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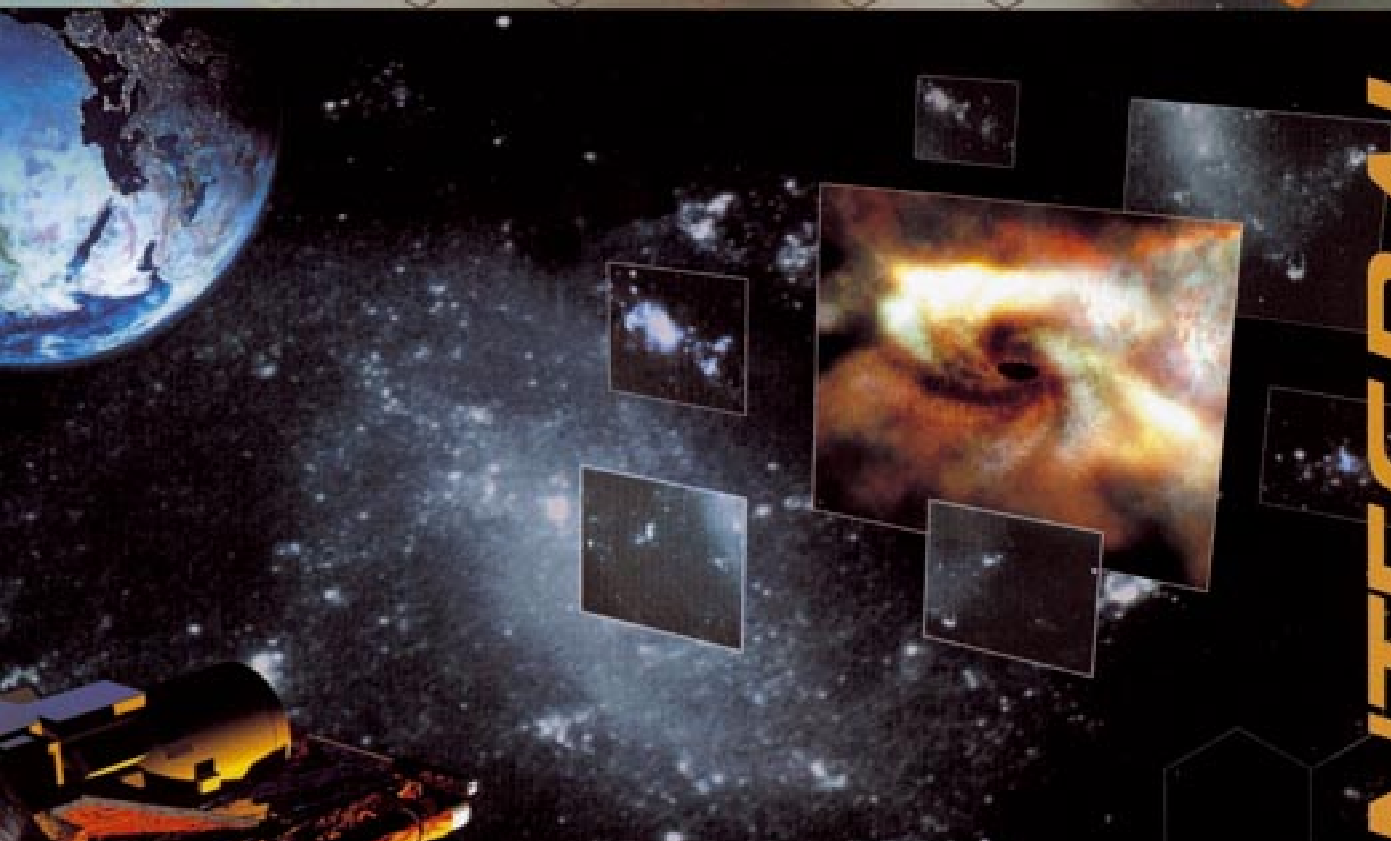
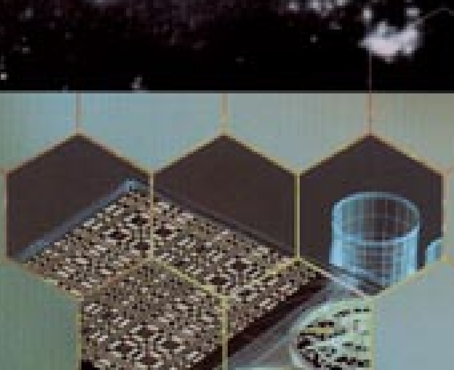
Tracking Extreme Radiation Across the Universe



INTEGRAL

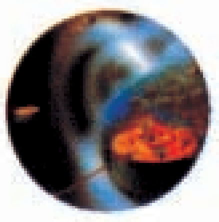


European Space Agency
Agence spatiale européenne

About ESA

The European Space Agency (ESA) was formed on 31 May 1975. It currently has 15 Member States: Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom. Canada is also a partner in some of the ESA programmes.

The ESA Science Programme has launched a series of innovative and successful missions. Highlights of the programme include:



Cluster, which is a four-spacecraft mission to investigate in unprecedented detail the interaction between the Sun and the Earth's magnetosphere.

Giotto, which took the first close-up pictures of a comet nucleus (Halley) and completed flybys of Comets Halley and Grigg-Skjellerup.

Hipparcos, which fixed the positions of the stars far more accurately than ever before and changed astronomers' ideas about the scale of the Universe.

Hubble Space Telescope, a collaboration with NASA on the world's most important and successful orbital observatory.

Huygens, a probe to land on the mysterious surface of Saturn's largest moon, Titan, in 2004. Part of the international Cassini mission.

ISO, which studied cool gas clouds and planetary atmospheres. Everywhere it looked, it found water in surprising abundance.

IUE, the first space observatory ever launched, marked the real beginning of ultraviolet astronomy.

SOHO, which is providing new views of the Sun's atmosphere and interior, revealing solar tornadoes and the probable cause of the supersonic solar wind.

Ulysses, the first spacecraft to fly over the Sun's poles.

XMM-Newton, with its powerful mirrors, is helping to solve many cosmic mysteries of the violent X-ray Universe, from enigmatic black holes to the formation of the galaxies.

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More information can also be obtained via the ESA Science Website at: http://sci.esa.int

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INTEGRAL

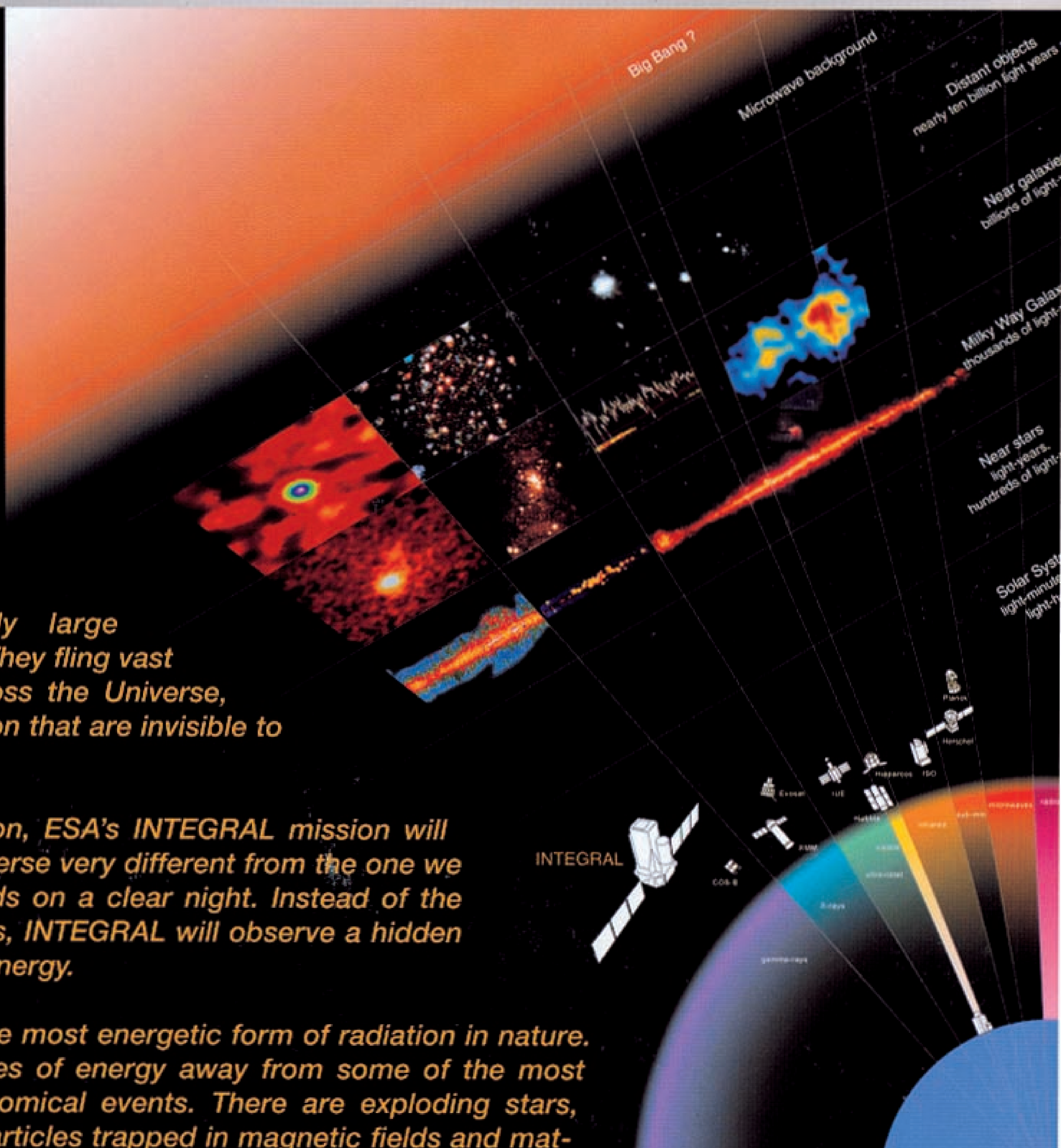
The international gamma ray astrophysics laboratory

Contents

Illustration by Medialab, © ESA 2002

Exploring the turbulent Universe

The light we see with our eyes is just one type of radiation that carries energy through the Universe. Scientists refer to light and its associated radiation as the electromagnetic spectrum. It consists of radio waves, microwaves, infrared radiation, visiblelight, ultraviolet light, X-rays and gamma rays. Each type of electromagnetic radiation is produced by different physical processes and so all carry their own privileged information about the Universe.



