More than meets the eye: unravelling the cosmos at the highest energies

Claudia Mignone and **Rebecca Barnes** explore X-rays and gamma rays and investigate the ingenious techniques used by the European Space Agency to observe the cosmos at these wavelengths.

Viewed with the naked eye, binoculars or a telescope, the starry night sky is an overwhelming and tranquil sight. But if we could view the sky in highly energetic X-rays and gamma rays, rather than the visible light perceived by our eyes, we would see a very different picture – a dramatic cosmic light show[w1] (Figure 1).

Some of the most powerful and violent phenomena in the Universe shine brightly at these short wavelengths, such as supernova explosions – the fiery demise of a massive star's life – and black holes, rapidly devouring matter. As a sign of their dynamic nature, many sources of X-rays and gamma rays exhibit distinct changes in their brightness, even over very short periods of time. Gamma-ray bursts, for example, appear as sudden bright flashes that last just a few seconds. These bursts arise from possibly the most extreme explosions in the cosmos (to learn more, see Boffin, 2007). Furthermore, X-rays and gamma rays are released through different physical processes than those responsible for the emission of visible light. This means that galaxies and other astronomical objects look different when imaged at the high-energy end of the electromagnetic (EM) spectrum[w2] (Figures 2 and 3).

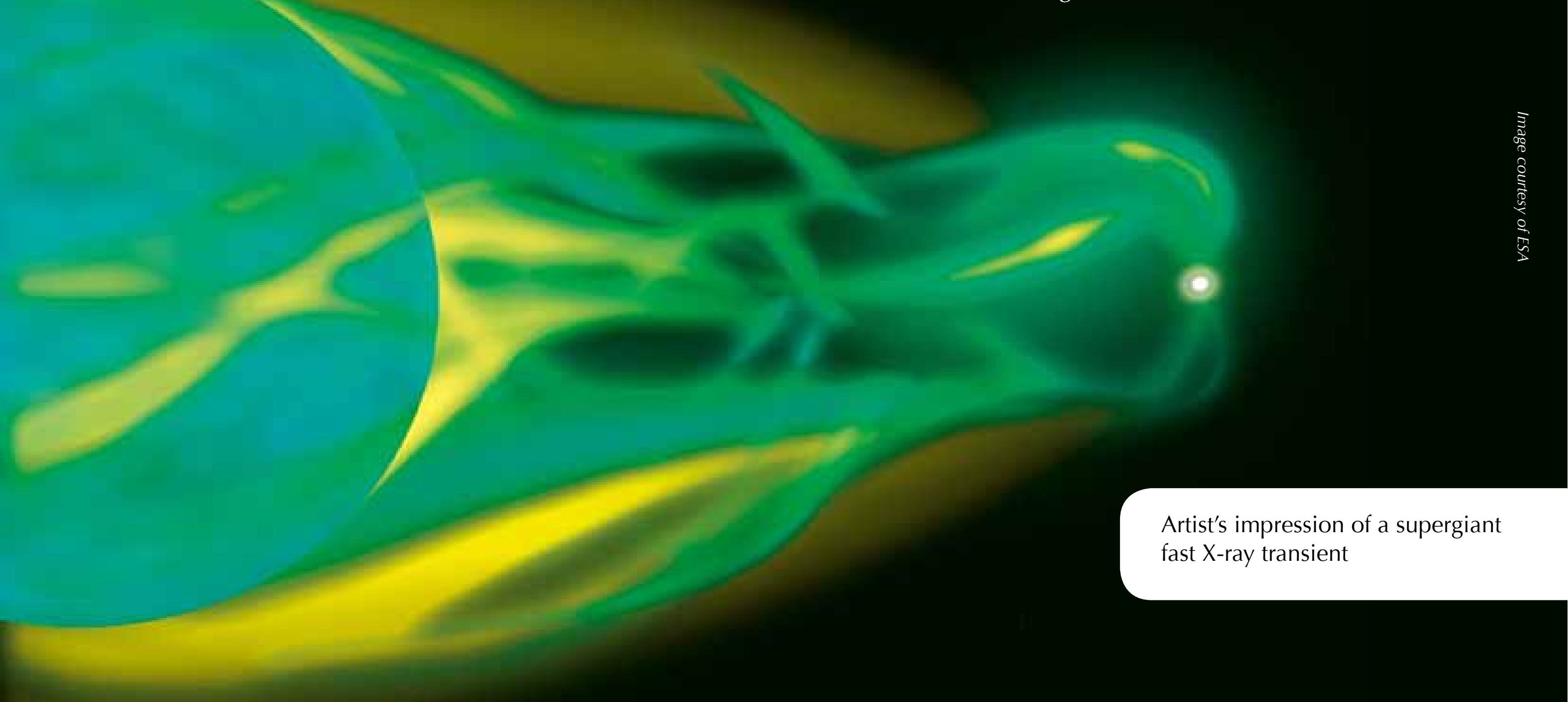


Image courtesy of ESA

Artist's impression of a supergiant fast X-ray transient

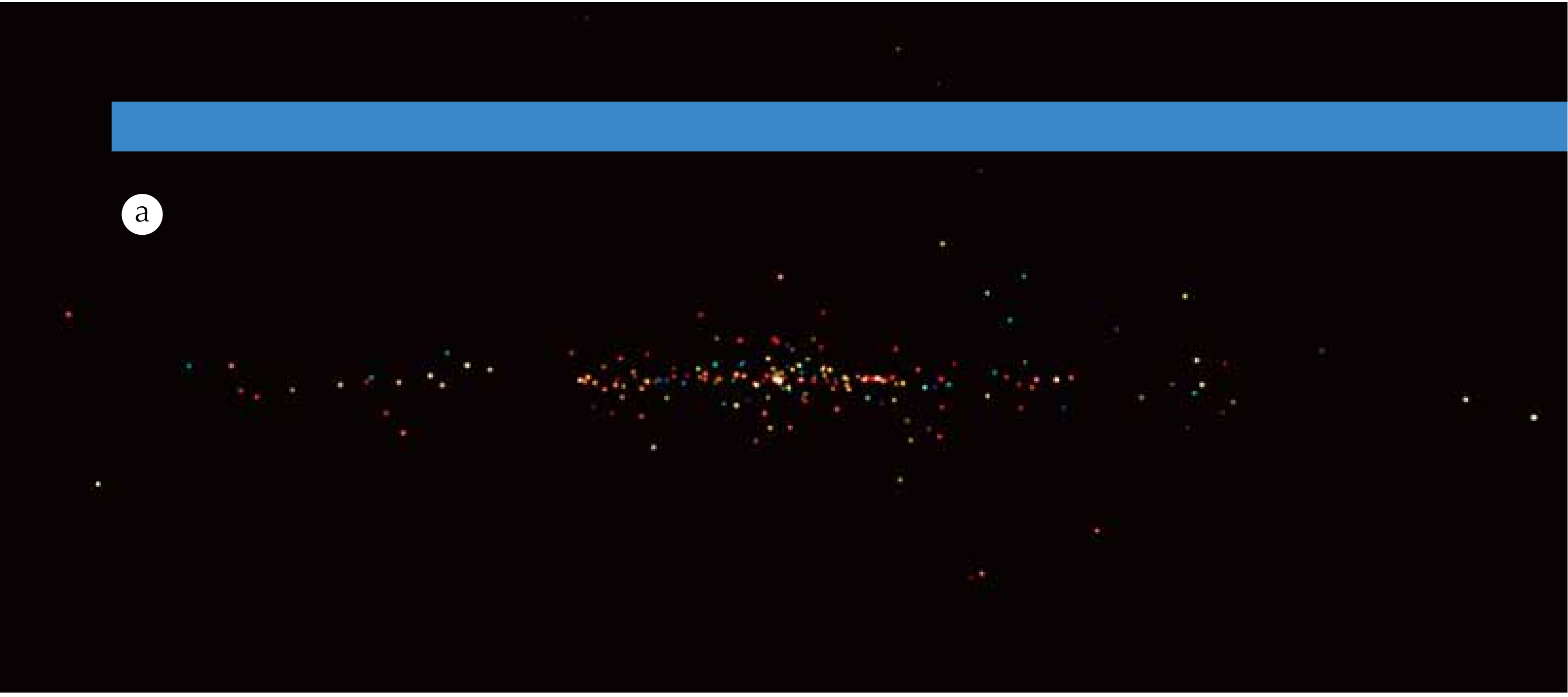


