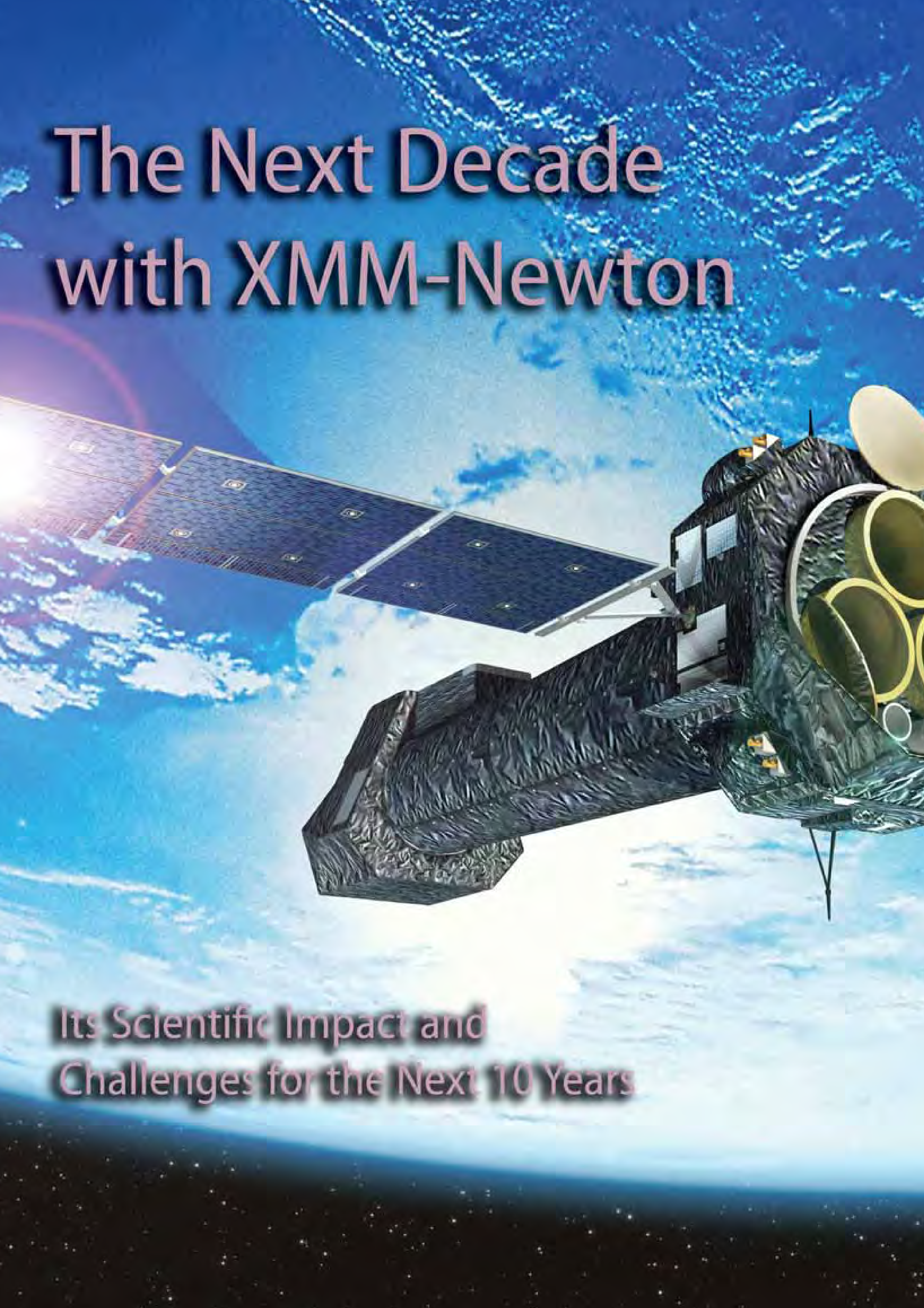
