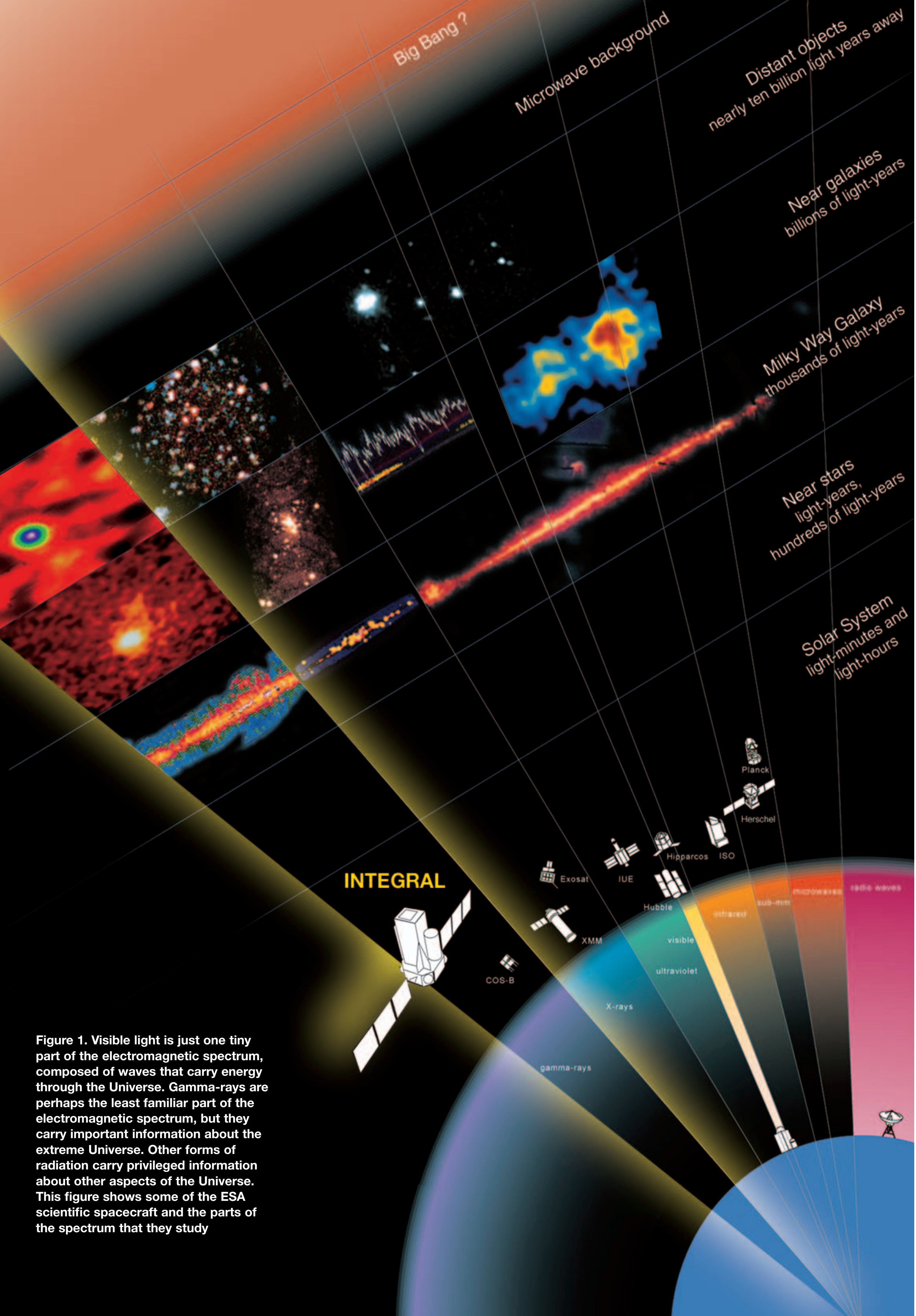

Figure 1. Visible light is just one tiny part of the electromagnetic spectrum, composed of waves that carry energy through the Universe. Gamma-rays are perhaps the least familiar part of the electromagnetic spectrum, but they carry important information about the extreme Universe. Other forms of radiation carry privileged information about other aspects of the Universe. This figure shows some of the ESA scientific spacecraft and the parts of the spectrum that they study

