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XMM-Newton in ESTEC

→ 10 YEARS OF DISCOVERY

Commemorating XMM-Newton's first decade

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XMM-Newton has had a major impact on modern astrophysics, with a steady stream of new results. The XMM-Newton spacecraft, instruments and ground segment are ready to continue this success for many years to come, and provide the worldwide scientific community with the means to address many exciting new challenges.

On 10 December 1999, an Ariane 5 lifted off from Europe's Spaceport in Kourou, French Guiana, carrying the 10-metre long XMM-Newton satellite. On this tenth anniversary, the leading scientific journal *Nature* reviewed the scientific impact of XMM-Newton and NASA's Chandra satellite. While both missions are X-ray observatories, they have very different strengths, with Chandra delivering magnificent images of the X-ray sky and XMM-Newton providing superb spectra. By combining these capabilities, astronomers have the best of all possible worlds.

XMM-Newton continues to be extraordinarily productive. Each year, between 1500 and 2000 scientists use XMM-Newton and publish around 300 peer-reviewed articles in leading journals. As of January 2010, around 2300 scientific papers have been published in major peer-reviewed journals based on data collected by XMM-Newton. Such a high scientific return places XMM-Newton among the most productive space- and ground-based astronomical observatories, including the Hubble Space Telescope.

Another way of judging the success of a scientific mission is by measuring how much scientists want to use it. Each year, scientists from all over the world apply for observing time on XMM-Newton and each year the cumulative amount of observing time requested exceeds by a factor of six or more the total time available. The time allocation committee can afford to be picky and select only the very best observing proposals, thereby contributing to the extraordinary success of the mission.

XMM-Newton has observed all types of astronomical sources, from nearby Solar System objects, such as comets, to some of the most distant objects known in the Universe. Astronomers use X-rays to explore the extreme Universe – matter just about to fall into a black hole, or trapped in the intense gravitational and magnetic fields around a collapsed star, or in giant intergalactic shocks in distant clusters of galaxies. Using XMM-Newton, astronomers have probed the distortions of space–time around black holes and discovered the role that supermassive black holes play in shaping the surrounding galaxies.

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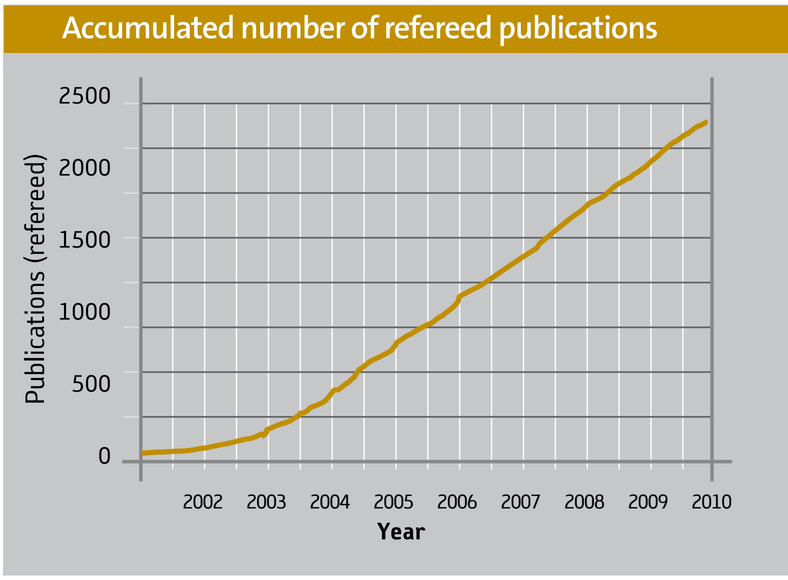
The starburst galaxy M82, taken by the Optical Monitor and European Photon Imaging Camera instruments on XMM-Newton, obtained as part of International Year of Astronomy 2009 activities (ESA/P. Rodriguez)



Accumulated number of refereed publications

The Solar System

XMM-Newton has also observed X-ray emissions from Mars, Jupiter, Saturn, several comets and from Earth's exosphere, the outermost part of the atmosphere that streams into space.

