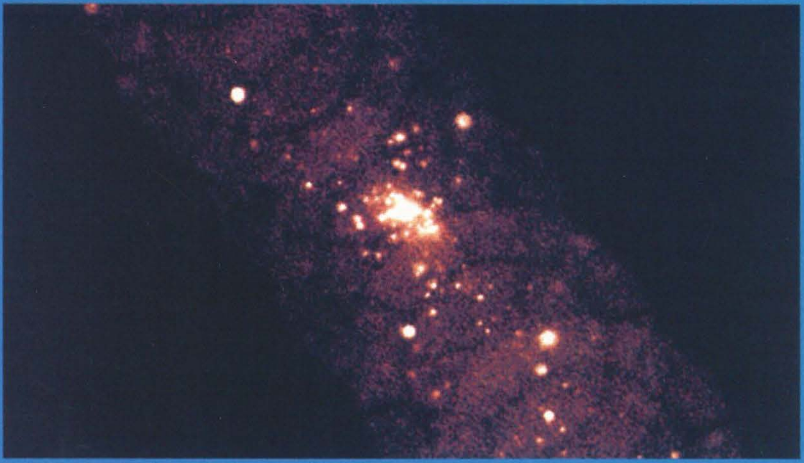
Radiation belts. Every line in this record represents one orbit of ESA's Hipparcos spacecraft. Twice in each orbit it flew through the swarms of particles in the radiation belts around the Earth. The enhanced background noise, shown here in red and yellow, is a nuisance for space astronomers.
Image: F. van Leeuwen (RGO, Cambridge), NDAC Consortium and the Hipparcos programme.

Gamma-rays

When Horizon 2000 was evolving, the recent Russian Granat (1989) and US Compton (1991) gamma-ray observatories were already in prospect, including the French and German instruments already mentioned. ESA's survey panel concluded that "an additional effort by Europe in the gamma-ray domain is not justified". Yet less than ten years later the scientific advisers were warmly commending a project for another gamma-ray observatory. In 1993 it was approved as an ESA mission called Integral. It is a medium-scale mission in the Horizon 2000 programme, a ranking made possible by sharing space technology with ESA's next X-ray mission.

Here is a striking case of opinions changing as instrumental technology advances. The very success of the recent missions confirms the scientific potential of Integral. Discoveries include gamma-ray blazars among the galaxies and unexpected concentrations of heavy elements in the dust of the Milky Way. The belief is that ESA's Integral will improve greatly on the performance of Granat and Compton when it is launched in 2001.

Besides using a special form of germanium in a detector to eliminate false readings, Integral will locate its gamma-ray sources by coded masks, already used in the Granat mission. It will also carry X-ray and visible-light instruments. One hope is that Integral may solve the riddle of the gamma-ray bursters, which have foxed the space astronomers for a quarter of a century, and which recent Compton results make more mysterious than ever. Among other special targets for Integral is the centre of the Milky Way, which may contain a giant black hole.



X-rays from the Andromeda Galaxy. Lying about 2 million light-years away, this galaxy is the farthest object visible to the naked eye. Like its sister the Milky Way Galaxy, it possesses many X-ray stars. Hundreds of them are seen in this image from the Rosat mission. Image: J. Trümper (MPE Garching)

X-rays

Rosat dominated X-ray astronomy in the early 1990s. This German-US-British mission combined the first whole-sky survey using a focusing telescope with operations in a pointing, observatory mode. Rosat was a triumph. For example it logged tens of thousands of active galaxies with violent events in their nuclei, and in one galaxy they traced hot winds pouring from a galaxy into the surrounding space. It found 400 individual X-ray sources in the nearby Andromeda Galaxy, more than the early X-ray satellite Uhuru logged in the entire sky.

What telescopes do X-ray astronomers want now? The Americans are bent on seeing fine detail in the X-ray sky. NASA is preparing a satellite called AXAF, with a focusing telescope 1.2 metres in diameter and 10 metres long. It will fly in the late 1990s as an X-ray equivalent of the Hubble Space Telescope.

Astronomers in Japan, Russia and Europe emphasise a different goal. The buzzwords are "multimirror" and "high-throughput spectroscopy", and what they mean is building more elaborate X-ray telescopes for the sake of high efficiency in collecting and detecting the X-rays. Cosmic sources can then be analysed without unduly long exposures.

At issue here is the low efficiency of previous X-ray focusing telescopes, which at best gathered only a few percent of the rays arriving from the field of view. Being shaped like a bucket without a bottom, an X-ray mirror focuses only those rays that happen to hit the inside wall of the bucket. To reduce the wastage, you can nest a number of mirrors inside each other. Einstein had four nested mirrors, and so will AXAF.

By contrast, the Japanese Asca satellite (1993) has four small telescopes each with 120 nesting mirrors. Their ability to see detail is very poor compared with what AXAF will offer, but Asca collects more X-rays than AXAF will, and it also extends the range of X-rays observed to higher energies. The forthcoming Italian-Dutch SAX satellite has four telescopes with thirty mirrors apiece. The Russian Spectrum-X Gamma spacecraft will carry a Russian-Danish pair of telescopes with 154 mirrors each.

These early multimirror telescopes sacrifice sharpness of vision, or resolving power, in the interests of simplicity, by using mirrors conical in form. For proper focusing, they should have part parabolic, part hyperbolic cross-sections, like the classic X-ray telescopes. Fully configured mirrors are used in two British-Italian telescopes for Spectrum-X Gamma, each of which contains twelve. They will also push the technology in another new direction by detecting the X-rays with cooled charge-coupled devices. These are special silicon chips and will operate at minus 100 degrees C to give high sensitivity and accurate measurements of the energy of the X-rays.

ESA's XMM mission, scheduled for launch in 1999, aims to nest together the largest practicable number of accurately fashioned parabolic-hyperbolic mirrors. The number selected is fifty-eight mirrors in each of three telescopes, with a maximum aperture of 70 centimetres. XMM will thus combine high efficiency in collecting X-rays with moderately high resolving power. The designation of XMM as a cornerstone mission of ESA's Horizon 2000 programme provides the resources needed to develop unusual instruments. As each mirror is a large but thin metal shell, and must keep its accurately figured shape, contractors in Germany and Italy face an interesting challenge in making the telescopes.

X-ray astronomy will therefore enter the 21st Century with NASA's AXAF probing the finest details of X-ray sources, and ESA's XMM collecting X-rays ten times faster and analysing them thoroughly.

Making a splash. Imaged by the Hubble Space Telescope, the Cartwheel Galaxy shows a ring of billions of young blue stars created by a shock travelling out from the centre. The dishevelled blue galaxy on the right may have shot right through the Cartwheel, causing waves like a stone splashing in a pond.
Image: K. Borne (STScI), NASA and ESA

Ultraviolet

Between X-rays and ultraviolet wavelengths is a no-man's land called the extreme ultraviolet, or EUV. Although solar physicists have long studied such emissions from the Sun, other astronomers avoided it. They thought that the commonplace hydrogen atoms in interstellar space would absorb all the EUV radiation below 91 nanometres wavelength. Encouraged by results from telescopes in the Apollo-Soyuz manned mission (1975) and NASA's Voyager interplanetary spacecraft, a British group put an EUV camera in the German Rosat X-ray satellite.

This "mission impossible" promptly found hundreds of very hot EUV stars. The interstellar gas is far from uniform, and massive stars, young white dwarfs and supernova remnants shine brightly through the low-density gas. In 1992 NASA launched EUV Explorer, which discovered an EUV jet in a distant galaxy.

Another NASA project, Lyman, with Canadian and British participation, is intended to bridge a wavelength gap between the EUV and the "normal" ultraviolet wavebands of IUE and the Hubble Space Telescope. The region of the spectrum to be explored by Lyman should give important information about the abundances of various light elements made in the Big Bang.

Enthusiastic users of IUE wonder what will replace this ageing spacecraft. An ESA-NASA study of a replacement lapsed after the Challenger shuttle accident in 1986. In principle spectrometers in Hubble can do IUE's business, but there are many other demands on Hubble's time.

Visible light

As the most famous space telescope of them all, Hubble operates with visible as well as ultraviolet light. After its belated launch in 1990, the revelation that the main telescope mirror was the wrong shape shocked the astronomers. Despite the hazy images, Hubble made many discoveries about stars and galaxies. Contributions by Europe's astronomers exceeded the 15 percent of Hubble observing time allotted to them as a result of ESA's participation in the mission.

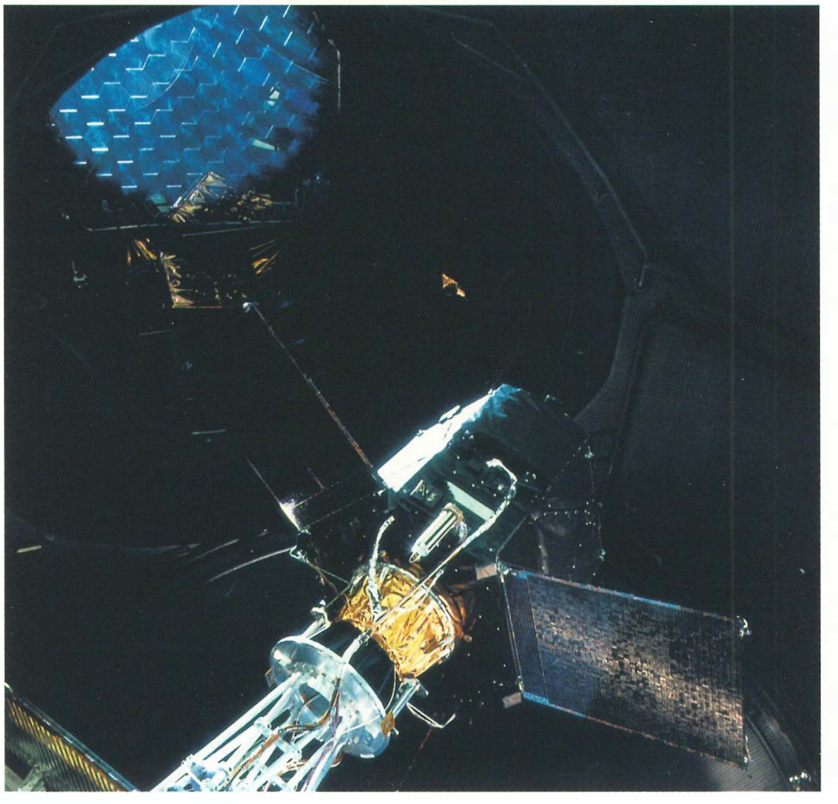
ESA's Faint Object Camera worked well, but vibrations in the solar panels supplied by ESA gave problems. The fitting of re-engineered solar panels was added to a hair-raising list of tasks for the astronauts who were to repair and refurbish the telescope. The shuttle crew that carried out the work successfully at the end of 1993 earned applause from a watching world and gratitude from the astronomers.

With corrected optics, Hubble is fulfilling all the hopes that originally inspired the mission in the 1970s. The first discovery after the refurbishment, in January 1994, was the detection of primeval helium in the Universe by an ESA-led team using the Faint Object Camera. By 1995, a volcano of other Hubble findings by US and European astronomers was erupting in the scientific literature.

Hubble is intended to last for fifteen years. Meanwhile ground-based observatories are acquiring giant telescopes with 8-metre and 10-metre mirrors, far larger in collecting area than Hubble's. Techniques of adaptive optics aim to correct the smearing of images caused by turbulence in the Earth's atmosphere. These may undermine the case for another general-purpose space telescope for visible light, although an 8-metre instrument in space has been mooted in the USA.

Smaller, special-purpose telescopes will still be able to accomplish much. ESA's SOHO mission (1995) will detect oscillations of the Sun's surface from an exceptionally stable and darkness-free vantage point in space. The oscillations reveal the nature of the Sun's interior. The same technique can be applied to the study of other stars. ESA has studied a space project called STARS to observe stellar oscillations, but has not yet adopted such a mission.

ESA's Hipparcos. This satellite revolutionized the methods of pinpointing the stars in the sky, and measuring their distances and motions. Here it is seen undergoing tests in a space simulator at the European Space Research and Technology Centre (ESTEC) at Noordwijk in the Netherlands, before its launch in 1989.



ESA's Hipparcos mission stands out among other astronomical space adventures by its sheer originality. In contrast to all the projects which, at their chosen wavelengths, seek to probe the energetic processes in stars and galaxies, Hipparcos is concerned with where exactly the stars are and how they move. Between 1989 and 1993 the European spacecraft logged the positions of the million brightest stars. It pinpointed 120,000 more precisely, and now computers are at work teasing out confusions due to the different distances and motions of the stars.

This is a monumental task, but when ESA publishes the results in 1997 they too will be monumental. Besides a self-consistent mapping of the sky far more accurate than any previous compilation, the Hipparcos Catalogue will give, in effect, an animated, 3-D view of the stars around us. The stars all have distances and motions of their own. Until now these were poorly known except for a few dozen of the nearest stars.

Many calculations in astrophysics, from the energy output of various types of stars to effects of unseen Dark Matter on the motions in the Galaxy, have relied on guesses about distances. Hipparcos will change all that. If ESA had done nothing else in space astronomy, this one visible-light telescope would guarantee it an unforgettable place in the history of science.

Success may breed a successor. The scientific survey panel outlining the Horizon 2000 Plus programme for ESA, for the period 2006-16, has recommended that an even more accurate star-plotting satellite should be considered for one of the major missions. It would use interferometers to combine the light from pairs of small telescopes spaced apart, and so to pinpoint objects as precisely as a much larger and heavier telescope.

Infrared and sub-millimetre wavelengths

ESA's ISO will rule the infrared sky for 18-20 months following its launch in 1995. Japanese astronomers have been considering a small mission for around the year 2000. At the beginning of the 21st Century NASA will launch SIRTF, aiming to extend the waveband further into the submillimetre range (0.1 to 1 millimetre) where the farthest infrared merges with the shortest radio waves. Like ISO, SIRTF will be cooled by liquid helium.

Looking ahead to 2005, ESA plans to launch a spacecraft called FIRST, which stands for Far Infrared and Submillimetre Space Telescope. As the last cornerstone mission of ESA's Horizon 2000 programme, this will be a culmination of two trends in space astronomy. One opens up the submillimetre band with advanced optical-like and radio-like techniques, allowing spectroscopic analyses of these wavelengths. The other trend is a preference for cooling systems that do not rely on expendable helium, which curtails a mission's operational life. FIRST should be good for more than six years.

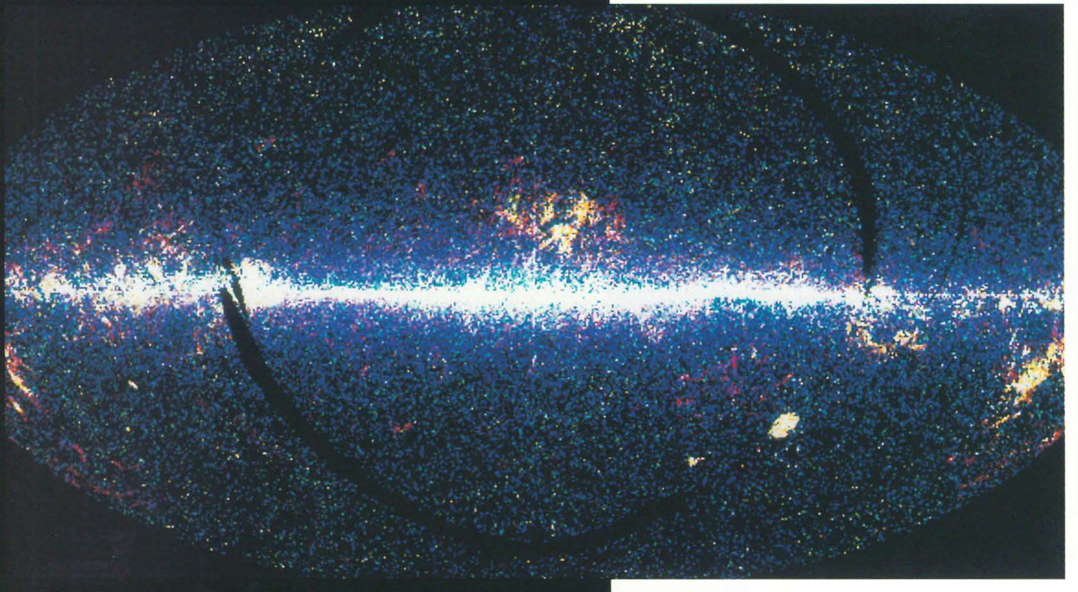
The submillimetre band has special claims to the attention of astronomers. Many important molecules, water for example, have characteristic emissions at these wavelengths. Cool dust clouds in the Universe, including those where stars are forming, radiate most strongly in the same waveband. And in the farthest reaches of the observable cosmos, shorter-wavelength emissions from galaxies and the precursors of galaxies are shifted to submillimetre wavelengths by the expansion of the Universe.

Ground-based British-Dutch and American submillimetre telescopes operate high in the dry air of Mauna Kea in Hawaii. Their view is limited to windows at certain wavelengths not absorbed by the atmosphere. Instruments carried in high-flying balloons and aircraft see many more submillimetre wavelengths arriving from the cosmos, and NASA is planning to fly a 2.5-metre infrared and submillimetre telescope routinely in a jumbo jet. It also has a small satellite, SWAS, dedicated to examining submillimetre emissions from clouds rich in molecules. Sweden is developing a submillimetre space telescope called Odin. With its 3-metre telescope operating in space, FIRST will out-perform all these missions.

As for the cooling techniques, a temperature of about minus 110 degrees C can be achieved by designing and operating the telescope so that it loses more heat to space than it acquires from the Sun and the Earth. This passive cooling can then be supplemented by other methods. A British infrared instrument in ESA's Earth observation satellite ERS-1 (1991) used a mechanical cooler to achieve a temperature of about minus 190 degrees C. The system, called a Stirling cooler, has since been developed under ESA contracts to chill equipment by stages to minus 269 degrees C, or 4 degrees above absolute zero.

Present concepts for FIRST envisage the use of more than eight Stirling coolers. Other cryogenic systems will then take the key parts of the instruments down to even lower temperatures. Astronomers hope that the cooling techniques evolved for FIRST can eventually be applied in other long-lived space telescopes, for the main infrared waveband.

An infrared interferometer may be a candidate, as in one of the options now under consideration for Horizon 2000 Plus. Two or more telescopes operating together could achieve much sharper images of infrared objects than any available so far.



Infrared targets. Point sources detected by the US-Dutch-British IRAS satellite (1983) are concentrated in the disk of the Milky Way Galaxy. This corresponds with the visible Milky Way, a small part of which is shown in the lower illustration. IRAS surveyed the whole sky. ESA's ISO satellite will examine selected objects in more detail and with a sensitivity a hundred to a thousand times higher.
Image: Infrared: IRAS data processed at NASA/IPAC; visible: European Southern Observatory

Radio waves and the microwave background

The Earth's atmosphere is beautifully transparent to radio waves from 1 centimetre to 10 metres in wavelength. Even clouds and daylight do not interrupt the work of radio astronomers. As a result they have usually found themselves at the back of the queue for space missions. Early spacecraft for long-wavelength radio astronomy, flown by NASA in 1963 and 1973, gave some preliminary results.

Since then, the chief interest has been in operating radio telescopes in space jointly with instruments on the ground. In principle this offers simultaneous observations with widely separated telescopes, from which one can infer fine details in the heart of a radio galaxy. The Russians and the Japanese are pursuing missions of this kind, with cooperation from European radio astronomers. A recent study contemplated a possible European-Russian-US project to fly a 25-metre radio dish working at millimetre wavelengths, but ESA has not made any commitment to conventional radio astronomy in space.

The cosmic microwave background may be more enticing. At wavelengths just a little longer than the submillimetre band of FIRST, the sky is filled with radio emissions peaking at 1.9 millimetres (160 gigahertz). These microwaves come from the edge of a very distant fogbank, beyond the farthest galaxies. According to the prevalent theory, the Universe began as a compact hot mass, in a Big Bang. As the Universe swelled, it cooled and the radiation now observed as microwaves supposedly broke free when charged particles were able to combine to make the first atoms. During the 1980s, astronomers were anxious to find relatively dense lumps in the fogbank, representing concentrations of gas available for gravity to gather into galaxies and stars.

The Soviet Prognoz-9 satellite (1983) carried a radio telescope operating at 8 millimetres. It looked for variations in the microwave background, but failed to evidence any. The theorists were quite worried. Then, in 1992, NASA's COBE satellite found a roughness in the background, by statistical methods. It did not, though, pinpoint any lumps reliably. That was first achieved by British and Spanish ground-based radio astronomers in 1994.

ESA has considered a super-COBE, under the title COBRAS/SAMBA. The spacecraft's waveband would straddle the peak of the microwave background. Relatively strong emissions from the Milky Way and other sources in the same waveband hinder the search for the primordial microwave lumps. Detailed study of these foreground features would enable scientists to subtract their effects with more assurance, and obtain a cleaner picture of the cosmic microwave background and its variations.

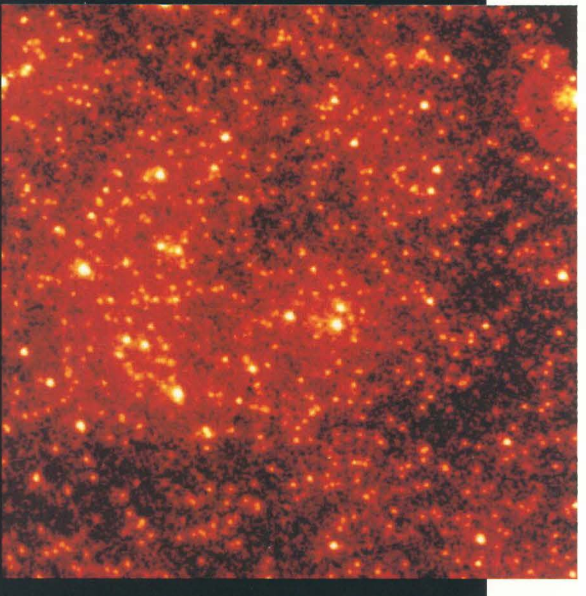
Other messengers

The light-like electromagnetic radiation of Maxwell's rainbow is not the only means by which the Universe delivers messages concerning its composition and behaviour. Energetic subatomic particles, supposedly originating from distant exploding stars, arrive as cosmic rays. Samples of the gas and dust that occupy the space between the Sun and the nearest stars blow into the Solar System on an interstellar breeze.

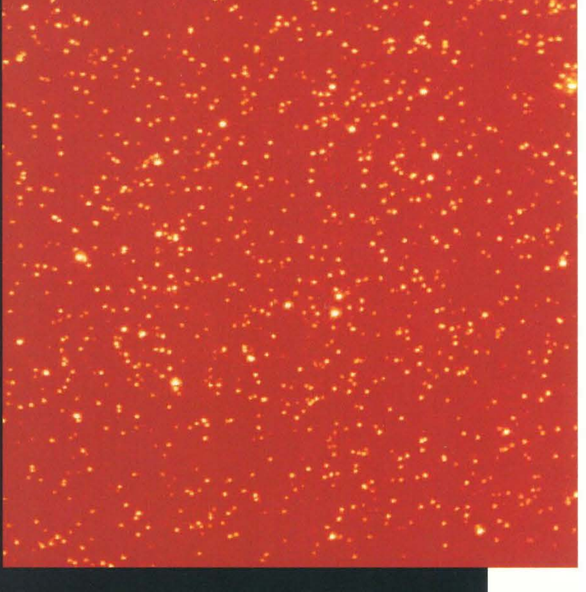
ESA's solar spacecraft Ulysses carries detectors for cosmic rays, neutral gas and dust. As the spacecraft flies over the poles of the Sun, it is sending back new information both about the nature of these interstellar messengers, and about the ways in which the Sun and the solar wind affect them. As a result of the Ulysses mission, astronomers will be better able to infer the pristine composition of the cosmic rays and the interstellar medium, before their encounters with the Solar System modify them.

Another kind of radiation permeates the Universe, so theorists believe, although observers have not so far managed to detect it directly. Accelerated masses should emit gravitational waves, causing ripples in space itself. The trouble for would-be observers on the Earth is that their instruments could detect only high-frequency waves coming from rare, cataclysmic events such as an exploding star.

Improving vision. ESA's Faint Object Camera in the Hubble Space Telescope here penetrates into the middle of a globular cluster of stars. It reveals many individual objects, where ground-based telescopes see only a blur. But the Hubble telescope was at first defective and it smeared the light, noticeably around the brighter objects. The lower image shows the improvement since the COSTAR system corrected the optics.



Pre COSTAR



Post COSTAR

Faint Object Camera team, ESA and NASA

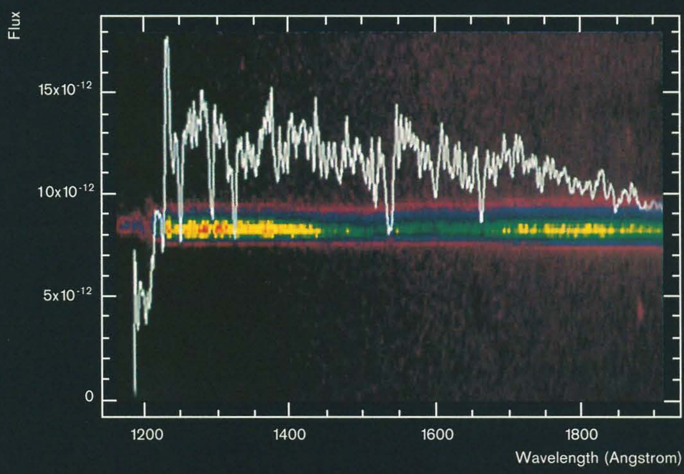
Europe's scientists hope to create a gravitational-wave detector in space during the second decade of the 21st Century, as part of ESA's Horizon 2000 Plus programme. In a concept now under study, laser beams would measure the distances between spacecraft millions of kilometres apart, with very high precision. This technique should be able to detect small distortions of space by gravitational waves of low frequency coming from commonplace sources such as nearby pairs of stars. Close interactions between very dense collapsed stars should be another important source of detectable signals. And while the microwave background marks the farthest and oldest events accessible by electromagnetic waves, a gravitational-wave background may reveal an even earlier stage in the history of the Universe.

IUE: old master of the ultraviolet

When the International Ultraviolet Explorer went into orbit around the Earth in January 1978, Jimmy Carter was US President, Leonid Brezhnev presided in Moscow, and Abba ruled the pop charts. IUE was meant to last for three years. After seventeen years in space it refuses to die and so spare the partners an embarrassing decision to switch it off. The mission is a three-way partnership of NASA, ESA and the British government. IUE came about through the persistence of Robert Wilson, an astrophysicist of London. Astronomers still wait in line to use an instrument that has worked non-stop since its launch.

IUE

Diagnosis of an exploding star. In 1993 a supernova event occurred in the relatively near galaxy M81, in the constellation of Ursa Major, and just 24 hours after its discovery the IUE spacecraft made a spectrum of its ultraviolet light (central band). Converting it into a graph of energy (in white), astronomers judged from the overall shape of the spectrum that gas around the exploding star was radiating at a temperature of 22,500 degrees. The tall spike at the left-hand end came from nitrogen atoms heated to about 1 billion degrees by a shock wave from the supernova.



They operate it from observatory centres at NASA Goddard near Washington DC, and at ESA's satellite-tracking station at Villafranca del Castillo near Madrid. IUE makes, on average, one one-hour observation every 90 minutes, around the clock. It intercepts ultraviolet light that cannot reach telescopes on the ground, and everything from nearby comets to distant quasars comes under IUE's analytical gaze. Here is one of the biggest successes in space science so far. Comparing IUE with the Hubble Space Telescope, the American astrophysicist Freeman J. Dyson spoke of "a little half-metre mirror sitting in the sky, unnoticed by the public, pouring out [results] while its big sister was still struggling to be born."

Instead of producing pictures of a planet or galaxy, IUE spreads its ultraviolet rays into a spectrum and so reveals which wavelengths are strong and which are weak. The resulting graphs can look cryptic to non-experts. Is that why IUE's extraordinary achievements are not as well known as they should be outside the astronomical community?

Having given astronomers five times the length of service they expected, the old master of the ultraviolet sky is showing its age. A loose piece of tape dangles in the telescope tube, and would send stray solar radiation into the sensors if the observing schedules did not keep the telescope turned well away from the Sun.

Targets are now acquired blindly by knowledge of their positions and by careful pointing of the telescope. This improvization works well, with the loss of only a few minutes' observation time per hour. Despite the failure of four out of six gyros, the pointing and slew control are still very precise. The back-up cameras are faulty, but the primary cameras remain fully operational. There is thruster fuel enough for another fifteen years.