The Integral Science

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The Integral mission will provide a view of the Universe very different from what we see when we look skyward on a clear night. Instead of the familiar stars that shine steadily from night to night, Integral will reveal a violent, highly variable Universe in which intense new sources can suddenly appear, emit almost unbelievable amounts of energy and then disappear, sometimes never to be seen again. Integral's task will be to collect gamma-rays, the most energetic radiation that comes from space, to allow astronomers to study such bizarre objects as black holes, neutron stars – objects so dense that a teaspoon full would weigh millions tonnes here on Earth – and the mysterious gamma-ray bursts, which may be signalling the explosive deaths of massive stars. All of these objects release vast amounts of energy, much of it in the form of gamma-rays. Integral, together with ESA's recently launched XMM-Newton X-ray observatory, is set to substantially improve our understanding of the turbulent Universe.

Introduction

Gamma-rays are even more powerful than the X-rays used in medical examinations. In fact, it would take about a million rays of visible light to match the energy of a single gamma-ray. Fortunately, gamma-rays from space cannot reach the ground because they are blocked by the Earth's atmosphere. This is why Integral has to observe from space, but even from here the task is very difficult because gamma-rays easily pass straight through the mirrors and cameras of normal telescopes. Instead, Integral will use two specially designed gamma-ray telescopes to register these elusive rays.

One telescope, the Spectrometer on Integral (SPI), will measure their energy very precisely, while the other, the Imager on Board the Integral Satellite IBIS), will provide very fine images. Together with the Joint European X-ray Monitor (JEM-X) and the Optical Monitoring Camera (OMC), all of the Integral instruments will observe the same region of sky at the same time. It will be a prime task of the astronomers who are going to use Integral to combine the measurements made with the different instruments in the best possible way to allow the overall properties of the gamma-ray sources to be studied.

Integral will continue the strong European tradition in gamma-ray astronomy that started with ESA's COS-B satellite in 1975. This was followed by the Russian-French mission GRANAT (1989-1998) and NASA's Compton Gamma-ray Observatory (1991-2000), to which European institutes contributed. The international High-Energy Transient Explorer satellite (HETE-2) was launched in 2000 and includes a French gamma-ray telescope and X-ray detectors. Soon, astronomers all around the World will have Integral, the most sensitive gamma-ray observatory ever.

Here we describe some of the key scientific objectives of Integral, present the first year's observing programme and describe the organisation of the scientific component of the ground segment.

Integral science objectives

Super-dense stars

When a massive star explodes, not all the material is ejected into space. Some of it can collapse into an extremely compact object known as a neutron star. A neutron star is only the size of a city, but may contain as much material as two or three stars like the Sun. It is no wonder that neutron stars are incredibly dense – a teaspoonful of neutron star 'stuff' would weigh millions of tons here on Earth! Some neutron stars have incredibly strong magnetic fields due to the original star's magnetic field being 'trapped' and concentrated during the collapse. As they spin, these magnetic neutron stars may emit strong radio pulses and are known as 'pulsars' (Fig. 2). If such magnetic neutron stars are located in

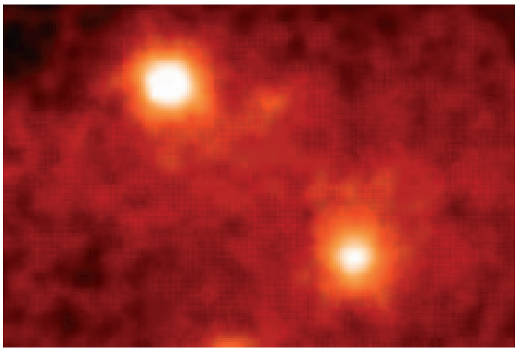

Figure 2. A gamma-ray view of a region of sky containing two spinning neutron stars or pulsars (the Crab and Geminga) and strong diffuse emission. It was taken with NASA's Compton Gamma-ray Observatory (courtesy of NASA)