Figure 1: a) An all-sky image at high-energy X-ray wavelengths from ESA's INTEGRAL space observatory, based on data collected in the 18-40 keV energy range (visible light corresponds to 1.65–3.1 eV). **b)** An all-sky image at visible wavelengths

This revolutionary view of the cosmos was revealed to astronomers in the early 1960s, with the beginning of the space age, when rockets and satellites allowed specially developed instruments to be carried beyond the obscuring barrier of Earth's atmosphere[w3]. The European Space Agency (ESA; see box)[w4] soon joined in, with the gamma-ray mission COS-B (1975) and the X-ray observatory EXOSAT (1983). Today, ESA operates two such observatories: the X-ray Multi-Mirror satellite (XMM-Newton), launched in 1999, and the International Gamma-Ray Astrophysics Laboratory (INTEGRAL), launched in 2002.

How do they work? As we explained in an earlier article (Mignone & Barnes, 2011), there is no physical distinction between X-rays, gamma rays, visible light and other types of EM radiation. All are forms of light, differing only in their wavelength (or, as the three are correlated, their frequency or energy; Figure 4). However, depending on their wavelength (or frequency, or energy), they interact very differently with matter. This has major implications for astronomy.

Traditional optical systems, such as our eyes, cameras, microscopes or telescopes, rely on lenses (or mir-

REVIEW

- Physics
- General science
- IT
- Ages 4-19

This article explains simply and comprehensibly how X-rays and gamma rays are collected from cosmic sources using modern space telescopes, and it provides some dramatic images.