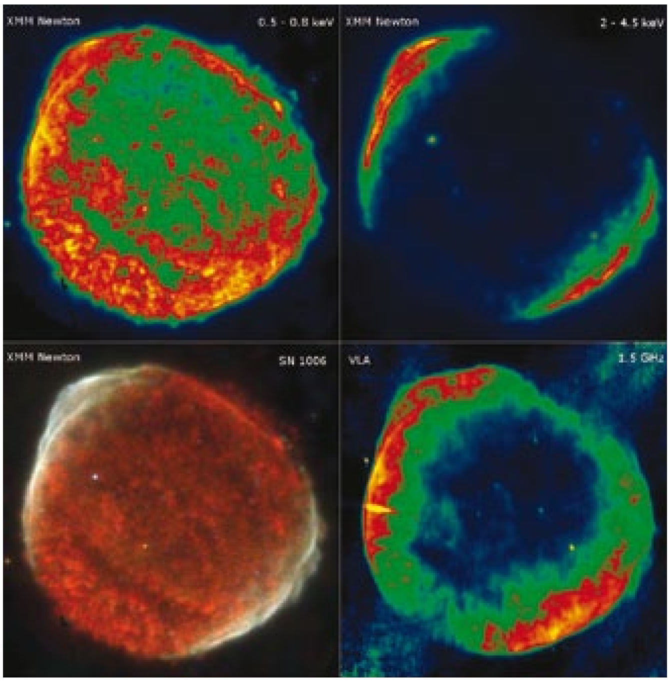
X-ray emission from comets was only discovered four years before the launch of XMM-Newton. This was totally unexpected, since comets are cold objects and X-rays typically come from sources with temperatures over a million degrees. Thanks to XMM-Newton, astronomers discovered that X-rays are also produced by a mechanism called 'charge exchange' which occurs when a highly ionised atom of the solar wind collides with a neutral atom of the comet gas. This atom captures an electron in an excited state and radiates a characteristic spectral signature as it drops into a less energetic state, which is easily observed by the sensitive instruments on XMM-Newton.

XMM-Newton has shown that Jupiter's aurorae emit copious amounts of high-energy X-rays. Although it had already been predicted theoretically, such an effect could not be detected before, because previous satellites lacked the required sensitivity. Jupiter's emissions have a different origin to that of X-rays from comets. They vary with time, probably as a result of changes deep inside Jupiter's magnetosphere.

XMM-Newton also observed Mars. In contrast to the compact emission from Jupiter's poles, the faint X-ray halo observed around Mars extends out to at least eight times the planet's radius. This emission arises from charge-exchange interactions in the tenuous martian exosphere, much like those in comets. This was the first definite detection of charge-exchange induced X-ray emission from the exosphere of another planet. Charge-exchange interaction is an important escape mechanism for atmospheric atoms that most likely contributed to the near-complete loss of the martian atmosphere in the early life of the planet.

The birth and death of stars

Star formation regions are the stellar nurseries where recently born stars coexist with protostars – objects that have not yet had enough time to evolve into stars – and giant molecular clouds that have not begun to collapse to form stars. XMM-Newton has made an extensive study of the nearest star-forming region, the Taurus Molecular Cloud. The cloud contains many 'T Tauri' stars, stars formed so recently that they are still contracting and accreting gas from the molecular clouds. As the gas spirals inward, it settles into a disc around the star. XMM-Newton observations have shown that this cool gas emits intense X-rays when it subsequently crashes into the surface of the star. The X-ray emission is bound to play an important role in the formation and subsequent evolution of planetary system around young stars.



