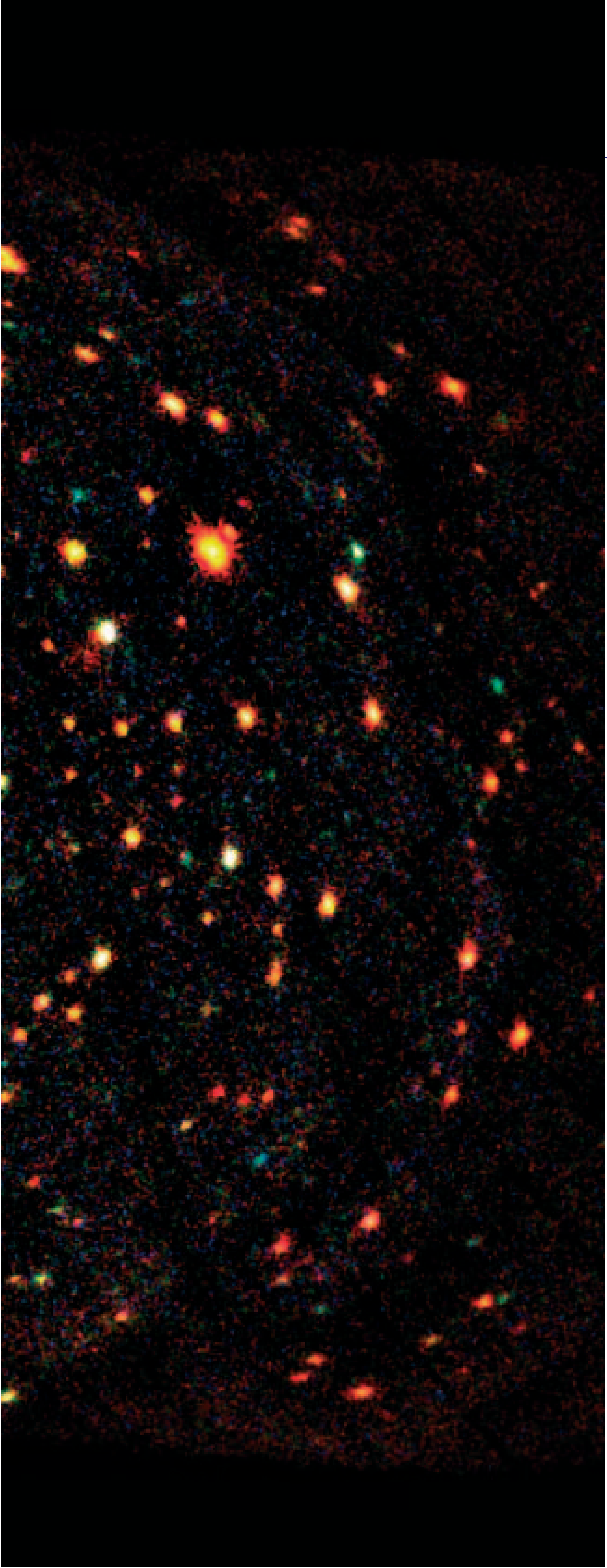
Five Years of Newton Science

Combining the images from all XMM-Newton EPIC cameras, the Lockman Hole provides the deepest ever X-ray survey of this region where observation of the early Universe is facilitated by the relative absence of intervening, absorbing material. The view gives a 'real colour' representation of all the sources, coded according to their X-ray hardness: red, green and blue correspond to the 0.5-2, 2-4.5 and 4.5-10 keV range, respectively. More than 60 new sources are detected in the 4.5-10 keV band alone

(Image courtesy of G. Hasinger, MPE Garching, Germany and ESA)



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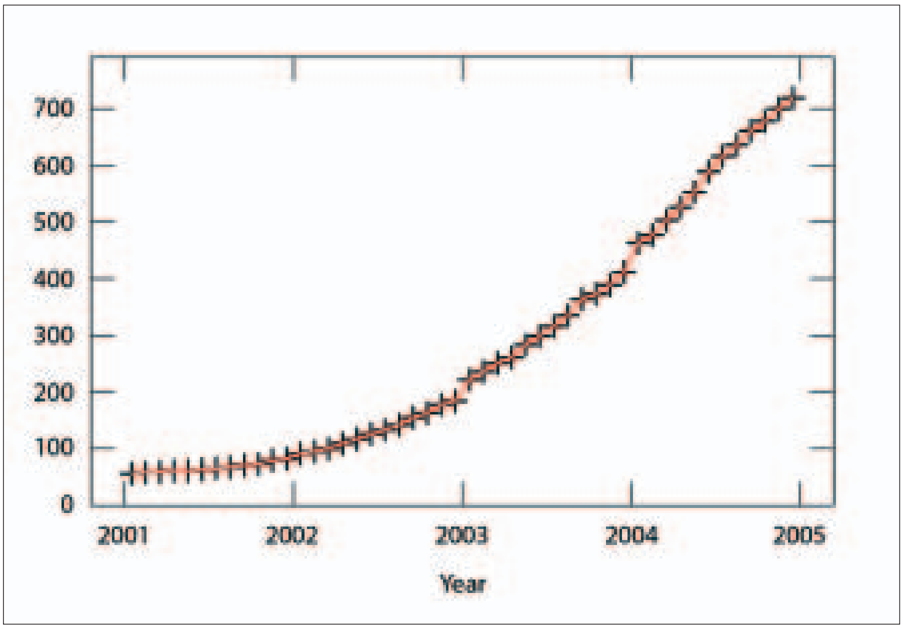
On 10 December 2004, it was five years since ESA's XMM-Newton observatory was successfully put into orbit. It is therefore time to stand back and ask where we stand with the scientific results and what new perspectives the mission has brought us. The answers are to be found in more than 700 publications in the refereed literature and the manifold oversubscription for every observing Announcement of Opportunity for the mission.

XMM-Newton was conceived as an observatory-type mission, which means that its observing programme is selected through a peer-reviewed, open submission process, resulting in observations of all kinds of astronomical objects. They range from comets and planets in our own Solar System, to the most distant quasars, which we observe at a time when the Universe was only 7% of its current age, which is estimated to be 13.7 billion years.

The fascinating aspect of the Newton observatory is that three main areas of science are addressed by this one mission: classical astrophysics, fundamental physics, and cosmology. This article highlights typical examples of the scientific research being conducted with Newton in each of these three areas, together with some of the most important results to date.