Data on IUE

Purpose
ultraviolet spectra of cosmic objects

Wavelength range
115 to 320 nanometres

Telescope aperture
0.45 metres

Responsible agencies
NASA, ESA and PPARC (UK, formerly SERC)

Name
from International Ultraviolet Explorer

Mass
0.7 tonnes

Length
4.2 metres

Launched
26 January 1978

Launch vehicle
Delta (NASA)

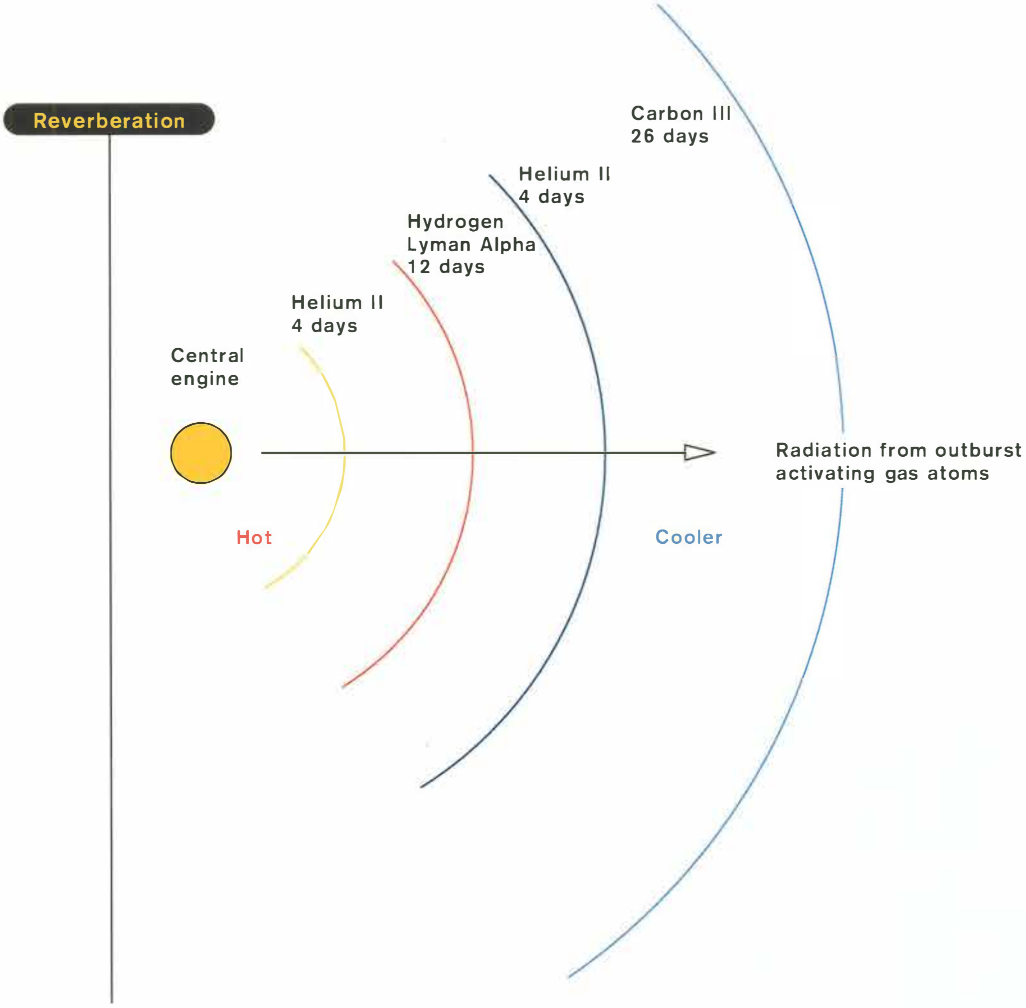
Orbit
26,000-45,000 km above Earth; inclined at 28 deg. to Equator, period 23 h 56 m

Operations
24 hr per day (16 hr NASA, 8 hr ESA)

Lifetime
17 years (by 26 January 1995)

Power
solar cells

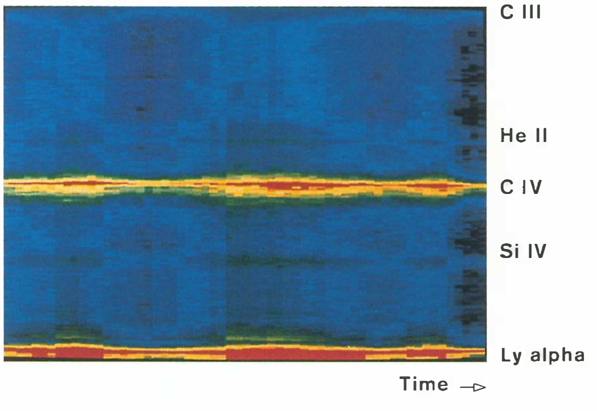
What happens in the heart of a stormy galaxy?



IUE still produces results at the very frontier of astronomical discovery. A current campaign to examine active galaxies is proof of that. Explosions and other disorders rack many of the vast assemblies of stars that populate distant space.
Astronomers have long puzzled over the wide variety of stormy behaviour that they see in galaxies, and which they suspect traces back to the actions of giant black holes consuming gas from their surroundings.
Evidently an eruption in the vicinity of the giant black hole (called more noncommittally the "central engine") reverberates through the surrounding gas, activating it at increasing distances. As shown in the diagram, carbon III for example perks up 26 days after the onset of a disturbance. Radiation from the central engine has reached a relatively cool region of gas, at a distance of 26 light-days. Although equivalent to 700 billion kilometres, this is still very close to the centre, on the scale of the galaxy.

In the accompanying illustration, the ultraviolet light from a variable galaxy, NGC 5548, is spread upwards in a spectrum, with longer wavelengths towards the top. Colours denote the intensity at each wavelength. As time passes, from left to right, the spectrum changes. In this experiment, IUE observed NGC 5548 every four days for eight months. Astronomers decode the cryptic-looking patterns to build up a picture of the stormy heart of the galaxy. First they label recognizable emissions from certain chemical elements, which also correspond to various temperatures prevailing in the gas of the galaxy. Then they see that time delays of days or weeks occur between a brightening of the background spectrum and intensifications of the labelled elements.

IUE Campaign: NGC 5548 Variability



The intensive study of NGC 5548 marked the start of a IUE campaign on active galaxies involving fifty-seven astronomers from eleven countries. Other active galaxies show similar reverberations. The timescales and the sizes of the emitting regions can vary widely, but the energy sources seem to be similar in active galaxies of very different kinds.

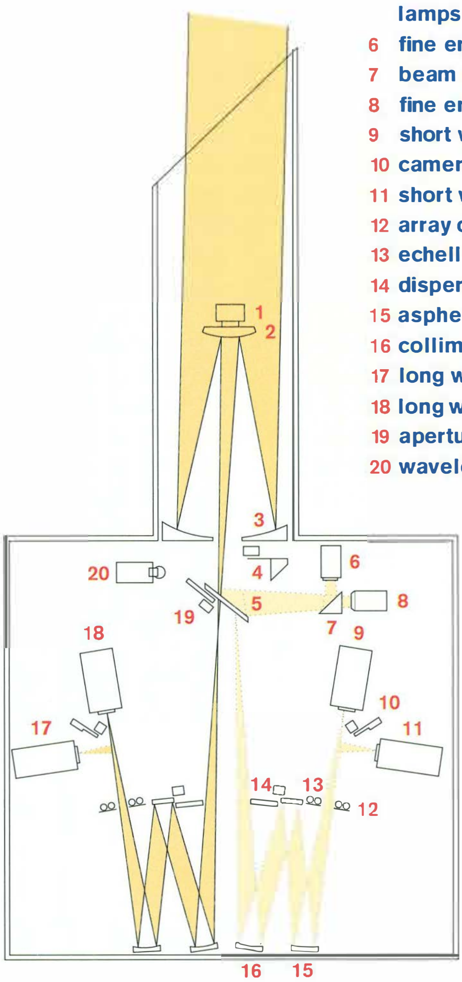
"This extended series of observations in the ultraviolet has meant nearly monopolizing the IUE," notes Danielle Alloin of Paris-Meudon. "But it has enabled us to study the central engines of active galaxies directly. So now we can test the theories of active galactic nuclei, by seeing cause-and-effect relations between the central engine and its surroundings."

Hands-on operations. An astronomer using IUE sits at a console at ESA's ground station near Madrid, and monitors the spacecraft's observations as they come in. He or she may then request adjustments to the observing programme, to get the best results.

The joy of ultraviolet spectroscopy

IUE optics

1 focus mechanism
2 secondary mirror
3 primary mirror
4 sun shutter with 45° mirror on rear
5 aperture plate with embedded fiducial lamps
6 fine error sensor No. 2
7 beam splitter
8 fine error sensor No. 1
9 short wavelength prime camera
10 camera select mechanism
11 short wavelength redundant camera
12 array of 8 tungsten UV floodlamps
13 echelle grating
14 dispersion mode select mechanism
15 aspherical grating
16 collimator mirror
17 long wavelength redundant camera
18 long wavelength prime camera
19 aperture select mechanism
20 wavelength calibration lamp



Astrophysics became an exact science in 1859, when Gustav Robert Kirchoff of Heidelberg explained the lines in sunlight. Whenever the visible light of the Sun was spread into a spectrum of colours, dark lines appeared at sharply defined wavelengths. Kirchoff realised that they were signatures of chemical elements present in the solar atmosphere.

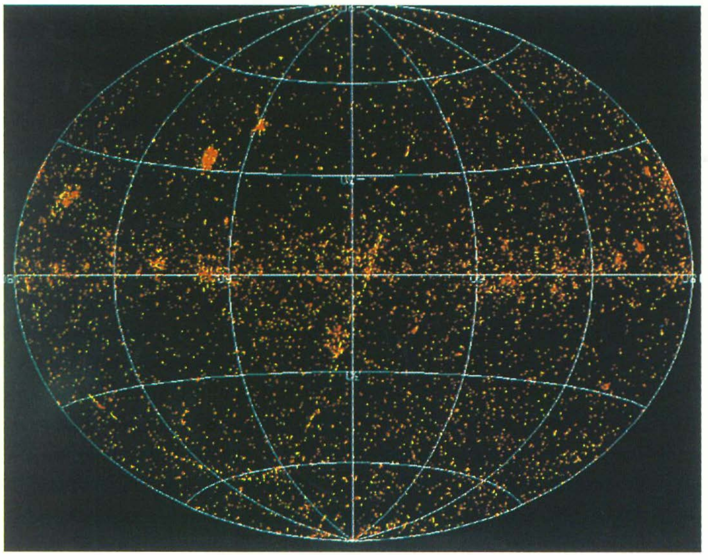
Other stars had compositions different from the Sun's, and astronomers learnt how to measure motions, temperatures and magnetism in distant objects, by subtle effects on the spectral lines. As a result spectroscopy, the science of analysing spectra, has largely superseded imaging at the modern frontiers of astronomy.

Ultraviolet spectroscopy, which is IUE's business, can be attempted only above the Earth's atmosphere, but it brings special benefits. The plainest signatures of the common elements of the Universe lie in the ultraviolet band. For example, hydrogen atoms signal their presence most vehemently by giving off, or absorbing, ultraviolet rays at a wavelength of 121.6 nanometres, called the Lyman alpha line. And the peaks of radiant energy of stars and other objects hotter than the surface of the Sun fall in the ultraviolet. IUE confirmed a discovery by its predecessor, NASA's Copernicus, that even small cool stars have hot, ultraviolet-emitting atmospheres.

NASA controls IUE for sixteen hours each day, and ESA for eight hours. The demand is such that for every astronomer who has the chance to use IUE, two or three disappointed people are turned away. Astronomers of any nationality can apply and two committees of their peers, for NASA and for ESA/UK, allot observing time on IUE on the basis of scientific merit.

A typical allocation is six eight-hour shifts. A successful applicant becomes a guest observer, the same term that the great mountain-top observatories use for their visitors. Sitting at the console at ESA's Villafranca ground station, alongside the telescope operator, the astronomer could just as well be out in a spaceship communing with the stars, without the hindrance of the atmosphere.

Filling up the sky. The locations of stars and other cosmic objects observed by IUE during its first fourteen years of operations show an impressive coverage. The red dots correspond with observations at long ultraviolet wavelengths, and the yellow dots with shorter wavelengths. The concentration of observed objects across the middle of this all-sky chart corresponds with the Milky Way's path around the sky.



The astronomer oversees the telescope's operations, and sees the results coming in. While sticking to the list of targets approved in advance by the IUE team, the astronomer can vary the length of exposure or the portion of the spectrum to be examined. IUE is the only astronomical satellite currently working in this congenial, interactive mode.
After staring fixedly at its target for the appointed time, to absorb sufficient ultraviolet energy, IUE transmits its results to the ground station. A spectrum unfolds, as a direct rainbow-like display or as computer-drawn plots showing the intensity at each wavelength. The distant star or galaxy is then talking to the expert. Its spectrum is saying: "Here I am," it says, "this is how hot I am and here's how fast I'm moving. These are some of my atomic ingredients. And here's a peculiarity to make you scratch your head."
Observers own their results for six months while they work out the scientific meaning. After that, the data go into the IUE Archives, held by each of the three partners. There they become available to anyone, in a magnificent stockpile of knowledge about the ultraviolet Universe. By 1994, the count of individual observations had passed the 90,000 mark.

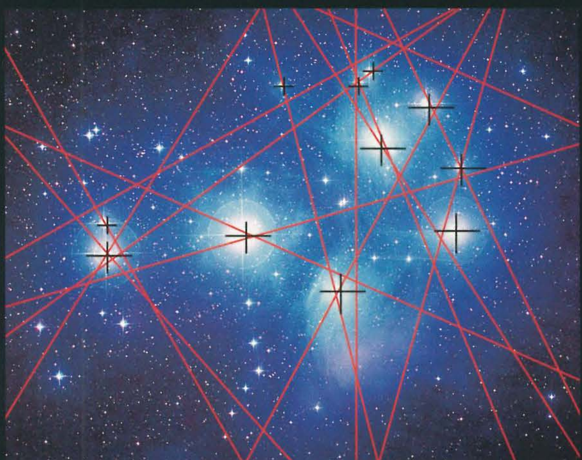
An eventful career

The ceaseless demand for observing time on IUE does not prevent the mission scientists from planning special campaigns of observations, or reacting to events in the sky. The return of Halley's Comet was long expected, and IUE first examined the comet in September 1985. It immediately saw the ultraviolet signature of decomposed water. Thereafter a joint US-European programme made regular observations until July 1986. The headline result from IUE was that Halley lost 300 million tonnes of water by evaporation of ice during its 1986 visit to the Sun.
Early in 1987 a star was seen to blow up in a nearby galaxy, the Large Magellanic Cloud. It was the closest supernova event ever observed by modern astronomers, and IUE's was the first telescope to be turned on the spot after those of the discoverers in Chile and New Zealand. Within 24 hours all suitable telescopes in the Southern Hemisphere and in space were looking at Supernova 1987A, as the event was tagged.
Before-and-after comparisons of IUE data revealed exactly which star had blown up. It was a hot blue star that had previously shone brightly in the ultraviolet, so confounding a belief of many astronomers that the kind of explosion observed would occur in a cool red giant star. IUE also detected chemical elements flung into space by the explosion, and a delayed light echo from an old ring of dust surrounding the star. Later observations of the dust ring by the Hubble Space Telescope enabled astronomers to compute the distance of Supernova 1987A, at 169,000 light-years.
During another astronomical drama, seven years later, IUE made 180 observations of Jupiter in the week in July 1994 when pieces of Comet Shoemaker-Levy 9 crashed into the planet. In anticipation of the event, IUE carefully studied Jupiter in its normal state. Changes in the spectra, when the impacts came, enabled astronomers to identity atoms and molecules stirred up and activated by the force and heat of the explosions.

IUE has been effective in other joint observations with telescopes in space and on the ground. In recent years IUE collaborated with X-ray satellites, the Japanese Ginga and the German-US-UK Rosat, in simultaneous observations of many objects at ultraviolet and X-ray wavelengths. Two campaigns concerned ordinary "cool" stars and active galaxies.
"We've given the theorists a hard time," says Willem Wamsteker, ESA's project scientist for IUE. "Their nice stories explained observations by ultraviolet *or* X-rays, but did not work for ultraviolet *and* X-rays, so they'll have to think again. That's how astrophysics progresses."

Hipparcos: the shape of the sky

Operations with the European Space Agency's Hipparcos satellite ended in August 1993, but the mission continues at full tilt in number-crunching computers across Europe. It tackles the most rudimentary yet the trickiest question in astronomy: in what directions do the various stars lie? A million million bits of information from Hipparcos promise an answer, and the largest computations in the history of astronomy are busily knitting them together. Only when every last stitch and tension is right shall we know the exact shape of the sky.



Pinpointing the Pleiades. Hipparcos scanned this famous open star cluster hundreds of times to measure the motions of its stars as they drift apart from a shared origin. Astronomers will be able to compute more precisely the age of the Pleiades and the cluster's direction and speed of motion relative to the centre of the Milky Way Galaxy. Pleiades image copyright: Royal Observatory, Edinburgh, and Anglo Australian Telescope Board

HIPPARCOS

Astronomers define the sky's shape as an imaginary celestial sphere, with the direction to a star given by angles like the geographers' longitude and latitude. But stars move, and the Earth is a moving, whirling and wobbling platform. Its air makes star images shiver and shift, and its gravity causes telescopes to droop slightly. No observatory on the ground can see the whole sky, and combined surveys are never seamless. Accumulated errors and uncertainties are like humps and hollows in the celestial sphere.

When experts compiled an input catalogue of 120,000 target stars for Hipparcos before it flew, they found that astronomers knew the directions of the stars to about one seven-thousandth of a degree. Hipparcos does better than a millionth of a degree. Now the computing teams seek a "sphere solution" in which all directions are consistent to a very high accuracy.

Although Hipparcos was a medium-size satellite, with just a dinky telescope seeing ordinary visible light, the mission is the most imaginative in the short history of space astronomy. And in the long history of stargazing it ranks with the surveys by Hipparchus the Greek in the 2nd Century BC and by Tycho the Dane in the 16th Century AD, both of which transformed human perceptions of the Universe. Other space missions add important chapters to the tomes of advanced astrophysics. Hipparcos makes the elementary textbooks out of date.

The mission was initially a French conception. In 1966, Pierre Lacroute of Strasbourg pointed out that a satellite could triangulate its way all around the sky, in much the same way as land surveyors use triangulation between hill-tops to measure distances accurately. A squint-eyed telescope in the satellite would look at stars in two directions at once and measure the angles between them.

The proposal aroused little interest at first. Astrophysicists hunting a black hole left star-finding to the technicians. Even the astrometrists who made a science of it felt a little démodés in the 1960s. Advances in astrometry nevertheless prepared the way for Hipparcos. Electronic photon counters went into the special star-logging telescopes called meridian circles. Other innovations included photographic sky-surveys and digital computers.

Colleagues wondered if Lacroute's idea was ambitious enough. He wanted a survey by satellite of a network of just 700 stars. By the efforts of other French astrometrists the project became a candidate mission for ESA in the mid-1970s. The multinational agency encouraged bolder thinking and a cross-fertilization of ideas. Scandinavian scientists made valuable suggestions about how to enlarge the scope of the mission.

What began as a basic exercise in cosmic geometry evolved into a comprehensive survey of the local region of the Milky Way Galaxy. With enthusiastic support from astrometrists across Europe, Hipparcos won the selection contest against more glamorous-seeming astrophysics missions.

Data on Hipparcos

Purpose
to pinpoint stars and measure their distances and motions

Wavelengths
375-750 nanometres

Telescope diameter
0.29 metre

Responsible agency
ESA

Name
an unusual spelling of Hipparchus, the Greek astrometrist (190-120 BC). Alternatively an acronym for High Precision Parallax Collecting Satellite

Prime contractor
Matra Marconi Space, France, with Aeritalia, Italy

Mass
1.14 tonnes

Launched
8 August 1989

Launch vehicle
Ariane 4

Orbit
560 - 35,900 km, inclination 6.8 degrees, period 10 hr 40 min

Spin rate
one revolution in 128 min

Ground stations
Odenwald, NASA Goldstone, ESA Perth, CNES Kourou

Observations terminated
24 June 1993

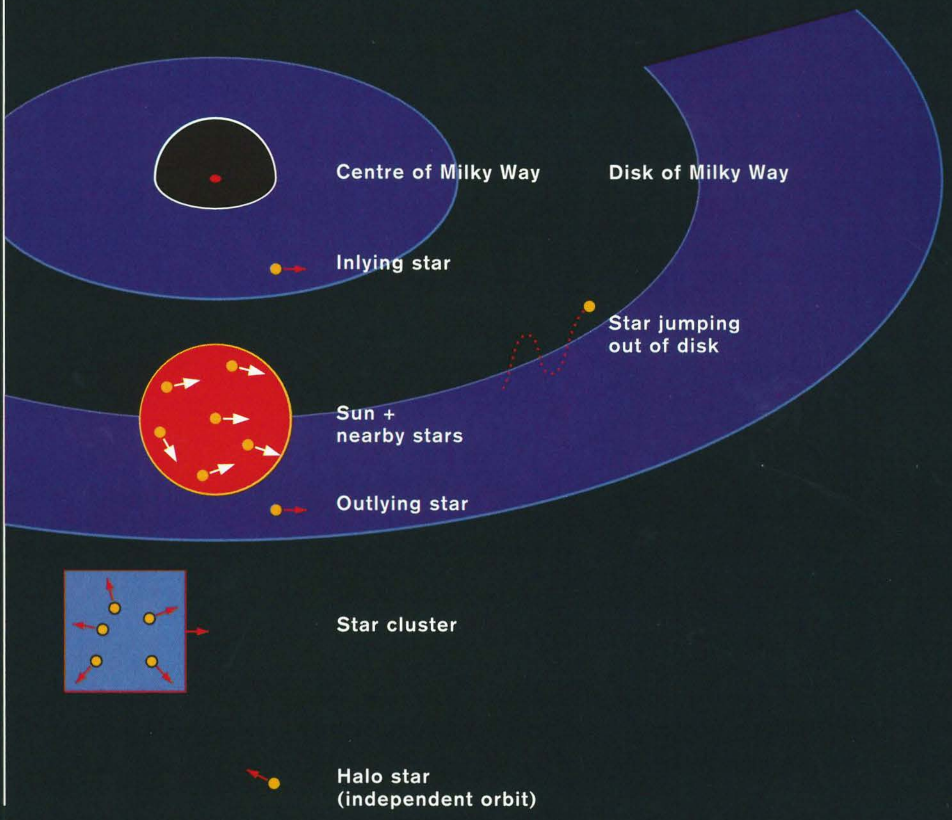
How do the stars move?

"When our final results are published, some very interesting new insights into the nature of our Galaxy, its structure and its evolution will emerge," says Michael Perryman, ESA's project scientist for Hipparcos.

Everything we know about our place in the Milky Way Galaxy comes from observations of the stars around us. Some of the brightest are humble objects that happen to be relatively close. Others are massive stars at greater distances. Most of them are companions of the Sun in a great orbital march around the centre of the Galaxy.

It is not an orderly throng. Some stars are sidling nearer to the Sun, and others are hurrying away. Motions towards us or away are easy to measure, by blueshifts or redshifts in recognizable spectral lines. Before Hipparcos, sideways motions were much harder to gauge.

Stellar motions



As Hipparcos has now assessed nearly every star within 250 light-years, it will give a vivid picture of our stellar surroundings. Experts will look to see whether any stars seem set to pass close to the Sun. If a nearby star possesses heavy planets, Hipparcos may detect a slight wobble in the star's motion as the planets revolve around it.

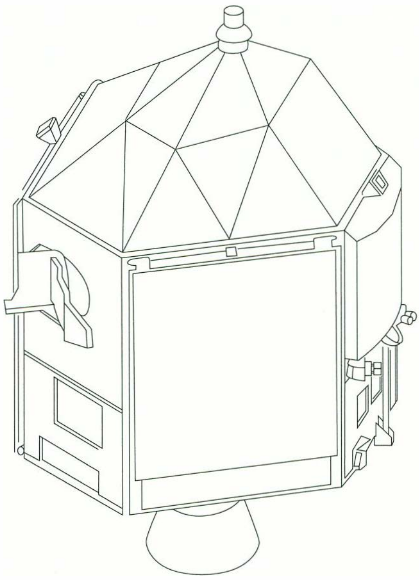
Stars are born in clusters and retain a memory of their common origin in a shared motion through the Galaxy. Perhaps siblings of the Sun will be discovered. The Hipparcos results will certainly show, for example, what other stars share an ancestry with bright stars of the Ursa Major constellation that belong to a dispersing group.

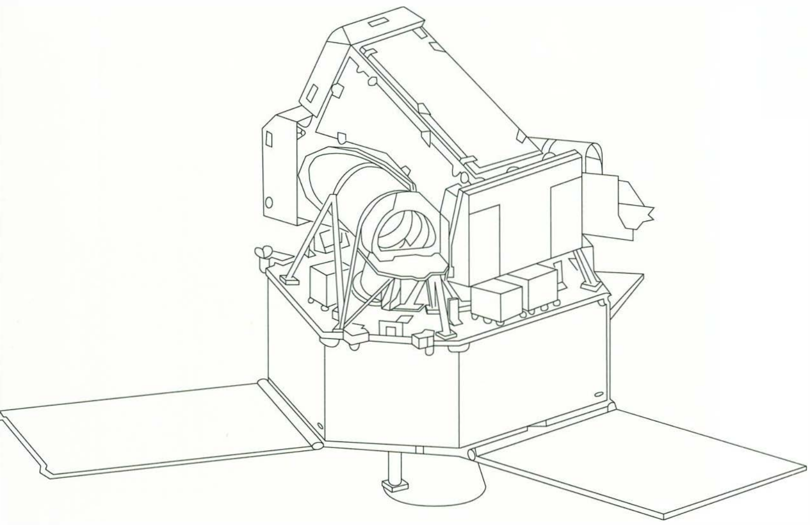
Hipparcos has also checked out many hot, bright blue stars in a ring around the sky called Gould's Belt. They may be the product of a ring of gas pushed out, in snowplough fashion, from a cluster of massive stars that exploded in rapid succession.

In open clusters like the Pleiades, related stars have stayed quite close together. From the motions of stars in dozens of open clusters, Hipparcos will establish their ages and their course and speed through the Galaxy. As open clusters range in age from millions to billions of years, they will show whether motions in the Milky Way have changed.

Looking towards the Galactic centre, and away from it, Hipparcos has logged the relative speeds of stars in their orbits at different distances. It has also looked up and down at stars making temporary excursions outside the flat disk of the Milky Way, and at halo stars on orbits that keep them independent of the disk.

These are some of the ways in which Hipparcos will sharpen our picture of the Galaxy where we live.





Inside Hipparcos. The appearance of the satellite at launch is shown in the upper diagram, and the arrangement of the telescope and its instruments in the lower diagram. Eleven European countries contributed to the construction of Hipparcos, with Matra in France overseeing the work and developing the instrumentation, and Aeritalia in Italy integrating and testing the spacecraft.

The wrong orbit

The Ariane 4 launcher performed perfectly on 8 August 1989, when it carried Hipparcos into its initial transfer orbit. The European Space Operations Centre at Darmstadt, Germany, then commanded the spacecraft to fire the onboard rocket motor that would lift Hipparcos to a circular, 24-hour, geostationary orbit. This would keep it in place over the same part of the rotating Earth, in the manner of the Meteosat weather satellites.

The onboard motor failed to fire. ESOC was then on its mettle to save the mission, first by stopping Hipparcos dipping repeatedly to within 200 kilometres of the Earth, where the thin air would soon burn it up.

The spacecraft's hydrazine thrusters lifted the low point to a safer 500 kilometres. The high point was 36,000 kilometres out, and each orbit took 10.7 hours to complete.

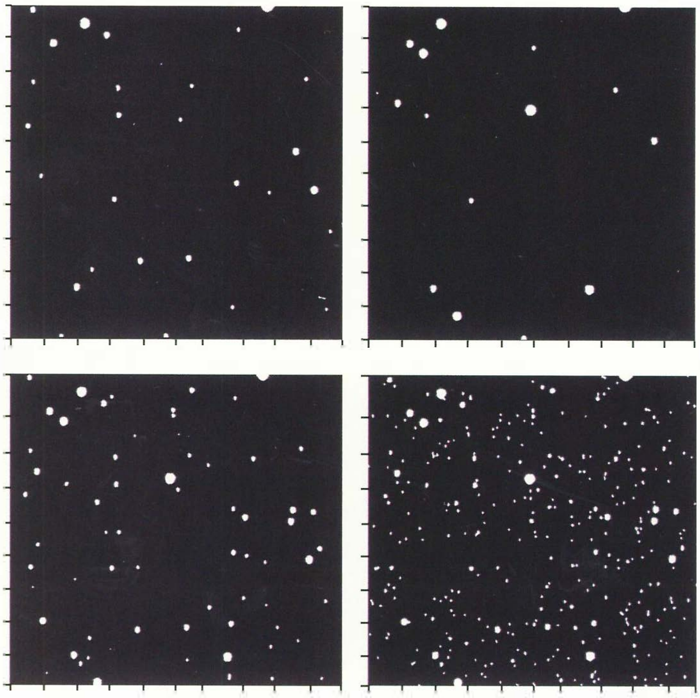
A single ground station at Odenwald in Germany had been assigned to communicate with Hipparcos full time, but now it could see it only for seven hours a day. Recruiting ESA's ground station at Perth in Australia and NASA's at Goldstone in California doubled the useful operating time. For other astronomical satellites, the wrong orbit could have caused headaches for the observing programmes. Because Hipparcos was designed to take a whole-sky view, it could contentedly make its measurements in any sequence, from any vantage point, at any time.