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Supernova remnant SN 1006. The upper images show how the X-ray emission varies with energy. The distribution of the high-energy X-ray emission is strikingly similar to that seen in the radio band (bottom right) (R. Rothenflug/CEA/DSM/DAPNIA/SAP and ESA)

Supernovae are the cataclysmic 'deaths' of massive stars. When a massive star runs out of nuclear fuel, its core collapses, leaving behind a neutron star or a 'black hole', depending on its mass. The resulting 'supernova' explosion ejects the outer layers of the star into space, producing powerful shock waves. The ejected material and the interstellar gas that sweeps away are heated to millions of degrees. Such supernova remnants therefore continue to emit intense X-ray radiation for thousands of years after the explosion. Investigations of the X-ray properties from the supernova remnant Cassiopeia A have concluded that the progenitor star had a mass of 12 times that of our Sun before it exploded. Furthermore, the bulk of the X-ray emission comes from two large clumps of iron-rich gas, which suggests that the supernova explosion was asymmetric and ejected 'bullets' instead of spherical shells.

In 1006 AD, monks at the Benedictine abbey of St Gallen in Switzerland described the observation of a new bright star in the sky. We know today that this was a supernova explosion, now labelled SN 1006. XMM-Newton observed its remnant almost exactly 1000 years later. SN 1006 is a shell supernova remnant, in which X-ray emission originates from electrons spiralling in an intense magnetic field. XMM-Newton measurements indicate that shell supernova remnants are important sites for the acceleration of the energetic cosmic rays that shower down on Earth's atmosphere and can endanger astronauts in space.

Neutron stars have a mass slightly greater than our Sun, but a radius of only a few kilometres. They are effectively whole stars compressed into the size of a city. Their gravity and internal pressures are so high that protons combine with electrons to form neutrons in their interior. Many neutron stars rotate rapidly and emit narrow beams of radio radiation – like a sort of cosmic 'lighthouse'. We detect the radio signal only when the rotating beams point in our direction, resulting in short and periodic pulses of emission, hence the name 'pulsars'.

Thanks to XMM-Newton, it has been possible for the first time to map the X-ray emission from pulsars, leading to the discovery of hot spots on their surface. Such hot spots had been predicted but could not be observed before XMM-Newton. Spectroscopic investigations of the neutron star 'Geminga' revealed a hot spot that is only 60 m across, about the size of a football field. It is amazing that such a tiny

↑ Artist impression showing HLX-1 (blue source to the upper left-hand side of the galactic bulge), located on the edge of the spiral galaxy ESO 243-49, and the strongest candidate to date to be an intermediate-mass black hole (H. Sagerud)

emission region can be detected in a star 500 light years (or 450 trillion km) away! XMM-Newton found hot spots in two further isolated neutron stars. The hot spots have different sizes and properties, varying in phase in one case and in anti-phase in the other. These findings show that the magnetic field and the surface temperature distributions of neutron stars are much more complex than expected.

Black holes

When a star more than eight times as massive as our Sun explodes as a supernova, it leaves behind a black hole. There are many of these stellar black holes within our galaxy, detectable via X-ray emission from gases heating up as they fall into the black hole. However, there is another sort of black hole, with masses in the range from millions to billions of solar masses.

These ‘heavyweights’ are located at the very centre of galaxies, such as in our own Milky Way. Understanding how these supermassive black holes form and their interaction with the surrounding galaxy is a key question in astronomy today.

The only way to assemble supermassive black holes is by repeatedly merging stellar-mass black holes together, and so we would expect to find many black holes of intermediate masses, say a few hundred times the mass of the Sun. Until recently however, the hunt for such intermediate-mass black holes had been unsuccessful. Several candidates had been proposed, but none confirmed. It is only recently that astronomers, using XMM-Newton, could finally claim success. They detected an X-ray source in galaxy ESO 243-49, called HLX-1, whose emission varies strongly and rapidly, implying that it originates from one single compact object rather than from a collection of unresolved independent sources.