By 31 December 2004, 718 publications in refereed journals were based directly on XMM-Newton observations, 306 of them published during 2004 alone. These cumulative statistics from 2001 onwards demonstrate that the number of publications per year is still increasing

Astrophysics

Solar-type stars

Although a significant fraction of the X-ray sources in the sky are stars, surprisingly little is known about their X-ray variabilities. As the variability of our Sun's emission, including that at high energies, is fundamentally important for the Earth's climate, it is essential to study the variability patterns of stars in the X-ray domain also. But the Sun itself must be put into context.

To this end, XMM-Newton has been observing four nearby solar-type stars every six months since the beginning of the mission. One of the first successes was the detection of a solar-type X-ray cycle in HD 81809 by F. Favata (see accompanying figure). HD 81809 is a so-called 'G2-type' star, which is a little bit more evolved than the Sun and shows a pronounced 8.2-year cycle in the optical band. The initial three years of XMM-Newton data show a large variation (a factor of ~10) in its X-ray luminosity, with a clearly defined maximum in mid-2002. Comparing the X-ray activity with the optical activity cycle, the data may imply a phase shift between them.

Hot stars

The heaviest stars (O and early B stars) can have masses about 100 times that of the Sun and show emission temperatures of up to 50 000 K. Their X-ray emission originates in their stellar wind, a concept that has been confirmed by high-resolution XMM-Newton observations. However, the first RGS spectra of this class of object already showed extremely broad emission lines of highly ionised elements: for example, hydrogen-like and helium-like ions of nitrogen, oxygen, neon and magnesium, indicating velocities of the order of 1000 - 1700 km/s (see figure). The magnitude of these observed velocities is far above the range expected before the launch of XMM-Newton and the scientific discussion about their origin is now underway. Further XMM-Newton observations will expand the observational database to allow solid testing of the current theoretical developments.

Supernovae and Gamma-Ray Bursts

The end point in the lifecycle of high-mass stars is reached through a luminous supernova explosion. The XMM-Newton observations of Gamma-Ray Bursts (GRBs) are important in this context. The satellite follows the X-ray afterglows through rapid (reaction time ~5 hours) Target of Opportunity (TOO) observations (as described by M. Santos-Lleó in ESA Bulletin No. 107) of selected bursts detected by other satellites, such as ESA's Integral mission. Outstanding results achieved so far have included the detection of emission lines in the afterglows of GRB

XMM-Newton and Its Instruments

XMM-Newton carries two different classes of X-ray instruments. The three European Photo Imaging Cameras (EPICs) – one based on pn-CCD technology and two on MOS-CCD technology – provide images of the X-ray sky, as well as spectra with moderate resolution and timing information. Two Reflection Grating Spectrometers (RGSs) produce spectra with very high energy resolution. An Optical Monitor complements the instrumentation.

The main scientific characteristics of the X-ray instruments are as follows:

	EPIC-pn	**EPIC-MOS**	**RGS**
Energy bandpass (keV)	0.15-15	0.15-12	0.35-2.5
Field-of-view (arcmin)	30	30	5
Spatial resolution (arcsec)	6	5	N/A
Temporal resolution (ms)	0.03	1.5	16
Energy resolution at 1 keV (eV)	80	70	3.2

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* Gamma-Ray Bursts, or GRBs, are internationally referred to by the last two digits of the year, followed by the month and day of their detection, i.e. this is the GRB of 11 December 2001

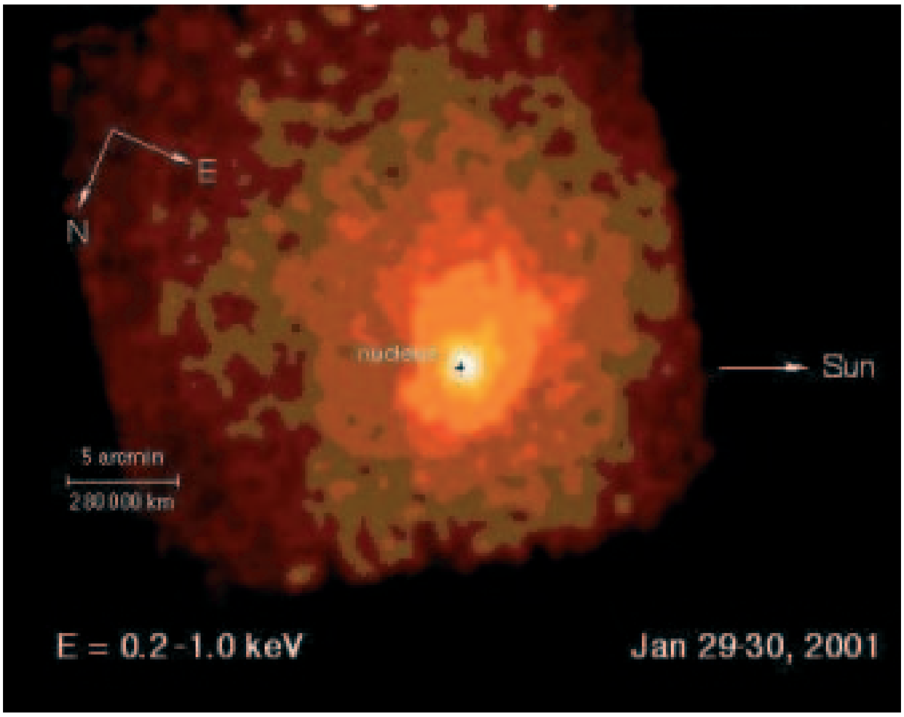
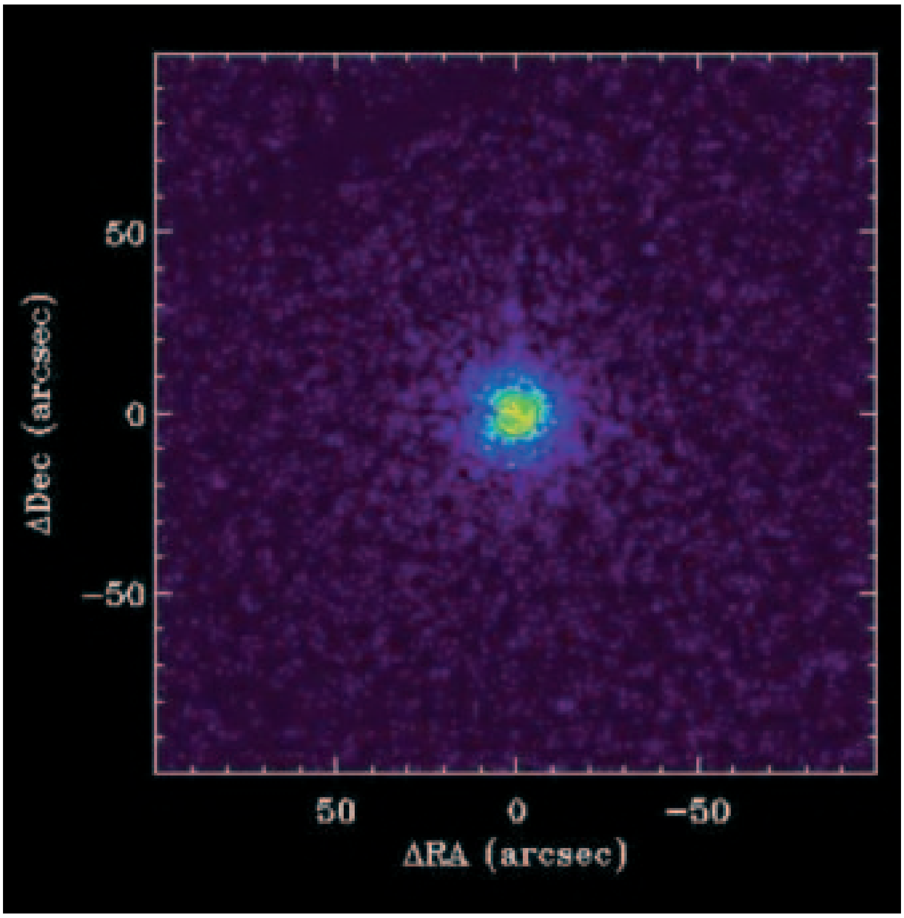


