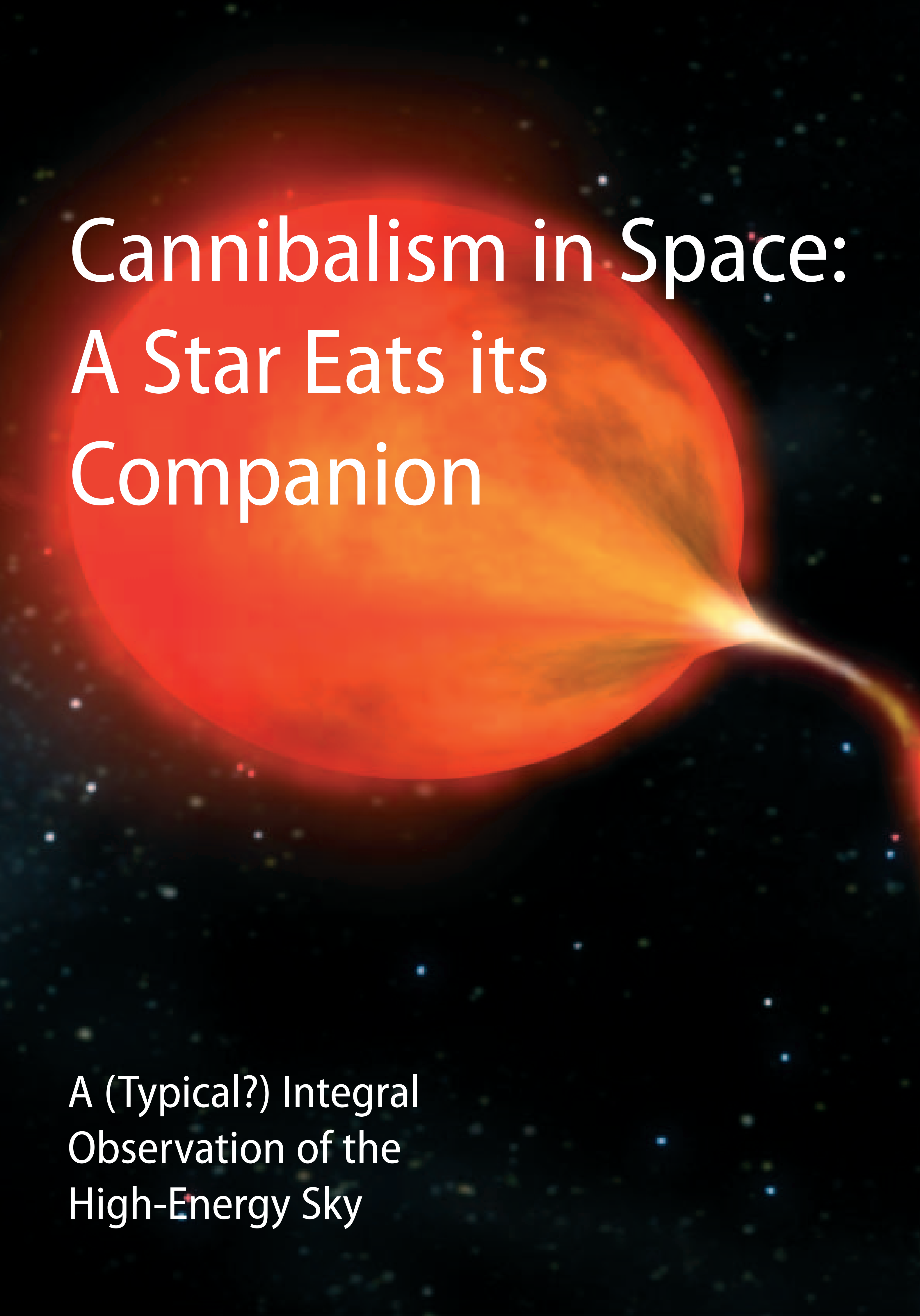