Furthermore, the measured X-ray luminosity is so large that it can only come from a black hole whose mass is at least 500 times that of the Sun. This means that HLX-1 is the first definitive example of the long-sought intermediate-mass black holes.

Stellar black holes often exhibit rapid variations of their X-ray flux that are almost, but not exactly, periodic (hence they are called quasi-periodic oscillations, or QPOs). The importance of this quasi-period is that it provides a direct measure of a fundamental scale in the source, such as the time it takes for a hot blob of gas to complete one revolution around the black hole. In other words, QPOs provide a yardstick with which we can estimate how the size and mass of black holes. For the last 25 years or so, scientists have also been searching for quasi-periodic oscillations in active galactic nuclei (AGN) and 'quasars', which are known to surround supermassive black holes. Their hunt was unsuccessful until, in 2008, thanks to its large sensitivity, XMM-Newton discovered quasi-periodicity in the X-ray emission from a bright AGN. Whereas oscillations in stellar black holes typically occur on a timescale of milliseconds, the AGN quasi-periodicity is about one hour, roughly a million times longer. This is consistent with the fact that massive black holes at the centre of AGNs are also about one million times larger and more massive than their stellar cousins.

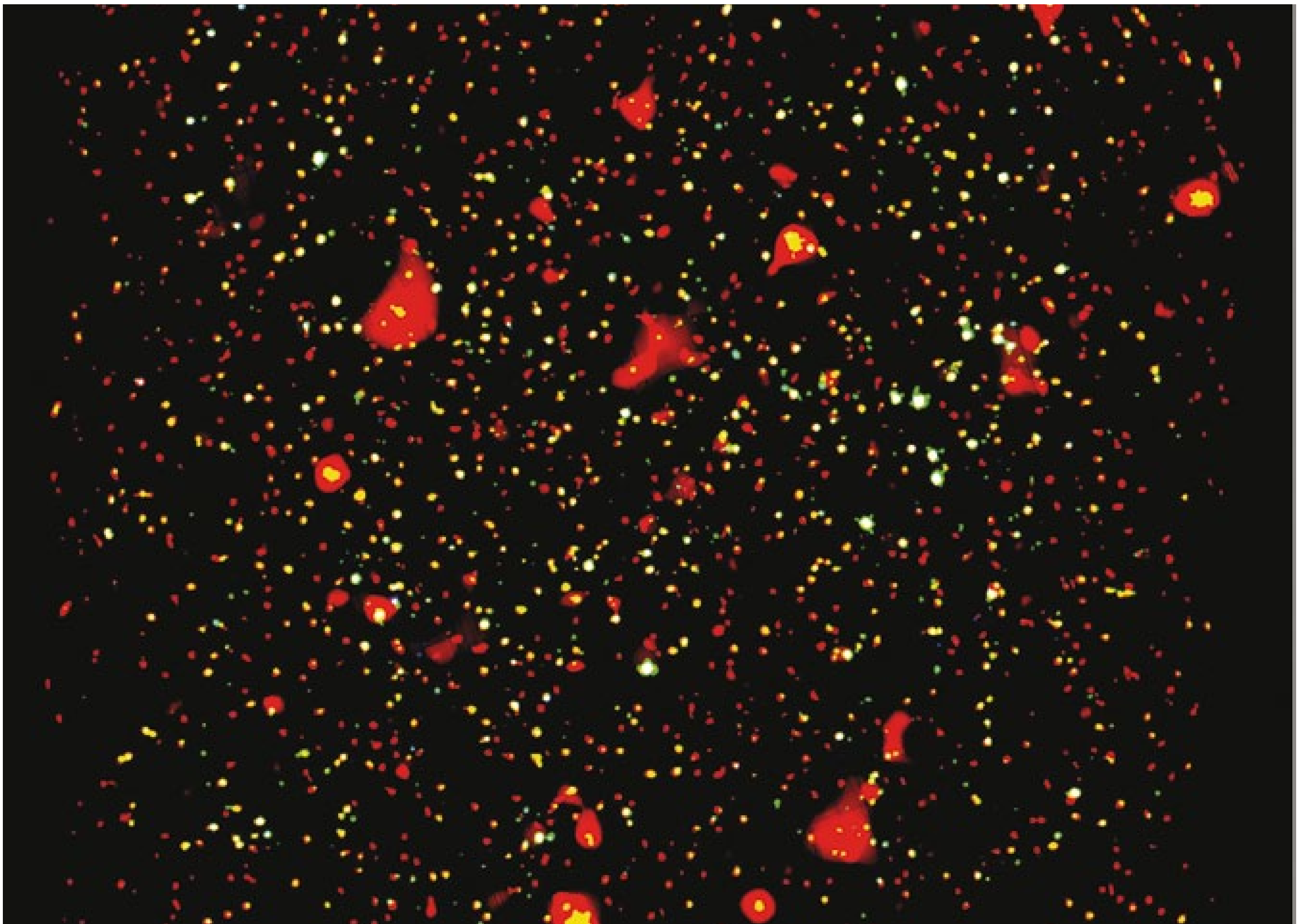
Galaxy clusters

Clusters of galaxies are the largest bound structures in the Universe and can contain many thousands of galaxies. But galaxies contribute only about 5% of the cluster mass. About 80% consists of 'dark matter', an unknown substance which is invisible, but reveals itself only through the gravitational pull it exerts on normal matter.