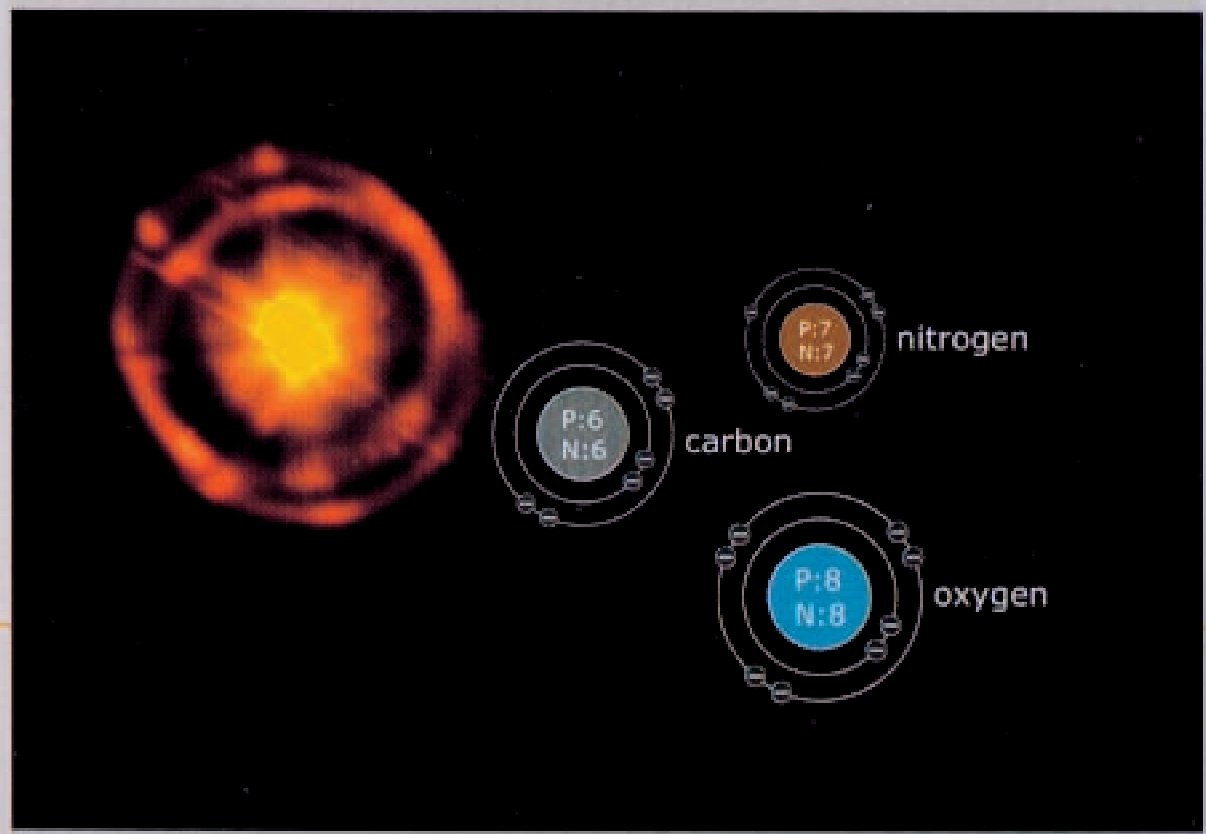
At cosmic distances there are unimaginably large explosions taking place. They fling vast quantities of energy across the Universe, mostly in forms of radiation that are invisible to our eyes.

By collecting this radiation, ESA's INTEGRAL mission will give us a view of the Universe very different from the one we see when looking upwards on a clear night. Instead of the serene beauty of the stars, INTEGRAL will observe a hidden cosmos of violence and energy.

Gamma rays represent the most energetic form of radiation in nature. They carry large quantities of energy away from some of the most cataclysmic of all astronomical events. There are exploding stars, colliding neutron stars, particles trapped in magnetic fields and matter being swallowed by black holes. All of these events release vast amounts of energy, with much of it carried on gamma rays.

INTEGRAL will collect these gamma rays, allowing astronomers across the world their clearest views yet of the most extreme environments in the Universe.

The atoms that make us



INTEGRAL will study the way elements are created and scattered through space by supernovae explosions.
Illustration by Medialab, © ESA 2002

Nature contains over 100 different types of atoms, known as elements, such as iron, oxygen, hydrogen, etc. Astronomers have been instrumental in understanding where this mix of chemicals comes from. In fact, science is now confident that **most of the atoms in our bodies and, indeed, in everything around us, were once in the hearts of stars.** From there, they were released into space at the end of the star's life, often in a violent explosion known as a supernova. The precise nature of how this happens remains elusive and is at the top of the list for INTEGRAL to investigate.

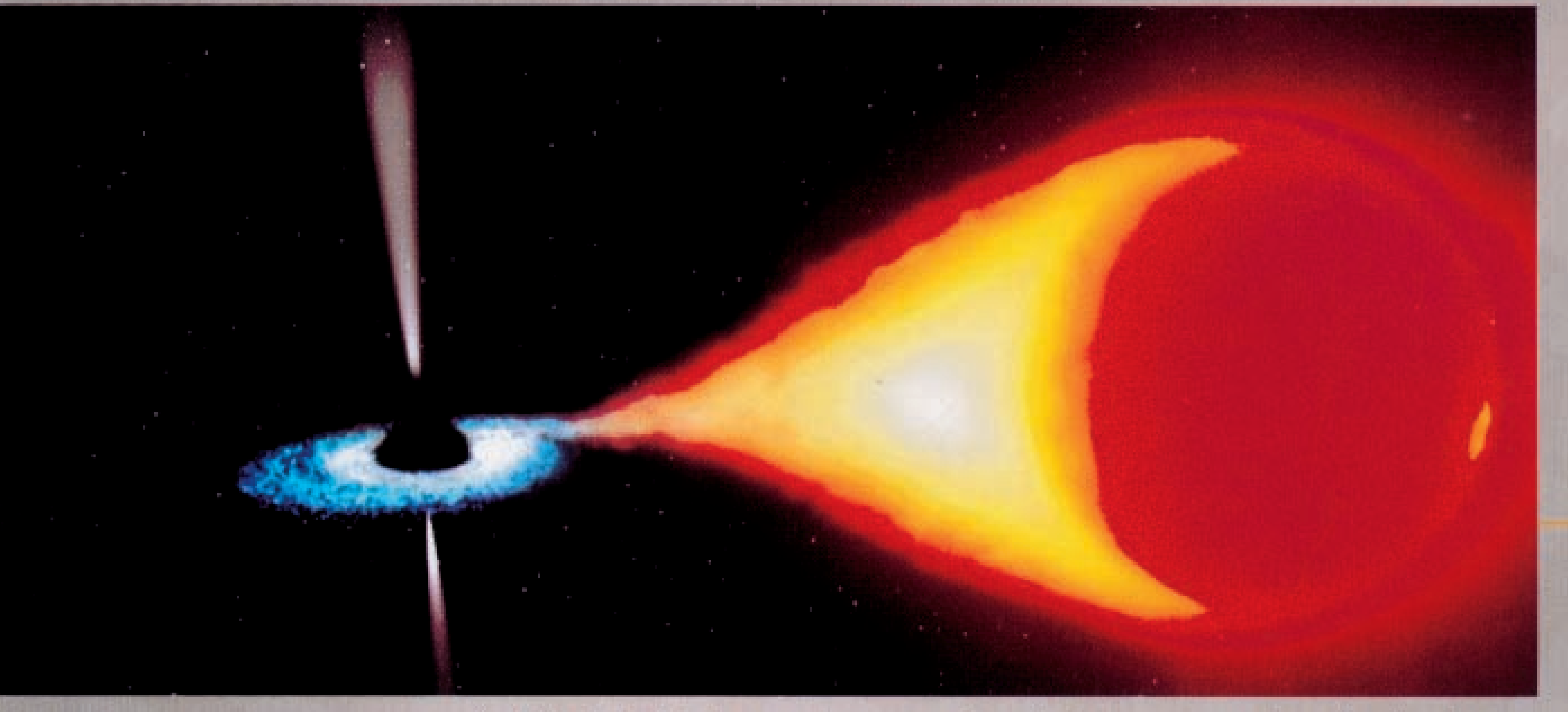
Today's abundance of elements can be measured directly on Earth and in meteorites. In addition, astronomical observations can reveal the composition of stars, galaxies and the interstellar medium. The original distribution of chemical elements is trickier but can be studied both theoretically and experimentally, for instance in laboratory investigations of nuclear and particle physics. Scientists believe that the very early Universe contained mainly hydrogen and helium, the lightest atoms, as a consequence of nuclear reactions that took place during the first few minutes of the Universe's life.