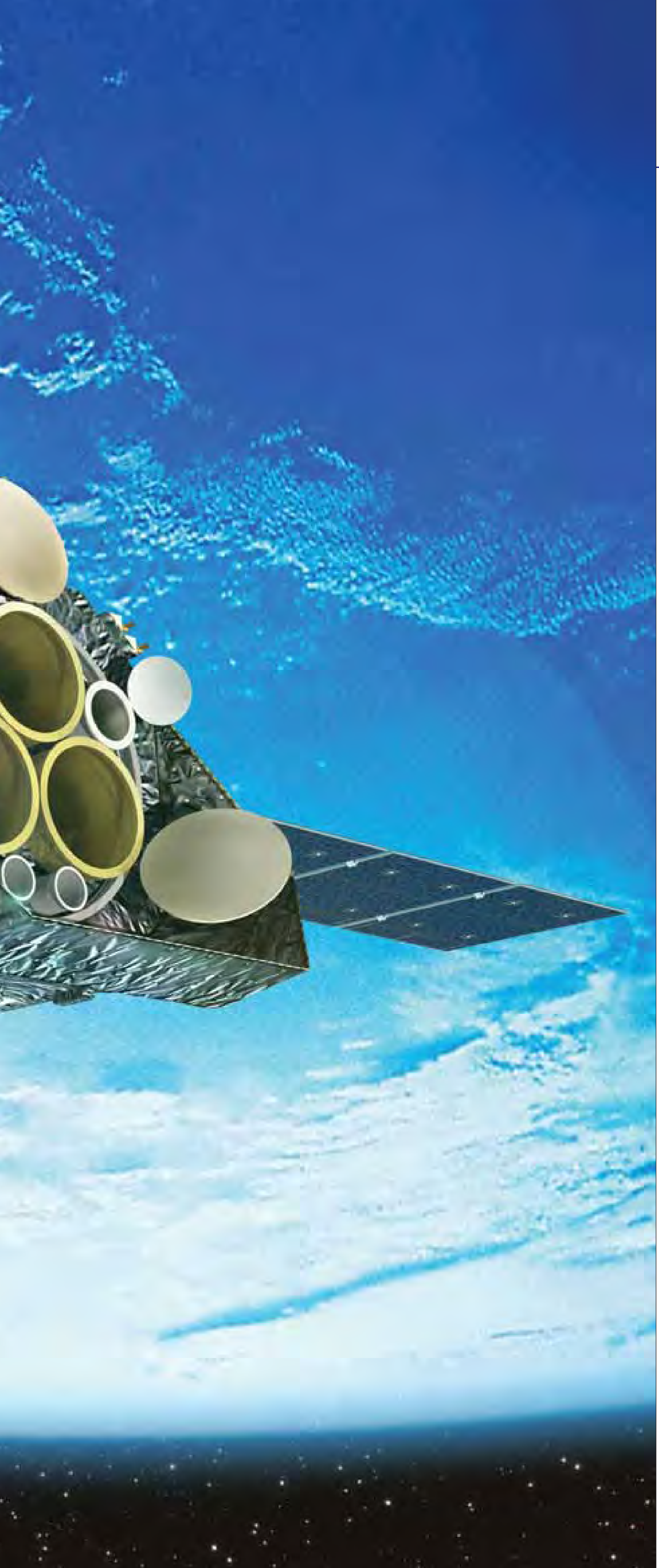
The Next Decade with XMM-Newton