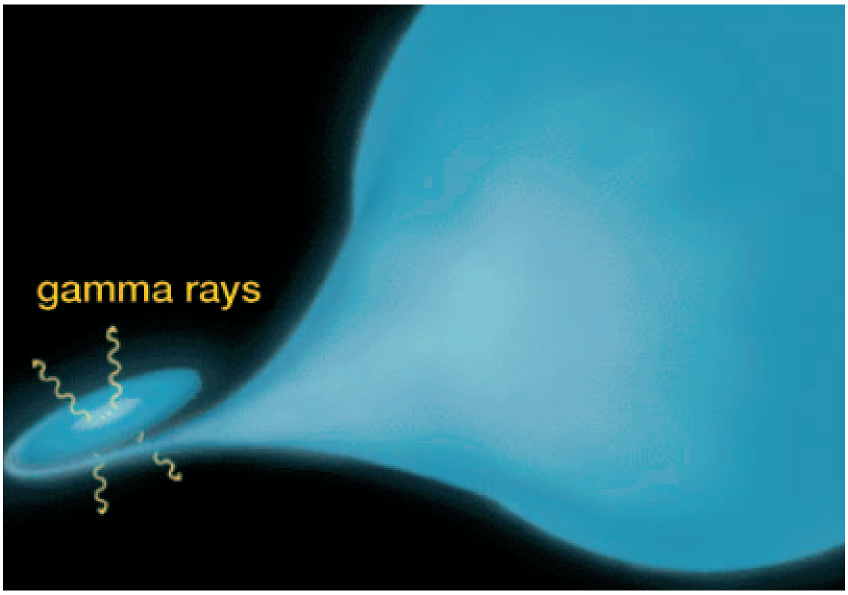

Figure 3. Artist's impression of an accreting binary system, in which material is falling onto a compact object such as a black hole or neutron star from the companion star, shown on the right of the picture. The companion star is distorted into an egg-like shape by the enormous gravitational field of the compact object. The material first spirals inwards in an accretion disk, getting hotter and hotter as it falls towards the compact object (just as water at the bottom of a waterfall is a tiny amount warmer than at the top). Towards the centre of the accretion disk, the material becomes so hot that it emits strongly in gamma-rays, the most energetic radiation in the electromagnetic spectrum

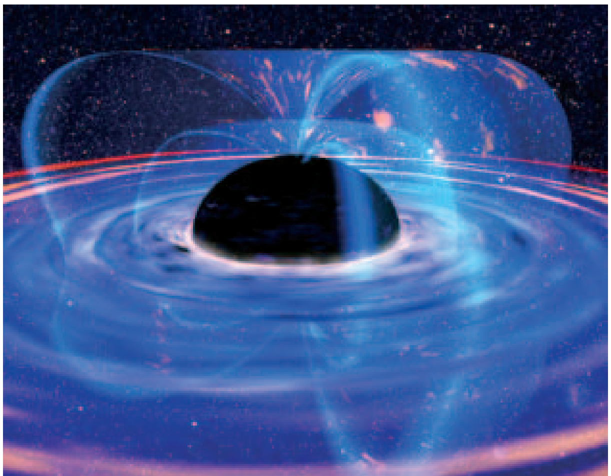

Figure 4. Artist's impression of a giant black hole, called MCG-6-30-15, located at the centre of a spiral galaxy similar to our own, but one hundred million light years away (courtesy of NASA/ Dana Berry)

binary systems and the companion star is close enough to transfer material onto the neutron star, they are known as 'accreting X-ray pulsars' (Fig. 3). As this material falls onto the neutron star it becomes extremely hot and emits large numbers of X- and gamma-rays. These binaries can therefore provide a natural laboratory in which to study the interaction of ultra-hot material with ultra-strong magnetic fields. Such conditions are simply too extreme to be reproduced in laboratories on Earth. Integral will capture images of the high-energy emission from these objects with unprecedented detail, allowing astronomers a clearer look than ever before.

However, neutron stars are not the most bizarre objects that Integral will observe. Neutron stars containing more than about three times the Sun's mass become unstable and collapse even further, becoming a 'black hole'. These are perhaps the strangest objects in the Universe because nothing, not even light, can escape from inside the black hole. So the presence of a black hole can only be inferred by its effect on the surrounding objects.

Understanding black holes

Understanding the nature and properties of black holes is one of the key scientific objectives of Integral. The masses of black holes are thought to range from a few times that of the Sun to many millions of times that of the Sun. Scientists believe that such giant black holes lie at the centre of many galaxies, including our own Milky Way. When there is material close enough to be drawn into the hole by the enormous gravitational field, it will emit phenomenal amounts of energy before disappearing into the black hole. Such systems are known as 'Active Galactic Nuclei', or AGN (Figs. 4 and 5). We believe that there is a million-solar-mass black hole present in the heart of our Galaxy. It is not currently active, although it may have been in the past.