Energetic protons in the Earth's radiation belt, through which the satellite ploughed twice in every orbit, gradually degraded the arrays of solar cells that powered Hipparcos. They brought an ever-present risk of catastrophic damage to some vital electronic system. With luck, the engineers thought, the spacecraft might work for three years.

It did better than that, but in June 1993 the mission controllers found that they could no longer communicate with the onboard computer. For nearly two months they tried to revive the brain-dead satellite, before the space operations were officially terminated in August.

Position references
Ground-based: 28 stars

Brightness references
Ground-based: 15 stars



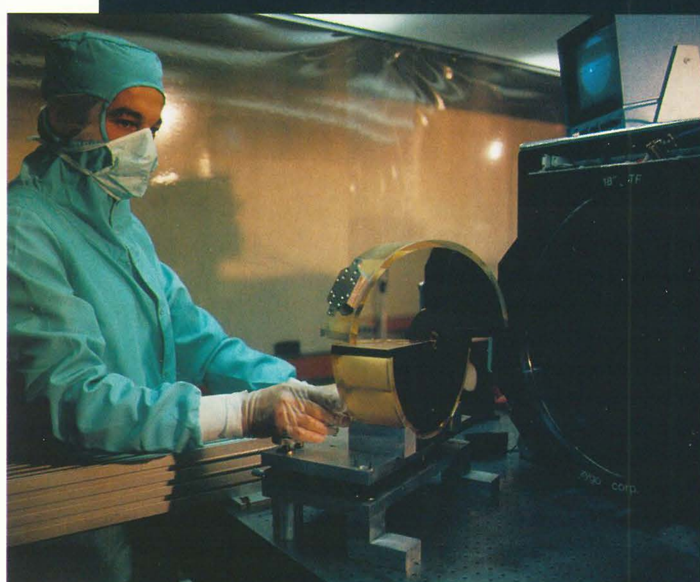
Hipparcos: 71 stars
Astrometry: ± 0.002 arcsec
Photometry: ± 0.003 mag

Tycho: 389 stars
Astrometry: ± 0.03 arcsec
Photometry: ± 0.03 mag (B and V)

Rich harvest. New catalogues multiply the number of positions (astrometry) and brightnesses (photometry) of stars usable as reference standards. These are from a 5-degree square in Ursa Major. Image: E. Høg (Copenhagen) and TDAC Consortium

Taking a broad view

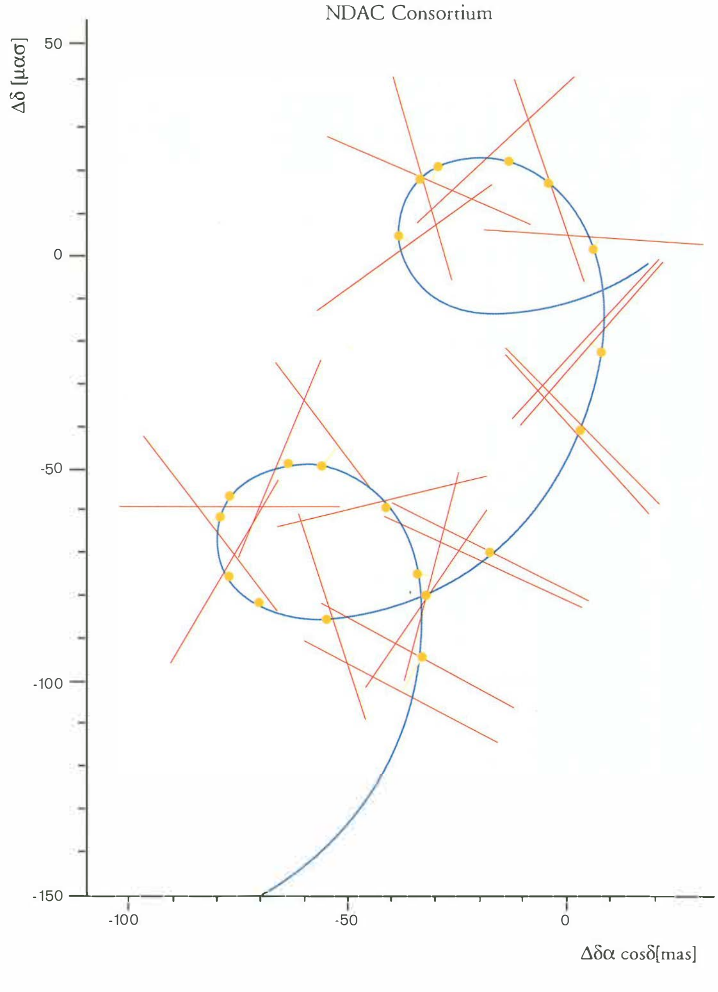
What had Hipparcos been doing? Rotating slowly, once in two hours, it scanned circles in the sky. As the seasons and years passed, the circles criss-crossed in every direction, like a ball of wool. Each target star showed up on one scanning circle or another about 300 times.
Two telescope tubes looked out in directions 58 degrees apart on the scanning circle.
To know why Hipparcos squinted, consider the parallax in the starry scene as the Earth orbits around the Sun. Nearby stars shift their positions compared with more distant stars. In Leo, for example, they appear to move eastwards in December and westwards in June. Astronomers use this parallax to measure a star's distance. But neighbours in the sky are a poor guide because they all make their various shifts in the same direction in the same season. Comparisons with stars in a quite different direction, say 60 degrees away, would be better. But an exact fraction of a whole circle (360 degrees) could cause mathematical mayhem, so the astronomers chose 58 degrees for Hipparcos.



At the heart of Hipparcos. The beam-combining mirror, which enabled the telescope to look at stars in two directions at once, is here seen undergoing optical tests. The mirror's surfaces were shaped to provide sharp images in conjunction with a spherical focusing mirror.

Open cluster. The stars are well spread in NGC 2516, making position-fixing relatively easy for Hipparcos.

Deducing the distance and speed of a star. An early example of Hipparcos data-processing shows observations of an inconspicuous star over a period of two years. Each defined a range of possible positions illustrated with a red line. A computer then figured out the track (blue) and true positions (yellow dots) most consistent with the data and the observation dates. The loops are due to Hipparcos's motion around the Sun in company with the Earth, which alters the vantage point and changes the apparent direction of the star. The width of the loops measures the star's distance, at 90 light-years. The distance travelled diagonally across the sky shows this star to be moving sideways at 10 kilometres per second, in relation to the Sun. The complete Hipparcos programme made hundreds of observations on each preselected star.
Credit:
L. Lindegren (Lund) and Hipparcos NDAC Consortium



Angled mirrors directed starlight into a 29-centimetre spherical mirror. The beam-combiner mirrors were shaped to operate jointly with the spherical mirror in delivering well-focused images from both telescope tubes to the field of view of an electronic detector, called an image dissector.
Each image represented about one degree of the sky, and contained at any moment three or four target stars. They drifted across the field of view as the satellite rotated. A fine grid in front of the detector acted like a vernier scale, fine-tuning a star's position as its light strobed through the slits of the grid. The image dissector sampled each star in turn, and signalled data for computing the relative positions of neighbouring stars. Comparisons between the two fields revealed with equal precision the separations of stars about 58 degrees apart. The brightness of each star was also measured.
While the main sensor was working through its list of 120,000 target stars, a second detector in the spacecraft was charting a million. This was a star mapper using a simpler system of grids to give a star's approximate position without elaborate computing. It enabled the satellite to measure its attitude in space. But when its data were processed on the ground, the star mapper generated a catalogue of its own, called Tycho. The positions are less precise than in the primary Hipparcos Catalogue, but still far better than in any ground-based listing.
"I'm a little embarrassed about it," says Erik Høg of Copenhagen, who conceived the Tycho operation as well as contributing to the core mission. "I was wondering how my astrometrist friends might use their meridian circles to help the Hipparcos project. That was when I realised that our little star mapper in space could put them out of business, as far as all the brightest stars are concerned."

The payoff

Data-processing began while Hipparcos was still operating. Two Europe-wide consortia work independently on the primary set of 120,000 stars for the Hipparcos Catalogue. They use different mathematical methods and aim at mutually checked results. Another consortium is preparing the Tycho Catalogue of a million stars. When they are finalized at the beginning of 1996 the astrometrists who have worked hard to produce the catalogues will have the first chance to cull discoveries from them.

A year later ESA will open the catalogues to all astronomers, as a celestial framework of exquisite precision from which mundane error has been eradicated. All astronomical positions, and all terrestrial measurements that rely on the stars, will thereafter be related to the sky of Hipparcos. For example, the Hubble Space Telescope will use the foreground stars to fix the positions of galaxies and quasars, so extending the influence of Hipparcos to the Universe at large.

Hipparcos has reportedly identified many thousands of previously unknown binary stars, where two stars orbit around each other, and tens of thousands of variable stars, which alter their output of light. And it has measured the distances of tens of thousands of stars accurately, for the first time, by pushing out the effective range for parallax from about 100 light-years to 1000 light-years. Astronomers rely on variable stars called Cepheids to discover the distances of galaxies.

So Hipparcos's measurements of variability and distance will underpin the use of Cepheids in estimating the scale and age of the Universe.

More generally, precise distances give precise luminosities for all kinds of stars. So theories of how stars burn, evolve and change colour will be tested far more rigorously. The survey includes X-ray stars, giant stars puffing clouds of gas, dying stars, and disorderly newborn stars. The distances and therefore the energy emissions of these objects have been a matter of guesswork until now.

On top of all this, motions of stars detected by Hipparcos animate the familiar stellar scenery. Each of the stars that looks so still in the night sky is engaged in a private odyssey through the Milky Way, which reflects its origins, and the architecture and dynamics of the Galaxy.

Jean Kovalevsky of Grasse, France, has been one of the driving forces throughout the conception and execution of the mission, and the subsequent data-processing.

He recalls: "Some people said Hipparcos was too difficult for Europe. Others thought it boring compared with more obvious astrophysical missions.

"Critics of the first kind are already put to shame. I can promise that the rest will be confounded too, when they see how our results impact on every branch of astrophysics from planetary science to cosmology."

Hipparcos data-processing consortia

INCA (Input Catalogue)

Leader
C. Turon, Meudon
Participating institutes in Belgium, Denmark, France, Germany, Netherlands, Spain, Switzerland, United Kingdom, USA

Main data-processing
OPM Meudon

FAST (Fundamental Astronomy by Space Techniques)
Hipparcos Catalogue

Leader
J. Kovalevsky, Grasse
Participating institutes in France, Germany, Italy, Netherlands, USA

Main data-processing
CERGA Grasse, CNES Toulouse, ARI Heidelberg, CSS Turin, SRON Utrecht, TU Delft

NDAC (Northern Data Analysis Consortium)
Hipparcos Catalogue

Leader
L. Lindegren, Lund
Participating institutes in United Kingdom, Denmark and Sweden

Main data-processing
RGO Cambridge, CUO Copenhagen, LO Lund

TDAC (Tycho Data Analysis Consortium)
Tycho Catalogue

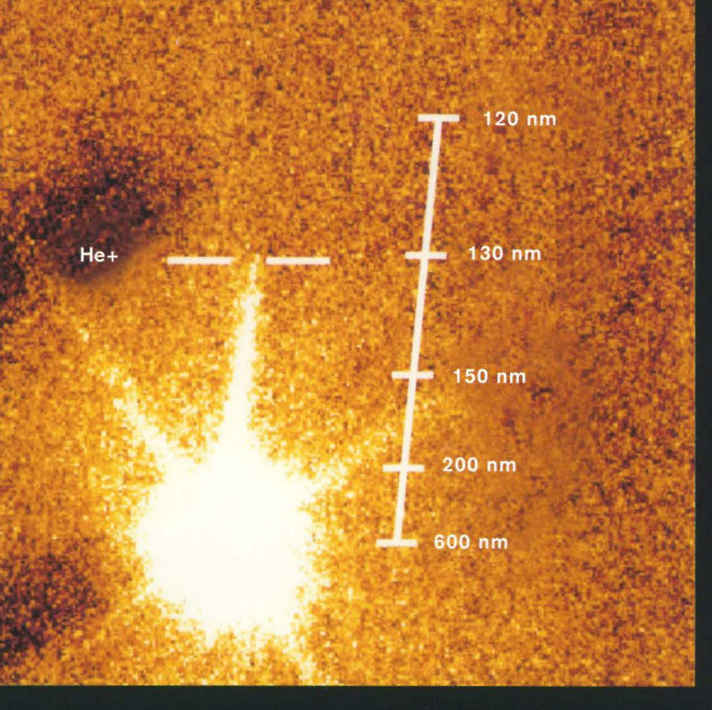
Leader
E. Høg, Copenhagen
Participating institutes in Denmark, France, Germany, Italy, Sweden, Switzerland, United Kingdom and USA

Main data-processing
CDS Strasbourg, AIT Tübingen, ARI Heidelberg, CUO Copenhagen

Hubble: the transparency of spacetime

Stars twinkle because the air is turbulent. The Universe is gloriously transparent to visible light, which paces out the history of spacetime in journeys of billions of years. In the last microseconds of its journey into telescope mirrors on the Earth, the light wobbles through our atmosphere and smudges the fine details of the cosmic scenery.
The Hubble Space Telescope was launched in April 1990, to evade this earthbound problem by putting a relatively large visible-light telescope beyond the atmosphere. It is also the biggest ultraviolet instrument ever flown in space, able to register wavelengths wholly blocked by the atmosphere.

HUBBLE



Primeval helium discovered. An ESA team used a prism in the Faint Object Camera in Hubble to spread the light of a distant quasar into a spectrum (near-vertical line). The abrupt blackout in the ultraviolet at 130 nanometres reveals the presence of ionized helium atoms in intergalactic space.

Had everything gone right for the Hubble Space Telescope, an account of its scientific work written several years after its launch might already read like a textbook of "astronomy in the Hubble era". But its 2.4-metre main mirror was wrongly shaped. The world held its breath as astronauts corrected Hubble's defective eyesight in December 1993.

Results since then are emerging at the cautious pace of formal scientific publication. So it is still timely to recall the forty-month struggle to make the most of a faulty telescope, and to note the role of Europe's astronomers during that phase.

The European Space Agency is NASA's partner for Hubble. With a nominal 15 percent stake in the mission, ESA provided the Faint Object Camera (one of the two imaging instruments), the solar panels that power the spacecraft, and a team of scientists and engineers at the Space Telescope Science Institute in Baltimore, Maryland.

In return, 15 percent of the telescope's use was promised to astronomers from ESA's member states. By 1993 the quality of the European astronomers' programmes had won them 20 percent of the observing time. The HST European Coordinating Facility at the European Southern Observatory in Garching, Germany, is manned by ESA and ESO staff to provide additional services for European astronomers. What follows is a brief account of Hubble's adventures from a European perspective.

Data on Hubble Space Telescope

Purpose
to see fine detail in the Universe by visible and ultraviolet light

Wavelength range
110-1000 nanometres

Responsible agencies
NASA (85%) and ESA (15%)

Name
from Edwin Hubble (US discoverer of expanding Universe c. 1930)

Mass
11.6 tonnes

Launch
April 1990

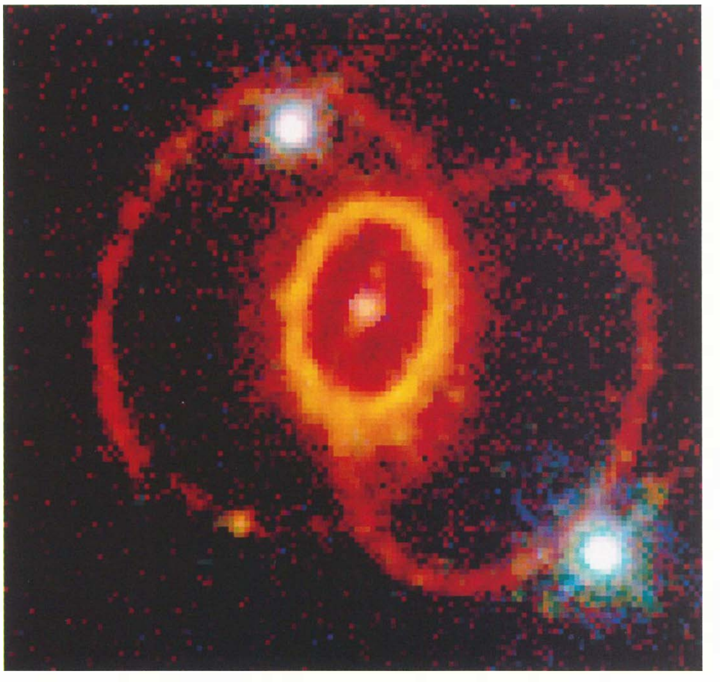
Launch vehicle
NASA Space Shuttle Discovery

Refurbishment
December 1993

Refurbishment vehicle
NASA Space Shuttle Endeavour

Intended lifetime
15 years

Power supply
solar panels



Rings around an exploded star. In 1994 the Hubble Space Telescope found this curious pattern like a dumbbell at the scene of a supernova event in the Large Magellanic Cloud, seven years earlier. The Wide Field/Planetary Camera 2 took the picture. The smaller ring is gas blown from the star. The larger rings may be painted on big gas bubbles by beams of radiation from a companion source.
Image: C. Burrows (ESA/STScI), NASA and ESA

Successes in hard times

An error in the grinding of Hubble's 2.4-metre main mirror went unnoticed until after the launch, when the telescope operators failed to focus any image sharply. In the grim summer of 1990 it seemed as though the pictures were no better than anyone else's. The space telescope had traded atmospheric smudging for a self-engendered spherical aberration, and many American astronomers were nonplussed.

Their European colleagues took up the challenge. With ESA's Faint Object Camera they demonstrated that underexposed images showed bright point sources looking much sharper. Leon Lucy of the European Southern Observatory at Garching knew a mathematical trick called deconvolution for processing the images and partly correcting the aberration. This method was steadily refined during the hard times before Hubble was put right. And results from Hubble even in its defective years inspired hundreds of scientific papers.

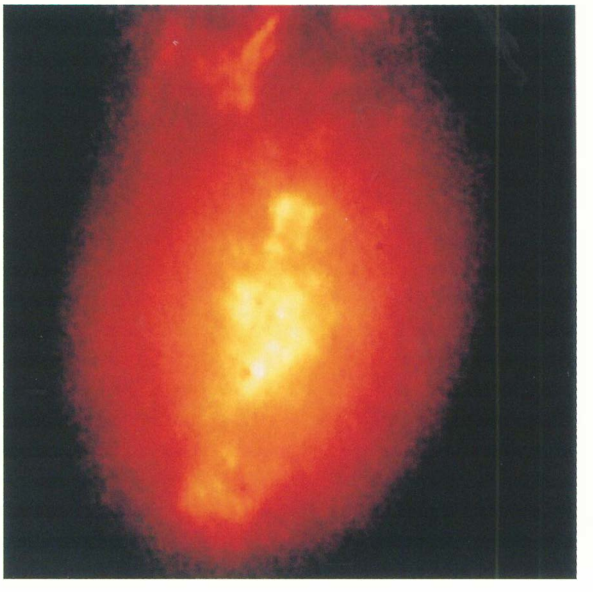
With NASA's Wide Field/Planetary Camera, astronomers at Leiden, in the Netherlands, discovered a large disk of dust surrounding a supposed giant black hole, and the curious linear shape of the most distant visible galaxy. Colleagues at Durham, UK, detected the most powerful gravitational lens ever seen, where Dark Matter in a cluster of galaxies produced enlarged images of a more distant galaxy.

ESA's Faint Object Camera made the first detection of auroras in the polar regions of Jupiter, and began chemical studies of Io, Jupiter's volcanic moon. Peering into congregations of stars too dense for ground-based telescopes to resolve, the instrument picked out stars rejuvenated by collisions in ancient globular clusters, and pinpointed the most massive star known, R136a1 in the Large Magellanic Cloud, 250 times heavier than the Sun.

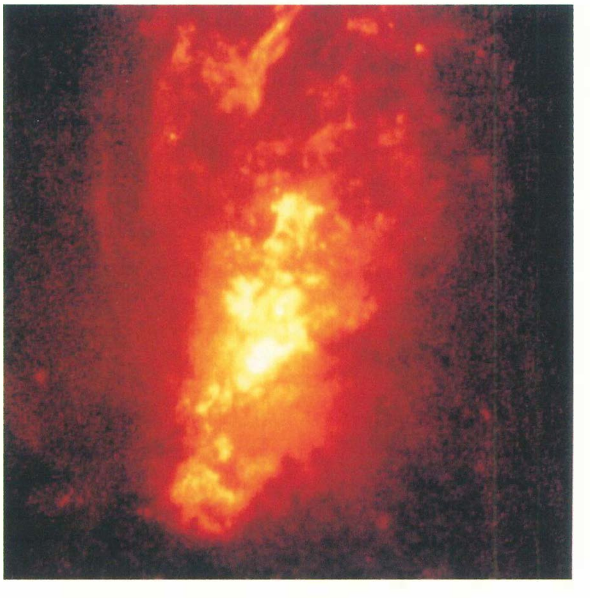
In that same nearby galaxy, the Faint Object Camera measured the growth of the expanding cloud of dust at the scene of a famous exploding star, Supernova 1987A. Among more distant galaxies, it found that an electron jet from galaxy M87 looked almost the same by ultraviolet as by radio. And together with the Wide Field/Planetary Camera, the Faint Object Camera revealed patterns of concentrated starmaking when galaxies collide.

In a last example of successes with the faulty Hubble, astronomers in Hamburg, Germany, used NASA's Faint Object Spectrograph to examine ultraviolet light from a distant quasar. They proved that generous supplies of the chemical elements existed surprisingly early in the history of the Universe.

Clearer details in an active galaxy. ESA's Faint Object Camera imaged the core region of galaxy NGC 1068 before (upper) and after (below) the Hubble refurbishment. Commenting on the dramatic improvement, Duccio Macchetto of ESA says "It's not just a prettier picture. We believe that, hidden from our view in this violent galactic nucleus, a giant black hole is at work. Now we can see knots and streamers in the gas clouds around it. At 60 million light-years, NGC 1086 is relatively close. By analysing its details we can make sense of similar active galaxies much farther away."



Pre-COSTAR



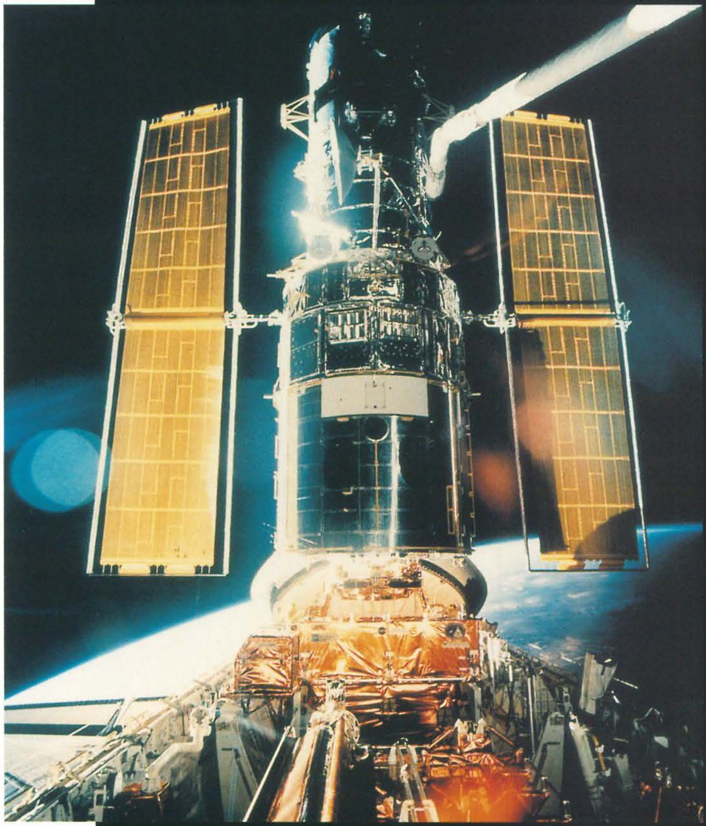
With COSTAR

D. Macchetto (ESA/STScI) et al., Hubble FOC team, NASA and ESA

The new beginning

The telescope operators and the astronomers had other worries about the spacecraft. One was a jitter caused by unexpected bending in ESA's solar arrays whenever Hubble passed into the Earth's shadow. New software minimized disruption of the carefully pointed observations, but engineers feared that the panels might snap off. Lesser electrical, electronic and mechanical problems accumulated as time passed.
Maintenance and refurbishment of Hubble by astronauts during its 15-year mission had always been envisaged, but the tasks multiplied alarmingly. The continuation of space astronomy demanded a dose of raw physical courage. Months of practice in the simulated weightlessness of a water tank prepared the crew of NASA's space shuttle Endeavour for their complex task.

Six Americans were joined by an ESA astronaut, Claude Nicollier from Switzerland, who worked the shuttle's manipulating arm. In 30 hours of space-walking by pairs of astronauts, spread over five days, all was accomplished. They replaced the NASA camera with another matched to the aberrated mirror, and inserted corrective mirrors into the telescope beam serving ESA's Faint Object Camera and other instruments. One old solar panel was badly bent and the astronauts had to jettison it in space. Redesigned solar panels supplied by ESA cured the jitters.
By January 1994 the recommissioned Hubble was giving excellent images. "It was our happiest New Year," recalls Duccio Macchetto, an Italian astronomer.
As an ESA appointee he is prominent in the Science Programs Division at the Space Telescope Science Institute.
"Within days of the telescope coming back into service we saw amazing sights," Macchetto says. "We observed the distant planet Pluto and its moon Charon as clear disks for the first time. Fuzzy-looking nuclei of galaxies became enchanting scenes, with distinguishable luminous clouds for us to puzzle over. And distant quasars at once began yielding more of their secrets."



Better than new. Hubble was photographed by the crew of the space shuttle Endeavour at the end of their heroic mission in December 1993, when they cured the Space Telescope's defects.
Image: NASA

Helium in the early Universe

A team of European astronomers led by Peter Jakobsen, of ESA's Space Science Department, made the first major discovery with the corrected optics. This was no fluke. Jakobsen's team had used the faulty Hubble to find the right target in the sky, and then waited for the refurbished instrument to look at it properly.

In the theory of the Big Bang, a thermonuclear explosion racked the cosmos when it was three minutes old, and converted a quarter of the newly made hydrogen into helium. Much of the mixture of gases was later swept into stars, galaxies and clouds of invisible gas. But there should also be a thin scattering of gas throughout intergalactic space.

Jakobsen suspected that many of the helium atoms would be ionized, lacking one of their two electrons. If so, they would kill the transparency of the Universe for ultraviolet light. He proposed to identify the primeval helium by its power to black out short-wavelength ultraviolet light coming from a distant quasar. The wavelength at which the blackout should set in could be calculated.

Most quasars were unsuitable because hydrogen atoms in intervening gas clouds already blotted out much of the ultraviolet. "It's a bit like trying to observe stars through small breaks in the clouds on an overcast night," Jakobsen explains, "except in our case the cloud cover spans nearly the whole observable Universe."

Between 1990 and 1993, ESA's Faint Object Camera examined twenty-five candidate quasars, using a prism to make a simple spectrum of their visible and ultraviolet light. One of them, 0302-003, was relatively clear of intervening gas clouds, but the poor optics prevented Hubble from obtaining a good spectrum. As soon as the refurbished Hubble was back in service, Jakobsen asked for a re-examination of this quasar.

For three hours in total, the Faint Object Camera drank in and spread the light of 0302-003. The helium blackout was far plainer than the team had dared to expect. Its onset was at 130 nanometres, exactly the wavelength expected for helium ions in intergalactic space, just this side of the quasar.

There were really three discoveries at once: (1) primeval helium, (2) a diffuse intergalactic gas never seen before, and (3) confirmation that the gas is ionized, presumably by radiation from quasars or similar intense objects.

When Jakobsen and his team formally reported their analysis six months later, an expert commentator in the journal Nature hailed it as "a breakthrough in cosmology".