Its Scientific Impact and Challenges for the Next 10 Years



Norbert Schartel
Directorate of Scientific Programmes,
ESAC, Villafranca, Spain

Arvind Parmar
Directorate of Scientific Programmes,
ESTEC, Noordwijk, The Netherlands

XMM-Newton is one of ESA's most successful science missions. Launched in December 1999, the spacecraft is technically able to continue this scientific success story and now, encouraged by its impressive scientific output, ESA has already extended XMM-Newton's operations well beyond its original 10-year design lifetime.

Introduction

X-rays open up a universe unseen to our eyes. In 1901, the German physicist Wilhelm Röntgen won the first Nobel Prize in Physics for the production and detection of X-rays. The prize was awarded only six years after the discovery, due to the immediate importance of X-rays as a medical diagnostic tool.

X-rays are also an important diagnostic tool for astronomers, since they are emitted by very hot gas or plasma at temperatures of several million Kelvin that cannot be detected by other means. Because X-rays are absorbed by Earth's atmosphere, astronomers had to wait until the advent of the space age to observe the X-ray sky.

Sir Isaac Newton

Sir Isaac Newton (1643–1727) was an English physicist, mathematician, astronomer, natural philosopher and alchemist. His book of 1687, *Philosophiæ Naturalis Principia Mathematica*, described universal gravitation and the laws of motion, which provided the foundations for classical mechanics and dominated scientific thinking for the next three centuries. Newton proved that the motions of objects on Earth and of celestial bodies are governed by the same set of natural laws by demonstrating the consistency between Kepler's laws of planetary motion and his theory of gravitation.

Newton discovered the principles of conservation of momentum and angular momentum. He invented the reflecting telescope and developed a theory of colour based on the observation that a prism decomposes white light into a visible spectrum. Newton shares the credit with Gottfried Leibnitz for the development of calculus.

The first cosmic X-ray source was discovered during a short rocket flight in 1962 (American astrophysicist Riccardo Giacconi was awarded the Nobel Prize in 2002, almost exactly 100 years after Röntgen, for his pioneering work leading to this discovery). X-ray astronomy then developed rapidly during the 1960s; the first X-ray satellite was launched in 1970 and discovered several hundred X-ray sources.

European involvement started shortly after with ESA's first X-ray observatory, Exosat, launched in 1983. The early and continued involvement in the field is an important factor in maintaining Europe's strong position in X-ray astrophysics today.

XMM-Newton, ESA's large X-ray observatory and second cornerstone of the Horizon 2000 programme, was launched in December 1999. It was named after the technique behind the mission (XMM stands for 'X-ray Multi-Mirror') and Sir Isaac Newton, the man who first explained the significance of gravity in the heavens (see box). Gravity is the driving force that creates black holes, neutron stars and other collapsed objects, which are among the main targets of XMM-Newton's studies, so it was only fit to associate Newton's name to this very successful mission.

XMM-Newton has been routinely collecting scientific data for more than eight years. With almost 200 000 individual sources, the XMM-Newton catalogue is the largest of its kind. Last autumn, ESA's Science Programme Committee approved mission operations until the end of December 2012, with further extensions possible assuming that the outstanding scientific return continues and that there are no major technical problems.

An XMM-Newton mirror module comprising of 58 nested mirror shells (ESA/Dornier Satellitensysteme GmbH)

XMM-Newton's Scientific Payload

The power of an astronomical telescope depends on how much incoming light can be collected. Nearly all materials absorb incident X-rays. It is therefore impossible to construct a mirror that reflects and focuses X-rays in the same way as in an optical telescope.

Instead, X-ray optics use a physical effect called 'total reflection' which occurs only with very small reflection angles, when the incoming ray is almost parallel to the mirror surface and thereby 'grazes' it. We can experience this effect with normal visible light, for instance when driving along a wet road at sunset, you can be suddenly dazzled by the reflection of the Sun's rays.

XMM-Newton carries three grazing incidence telescopes. Each telescope consists of 58 gold-coated mirror shells that are nested inside one another like a Russian doll. XMM-Newton provides high-quality X-ray and optical/UV data from six instruments simultaneously: three European Photon Imaging Camera (EPIC) cameras, two Reflection Grating Spectrometers (RGS) and the Optical Monitor.

An EPIC detector is positioned behind each of the three X-ray mirror modules. Two MOS-CCD cameras share two of the modules with the RGS grating arrays and a pn-CCD detector is located behind the other telescope position, providing images of the X-ray sky as well as spectra with moderate resolution and timing information. The spectrometers disperse the light from the telescope to produce high-resolution X-ray spectra of all types of celestial objects.

Importance to the Scientific Community

An objective measure of the impact of XMM-Newton is the number of scientists who use its data, and there are several ways to estimate this number.