For science teachers in primary schools, the article may provide motivation to build a model telescope in lessons, for example using recycled materials – or to use the downloadable satellite models on the ESA website[w4]. The colourful images can also form part of a class exhibit.

Science or physics teachers at secondary school (students aged 11-16) can link to the topic of gamma-ray imaging techniques using a pinhole camera. This would be appropriate in optics lessons, emphasising that both the pinhole camera and coded-mask imaging work without an optical lens.

Images taken by ESA's observatories[w4] would be a useful support for teaching space observation, helping to familiarise students with the different astronomical phenomena (e.g. galaxies, black holes, supernovas, neutron stars, or the annihilation of matter and anti-matter) mentioned in the article. It could also encourage students to do some research of their own on related areas within the curriculum.

For teachers of older school students, it would be interesting to discuss the type of telescopes for high-energy astronomy that are on board the space observatories XMM-Newton and INTEGRAL, and the techniques used to filter the data until the images are fully extracted (this could be linked to IT lessons). Students could compare the structure of telescopes in the high-energy end of the spectrum to that of the optical telescope, and investigate the difficulties encountered when building them.

Stephanie Maggi-Pulis, Malta

Images courtesy of ESA / F Lebrun / CEA Saclay, Service d'Astrophysique (a); ESO / S Brunier (b)

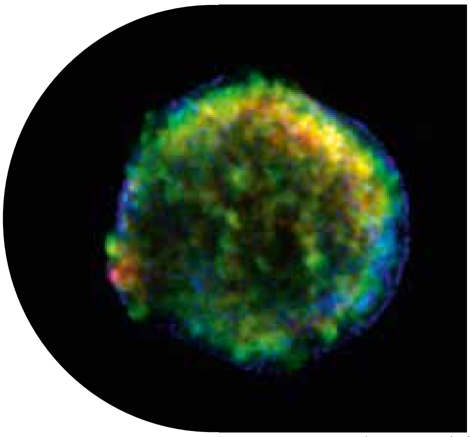
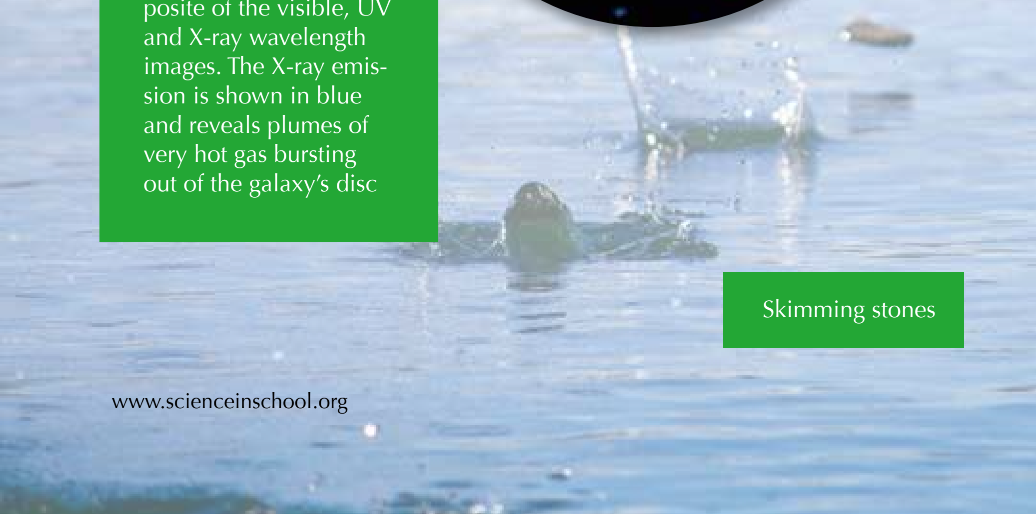


Figure 2: The Tycho supernova remnant as viewed by ESA's XMM-Newton. This remnant is relatively young and is associated with a supernova explosion that was observed in 1572 by the Danish astronomer Tycho Brahe

Image courtesy of Marco Iacobelli (XMM-Newton SOC) and ESA

Figure 3: The Cigar Galaxy (M82), as viewed by XMM-Newton, at visible and ultraviolet (UV) wavelengths (left) and at X-ray wavelengths (right). The central image is a composite of the visible, UV and X-ray wavelength images. The X-ray emission is shown in blue and reveals plumes of very hot gas bursting out of the galaxy's disc

Image courtesy of ESA



Skimming stones

Image courtesy of Killy Ridolis; image source: Wikimedia Commons

rors) that refract (or reflect) light rays and focus them into a single point to produce images. However, this is difficult with some light rays. Because X-rays and gamma rays have wavelengths of a similar size to atoms and sub-atomic particles, respectively, they cannot easily be reflected or focused like visible light, but tend instead to be absorbed when they strike denser materials (Figure 5).