The hot gas emits intense X-rays, making clusters among the brightest sources of the X-ray sky. Theory predicted that, pulled by gravity, intergalactic gas would accumulate toward the centre of the cluster and become denser and cooler than at the periphery. Much to everyone's surprise, however, early XMM-Newton observations immediately ruled out the existence of such cooling flows. Indeed, the emission line characteristics of a cool gas were completely missing from the observed clusters' X-ray spectra.

Investigators concluded that some unknown mechanism existed that was able to warm up the gas and prevent it from cooling as it accumulated toward the centre of the clusters. Here, deep images obtained with Chandra played a significant role, as they revealed gigantic jets and winds originating from the AGN located at the centre of the cluster. Calculations immediately showed that such jets inject tremendous amount of energy into the intergalactic gas, thereby keeping it warm. The emerging picture is therefore that of a self-controlling 'cosmic feedback' machine: as intergalactic gas cools and falls towards the central galaxy in the cluster, it piles up in the vicinity of the supermassive black hole which lies at its centre. A fraction is eventually swallowed by the black hole but excess amounts of gas are ejected back into the intergalactic

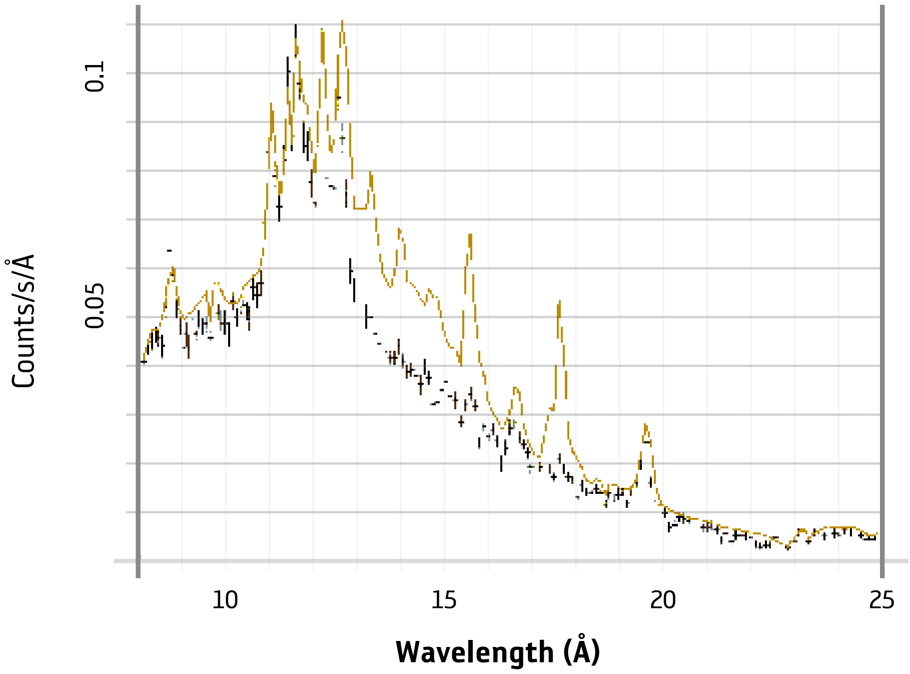
↓ This false X-ray colour image is XMM-Newton's view of the deep Universe, showing thousands of faint X-ray sources in the XMM-COSMOS survey field. Most of the sources are distant active galactic nucleii with about 10% being extended clusters of galaxies (G. Hasinger/N. Cappelluti/XMM-COSMOS/ESA)