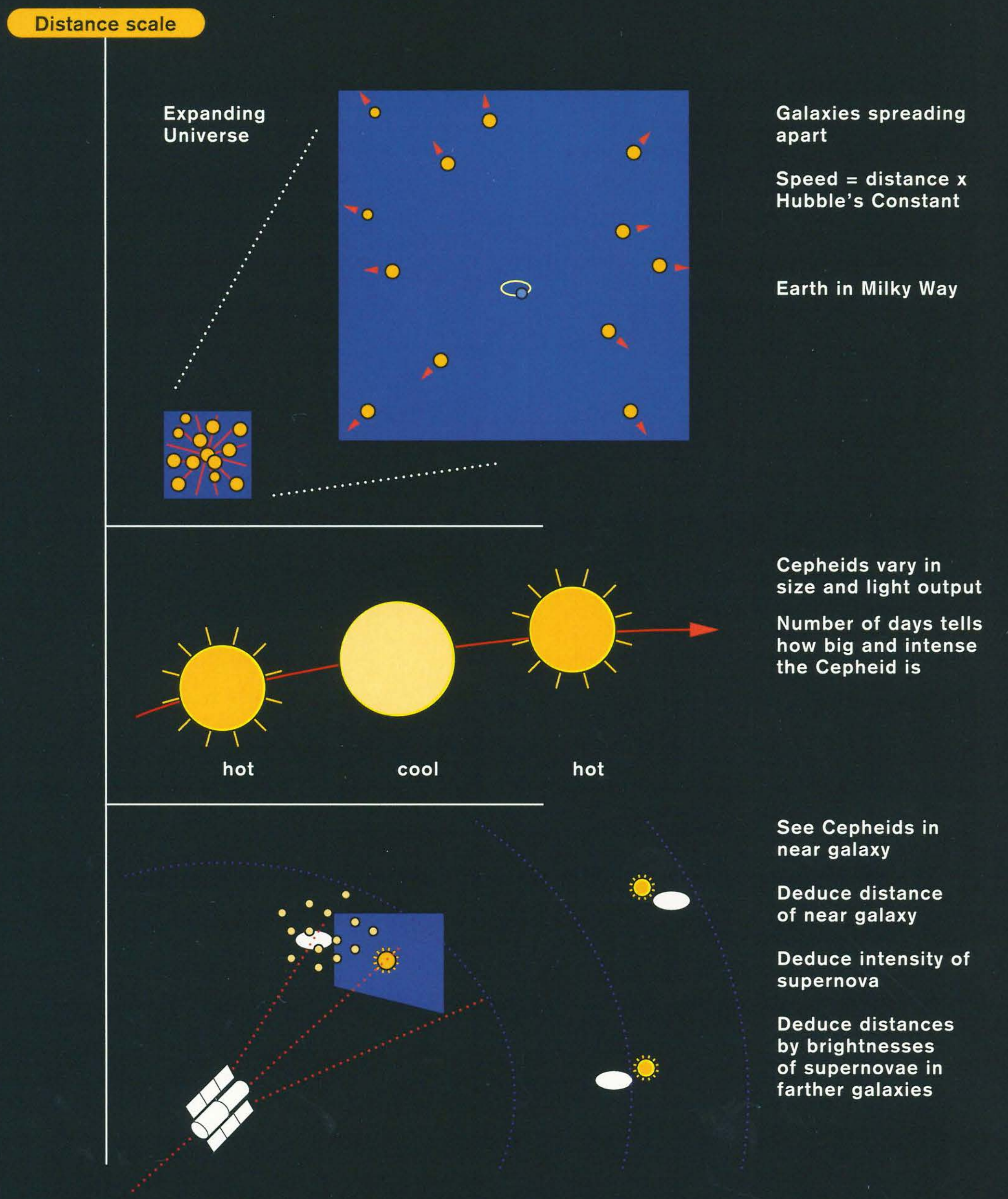
How old is the Universe?

If the Hubble Space Telescope fixes the Hubble Constant, that will be fitting. Both are named after Edwin Hubble, the American astronomer who discovered the expansion of the Universe. The Hubble Constant relates the present speeds of the galaxies to their distances from the Earth. Remote galaxies recede faster than the near ones, and you can calculate back to a time when the stuff of all the galaxies was crowded in one place. The speeds are quite easy to measure, by redshifts which lengthen the wavelengths of the galaxies' light. Gauging their various distances, though, is so difficult that even the most recent estimates leave the Hubble Constant veering erratically between 37 and 90 units (kilometres per second per megaparsec).

Nature helps by exploding a standard nuclear bomb, called the Type 1a supernova. A star dumps gas on to a companion dwarf, which then blows up when its mass is exactly 44 per cent heavier than the Sun. The visible light emitted is always the same, more than 6 billion times more intense than the Sun's. If you knew that peak luminosity exactly, you could reckon the distances of galaxies more than 500 million light-years away, in which astronomers have recorded Type 1a supernovae and measured their different brightnesses as seen from the Earth. Compare the distances with the redshifts, and you would have the Hubble Constant.

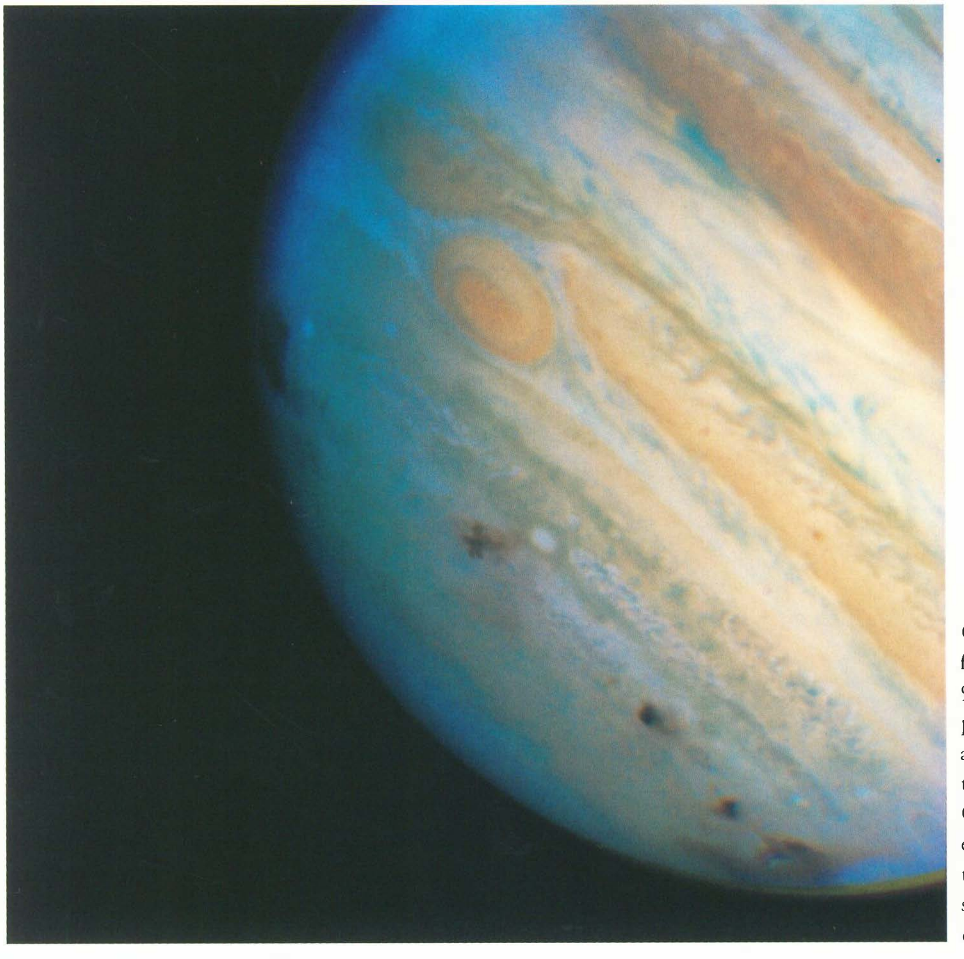
A Hubble Space Telescope programme aims to find the exact luminosity of the Type 1a supernovae, by measuring by other means the distances of some of the nearer galaxies in which such events have occurred. Hubble picks out stars called Cepheids, which wax and wane every few days or weeks, as they swell and shrink like a breathing lung. Their rates of winking tell the astronomers how luminous the various Cepheids are, inherently, and their brightnesses give the distance to the galaxy.

Even before its refurbishment, Hubble had spotted Cepheids in the relatively close galaxies IC 4182 and NGC 5253, which had Type 1a supernovae in 1937 and 1972 respectively. In 1994, the refurbished telescope examined the more distant NGC 4496 (supernova 1960) and NGC 4536 (supernova 1981). Early results indicated a value for the Hubble Constant of about 50 units.



This implies a maximum of about 20 billion years since everything was crowded together. But gravity has probably slowed down the galaxies since the expansion began, in which case the true age of the Universe may be 13-14 billion years.

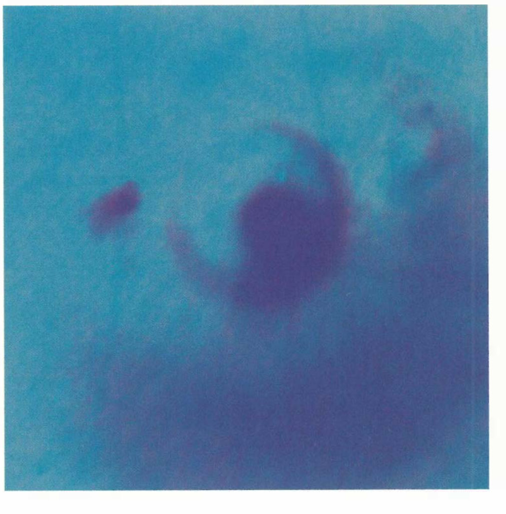
The ways of science are seldom smooth, however. In October 1994 another group using the Hubble telescope announced a quite different value for the Hubble Constant. Wendy Freeman of Pasadena and her colleagues observed Cepheids in galaxy M100 and judged its distance to be 55.7 million light-years. From that they conclude that the correct value is about 80 units, implying a younger Universe.



Comet strikes on Jupiter. In July 1994 fragments of Comet Shoemaker-Levy 9 exploded in collisions with the giant planet and left dark spots in its thick atmosphere. They were plainly visible to NASA's new Wide Field/Planetary Camera in Hubble. A flattened enlargement (below) of an image taken ninety minutes after a large blast shows the noise racing outwards in a conspicuous ring. A dark crescent nearly as wide as the Earth consists of material flung out by the event. The small spot on the left marks a previous impact.
Images: Hubble Comet Team, NASA and ESA

Much more coming

In July 1994, Hubble obtained splendid pictures of Jupiter, showing the impact sites of the fragments of Comet Shoemaker-Levy 9. And by 1995 other results from American and European astronomers were flooding into the scientific literature. Sharper impressions of colliding galaxies and very distant galaxies aroused strong interest. New observations of quasars cast doubt on the traditional idea that these intense sources of light necessarily inhabit galaxies. Before long it will indeed be time to redefine astronomy "in the Hubble era".



ISO: cool astronomy by infrared

Do you want to target your favourite galaxy with the European Space Agency's new infrared telescope? You are too late. The call for proposals went out to the world's astronomers in April 1994 and brought in enough applications to keep the Infrared Space Observatory busy for more than three years. As ISO's expected life is only about twenty months, the committee that allocates observing time has hard choices to make.

A shy young star. Infrared emissions reveal a new star hiding among dust clouds close to a well-known young star. It causes outbursts previously attributed to the known object, so both stars have to be reinterpreted. European astronomers discovered the new star from ground-based observatories, using a camera similar to ISO's. In space, fainter objects are discernible across a broader waveband of infrared rays.
Image: G. Olofsson (Stockholm Obs.) and P.O. Lagage (CEA SAp, Saclay), CAMIRAS camera, Nordic Optical Telescope.

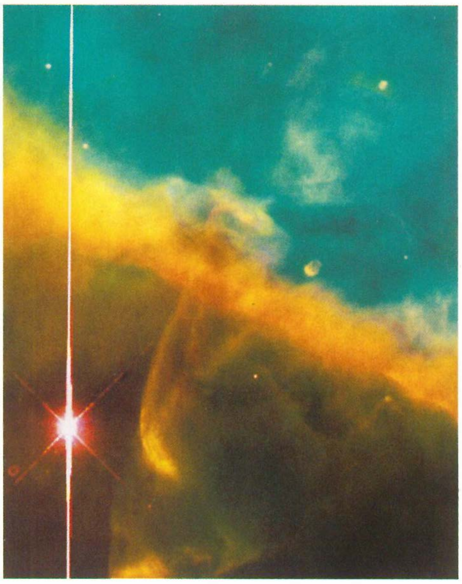
ISO

You and your galaxy must now wait until ISO is flying, in the latter part of 1995, and then you had better have extraordinary scientific reasons for intruding into its programme.

Infrared wavelengths are measured in microns, or thousandths of a millimetre. They are too long to be perceptible to human eyes, but human skin can feel them as radiant heat from warm objects. All but the very coldest objects in the Universe give off infrared radiation, whether nearby comets or distant galaxies. As cool material is widely scattered, the infrared sky is painted with a broader brush than the pointilliste visible stars. Infrared rays can also penetrate a fog of dust that often surrounds objects of interest, including newborn stars and the centre of the Milky Way Galaxy.

"ISO will explore the cool Universe and the hidden Universe," says Martin Kessler, ESA's project scientist. "For example, the cool and partly hidden material includes the gas and dust drifting between the stars. This is the cosmic soup from which planets and ultimately life arose. Intensive examination of its molecules and dust grains is one of ISO's key tasks."

The Earth's air radiates in the infrared, producing foreground interference for infrared telescopes working on the ground. Moreover, water vapour and carbon dioxide in the air absorb wide bands of wavelengths, leaving ground-based infrared astronomers with narrow "windows" up to 40 microns and a blackout at longer wavelengths. So there is good reason to send the instruments into space.



Plume from a young star. The Hubble Space Telescope imaged this long jet of gas ejected into space from a newly formed star in the Orion Nebula.
In earlier stages of starmaking, inflows and outflows of matter occur in dense clouds. ISO will see such events more clearly, by infrared light.
Image: C.R. O'Dell (Rice U.), NASA and ESA

In 1983 the US-Dutch-British IRAS inaugurated infrared space astronomy in a comprehensive fashion. The satellite mapped 250,000 cosmic infrared sources, and large areas of diffuse emission too. After ten busy months, its survey of the sky was almost complete when the exhaustion of helium coolant ended the mission.

That is the snag about an infrared satellite. Observing the cool Universe requires cool instruments, working at temperatures close to absolute zero, minus 273 degrees C. Only helium remains liquid, and it has to be slowly vented to maintain the low temperature. ISO too will be limited by its helium supply, though it should operate roughly twice as long as IRAS.

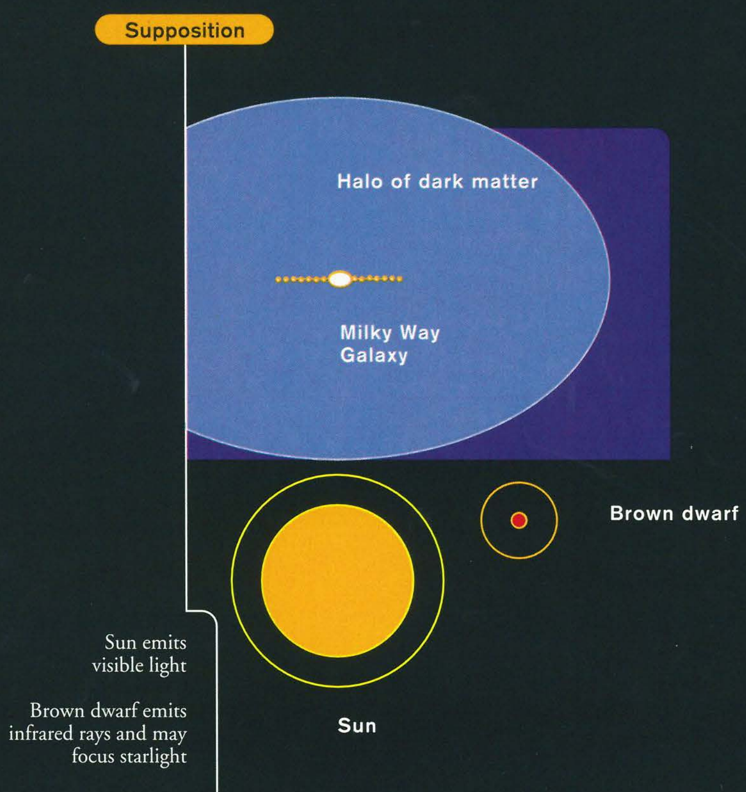
Besides giving unusual impressions of familiar features of the Universe, IRAS found cool disks of dust surrounding certain stars, and also ultraluminous infrared galaxies. These are congregations of stars so beset with dust that they give off twenty times more energy in the infrared than in visible light. A decade later astronomers still quarry the IRAS catalogue for new discoveries. But they crave a closer look at many individual objects with more sensitive and more analytical detectors. Hence the demand for observing time on ISO.

Do brown dwarfs rule the Universe?

One of ISO's tasks will be to look for invisible objects that may swarm in a halo around the Milky Way Galaxy.

The Universe is dominated by unidentified Dark Matter, which far outweighs the visible stars and galaxies. Its gravity makes galaxies race about, and causes stars to travel faster than expected in the Milky Way. Astronomers are embarrassed that they don't know what the main constituent of the Universe is.

Is Dark Matter a mass of ghostly subatomic particles, distinct from ordinary matter? Or is it lumps of ordinary matter that happen to be non-luminous? Malnourished black holes, perhaps. Or brown dwarfs, which are starlike masses of gas much smaller than the Sun, and too cool to burn.



In 1993 French and US-Australian teams reported small objects in the halo of the Milky Way, wandering across the lines of sight to stars in a nearby galaxy. They estimated their masses to be in the right range for brown dwarfs. Many astronomers remained sceptical, but support for the brown-dwarf theory came in 1994 when American astronomers announced a halo of faint light around a spiral galaxy seen edge-on. The population of brown dwarfs could include some red dwarfs, slightly larger objects glowing as very feeble stars. The Hubble Space Telescope has observed a red dwarf, feebler than the Sun by a factor of 60,000, lying at a distance of 25 light-years.

Brown dwarfs should radiate as point sources in the infrared. ISO's sensitive camera will look out into the halo of the Galaxy through preselected breaks in the interstellar clouds that otherwise obscure the view. These "holes" are in the constellations of Ursa Major and Horologium.

Hundreds of exposures, devoting up to half an hour on small patches of the sky, should reveal previously unseen objects. These could include some of the brown-dwarf attendants of the Milky Way and also some very distant galaxies. Supplementary observations at longer wavelengths by another instrument will distinguish between them.

ISO will also spend a little time looking for brown dwarfs in the haloes of other galaxies. If brown dwarfs are the answer to Dark Matter, or at least a part of the answer, ISO may help to solve one of the chief riddles in current cosmology. The verdict is in Nature's hands

A flying freezer. ISO chills its infrared detectors below minus 271 degrees C, by letting helium boil away at a temperature of 1.8 K (degrees above absolute zero). A tank filled with 2140 litres of superfluid helium allows the loss of a trickle of gas for 18 months or longer. The cold gas passes through heat exchangers that maintain the whole telescope within a few degrees of absolute zero. In this photo of the flight model under test, the panels running down the left-hand side carry solar cells for generating electric power and also act as a sun screen for the satellite. Note also the slanting shade at the top which keeps sunlight out of the telescope.

Data on ISO

Purpose
infrared astronomy

Wavelength range
3-200 microns (micrometres)

Telescope aperture
0.6 metres

Responsible agency
ESA; cooperation with ISAS (Japan) and NASA (USA) extends the ground-station coverage and observing programme

Name
from Infrared Space Observatory

Prime contractor
Aerospatiale, Cannes, France

Mass
2.4 tonnes

Length of spacecraft
5.3 metres

Launch
1995

Launch vehicle
Ariane 44P

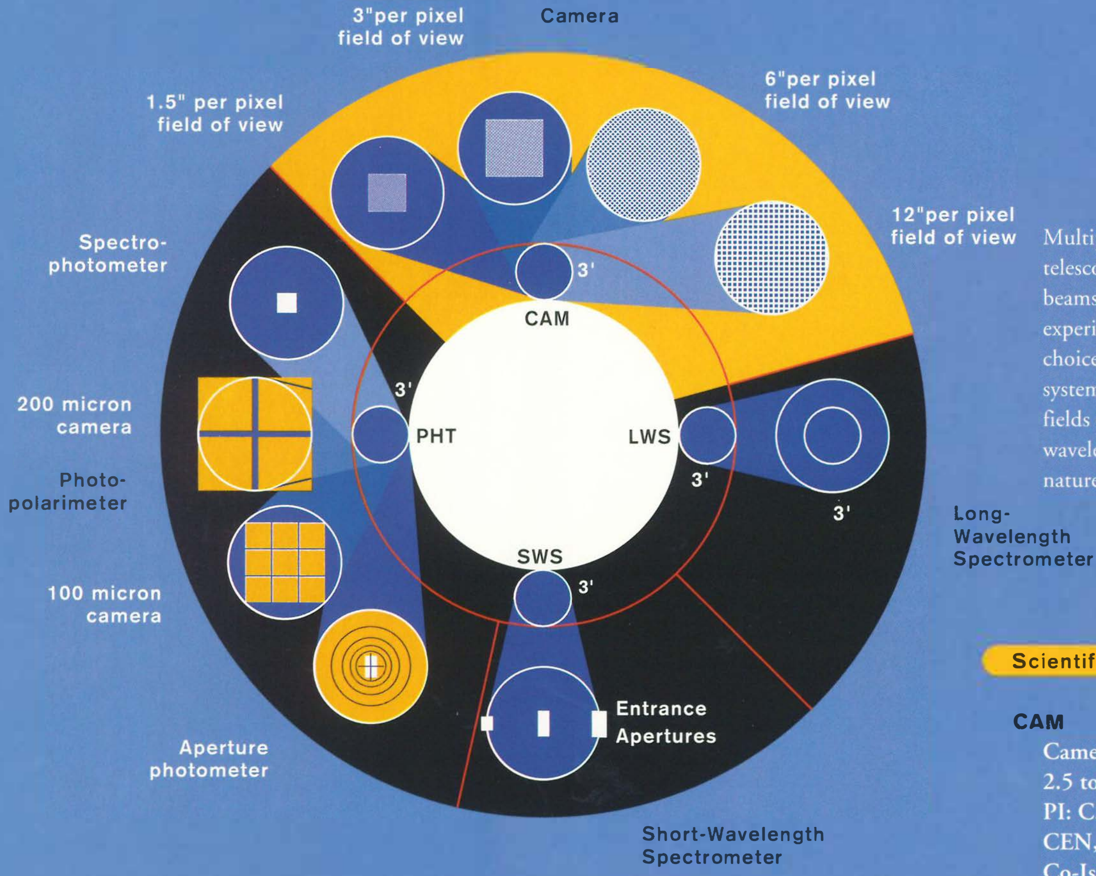
Orbit
24-hr eccentric orbit
1,000-70,000 km above Earth; inclined at 5 deg. to Equator

Operations
16 hr per day (outside radiation belts)

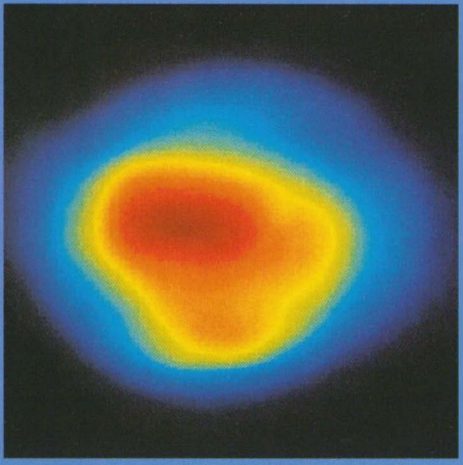
Ground stations
ESA Villafranca and NASA Goldstone

Lifetime
18 months or more (helium-limited)

Power supply
solar cells



Multiple sensors. A single 0.6-metre telescope in ISO feeds infrared beams via a pyramidal mirror to four experiments incorporating a wide choice of camera settings and systems for spectral analysis. The fields of view and the selection of wavelengths can vary to suit the nature of the object examined.



Saturn by infrared. This curious view of the ringed planet, at a wavelength of 10 microns, is dominated by strong emissions coded dark red. They come from active weather in the upper left-hand portion of Saturn's visible face. The rings of Saturn appear weaker at this wavelength, making leftward and rightward extensions of the faint blue region.
Image: P.O.Lagage (Saclay) and F. Sibille (Lyon), CAMIRAS camera, Canada-France-Hawaii Telescope

Scientific instruments

CAM
Camera and polarimeter
2.5 to 18 microns
PI: C. Cesarsky
CEN, Saclay, France
Co-Is: F, E, I, S, UK, USA

PHT
Imaging photo-polarimeter
2.5 to 200 microns
PI: D. Lemke
MPI für Astronomie
Heidelberg, Germany
Co-Is: D, DK, E, IRE, SF, UK, USA

SWS
Short-wavelength spectrometer
2.5 to 45 microns
PI: Th. de Graauw
Lab. for Space Research
Groningen, Netherlands
Co-Is: NL, B, D, USA

LWS
Long-wavelength spectrometer
45 to 180 microns
PI: P. Clegg
Queen Mary & Westfield
College, London, UK
Co-Is: UK, F, I, USA

PI = Principal Investigator
Co-Is = countries of Co-Investigators

Planets and their origins

The Hubble Space Telescope has demonstrated that, even in the era of interplanetary probes, observations of the planets from the distance of the Earth are still valuable. Visits by spacecraft are limited both in duration and in the capacity of the onboard instruments. So ISO, from its vantage point in Earth orbit, will spend many hours observing planets, moons, asteroids and comets, especially to diagnose their chemical constituents. There will be appropriate attention to Titan, the hazy moon of Saturn that is the target of ESA's Huygens probe.

A mystery surrounds the variable proportions of heavy hydrogen atoms (deuterium) found in the atmospheres of various planets and moons. They seem to fingerprint different origins. Titan, for example, has about ten times as much deuterium, in relation to ordinary hydrogen, as nearby Saturn.

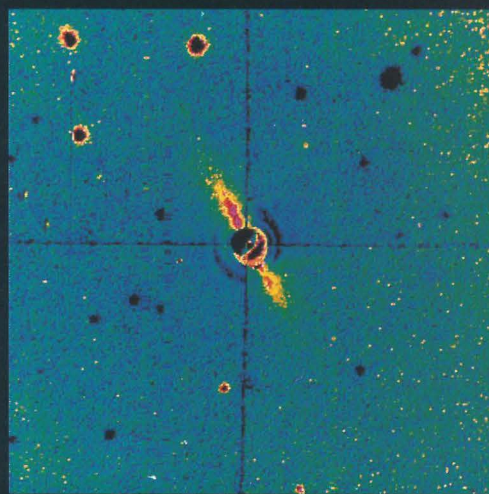
The theory is that the giant planet sucked hydrogen from the primeval gas cloud, while Titan and other small bodies, including the Earth and Mars, may have obtained their hydrogen from water ice in impacting comets. Comet ice is enriched in deuterium. ISO will pursue this question by measuring the proportions of deuterium and other atomic and molecular fingerprints in the giant outer planets (Jupiter, Saturn, Uranus and Neptune) and also in Titan, Mars and comets.

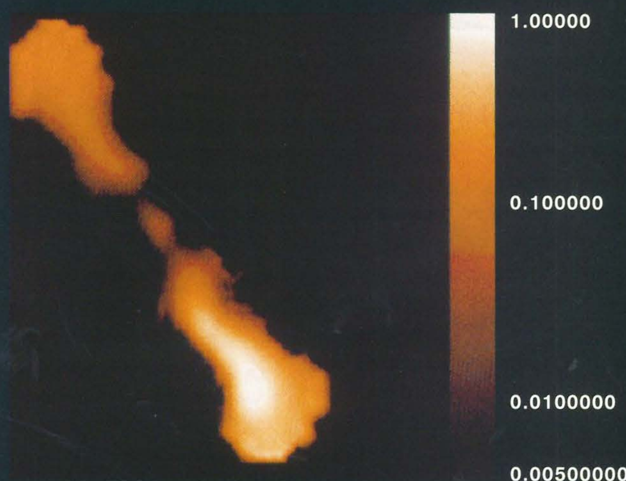
For anyone seeking the cosmic origins of human life, the creation of the planets was a milestone. And those who wonder whether or not life exists elsewhere in the Universe need an estimate of how widespread planets are. Many astronomers have imagined that solitary stars are almost certain to possess planets, but that is unproven.

ISO will follow up the discovery by IRAS of infrared-emitting disks of dust surrounding certain stars, including the bright star Vega. Astronomers think that the Sun's own planets formed from just such a dust disk, and the theorists are reassured to see examples elsewhere. But planet formation clears most of the material away. The Solar System seen from afar would not look like a dust disk.

