The XMM-Newton Observatory – A Year of Exciting Science

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The XMM-Newton space observatory – a Cornerstone mission in ESA's Horizon 2000 Programme and originally referred to as the High-Throughput X-ray Spectroscopy Mission – was placed into a 48-hour orbit by the first commercial Ariane-5 launch (V504) on 10 December 1999. This brief survey of the scientific results obtained during the first year of XMM-Newton operations clearly illustrates that the observatory is more than living up to expectations and already providing unique and promising results, even before full scientific data analysis gets officially underway.

Introduction

Following an original mission proposal made to the Agency in 1982, the primary objectives for XMM-Newton were initially discussed by the scientific community at an ESA-organised workshop in Lyngby, Denmark, in June 1985. High-quality X-ray spectroscopy of faint sources was identified as the next major step following a series of X-ray missions flown in the 1990s. Spectroscopy is one of the key tools for the scientific interpretation of astronomical data, involving the separation of X-ray 'light' in such a way that the composition, temperature and density of the extremely hot gases in the Universe can be studied under a variety of circumstances.

Previous observatories have detected X-ray emission from a large variety of celestial sources, including halos of gas around massive galaxies, nuclei of 'active' galaxies, accretion disks around compact objects (like black holes, neutron stars), stellar coronae and supernovae remnants. Until now, high-resolution spectroscopy has played a modest role in X-ray astronomy due to a lack of sophisticated instruments and to a paucity of X-ray photons: one needs large collecting areas to capture them at a sufficient rate. The X-ray collecting power of previous observatories was largely inadequate for such detailed analysis.

XMM-Newton was designed to provide a major step forward by addressing these deficiencies: high-quality spectral measurements require powerful telescopes with the highest possible collecting area. ESA therefore established a design consisting of three multi-mirror grazing-incidence telescopes, and a payload complement including three European Photon Imaging Cameras (EPIC, Principal Investigator: M.Turner, Leicester University, UK) and two Reflection Grating Spectrometers (RGS, PI: A. Brinkman, SRON, Utrecht, The Netherlands), together with an Optical Monitor (OM, PI: K. Mason, MSSL, Dorking, UK) for complementary observations at optical wavelengths.

The payload

The overall layout of the instrument package on the XMM-Newton observatory is shown in Figure 1. At the left-hand end are three large cylindrical structures, which are the mirror modules. Two of these are shown with the RGS grating at their exit. The detectors are located at the right-hand end of the spacecraft. The green horns are the cooling radiators behind the EPIC MOS cameras. The red and pink plates are the radiators behind the RGS and EPIC PN detectors, respectively. The OM is located on the mirror platform.

Mirrors

One of the major features of the XMM-Newton observatory is its ability to make X-ray images of the sky. This is achieved by reflecting X-rays off metallic mirrors under grazing-incidence conditions. In order to deliver a high throughput of X-ray photons, each of the three XMM-Newton telescopes consists of 58 quasi-conical mirrors. X-rays are reflected on their inner gold-coated surfaces. The large collecting effective area of the telescopes is achieved by nesting the 58 mirrors in a confocal configuration and thereby filling their entrance aperture as much as possible. This design requires the production of a large quantity of thin mirrors with ultra-smooth reflecting surfaces. A replication technique involving the electro-forming of nickel mirrors from super-polished mandrels was selected (see ESA Bulletin No. 100). This technique was pioneered for the ESA mission Exosat (1983–1986).

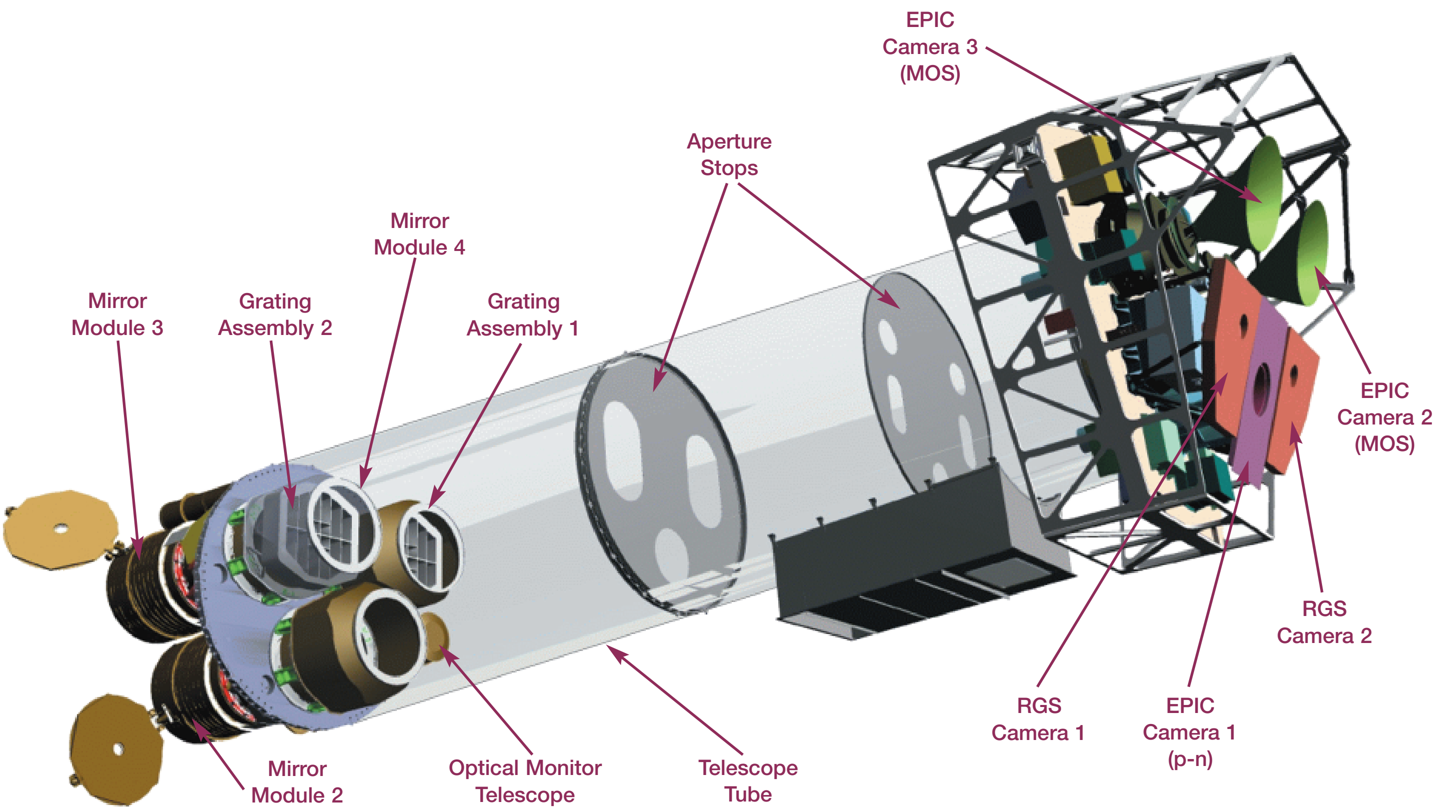


Figure 1. Exploded view of the XMM-Newton spacecraft

XMM-Newton's three X-ray telescopes and the associated instruments, RGS and EPIC, as well as the Optical Monitor, are operated simultaneously and directed at the same point on the sky, thus providing optimum coverage of each target using this complementary suite of instruments.