Subsequently, the first stars and galaxies appeared and the balance began to alter. Nuclear fusion, inside stars and supernovae explosions, has created the other elements, by combining lighter elements into heavier elements. This is also called 'nuclear burning' and continues around us today. Most stars, including our Sun, are constantly fusing hydrogen to helium. When all the hydrogen has been burnt, helium itself becomes the fuel. Most stars stop there, puffing off their outer layers into space, so that the enriched gas can become the raw material for the next generation of stars and planets.

A star that contains several times more mass than the Sun, however, goes further, creating carbon, oxygen, silicon, sulphur, and iron. Up to this point, the process releases energy. An input of energy is then required to create elements heavier than iron and nickel, when all the fuel in a star's core has been burnt. These heavier elements, such as gold, lead and uranium are formed during the supernova explosion and scattered through space, where they, too, can be incorporated into new celestial objects.

During such a violent explosion, gamma rays are produced in great quantity and, as these pass through the gaseous debris, **the newly created elements leave their 'fingerprints' on the radiation.** Observations of these fingerprints, called gamma-ray lines, by INTEGRAL will provide the most direct method yet of studying the formation of elements. In fact, INTEGRAL will be able to look for the chemical composition of a whole range of celestial objects that emit gamma rays.

The hourglass shape at the centre of this image is the aftermath of a supernova explosion from 1987.
Hubble Heritage Team (AURA/STScI/NASA)



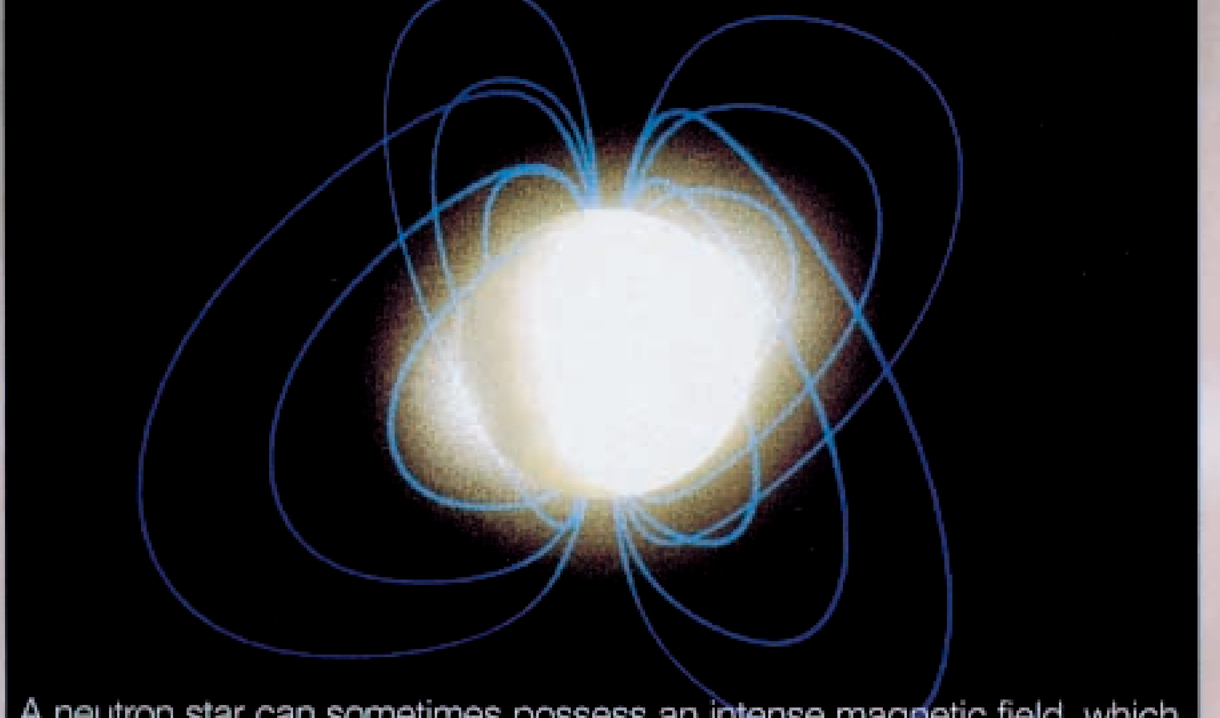
A stellar black hole can be seen when it rips a companion star to pieces.
Illustration by Medialab, © ESA 2002

The densest objects in the Universe

When a massive star explodes, not all the material is ejected into space. Some of it collapses into an extremely compact object known as a neutron star, inside which gravitational forces crush protons and electrons together, turning them into particles known as neutrons. **A neutron star contains about a few solar masses of material, squeezed into a radius of only 20 km**. This means the matter is so compressed that a thimble full of it would weigh millions of tonnes on Earth. Fast-spinning neutron stars, whose radio emissions seem to pulse on and off, are called pulsars.

Beyond the mass limit of a neutron star - about three solar masses - gravity becomes overwhelming and collapses the star even further, creating a black hole. These are perhaps the strangest objects in the Universe because nothing, not even light, can escape from inside a black hole. So, **the presence of a black hole can only be inferred by its effect on surrounding celestial objects and other interstellar material.**

Virtually all types of compact objects are significant sources of high-energy emission because of the enormous gravitational fields they tend to generate. Gravitational fields can accelerate particles in the vicinity to extreme velocities, which then emit gamma rays and X-rays.
INTEGRAL will capture images of the high-energy emission from such compact objects with unprecedented detail, allowing astronomers a clearer look than ever before at these enigmatic objects.



A neutron star can sometimes possess an intense magnetic field, which can also accelerate particles and cause them to emit gamma rays.
Illustration by Medialab, © ESA 2002

Family portrait: matter and antimatter

Antimatter was discovered by Carl Anderson at the California Institute of Technology, in 1932. During his experiments, he found a fascinating particle that was as light as an electron but positively instead of negatively charged. Paul Dirac, a theoretician from Cambridge University explained that the new particle, named a positron, was the antimatter counterpart of our electron. Antimatter is opposite in every way to more normal matter, except for the mass of the particle, which is the same. When a matter particle meets its antimatter counterpart, they will annihilate into gamma rays.

Giant black holes

Gigantic black holes, the size of our Solar System, are thought to lurk in the hearts of most galaxies. Illustration by Medialab, © ESA 2002

A giant black hole is quite probably lurking at the centre of most galaxies, including our own Milky Way. From observations at radio and infrared wavelengths, astronomers know that the heart of our galaxy is a site of violent activity. At gamma-ray energies, its behaviour is even more extreme. **Arching up from the centre of the galaxy is what appears to be an enormous cloud of antimatter**. It is glowing brightly with gamma rays, created as the antimatter annihilates its normal matter counterparts. INTEGRAL will pursue this investigation into the astrophysical processes at work near the heart of the Milky Way.

Family portrait: black holes

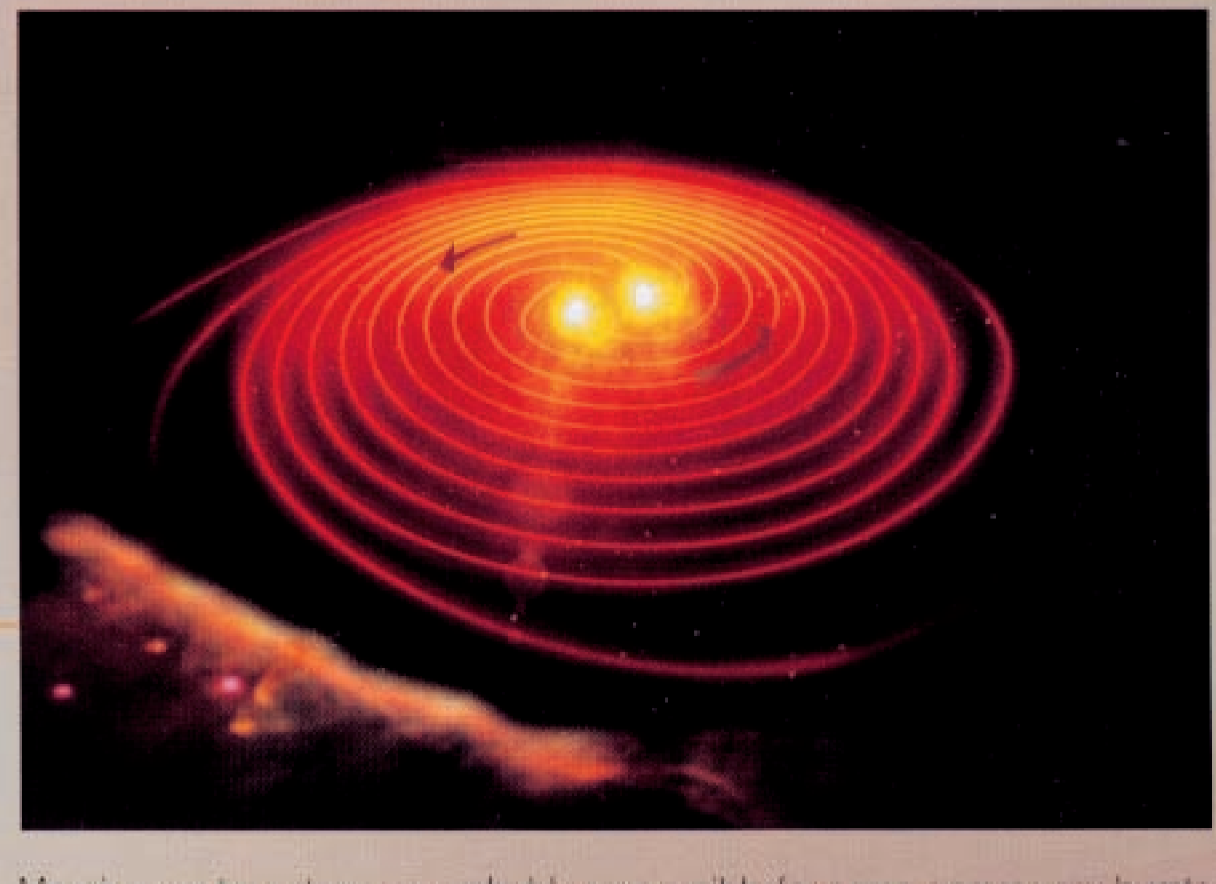
There are two main types of black hole, the stellar variety and the supermassive ones. Stellar black holes are created by supernovae and their bigger cousins, hypernovae. They contain a few times the mass of the Sun. This matter is squeezed into a tiny sphere, just a few kilometres across. Examples can be found throughout a galaxy and are sometimes found orbiting other stars, tearing them to pieces with their strong gravitational pull.
The supermassive black holes are monsters!
The smallest contain a few hundred thousand times the mass of the Sun, whilst the biggest contain billions of solar masses. All of this is packed into a sphere that is approximately the size of our Solar System. Supermassive black holes are only found in the very centres of galaxies and are thought to be a natural by-product of the galaxy's formation.
Recently, a third type containing between 10 and 1000 solar masses, have been discovered in nearby galaxies. Their origin is unknown at present.
When matter falls into a black hole of whatever size, just before it disappears forever, the matter can emit gamma rays that shoot across the Universe in a kind of cosmic cry for help!