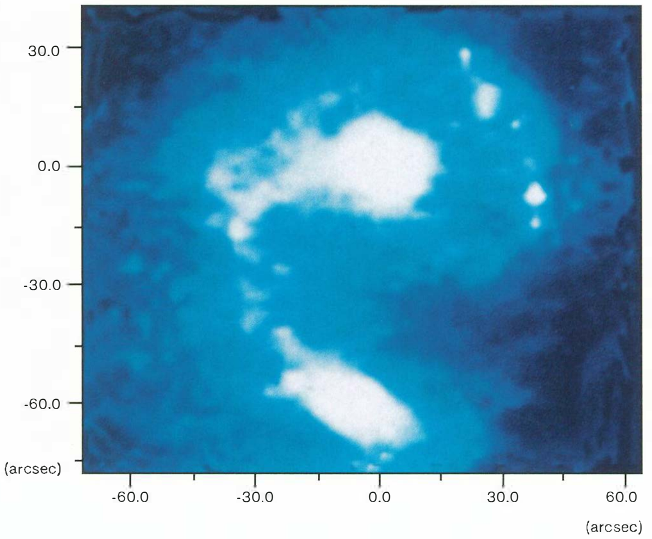
"The presence of a disk around a star may tell us that the star was not able to make planets," comments Harm Habing of Leiden, who will lead a programme looking for Vega-like disks. "With ISO," he explains, "we shall search for disks in some 100 mature stars of various masses and ages out to a distance of 100 light-years. We want to know how common the dust disks are, and whether they vary in density and thickness with the passage of time, or according to differences in the stars' environments.

"And there is another ISO programme of similar size that will study young stars. These may have fatter disks, that may be detectable within a distance of 300 light-years. But anyone looking for planets by other means," Habing concludes, "may be well advised to concentrate on those stars where we do not find disks."





Dust around a star. The upper image of Beta Pictoris, with the star itself masked, shows edge-on a disk of dust similar to that from which the Earth and other planets supposedly formed, in the vicinity of the newborn Sun. The disk was discovered by the IRAS infrared satellite. ISO will find and examine many more examples.
Meanwhile, ground-based infrared observations (below) show the dust concentrated in an outlying ring. Dust closer to the star may have been consumed in building planets.
Visual image: B. Smith (Arizona) and R. Terrile (JPL); infrared: P.O. Lagage and E. Pantin (CEA SAp, Saclay), TIMMI camera, 3.6-m. ESO telescope.

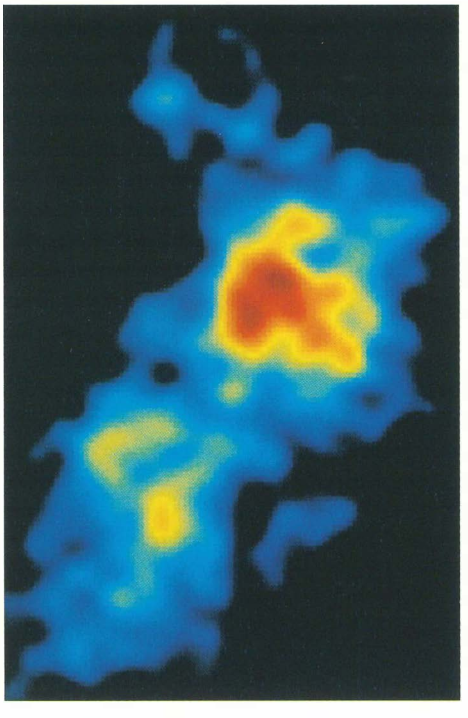


Colliding galaxies. A ground-based infrared telescope obtained this image of two galaxies called the Antennae. They are colliding and show intense activity at short infrared wavelengths. Such collisions give rise to "starburst" galaxies, which exhibit rapid star formation and high luminosity at longer infrared wavelengths, where ISO will observe them.
Image: UK Infrared Telescope, Mauna Kea/Royal Observatory, Edinburgh

The evolution of galaxies

We are children of the Milky Way Galaxy, which created the chemical elements now in our bodies and kept them available for making the Sun and the Earth.
A characteristic product of element-making in exploding stars is dust, and in the Milky Way and other fertile galaxies cool interstellar dust radiates in the infrared waveband. At large distances, corresponding with events within the first few billion years after the Big Bang, the redshift due to the expansion of the Universe is so great that all visible light becomes infrared. For these reasons, ISO has a special opportunity to investigate the origin and evolution of the galaxies.
Starburst galaxies, apparently the result of collisions, make and explode stars at such a rate that they are exceedingly dusty, and exceptionally bright in the infrared. Observations by ISO will draw the attention of astronomers to mergers of galaxies. The collisions, over many billions of years, have reduced the number of elegant spiral galaxies and made egg-like elliptical galaxies instead. ISO will be able to compare the proportions of different types of galaxies in distant and therefore early clusters, with nearby, recent clusters.

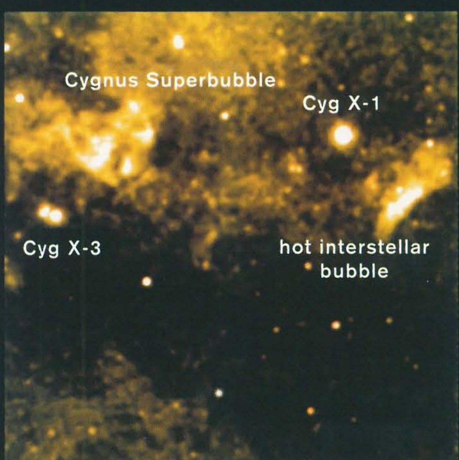
"Galaxies are where the action is in the Universe," says Catherine Cesarsky of Saclay, France, who is charge of the main imaging camera in the spacecraft. "So, of all that we can do with ISO, trying to trace the entire history of the galaxies is for me the most exciting thing. We shall look for their birth, and for the subsequent changes due to internal and external events. In nearby galaxies and the Milky Way itself, we shall see the outcome of this evolution, and what it means for starmaking and planet-formation today."



A frantic galaxy. Intense infrared rays, coded red here, come from concentrated regions in galaxy NGC 4536. Rapid starmaking may result in dust from short-lived stars, which glows strongly in the infrared. By visible light, the galaxy has a very small bright centre. ISO should help to tell when internal "engines" affect the galaxies, and when external collisions alter the behaviour of these great assemblies of stars.
Image: M. Dennefeld (Paris) and P.O. Lagage (Saclay), CAMIRAS camera, Canada-France-Hawaii Telescope

XMM: an appetite for cosmic X-rays

A new picture of the sky shows the hot places in the Universe. Wherever temperatures soar to millions or billions of degrees, X-rays pour out. They are, though, blocked from view by the Earth's air. X-ray telescopes in space can see the sources, which range from the surprisingly hot atmospheres of commonplace stars to the gravity-powered furnaces surrounding giant black holes in distant galaxies.
Immense clouds of hot gas pervade the galaxies and clusters of galaxies. A background glow of X-rays fills the sky and may be announcing the origin of the galaxies.



A powerful vampire star. Cygnus X-3 is on the left in this X-ray image from the German-US-British Rosat mission. It lies about 25,000 light-years away, and in visible light it is too faint to see. The intense X-rays are generated by gas falling from a star on to a nearby neutron star, which sucks in the gas and accelerates to almost the speed of light. Cygnus X-3 is also a source of cosmic rays, energetic atomic particles that course through the Milky Way Galaxy. Cygnus X-1, on the right, is a suspected black hole. Image: J. Trümper (MPE Garching)

XMM

And the archetypal X-ray star is a vampire, a white dwarf or neutron star that sucks gas from a companion star and heats it by intense gravity. In some cases the vampire may be a small black hole.
X-ray astronomers have spent an exciting quarter of a century finding these things out. The first successful X-ray satellite, NASA's Uhuru, flew in 1970 and charted 339 cosmic sources. Since then, a long succession of American, Russian, European and Japanese missions have made X-ray observations the strongest strand of astronomy in space. Rosat, a German-US-UK collaboration launched in 1990, pushed up the number of known X-ray sources to 120,000. The European Space Agency's XMM will see millions. Due for launch in 1999, it will be the most sensitive X-ray satellite ever built. NASA's AXAF (1998) will hunt for small, faint sources and see fine details better than XMM. Where XMM scores is in having telescopes of an adventurous design that give it a gargantuan appetite for X-rays, surpassing AXAF's.

Whether a cosmic X-ray source is observable depends on how many hours of telescope time must be devoted to gathering enough X-rays from it. Astronomers reckon the X-ray sources in units called milli-Crabs, meaning so many thousandths of the X-ray brightness of the famous Crab Nebula, an exploded star. The brightest persistent source, the vampire star Sco X-1, clocks in at 20,000 milli-Crabs, and the brightest quasar 3C273 at 6 milli-Crabs.

The X-ray telescopes in XMM will register a milli-Crab source in a second or so. An hour's observation will easily pick up micro-Crab sources, with only a millionth of the Crab Nebula's brightness. In a day XMM will see more X-ray sources in a small area than Uhuru found across the whole sky in three years.

XMM's capacity to pick out large numbers of objects is incidental to its main purpose, which is to make X-ray astronomy a more exact science. The keyword is spectroscopy. The spreading of light into a spectrum is indispensable for astronomers working in the visible and ultraviolet. By latching on to precise wavelengths emitted by atoms, spectroscopy measures a source's composition, temperature, motion, and so forth. XMM will make spectroscopy routinely available to X-ray astronomers too, so that they can convert vague theories into quantified descriptions of each source.

X-ray objects towards the centre of the Milky Way, as seen by ESA's Exosat. Image: X-ray Astronomy Group, U. Leicester

XMM is meant to last at least two years, and hopefully ten. It will be operated as an observatory for the use of the world's astronomers. They will exploit its capacity not merely to observe millions of objects but to do broadbrush spectroscopy on them, and detailed spectroscopy on perhaps 30,000 over ten years. That is why ESA's formal name for XMM is the High-Throughput X-ray Spectroscopy Mission.

Data on XMM

Purpose
X-ray spectroscopy of cosmic objects

Wavelength range
0.1 to 5 nanometres

Name
from X-ray Multi-Mirror, but formally called High Throughput X-ray Spectroscopy Mission

Responsible agency
ESA

Role in Horizon 2000 programme
2nd cornerstone mission

Prime contractor
Dornier, Germany (Phase B)

Mass
more than 3 tonnes

Telescopes
three 0.7-metre X-ray telescopes
one optical telescope.

Length
10 metres

Launch
1999

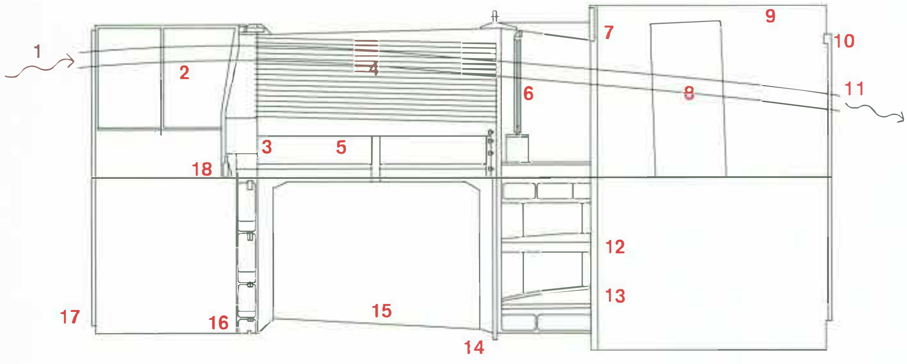
Launch vehicle
Ariane 5

Orbit
eccentric 48-hour orbit around the Earth
7000-120,000 km altitude; 60 deg. inclination to Equator

Operations
40 hours per orbit
via ESA Redu ground station, Belgium

Lifetime
2 to 10+ years

Power supply
solar cells



One of three. This diagram of an XMM telescope gives an impression of the engineering finesse involved. The fifty-eight nesting shells that focus the X-rays have to be accurately positioned.

1 X-rays from Source
2 Entrance Baffle
3 Micro Balance
4 Mirror (58 shells)
5 Blocking Shell
6 Magnetic Deflector
7 RGA Interface
8 Reflection Grating Assembly (RGA)
9 Exit Baffle
10 Exit Door
11 X-rays to Focus
12 RGA Backup Fitting
13 Backup Fitting for Mirror Support Platform (MSP)
14 Spacecraft MSP Interface
15 Interface Structure
16 Spider
17 Entrance Door
18 Alignment Lens

Precision times three times fifty-eight

Any X-ray imaging telescope is a work of art, and XMM will carry three masterpieces. Galileo wouldn't recognize them as telescopes at all, but lenses and even the broad mirrors of modern visible-light astronomy are useless for focusing X-rays. The way to persuade X-rays to change course in an orderly way is to glance them off a metal surface at a shallow angle. Forty years ago the German physicist Hans Wolter invented a barrel-shaped mirror, subtly angled along its length, that would bring to a focus X-rays entering near its rim.

Scientists in the USA adapted the Wolter mirror into the first imaging X-ray telescope, flown in NASA's Einstein satellite in 1978. As one Wolter mirror collects incoming X-rays only in a narrow ring, the Einstein instrument had four mirrors nested one inside another like Russian dolls. In NASA's AXAF satellite, a telescope 1.2 metres wide will also have four nested mirrors. Yet altogether they will focus only about 10 percent of the X-rays entering from the field of view.

Each of the three XMM telescopes will have fifty-eight nested mirrors, and 60 percent of all the X-rays entering will find a mirror properly positioned to guide them to the common focus. Even though the aperture area of an XMM telescope is one-third of AXAF's, its gathering power is about three times as great, or ten times with the three telescopes.

Japanese astronomers have made a start in multi-mirror X-ray spectroscopy with their Asca satellite (1993). Forthcoming Italian-Dutch and Russian spacecraft will continue the trend. The special quality of XMM comes from its use of many accurately formed mirrors, to combine the high capacity with good focusing.

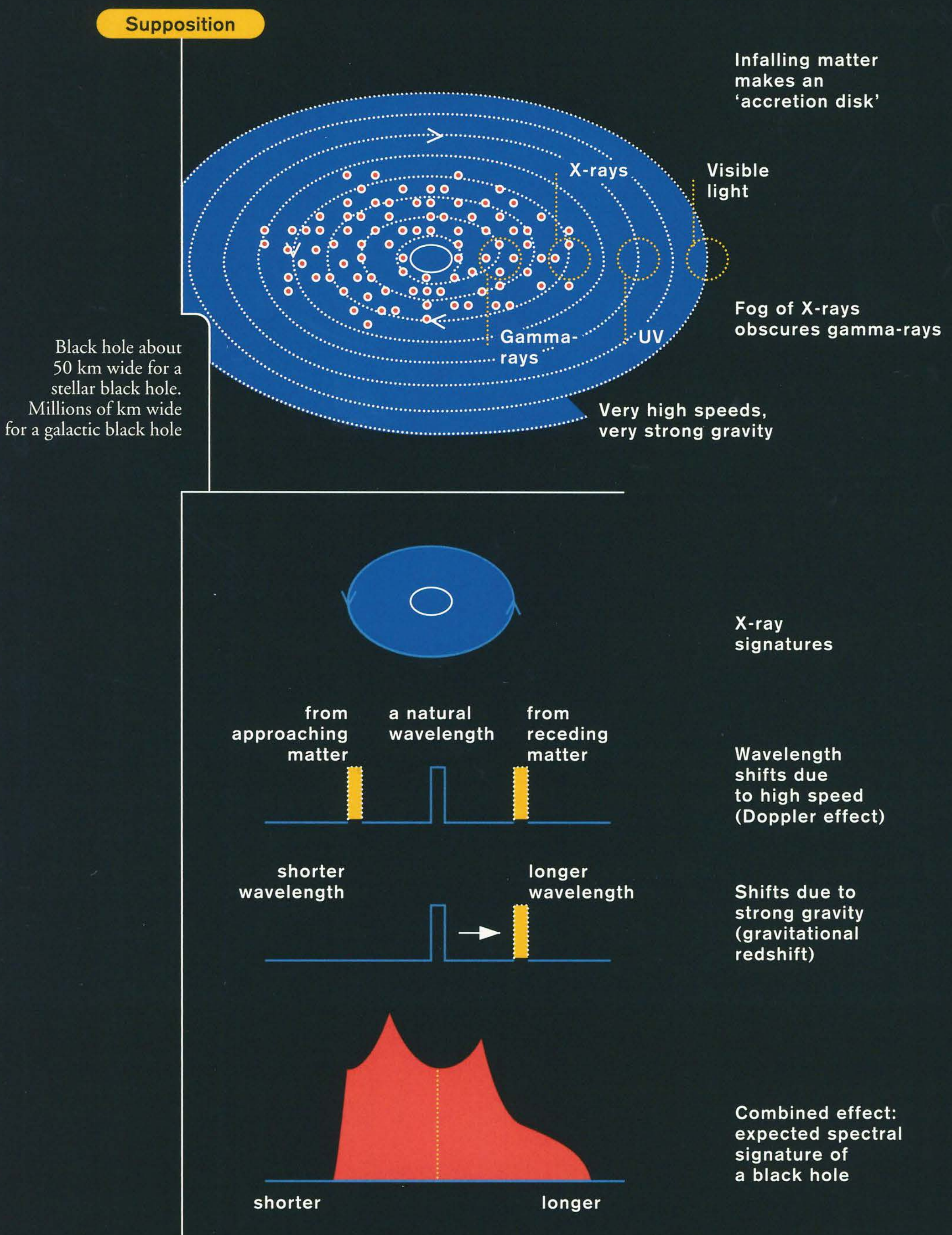
"Our biggest problem is to prevent the mirrors deforming during assembly," says Robert Lainé, ESA's project manager for XMM. He first learnt about X-ray telescopes for the Exosat mission, and now he leads Europe's engineers through a formidable task in instrument-making.

"We have commissioned Carl Zeiss in Germany to make fifty-eight solid mandrels, or moulds, which have the shape of the final mirror. on the nickel surfaces of aluminium cores," Lainé explains. "They shape them with the parabolic cross-section needed at the front end and the hyperbolic section at the back, to an accuracy of about a thousandth of a millimetre. And they polish them to a local smoothness a thousand times better than that."

"Then Mediolario in Italy, who are associated with the German company Kayser Threde, form the mirrors on the mandrels by electrodeposition. They lay down a gold reflecting surface on the mandrel's polished surface, and then back it with less than a millimetre of nickel, which has to go on very evenly. Ease it off the mandrel and you have an X-ray mirror. Do that three times on fifty-eight mandrels and you have enough mirrors of different sizes for XMM's three telescopes."

"The trouble is that these carefully shaped mirrors are large, with a diameter up to 700 millimetres and a length of 600 millimetres, but they also have to be thin. They can easily sag under their own weight. We have to devise careful ways of hanging them before assembly, to minimize any deformation."

"Only when they are glued to the spiders that hold them in their nested positions," Lainé concludes, "do the mirrors become rigid enough to survive normal handling and the space environment."


Supposition
Infalling matter makes an 'accretion disk'
X-rays
Visible light
Fog of X-rays obscures gamma-rays
Gamma-rays
UV
Black hole about 50 km wide for a stellar black hole. Millions of km wide for a galactic black hole
Very high speeds, very strong gravity
X-ray signatures
from approaching matter
a natural wavelength
from receding matter
Wavelength shifts due to high speed (Doppler effect)
shorter wavelength
longer wavelength
Shifts due to strong gravity (gravitational redshift)
Combined effect: expected spectral signature of a black hole
shorter
longer

Do black holes really exist?

The spookiest idea in astrophysics is that concentrations of mass can create traps of gravity from which nothing can escape, not even light. At the edge of such a black hole, time itself stops. For thirty years astrophysicists have invoked black holes to explain violent events in galaxies. Yet no one has proved beyond all doubt that Nature makes them. Perhaps XMM will do so.

Circumstantial evidence is strong, but even those who are convinced that black holes exist would like a much clearer picture of what goes on in their environs. The issue will be settled by detecting, close to an active black hole, processes that leave literally no room for any other explanation.

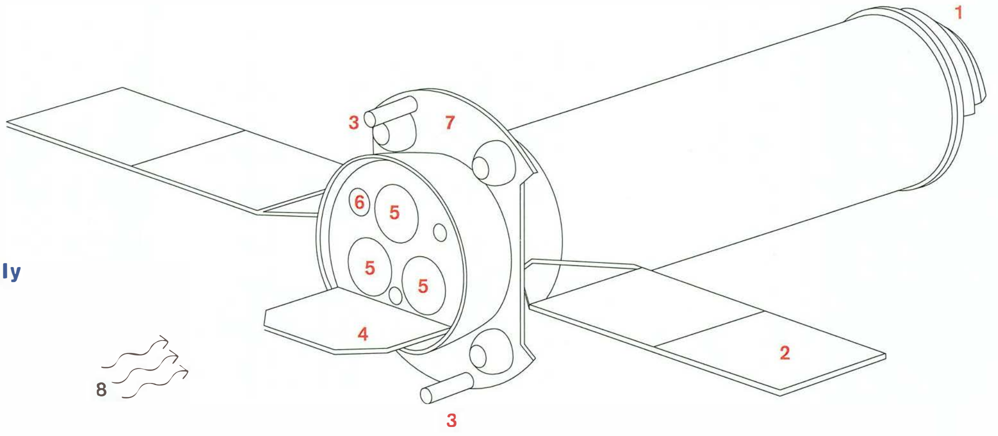
By definition black holes release no radiation, but matter falling into them does, as it swirls to its doom in a flat disk that grows hotter towards the centre. The disk emits visible and ultraviolet light near its outer edge, and gamma-rays just before the matter disappears into the black hole.

But other processes blanket the gamma-rays. The closest clearly detectable emissions are X-rays coming from a distance of perhaps three times the black hole's diameter.

By picking out X-rays from particular elements, of known wavelength, XMM will define the fierce conditions in the disk. The high speed of the swirling matter will smear a particular wavelength across a wide band. The intense gravity will increase all the resulting wavelengths by what astrophysicists call the gravitational redshift. And the rate at which the emissions vary will set an upper limit to the diameter of the source.

"The Japanese Asca X-ray satellite is giving us a foretaste of what XMM will do," says Andrew Fabian, an astrophysicist of Cambridge, UK. "It detects very high velocities in the X-ray emitting gas near suspected black holes, and the first hints of the gravitational redshift. With greater sensitivity and precision, XMM should give us a detailed impression of the scene."

"Supporters of every X-ray mission hope that theirs will be the one that finally confirms the black holes," Fabian notes wrily. But he adds, "XMM has the best chance."



XMM features

1 **Focal Plane Assembly**
2 **Solar Array**
3 **Antenna**
4 **Aperture Door and Mirror Sunshield**
5 **Mirror Modules and Baffles**
6 **Optical Monitor**
7 **Spacecraft Equipment Platform**
8 **X-rays**

Scientific instruments

EPIC
Prime focus cameras
for imaging spectrograph
PI: G.F. Bignami
IFC, Milan, Italy
Co-Is: I, D, F, UK

RGS
Secondary focus spectrometer
PI: A.C. Brinkman
SRON, Utrecht, Netherlands
Co-Is: NL, CH, UK, USA,

OM
Optical monitor 160-1100 nanometres
PI: K.O. Mason
MSSL, Holmbury St Mary, UK
Co-Is: UK, B, I, USA

PI = Principal Investigator
Co-Is = countries of Co-Investigators

Registering the X-rays

The focal length of its X-ray telescopes, 7.5 metres, means that XMM has to be long. The focused images fall on silicon chips adapted as sensitive radiation detectors, called charge-coupled devices or CCDs. Japan's Asca is the first X-ray satellite to demonstrate the benefits of CCDs, which are far superior to the traditional detectors used in previous missions. One of the XMM telescopes uses an advanced CCD camera capable of detecting rapid variations in intensity, down to intervals of a thousandth of a second or less, which is important for tracking down black holes.

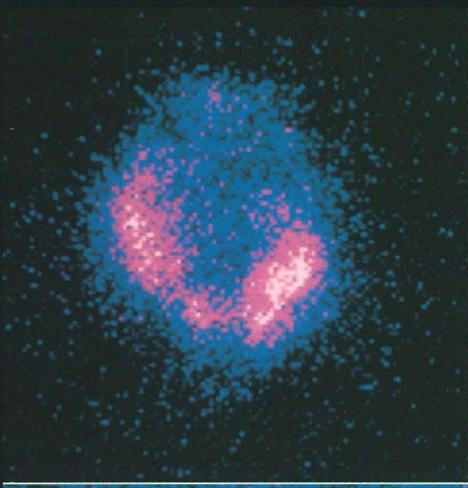
The CCD cameras in all the XMM telescopes can distinguish X-rays of different wavelengths by the energy delivered to a picture element by each X-ray particle, or photon. The low count rates of X-ray astronomy are an advantage, because there is little chance of two photons arriving in the same picture element during one counting interval. By measuring the proportions of X-rays of different wavelengths, the cameras can give a impression of the spectrum of a source. This broadbrush spectroscopy is called spectrophotometry.

For more thorough analysis of the spectrum, two telescopes will divert part of the incoming beam with stacks of gratings that diffract the X-rays, fanning out the various wavelengths on to a CCD strip at a secondary focus. A continuous spread of energy across the waveband will be due to pervasive thermal and physical processes in the cosmic source. Spikes or "lines" will stand out at particular wavelengths, corresponding with individual chemical elements.

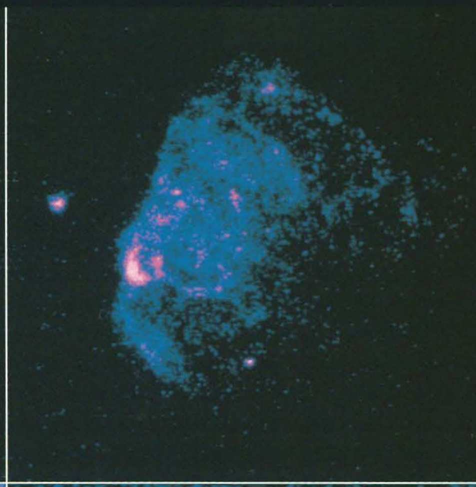
The atoms emitting the lines are almost naked, having been stripped of nearly all their electrons in the high temperature prevailing in the X-ray source. Particularly conspicuous and useful for the astronomers, because of their abundance in the cosmos, are the highly ionized forms of oxygen and iron.

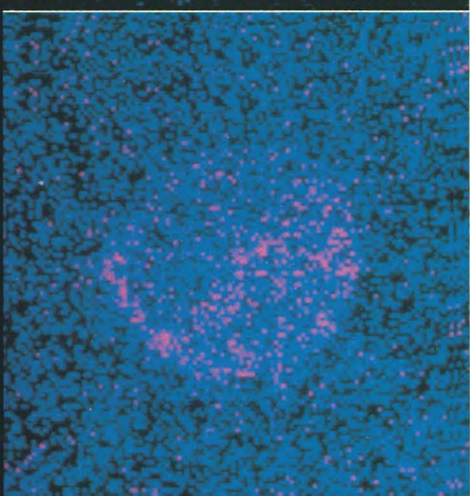
Besides its X-ray telescopes, XMM carries a sensitive conventional telescope to observe the same part of the sky by ultraviolet, visible and infrared light. The astronomers will know exactly what the X-ray telescopes are looking at, and will be able to investigate objects of interest immediately, across a broad spectrum.

Exosat CMA
The supernova remnant Cas-A

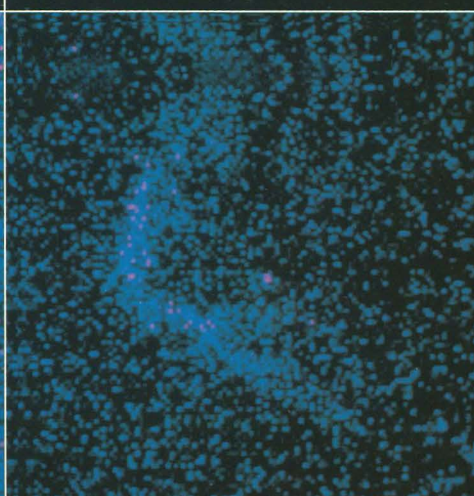


Exosat CMA (Lexan)
The Puppis-A supernova remnant





Exosat CMA
The supernova remnant SN1006



Exosat CMA
The supernova remnant RCW86

Remnants of exploded stars. Images from ESA's earlier X-ray mission Exosat (launched in 1983) show the emissions from the cloud of material flung out from supernova events. XMM will detect undiscovered supernova remnants in our Galaxy and also in neighbouring galaxies, and analyse the processes that generate the X-rays.