Image of comet McNaught-Hartley (C/199 T1) taken with XMM-Newton's EPIC-pn camera
(Courtesy of K. Dennerl, MPE, Germany, and ESA)



XMM-Newton EPIC-pn image of Mars showing X-ray fluorescence emission from its atmosphere, mainly from oxygen
(Courtesy of P. Rodríguez, XMM-Newton SOC, Spain, and ESA)

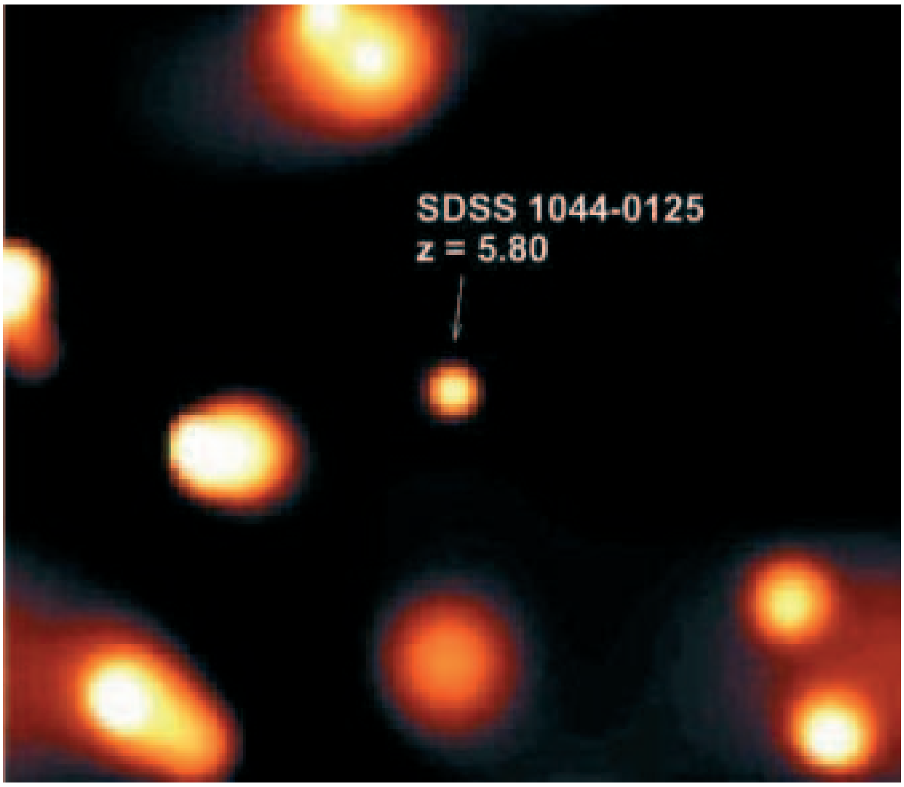
011211* by J. Reeves and of GRB 030227 by D. Watson. The first of these detections was the starting point for a scientific discussion that has led to our current understanding that GRBs are closely connected with supernova explosions.

One of the most fascinating XMM-Newton TOO observations so far was that of GRB 031203. The images reveal the first detection of a time-dependent X-ray halo, which appeared as concentric ring-like structures centered on the GRB location (see accompanying figure). The radii of these structures increased with time, consistent with small-angle X-ray dust-scattering. The rings are due to dust concentrated in two distinct slabs in our Galaxy, located 2900 and 4500 light-years away. Although the detected halo was caused by dust in our Galaxy, it must be realised that halos around GRBs provide enormous potential for making very accurate cosmological distance measurements. With a little luck, future XMM-Newton observations will be able to demonstrate this.

Neutron stars

Supernovae not only 'announce' the death of a high-mass star, they also give birth to compact objects. As an example, we can look to a star with a mass ten times that of the Sun. During the explosion, most of the material of the pre-supernova star is ejected into space, but its inner core, which is only about 1000 km across, collapses under its own gravity and creates a neutron star. Neutron stars are typically the equivalent of 1.4 solar masses and have radii of about 20 km. In these objects, the gravitational force is so strong that it becomes energetically advantageous to unify electrons and protons into neutrons. Therefore the great majority of their nuclear particles are neutrons – hence the name 'neutron star'. In some senses, they are both a star and a giant atomic nucleus.