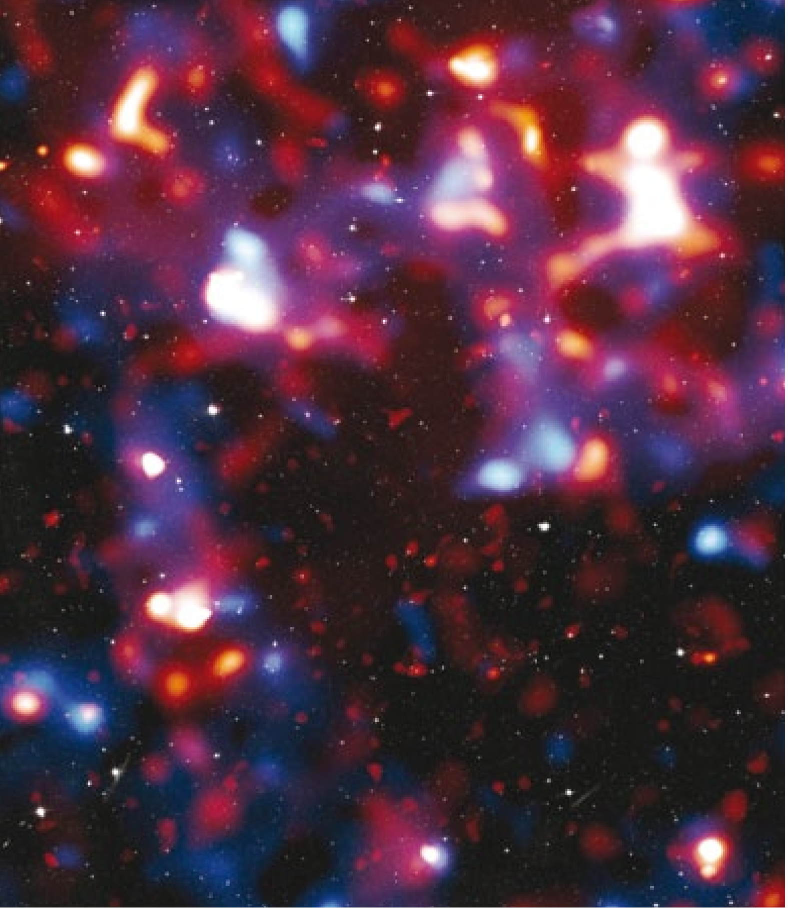
Composite of XMM-Newton and Hubble Space Telescope colour images of NGC 7009, the Saturn Nebula, showing the hot X-ray-emitting gas (blue) relative to the cool, ionised nebular shell seen in visible wavelengths (M. Guerrero, Univ. Illinois/ESA)

medium in the form of jets and winds that then heat the gas. Since it cannot cool, the gas stops raining toward the central galaxy in the cluster. Without inflowing material, the black hole is starved and shuts down its wind and jet. A new cycle is thus ready to start.