However, from radio and optical observations it is known that the heart of our Galaxy is still a site of violent activity, perhaps resulting from past activity. At gamma-ray energies, this behaviour is brought clearly into view. Arching up from the centre of the Galaxy is an enormous cloud of anti-matter that is glowing brightly in gamma-rays, created by the annihilation of matter and anti-matter (Fig. 6). Integral will investigate the nature of this

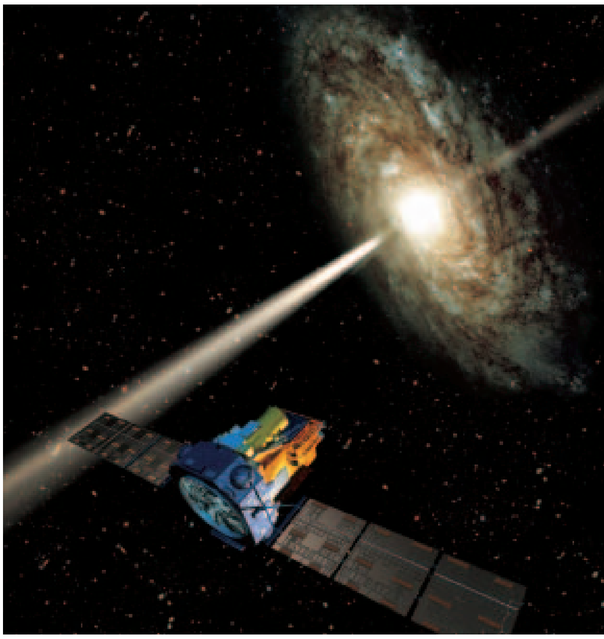

Figure 5. Integral observing a galaxy that contains a massive black hole at its centre. From the region near the black hole two narrow jets are emitted. Integral will study the unknown mechanism responsible for jet production around massive black holes and also in the smaller black holes closer by in our own Galaxy

emission with unprecedented sensitivity and so help us to understand the nature of the giant black hole at the centre of our Galaxy.

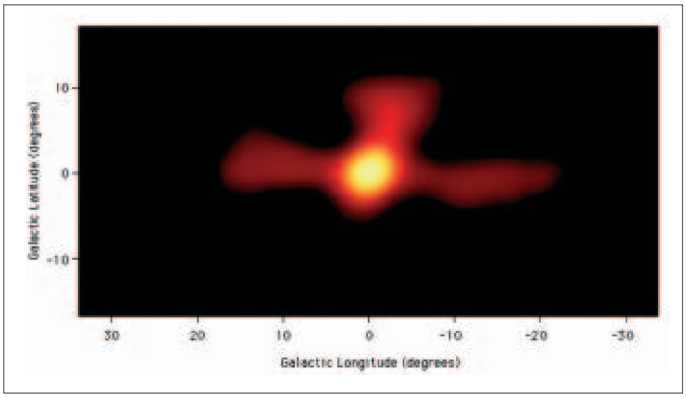

Figure 6. The very centre of our Galaxy is a violent place, as shown in this Compton Gamma-ray Observatory image. The nucleus is the bright spot at the centre, the horizontal structure lies along the Galactic Plane, and the mysterious 'anti-matter' cloud is located above the nucleus (courtesy of D.D. Dixon, Univ. of California Riverside, and W.R. Purcell, North-western University)

Integral will study yet another class of black holes. These are black-hole systems with masses just a few times that of the Sun. If these black holes are in binary systems, then the companion star can provide material that falls into the black hole. As this happens, the material gets extremely hot and emits X- and gamma-rays. Thus, the presence of intense X- and gamma-ray emission from a binary system may indicate the presence of a black hole, hidden from direct view. Many of these systems are 'transients', meaning that they do not give off gamma-rays most of the time and usually remain hidden amongst the billions of stars in our Galaxy. The study of these transient outbursts is of prime scientific importance and most weeks Integral will devote time to a search for new transient sources. Whenever a new transient is discovered, the Integral scientists will alert the worldwide astronomical community so that observations with other facilities and satellites can be organised. Integral will be able to address many outstanding problems in black-hole research, such as whether there are distinctive spectral signatures that can be used to discriminate between black holes and their cousins, the super-dense neutron stars.