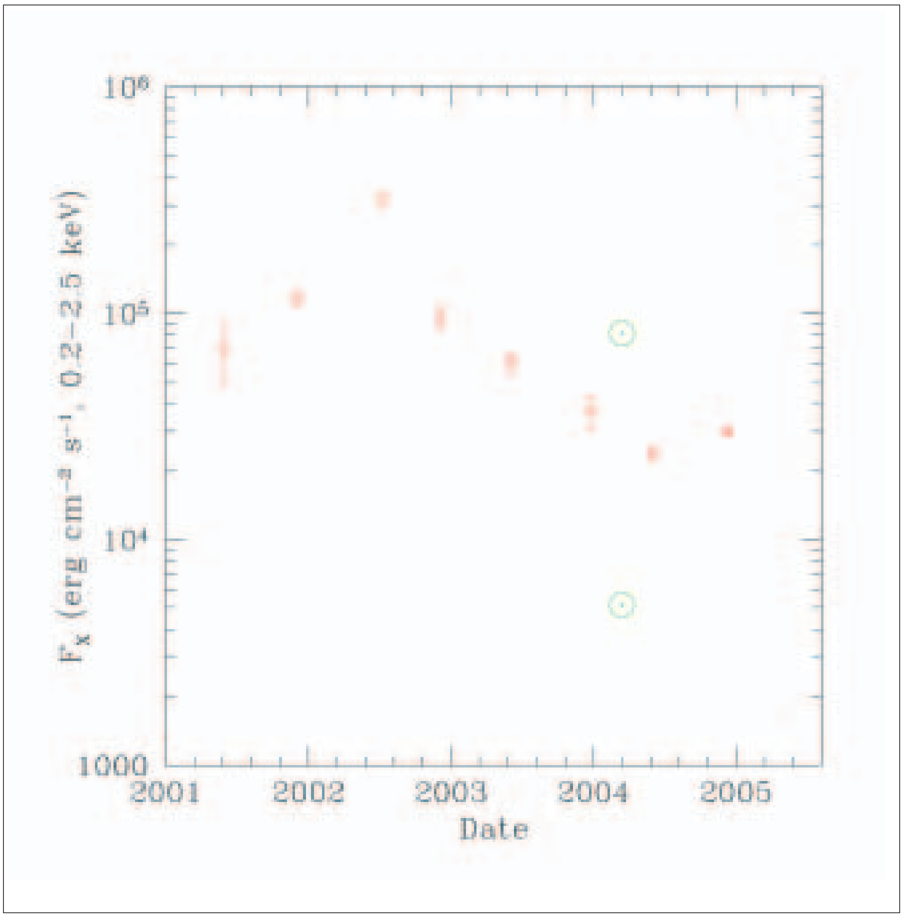
XMM-Newton's observations of neutron stars brought a great surprise in that the



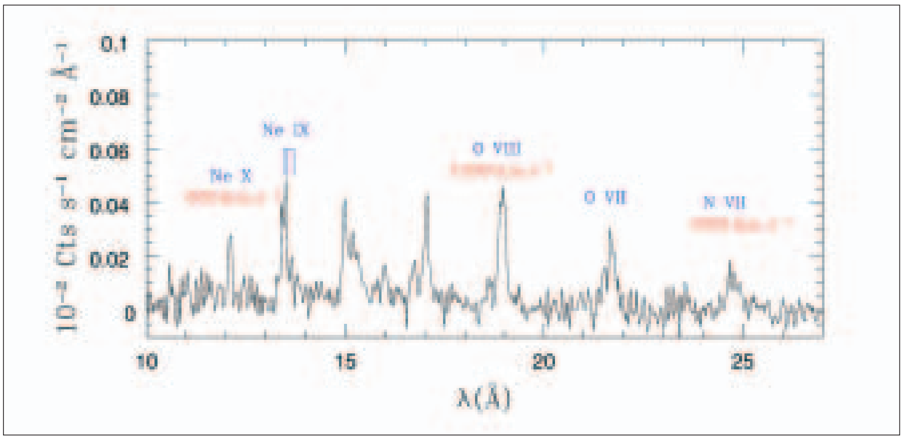
XMM-Newton EPIC-pn image of the high-redshift quasar SDSS 1044-0125 at z = 5.8
(Courtesy of M. Guainazzi, XMM-Newton SOC, Spain, and ESA)

measured spectra are in contradiction with the pre-XMM-Newton expectations. Most neutron stars have featureless X-ray spectra, but the high effective area of Newton's detectors has allowed impressive progress in unexpected directions. Based on EPIC data, P. Caraveo detected two elongated parallel X-ray tails trailing the pulsar Geminga (see accompanying figure). They are aligned with the object's supersonic motion through the interstellar medium, and have a spectrum produced by electron-synchrotron emission in the bow shock between the pulsar wind and the surrounding medium. The detection of a pulsar bow shock allowed the pulsar's electron injection energy, the shock's magnetic field and the local matter density to be gauged.

G. Bignami published the first detection of so-called 'resonant cyclotron absorption' in an isolated neutron star based on XMM-Newton spectra of the object designated 1E1207.4-5209. The star's spectrum shows four distinct features, regularly spaced at 0.7, 1.4, 2.1 and 2.8 keV, which vary in phase with the star's rotation (see figure). A further highlight of XMM-Newton pulsar observations is the detection by P. Caraveo et al. of hot-spot(s) long thought to exist as a result of heating from accelerated particles, but hitherto not found. It may provide the missing link between the X-ray and gamma-ray emissions of pulsars. Phase-resolved spectroscopy of Geminga reveals a hot thermal emission originating from an ~60 metre-radius spot on the pulsar's surface. A. De Luca has found such hot-spots in the XMM-Newton observations of two further isolated neutron stars: PSR B0656+14 and PSR B1055-52. These hot spots have very



The red data points show the evolution of the X-ray surface flux (in the 0.2-2.5 keV band) of HD 81809 from April 2001 to November 2004. For comparison, the typical X-ray surface flux of the Sun at the minimum and maximum of the solar cycle is plotted in green
(Courtesy of F. Favata, ESTEC, The Netherlands, ESA)