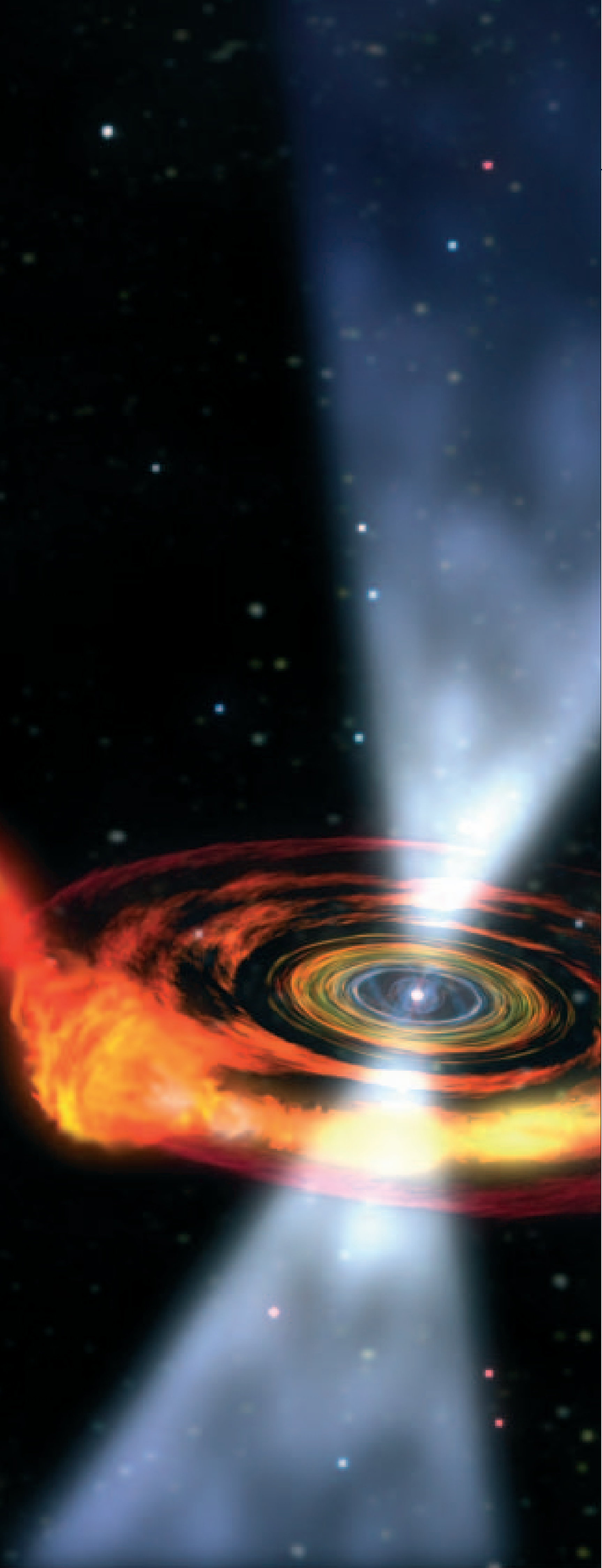