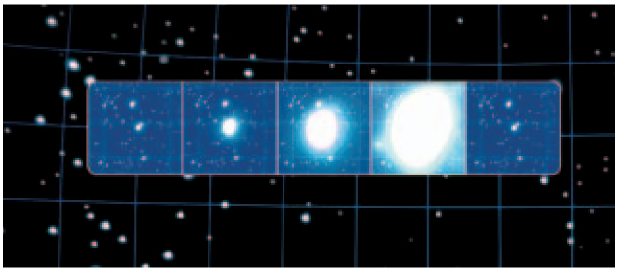

Figure 7. The sequence of five images is an artist's impression illustrating how a gamma-ray burst can flare dramatically over a short time interval, before disappearing never to be seen again. Gamma-ray bursts occur anywhere on the sky and it is impossible to predict when, or where, one will occur next

Probing the mysterious bursts

Around once a day, astronomical satellites detect sudden bursts of gamma-rays coming from anywhere in the Universe (Fig. 7). These bursts can be briefly the brightest objects in the gamma-ray sky, but are never seen to repeat. For many years, astronomers had no idea how far away these explosions were. This changed in 1997 when the Italian-Dutch satellite BeppoSAX provided accurate burst positions quickly enough to allow the still glowing debris to be detected in optical, radio and X-ray telescopes (Fig. 8). These observations showed that gamma-ray bursts occur at huge distances, similar to those of the farthest galaxies, and therefore that they are incredibly energetic, briefly glowing brighter than a billion stars.

Astronomers believe that this colossal amount of energy could be released when a massive star catastrophically collapses in on itself leaving a black hole, in a massive explosion known as a 'hypernova'. Not all gamma-ray bursts may have the same origin, and some astronomers believe that colliding neutron stars or black holes may be responsible for some of the bursts (Fig. 9). More observations of the glowing debris are desperately needed in order to understand what is really happening. However, now that BeppoSAX is no longer operating, it is much harder to find suitable gamma-ray bursts to investigate. The large fields of view of the Integral gamma-ray instruments will allow the chance detection of a few gamma-ray burst per month, a similar rate to that provided by BeppoSAX. In addition, Integral itself will be able to search the glowing debris for evidence of the atoms created.

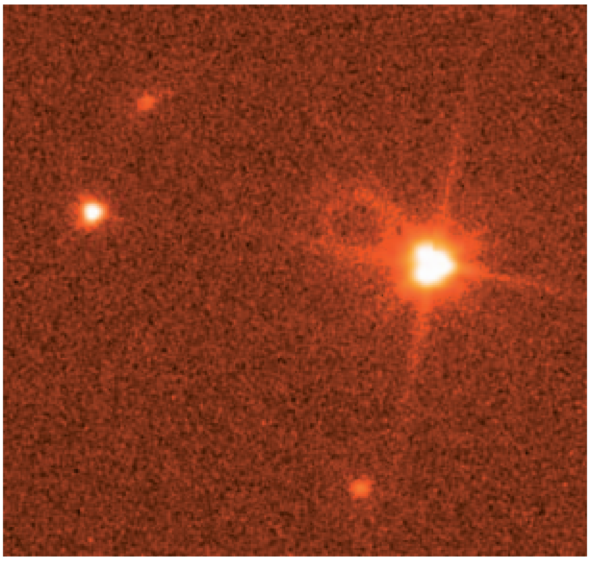

Figure 8. The optical counterpart of the gamma-ray burst of 1 March 2000. The RXTE, Ulysses and NEAR spacecraft all detected a 10 second burst of gamma radiation. Within 48 hours, astronomers detected a counterpart using optical, infrared, millimetre and radio telescopes. The Hubble Space Telescope captured this optical image and was the first to obtain an accurate distance to the explosion, placing it most of the way across the visible Universe. The Keck II telescope in Hawaii quickly confirmed and refined the distance measurement (courtesy of A. Fruchter, STScI)

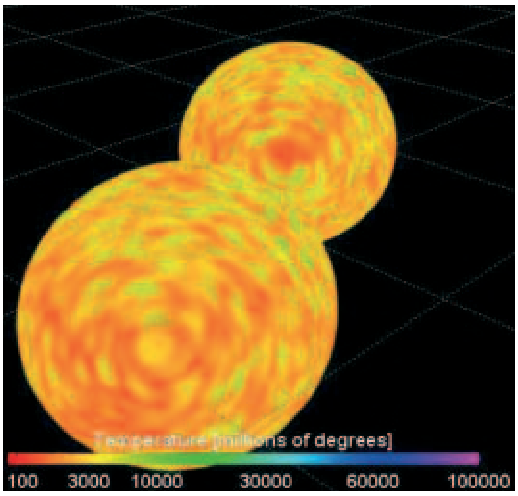

Figure 9. Scientists believe that colliding neutron stars, such as those depicted in this computer simulation by S. Rosswog (Univ. of Leicester) et al. may be a cause of gamma-ray bursts – the most powerful explosions in the Universe. As the neutron stars merge, they tear each other apart, briefly forming an accretion disk and jets before turning into a black hole. Some astronomers now believe that heavy elements, such as the gold in your jewelry, are most easily made in rare neutron-rich explosions such as these collisions. It is a strange thought that you may be wearing a souvenir of one of the most powerful explosions in the Universe!