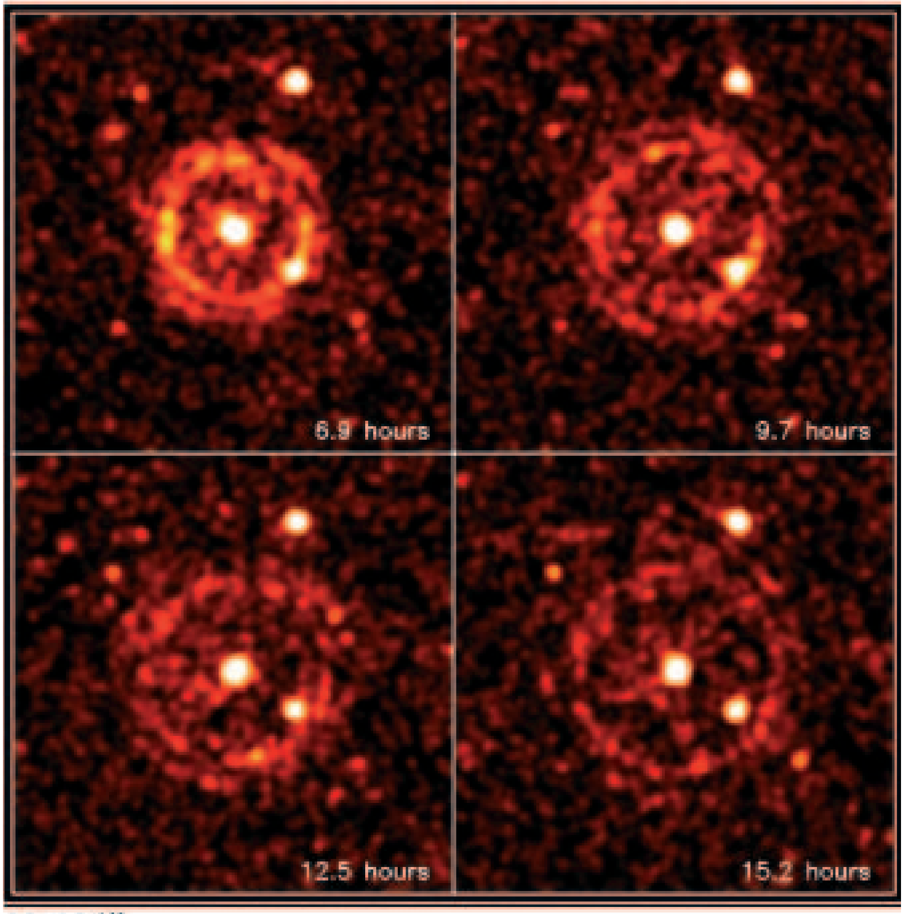


Combined RGS spectrum of the hot star 9 Sgr. Emission lines of ionised neon, nitrogen and oxygen are identified in blue. The velocity-widths of three lines are provided in red
(Courtesy of G. Rauw, Université de Liège, Belgium, and ESA)

different apparent dimensions and lack any common phase alignment: in the case of PSR B1055-52 they vary in phase, but in anti-phase in the case of PSR B0656+14. These findings indicate that neutron-star magnetic-field configuration and surface-temperature distribution are much more complex than was expected from pre-XMM-Newton assumptions, and further observations are clearly needed.

Isobaric cooling-flow clusters of galaxies

Our previous examples of XMM-Newton results have concerned stars and their lifecycles. To round off the astrophysics section, we turn in contrast to extragalactic objects. Clusters of galaxies are one of the classical topics in X-ray astrophysics. Whereas in the optical energy band they are recognised only through the detection of, often small, fluctuations in the galaxy distribution, they are among the brightest objects in the X-ray sky, where the hot gas between the galaxies is observed. Before XMM-Newton, the physics of many clusters was described with the isobaric cooling-flow model: in the outer parts of the cluster the density is too low to allow effective cooling though radiation, i.e. the cooling time is longer than the lifetime of the cluster. The situation is different in the innermost parts: here the density allows an effective cooling, which should lead to a reduction in the material's temperature. The first XMM-Newton observations of cooling-flow clusters already showed completely unexpected spectra. The lines that should be characteristic for the emission of low-temperature gas, i.e. the cooled gas expected in the centre of the cluster, are missing (see figure). The cores of clusters must therefore be cooling much more slowly than expected according to the isobaric cooling-flow model favoured before XMM-Newton. A huge number of studies, theoretical as well as experimental, based on further XMM-Newton observations are currently ongoing, reflecting the universal importance of cooling mechanisms in astrophysics.

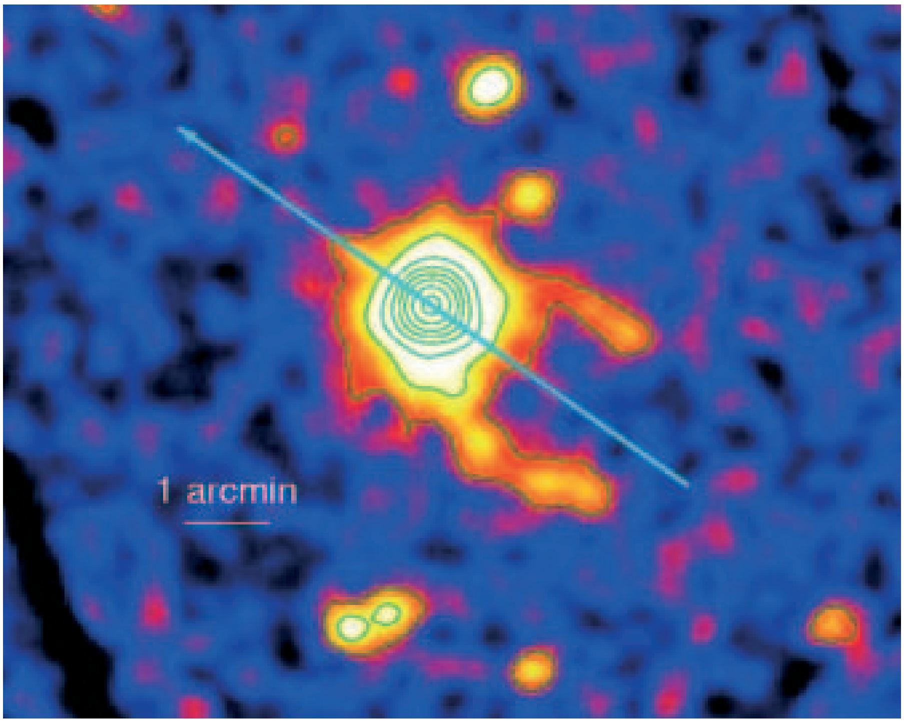


EPIC-MOS images of the time-dependent, dust-scattered X-ray halo around GRB 031203 at four different times after the burst. The ring-like structures increased with time, which is consistent with small-angle X-ray scattering.
(Courtesy of S. Vaughan, University of Leicester, UK and ESA)

Fundamental Physics

The equation of state of cold nuclear matter

The equation of state, i.e. the relationship between pressure and density, of cold nuclear matter can be studied only for a restricted parameter range with accelerator experiments in Earth-based laboratories.