- As of January 2008, refereed publications based on XMM-Newton data have been published by 575 different main authors and 3500 co-authors.
- As explained below, every call for observing proposals has been heavily

	EPIC-pn	EPIC-MOS	RGS
Energy bandpass (keV)	0.15-12	0.15-10	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

The main characteristics of XMM-Newton's X-ray instruments

over-subscribed. For example, 586 valid proposals were received in response to the 2007 announcement. These were submitted by 424 different principal investigators. If co-investigators are included, about 1560 scientists from 33 different countries participated in this call.
- 1730 registered scientists retrieve data from the XMM-Newton on-line archives or download the software needed to process them.

We estimate that between 1500 and 2000 scientists use XMM-Newton routinely. This is approximately 20% of all professional astronomers worldwide. Indeed, XMM-Newton is an observatory open to the entire scientific community. However, because observing time is so valuable, its use is strictly regulated and optimised.

Each year, ESA issues an Announcement of Opportunity to which scientists from all over the world are invited to respond by submitting an observing proposal. The scientific importance and quality of all proposals are assessed by an Observing Time Allocation Committee (OTAC) composed of senior astronomers selected for their scientific excellence.

The OTAC evaluates all the submitted proposals and awards XMM-Newton observing time only to those proposals with the largest potential for discovery. The proposals that fail to get observing time do so, not because they are bad, but because the pressure is so high that only the best ones survive the selection. In 2007 for instance, the total amount of observing time requested was nearly eight times larger than was available. This large rejection rate is distressing but is also an indicator of the importance of XMM-Newton to the scientific community.

Scientific Impact

The number of publications based on XMM-Newton data is growing steadily at a rate of around 300 articles in refereed scientific journals each year. But quantity does not say it all. What about the quality and importance of XMM-Newton results? It is possible to assess the importance of a given scientific publication by counting the number of times it was mentioned, or cited, in other refereed articles. A 2007 analysis by Prof. V. Trimble and Dr J.A. Ceja showed that, with an average of 31.4 citations per article, XMM-Newton results have the highest impact ratio of all observatories. Furthermore, 47% of XMM-Newton articles are amongst the top 10% most cited publications, and 9.1% belong to the top 1% most cited class.

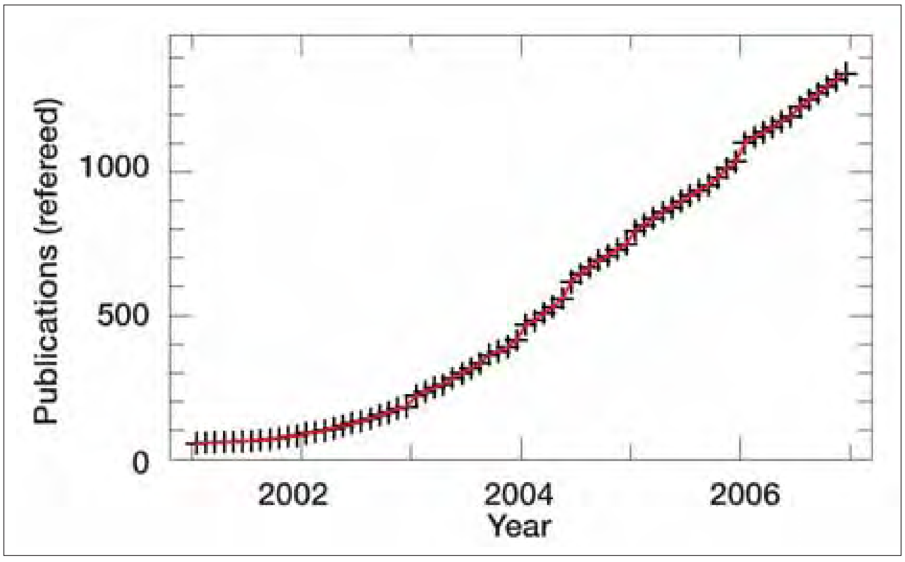
Extended Mission Operations

XMM-Newton operations were originally approved for 2.25 years of operations with a design lifetime of 10 years. XMM-Newton will exceed its design lifetime at the end of 2009. To plan for operations beyond this date, an independent review of operations (the Mission Extended Operations Review) was conducted in 2007.