The fact that X-rays and gamma rays are absorbed by dense materials makes them suitable for many applications, including medical scans and investigations of materials[w6]. For astronomers, however, it is a problem: being easily absorbed, these types of radiation are very difficult or impossible to focus; thus obtaining sharp images of their sources is a challenge.

Nonetheless, scientists have developed techniques to detect X-rays and gamma rays coming from the cosmos. They differ greatly from techniques used in traditional optics and that, together with the fact that they operate in space, means that telescopes for high-energy astronomy look nothing like optical telescopes.

X-ray observing techniques

Although it is difficult to reflect X-rays, it is not impossible if they hit the telescope's mirror at a very small angle – think of a pebble skimming across the surface of the water. However, whereas an incidence angle

Image courtesy of ESA / AOES Medialab

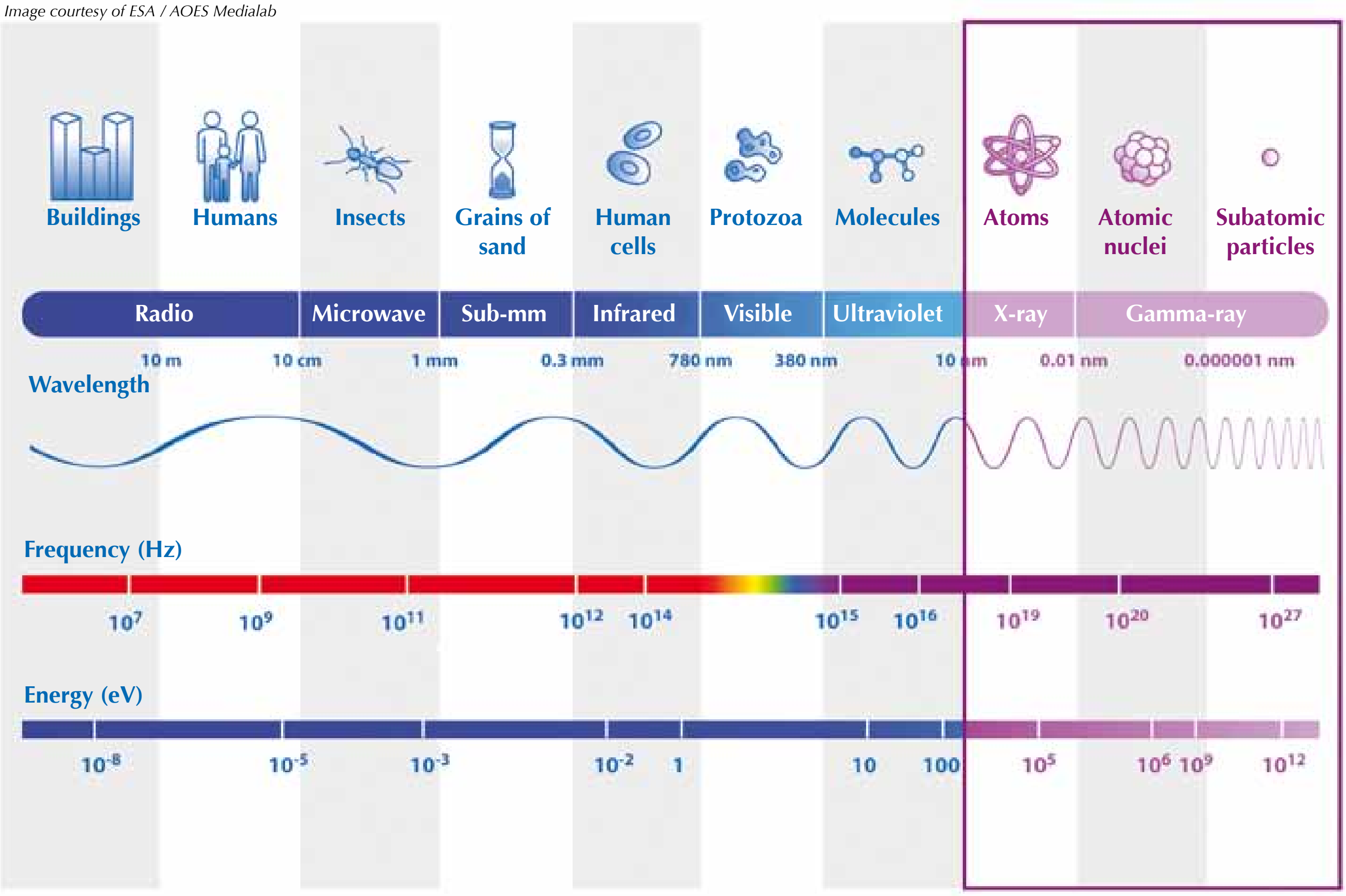


Figure 4: A scheme of the EM spectrum highlighting X-rays and gamma rays, with indications of wavelength, frequencies and energies across the spectrum