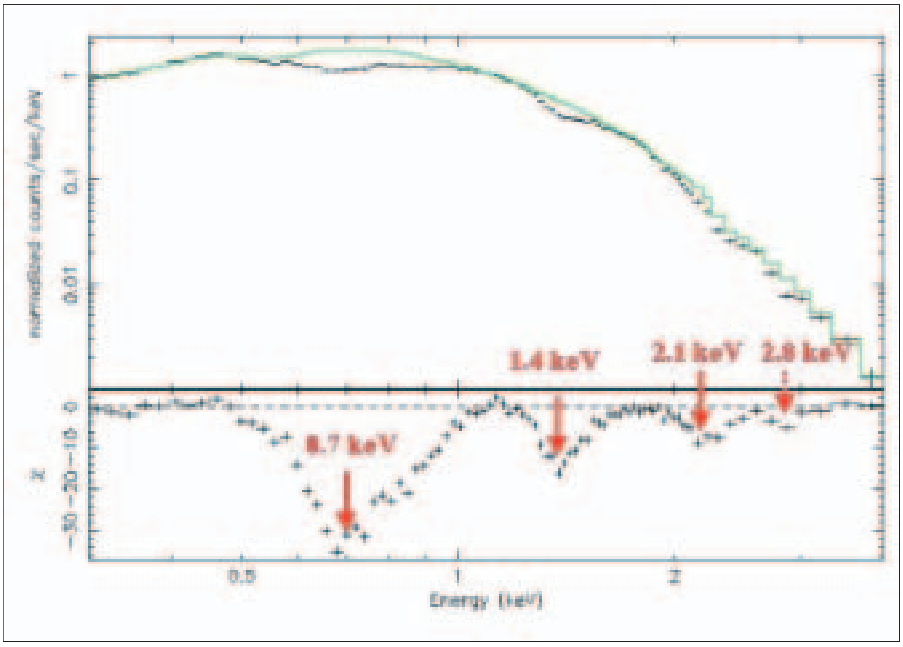


XMM-Newton image of Geminga, captured using the EPIC camera, showing the discovery of the twin tails. The motion of Geminga across the sky is indicated, showing that the tails are trailing the neutron star
(Courtesy of P.A. Caraveo, INAF/IASF, Italy, and ESA)

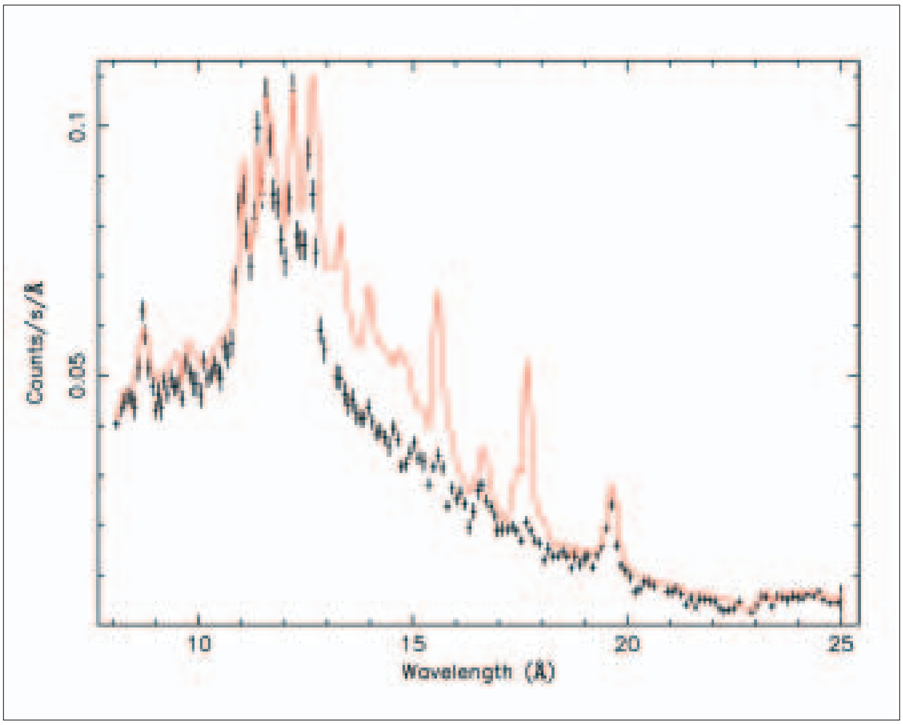
Given the fundamental properties of neutron stars, the most straightforward method of determining these quantities is by measuring the gravitational redshift of lines originating at the neutron star's surface. As the equation of state of nuclear matter implies a mass/radius relation for neutron stars, a measurement of the gravitational redshift at the neutron star's surface directly constrains the mass-to-radius ratio. J. Cottam et al. have discovered absorption lines in the XMM-Newton spectra of 28 bursts of EXO0748-676. The authors identify the most significant features with ionised iron transitions, all with a redshift of $z = 0.35$. For a plausible range of masses (M ~ 1.3-2.0 solar masses), this value is consistent with models of neutron stars composed of normal nuclear matter, while it excludes some models in which the neutron stars are made of more exotic matter. Given the importance of this question, XMM-Newton will observe 1E 1207.4-5209, one of the most promising neutron stars for a further gravitational redshift measurement, several times during the next year.

General relativity

X-ray observations of astronomical objects are among the most important approaches for studying the strong gravitational field. Observations near to the event horizon of black holes might even be possible. An overview of XMM-Newton observations of several objects showing broad iron emission lines, which are explained by material rotating with relativistic velocities around a black hole, was given in ESA Bulletin No. 114 by M. Guainazzi. A very fortunate observation led to the detection of the brightest X-ray flare detected so far from Sgr A, the super-massive black hole in the centre of our Galaxy. Its power/density spectrum shows five distinct peaks at periods ranging from ~100 s to 2250 s. Aschenbach could identify each period with one of the characteristic gravitational cyclic modes associated with accretion disks in such a way that a consistent value for the black hole's mass and its angular momentum is obtained. Recently the high effective imaging area of XMM-Newton has allowed an extremely



EPIC-pn spectrum of the neutron star 1E1207.4-5209. The data points are given in black, whereas the continuum model is coloured green. The residuals with respect to the continuum fit (lower panel) show the 'harmonic' marks due to the resonant cyclotron absorption
(Courtesy of G.F. Bignami, Centre d'Etude Spatiale des Rayonnements, France, and ESA)



Combined RGS spectrum of the cluster of galaxies 2A 0335+096 from an ongoing study. The black crosses are data points and the red line shows the predicted spectrum according to the previously favoured isobaric cooling-flow model. Between 12 and 18 Angstroms, the data are clearly different from the model, because the predicted lines from ionised iron are absent in the RGS data. This indicates that the cores of clusters are cooling much slower than expected
(Courtesy of J. de Plaa & J. Kaastra, SRON, The Netherlands, and ESA)

important step to be made: K. Iwasawa et al. have detected the modulation of a transient FeK_α emission feature in the XMM-Newton spectra of the Seyfert galaxy NGC 3516. This feature varies systematically in flux at intervals of 25 ksec, whereas the peak moves in energy between 5.7 and 6.5 keV (see figure). The spectral evolution of the feature agrees with emission arising from a spot on the accretion disc at between 3.5 and 8 Schwarzschild radii (the radius of a black hole below which nothing, not even light, can escape). A similar transient behaviour for the iron line is reported by J. Turner for the XMM-Newton spectra of the Seyfert galaxy Markarian 766. In order to study the innermost region of this black hole in more detail, and especially to 'see' the strong gravitational field, XMM-Newton will observe Markarian 766 for more than 500 ks during 2005.