EPIC

Located at the focal plane of each of the XMM-Newton mirror assemblies is an EPIC (European Photon Imaging Camera) detector. These each employ several charge-coupled-device (CCD) sensors to record the position and energy of each X-ray photon that is detected. Two of the EPIC cameras employ MOS (metal-oxide-semiconductor) technology CCDs, which have been specially developed from a more conventional TV-camera sensor. The third EPIC camera uses a more novel PN CCD technology, which is fabricated from a single wafer of silicon. Both CCD camera types are operated at a temperature of -100°C. This is achieved through the use of a passive radiator cooling plate, which effectively uses deep space to cool the instruments. The cameras are equipped with filters to block visible light from reaching the detector. The EPIC instruments operate in the 0.2–10 keV range and, in combination with the XMM-Newton mirror assemblies, they provide the largest X-ray imaging collecting area ever.

RGS

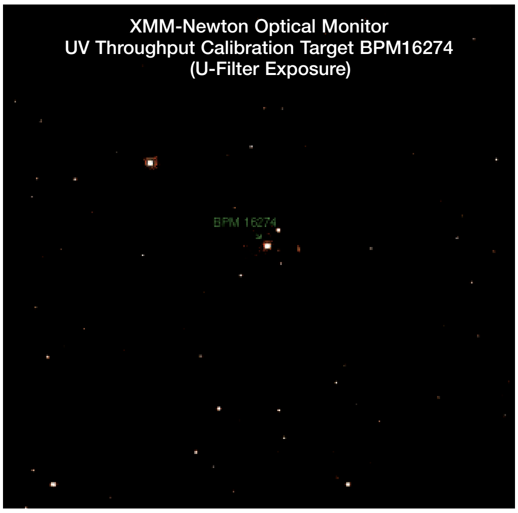
Two of the three X-ray telescopes consist of a combination of a mirror assembly and a reflection-grating assembly used by the RGS experiment (the greyish grid-like units in two of the three modules to the left in Fig. 1). The reflection gratings behave like a prism with visible light, and reflect X-ray photons with an angle that depends on their wavelength (energy). The diffracted photons are collected by a strip of 9 CCD detectors at a position that provides a measurement of their wavelength. Part of the beam exiting the X-ray telescopes passes through the stack of gratings without being intercepted. These photons are imaged on the MOS-detectors in the EPIC cameras located at the prime foci of each of the X-ray telescopes.

The Reflection Grating Spectrometer (RGS) is a dispersive spectrometer that, for the first time in X-ray astronomy, uses reflection gratings as dispersive elements. The instrument provides high spectral resolving power over the wavelength band from 0.33 to 2.5 keV, an energy range that contains the major characteristic emission lines of the most abundant heavy elements. The instrument permits measurements of relative intensity for different emission lines of the same species, and thus allows the temperatures, densities and chemical abundances in hot gas to be measured.

OM

The Optical Monitor (OM) is an instrument with a primary mirror of 30 cm diameter, based on a modified Ritchey-Chrétien design. Because of the low sky background in space, the sensitivity of the OM, using a relatively small mirror, is comparable to that of a 4-m telescope at the Earth's surface. The OM operates in the blue part of the optical spectrum and in the ultraviolet (160–600 nm). Its ultraviolet (UV) sensitivity adds a unique and valuable feature to the XMM-Newton mission, because UV light is not accessible from the ground as it is absorbed by the Earth's atmosphere. The value of having simultaneous optical coverage with the X-ray instruments was a lesson learnt from Exosat.

The OM instrument is co-aligned with the X-ray instruments, but only covers the central 17x17 $arcmin^2$ of the 30 by 30 $arcmin^2$ field-of-view of the X-ray imaging cameras (EPIC). The incident light is focussed by the primary and secondary mirrors onto one of two redundant detector chains. Each detector chain consists of a filter wheel, a photon counting detector (multi-channel-plate intensified CCD) and its processing electronics. The OM filter wheel is equipped with different filters to select specific portions of the visible or ultraviolet colours of interest. In addition, the wheel is equipped with 'grisms' – dispersive elements very much like a high-quality prism. These decompose the light from a source to allow detailed study of its spectrum. Where the filters in the EPIC instrument are intended to reject visible light, the filters in the OM instrument are used to look at different wavelength bands. These filters are designed such that an easy comparison with ground-based measurements (using similar filter arrangements) can be made. Their effect in terms of a changing view of the sky in the different filters is illustrated in Figure 2.



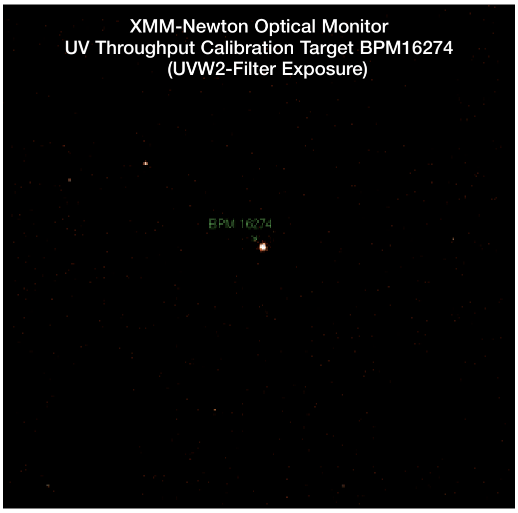


Figure 2. OM image of the field centred on the white dwarf BPM16274 in the visible (left) and in the ultraviolet (right). Objects that are relatively bright in the UV are rare, allowing ready identification

Calibration

After the initial in-orbit activation and commissioning activities, the first scientific operations involved extensive and accurate calibration of the payload. Calibrating instruments like those on XMM-Newton involves observing a well-known object and checking to see if the response of the instruments matches that predicted on the basis of its known performance on the ground, and the characteristics of the astronomical object. Until this is completed, and the instrument's performance is fully understood, astronomers cannot be sure that the data they receive correctly interprets the brightness or positions of any objects. For XMM-Newton, these in-orbit measurements lasted some three months.

One of the major activities in calibrating the mirror modules on XMM-Newton is to establish the precise imaging performance in terms of sharpness and throughput. As part of this exercise, the satellite observed the open stellar cluster NGC 2516. Figure 3 shows an EPIC-MOS observation of this object, where more than a hundred stars were detected. The figure shows that the sources are, on average, brighter close to the centre of the field of view. This artefact results from a vignetting effect caused by the X-ray telescopes. Also, the images of individual stars vary significantly over the field of view due to geometrical off-axis aberrations induced by the grazing-incidence optics. These instrumental effects need to be corrected when building a true, corrected image of the sky. In-orbit calibration activities also included the precise determination of the pointing of the instruments relative to one other, and the characterisation of the telescope imaging properties and effective collecting area.

The calibration of the Reflection Grating Spectrometer (RGS) was centred on the determination of the energy scale, which depends on the exact alignment of all individual units in the light path of the X-ray photons (mirror, grating and camera). This could not be determined to final accuracy on the ground because the high quality of the mirrors required a test facility in which the X-ray source is more than 500 m away from the detectors. An illustration of how such a calibration can be performed is shown in Figure 4.

After completion of the alignment of the RGS instrument, and consequently the energy-scale calibration, the detection efficiency (effective area) and the detailed response of the instrument to individual emission lines were calibrated. Figure 2 illustrates part of the calibration of the optical monitor. The images show the field of the calibration target BPM16274 at different wavelengths. The number of sources visible in the UV image centred around 190 nm is significantly reduced compared to the number seen at visible wavelengths around 370 nm. The target BPM16274, a white dwarf, in the centre of the image remains as one of the few sources also visible at UV wavelengths. Because this is a source with known, stable properties, it is one of those used to calibrate OM performance.