The violence in the centre of some other galaxies can be even more dramatic. Such a place is called an Active Galactic Nucleus (AGN) and there are various types. Regardless of their classification, however, all AGNs emit a wide range of radiation that varies in intensity over time scales ranging from a fraction of a day to several months. Most astronomers now believe that it is matter falling into a very massive central black hole that powers an AGN. High-energy emission, in the form of gamma rays and X-rays, is generated as the matter swirls around the black hole in a disc, waiting to be pulled inwards. Narrow jets of matter shoot away from the black hole but **how these jets are formed and what makes them so narrow is still not understood.**

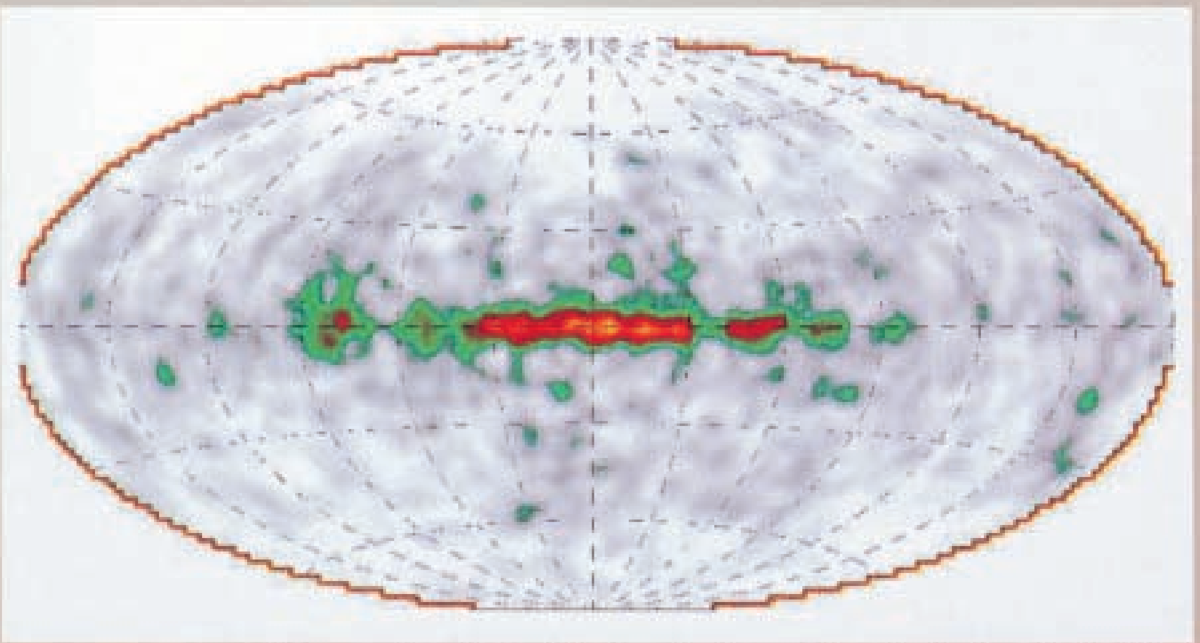
There are AGNs so bright that they outshine their host galaxy. These are known as quasars and are some of the most luminous objects in the Universe. However, they are difficult to observe because most of them are billions of light years away.

INTEGRAL will be the best-equipped satellite to study these celestial powerhouses, peering into their hearts to unlock the secrets of how they formed.

Mysterious bursts



Merging neutron stars are probably responsible for some gamma-ray bursts.
Illustration by Medialab, © ESA 2002



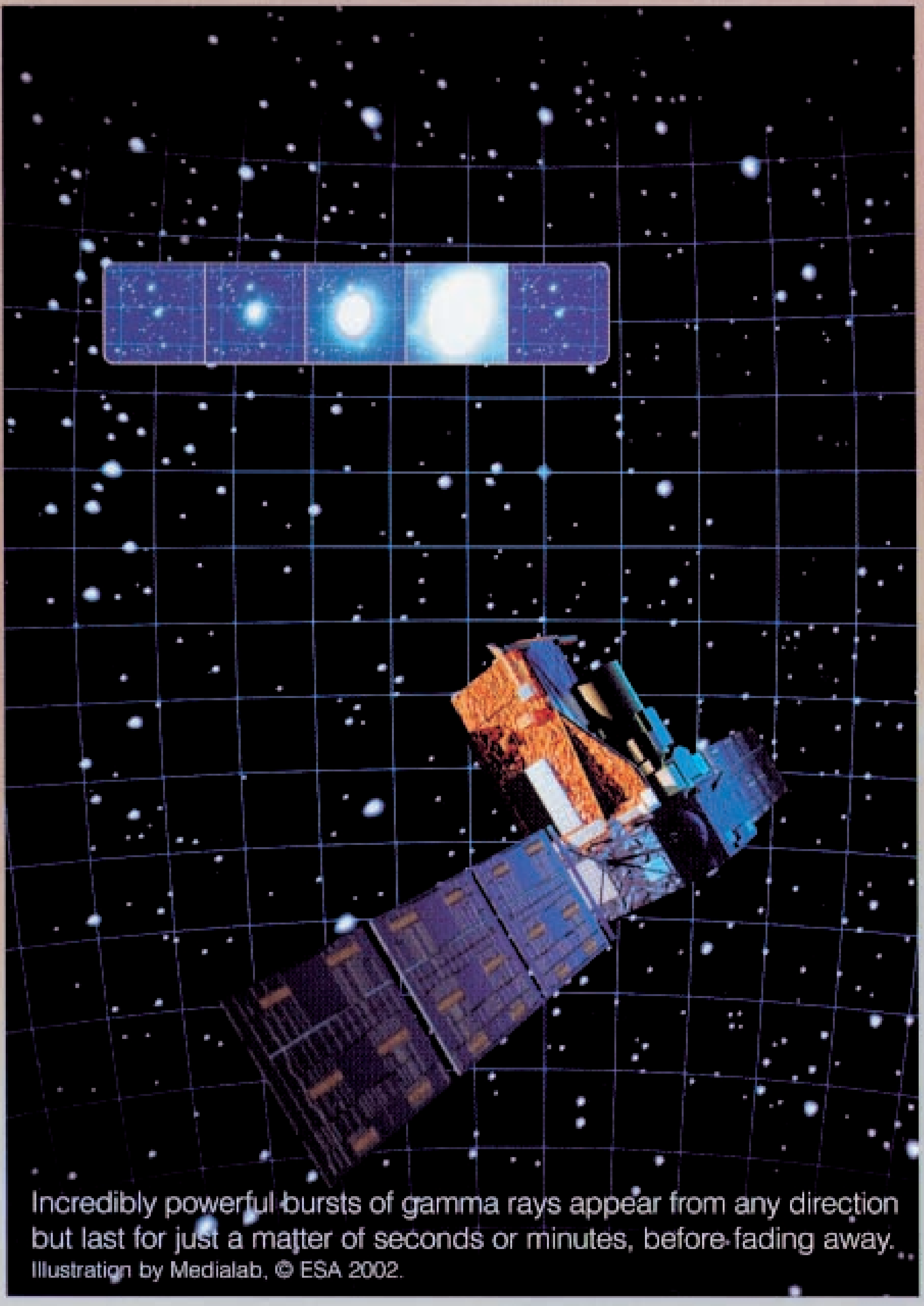
An image of the full sky, showing gamma rays from radioactive aluminium, produced in supernovae, concentrated along the Milky Way.
The COMPTEL collaboration and NASA.

There are even more mysteries.

Astronomical satellites register sudden bursts of gamma rays, always from a random direction, roughly once a day. These bursts may last a hundredth of a second, or anything up to 90 minutes. They become, briefly, the brightest objects in the gamma-ray sky but are never seen to repeat. **For over twenty years, astronomers had no clues about how far away these explosions occurred.** Then, during 1997, the Italian-Dutch satellite BeppoSAX provided accurate X-ray measurements so quickly that a burst's location could be pinpointed, enabling follow-up observations with optical and other telescopes. These observations confirmed that the gamma-ray bursts are extremely distant and therefore must be caused by tremendous explosions equal to the radiance of millions of billions of stars.

Where does this energy come from?