This mechanism is of central importance in astrophysics today, because it connects clusters of galaxies, galaxies and the supermassive black holes at their centres. All these objects were previously thought to evolve independently. Now we have a mechanism that not



An XMM-Newton spectrum of the cluster of galaxies 2A 0335+096. The black crosses are from the Reflection Grating Spectrometer and the red line shows the predicted spectrum from previously favoured cooling models. The difference between the two reveals the lack of cool material and indicates that the cluster core is much hotter than predicted (J. de Plaa/SRON/ESA) only connects them, but also even regulates and somehow coordinates their growth. The discovery of this mechanism is as fundamental for the understanding of galaxies and clusters as was the discovery some 60 years ago of nuclear fusion for the understanding of stars.



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The distribution of normal matter (red) determined mainly by XMM-Newton, dark matter (blue) and the stars and galaxies (grey) observed with the Hubble Space Telescope. It shows that normal matter, mostly in the form of clusters of galaxies, accumulates along the densest concentrations of dark matter (NASA/R. Massey, Cal. Tech./ESA)

Dark matter and dark energy

The new millennium has seen a revolution in our understanding of the nature of the Universe. Astronomical observations have shown that only 4% of the Universe consists of the normal matter, the atoms and molecules we are used to here on Earth. Another 23% is made of the mysterious 'dark matter', while the remaining 73% of the Universe consists of the even more mysterious 'dark energy'. X-ray observations have made important contributions to this revolution and a deeper understanding of these mysterious components is one of the most promising areas for future missions such as the International X-ray Observatory.

By combining deep XMM-Newton and Hubble Space Telescope observations of the same region of the sky, scientists were able to reconstruct the first three-dimensional large-scale map of the distributions of both normal and dark matter. On such large scales, the Universe appears patchy, with matter distributed along a gigantic network of filaments and clumps. Clusters of galaxies – normal matter – tend to concentrate toward the nodes of this network where the density of dark matter is the highest. These observations provide a striking confirmation of current models of structure formation in the Universe, whereby normal matter is pulled by gravity toward concentrations of dark matter, where it collapses to form stars and galaxies.

The future

As we look into the future it is difficult to predict with any reliability the next major areas of discovery and impact, although it is probable that deeper and wider surveys with XMM-Newton will yield a wealth of new discoveries. There are potential investigations that span from the study of the large-scale structure of the Universe to understanding the sub-nuclear composition of neutron stars.

Targets of interest extend from the Sun's wind to deep surveys of the extragalactic sky to provide a complete census and evolutionary history of AGN. In addition, long uninterrupted studies of broad emission lines emitted near black holes will furnish unique insights into strong gravity. Long observations of individual galaxy clusters will probe and refine our understanding of the feedback mechanism by which the energy from AGN is coupled to the intra-cluster gas temperature and density.

The scientific return from XMM-Newton will continue to be enhanced by collaborations with ground-based and other space telescopes. Understanding the birth of stars and planetary systems is one of today's most important astronomical topics. Combined X-ray, infrared and sub-millimetre measurements from ESA's Herschel and XMM-Newton observatories and ground-based facilities will be crucial to studying accretion and outflow processes in young stars and proto-planetary discs.

The nature of dark energy will be investigated by X-ray observations of distant galaxy clusters, such as those being discovered with ESA's Planck satellite. As a matter of fact, the growth rate of galaxy clusters, as a function of cosmic time, is a sensitive measure of the relative strengths of dark matter (which causes the clusters to collapse) and dark energy (which causes them to expand). Measuring the interplay between these two forces and how it varies with time will undoubtedly shed light on this mysterious stuff that makes up 96% of the Universe. ■