Redshift

The light emitted by a source has undergone a 'redshift' if emission or absorption features are seen at longer wavelengths than expected from measurements on Earth. In visible light, this causes the features to be shifted towards the red end of the spectrum, hence the name. In this article, two kinds of redshift are mentioned: cosmological redshift and gravitational redshift. Both can be properly understood only in the context of the famous general Theory of Relativity published by Albert Einstein in 1916 (Annalen der Physik, Band 49, page 50).

Cosmological redshift is a consequence of the Big Bang and the fact that the Universe is expanding: the greater the distance to an object, the larger its redshift. For example, all the stars that can be seen with the naked eye have a redshift (z) of 0. At present, the most distant objects known have z-values of around 6.5. Gravitational redshift is observed when we study objects with a high mass. With increasing mass (or decreasing radius) the spectra become redder, i.e. they show a higher z-value. To understand gravitational redshift, we can imagine that light needs energy to escape from the gravitational field, similar to a rocket being launched into orbit.

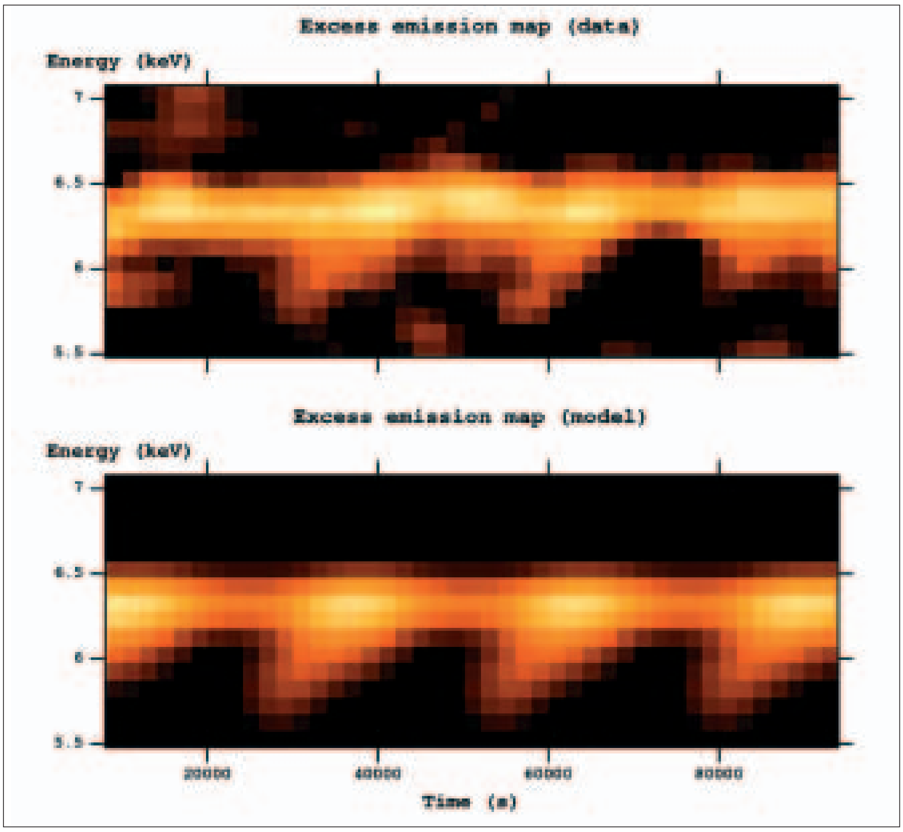
Cosmology

Absorption in high-redshift quasars

The quasi-stellar object (quasar) APM 08279+5255 is one of the most luminous objects in the Universe and therefore a promising candidate for answering cosmological questions. The XMM-Newton EPIC spectrum of this high-redshift ($z = 3.91$) quasar reveals a high-column-density absorber in the form of an absorption edge of significantly ionised iron and corresponding ionised lower energy absorption (see figure). These findings confirm a basic prediction of phenomenological geometry models for the quasar outflow. The iron to oxygen ratio of the absorbing material is significantly higher than the solar ratio, putting an important lower limit on the age of the Universe, which is in agreement with the results of the background measurements of the COBE mission, but in contradiction with previous estimates.