Image courtesy of ESA / AOES Medialab

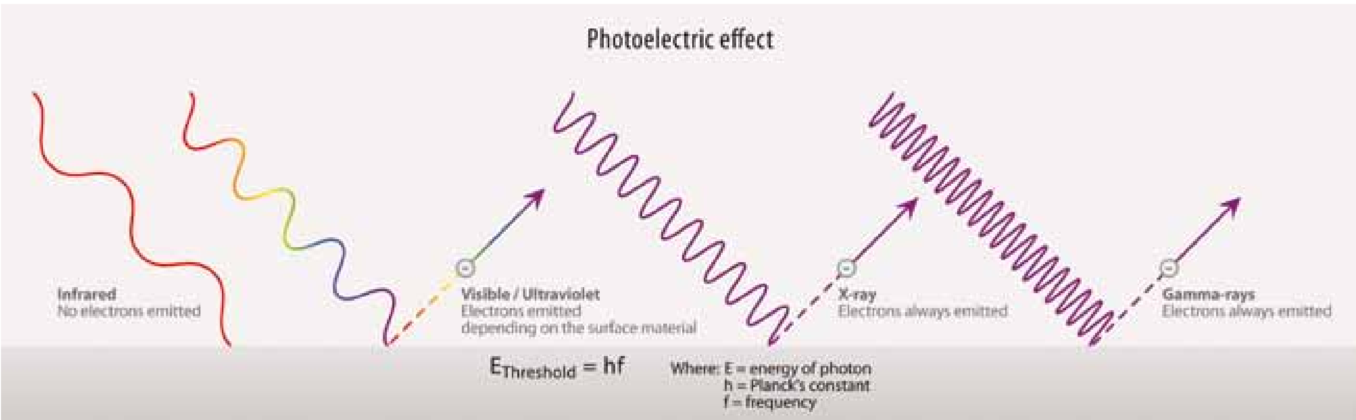


Figure 5: Light rays striking a surface will be absorbed if their energy is higher than a certain threshold value, which depends on the surface material. The energy of the absorbed light is transferred to electrons in the material, which are then emitted. This phenomenon, known as the photoelectric effect[w5], is one of several phenomena that occur when highly energetic radiation interacts with matter. For a dramatic way to teach the subject at school, see Bernardelli (2010)

Image courtesy of ESA / AOES Medialab

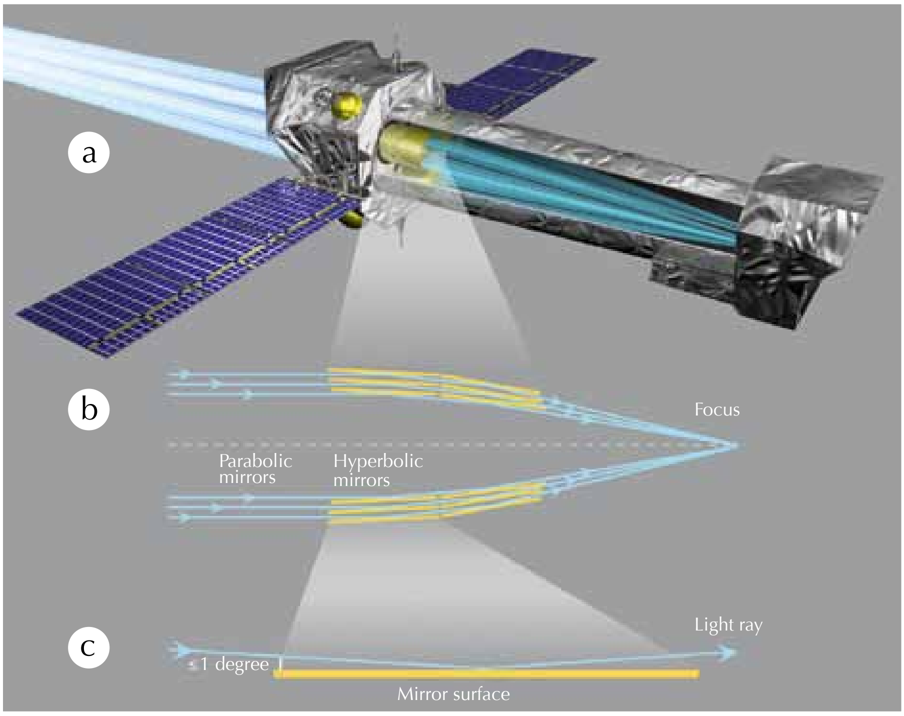


Figure 6:

a) The light path of X-rays through XMM-Newton. The spacecraft carries three telescopes each consisting of 58 nested, gold-coated, tube-like mirrors.

b) The combination of parabolic and hyperbolic mirrors used is shown in cross section through one of the telescopes.

c) X-rays that graze the mirror surfaces are reflected twice and focused onto a detector. The X-rays must graze the mirror at angles of 1° or even less, or they are likely to be absorbed

as large as 20° will allow the stones to bounce, X-rays can be reflected only at much smaller angles: 1° or even less. The X-rays must barely graze the mirror, or they are likely to be absorbed.