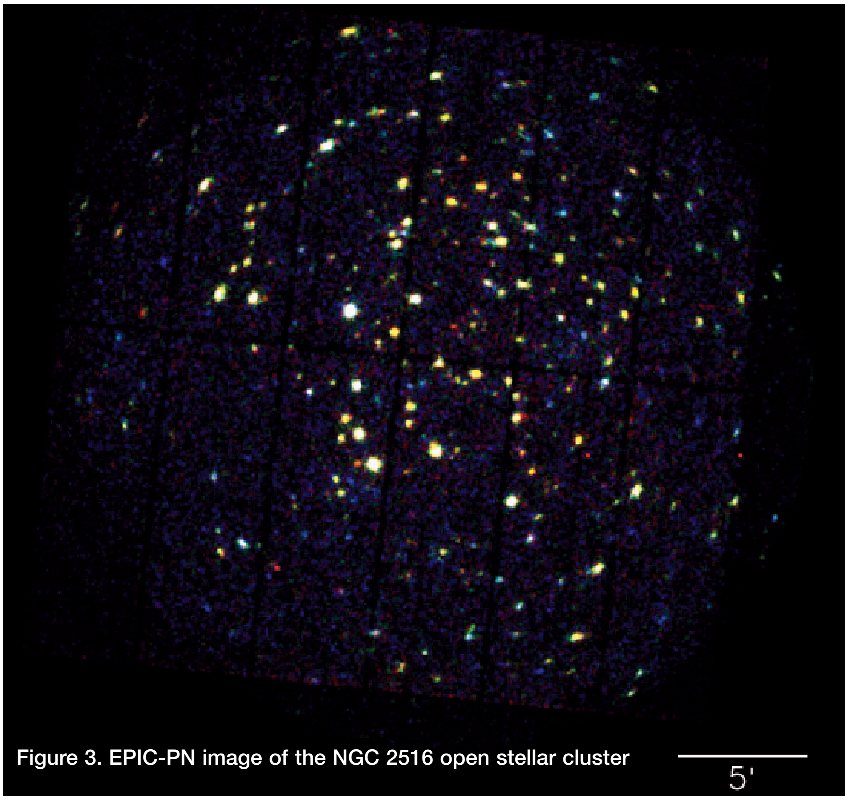


Figure 3. EPIC-PN image of the NGC 2516 open stellar cluster

Scientific results

The XMM-Newton observatory is open to the astronomical community at large for observations. This is achieved through an Announcement of Opportunity (AO), also known as a 'Call for Observing Proposals'. This process for XMM-Newton took place in the summer of 1999, and the best observing proposals were selected through peer review. Another component of the early observing programme for XMM-Newton is the performance verification phase, which consists of a series of observations dedicated to proving that the XMM-Newton observatory can actually achieve what was originally discussed at the 1985 Lyngby workshop. The current XMM-Newton observing programme thus consists of:

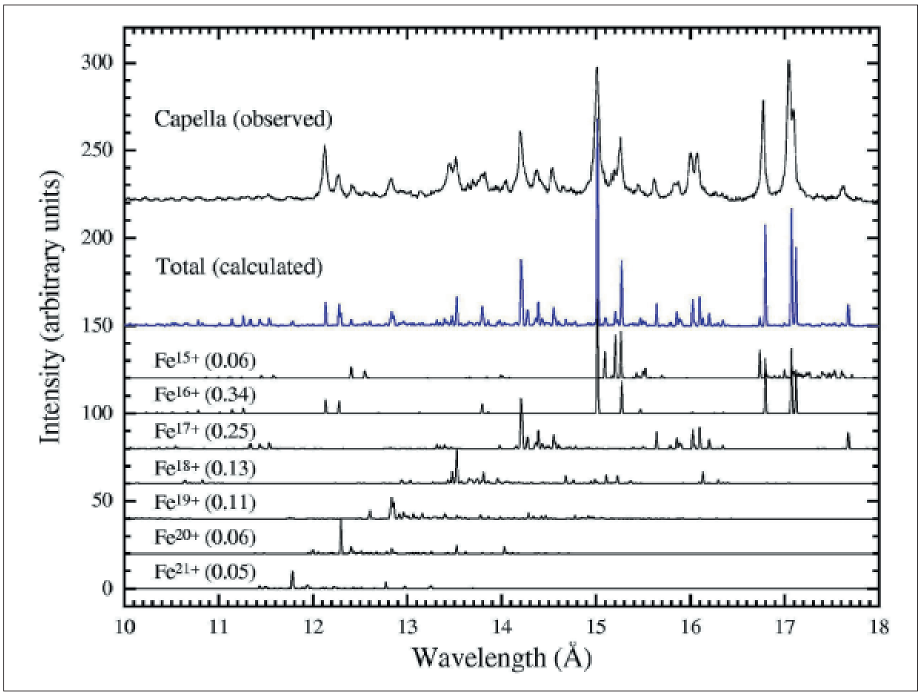
– calibration observations
– performance-verification observations
– guaranteed-time observations
– open-time (AO) observations
– targets of opportunity.

Targets of opportunity are observations for which dedicated time is allocated by the Project Scientist, and can be scheduled on a very short time scale. They allow for 'instantaneous' observations of the more interesting transient astrophysical phenomena. Many of the recent observations are currently being analysed in detail, and the following sections provide a preview of what are clearly exciting prospects for X-ray astronomy

Clusters of galaxies

Clusters of galaxies are among the largest structures in the Universe, consisting of hundreds of galaxies bound together by their mutual gravitational attraction. They are of great interest for cosmologists as indicators of how the early Universe evolved, when the initially smoothly distributed matter started to clump together and form the structures that we can now observe in detail in X-rays. Visible-light images of a cluster of galaxies show the galaxies themselves, but not the hot gas that often lies between them. In contrast, an X-ray

Figure. 4. Observed RGS spectrum of Capella (top). The blue line displays the sum of the individual contributions of several species of highly ionised Fe. The energies of the related emission lines are accurately known from ground measurements in Tokamak plasmas. These known emission lines can be used to fit the measured spectrum using the RGS internal alignment as the adjustable component