Creating the atoms

Scientists are confident that most of the elements that we are made from were once in the hearts of stars. From there, they were released into space at the end of a star's life, often in a violent explosion called a 'supernova'. The precise nature of how this happens remains elusive and is one of the top goals of Integral.

The abundances of the 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. Scientists believe that the very early Universe consisted almost entirely of hydrogen and helium, the simplest elements. All of the other elements were created inside stars or in supernova explosions. Most stars, including the Sun, generate energy by changing hydrogen into helium. When all of the hydrogen is burnt, helium can 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. The remaining core of the star gradually cools becoming a 'White Dwarf' star, about the size of the Earth.

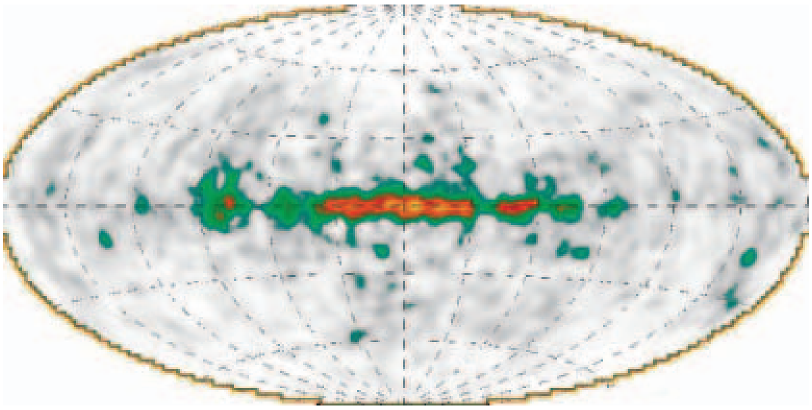

Figure 10. An all-sky map in the light of the 1.8 MeV gamma-ray line from the radioactive decay of aluminium. This map, displayed in galactic coordinates, combines data from nine years of observations by the COMPTEL instrument on the Compton Gamma-ray Observatory. The diffuse line emission is clearly concentrated in the Galactic Centre and along the Galactic Plane. Individual local enhancements, or 'hot spots', are also visible (courtesy of COMPTEL Collaboration and S. Plüschke, MPE)

Not all stars continue shining faintly into a ripe old age. The most massive stars have very short lifetimes that may end in a massive supernova explosion. When such a massive star is blown apart, it may distribute elements such as carbon, oxygen, nitrogen, silicon, and sulphur into space. Heavier elements such as nickel can be formed during the supernova explosion itself and scattered into interstellar space. During the explosion, large numbers of gamma-rays are produced and as these pass through the cosmic debris, the newly created elements can be studied by their effect on the gamma-rays. Integral observations of these gamma-rays will provide the most direct method yet of studying the formation of the elements.

The COMPTEL instrument onboard NASA's Compton Gamma-Ray Observatory has for the first time produced an all-sky map in the light of the 1.8 MeV gamma-ray line produced during the radioactive decay of aluminium (Fig.10). This diffuse glow – possibly from the remnants of many galactic supernovae or novae explosions, or the result of stellar winds from very massive, young and hot stars – shows the clear presence of the Galactic Centre and the Galactic Plane. Integral will investigate the broad-scale distribution of this diffuse radiation with unprecedented sensitivity, energy resolution and imaging. Various 'hot spots' in the map could move at various relative velocities – measurable via slight shifts in the energy of the line due to the Doppler effect, and indicating the influence of galactic rotation.

The Integral Science Ground Segment

The Integral ground segment consists of two major elements, the Operations Ground Segment (OGS), described elsewhere in this Bulletin, and the Science Ground Segment (SGS). The SGS itself consists of two components, the Integral Science Operations Centre (ISOC), which is provided by ESA, and the Integral Science Data Centre (ISDC), which is nationally funded in the same way as the Integral instruments. The main interfaces and information flows are shown schematically in Figure 11. The ISOC, located at ESTEC, issues the Announcements of Opportunity (AOs) for observing time and handles the incoming proposals.