The review focused on the expected performances of the spacecraft, the instruments and ground segment, and examined a new simpler operations concept. This concept strongly reduces costs by combining the Integral and XMM-Newton Mission Operations teams at ESOC and automating the real-time monitoring of the instruments. Combined operations started in the winter of 2007 and have been running smoothly since then.

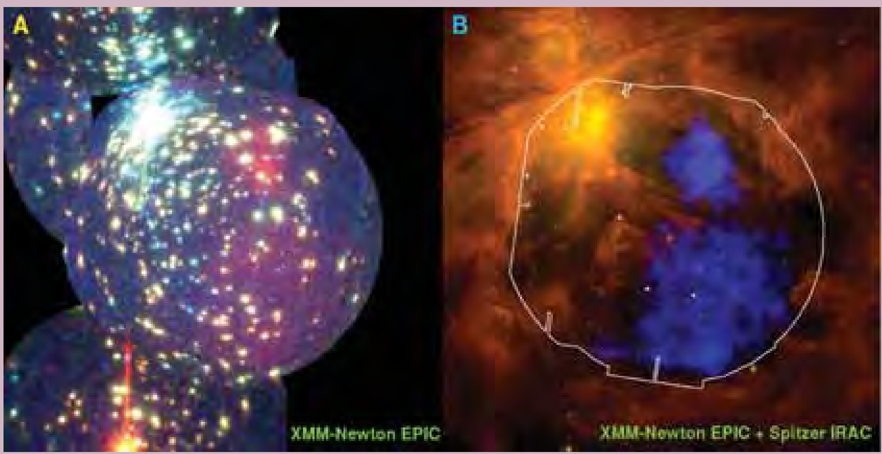
The status of the satellite and the instruments remains excellent. On-board consumables are sufficient to operate for at least another 10 years. The spacecraft is being operated on all its prime hardware chains with no redundant units having been used so far. The instruments are standing up to the harsh environment of space very well and are expected to continue providing outstanding results for many years to come.

The cumulative number of publications in refereed journals that use XMM-Newton data



Scientific Highlights

The far-reaching impact of XMM-Newton is illustrated by some recent scientific highlights.



The Orion nebula with its hot gas cloud. (Left panel) An X-ray image obtained with XMM-Newton. The diffuse X-rays emitted by the million-degree cloud appear reddish in this false colour picture. (Right panel) The same diffuse X-rays from the hot gas discovered by XMM-Newton (blue) overlaid on Spitzer IR data of the Orion region (AAAS/Science XMM-Newton EPIC (Guedel et al.), AAAS/Science (ESA XMM-Newton and NASA Spitzer data)

Million-degree plasma in the Orion nebula
XMM-Newton observations allowed Dr M. Guedel and colleagues to discover a huge cloud of very hot gas filling part of the Orion Nebula. The hot gas seems to stream out of the nebula into the neighbouring interstellar medium.

The Orion Nebula is the nearest dense star-forming region to Earth. It contains stars much more massive than the Sun. It is visible to the naked eye as a fuzzy patch of light located just below the three belt stars in the constellation of Orion. While gas in star-forming regions is usually relatively cool, XMM-Newton discovered that the Orion Nebula also contains a huge cloud of extremely hot gas, or plasma, heated to millions of degrees.

This cloud is invisible in optical or infrared images but is prominently seen in XMM-Newton images. The researchers speculate that the plasma originates from shocks formed as the fast stellar wind ejected by the most massive star in the nebula's centre runs into the cool and dense Orion gas. That a single massive star could create such huge hot plasma cloud came as a surprise since it was generally thought that powerful supernova explosions would be required, or at least a large number of massive stars whose winds collide with each other.

The XMM-Newton observations therefore suggest that such X-ray outflow phenomenon should be common in star-forming regions, and therefore widespread throughout our galaxy. This discovery is not just a matter of scientific curiosity. The outflows help enrich the interstellar medium with heavy elements such as carbon and oxygen. Accordingly, this result changes our view of how material may have come together in the formation of Earth-like planets and possibly life itself.

Stellar remains linked to the oldest recorded supernova
When a massive star runs out of nuclear fuel, it collapses and explodes as a supernova that can briefly outshine an entire galaxy. The explosion ejects the outer layers of the star into space producing powerful shock waves. The remains of the star and the material it encounters are heated to millions of degrees and emit intense X-ray radiation for thousands of years as a supernova remnant.