Cannibalism in Space: A Star Eats its Companion

A (Typical?) Integral Observation of the High-Energy Sky



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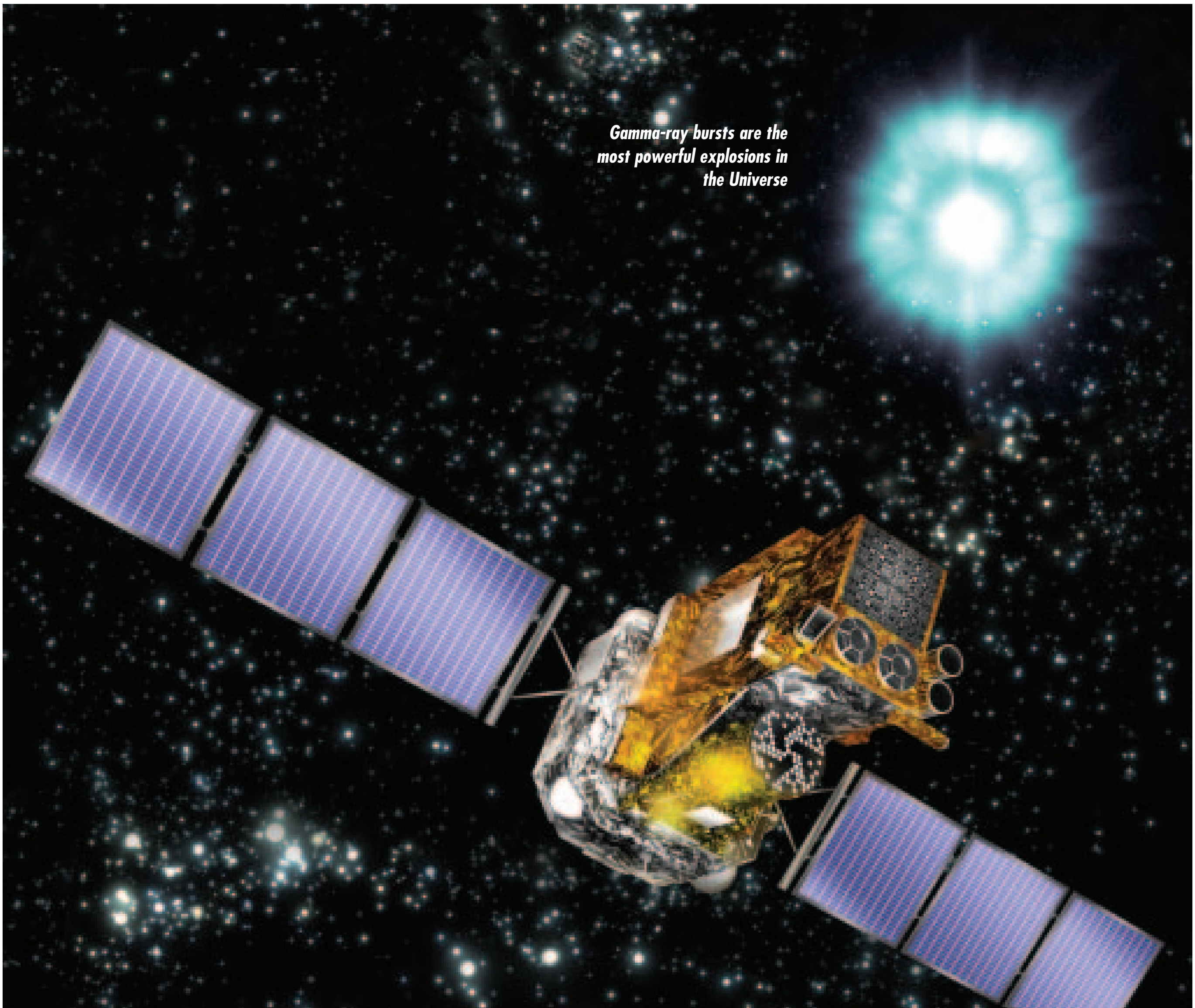
The work of ESA's Integral high-energy observatory usually follows a long-term plan that is established every year by selecting only the very best of the numerous observing proposals from the scientific community. However, nature does not always follow the same plan, so Integral and the people who keep it running have to react to unforeseen and sudden 'Targets of Opportunity'. The case here is neutron star IGR J00291+5934, an incredibly dense object with a mass similar to that of our Sun's compressed into a rapidly spinning sphere only a few kilometres across. Not only that, but it is busy swallowing its stellar companion.

Introduction

The Integral mission

The scientific research with ESA's Integral (INTErnational Gamma-Ray Astrophysics Laboratory), launched on 17 October 2002, focuses on celestial objects that radiate in the energy band between 10 000 and 10 million electron volts (eV). On average, these gamma-rays are 10 000 to 10 million times more energetic than the photons reaching our eyes from the Sun and stars. They are generated by the most energetic and



Gamma-ray bursts are the most powerful explosions in the Universe

Why Observe Gamma-rays?