To achieve this small angle – and focus the X-rays to a single point – the mirrors used in X-ray telescopes look rather like a funnel (Figure 6). In fact, the mirror shape is a combination of a paraboloid and a hyperboloid, ensuring that the X-rays that graze it are reflected twice. In this way, light is focused onto a detector to form an image of the X-ray source.

This ingenious technique, called grazing incidence optics, has one main drawback: to be reflected and focused, the X-rays must be travelling almost parallel to the tube-like mirrors, so these telescopes collect only limited amounts of X-ray radiation. A powerful telescope is one that collects large amounts of light from distant cosmic sources; this is usually achieved with very large mirrors. In contrast, to maximise their power, X-ray telescopes have several mirrors nested within one another, creating a structure that resembles a giant leek. The three telescopes on board ESA's XMM-Newton space observatory, for example, each consist of 58 nested mirrors (Figure 7)[w7].

Besides their bizarre shape, XMM-Newton's mirrors differ from conventional telescope mirrors in that they are made of gold-coated nickel rather than aluminium-coated glass: the heavier elements are more likely to reflect incoming X-rays (to learn more, see Singh, 2005).

Gamma-ray observing techniques

If focusing X-rays is challenging, focusing gamma rays – the most energetic form of light – is almost impossible. To produce images of cosmic sources in this portion of the EM spectrum, therefore, astronomers had to find alternative methods.

Many instruments for gamma-ray astronomy, including those on board ESA's INTEGRAL space observatory, rely on a technique called coded-mask imaging. This works similarly to a pinhole camera, which has no lens, just a tiny hole through which light rays pass, projecting an inverted image on the opposite wall of the camera.

In place of the pinhole camera's single hole, a coded-mask camera has a mask with a special pattern of holes and opaque spots in front of a detector. Gamma rays that pass through the holes illuminate some pixels on the detector, while others are blocked by the mask's opaque spots and cast shadows on the detector.

The pattern of bright and dark pixels contains information about the location of gamma-ray sources in the sky, and the intensity of the illuminated pixels gives information about their brightness[w8]. Albeit not detailed, the resulting images are useful to

Image courtesy of ESA

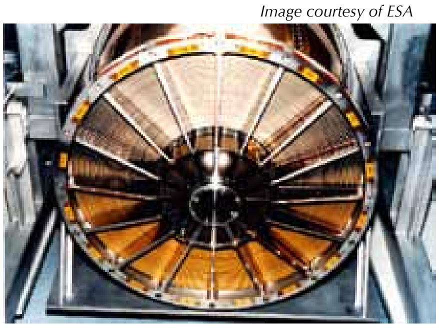


Figure 7: The nested mirrors constituting one of the three telescopes on board XMM-Newton

Images courtesy of ESA / AOES Medialab

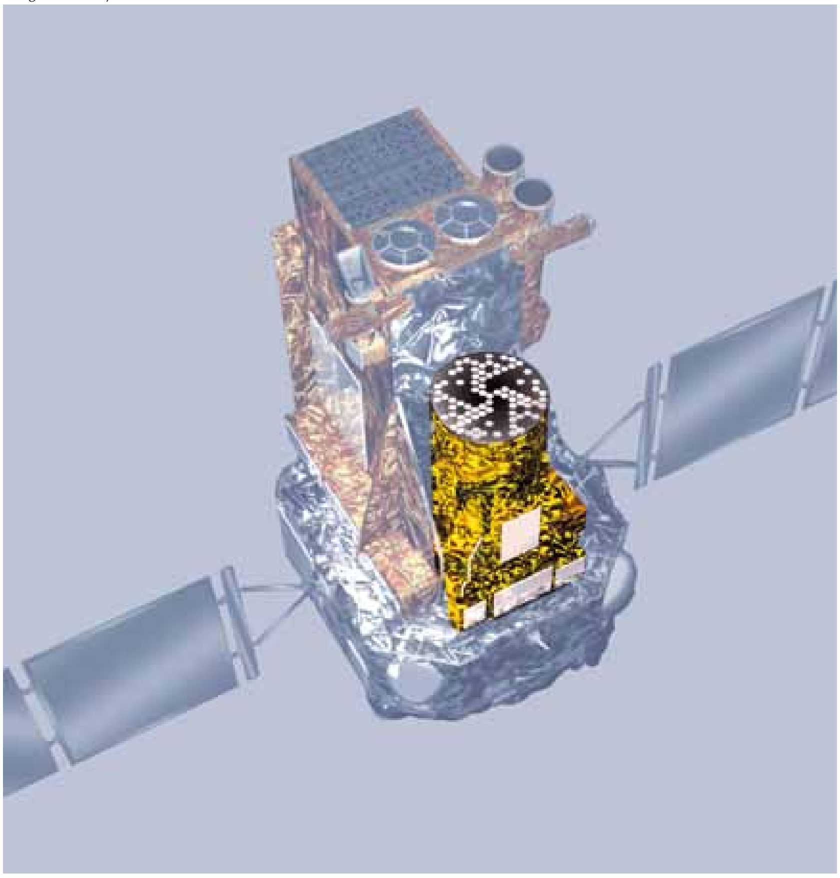
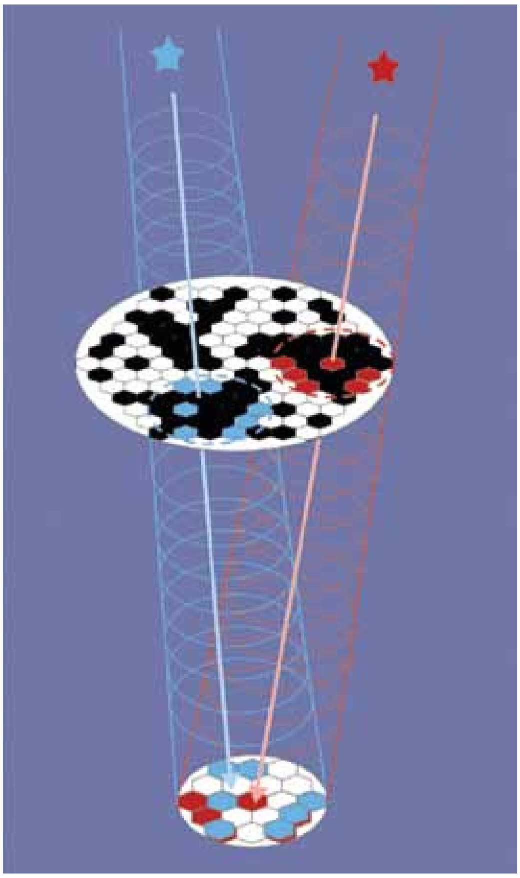