This colossal amount of energy may be released when compact objects, such as neutron stars or black holes, collide. Astronomers know of a small number of neutron stars in our galaxy that are in orbit around one another and may merge in the far future. **There is also mounting evidence that incredibly powerful supernovae, called 'hypernovae', are the source of the gamma-ray bursts.** INTEGRAL will be able to look at the glowing debris for the telltale signs of elements created when a star explodes.



Incredibly powerful bursts of gamma rays appear from any direction but last for just a matter of seconds or minutes, before fading away.
Illustration by Medialab, © ESA 2002.

Observing the invisible

INTEGRAL's task will be to gather the most energetic radiation in the Universe. **Gamma rays are even more powerful than the X-rays used in medical examinations**, yet most gamma radiation from space cannot be tracked from the ground because it is blocked by Earth's atmosphere. That is why INTEGRAL has to be a satellite-based observatory.

Even from orbit, observing gamma rays is a difficult task. They are five million times more energetic than visible light and, because of this, they pass right through matter with hardly any interactions. This is a double-edged sword. On the one hand, it means that they carry pure information about the objects that created them. On the other, their ability to penetrate matter means that they are difficult to detect because they pass straight through traditional mirrors and cameras.

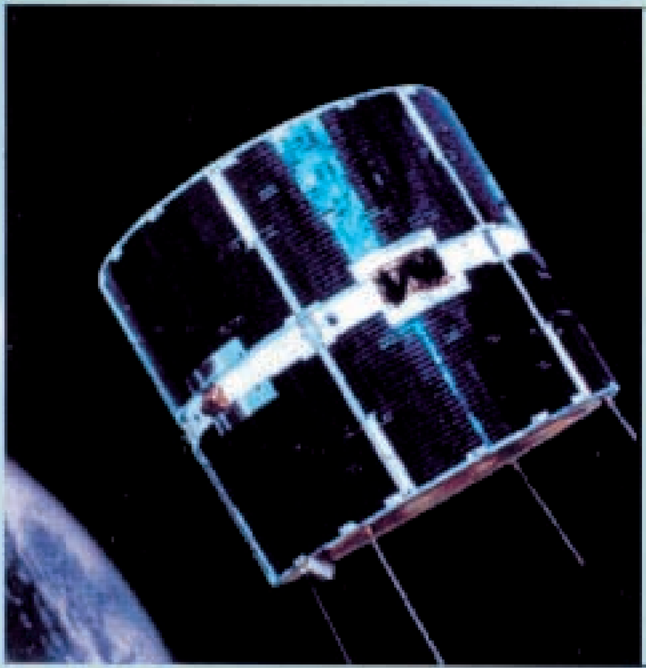
INTEGRAL uses two specially designed gamma-ray telescopes to register these elusive rays. One telescope will take pictures using the gamma rays and the other will measure their energy. The gamma-ray telescopes are supported by two others, an X-ray monitor and an optical camera.

Gamma rays in the electromagnetic spectrum

All types of electromagnetic radiation can be characterized by a wavelength, given in metres or fractions of a metre. A nanometre, for instance, is one thousand-millionth of a metre. Red light has a wavelength of 700 nanometres and violet light 400 nanometres. INTEGRAL studies radiation with even shorter wavelengths, from 0.4 down to only 0.0008 nanometres!

The shorter the wavelength, the higher is the energy of the radiation. The energy of radiation is usually given in electron-Volts or eV, a unit of energy used in particle physics. Visible light has an energy of 2 to 4 eV, while X-rays carry thousands of eV, i.e. kilo-electron-Volt or keV. INTEGRAL studies radiation in the energy range from 3 keV right up to 15 MeV (15 mega-electron-Volt or 15 million eV).

All four instruments point to the same region of the sky and take observations simultaneously. **This will be the first time such measurements have been made** concurrently and will allow a clearer identification of the gamma-ray sources. By comparing the optical, X-ray and gamma-ray data, astronomers will have taken a key step forward in studying high-energy processes in the violent Universe.

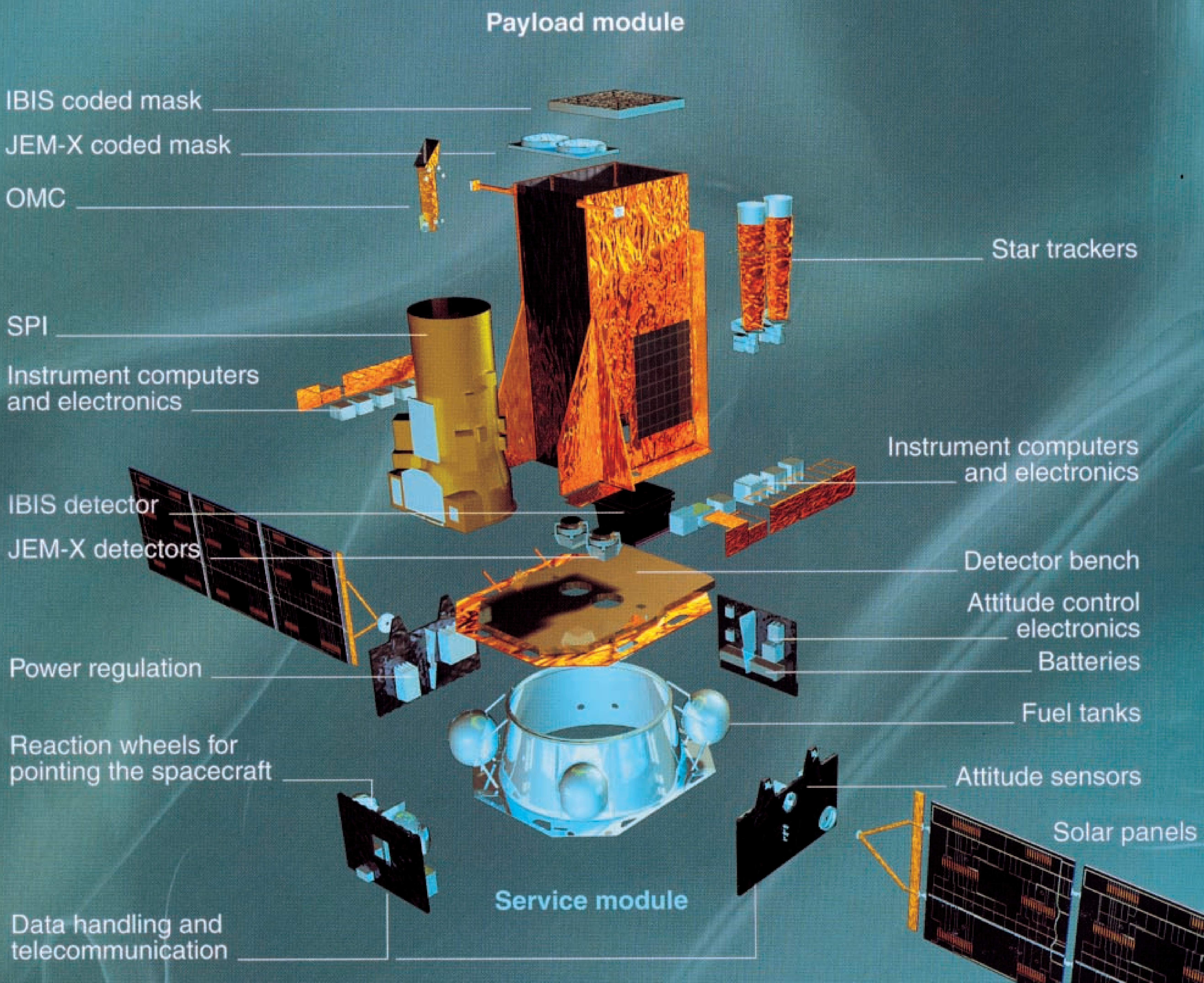


ESA's COS-B satellite. Photo: ESA

Continuing a tradition

**ESA's first gamma-ray satellite was COS-B.
Launched during 1975, it put European astronomers at the forefront of the field. COS-B was followed by the Russian-French mission GRANAT (1989-1998) and NASA's Compton Gamma-ray Observatory (CGRO) (1991-2000). In October 2000, the international High Energy Transient Explorer (HETE-2) satellite was launched, carrying a French gamma-ray telescope and X-ray detectors. Now astronomers all around the world will also have INTEGRAL, the most sensitive gamma-ray observatory ever launched.**