Light, or electromagnetic radiation, comes in many forms. There are radio waves, microwaves, infrared light, visible light, ultraviolet light, X-rays and gamma rays, all of which form the 'electromagnetic spectrum'. Oddly enough, visible light – to which human eyes are sensitive – is the smallest band of all. To our eyes, what we see seems like the entire Universe, but there is *much* more out there.

Different types of objects in the Universe emit different types of radiation. Our Sun is a rather obvious source of visible light. But it also glows in radio waves, infrared, ultraviolet and X-rays. Some objects emit only radio waves or X-rays. This is why it is important to study the Universe with various kinds of space observatories.

Integral is concentrating on the gamma-rays. These are produced by spectacular events such as stars exploding, matter falling into black holes and celestial objects colliding. By collecting gamma-rays, astronomers can see these violent events and judge how they shape the Universe.

For example, some chemical elements are created during explosions in which individual stars blow themselves to pieces. The new chemicals leave gamma-ray fingerprints in the fireball for astronomers to find. By studying these, Integral is piecing together how these chemicals are created.

Integral is also studying the mysterious blasts known as gamma-ray bursts. These explode at random in distant realms and are probably caused by the collision of neutron stars or perhaps the explosion of large stars.

violent events in the Universe. Integral detects these high-energy photons using two main gamma-ray instruments: the SPI spectrometer provides precise spectral information, and the IBIS camera images the objects with high accuracy. They are supplemented by two monitoring instruments covering the soft X-ray range below 10 000 eV (JEM-X) and the optical wavelength band (OMC). For a detailed description of Integral, its instruments, performance and ground segment, see the set of articles in *Bulletin* 111, August 2002.

The celestial objects of interest to the scientists using Integral include black holes in our Galaxy and local galaxies, neutron stars, X-ray binary stars, pulsars, remnants of supernova explosions and gamma-ray bursts. Studying the gamma-ray emission lines from the radioactive decay of excited heavy atomic nuclei or from the annihilation of electrons with their positron anti-matter equivalents is also important.

The observing programme

Integral is operated like a ground-based observatory, with the vast majority of its time used by astronomers at large. Proposals by the scientific community for Integral observations are solicited by ESA once a year and assessed by the Time Allocation Committee. Then, scientists at the Integral Science Operations Centre (ISOC) in ESA's European Space Astronomy Centre (ESAC, E) create a long-term observing plan. This is an optimised sequence of observations (targets, pointings and exposure durations), taking into account all the scheduling constraints, such as spacecraft pointing avoidance zones and observations that have to be performed at particular times. The Mission Operations Centre (MOC) in ESA's European Space Operations Centre (ESOC, Darmstadt, D) translates this plan into a sequence of spacecraft commands for uplinking to Integral from one of the ground stations, in Redu (B) or Goldstone (USA).

When a target has been observed, the data are downlinked in real-time to the ground stations and then forwarded to the Integral Science Data Centre in Versoix (CH), where they are processed and archived before being dispatched to the proposers for scientific analysis. Usually, therefore, the observing programme follows a sequence planned for the entire year, until a new set of proposals is solicited and selected.

At this point, readers may conclude that operating Integral is a routine matter, with very little to be done on the ground after the observing programme has been established and sent to the spacecraft.

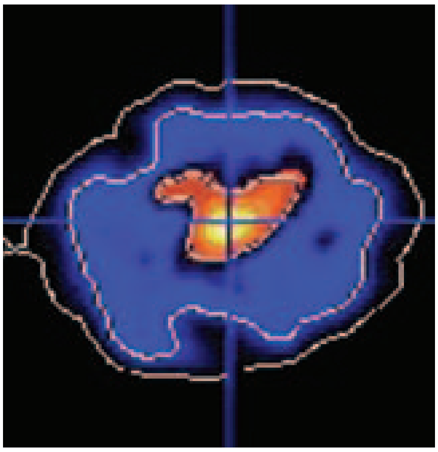
However, this is far from the truth.

The variable high-energy sky

A key characteristic of the high-energy sky is that a large majority of the gamma-ray sources vary with time. Some previously regarded as steady display sudden outbursts on every intensity scale. Others have regular outbursts. Sky areas supposed to be empty suddenly reveal new sources; these often turn out to be previously undetected persistent but weak sources that suddenly burst into life for an arbitrary period. Some sources may vary with a quite regular pattern, known from observations before Integral was launched.