Figure 8:
a) Artist's impression of INTEGRAL highlighting SPI, one of the coded-mask instruments on board the spacecraft.

b) How the coded-mask camera works: gamma-rays from two different astronomical sources pass through the mask's holes. Some of the incident gamma-rays can pass through the mask and illuminate pixels on the detector below (shown in blue and red, depending on the source), while others are blocked by the mask's opaque spots, casting shadows on the detector (shown in white)



probe some of the most powerful phenomena in the Universe (Figures 8, 9 and 10).

Coming up…

As you read this article, ESA's XMM-Newton and INTEGRAL observatories are circling Earth, keeping watch over the ever-changing, high-energy Universe and helping to unravel celestial wonders. In our next article, we will explore some of these phenomena, such as the turbulent life and death of stars in the Milky Way, and gigantic black holes at the centres of distant galaxies.

References

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Mignone C & Barnes R (2011) More than meets the eye: the electromagnetic spectrum. *Science in School* **20**: 51-59. www.scienceinschool.org/2011/issue20/em

Singh KP (2005) Techniques in X-ray Astronomy. *Resonance – Journal of Science Education*. **10(6):** 15-23. www.ias.ac.in/resonance/June2005

Web references

w1 – For a movie based on INTEGRAL data, comparing the appearance of the sky as observed in visible light and in gamma rays, as well as the variability of the gamma-ray emission of sources in the bulge of the Milky Way, see:

Image courtesy of ESA / INTEGRAL / M Fiocchi

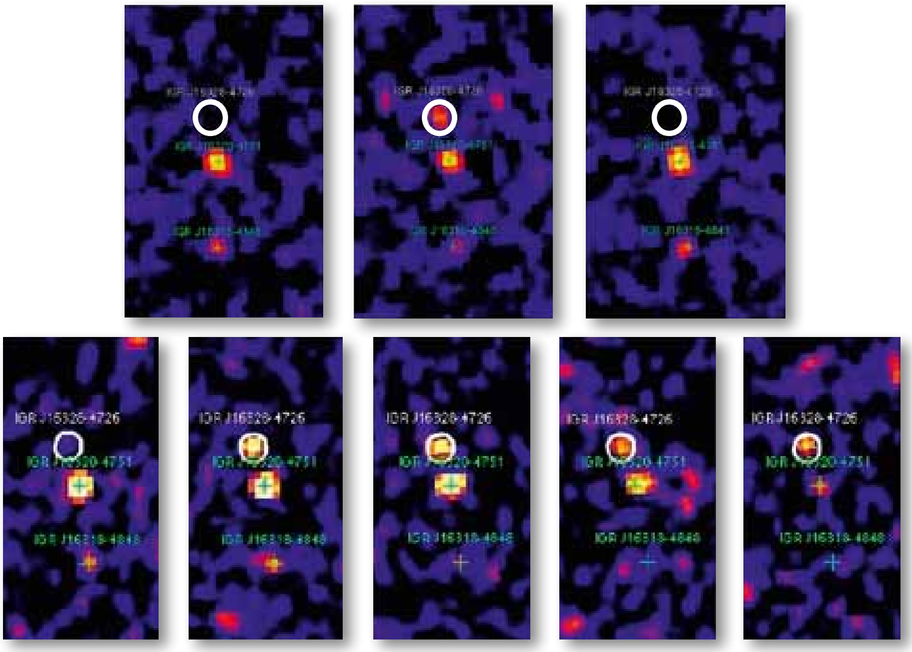

Figure 9: INTEGRAL images of the intermittent source IGR J16328-4726 (encircled). This astronomical source has been monitored over several years with INTEGRAL in the energy range 20-50 keV. As can be seen, the brightness of the source varies significantly over time. Astronomers believe that the source is a supergiant fast X-ray transient: a binary system consisting of a very luminous, supergiant star and a compact object, such as a neutron star or a black hole, orbiting one another. The irregular flow of matter from the supergiant star to the compact object is believed to cause the intermittent nature of these sources

Figure 10: Artist's impression of a supergiant fast X-ray transient

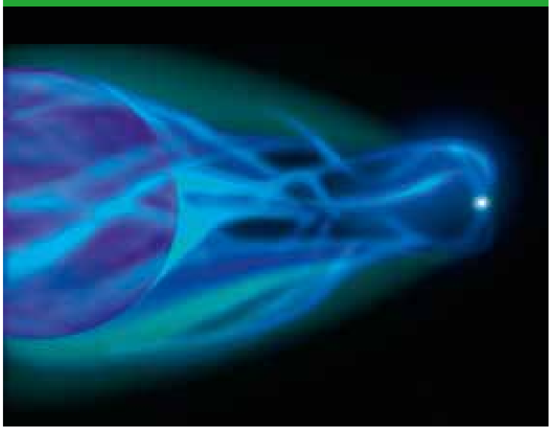

Image courtesy of ESA

http://sci.esa.int/GalacticBulge_video

w2 – To watch an animation showing the different appearance of the galaxy M82 in visible light, ultraviolet and X-rays, see: http://sci.esa.int/science-e-media/img/40/M82Zoom410x354.gif

w3 – To read or listen to Riccardo Giacconi's 2002 Nobel lecture, 'The Dawn of X-ray Astronomy', visit http://nobelprize.org/nobel_prizes/physics/laureates/2002/giacconi-lecture.html

w4 – For more information about ESA, see: www.esa.int

To learn more about the activities of ESA's Directorate of Science and Robotic Exploration, visit: http://sci.esa.int

Education materials produced by ESA are freely available to teachers in the 18 ESA member states. Many are translated into several European languages. See: www.esa.int/educationmaterials

Instructions and patterns for building paper models of many ESA spacecraft (including XMM-Newton and INTEGRAL) can be downloaded here: www.esa.int/classroomtools

The ESA multimedia gallery offers over 10 000 images, videos and animations related to space. See: www.esa.int/esa-mmg/mmghome.pl

To see all ESA-related articles in *Science in School*, see: www.scienceinschool.org/esa

w5 – For an interactive simulation of the photoelectric effect, as well as some associated activities, see the PhET website (http://phet.colorado.edu) or use the direct link: http://tinyurl.com/679wytg

To learn more about the photoelectric effect, see: http://physics.info/photoelectric

w6 – To browse *Science in School* articles about how high-energy X-rays (*synchrotron light*) are used in scientific research at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, see: www.scienceinschool.org/esrf

Like ESA, ESRF is a member of EIROforum[w9], the publisher of *Science in School*.

w7 – For an animation of the light path through XMM-Newton's telescopes, see: http://sci.esa.int/jump.cfm?oid=45618

w8 – To learn more about the coded-mask camera, see www.sron.nl/~jeanz/cai/coded_intr.html

More about ESA

The European Space Agency (ESA)[w4] is Europe's gateway to space, organising programmes to find out more about Earth, its immediate space environment, our Solar System and the Universe, as well as to co-operate in the human exploration of space, develop satellite-based technologies and services, and to promote European industries.

The Directorate of Science and Robotic Exploration is devoted to ESA's space science programme and to the robotic exploration of the Solar System. In the quest to understand the Universe, the stars and planets and the origins of life itself, ESA space-science satellites peer into the depths of the cosmos and look at the furthest galaxies, study the Sun in unprecedented detail, and explore our planetary neighbours.

ESA is a member of EIROforum[w9], the publisher of *Science in School*.

w9 – To find out more about EIROforum, visit: www.eiroforum.org

Resources

The Science@ESA vodcasts explore our Universe through the eyes of ESA's fleet of science spacecraft. Episode 5 ('The untamed, violent Universe') offers a glimpse of the hot, energetic and often violent universe, and the ESA missions that detect it using X-ray and gamma-ray astronomy. See: http://sci.esa.int/vodcast

If you enjoyed this article, you might like to browse all the astronomy articles in *Science in School*. See: www.scienceinschool.org/astronomy

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To learn how to use this code, see page 65.

Skimming stones

Image courtesy of Euan McIntosh, image source: Flickr