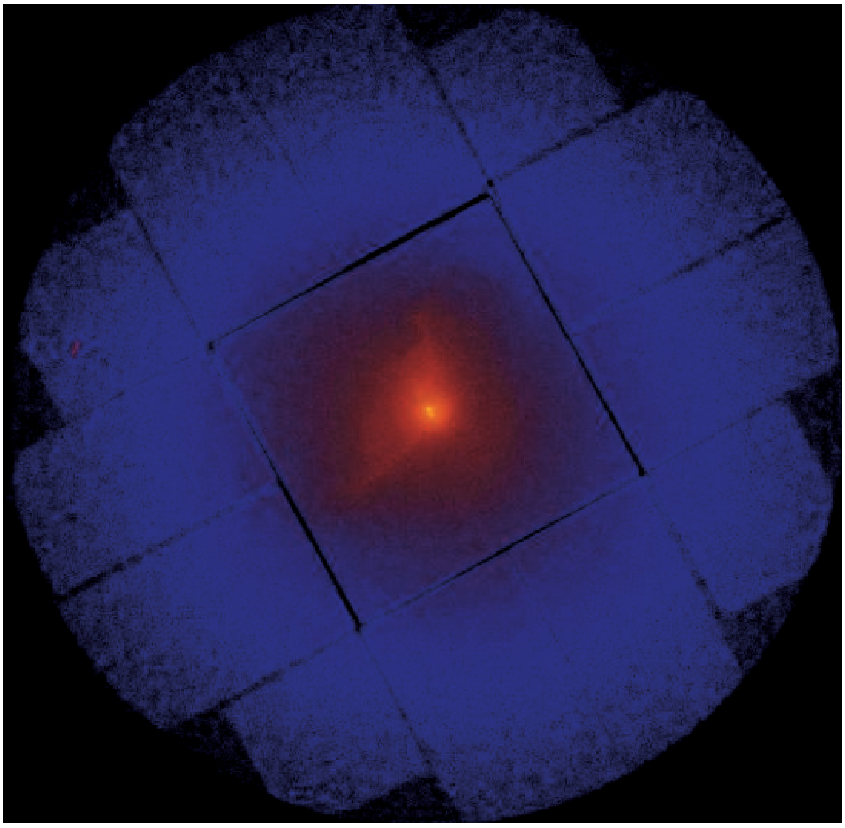


Figure 5. EPIC-MOS image of M87 in the Virgo cluster of galaxies

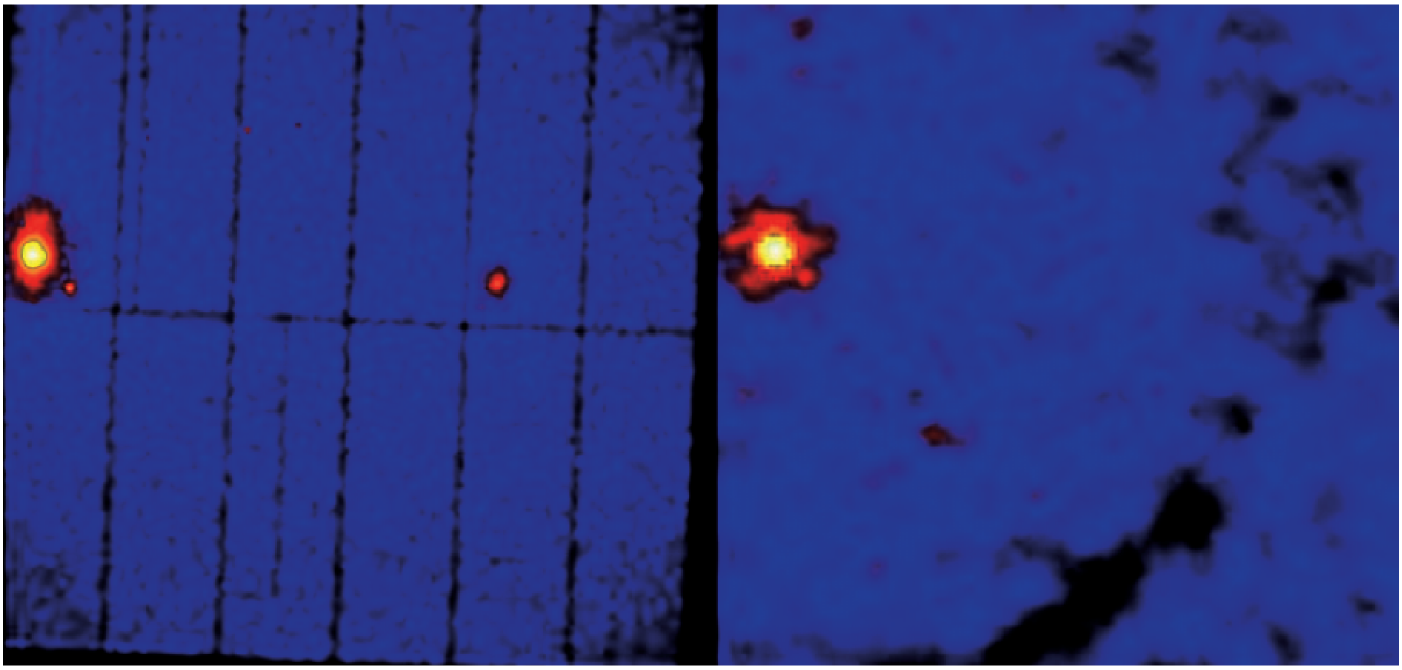
Figure 6. On the left is an EPIC PN image of a serendipitously discovered cluster of galaxies (red patch to right of centre) in the field of a Milky Way supernova remnant (left part of image). On the right is a Rosat low-energy X-ray picture of the same field

image mainly shows these hot gases, which at millions of degrees shine brightly in X-rays, and some of the constituent galaxies appear more faintly.

In Figure 5, we see the EPIC camera image of a part of the relatively nearby Virgo cluster. The picture is centred on the bright galaxy M87, which appears as two bright points (actually the very core of the galaxy and a previously known 'jet' of high-energy particles streaming away from the centre). The hot gas of the cluster surrounding M87 is seen as extended diffuse light. This exhibits some structure due to shocks and violent motions in the gas. This is caused by galaxies moving through such clusters with very high velocities, up to hundreds of kilometres per second. Finally, towards the outer edge at the left side of this image, a small red object is seen which is the emission of an individual galaxy standing out against the hot gas.

During calibration observations of a region of the Milky Way, in one of the images taken by the EPIC X-ray cameras, a new object was discovered, an impressive X-ray source of unexpected brightness (to the right in Fig. 6). The target of interest had been the bright supernova in the left of the picture. Previous pictures of this region taken by the Rosat observatory had shown nothing similar. In the energy range observed by Rosat, low-energy X-rays from most objects have been absorbed by all of the gas and dust in the Milky Way. Inspection of the X-ray emission spectrum of the newly discovered source (Fig. 7) clearly identifies it as an extragalactic source, as the Fe emission line is clearly red-shifted from the energy that it would have had if it had been a local (i.e. Milky Way) source. Such red shifts, caused by the velocity with which the source is moving away from the Milky Way, can be used to determine the distance of the source as a fraction of the total size of the Universe. The extent of the source, combined with its red shift, indicates that this is indeed a cluster of galaxies.

This case clearly illustrates how the 'grasp' of the XMM-Newton observatory, especially at the higher energy X-ray end, allows for many new discoveries to be made.



Supernova remnants

At the end of their life span, many stars detonate in violent explosions known as supernovae. Such cataclysmic events were recorded throughout history because they drastically changed the night sky, and were sometimes even visible during daytime. From Chinese and Arabic records it is known that in May 1006 a new star appeared which was probably visible for three months, even during daylight.

Supernova explosions are the most energetic stellar events known. Despite their huge brightnesses soon after explosion, most of their energy appears as motion of matter. The outer layers of the star are ejected into space with an initial velocity of the order of 10 000 km/sec. The explosion expands as a blast wave and at some stage it will sweep up sufficient interstellar matter to start emitting copious amounts of X-rays.

One of the most powerful analysis tools for these objects is study of their morphology in the individual characteristic emission lines (Fig. 8). The collecting power of XMM-Newton allows for such detailed analysis of a wide variety of supernova remnants.

Figure 9 shows a raw EPIC-MOS image of the supernova remnant E0102-70 (bottom left) located in the Small Magellanic Cloud. The angular diameter of this remnant resulting from the explosion of a massive star about 1000 years ago is 40 arcsec (about 1/50th the diameter of the full Moon). This has to be compared with the on-axis point response of the XMM-Newton telescopes at low energy, which exhibit narrow cores just a few arcseconds wide, but have broad wings extending over more than 60 arcsec which are typical of X-ray grazing-incidence optics. The E0102-70 raw image was corrected for the telescope response using a deconvolution technique for the restoration of blurred images. The deconvolved image (Fig. 9, bottom right) reveals that the X-ray emission from the multimillion-degree shocked material is concentrated in a thick ring with sharp edges. The deconvolved image also shows bright blobs, indicating that the ejecta material pushing into the interstellar gas is breaking into clumps, dispersing heavy elements into space.