The reason for all this variability lies in the nature of these sources. Many are in binary stellar systems, and material from the companion star is accreted onto the compact object. This accretion process, which releases large amounts of energy, can appear to be highly variable for a range of reasons: the radiation may be temporarily blocked from view by the companion, nuclear explosions on the surface of the compact object, reconnections of intense twisted magnetic fields, or the continuous fast rotation of the dense object (a 'pulsar').

In other words, the high-energy sky looks like a Christmas tree, with candles flickering at every time scale imaginable. Many of these outbursts are relatively bright and provide plenty of photons (which are rather scarce in gamma-ray astronomy). This means that the data can be easily analysed and exciting new scientific results are obtained almost every time. This is what makes these observations so exciting.

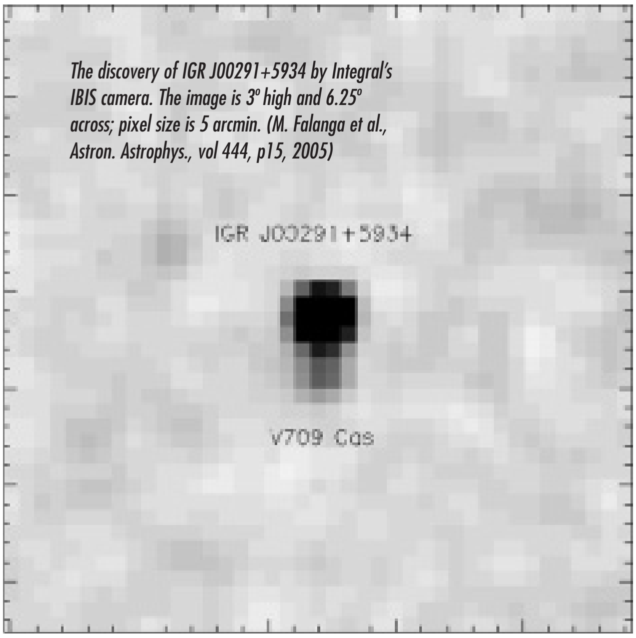


Integral views electron-positron annihilation at the centre of our Galaxy (J. Knödleseder et al., Astron. Astrophys., vol 441, p513, 2005)

Most of these events are unpredictable by their very nature, so they are commonly called 'Targets of Opportunities' (ToOs). Any mission exploring this energy regime should be prepared to react rapidly to such dramatic events. The Integral observing programme, stored in a database, already contains a number of accepted ToO observation proposals that can be activated if the unique event described in the proposal really happens. In that respect, we are not totally unprepared.

The entire ground network needs to be prepared because an alert could be received from either the external science community or ISDC at any time – 7 days a week, 24 hours a day. In the case of Integral, the call could come from the astronomers at ISDC monitoring the data as they are received, pointing out that something strange is going on in the sky right now – an opportunity not to be missed!

Such an alert was received by the Integral team on 5 December 2004, when Maurizio Falanga from the Commissariat à l'Energie Atomique (CEA), Saclay (F) requested that the spacecraft be repointed towards a powerful new source as soon as possible.



The discovery of IGR J00291+5934 by Integral's IBIS camera. The image is 3° high and 6.25° across; pixel size is 5 arcmin. (M. Falanga et al., Astron. Astrophys., vol 444, p15, 2005)

Changing Plans

It was a quiet Sunday in December. Erik Kuulkers, the ISOC duty scientist was enjoying the weekend and a nice Sunday lunch at home. Suddenly, at 13:37, the peace was interrupted by a familiar beep: a text on his mobile phone. Most of the time this means work ahead. A quick check confirmed that a request to trigger a ToO observation of IGR J00291+5934 had indeed just been received by the Integral helpdesk computers. Abandoning his plans for a calm pre-Christmas Sunday, Erik went off to work.