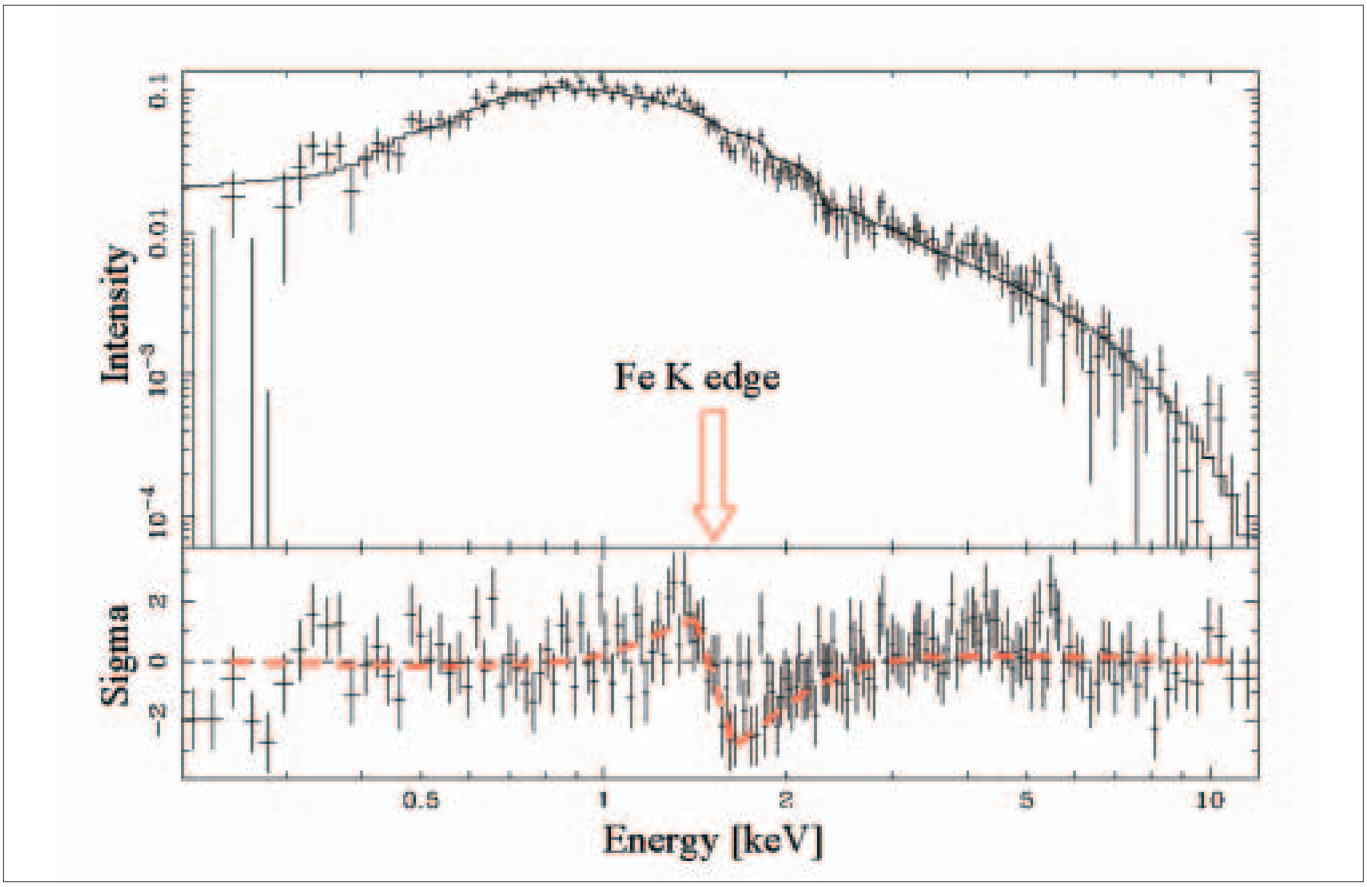
The luminosity/temperature relation for clusters of galaxies

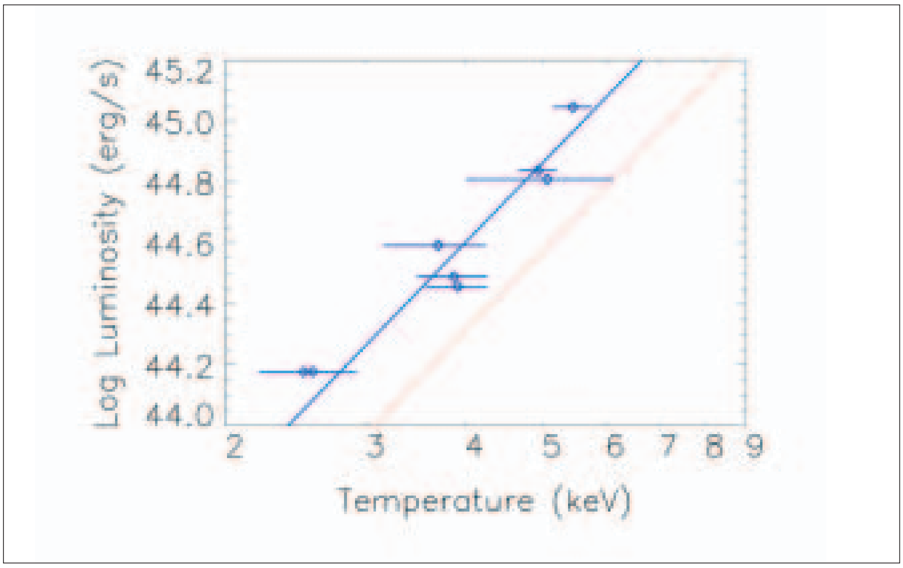
Clusters of galaxies are the largest gravitationally bound structures in the Universe, and as such are preferred objects for studying the large space-time scale structure. Based on XMM-Newton observations, D. Lumb et al. have studied galaxy clusters in a redshift range from $0.45 < z < 0.62$ to constrain the luminosity/temperature relation, and with this to ultimately determine the values of the matter



The upper panel shows the smoothed excess-emission map in the time-energy plane for the FeK$_\alpha$ as measured for NGC 3516. The colour-coding is according to a 'black body'. The spectral evolution agrees with emission arising from a spot on the accretion disc located 3.5 - 8 Schwarzschild radii from the black hole. The lower panel shows a theoretical picture for comparison (Courtesy of K. Iwasawa, University of Cambridge, UK and ESA)

EPIC-pn spectrum of the quasar APM 08279+5255 (z = 3.91) revealing a high-column-density absorber in the form of an absorption edge of significantly ionised iron (Courtesy of G. Hasinger, MPE, Germany, and ESA)





The blue data points were obtained from XMM-Newton observations of galaxy clusters for a redshift range $0.45 < z < 0.62$. The blue line represents the best fit of the luminosity/temperature relation for these clusters of galaxies. For comparison, the luminosity/temperature relation for low-redshift clusters is provided in red (dotted line). The difference between the two reveals an evolution of the relation with redshift (Courtesy of D. Lumb, ESA/ESTEC, The Netherlands)

density and, to a lesser extent, the cosmological constant. Comparing the luminosity/temperature relation that they found with the relation for low-redshift clusters of galaxies, the data reveal an evolutionary trend in the luminosity/temperature relation with redshift (see figure). These results are highly interesting as the trend found allows several different interpretations, thereby affecting both our understanding of the cluster physics and the evolution of the cosmological parameters. A main aspect of future XMM-Newton studies will be to expand the sample of long-exposed galaxy clusters to even higher redshifts in order to provide data for further studies.

Conclusion

Although the space available here has allowed only a cursory sampling of the main areas addressed by XMM-Newton observations, there can be little doubt that the mission has already answered an enormous number of scientific questions, and that its observations have radically changed our understanding of many astrophysical objects. But this is not the end of the road, as even more questions have been thrown up by the latest progress and are now also awaiting answers. Given the unique characteristics of XMM-Newton's instruments, we are confident that many of these questions will be answered in the coming years.

The fact that so many scientific challenges remain to be addressed is underlined by the continuously high over-subscription rate (between 7 and 9 times) for XMM-Newton observing time in the proposals received in response to every Announcement of Opportunity issued.