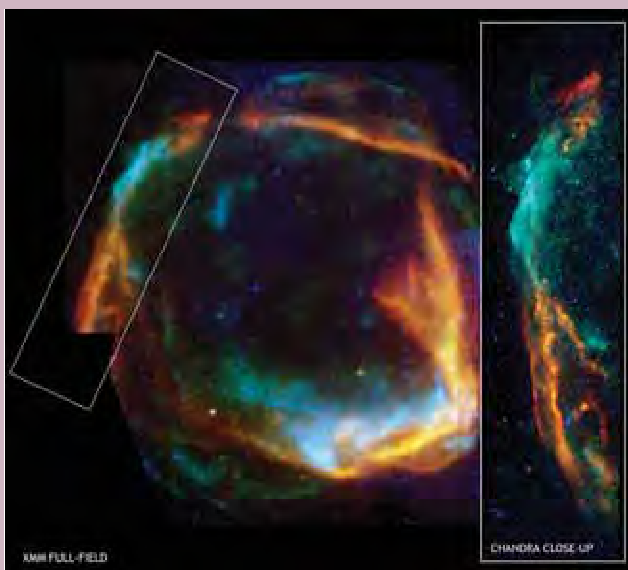
Dr J. Vink and colleagues examined XMM-Newton observations of a supernova remnant called 'RCW 86', along with data from a similar but complementary NASA X-ray observatory AXAF-Chandra, to estimate when the star exploded. They calculated how quickly the shell is expanding. Combining the expansion velocity with the

The Future

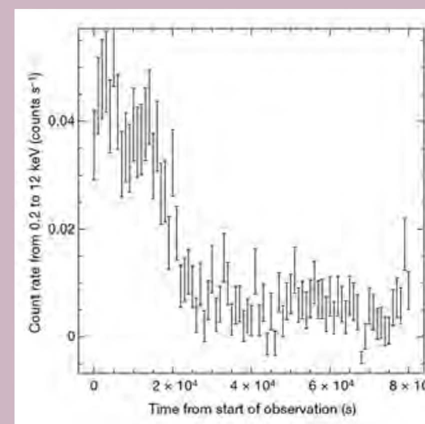
In June 2007, 125 scientists gathered at ESA's European Space Astronomy Centre to discuss the future science objectives of XMM-Newton. Many new scientific questions were presented and many scientifically exciting and innovative research programmes were outlined. Although the hazards of the peer review process make it impossible to predict what exactly will XMM-Newton's next great discovery, the workshop participants were not short of ideas for new avenues of research exploiting XMM-Newton's unique capabilities.

The formation of stars and, ultimately, of planetary systems, is a topic of expanding interest and attacks one of the most fundamental problems in astrophysics. The great prospect lies ahead of combining the spectroscopic diagnostics from XMM-Newton with those of ESA's soon-to-be-launched Herschel infrared observatory. This will provide unprecedented insights into the formation of stars and the nursery of planetary systems.

XMM-Newton with its large field of view, good spatial resolution and excellent sensitivity is uniquely suitable



A combined XMM-Newton and AXAF-Chandra X-ray image of RCW 86 showing the expanding ring of debris, or shell, that was created by the supernova explosion. Both images show low, medium and high-energy X-rays in red, green and blue, respectively. The AXAF-Chandra observations focused on the north-east side of RCW 86. (ESA, NASA/CXC, University of Utrecht/J. Vink)



Results from a 100 000-second XMM-Newton observation of NGC 4472. The EPIC-pn count rate is plotted against time since the start of the observation. The rapid decrease in count rate by a factor of seven is the key to identifying the object as a black hole (Nature)

size of the shell allowed them to determine the age of the remnant and demonstrate that it is only 2000 years old, much younger than the previous estimate of 10 000 years.

The revised age for RCW 86 probably explains an astronomical event observed almost 2000 years ago. In 185 AD, Chinese astronomers (and possibly the Romans) recorded a new bright star. The star took about eight months to fade from sight, which is consistent with modern observations of supernovae. RCW 86 had previously been suggested as the remnant from the 185 AD event, based on the historical records of the object's position. But uncertainties about the age provided significant doubt on the identification.