Figure 9 (top) shows another example of a raw (left) and deconvolved (right) EPIC-MOS image of a supernovae remnant, N132D. This remnant also results from the explosion of a massive progenitor star. Its diameter is about 80 arcsec, and its estimated age of 1300 years is similar to that of E0102-70. However, the

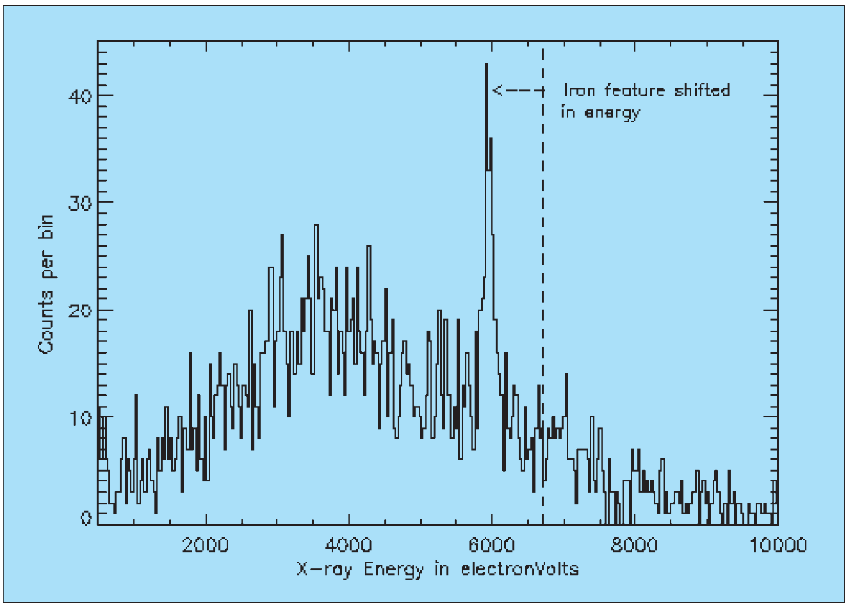


Figure 7. X-ray spectrum of the cluster of galaxies in Figure 6. The vertical dashed line represents the energy where the iron line feature would occur if not red-shifted

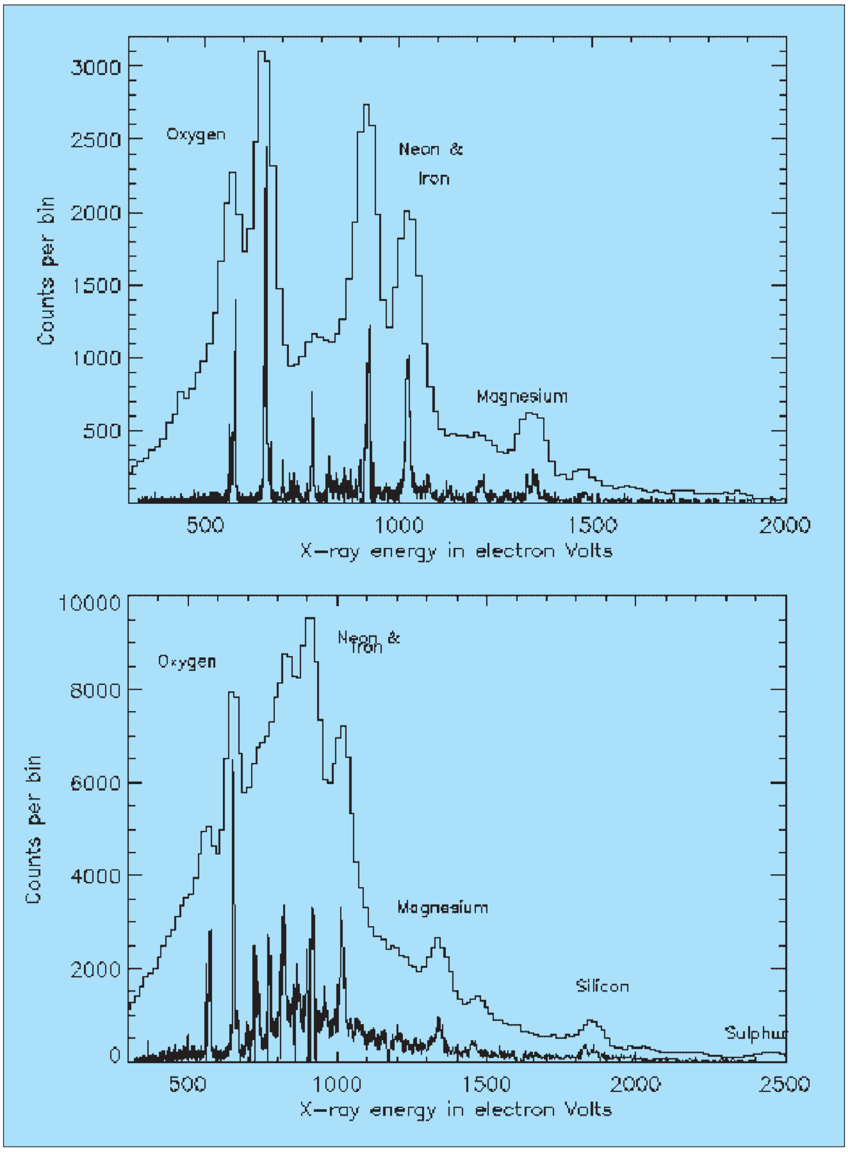


Figure 8. X-ray spectra of supernova remnants 1ES0102 (top) and N132D (bottom), with the RGS and EPIC spectra overlaid and the characteristic emission lines and their originating species indicated

