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

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

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

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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. The European Space Agency (ESA; see box) 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-

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

**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, 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).
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 traveling 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).

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. Albeit not detailed, the resulting images are useful to...
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


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:

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


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

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

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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
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Resources

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