Checks and balances

Upon arrival at the ISOC, the first task was clear: verify that the request was justified. In many cases, there is already an accepted observation proposal with specific criteria to activate it. Of course, the astronomers know the criteria that they or the Time Allocation Committee have set. But in the excitement to get their chance, astronomers frequently try to trigger an observation without checking these criteria, reacting prematurely. But not in this case – the criteria were indeed met and the location of the source did not violate any spacecraft pointing constraints. The next question was the requested reaction time: this turned out to be rather short, within a day, if possible. This meant that the planning for the current 3-day orbit around the Earth would have to be changed, always a delicate task for the MOC, who have to merge the old and new planning seamlessly. Finally, the long-term planning for the current and upcoming orbits was reviewed to see which observations could be shifted to later in order to accommodate the imminent ToO, if accepted. The current main target was supernova remnant Cas A, a very long observation that had not been easy to fit into the overall available time.

With all the facts collected, Erik called the Integral Project Scientist, Christoph Winkler, who has the last word on the planning of scientific observations. So now his Sunday afternoon was also interrupted. The two scientists discussed the case and Christoph evaluated the impact of accepting the ToO, both scientifically and operationally. Finally, the decision was clear: the requested observation should be done as soon as possible.

Reshuffling the programme

By now it was nearly 16:00. Quickly, Erik informed the lucky observer that his observation would be scheduled and called colleagues at MOC in Darmstadt, whose weekend routine was also to be upset as the observing programme was about to be reshuffled. First, a suitable slot within the ongoing observation programme had to be found, keeping in mind both the pressure to start this ToO as soon as possible and the requirement to give Darmstadt enough time for the necessary checks and verifications on their side. And there was an additional complication: a short calibration observation that could not be moved around freely.

Evaluating all the constraints, Erik settled for a plan in which the first

Erik Kuulkers, Operations Scientist on duty at ISOC, studies the target visibility map for the ToO observation

The Integral control room at ESOC. From left to right: Orlane Bergogne (Spacecraft Operations Engineer, SOE), checking the instrument configuration; Michael Schmidt (Spacecraft Operations Manager, SOM) supervising the replanning activities; Salma Fahmy (Mission Planner) performing the replanning; Paolo Lippi (Analyst) checking the consistency of the database; Atef Soliman (SPACON) loading the new timeline; Federico di Marco (Attitude & Orbit Control System Operations Engineer) checking the slew sequence

observations of the ToO would begin on Monday afternoon, less than 24 hours from the time of planning, but late enough so that MOC's main activities could be performed on Monday morning.

Trying to create the changed planning files, Erik encountered another difficulty: a strange problem with inserting the necessary 'Reaction Wheel Bias' (more on this below). Cursing his luck at running up against such an issue on a Sunday, he tried several options but finally sent the planning files as they were to MOC to give his colleagues a chance to evaluate the new slews and pointing positions on the sky. By 18:15, all the files had been sent, the observer had been informed about the intended schedule of his first observations, the scientific community at large using Integral had been informed about the change in the observing programme, and the duty scientist could leave to enjoy what was left of his weekend. The current observations did not cover all of the requested time, but the rest could be planned more calmly, after the results from the first observation had been evaluated. (The remaining observations were scheduled for Wednesday night as part of the next orbit.)

Getting Integral Ready

Monday started as any other day during Integral's routine operations phase. The Spacecraft Controllers (SPACONs) performed the shift hand-over, the Spacecraft Operations Manager (SOM) arrived and talked to the SPACON on shift to get the latest news, and the rest of the Flight Control Team of Analysts and Spacecraft Operations Engineers (SOEs) arrived one after the other. During the status checks, the need for replanning the ongoing orbit was identified because there was fresh input from ISOC over the weekend. Since there was no accompanying alert for an immediate process and since the automatic processing of the planning file did not reveal any urgency, the replanning was postponed to later on Monday morning.

The activities at MOC started again when SOM Michael Schmidt contacted Mission Planner Salma Fahmy with a call along the corridor: "*We've got a Target of Opportunity that requires some replanning*". After the usual round of comments ("*Oh, not another ToO!*"), MOC contacted ISOC to discuss the proposed replanning.