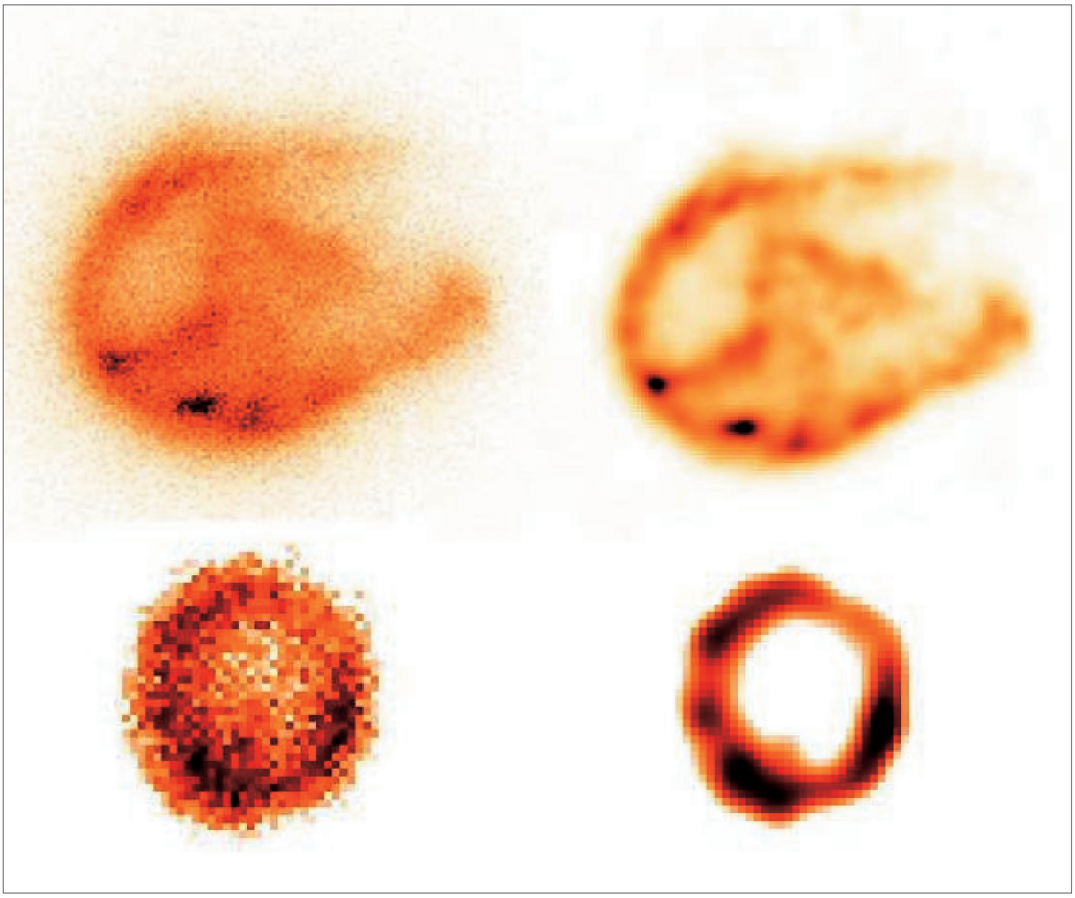


Figure 9. EPIC images of SNRs E0102-70 (bottom) and N132D (top) before (left) and after (right) deconvolution with the X-ray telescope point response

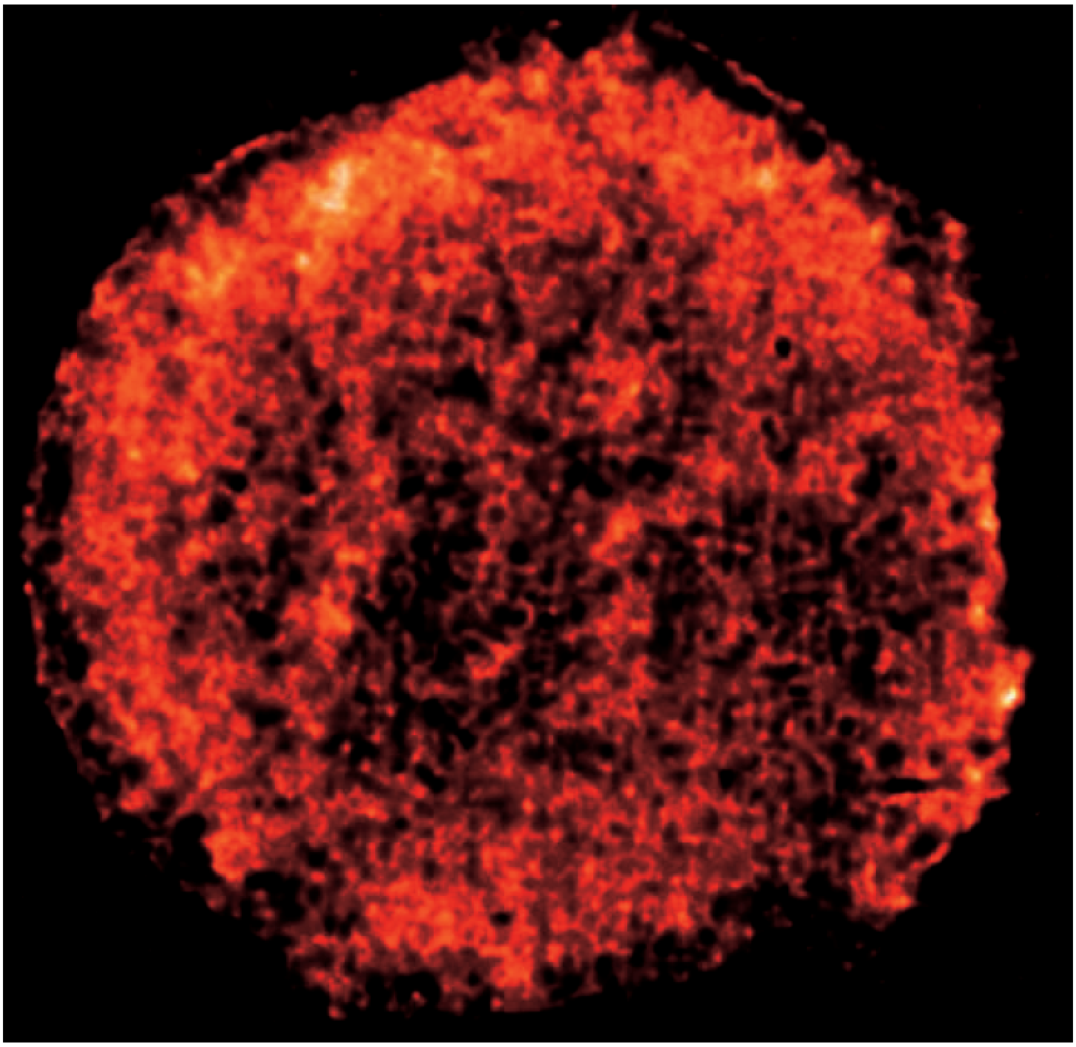


Figure 10. EPIC-MOS image of the Tycho SNR

deconvolved image of N132D reveals a more complex spatial structure. An outer shell with sharp edges is visible, but an extended region of diffuse emission with filament structures is also present. These two examples illustrate the ability of XMM-Newton's telescopes to study extended objects in X-rays with an accuracy comparable to that of ground-based optical telescopes, even at so remote a location as our neighbouring galaxies.

The EPIC and RGS data show further differences between these two supernova remnants in terms of their temperatures and chemical abundances. Figure 8 compares the X-ray spectra, clearly showing differences in intensity of the different emission lines from chemical elements. The RGS spectra reveal far sharper features, which are necessary for the most detailed analysis, but these are averaged over the whole remnant and so do not allow spectral studies on a small spatial scale. The EPIC data provide less detailed spectral information, but can be spatially resolved. This uniquely powerful combination of instruments gives a completely new view of, and a wealth of physical diagnostics for the conditions following such cataclysmic events.

Figure 10 shows the image of the Tycho supernova remnant obtained with the EPIC camera. This is a remnant of the stellar explosion witnessed by Danish astronomer Tycho Brahe in the 16th century. The majority of the chemical elements that make up planets, and support life itself (carbon, nitrogen, oxygen, etc.), were created in such events. Because details of how these explosions occurred, and how the elements may have been mixed up, remain unclear, astronomers expect new X-ray data to shed more light on the problem.

With EPIC's unique combination of spatial and spectral resolving power, it is possible to extract information from each chemical element in turn. As an indication, successive images made in the light of different chemical elements are shown. This shows that the locations of maximum intensity differ slightly for different chemical elements; this closely relates to the pre-supernova environment as well as the geometry of the original explosion (Fig. 11).