First black hole found inside a globular star cluster
Thanks to XMM-Newton observations, Dr T. Maccarone and colleagues discovered the first black hole located inside a globular star cluster. This finding is important to help astronomers understand how stars move in clusters and how black holes grow and evolve.

Globular clusters are dense groups of thousands to millions of stars and many scientists doubted that black holes could survive in such regions as the gravitational pull of the cluster's myriad stars would mean that newly formed black holes would be rapidly ejected from the cluster in a kind of 'slingshot effect'.

Black holes are by definition invisible, but the region around them can flare up when the black hole 'feeds'. When material falls into a black hole, it is heated to very high temperatures and radiates brightly in X-rays. XMM-Newton is extremely sensitive to variable X-ray sources and can efficiently search across large parts of the sky.

Dr Maccarone's team found the X-ray signature of a 'feeding' black hole in a globular cluster orbiting the giant elliptical galaxy NGC 4472. NASA's AXAF-Chandra confirmed that the black hole was indeed located inside the globular cluster.

This new object is so luminous and varies so rapidly that this rules out any type of explanation other than a black hole. Its X-ray luminosity changed by a factor of seven in a few hours, implying that the source cannot be a chance superposition of several close objects. The new findings provide the first convincing evidence that some black holes might not only survive, but also grow and flourish in globular clusters.

for following up on one of the most unexpected discoveries of recent years. In 2006 the remnants of a new class of supernovae were detected in XMM-Newton images of the Small Magellanic Cloud, one of the galaxies closest to our own. The importance of collecting large and complete samples as a way to uncover rare galactic objects cannot be overemphasised. This is best achieved by carefully mapping nearby galaxies such as Andromeda or the two Magellanic clouds, a task for which XMM-Newton is ideally suited.

XMM-Newton's sensitivity and good spectral resolution pay off in so many ways. In 2006, *Astronomical Notes* devoted an entire issue to the properties of iron lines emitted in the vicinity of black holes. General relativity tells us that the strong gravitational field from the black hole extracts energy from the light. The net effect is to distort the profile of an emission line, giving it a characteristic broad and asymmetric shape easily spotted with XMM-Newton.

XMM-Newton recently uncovered the existence of broad asymmetric lines in neutron stars as well. This opens the possibility of measuring directly the mass of neutron stars and thereby the equation of state of the extremely dense matter they are made of. This one discovery opens up a whole new research avenue and illustrates the mission's powerful capabilities.

The existence of dark energy was discovered only ten years ago, when XMM-Newton was under final construction. Together with dark matter, dark energy accounts for over 95% of the energy content of the Universe. Not surprisingly, understanding its nature has become one of the key questions in physics today, and XMM-Newton has a part to play here.

Dark energy cannot be detected and measured directly. Significant progress is expected in the next few years when it becomes possible to combine data from XMM-Newton with those from ESA's Planck mission, to be launched at the end of 2008. Planck will discover thousands of clusters of galaxies. In particular, it will increase the number of known distant clusters by a factor of 100. These far-away clusters can be used as yardsticks to measure the growth of structures in the Universe from the time when it was several billion years younger.

Using XMM-Newton data in combination, it will be possible measure the mass and the temperature of these far-away clusters and compare them with those of nearby 'modern' clusters. By studying how the cluster properties evolve with cosmic time, it will be possible to infer the effects of dark energy on normal matter as the Universe expands. This technique will provide important clues as to what dark energy really is.

XMM-Newton is one of ESA's most successful science missions ever, and while we may look forward to its eventual successor, both scientifically and technically, XMM-Newton has the potential to continue observing and making discoveries in the X-ray sky for at least another decade. The large amount of observing time requested each year and the lively debate in the scientific community show that astronomers worldwide are well aware of this. esa

Explore the XMM-Newton sky in Google Earth:

Astronomical images and spectra taken with XMM-Newton can be displayed in Google Earth.
http://earth.google.com/gallery/kml_entry.html#tXMM-Newton%20Gallery