Waiting to be explored. When the German-built Rosat X-ray satellite simply kept staring at a small part of the sky in Ursa Major for 42 hours, dozens of new faint sources came into view. The packing was equivalent to some 400 X-ray sources in a square degree, or more than ten million in the whole sky. "The X-ray sky is rich in interesting objects," says Joachim Trümper of Garching, the doyen of German X-ray astronomers. "This deep search by Rosat gives a forceful impression of why more powerful instruments like XMM are justified."

Image: J. Trümper (MPE Garching)

A discovery machine

Astronomers have a long list of targets for XMM. They wish to review and consolidate the findings of X-ray astronomy so far, and make new discoveries of which only XMM is capable.

That ordinary stars emit X-rays from their atmospheres, or coronas, is a phenomenon first found in the Sun. The heating of the coronas to X-ray temperatures is a mystery. XMM will look for an answer by comparing stars of many different sizes and conditions. It will detect variations from hour to hour, and use its spectroscopic powers to relate the X-ray emissions to the motions and temperatures of the gas.

Vampire stars, formally called X-ray binaries, are the products of star death in one of a pair of stars orbiting in close company. Extremely dense forms of matter are represented in the white dwarfs, neutron stars or black holes that suck gas from their companions. XMM will see the X-ray binaries clearly even in neighbouring galaxies. By spectroscopy it will describe the dense objects in detail, and reveal how the gas swirls around them and crashes into them.

Part of the joy of this powerful observatory is that, when examining one targeted X-ray source, it will automatically gather detailed information on hundreds of other sources that happen to be in the same field of view. This serendipitous part of XMM's operations may throw up a surprise at any time. It will also provide abundant statistical data on sources of all kinds, which can solve cosmological problems about the overall nature and history of the Universe.

Many of the X-ray sources seen serendipitously will be distant active galaxies. If a giant black hole lurks in the nucleus of a galaxy, and creates uproar by swallowing stars and gas, X-rays would emanate from very close to the black hole. This makes X-rays ideal for spectroscopic observation of the extraordinary conditions there.

And astrophysicists are perplexed by wide differences in the appearance of the various disturbed galaxies.

By sampling many thousands of them, XMM will either show that the differences are more apparent than real, or else define the physical processes that create the differences.

By locating powerful X-ray galaxies out to the limits of the visually observable Universe, XMM will look back in time to the era of galaxy formation. This may be the source of the X-ray background that fills the sky. According to one theory, it originates from large numbers of galaxies that were active early in the history of the Universe, and gave off X-rays while other emissions were stifled.

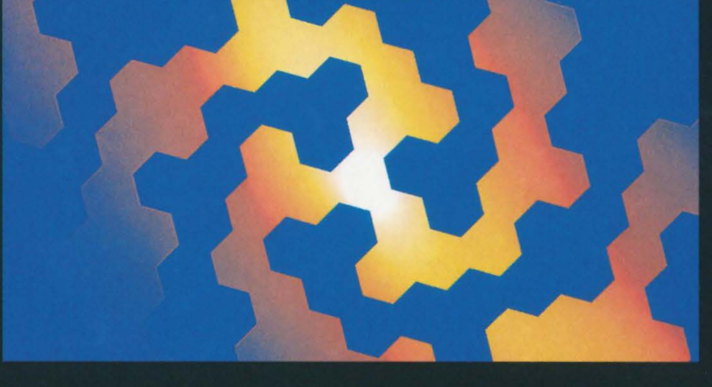
"XMM will be at the cutting edge of 21st Century astronomy," says Tone Peacock, ESA's project scientist. "Other observatories in other wavelengths will be following up our discoveries."

Integral: gamma-rays and violent Nature

Improvements that took centuries for telescopes on the ground are compressed into decades in space astronomy, as the baton of discovery passes from one satellite to the next. Unless each newcomer adds considerably to what its predecessors have done, its cost is hard to justify.
Thus the European Space Agency's COS-B pioneered gamma-ray astronomy in space twenty years ago, but the satellites of the 1990s, NASA's Compton Observatory and Russia's Granat, are far more effective. And ESA's new gamma-ray observatory Integral, due to fly in 2001, will be ten times better still.

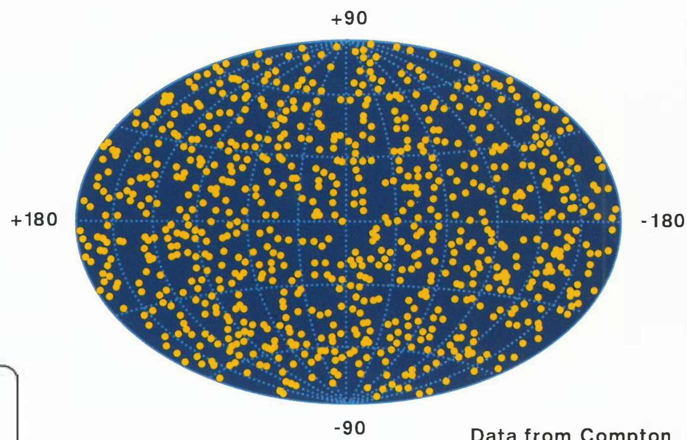
A coded mask. Superimposed on a part of the gamma-ray sky is a specially computed mask to go in front of the Imager in ESA's new Integral satellite. Shadows of the mask falling on an array of detectors will define the directions of gamma-ray sources more precisely. Germanium detectors in the Spectrometer will gauge the energy of gamma-ray particles with unprecedented sensitivity and precision.

INTEGRAL



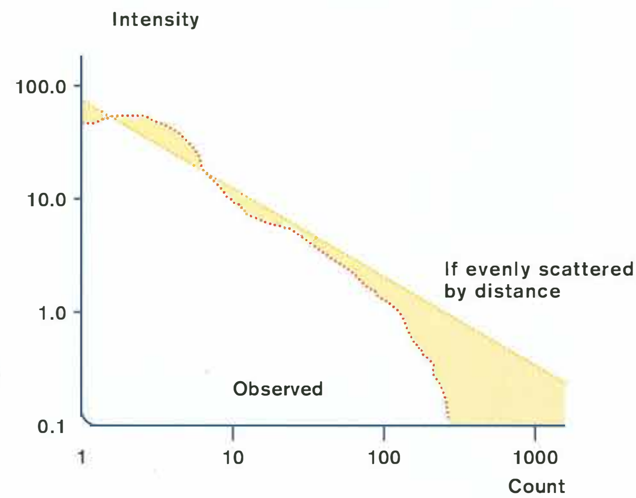
On the Earth, gamma-rays are notorious as penetrating radiation from radioactive materials, yet gamma-rays arriving from the distant Universe cannot pass through the air. Gamma-ray telescopes in space detect radioactive materials in the Universe. But they also pick out events and scenes of ferocious release of energy, usually wrought by intense gravity rather than nuclear forces. Gamma-rays show Nature in its most violent moods.

Gamma-ray bursts

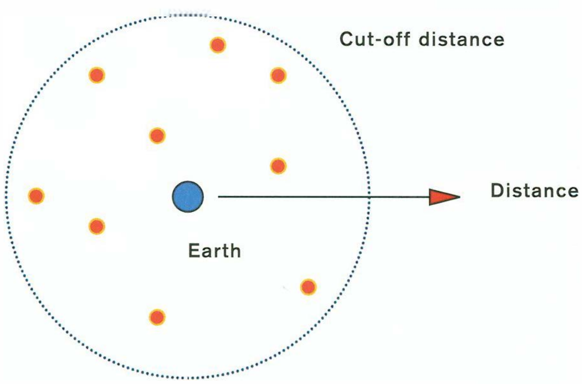


Compton sky map of gamma-ray bursts shows an even scatter in direction

Data from Compton GRO, BATSE/NASA



Counts at different intensities show an absence of very weak (distant) gamma-ray bursts



So gamma-ray bursts are scattered throughout cosmic space but only out to a certain (unknown) distance

Data on Integral

Purpose
to observe and analyse cosmic gamma-ray sources

Waveband
10 MeV to 15 keV (0.0008 to 0.2 nanometres)

Responsible agency
ESA, with contributions from Russia and NASA

Role in Horizon 2000 programme
medium-size mission M2

Name
from International Gamma-Ray Astrophysical Laboratory

Mass
3.6 tonnes

Length
6 metres

Launch
2001

Launch vehicle
Proton (Russia)

Orbit
72-hr eccentric orbit around the Earth 48,000-115,000 km above Earth; inclined at 51.6 deg. to Equator

Ground stations
ESA Villafranca, plus NASA Goldstone and perhaps Canberra

Operations
24 hr per day with three stations

Lifetime
2 to 5 years

Power
solar cells

What are the mysterious gamma-ray bursts?

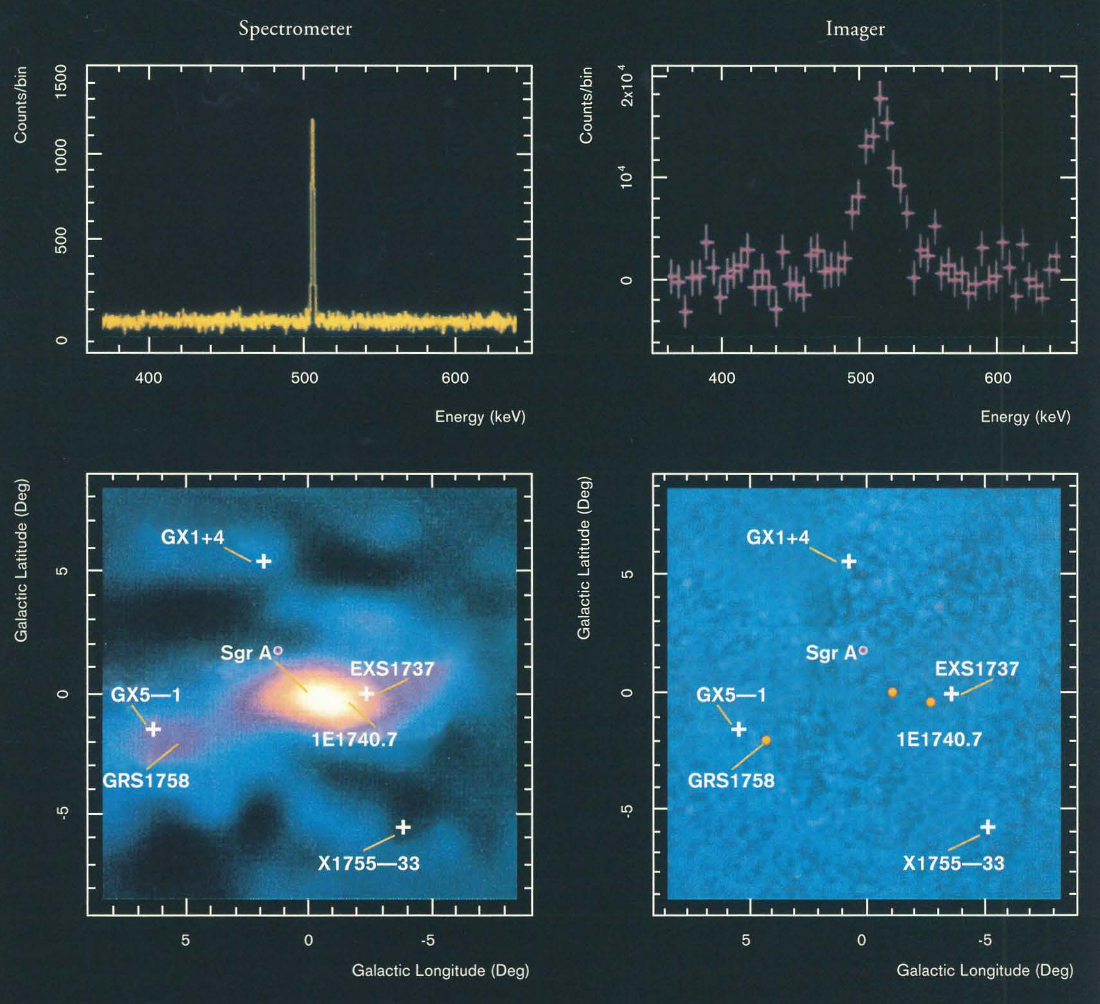
About twice a day, somewhere or other in the Universe, a very violent event generates a burst of gamma-rays. It may last a hundredth of a second, or anything up to 90 minutes. Some bursts are briefly the brightest objects in the gamma-ray sky, while others are fainter. In the late 1960s American satellites watching for gamma-rays from Soviet nuclear weapons tests detected these explosions in the Universe instead. Astronomers heard about them in 1973, and for more than twenty years their imaginations have run riot, without reaching any agreed conclusion. Suggestions range from collisions of comets in the vicinity of the Solar System (implausible) to collisions of very dense neutron stars in distant galaxies (astounding but beguiling).

NASA's Compton Observatory has found that the bursts are scattered evenly around us in a shell. This rules out any simple association with the Milky Way Galaxy, which makes a pronounced ring around the sky. What's more, there are no sources more than a few hundred times fainter than the brightest sources. That means that the shell has an outer limit. The only logical limit, according to some astrophysicists, is the far side of the realm of galaxies, so far back in time that no galaxies existed. If so, the gamma-ray bursts map almost the entire Universe.

ESA's Integral mission has a special strategy for helping to clear up the mystery. Instead of scanning the sky for daily events, as Compton has done, the Integral astronomers will wait for the few events that will occur each year in its field of view, while their instruments are observing more normal gamma-ray targets. They will then automatically analyse the gamma-ray emissions from the bursts, more carefully than ever before. And because Integral will be staring at the same patch of sky for several days on end, the astronomers will be able to search the scene of a burst for any weak signs of a warm-up or aftermath to the event.

No one has ever seen a flash of visible light associated with any gamma-ray burst. A small Optical Transient Camera in Integral will watch the same area of the sky as the gamma-ray and X-ray instruments. Success in matching an event to a visible flash could be the observational breakthrough needed. ESA's project scientist, Christoph Winkler, says of the gamma-ray bursts,

"I believe that Integral has a special chance to solve the riddle."



What the Galaxy's heart may look like. These are computed simulations of the possible appearance in Integral's instruments of the centremost part of the Milky Way, as seen by gamma-rays from annihilated positrons. The Spectrometer (left) will pick out the characteristic emission more cleanly, and the Imager (right) will be more exact about the locations of the sources. The labelled points are positions from which astronomers have previously reported gamma-rays or X-rays.
Images: G. Skinner (Birmingham, UK)

Exploding stars and black holes

As on the Earth, radioactive materials scattered in interstellar space emit gamma-rays of characteristic energies. The strongest sources are clouds created by exploded stars, which stock the Milky Way Galaxy with fresh supplies of chemical elements, including radioactive forms. This way of finding defunct stars and new raw materials offers rich pickings for Integral, which will spend several months mapping the Milky Way and looking for undiscovered sites of exploded stars.

Integral may also help to clear up a puzzle posed by NASA's Compton gamma-ray satellite. Compton has used the 1.8 MeV gamma-rays from aluminium-26 to trace the whereabouts of elements made by thousands of exploding stars in the past million years or so, all around the Milky Way. Astronomers expected a fairly uniform scattering. Instead they found patches of intense aluminium radiation sprawling across several degrees of the sky, with fainter regions in between.

"The bright spots were a big surprise," says Volker Schönfelder of Garching, Germany, whose COMPTEL instrument mapped them. "Are they scenes of strangely concentrated stellar explosions? Are they just a few nearby supernova remnants? Or are the bright spots telling us something quite different, which we've not been clever enough to think of yet?"

Radioactivity is only the most familiar of a wide range of physical processes that create gamma-rays in the Universe. For example, the random encounters of very energetic cosmic-ray particles and interstellar gas create a diffuse emission of gamma-rays all around the disk of the Milky Way. This provides a means of studying the behaviour of cosmic rays, and also the distribution of gas in the Galaxy.

An end-product of a variety of processes is gamma-radiation at 0.5 MeV, called the "annihilation line". It appears when a commonplace electron meets a rare anti-electron, or positron, and they destroy each other. As gamma-radiation of greater energy can create electrons and positrons, much of it changes spontaneously into this form. But positrons can be liberated by other means, including radioactive decay, and natural accelerators in the vicinity of black holes may produce beams of positrons.

In 1991, the French coded-mask gamma-ray telescope in the Soviet Granat satellite detected very strong 0.5 MeV gamma-rays during an intense, shortlived X-ray eruption from a source called Nova Muscae. From other evidence, astronomers concluded that Nova Muscae was a stellar black hole having a snack of gas. The gamma-ray instrument also saw emissions at around 0.2 MeV, which may have been the result of the 0.5 MeV emissions being scattered by the disk of hot gas that, so the theory says, swirls around a black hole. Integral will scan the dense regions of the Galaxy every few days looking for similar events. It may detect new candidate black holes at a rate of one a month.

There are gamma-ray hot-spots near the centre of the Milky Way, where some astronomers suspect a giant black hole may have its lair. The picture is confused by the presence of several objects, which may include small black holes. Observations by Integral, including the search for positron beams, may clear up vexed issues concerning the centre of our Galaxy.

Scientific instruments

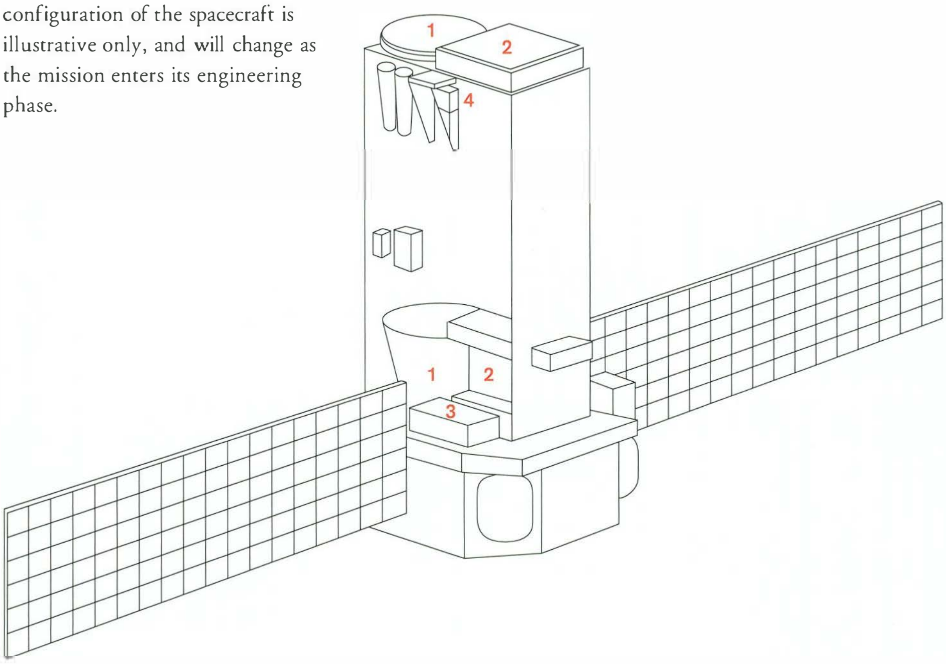
1 Imager
Gamma-ray telescope
using coded mask, caesium
iodide scintillators and
bismuth germanate shield
2500 sq. cm. detector area
70 keV to 10 MeV

2 Spectrometer
Gamma-ray spectrometer
using coded mask,
germanium-70 detectors
and bismuth germanate shield
327 sq. cm. detector area
15 keV to 10 MeV

3 X-Ray Monitor
X-ray telescope using coded
mask, xenon-filled imaging
proportional counter
1000 sq. cm. detector area
3-120 keV

4 Optical Transient Camera
using 30 mm f/1.0 lens
and charge-coupled device
with 2048 x 1024 pixels
550-850 nanometres (yellow to near-IR)

The model payload for Integral. As visualized in a 1992-3 study, two gamma-ray instruments, Imager and Spectrometer, are supported by monitors of X-rays and visible light. Descriptions of the instruments are undergoing revision. The configuration of the spacecraft is illustrative only, and will change as the mission enters its engineering phase.



A trick with a mask

Where other astronomers characterize cosmic emissions by their wavelengths, gamma-ray astronomers use units of MeV. A gamma-ray particle of 1 MeV carries as much energy as an electron accelerated through a million volts. As this is almost a million times the energy of a particle of visible light, a cosmic object equally bright in the two wavebands will emit much smaller numbers of gamma-ray particles. Exposures of days or even weeks may be needed to collect sufficient of them to be sure of an observation.

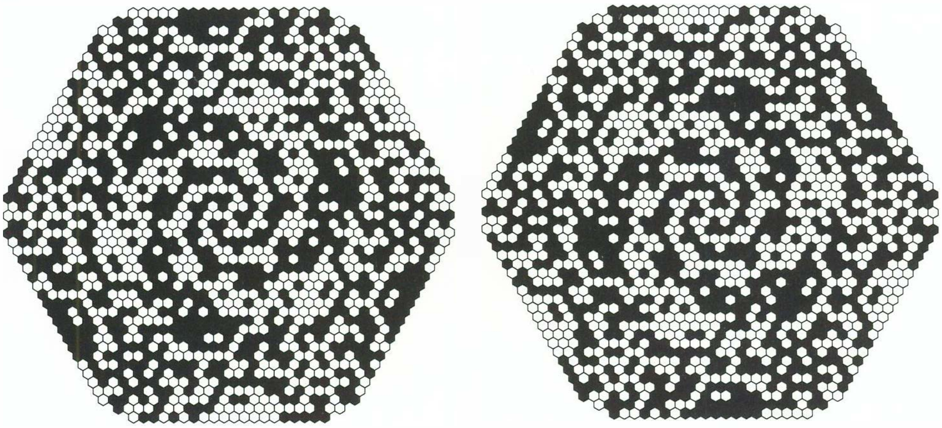
Gamma-ray astronomers have other problems not shared by their colleagues working in different wavebands. Their detection methods are essentially those of the particle physicists, who trace the interaction of gamma-rays with matter through ranks of solid-state detectors or spark chambers. Focusing telescopes, even of the peculiar glancing kind used by X-ray astronomers, are not feasible for gamma-rays. Pinpointing the sources accurately has been difficult and time-consuming, because of the use of scanning methods that block out of most the incoming radiation at any one moment.

Integral exploits a trick called the coded mask, invented in Europe, which images cosmic gamma-rays efficiently without a focusing telescope. Put in front of the detectors a mask that carries a mathematically conceived pattern of holes and opaque regions. Let cosmic sources in different directions in the field of view cast overlapping shadows of the mask on the array of detectors. Count the gamma-rays reaching each position. Then use a computer to disentangle the shadows and work out the direction and intensity of each source.

Space researchers in the UK demonstrated the coded-mask technique with X-rays, first in a sounding rocket in 1976, and then in 75 hours of observation in ESA's Spacelab-2 aboard a NASA shuttle flight in 1985. French and Russian colleagues adopted the technique for gamma-ray and X-ray instruments in the Russian Granat spacecraft, launched in 1989.

Integral will carry two coded-mask gamma-ray telescopes of advanced design, called the Imager and the Spectrometer. Computers will process the data from the Imager to fix the positions of bright point sources by the shadows they cast, to about a hundredth of a degree, and to map extended sources with resolving power up to a few tenths of a degree. For comparison, in the early days of gamma-ray astronomy COS-B had a resolving power of 2 degrees.

"Just as important as the coded masks is the spectroscopy with germanium detectors," says Christoph Winkler, ESA's project scientist for Integral. "We shall increase the proportion of germanium-70 from the natural 20 percent to more than 90 percent. American scientists have tested gamma-ray detectors using germanium-70 in balloon flights. They greatly reduce the background noise due to radioactivity — beta decay. And by techniques that look for signals in more than one part of the detectors we can eliminate this contamination almost entirely."



A proposed coded mask for the Imager. Gamma-ray particles will pass through a honeycomb mask (left) in which half the apertures are blocked by tungsten. Those that pass through will continue to a honeycomb array of detectors set 4 metres beyond the mask. There is no one-to-one correspondence between the entry hole and the position of the detector triggered by the photon. But the pattern of masking is such that a rotation of 60 degrees (right) opens the closed elements and closes the open ones. Statistical methods can then compute the scenery of gamma-ray sources most likely to have produced the patterns of detector-activation observed.

The Spectrometer will operate at minus 190 degrees C, chilled by a mechanical cooler. It will measure the energy of gamma-rays to an accuracy of better than 0.2 percent, which means a 40-fold improvement on current space missions. For example, astronomers will be able to discover the temperatures and condition of materials from which gamma-rays are emitted, and distinguish between cold, warm and hot states of interstellar gas. Integral will carry an X-ray telescope using a coded mask, and also a camera for visible light. The mission will employ much of the same spacecraft engineering as ESA's XMM X-ray satellite, which is due to fly two years earlier. The fact that the operations of XMM and Integral will overlap may offer special opportunities for joint observations of selected objects across a very wide range of the spectrum.

Beyond the Milky Way

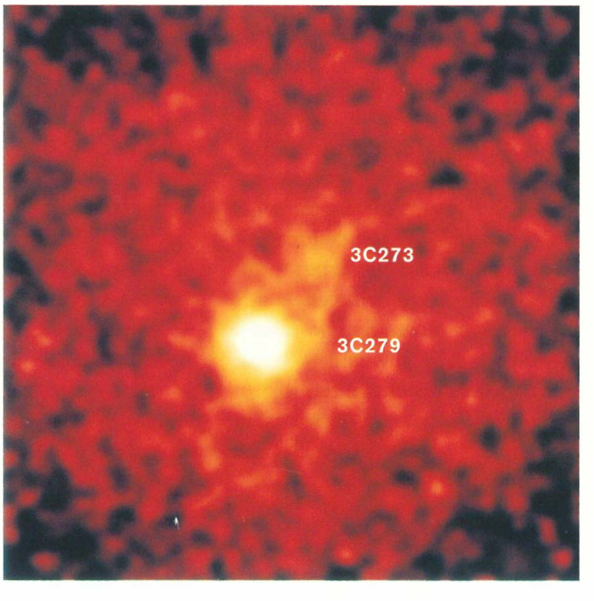
The spectacular element-making explosions of stars called supernovae are rare in our own Galaxy, but are seen quite often in neighbouring galaxies. Scrutinizing the gamma-rays from the newly emerging clouds of debris enables astronomers to see directly the nuclear processes by which the atoms in our bodies were created in stars long ago. Integral will be able to monitor supernovae at distances of tens of millions of light-years.

The present gamma-ray observatories have aroused excitement among astrophysicists by their discoveries of gamma-ray galaxies, also called blazars. Here the theory is that a jet of electrons emerging from the vicinity of a giant black hole in the heart of an active galaxy is pointing straight at the Earth. Colliding with particles of ordinary light, they transfer energy and promote these photons into gamma-ray particles.

As gamma-ray astronomers begin to look beyond the Milky Way, their horizons broaden towards the limits of the observable Universe. Apart from blazars and other objects, short-lived gamma-ray bursts may be coming from cataclysms, so far unexplained, far out among the galaxies. But the more the existing gamma-ray observatories discover, the greater the need to check emergent theories with sharper observations.

A mission for the world

The Russians and Americans are supporting ESA's Integral project for a much more sensitive gamma-ray observatory. NASA's Compton Observatory will be coming to the end of its useful life by the end of the decade, and Integral is due to fly in 2001. A Russian Proton rocket will put it into an unusually high orbit. "It's a privilege to operate our imaging telescope on Compton," Volker Schönfelder remarks, "but I'm also happy that I now have the chance to participate in its European successor, especially since there are only a few flight opportunities for gamma-ray telescopes in a scientist's professional life. We see many fine sights already, but some things tantalize us and make us wish for the greater sensitivity and resolving power that Integral will provide."

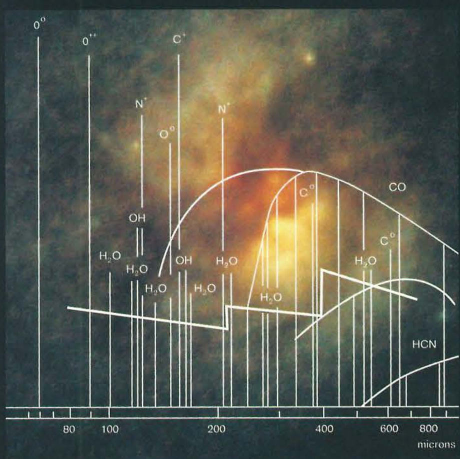


A gamma-ray blazar. Of two active galaxies close together in the sky, 3C 273 is bright by visible light and a weak gamma-ray source. A dimmer-looking object, 3C 279, is seen by NASA's Compton satellite to be far brighter in gamma-rays. Called a blazar, 3C 279 is thought to convert light into gamma-rays in a jet of electrons beamed exactly in our direction.
Image: C.E. Fichtel (NASA Goddard) and EGRET team/Compton Gamma-Ray Observatory

FIRST: the molecular universe

The most important thing that the Universe did was to combine atoms into molecules. On at least one moist planet the consequences were remarkable, where carbon-based molecules made living cells. Eventually, in the human species, the molecular assemblies became smart enough to enquire into their own origins.