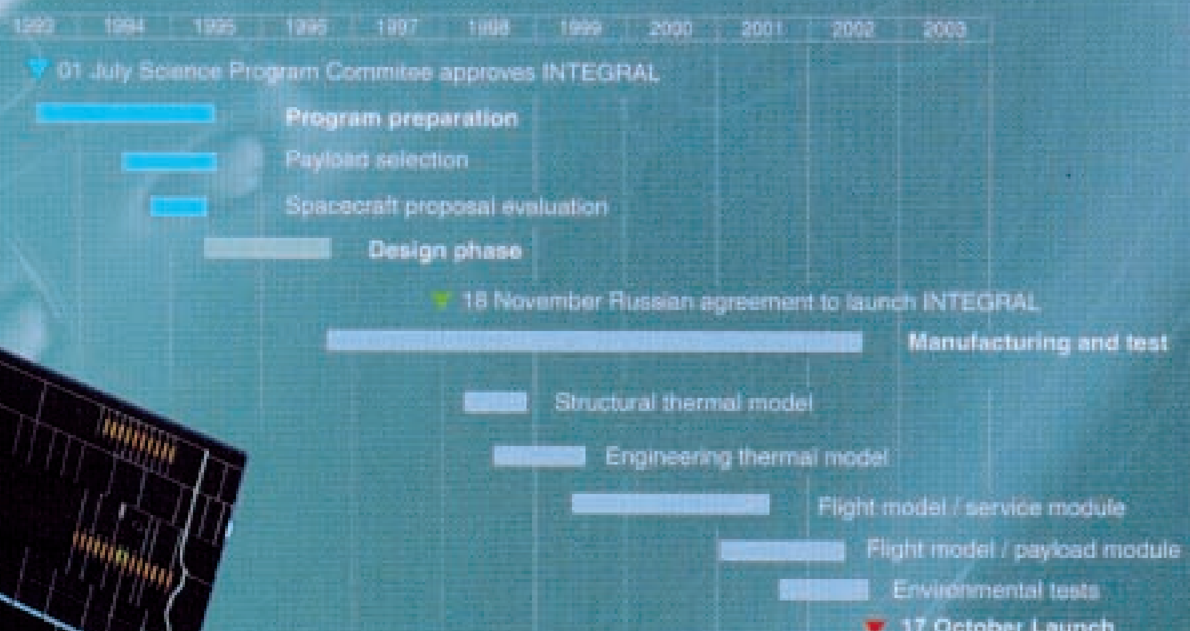
The INTEGRAL spacecraft

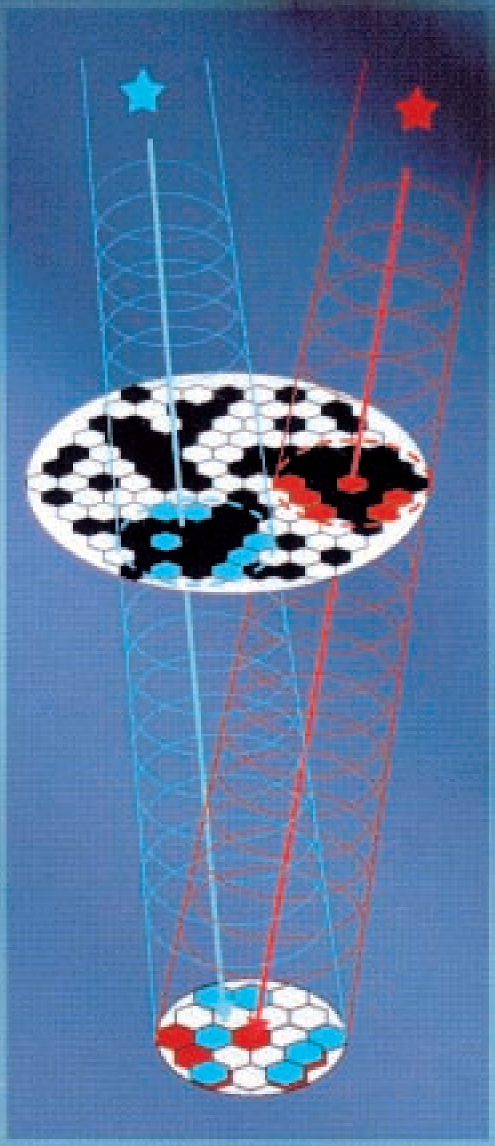


The INTEGRAL spacecraft is composed of two main sections, the service module and the payload module. The service module is the lower part of the satellite. It provides essentials such as power (via solar panels), satellite control and the communications link to the ground. The payload module is connected to the service module and consists of the four scientific instruments. To reduce the cost as much as possible, the service module design from ESA's XMM-Newton satellite was reused.

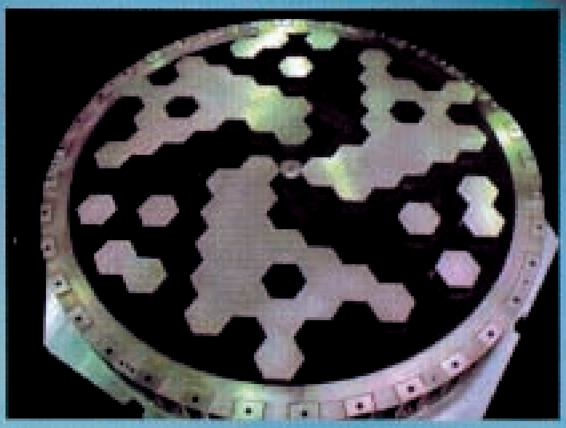
Industrial contractors from all over Europe built the spacecraft, and the experiments were contributed by academic and industrial consortia, also from various European countries. In addition, the Russian Space Agency agreed to launch INTEGRAL free, in exchange for observing time.

The launch is the culmination of almost a decade of work, started in 1993. After much preparation, the prime contractor (Alenia Aerospazio) was chosen. The design phase started in 1995 and was followed by the building of various test models of the spacecraft. This lasted until 1999, by which time the tests were complete and the actual spacecraft, known as the flight model, was constructed. In 2001, the finished spacecraft began its final tests, ready for launch at the end of 2002.





Gamma rays from different objects pass through different regions of the coded mask before striking the detector. The resulting pattern is a sequence of overlaid shadows which a computer must disentangle, to create an image of the objects.



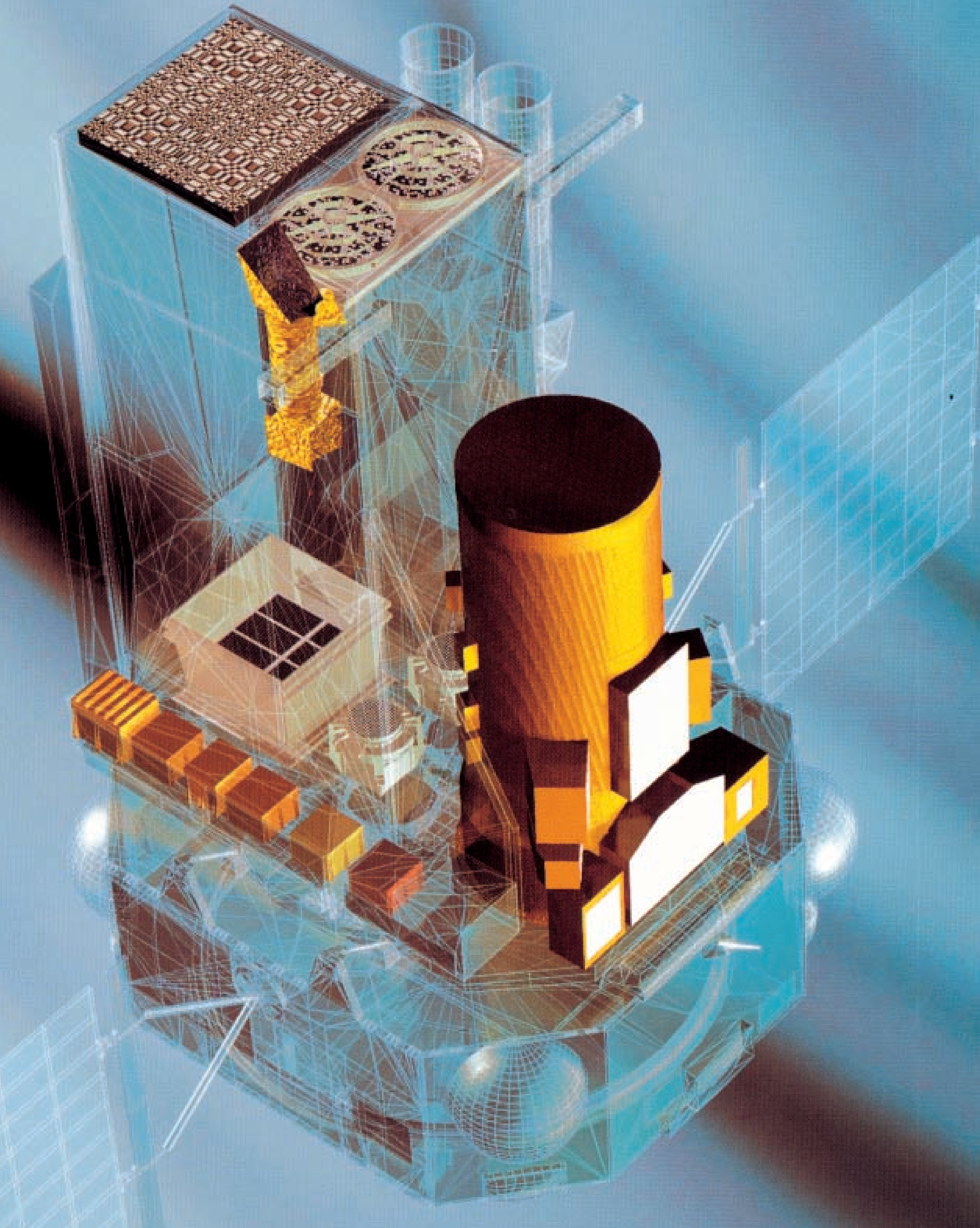
The coded mask being used on SPI. Photo: ESA

To catch a gamma ray

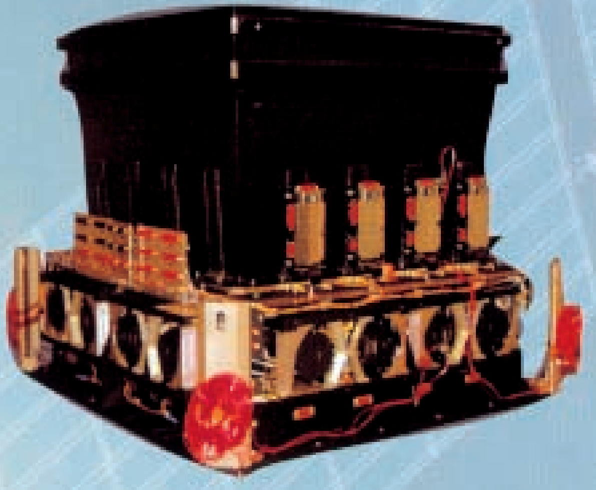
Because gamma rays and X-rays are so difficult to focus, three of INTEGRAL's four science instruments rely on a technique called coded-mask imaging. In this method, traditional mirrors and lenses are replaced with a mask, which contains a pattern of holes. Gamma rays can pass through these holes but are blocked if they fall onto the mask itself. In effect, the mask casts a shadow. The gamma rays that make it through the holes fall onto the detector, recording the shadow pattern.