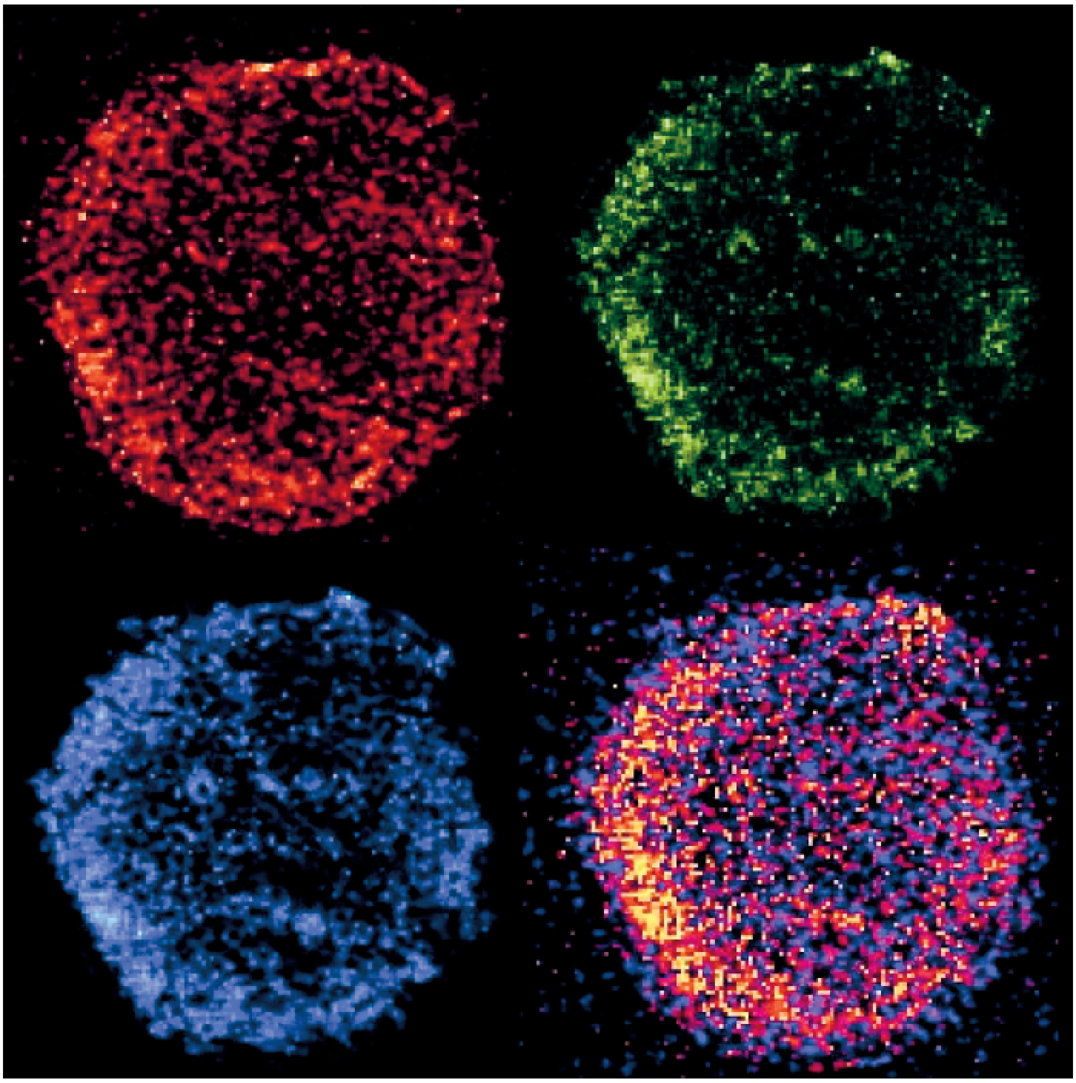


Figure 11. EPIC images of the Tycho SNR in calcium (red), sulphur (green), silicon (blue) and iron (yellow) emission lines. Careful inspection shows that the images are brighter in different locations

Deep surveys and the Lockman Hole

The very first observations in X-ray astronomy, made 40 years ago, revealed that the sky 'glows' with a uniform faint emission. Progressively more detailed studies have shown that most of this background glow is actually the superposition of the flux of many so-called 'active galaxies'. The Rosat observatory showed that, with possibly a thousand such objects in every square degree, the origin of the low-energy X-ray background was at last resolved.

However, the typical X-ray spectra of these active galaxies, when extrapolated to higher energies, do not match the spectrum of the diffuse background. Most astronomers believe that this puzzle could be explained if there are many galaxies harbouring hidden black holes at their centres. These massive black holes may have been formed early in the history of the Universe, and should be seen radiating copious amounts of energy at all wavelengths. However, large discs of swirling gas and dust surrounding the black holes may be very effective at blocking our view of this radiation at most wavelengths. Energetic X-rays should be able to penetrate these absorbing layers, so astronomers are keen to use XMM-Newton to check out their theories that more faint galaxies should be detectable with the improved ability to see to higher and higher X-ray energies.

The first tantalising glimpse of XMM-Newton's power to stare deeply into the Universe's past comes from an observation of the Lockman Hole. This region of sky, named after its discoverer, was selected as a location with a patch of very low absorbing material from the Milky Way, thus allowing one to look very deep into the Universe. It is also one of the best-surveyed regions by previous missions.

Figure 12 shows the image accumulated after about 30 hours of observing this area. The colours have been chosen to highlight the different X-ray energies emitted by the sources: red is used for low-energy X-rays previously seen with Rosat, whereas green and blue represent progressively more energetic X-rays. As predicted, there do seem to be additional galaxies shining through in this range.

Figure 13 shows a census of the objects seen in the highest (5–10 keV) energy range. This graph shows that as we move progressively to fainter and fainter objects (leftwards), the number of objects per square degree increases. The sensitivity of XMM-Newton in this energy range is an enormous improvement over previous observatories. This survey is already a factor of 20 better than the previous best Beppo-SAX observatory surveys in this range.