In the planning process, ISOC provides a set of data files, including the Preferred Observation Sequence (POS), which defines the required science operations and provides the information that MOC needs to generate the spacecraft commands. The problems with this ToO was that the operations of the affected revolution were already taking place. The official lead time for the replanning was 8 hours, including a small margin.

The feedback from ISOC was: "*We have the approval by the Project Scientist that the ToO is so important that we should override the planned observations and we have sent a revised POS.*"

"*Well*", MOC told ISOC, "*we hope that a RWB [Reaction Wheel Bias to offload the wheels] has been introduced before the first slew*."

It was at this point that the Flight Dynamics (FD) team got involved. The Mission Planner informed the on-call FD staff, and warned him that a replanned POS (RPOS) had arrived and had to be processed. Some parts of the processing are automated, but there is still a considerable amount of manual effort. Therefore, everyone met in the control room.

The RPOS file is imported manually, as opposed to the fully automatic import for the routine POS files. The FD and the Flight Control Team checked the file by eye, in particular to verify that all the RPOS rules were met. "*Uh-oh!*" There was no RWB before the first slew. "*Well, the time of divergence is in about 4 hours and luckily there was an RWB planned in about 2 hours. If we can get the RPOS processed by then, there should be no problem.*"

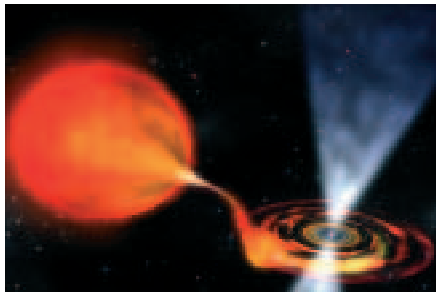
A quick call was made to ISOC to let them know and check that this approach was acceptable; the rest of the processing got underway. All aspects of the POS were checked, some visually such as the instrument mode parameters and telemetry bandwidth allocation, and some by the FD software, such as attitude constraints.

About an hour later, the RPOS had been processed, the Enhanced POS (EPOS) and the corresponding timeline had been generated, and it was time to make the switch to the new timeline. It was important to find a gap in the timeline when there was no commanding in order to stop the Autostack on the control system, abort the old timeline and load the new one. (Of course, before applying the new timeline the paperwork had to be completed. All the planning products were cross-checked and signed by the various people responsible.) With about 4000 commands in one timeline, the loading took a few minutes. In addition, the running FD software tasks had to be stopped and new ones scheduled for the new timeline. So a window of at least 10 minutes was needed. Owing to the observational pattern of a slew every 30 minutes followed by a period of stable pointing with no commanding, finding a slot was not a problem. It was decided to upload the new timeline after the next slew.

The Mission Planner, SPACON and FD observed the end of the slew and waited for the FD job to run to update the parameters for the next slew. "*Ding-dong*!" This was the notification by the control system that the update had arrived. "*Action!*"

The SPACON aborted the timeline, FD rescheduled the jobs, the new timeline was loaded, the updated Task Parameter File was applied to the new timeline, all associated documents were updated – and the job was done.

Everyone resumed their routine work as Integral's instruments observed the new target. The data were routed within a few seconds to the Science Data Centre, where a preliminary check of the results was made.



A neutron star pulsar consumes material from its close stellar companion

The ToO Observations of IGR J00291+5934

This 'new' source was serendipitously discovered by Integral within its wide field-of-view during a routine short observation around the constellation Cassiopeia, in the outer reaches of the Milky Way, when it suddenly flared on 2 December 2004. It was designated as IGR J00291+5934, where IGR denotes an 'Integral Gamma-Ray' source, and the numbers give the coordinates on the sky. On this day, the source proved to be bright enough to warrant a dedicated, longer Integral observation for in-depth investigation. Normally these sources stay bright for a few days, but some transient sources unexpectedly fade in less than a day without warning. So it is always exciting to await the outcome of the observation and analysis of the data. In this case, the observations were highly successful and the results were rapidly published in the leading scientific journal *Astronomy and Astrophysics* (see also the ESA news release at *http://www.esa.int/esaSC/SEMWSAA5QCE_index_2.html*).