All proposals for observing time on Integral by the scientific community are assessed by an independent Time Allocation Committee (TAC). The accepted proposals are then processed at the ISOC into an optimised observing plan, consisting of a timeline of target positions, together with the corresponding instrument configurations. As part of this optimisation, the ISOC checks for targets close together in the sky which can be observed in a single pointing – so saving observing time. This is particularly important for Integral, where the observations are generally long and the fields of view of the gamma-ray instruments are very large. Optimised observing plans are then forwarded to the Mission Operations Centre at ESOC for the creation of the corresponding commands to be sent to the spacecraft.

observing programme, which will be forwarded to the Missions Operations Centre as before. The revised observing plan will be then made available on the World Wide Web so that astronomers who are planning coordinated observations will know the exact time that Integral will be observing. In order to support Integral users who have questions about any there is a Web-based Help Desk provided, jointly operated by the ISOC and ISDC.

The ISDC, located at Versoix in Switzerland, will receive raw science telemetry together with relevant ancillary spacecraft data from 0the OGS. These science data will be processed, taking into account the instrument characteristics, and raw data will be converted into physical units. Using the incoming science

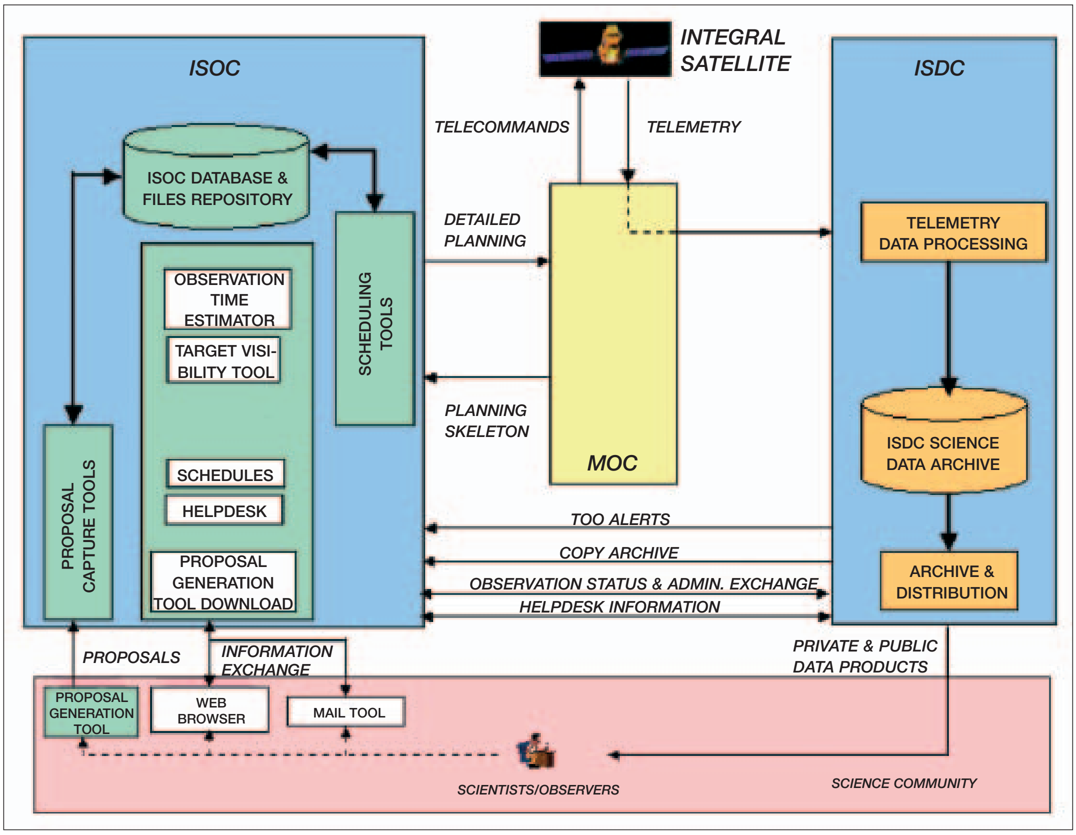

Figure 11. The blue boxes show the two parts of the Integral Science Ground Segment – the ISOC and ISDC – together with the main interfaces and information flows to the Mission Operations Centre (MOC), the scientific community and the Integral satellite