Molecules emit particular infrared and radio wavelengths that reveal their identities. Concentrations called molecular clouds are scattered through the Milky Way Galaxy. Here the density of interstellar gas and dust is much higher than usual, and gravity can squeeze the clouds into ever-denser concentrations of matter, to make new stars.



Chemistry at 300 million light-years. A predicted FIRST spectrum shows expected signatures of water, hydroxyl, carbon monoxide and hydrogen cyanide molecules, as well as carbon, nitrogen and oxygen atoms, in the dusty galaxy Arp 220. Arp 220 image: E. Shaya (Maryland) and Hubble WFPC team, ESA and NASA

FIRST

A giant molecular cloud can be 200-300 light-years wide and 100,000 times heavier than the Sun.

During the past thirty years astronomers have fingerprinted more than ninety molecules in interstellar clouds, ranging in complexity from carbon monoxide to exotic molecules containing dozens of atoms. To match the observed emissions, chemists have to create weird molecules and fragments in laboratory chambers that simulate interstellar space. Some complex molecules evolve by successive reactions in the interstellar medium. Others seem to come from the break-up of large football-like molecules of carbon, called fullerenes or bucky-balls, created in the vicinity of dying stars.

Cosmic chemistry proceeds mainly in cool clouds, and from these the molecules and atoms radiate most strongly at wavelengths of some tenths of a millimetre. The Earth's air is full of molecules, which blot out most of the cosmic emissions. Glimpses from high mountain-tops and airborne observatories give the cosmic chemists hints of riches to come. When the European Space Agency's satellite for submillimetre astronomy soars above the atmosphere in 2005, with a 3-metre telescope and cryogenically cooled instruments, it will unveil the molecular universe.

Astronomers will use the Far Infrared and Submillimetre Space Telescope, FIRST, to trace the history of molecules since the Big Bang. The molecules will also serve as probes of the physical conditions that prevail in strange environments. And molecules and microcrystals come together to make the interstellar dust flung out by exploding stars. Before star-making and planet-making recycle the dust, it spends most of its time in cold clouds at around minus 250 degrees C, again radiating in the submillimetre band.

FIRST's special powers will come from its superiority in an unusual range of working wavelengths. The submillimetre waveband is precisely at the meeting point of infrared and radio astronomy. While some members of the scientific team speak of the telescope and microns, others talk of the antenna and define the waveband in gigahertz.

"Superb instruments are guaranteed by special expertise available in Europe," says Pierre Encrenaz of Paris, who led a study of techniques for FIRST in 1992-3. "The development of ESA's ISO satellite gives us high confidence on the infrared side. On the radio side, we have unrivalled experience in ground-based astronomy at millimetric and submillimetric wavelengths."

"So when we promise that FIRST will be ten times better than any predecessor," Encrenaz concludes, "we know what we are talking about, because we ourselves are part of the competition."

Data on FIRST

Purpose
far infrared and submillimetre astronomy

Wavelength range
0.085 to 0.9 millimetre
= 85 to 900 microns = 300-3500 gigahertz

Telescope aperture
3 metres

Launch
2005

Responsible agency
ESA

Role in Horizon 2000 programme
the fourth cornerstone mission

Name
from Far Infrared and Submillimetre Space Telescope

Mass
2.5 tonnes

Length
6.5 metres

Launch vehicle
Ariane 5 (shared launch)

Orbit
24-hr eccentric orbit around the Earth
1000-70,600 km above Earth; inclined at 7 deg. to Equator

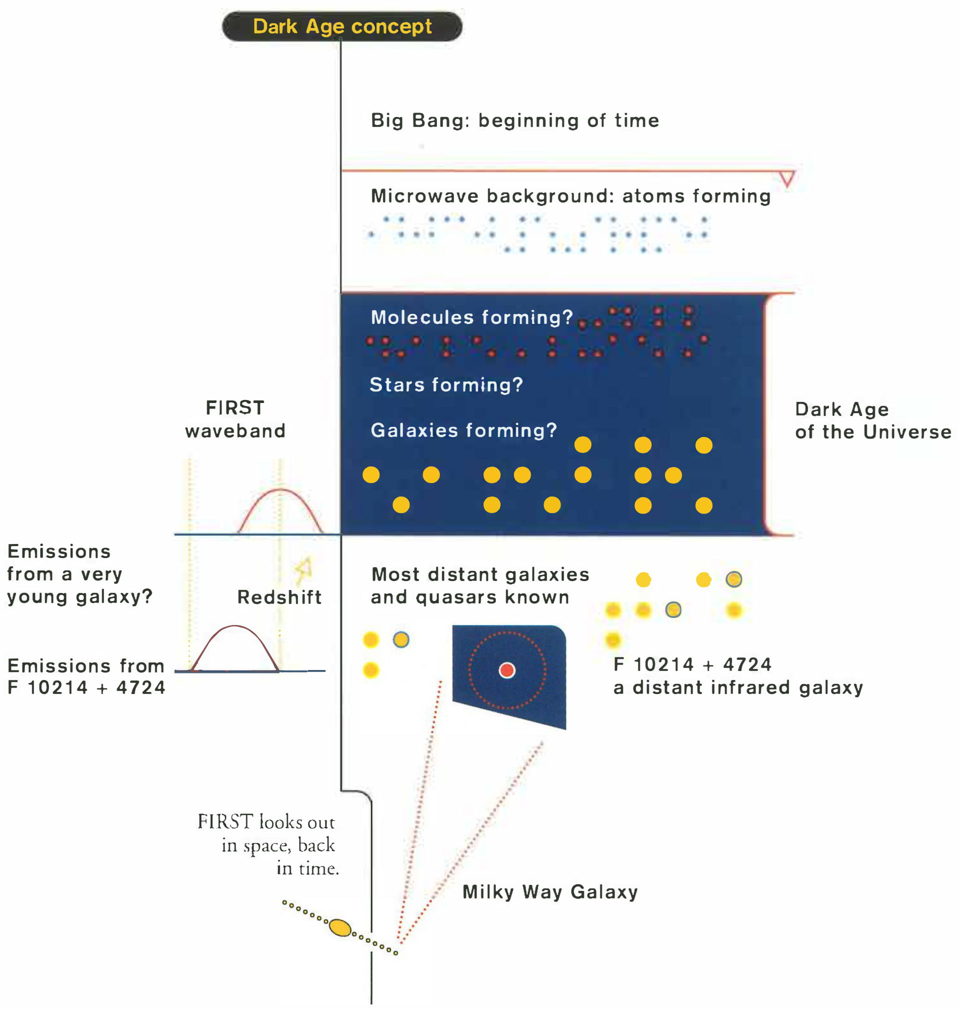
Operations
17 hr per day

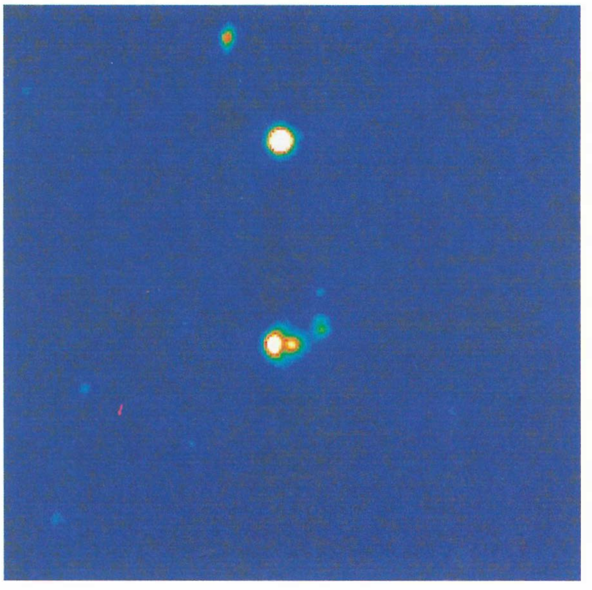
Lifetime
2 to 6 years

Power
solar cells

How and when did galaxies form?

A wide gap in knowledge exists between the most distant visible galaxies and the microwave background beyond them, where clumps of gas correspond to millions of galaxies waiting to be born. Somewhere in the intervening spacetime, the Dark Age of the Universe, galaxies came into existence. These teeming assemblies of stars, which include our own Milky Way, are the characteristic units of visible matter in the Universe. To understand galaxies properly astronomers need to know how and when they formed, and what they were like in their infancy. A crucial question for cosmologists is whether they appeared individually, or in small or large clusters.





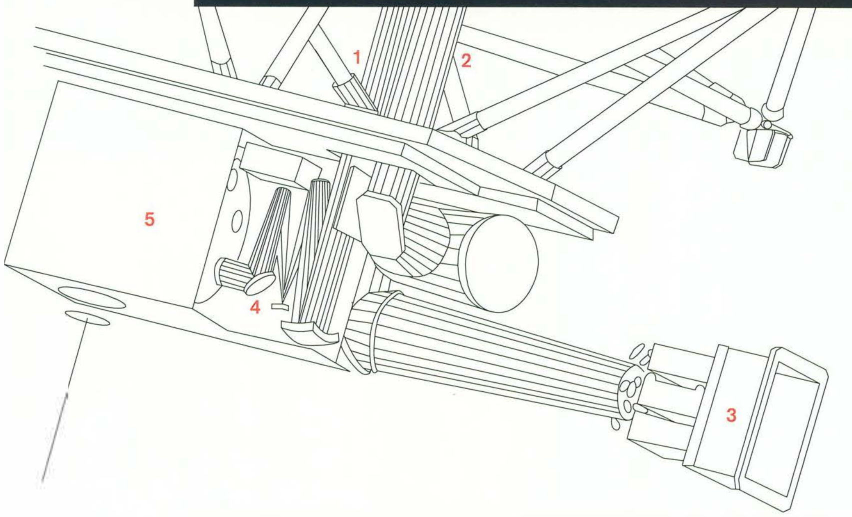
Very dusty and very distant. The large Keck telescope in Hawaii obtained this image of the infrared galaxy IRAS F10214+4724 and established that it lies at an immense distance. The infrared emissions show that the galaxy is unusually thick with dust from exploded stars. Galaxies like this, readily detectable by FIRST, will provide new beacons for exploring the young Universe.
Image: J. Larkin, K. Matthews, T. Soifer (Caltech): Keck Telescope

Quasars are known at greater distances than the galaxies, and therefore farther back in time. They are presumably powered by giant black holes inhabiting galaxies that are not otherwise visible. Some radio sources may well be young galaxies too, but astronomers cannot judge their distances without visible counterparts. To be make sure of their story of the birth of the galaxies, they need to detect large numbers of very young examples beyond the range of visible-light telescopes.

"FIRST seems to be ideal for chronicling galactic origins," says Michael Rowan-Robinson of London. "There are reasons to think that primeval galaxies were very dusty and radiated most intensely in the infrared. But in the early period of interest, the expansion of the Universe multiplies by six times or more all the wavelengths emitted by galaxies. This enormous redshift converts infrared into submillimetre radiation, which FIRST will see more clearly than any other instrument now in prospect."

The spacecraft will look intently, for many weeks, at a region of the sky seen through a window in the local dust of the Milky Way. Calculations suggest that FIRST will identify thousands of infrared galaxies for the first time, including many at great distances where the first galaxies must reside. And even earlier in the Dark Age, for hundreds of millions of years a warm gas was the main constituent of the Universe. FIRST will look for molecules in the primeval gas and so carry cosmic chemistry back to within a few million years of the Big Bang.

The model payload. Instruments for FIRST were planned by a team of European scientists in 1992-93. The designs will be confirmed or varied towards the end of the decade. The detectors will have to operate at very low temperatures, achieved by using an array of Stirling-cycle mechanical coolers developed by British engineers. This technology will extend the life of the mission, as compared with older cooling methods (as in the IRAS and ISO spacecraft) that rely on venting helium.



Watery shocks and icy capsules

Life's indispensable medium, water, originates in cosmic factories. The theory is that blast waves from exploding stars, or fierce winds from newborn stars, jolt the hydrogen and oxygen of interstellar space to make water molecules. FIRST will examine shocked interstellar gas for newly-formed water and follow its fortunes in molecular clouds, and in the throng of material rushing together to make new stars and planets.

FIRST will pick up the story of water nearer home by monitoring the evaporation of ancient ice when comets fly near the Sun. Its molecular studies will complement ESA's comet missions, Giotto and Rosetta. And like the Huygens mission to Titan, FIRST will test the theory that the Earth's atmosphere and ocean came from impacting comets. Scanty water vapour traced through the atmosphere of Mars will elucidate the red planet's weather, at a time when surface exploration is expected to resume.

Water ice is a constituent of interstellar dust. It freezes on stony grains and tarry mixtures of carbon compounds. The icy capsules that result testify to the capacity of the Universe to engender life. FIRST can observe the dust clouds not only in the Milky Way Galaxy but in other galaxies too.

Molecules and dust grains are not passive by-products of physical events. The chemical flavours of the clouds affect the rate at which they collapse to make stars. And as icy capsules unwrap in the heat, the flavours change. This physical and chemical interplay has dramatic effects. It created the contrast between the rocky Earth and gassy Jupiter. FIRST will enable astronomers to trace similar molecular processes at work in the wider Universe of stars and galaxies.

Model payload

1 FIR feed
2 MFH feed
3 MFH local oscillator
4 FIR optical path
5 FIR detectors

FIR: far-infrared instrument
Imaging and spectroscopy 0.085 to 0.3 mm
with one photoconducting array
Imaging photometry 0.3 to 0.9 mm
with two bolometer arrays
Minimum detector temperature 0.15 K

MFH: multi-frequency heterodyne receiver
Spectroscopy 0.27 to 0.6 mm
(1113 to 490 GHz)
with nine heterodyne mixers
Minimum detector temperature 4 K

Clouds of gas and dust. An infrared image of starmaking regions in the Orion constellation, from the IRAS satellite, gives an impression of the sprawling clouds that FIRST will explore in molecular detail.
Image: IRAS/NASA/JPL

Incubating stars

"We have not yet conclusively identified any true protostars," says Göran Pilbratt of ESA's Space Science Department. "But we're sure that FIRST will help us find them."
Protostars are cosmic eggs, and the missing link in the astronomers' story of how the Sun and other stars came into being by the collapse of clouds of gas and dust. The hot embryo of a new star is thought to be surrounded by an eggshell of dark gas and dust that glows only at submillimetre wavelengths, radiating into cosmic space the intense heat of the star's formation. The star hatches when its emissions grow strong enough to push apart the dust shell and let visible light escape.

Our Galaxy, the Milky Way, makes several new stars every year and their incubation takes hundreds of thousands of years, so there must be many protostars to look for. The Orion constellation and other nebulous regions are well-known sites of star formation. But by the time the infant stars show up at visible wavelengths, or even in the infrared penetrating the dust clouds, starmaking is virtually complete.
ESA's infrared satellite ISO, due for launch in 1995, will attempt to spot protostar candidates at the extremity of its wavelength band, 0.2 millimetres. The expected peak emission from a protostar is at 0.3 millimetres, comfortably in the middle of FIRST's waveband when it flies ten years later. With its high sensitivity, the spacecraft will be able to detect protostars out to a distance of 5000 light-years, which brings many stellar hatcheries within its reach.

FIRST will not only identify many protostars unambiguously, but study them in detail. Its identifications of the molecules present will give a new chemical perspective on star formation. For example emissions from particular molecules, called cooling lines, play a direct part in removing excess heat that could disrupt the process of collapse. And wavelength shifts in the radiation of molecules will reveal the speed of gas falling towards the protostar, even if it is as slow as a few hundred metres per second.
In the Milky Way and other spiral galaxies, new stars are concentrated mainly in the bands that make the bright spiral arms. Unable to explain this elegant feature by other means, some astronomers suspect that neighbouring galaxies set up waves that compress the starforming gas. FIRST will be able to map regions of starbirth in nearby spiral galaxies in unprecedented detail, and so may help to solve a long-standing puzzle.

The dustiest galaxies

Arp 220 is an ultraluminous infrared galaxy, which puts out ten times more energy as infrared rays than as visible light. Thick dust obscures regions where starmaking proceeds at a fierce rate. Astronomers interpret the event as a collision of galaxies, causing shocks in the interstellar gas that provoke the mass-production of stars.
There may well be a link between the galactic collisions and the quasars and active galaxies, where giant black holes are thought to cause the violent outbursts, as they feast on stars and gas. Besides consuming gas in the creation of new stars, the turmoil in colliding galaxies can also feed some of their gas into the giant black holes that may exist within either or both of them.

In Arp 220 and many similar galaxies, including M82 which is relatively close, FIRST will detect various molecules and use them as indicators of physical conditions in interstellar gas. And the strength of submillimetre emissions from dust will enable astronomers to calculate the total mass of dust in each galaxy, and the rate of star formation.
Astronomers realised the peculiarity of Arp 220 when the satellite IRAS detected its strong infrared emissions in 1983. IRAS also logged, among many other objects, a distant and faint galaxy F10214+4724. Ten years later, the Keck telescope in Hawaii showed it to be another dusty starburst galaxy, but so remote and travelling away so fast that its strongest emissions must be shifted into the submillimetre band. If, as seems likely, many more such objects await detection, this discovery gives FIRST new opportunities to explore the most distant reaches of the realm of galaxies.

Worth waiting for

FIRST is last, in the sense that it is the last cornerstone mission of ESA's Horizon 2000 programme. For the enthusiasts, this means a twenty-year wait, from the original conception of the spacecraft to its completion. The selection of teams to develop the instruments will not be made until the end of 1997. Then years of work will follow, until an Ariane 5 rocket heaves FIRST into space in 2005 and astronomical observations are radioed back to the Earth.
Critics sometimes question the wisdom of announcing scientific space missions so far in advance. Certainly it would be rash to finalize the instrumentation and the design sooner than necessary. But the long lead time makes possible the technological development needed to match the scientists' ambitions to a realistic budget. Any discoveries made in the meantime, by smaller satellites and airborne instruments, will only sharpen the desire for a powerful general-purpose observatory working across the whole submillimetre band. All in all, FIRST is well worth waiting for.

esa

PART 3

Horizon 2000 Plus

Overview: hard tasks for the new century

Twenty years is a long time in science. Unexpected discoveries prompt new questions. Each intake of young scientists has fresh ideas that challenge the concepts of their professors. No one knows what issues will preoccupy researchers a decade or two hence.

Nevertheless, the scientists, officials and national delegates who shape and authorize the European Space Agency's science programme must already look ahead to the second decade of the 21st Century. Only by farsightedness can a relatively modest annual budget avoid cash-flow crises and cope with the problems that crop up in every project, while providing Europe's space scientists with an uninterrupted succession of world-class missions.

Choosing hard tasks is the way to resolve the contradiction between long-term planning and the unpredictability of research. Some major questions in science seem certain to remain unanswered until extraordinary new instruments appear. In space research this means spacecraft that are cleverer than any available so far. Normally the scientists advising ESA are cautious about the technical feasibility of proposed missions. When they look twenty years ahead they must ask themselves if their ideas are daring enough.

In a series of meetings spanning ten months in 1993-94, a survey committee of scientists reviewed 110 proposals instigated by thousands of researchers in Europe, and some in the USA. With what the chairman Lodewijk Woltjer, of St Michel, France, called "a surprising degree of unanimity," the committee then made its choices. It nominated three major missions for ESA's Horizon 2000 Plus Programme, which spans the period 2006-16.

These cornerstone projects cover a wide range of science. One is a new venture in the Solar System, to explore the enigmatic planet Mercury, close to the Sun. The second mission, in astronomy, will use two or more visible-light or infrared telescopes to achieve an unprecedented sharpness of vision. It will apply the technique of interferometry long favoured by radio astronomers. The third proposal is for a space mission to detect gravitational waves.

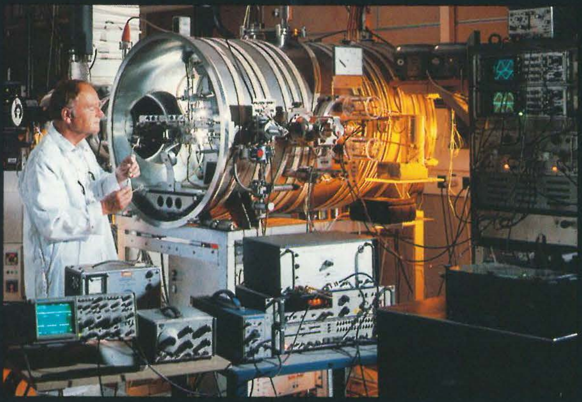
The scientists recommend European self-sufficiency in respect of these cornerstone missions of Horizon 2000 Plus. While being open to participation by other agencies, their execution should not depend on decisions taken elsewhere. Opportunities for cooperation nevertheless abound in the space-science community of the post-Cold War world.

"More and more offers of cooperation are coming from renowned space scientists outside our member states," observes Roger Bonnet, ESA's Director of Science. "They like working with us, I believe, because ESA has shown itself to be the most reliable partner in space science. That is thanks to our stable budget and the fact that we have never cancelled a mission already approved."

The survey committee noted possibilities of inter-agency collaboration in the medium and small missions of Horizon 2000 Plus. The funding reserved for these projects will allow Europe to react to new opportunities, and to scientific questions not yet identified, by selecting and flying scientific missions on shorter timescales than for the cornerstone missions. The survey committee therefore refrained from being too prescriptive, but some of the ideas that it mentioned give an impression of how ESA's programme may be enriched.

To satisfy the intense interest in the Sun among Europe's scientists, as evidenced by the current Ulysses, SOHO and Cluster projects, at least one solar mission will be included in Horizon 2000 Plus. ESA might take part in an international project to observe the Sun in 3-D, from spacecraft distributed around the Earth's orbit. The survey committee also commended the idea of joining with other space agencies to build a probe that would fly right into the Sun's corona.

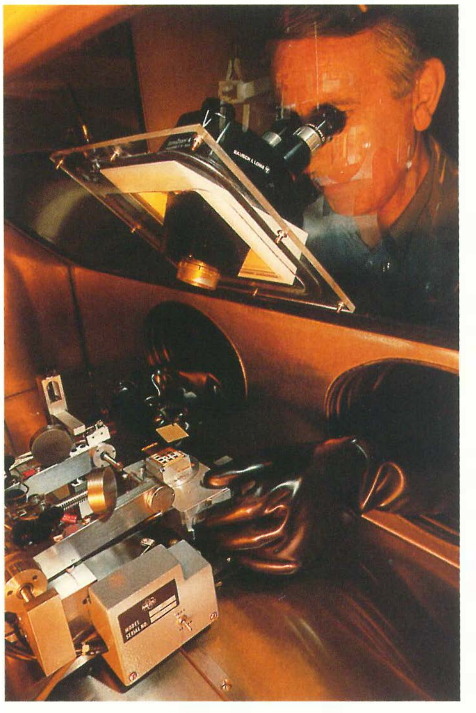
The Horizon 2000 Plus report hints at a possible new propulsion system. The exploration of the Sun and the Solar System relies on chemical rockets and planetary swingbys, to achieve the necessary trajectories by manoeuvres that can take several years. Space engineers believe that solar-electric propulsion could reduce the longueurs. Huge solar panels would power an electric rocket delivering a small but incessant thrust to a spacecraft. Solar-electric propulsion remains a possibility for the 21st Century and the solar coronal probe might be an early application.



Electric propulsion. ESA's technologists have researched for many years the possibility of driving a spacecraft with electric thrusters.

Mars is another prime target, and ESA already belongs to an international working group set up to plan concerted operations on the red planet. Present uncertainties make an ESA Mars mission hard to define. Even so, the survey committee thought that ESA should be ready for "substantial participation" when the opportunity arises.

As for astronomy, besides the interferometer mission, the scientists urged ESA to continue its role in the Hubble Space Telescope and in possible successor programmes in the visible and ultraviolet wavebands. They noted that the international manned space station might provide an opportunity for testing or implementing a major new X-ray or gamma-ray mission. Technological studies of lightweight X-ray multiple-mirror telescopes and improved electronic X-ray detectors were also recommended. Looking at the far edge of Horizon 2000 Plus, the survey committee visualized an X-ray satellite even more powerful than ESA's forthcoming XMM, for the period after 2016. A further infrared astronomy mission is also in prospect.



Spaceworthy instruments. ESA's Space Science Department can make special electronic assemblies for experiments in satellites.

The engineering challenge

The cornerstone missions, designated for Mercury, interferometry and gravitational waves, will each cost ESA about 640 million ECU ($ 800 million) at 1995 prices, with further contributions from the experimenters' institutes and national funding agencies. Therefore they will be major opportunities for Europe's aerospace, electronics and instrument-making industries. All of them require new technology to help push back the boundaries of knowledge.

By implementing the missions within a defined but not over-hasty timescale, ESA will give to Europe's engineers the kind of stimulus to innovation which, in other parts of the world, comes from defence programmes. New materials for lightweight and ultra-stable structures, novel methods of cooling, sensitive instruments and control systems, smart electronic and optical circuits – these are all examples from the technological shopping lists of Horizon 2000 Plus.

Question marks are still attached to these cornerstone missions. At the time of writing, the programme has still to be approved in principle by the national delegates on ESA's Science Programme Committee. Achieving all three major missions in the period of Horizon 2000 Plus would require moderate increases in the annual science budget, starting in the year 2000. This is the cost of widening ESA's science domain to include fundamental physics, without cutting back on its commitment to research in the Solar System and astronomy.

Confirmation and scheduling of the individual missions within Horizon 2000 Plus will come later, depending on the progress with the technology they need. In the case of interferometry, a choice will have to be made between visible light and the infrared. The survey committee's recommendations of 1994 nevertheless encapsulate the hopes of Europe's scientists for future space research, and for the technological developments that will make it possible. The proposed cornerstone missions give a broad shape to ESA's Horizon 2000 Plus science programme, and show how to maintain the momentum established in the present Horizon 2000 programme.

This Overview pays attention to engineering aspects of the missions, because the wishes of the scientists are at the margin of what is possible today. Some would be far too expensive to attempt now. An engineer, it is said, is someone who can do for a dime what any fool can do for a dollar. The challenge of Horizon 2000 Plus is to use ingenuity and technological research to fulfil novel and ambitious projects within the allotted budgets.

A mission to Mercury

Heat is the main threat to any spacecraft venturing to the innermost planet. The sunshine near Mercury is roughly ten times more intense than it is near the Earth, and radiation from the hot planet will add to the thermal load on a spacecraft flying over it. The scientists want a mission to explore Mercury more thoroughly than has been possible hitherto, but they know they are posing problems for their engineering colleagues.

ESA's cornerstone mission will require a spacecraft to operate in orbit around Mercury for at least three months. That is the time taken for the planet to revolve once around the Sun. If other space agencies join in, it may be possible to add a lander that will descend to the planet's surface, or a sub-satellite that will make simultaneous observations in other regions of the planet's environment. A Venus probe, to be released en route to Mercury, is another option.

The shape and size of the Mercury spacecraft, and its orientation relative to the Sun, affect the input of heat. So does the choice of orbit around the planet. This has to take account of the planet's own eccentric orbit, which makes the sunlit surface exceptionally hot at Mercury's closest approach to the Sun.

Even when these operational factors have been adjusted, to minimize the heating without compromising the mission's scientific objectives, the solar intensity will still roast the orbiter like a chicken on a spit. Besides paying attention to paint, to reflecting and radiating surfaces, and to thermal blankets for insulating vital components, the engineers may wish to employ mechanical coolers. Stirling coolers rely on the simple compression and expansion of a sealed volume of gas. They are already in use in ESA's ERS Earth observation satellites. Ultra-cold versions are being developed under ESA contracts for the FIRST astronomical satellite. For the Mercury mission, Stirling coolers might be adapted to operate in warm conditions.

Inevitably, though, some parts of the spacecraft will be uncomfortably hot, and the technological challenge is to operate mechanical and electronic equipment at high temperatures. The solar cells providing power for the spacecraft will have an over-abundance of sunlight to drive them. ESA's engineers will be looking to developments in gallium-arsenide solar cells, instead of the traditional silicon, and to heat-resistant glues for bonding them to the spacecraft.

The dish antenna of the orbiter must keep pointing steadily at the Earth while the spacecraft rotates. Any failure of the despin motor, which accomplishes this, would kill the mission because the scientific data could not reach the ground stations. The despin motor in Giotto, ESA's comet interceptor, caused much anxiety during its development but in the end it worked faultlessly. For the Mercury mission, the motor and the associated rotary joints feeding radio signals to the antenna must be fit for high-temperature operation.