When gamma rays from another direction pass through the holes, they arrive from a different angle and the resulting shadow, cast by the mask, is in a different place on the detector. In this way, it 'codes' the radiation so that a computer program, which knows the shape of the mask's shadow, can be used to disentangle the overlapping patterns and convert them into an image of the gamma-ray sources in the sky.

The INTEGRAL instruments



The imager, IBIS



The Imager, IBIS (Imager on Board the INTEGRAL Satellite) will give sharper images than any previous gamma-ray instrument. IBIS will locate sources to within a precision of 30 arcseconds, which is the equivalent of measuring the position of individual people in a crowd situated at a distance of 1.3 km. The instrument works in the energy range 15 keV to 10 MeV. It consists of a detector and a coded mask made of tungsten that is placed 3.2 m above it. The detector uses two layers of sensitive picture elements (pixels) located one on top of the other. The top layer is made of 16,384 cadmium-telluride (Cd-Te) pixels and will detect the low-energy gamma rays. The second layer consists of 4,096 caesium-iodide (CsI) pixels, and will capture the high-energy gamma rays. Comparing the results from the two layers allows the paths of the gamma rays to be tracked in 3D. The principal investigating institutions for IBIS are IAS Roma, Italy, CEA Saclay, France and TESRE Bologna, Italy.

INTEGRAL provides, for the first time, simultaneous observations with the same satellite at visible, X-ray and gamma-ray wavelengths for some of the most energetic objects in the Universe.

The optical monitor, OMC

The OMC offers INTEGRAL the opportunity to make automatically, simultaneous observations of the visible light coming from the gamma-ray and X-ray sources. Such observations are particularly important in high-energy astrophysics because emission from a source can change very rapidly.

The OMC can register objects of magnitude 18.2 in a 1,000 second exposure and is basically a traditional refracting telescope (i.e. one that uses a lens to focus light). It has a 5 cm lens and a CCD (charge-coupled device) detector in the focal plane. The principal investigating institution is INTA/LAEFF, Spain.

The X-ray monitor, JEM-X

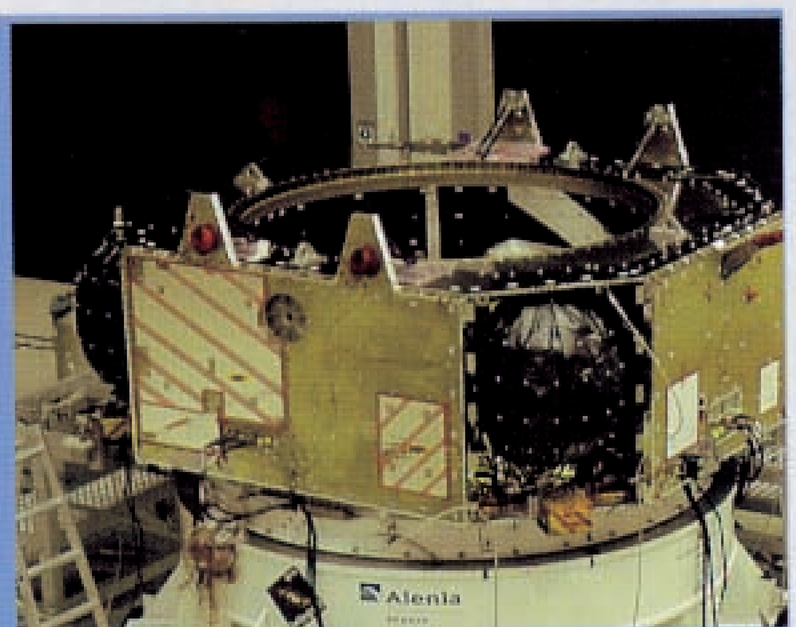
The Joint European X-Ray Monitor, JEM-X, plays a crucial role in the detection and identification of the gamma-ray sources. JEM-X is a pair of telescope that will make observations simultaneously with the main gamma-ray instruments and will provide images in the 3 to 35 keV energy range with an angular resolution comparable to that of IBIS.

Like IBIS and SPI, it uses the coded-mask technique. Two coded masks are located 3.2 m above the detection plane. The detector, a so-called Imaging Micro-Strip Gas Counter, consists of two identical gas chambers filled with a mixture of xenon and methane at a pressure of 1.5 bar, i.e. 1.5 times the normal atmospheric pressure at sea level. The principal investigating institution is DSRI, Denmark.

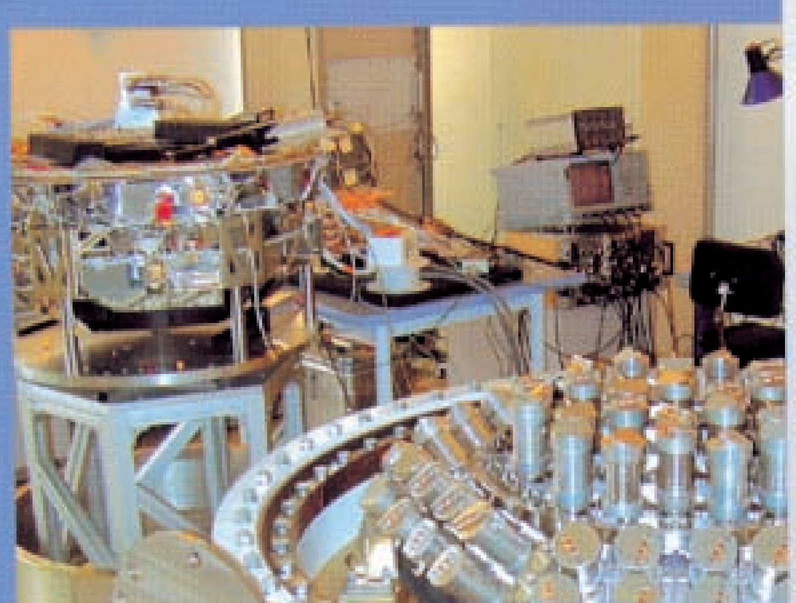
The spectrometer, SPI

The SPI (Spectrometer on INTEGRAL) will allow gamma-ray energies to be measured with exceptional accuracy. It will be much more sensitive to fainter radiation than any previous high-accuracy gamma-ray instrument. SPI will be used to analyse gamma-ray sources over an energy range between 20 keV and 8 MeV, using an array of 19 hexagonal high-purity germanium detectors, cooled to -183 degrees Celsius (90 Kelvin). To reduce interference, the detector is shielded by bismuth germanate oxide crystals, extending around the bottom and side of the detector almost completely up to the coded mask. As a consequence of its construction, SPI is extremely heavy, with a mass of 1,300 kg. The principal investigating institutions for SPI are CESR Toulouse, France and MPE Garching, Germany.

The path to INTEGRAL

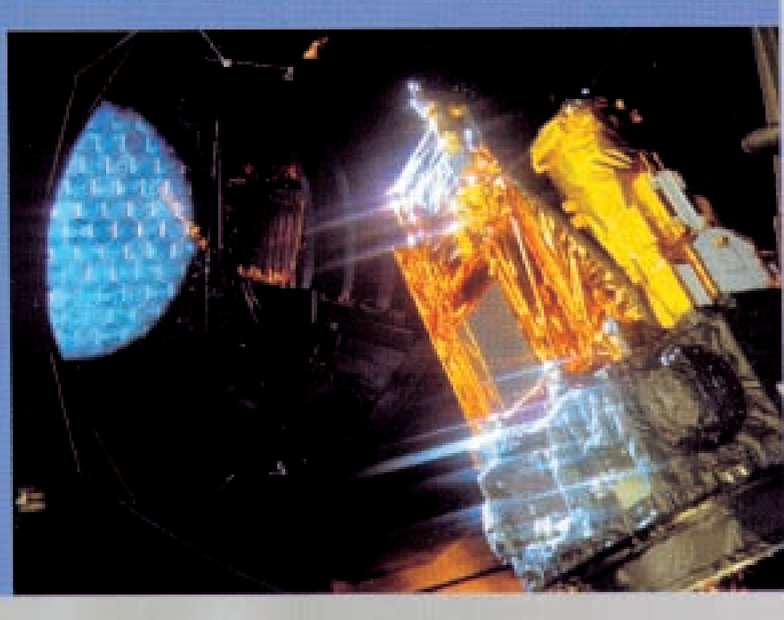


The service module carries the equipment to make the spacecraft function. Photo: ESA