As discussed above, the gamma-ray sky is very variable, and interesting new targets may unexpectedly appear anywhere in the sky. These targets may be discovered using Integral itself, or by other satellites or ground-based observatories. When this happens, the astronomers who made the discovery may request a Target of Opportunity (TOO) observation with Integral. This is a request to interrupt the already planned sequence of Integral observations within 20 to 36 hours and observe the newly discovered target due to its high scientific priority. The Project Scientist will decide on the basis of scientific merit whether to proceed with the TOO request. If the request is granted, the ISOC will generate a new

and housekeeping information, the ISDC will routinely monitor the instrument science performance and conduct a quick-look science analysis in order to search for unusual and interesting events. Many of the TOOs expected during the life of Integral are likely to be detected at the ISDC in this way. As well as keeping an eye on the long-term health of the instruments, the ISDC will distribute science data products such as images and spectra for all four Integral instruments. These will be obtained using standard software-analysis tools developed by the ISDC and the instrument teams. By using these products astronomers who are not experts on the Integral instruments will be able to analyse

Integral data. Another very important role for the ISDC is to produce the Integral science archive for use by the astronomical community. A copy of this archive will be maintained at the ISOC.

The Integral observing programme

Integral is an observatory-type mission with a nominal lifetime of 2 years with an extension of up to 5 years technically possible. Most of the observing time (65% during the first year and 70% in year 2) will be awarded competitively to the members of the scientific community. The remaining fraction of time (i.e. 35% in year 1) is reserved for the Integral Science Working Team (ISWT) for its contribution to the mission. The main task of the ISWT is to monitor and advise ESA on all aspects of the Integral mission that affect its scientific performance. The ISWT consists of the instrument and ISDC Principal Investigators, representatives of the Russian and the US communities and the Mission Scientists who are independent of the instrument teams. In the first year, this 'guaranteed time' will be devoted to: (i) a Galactic Plane survey, (ii) a deep exposure of the central radian of the Galaxy, and (iii) pointed observations of selected regions and sources and TOO follow-up observations. In accordance, with ESA's policy on data rights, all scientific data will be made available to the scientific community one year after they have been released to the observer. Due to the intrinsically faint source intensities and comparably high background radiation, typical observations will last between about one day and three weeks and observers will receive data from all the simultaneously operating instruments onboard Integral.

The Integral open time observing programme for the first year has already been selected by the TAC, which was chaired by Prof. E.P.J. van den Heuvel of Amsterdam University. Observing time on a satellite is a very precious resource and Integral will only be able to carry out the very best of the 291 proposals received when ESA asked for ideas for the first year's observing programme. Indeed, astronomers asked for more than 19 times the open observing time available on Integral for the first year of operations. This remarkable over-subscription is testament to the scientific capabilities of the mission and the interest of the astronomical community in the topics that Integral addresses.

The open time programme provides for a wide variety of innovative studies of objects and phenomena never before accessible with such a powerful mission. About 40% of the observing time will be devoted to observations of compact objects such as stellar-mass black holes and neutron stars, 30% to the study of extragalactic objects such as AGN, and about 25% to the study of the formation of the elements. The TAC selected about twice as many observations as can be performed by Integral in the first year. This is to allow the ISOC some flexibility in planning which target is to be observed when, in order to minimise the time spent manoeuvring between targets. This planning has to take into account that some observations must be performed at certain times. This normally occurs when an observer needs simultaneous observations with other (ground or space-based) observatories, or because the object being studied may be variable and the proposed investigation can only be conducted at certain times (e.g. an observer may wish to study the eclipses of a binary star). In addition, Integral cannot point at any part on the sky at any time. This is because the solar arrays, which provide Integral's power, need to be pointed towards the Sun. The best proposals that are unlucky enough not to be scheduled in the first year will automatically be carried over to the next year.

Conclusions

With ESA's XMM-Newton X-ray observatory producing a wealth of new scientific results, astronomers from all over the world are eagerly awaiting the views of the even higher energy gamma-ray Universe that Integral will provide. The improved imaging and spectral capabilities of Integral compared with previous missions, as well as the simultaneous X-ray and optical monitoring, will provide the scientific community with an unprecedented opportunity to investigate the nature of the extreme Universe in the next years.

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