What did we learn from these observations?

Neutron stars and pulsars

Pulsars are rotating neutron stars, which are created during stellar explosions. They are the remnants of stars of 8–10 times the Sun's mass that ended their lives in supernova explosions. These remnants still contain about the mass of our Sun but concentrated in a 10–20 km diameter! The extreme pressure forces electrons to combine with protons to form neutrons; the entire star is essentially one big atomic nucleus consisting of neutrons. Often, they are also rapidly spinning pulsars. Discovered by radio astronomers about 50 years ago, pulsars beam electromagnetic radiation from their polar regions, like a lighthouse sweeping its beam across the Earth at regular intervals. The extreme regularity of the pulse intervals makes them the most precise clocks in the Universe – much better than even atomic clocks on Earth.

The fastest accreting millisecond-pulsar

On 3 December 2004, using Integral's data of the discovery made the day before, and 2 days before the Integral alert was submitted, scientists observed the object with NASA's Rossi X-ray Timing Explorer (RXTE), a satellite specialised in high-precision X-ray timing measurements. These revealed that it was a pulsar, or more precisely an 'X-ray millisecond pulsar'. IGR J00291+5934 emits around 600 pulses a second, one of the fastest known. This corresponds to a rotational period of this solar-mass object of only 1.67 millisec (37 500 rpm!). This is much faster than most other pulsars in binary systems, which rotate every few seconds. (For comparison, the Sun takes about 25 days.) Only a few isolated (radio) pulsars are known to spin even faster. So, IGR J00291+5934 could be the 'missing link' between the relatively slow accreting pulsars in binary systems and the very fast isolated pulsars, having finally lost their companions in their old age.

Photons from polar regions

Many neutron stars have strong magnetic fields, which were frozen in during the collapse of their progenitors. This can create incredibly strong magnetic fields for a small, city-sized neutron star. Charged particles in the accreting flow are channelled along these magnetic field lines onto the polar regions of the neutron star (like solar particles in Earth's field generating our polar aurorae) where they finally hit the surface close to the poles, creating hot spots. Integral directly observed the photons from these spots, finding they account for most of the emission at energies above 30 000 eV. The key observation behind this result was the fact that Integral measured gamma-ray pulsed emission from IGR J00291+5934 up to energies of 150 000 eV exactly in phase with the 1.6 millisec X-ray pulsations recorded by RXTE. This proves that the observed high-energy emission must be connected with the polar regions emitting the lighthouse-beam radiation. Before this, such high-energy photons had never been seen in the pulsed emission from these objects.

Cannibals at work

Using the timing information on IGR J00291+5934, it was found that the companion star is perhaps as small as 40 Jupiter masses. The two stars orbit one another in only 2.5 hours. The binary system is very small: the stars are so close that they would fit into the radius of the Sun. The observations support the theory that the two stars are close enough for accretion: material is flowing from the companion into a disc around the neutron star before falling to its surface. If this process continues, the companion will be completely consumed by the much smaller star. This conclusion can be drawn once a change in the spin period is observed. Neutron stars – spinning rapidly at birth – gradually slow down after a few hundred thousand years. Neutron stars in binary systems, however, can do the opposite, accelerated by the angular momentum of the in-falling material from the companion. For the first time, this speeding up was observed directly in high-energy data. This is direct evidence for the star spinning faster and faster, as it cannibalises its companion. Over about 100 000 years, the spin will speed up by 0.6%, from 1.67 millisec to 1.66 millisec.

Conclusions

The observations of this ToO show that nature always has surprises and new questions to offer. Space observatories such as Integral, with their dedicated operational staff, are ideally suited to providing the right tools to find the answers. Over its first 3.5 years of operations, Integral has observed 29 Targets of Opportunity for a total of almost 8 million seconds.

Detailed information on Integral and its mission can be found at http://www.esa.int/SPECIALS/Integral/ and http://integral.esac.esa.int/