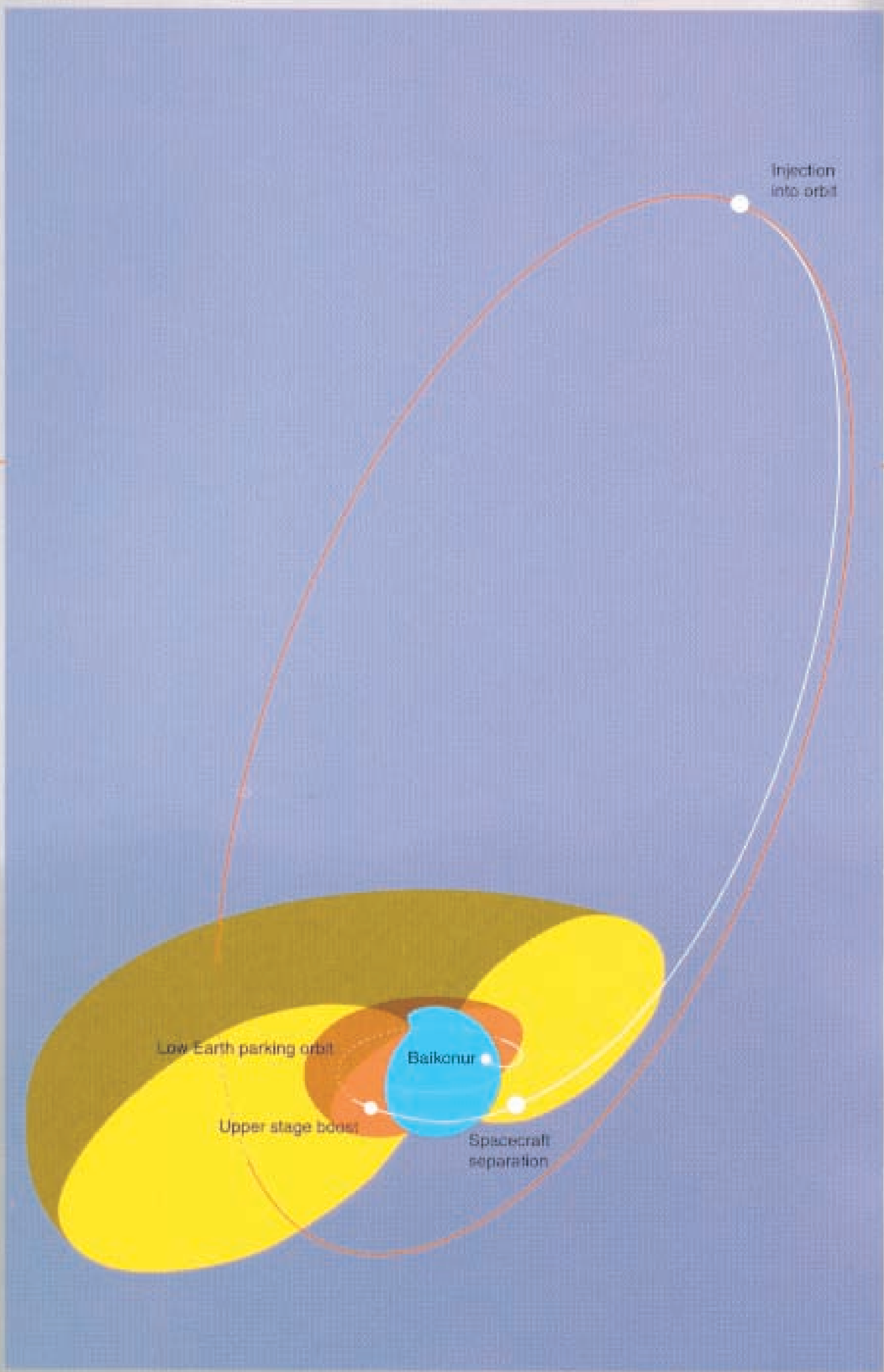
The scientific instruments are built and tested before being fitted into the payload module and mated with the service module. This is the detector for SPI. Photo: ESA

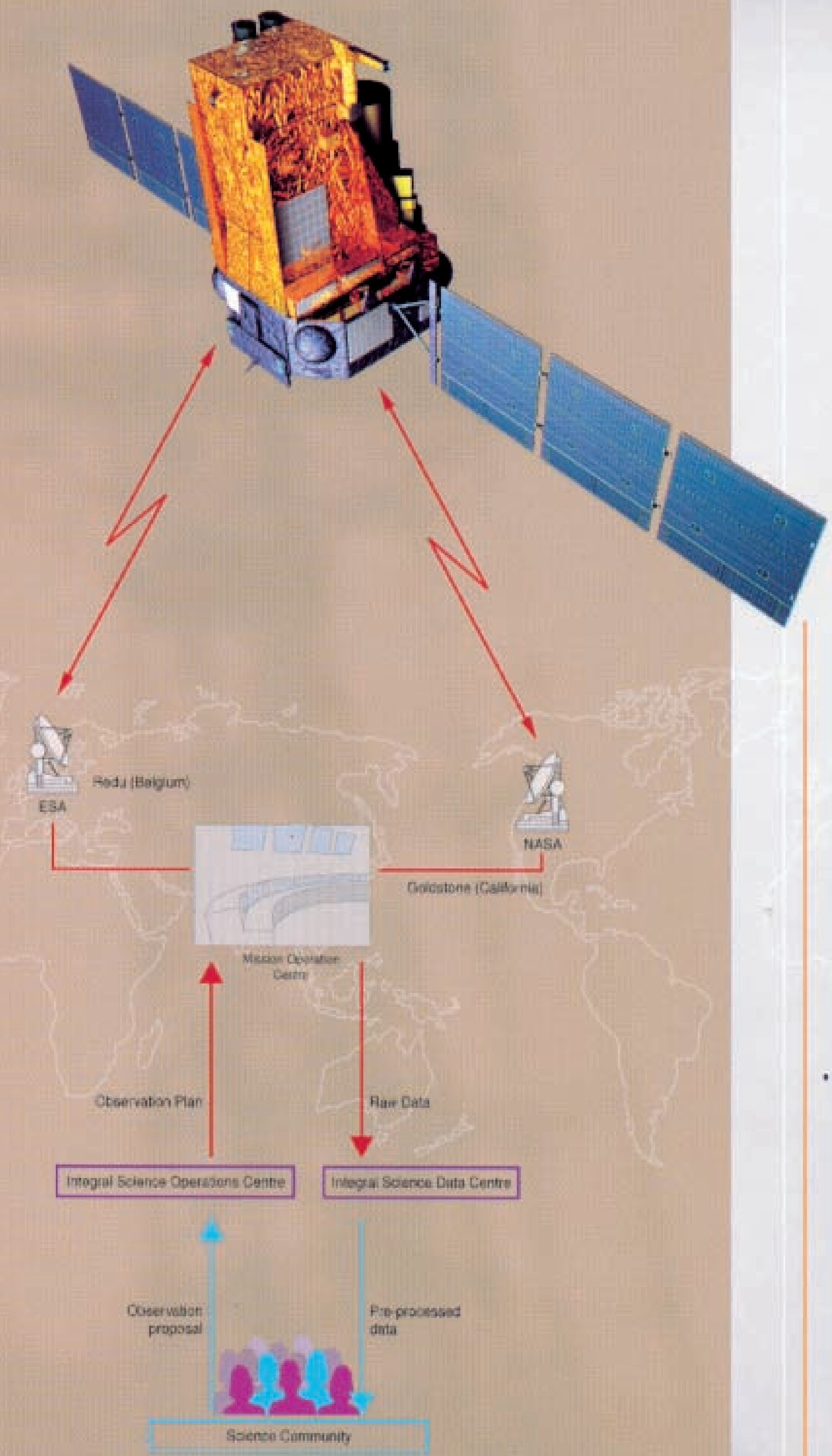
INTEGRAL is fully assembled for the first time. Photo: ESA



The whole satellite is subjected to the harsh conditions it will encounter in orbit, in the Large Space Simulator at ESA's European Space Research and Technology Centre (ESTEC) in the Netherlands. Photo: ESA

INTEGRAL's mission will begin on 17 October 2002 at around 10am local time, when a Russian Proton rocket lifts the satellite into orbit from Baikonur Cosmodrome in the Republic of Kazakhstan, about 2,100km southeast of Moscow. The Proton is Russia's largest operational launch vehicle. It is more than 57m tall and its mass at lift-off is almost 700 tonnes. Photo: ESA





The Proton rocket will place INTEGRAL into a low parking orbit. About 50 minutes later, another rocket will fire, putting INTEGRAL into a transfer orbit. The satellite will separate from this rocket and use its own propulsion system to manoeuvre into a final 72-hour orbit that will cycle the spacecraft between altitudes of 10,000 km and 153,000 km above the Earth. This is essential because INTEGRAL must stay above Earth's radiation belts, otherwise its view of the Universe will be distorted. The radiation belts are subatomic particles (a small concentration of protons, surrounded by a larger, more diffuse assemblage of electrons) that are trapped in the Earth's magnetic field. INTEGRAL will spend 90% of its orbit outside the radiation belts.

Two tracking stations, one at Redu in Belgium, the other at Goldstone in California, United States, will communicate between the satellite and the ground stations.

The INTEGRAL Science Operations Centre, ISOC, at Noordwijk, in the Netherlands, determines which targets INTEGRAL will observe. The list is based on proposals submitted by the scientific community and selected on the basis of their scientific merit.

The Mission Operations Centre (MOC) is located at ESOC, the European Space Operations Centre, in Darmstadt, Germany. Here, they transform the list of observations into commands that INTEGRAL will understand. They also ensure the correct performance of the spacecraft.

Finally, after the observations have been made, the raw science data is forwarded to the INTEGRAL Science Data Centre, ISDC, in Versoix near Geneva, Switzerland, where it is converted into usable data files, distributed to astronomers and archived.

INTEGRAL mission overview

Purpose	Detecting gamma radiation from space with unprecedented sensitivity Simultaneous observations at X-ray and optical wavelengths
Spacecraft	4.1 tonnes at launch, 5 m high, 3.7 m in diameter Solar panels span 16 m when deployed
Scientific payload	2 tonnes, 4 instruments
Launch	17 October 2002, from Baikonur on a Russian Proton launcher
Orbit	72-hour, 10,000-153,000 km altitude, 51.6 degree inclination
Ground stations	Redu (Belgium) ESA and Goldstone (California, United States) NASA
Mission lifetime	2 - 5 years
Prime contractor	Alenia Aerospazio, Turin, Italy
Programme	Selected by ESA in June 1993 as a medium-size scientific mission (M2) in the Agency's Horizon 2000 Programme

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