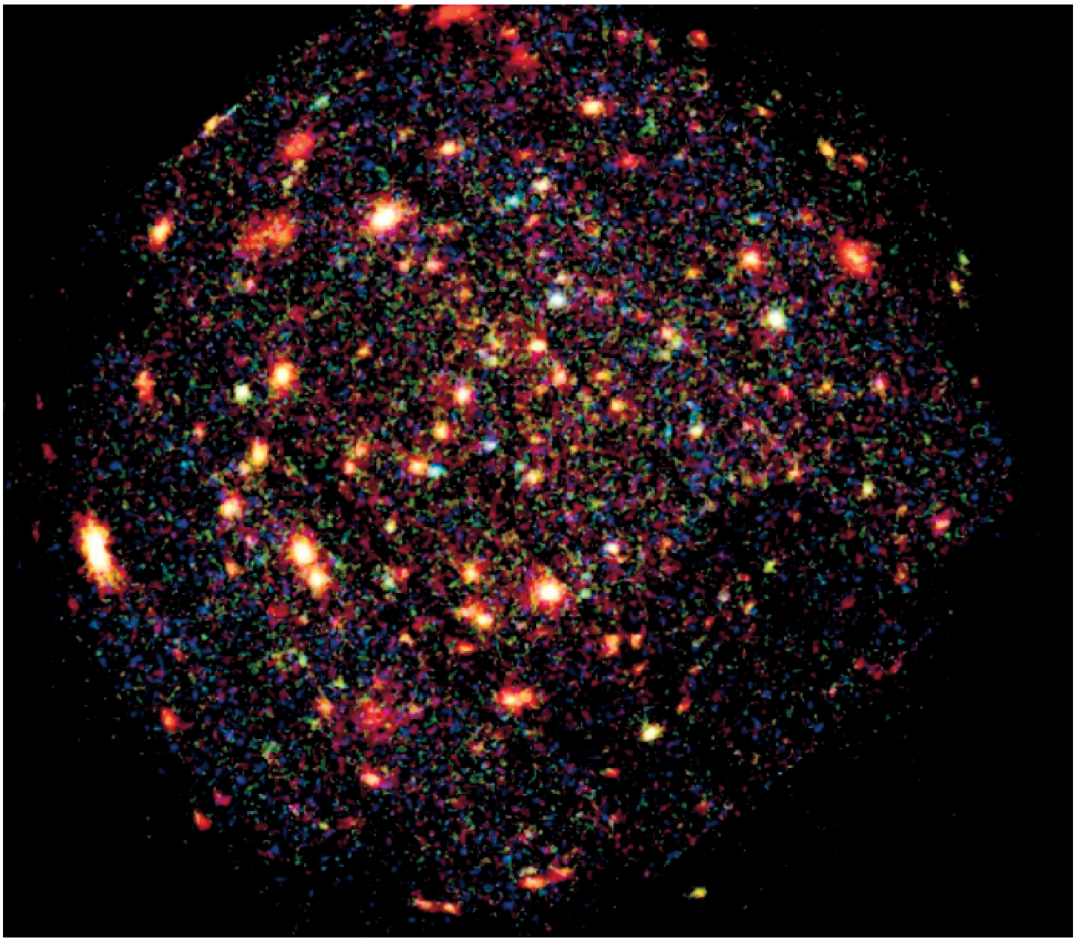


Figure 12. Combined EPIC-MOS and EPIC-PN full-energy-range image of the Lockman Hole. Red objects are low-energy (less-absorbed) sources seen clearly with previous Rosat observations. Green and blue objects represent much more energetic sources seen clearly for the first time by XMM-Newton

Initial efforts are starting to see if this behaviour can be predicted by models of the evolution of galaxies over the history of the Universe. It is clear that XMM will make a significant contribution to our understanding of the ubiquity of black holes and their substantial contribution to the previously missing energy budget of the Universe.

Among the many interesting objects that turned up in the XMM-Newton image are two slightly more diffuse red patches (lower left and upper left from the centre). One of these is a cluster of galaxies at a red shift of about 1.2 (this means we are seeing the light from a cluster that originated when the Universe was less than half its current age). XMM-Newton measurements of the temperature and mass of this cluster show it to be far more massive than most cosmologists believed clusters could ever be so early in the Universe.

The utility of the OM observations of the same fields is demonstrated in Figure 14. On the left, we see a portion of this field taken using a filter with no colour discrimination. The same area as observed by the different colour filters of OM is shown on the right. The combination of UV and optical filter images provides a false-colour image. It is evident that OM not only matches the power of large ground-based telescopes, but the addition of its ultraviolet capability provides new colour discrimination. For example, it is likely that very blue objects are galaxies undergoing an intense episode of star formation, which produces many young hot blue stars. Such information can lend considerable strength to the identifications of faint objects seen in the X-ray cameras' images.

Conclusion

XMM-Newton's exceptional combination of instruments for spectroscopic studies has already demonstrated the power of analysing the physical conditions around stars in our cosmic neighbourhood. The phenomena of stellar supernova explosions that created the chemical building blocks of planets and life itself are being investigated even as far away as neighbouring galaxies. The details provided by this ground-breaking new generation of instruments will keep astronomers busy, trying to understand the complex distribution of hot gases. The unmatched collecting power of XMM is also being used to study the deepest parts of the Universe, challenging some of the more important theories about the structure and evolution of the Cosmos.

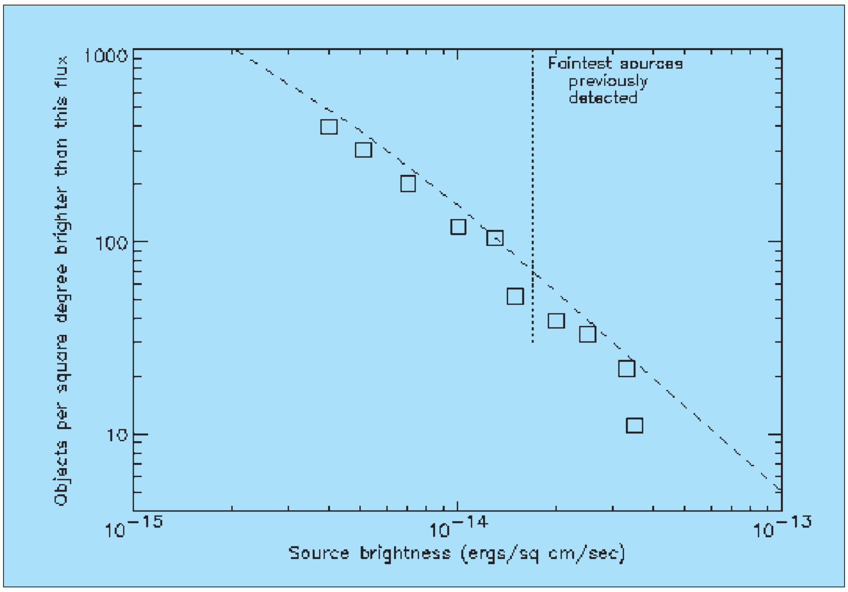


Figure 13. Density of sources in the sky in the 5–10 keV energy band. Squares represent the measured data in the XMM image, while the dashed line is a prediction based on models of galaxy evolution. The dotted vertical line indicates the limit of deep surveys conducted previously in this energy band

Acknowledgement

The authors would like to acknowledge the contributions of literally hundreds of people involved in building and operating the XMM-Newton spacecraft and its instruments. The work described above could not have been done without their dedication and professionalism.

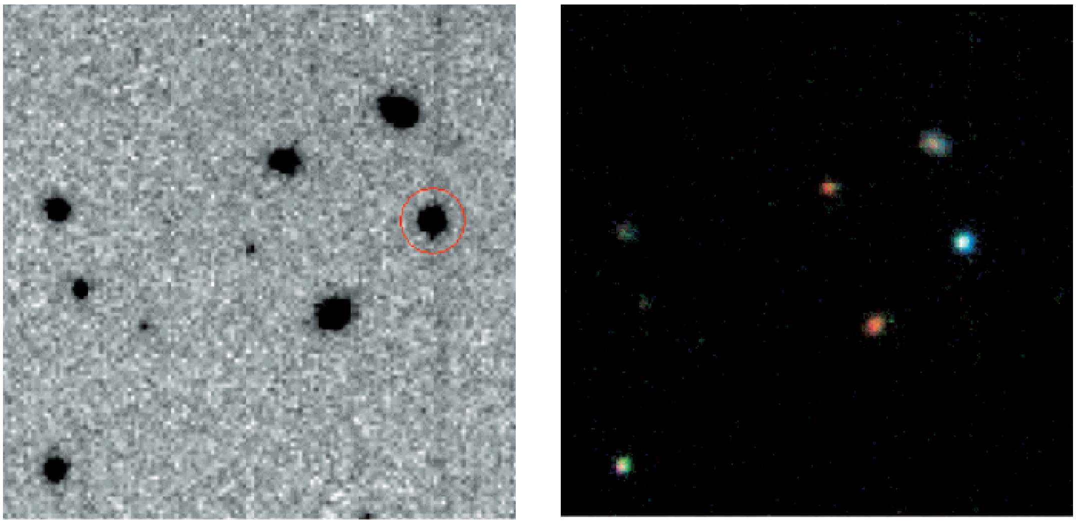


Figure 14. Small section of the Lockman Hole field in the visible range. Left: OM image using the white-light filter. Right: OM image in false colour