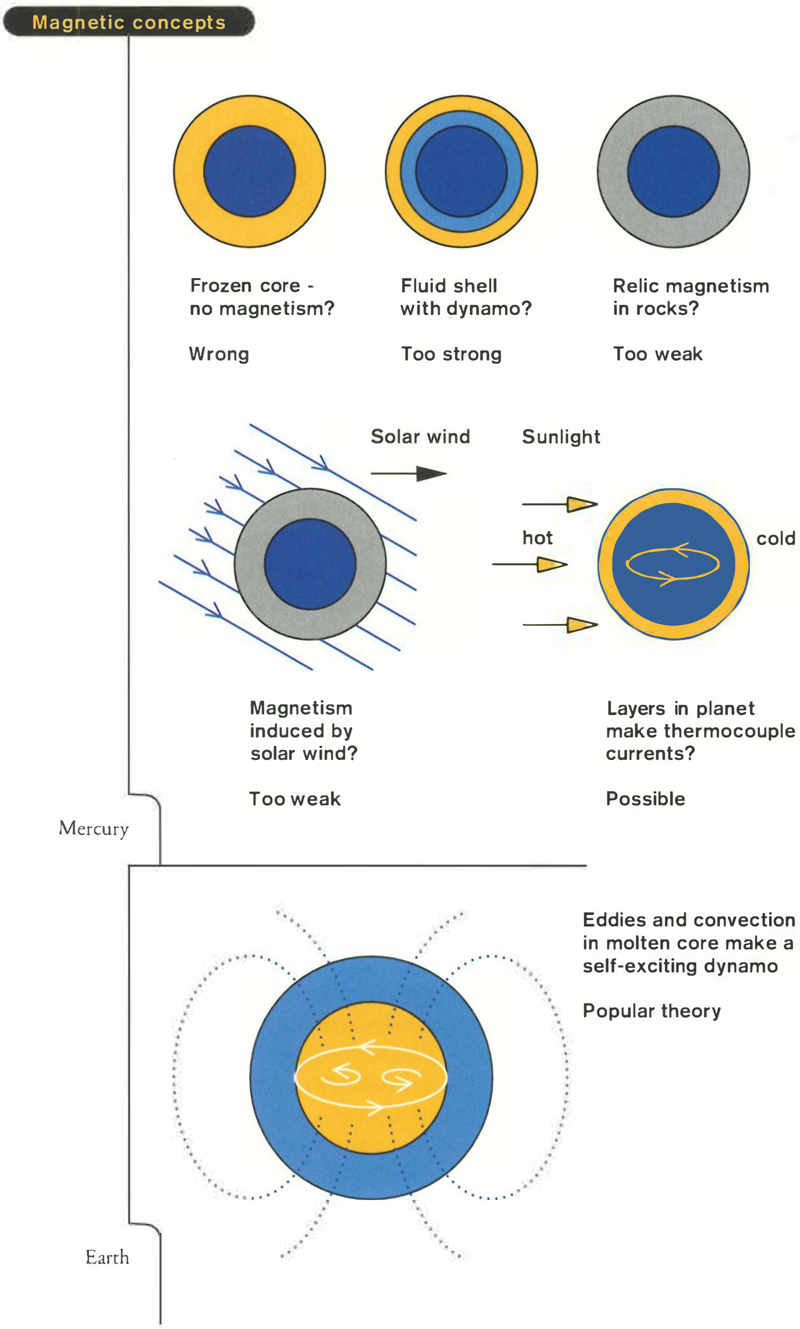
The scientists also want the spacecraft to be magnetically clean. Careful engineering must ensure that batteries, current supplies, motors, a camera and the various scientific instruments all operate without exuding significant magnetic fields. Otherwise they would frustrate one of the chief aims of the mission, which is to chart Mercury's rather feeble magnetism.

Planetary scientists need to know why the planet has any magnetic field at all. Its detection by NASA's Mariner 10 spacecraft, during brief flybys in 1974-75, was a big surprise. The planet's high density, compared with the Earth's, is another puzzle. It evidently consists mainly of iron. Did Nature simply prefer that element when building a planet near the Sun? Or did a cataclysmic collision blast away most of Mercury's lighter rocks? The airless planet also interacts with the wind of electric particles from the Sun, and will offer a fascinating comparison with events around the Earth.

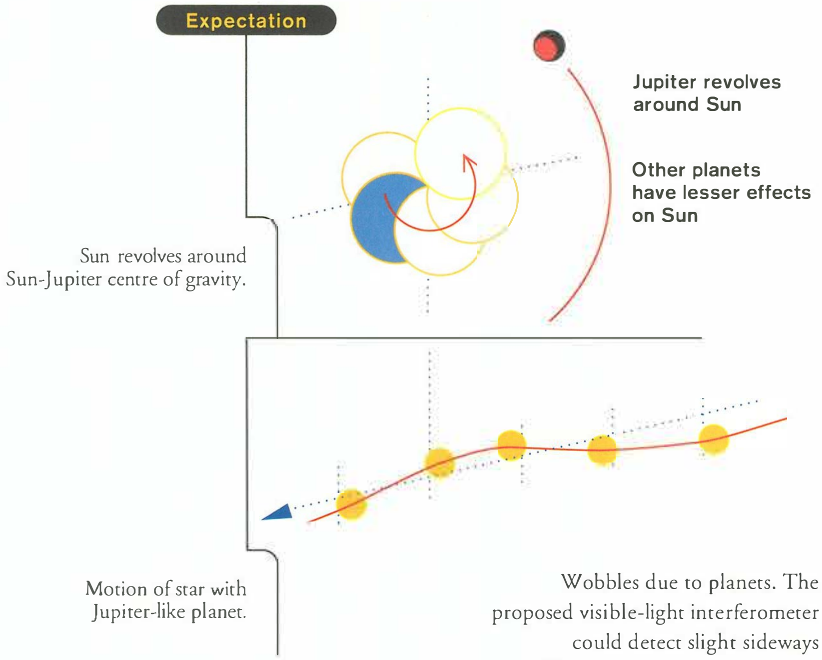
Despite some special difficulties, the Mercury mission is an extension of current space technology. The spacecraft will probably resemble, in some salient features, the satellites of ESA's Cluster mission of 1995. For this reason, experts are convinced that the Mercury mission is both feasible and affordable, within the limits of a cornerstone budget.

It also gives a foretaste of the far more severe heating problems that would await a solar coronal probe, mentioned as a collaborative option for Horizon 2000 Plus. If a spacecraft were to fulfil the wish of solar physicists, by flying through the Sun's atmosphere at a distance above its surface equal to 1.5 times the Sun's diameter, it would experience sunlight 2900 times stronger than at the Earth.

The puzzle of Mercury's magnetism. Theorists have a hard time trying to explain it, but ESA's mission to the planet may help to solve the mystery.



Ordeal by light. In ESA's Large Space Simulator at Noordwijk in the Netherlands, powerful xenon lamps imitate the effects of solar radiation on spacecraft, during pre-flight tests.



Wobbles due to planets. The proposed visible-light interferometer could detect slight sideways oscillations in the motions of stars across the sky, revealing the presence of massive planets. In these diagrams the motions are exaggerated.

Keen-eyed interferometry

How do you equip a spacecraft with pairs of telescopes separated by several metres, and prevent them shifting their relative positions by as much as the width of an atom during their operations? To any engineer familiar with vibrations, flexing and the internal changes in temperature that occur as a spacecraft spins or slews its orientation, this is a tall order.

Yet astronomers who want keen-eyed instruments for the 21st Century require rock-steady performance. If construction methods or active control techniques cannot quite achieve it, then internal measuring devices must detect microscopic movements, from moment to moment. They should transmit the news about any departures from the norm, along with the spacecraft's observations of the stars.

In an interferometer, combined operations by pairs of separated telescopes achieve the same sharp-sightedness as a single large telescope. Light waves from a distant object, gathered by the two telescopes and brought together, will interfere with each other. Sometimes they add together and sometimes they cancel out. For a point source in the sky, the result is a pattern of bright and dark stripes, which peaks in intensity at a well-defined centre. Any movement in the optical system would alter the lengths of the paths followed by the two light beams before they come together, so making the interpretation of the interference pattern unreliable.

Stringent requirements for mechanical stability arise in the visible-light option for the interferometric cornerstone in Horizon 2000 Plus. Europe's scientists see it as the way to follow up the success of ESA's astrometric mission Hipparcos, which is already pinpointing the positions of stars far more accurately than is possible from the ground. An interferometric mission could bring further spectacular gains.

A spacecraft for this astrometric purpose requires two or three interferometers looking in different directions in the sky. The relative orientations of the mirrors must remain constant to about a billionth of a degree, for hours on end, while the interferometers scan a ring around the sky and measure the angles between many pairs of stars.

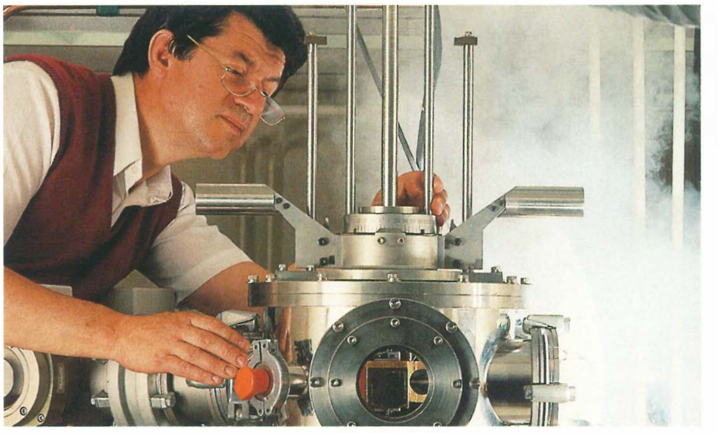
One concept for such a mission is called GAIA or the Global Astrometric Interferometer for Astrophysics. It would use pairs of telescopes, each 0.55 metres wide and spaced 2.5 metres apart. Three such interferometers would look out sideways from a cylindrical satellite configured to fit inside the nose fairing of the Ariane 5 launcher.

Larger and more widely spaced telescopes could pinpoint the stars even more accurately and observe fainter objects. A greater number of distant quasars would come within the scope of the instrument. Astrometrists could then relate the positions of foreground stars to the wider Universe, as charted by radio astronomers with their own very-long-baseline interferometric methods. But with, say, two pairs of 1-metre telescopes spaced 10 metres apart, the problem of maintaining steadiness within the optical system would be even more severe.

An interferometer of moderate size, like GAIA, could in principle fix the positions of 500 times as many stars as Hipparcos, and with 200 times the accuracy. It would operate in a survey mode, to chart the whole sky. Its very accurate plotting would reveal in precise detail the influence of the Sun's gravity, which bends the paths of starlight and so shifts the apparent positions of the stars. The shifts are expected by Albert Einstein's theory of gravity. If his predictions were wrong by as little as one part in a million, the astrometry mission would find him out.

The payoff for astronomers would be rich and varied. Better and more distant measurements of the motions of stars would give, for example, a clearer picture of the distribution of the mysterious Dark Matter in the Milky Way Galaxy. Theorists would be anxious to know just how far away the globular clusters are, because these are the oldest constituents of the Galaxy. Even the distances of giant stars in the nearest galaxies, the Magellanic Clouds, would be directly measurable.

Another special dividend from a visible-light interferometric mission would be the detection of slight wobbles in the motions of nearby stars, due to the gravitational influence of planets orbiting around them. Indeed, the interferometric survey would reveal what proportion of stars possess planets. That is an important statistic for anyone pondering the question of whether life exists elsewhere.



New ways of making things. Developing novel materials for space applications, and learning how to handle them, are tasks for ESA's Materials and Processes Laboratories.

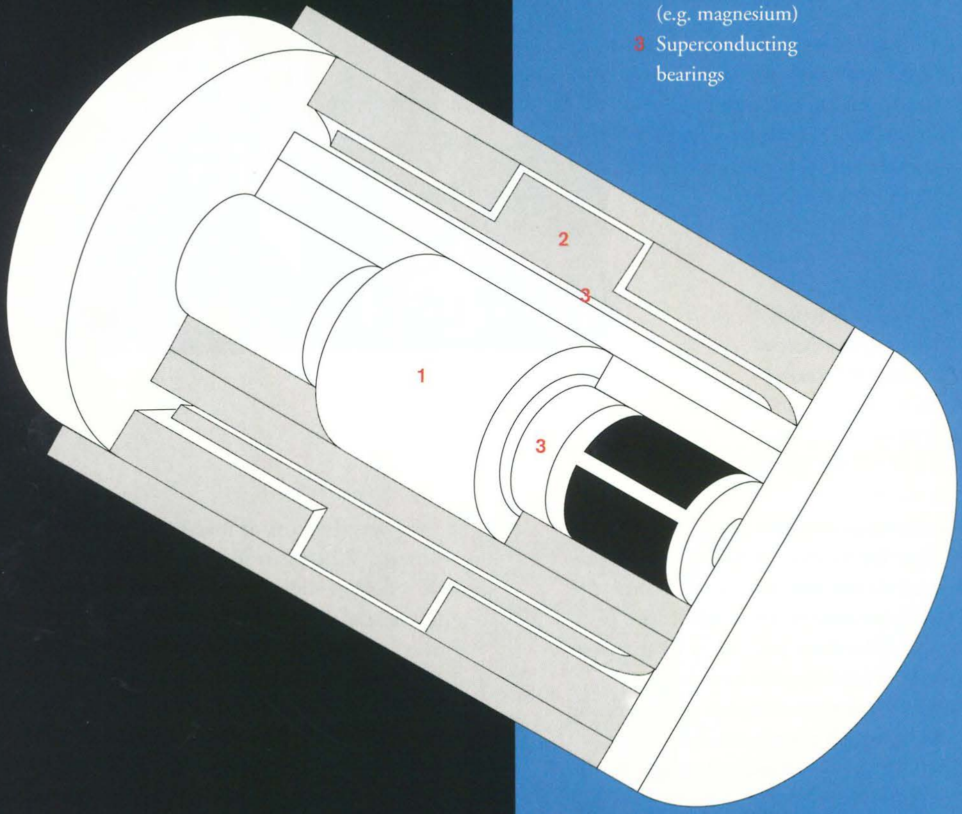
A search for living planets

An infrared interferometer might detect the planets of other stars directly. Supporters of this rival candidate for ESA's interferometric mission want to overcome the difficulty that prevents conventional telescopes from seeing alien planets. The close proximity of the parent star drowns out the planets' feeble emissions.
Interferometry can separate the objects in examining nearby stars. And although the planets are too faint to detect by visible light they emit more strongly in the infrared waveband.
A proposal called Darwin caught the fancy of the survey committee. French, British and American groups pointed out that the right kind of interferometer could detect ozone in the atmosphere of an Earth-like planet of another star. The belief is that only living things can produce free oxygen gas in the Universe, which is needed for ozone-making.
A dip in the infrared emission from a planet at 9.7 microns would be the signature of ozone, and perhaps the very first sign of life beyond the Earth. To find it would be a triumph, but the case for a mission of the Darwin type does not rest on a single objective. The direct observation of any alien planets, living or not, and a preliminary investigation of their atmospheres, would be remarkable achievements.
The mission could also provide the world's infrared astronomers with a general-purpose observatory rivalling the Hubble Space Telescope in its capacity to see fine detail. Special targets would include very distant galaxies, star-forming clouds in the Milky Way, and the Sun's own planets. The interferometer could monitor Jupiter's weather and discover comets in the distant outskirts of the Solar System.
As with the visible-light interferometric option, the proposal is enticing but there are formidable technical snags. One is of Nature's making. Dust that pervades the inner Solar System produces the so-called zodiacal light and emits strong infrared rays. It might be possible to evade the worst of this foreground interference by sending the infrared interferometer far out into space, beyond the Asteroid Belt.
The long wavelengths of infrared rays demand a large instrument. When European and American astronomers mention figures such as 1 to 4 metres for the telescope diameters, and 10 to 30 metres for their separation, the engineers wonder how such a monster could be launched and deployed. New ways of constructing lightweight, high-quality reflecting telescopes will need to be studied. The requirements for mechanical stability may be less severe than for the astrometric interferometer. But observations of the faintest objects, including planets of other stars, would require very sensitive and noise-free electronic detectors for the infrared. And as with all infrared missions, a big problem may be to cool the telescopes and detectors to low temperatures.

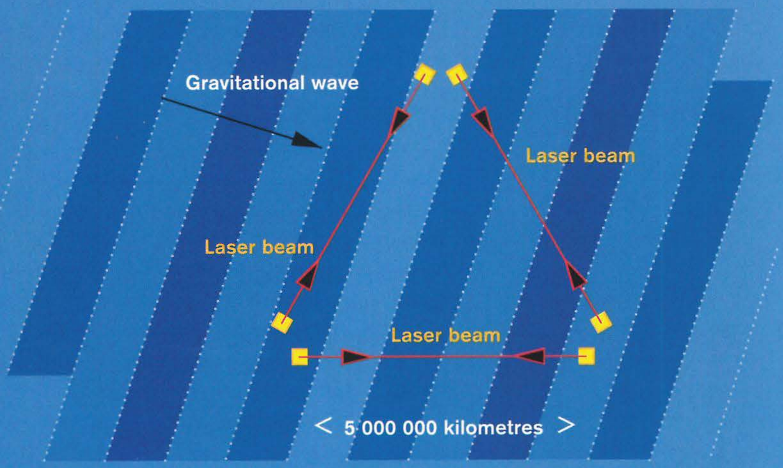
Elaborate helium cooling systems like those in ESA's current Infrared Space Observatory (ISO) would be awkward, to put it mildly, and reliance on helium curtails the life of a mission. Instead, as in ESA's FIRST spacecraft, the interferometer telescopes would be cooled passively, by screening them from the Sun and encouraging them to radiate their heat into space. Mechanical refrigerators would keep the electronic infrared detectors at a much lower temperature.
The survey committee proposed that ESA should study both options: the visible-light astrometric interferometer and the infrared imaging interferometer. Special attention should be paid to the related technology. After some years, a review of the relative performance of the two options would lead to one being selected for the interferometric slot.
"Don't forget we're looking 10 or 20 years ahead," says Steven Beckwith of Heidelberg, who played a prominent part in evaluating astronomical possibilities for Horizon 2000 Plus. "ESA will get better value for money if it keeps the competition going for a while, and doesn't let ideas become fixed too early. And moderate expenditure on technological research should show which of the hard tasks can be done more reliably — maintaining structural alignments in an astrometry mission, or cooling an infrared interferometer."

STEP concept

1 Test mass
(e.g. platinum)
2 Test mass
(e.g. magnesium)
3 Superconducting
bearings



LISA concept



Checking up on Einstein. Two missions now contemplated by ESA take its scientific programme into the realm of fundamental physics. In the STEP satellite, test masses made of different materials could test Einstein's conviction that all objects fall at the same rate under gravity, using superconducting sensors to reveal the slightest differences in their motions in orbit. Einstein's theory of gravity also predicts that cosmic space must be distorted by gravitational waves passing through it. LISA is conceived as a gravitational-wave detector employing laser beams to measure very small changes in the distances between widely separated spacecraft.

A step into fundamental physics

The possibility of checking an Einsteinian prediction about the bending of starlight was mentioned in connection with the astrometric option for ESA's interferometric mission. Other aspects of Einstein's theory of gravity, which he developed in Berlin in 1915 and called general relativity, are high on the list for investigations in space.
Alongside quantum mechanics, general relativity ranks as one of the pillars of modern physics. While experimental tests of quantum predictions are very precise, the verification of general relativity is sketchier. Physicists cannot rule out the possibility that Einstein's theory, like Newton's before it, is just a close approximation to reality. Cosmologists and particle physicists face theoretical problems that seem to require subtle changes to general relativity.
Technologies for testing it have already been contemplated by ESA. A project called STEP is one of several candidates in the competition for future medium or small-scale missions. It might fly in 2003, or thereabouts, within the present Horizon 2000 programme. Nevertheless it merits a brief description here because it introduces the new theme of fundamental physics, as envisaged for Horizon 2000 Plus.

Einstein puts his trust in a proposition called the equivalence principle. Everything, regardless of its composition or mass, supposedly falls at exactly the same rate under gravity. In popular mythology, Galileo dropped different materials from the Leaning Tower of Pisa, and they hit the ground at the same instant. STEP stands for Satellite Test of the Equivalence Principle. It would create a Leaning Tower of great height, by observing masses exposed to "free fall" as the satellite orbited the Earth.
The conditions that Nature provides in space, for fundamental physics, are nearly perfect but not quite. Although objects float weightlessly, the engineers would still have to enable the test masses to move without friction. That would mean using superconductivity to achieve levitation.

Again, spacecraft obey the laws of gravity with almost mathematical precision, yet even 350 kilometres above the Earth STEP would feel a slight resistance from the outer fringe of the atmosphere. The drag could mask the subtle gravitational effects sought by the experimenters. The spacecraft would therefore have to operate in a drag-free mode.
Accelerometers would detect any extraneous force acting on the spacecraft, and small thrusters would counteract it. Thrusts envisaged for the control of a 1-tonne spacecraft are measured in millinewtons, and are roughly equivalent to the weight of a postage stamp. For a bolder venture in checking up on Einstein, even more delicate control would be necessary.

The search for gravitational waves

Europe's scientists gave an emphatic vote for fundamental physics when they urged ESA to prepare for a cornerstone mission to look for gravitational waves in space. General relativity predicts the creation of waves by masses in strong relative motion. Travelling through the Universe at the speed of light, their effect would be to distort space itself.

Gravitational waves should cause rhythmic changes in the measured distance between two spacecraft. But the effect will be very small and hard to detect. Laser beams passing between the spacecraft can do the trick, provided great care goes into the design of the spacecraft and their optical systems. Technological requirements include lasers producing infrared waves of sharply defined wavelength and high reliability, structural stability in the spacecraft, and delicate control of the operations.

Even the pressure of sunlight falling on the spacecraft could spoil the observations. As with STEP, extraneous forces must be cancelled in drag-free operation. Field-emission electric thrusters are expected to do the work. Their thrusts will be measured in micronewtons and their operation has to be controlled by an accelerometer of exceptional sensitivity.

A magic cube, about the size of a child's building block but made of a gold-platinum alloy, is the centrepiece of the onboard system as currently envisaged. It floats weightlessly inside a gilded cage. When an extraneous force shifts the spacecraft, inertia will leave the cube unmoved. Electrostatic detectors will sense the relative motion between the cube and the cage, and command the thrusters to cancel the slight excursion.

The proof mass, as the magic cube is called more formally, is not merely a sensor. Floating in space, immune to non-gravitational forces, it defines the position of the spacecraft like a surveyor's trigonometric point. One surface of the proof mass serves as a mirror in an optical system that measures changes in the distance to a proof mass in an identical spacecraft far away.

An infrared laser beam goes continuously from one spacecraft to the other. This second spacecraft locks its own laser to the incoming wave, and sends its beam back towards the first spacecraft. A radar expert would call this a phase-locked transponder, meaning that the peaks and troughs of the received and transmitted waves exactly coincide.

The optical system in the first spacecraft compares the outgoing and incoming waves. If the distance between the two spacecraft alters by as much as 10 millionths of a wavelength, or 10 billionths of a millimetre, a detectable shift should occur in the relative positions of the peaks and troughs. As the spacecraft are to be millions of kilometres apart this precision is awesome, but necessary for detecting the gravitational waves.

Six spacecraft, each with its proof mass, would operate in the Laser Interferometer Space Antenna, or LISA, which is ESA's preliminary concept for the gravitational-wave mission. They are visualized as being deployed in pairs at the corners of a triangle. Each side, 5 million kilometres long, is served by two spacecraft that monitor the intervening distance. They also exchange signals with their neighbours at the corners.

After launch as a single payload by an Ariane 5 rocket, which would fling them clear of the Earth's gravity, the six LISA spacecraft would travel in pairs, using their own rocket motors to put themselves into similar orbits around the Sun. Achieving the right relative positions, and then aiming the laser beams correctly, promises an interesting time for the mission controllers.

The survey committee for Horizon 2000 Plus rated the gravitational-wave mission as by far the most important proposal for fundamental physics in space, but judged it to be a "demanding" project. Several years of technology development will be needed to bring it to the necessary level of maturity, and to cut costs without reducing the number of spacecraft below six.

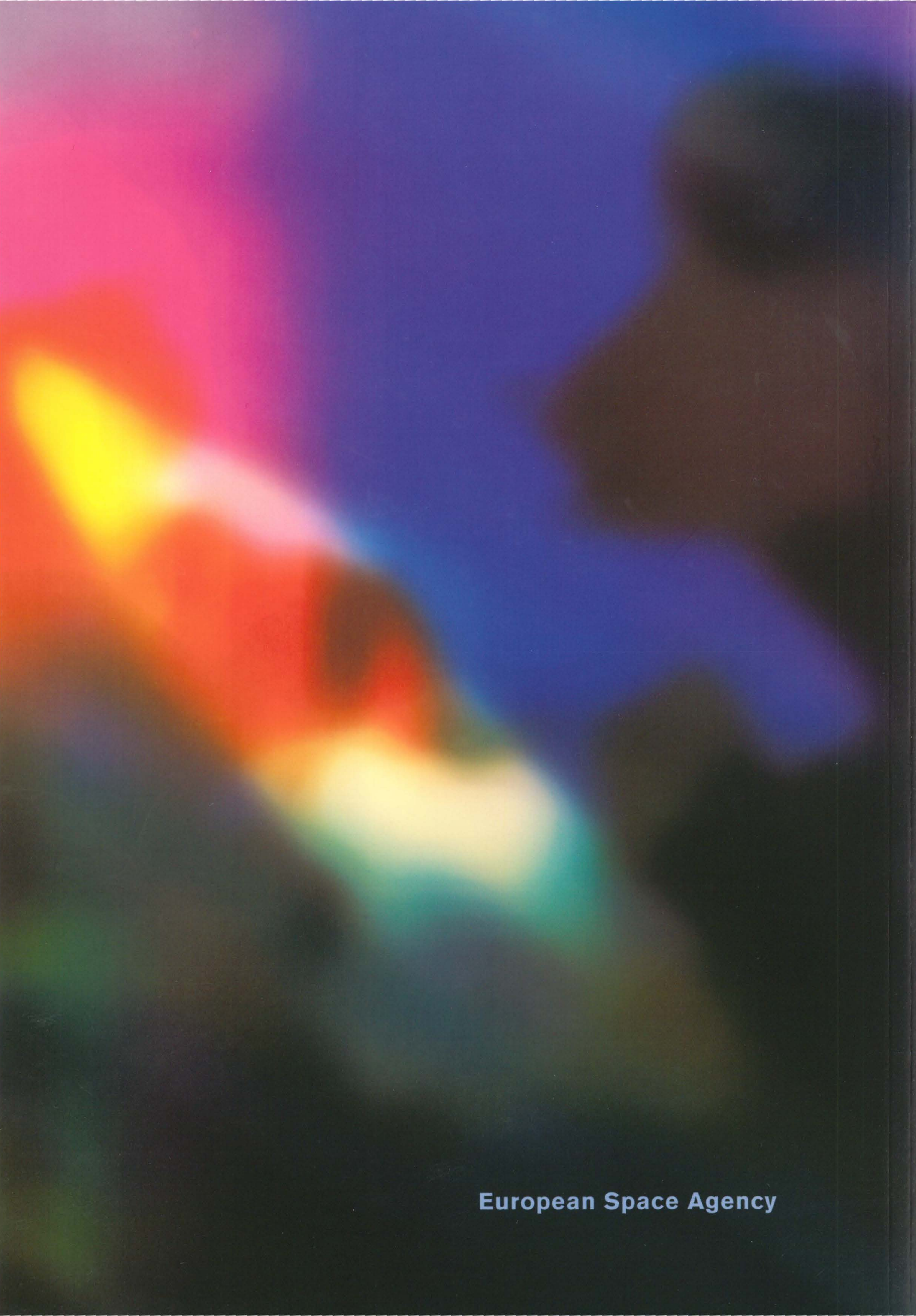
A gravitational-wave mission wins either way. If it failed to find the supposedly commonplace gravity signals from nearby double stars, that would overturn a key theory of physics and so would count as a big result. The more likely outcome is the successful detection of gravitational waves, which would also be a major discovery for physicists.

Gravitational waves would open yet another window on the Universe, quite different in kind from the various electromagnetic waves serving astronomy so far. For example, the dumping of matter from one star to another, which can play a big part in stellar evolution, should create gravity signals. So should close encounters between collapsed stars, in the form of white dwarfs, neutron stars or stellar black holes.

An exciting possibility concerns a direct test of the theory that the Universe started in a Big Bang. Some physicists suspect that the turmoil of masses during such an event should produce gravitational waves, which may be perceptible by the ESA mission. If so, it might give scientists a direct impression of the conditions in which the matter and forces of the cosmos came into existence.

Predictions of general relativity and quantum theory, about what happens in extreme conditions like those that would prevail in the Big Bang, contradict each other. Einstein's gravity can supposedly compress everything into a mathematical point, while quantum theory requires that matter and energy retain a certain volume - small perhaps, but not infinitely small. This discrepancy creates a crisis at the heart of modern theories. By giving access to extreme events, whether around black holes or at the birth of the Universe, gravitational waves may help to resolve the contradiction.

Physics can hardly get more fundamental than that.



European Space Agency