XMM-Newton In-Orbit Calibration

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Two years after launch of the XMM-Newton Observatory saw a gathering of about 350 scientists at ESTEC for the Conference 'New Visions of the X-ray Universe'. This huge interest in the mission and the rapidly increasing number of scientific papers published as a result of XMM-Newton observations show the importance of ESA's latest observatory for astrophysics in the 21st century.

A vital part of the scientific interpretation that enables this work is the accuracy and reliability of the instrument calibration. To highlight this feature, a session at the Conference was devoted to a Calibration Workshop, allowing the instrument teams to explain the details of the improving knowledge and remaining limitations. This article reflects some of the presentations made in that Workshop, and reviews the general in-orbit calibration activities, explaining some of the complexities involved.

Introduction

We are familiar with the high-resolution, often dramatic, images being produced by astronomical observatories in recent years. While astronomers frequently infer vital information from such images, more detailed diagnostics of temperature, pressure, chemical composition and dynamical state are indispensable for probing the true nature of celestial objects. Spectroscopy is perhaps the major tool for accomplishing these astronomical investigations, and so XMM-Newton was conceived as a mission to exploit X-ray spectroscopy as a tool for probing the conditions in some of the hottest and most extreme environments in the Universe.

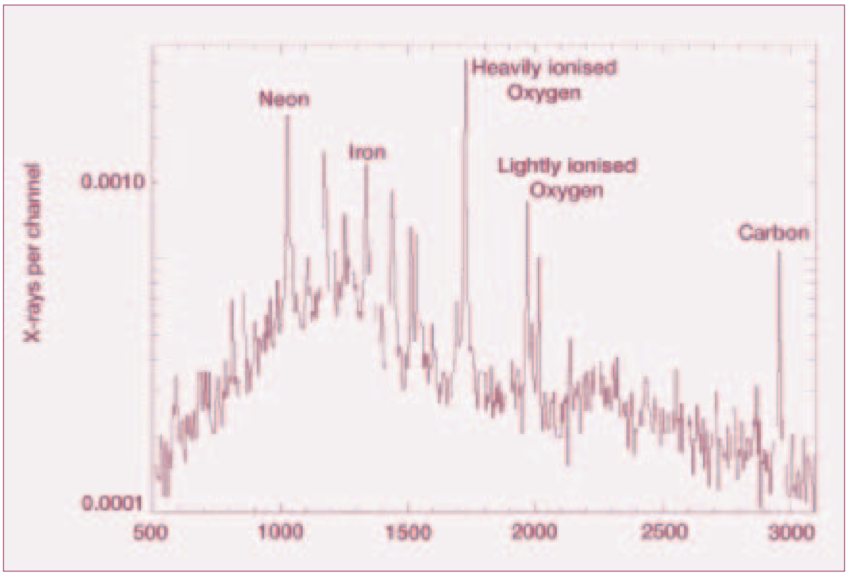


Figure 1. A typical spectrum produced by the XMM-Newton Reflection Grating Spectrometer (RGS) instrument. The horizontal axis is proportional to the energy of incoming X-rays. Strong features have been identified with different states of certain ionised elements in the hot atmosphere of the star being observed

In Figure 1 we highlight how this can be done, with the spectrum detected by the XM-Newton Reflection Grating Spectrometer instrument plotted as intensity versus wavelength. The relative intensities of the different bright features reflect the probability of transition of electrons between different energy states of ionized atoms, and are in turn directly related to the temperature and density of the plasma responsible for the X-ray emission. However, unless we know precisely the relative detection efficiency of the instrument for each wavelength, this diagnostic is lost. This example therefore illustrates the essence of the calibration activity – namely that we must have an accurate description of the instrument parameters and how they affect the recorded data. Moreover, we need to specify for the scientific end-users how reliable this information is.

Cosmic standards

For many years, the community of ground-based astronomers observing in the visible wavelengths of light has used 'spectrophotometric' standards – namely stars with well-known characteristics of light emission in different colours – for calibration activity. Essentially each new instrument or telescope has only to look at a handful of these different standard stars to be able to reference its performance to other instruments, and to the fundamental physics knowledge that is embodied in the simple emission mechanisms of these stars.

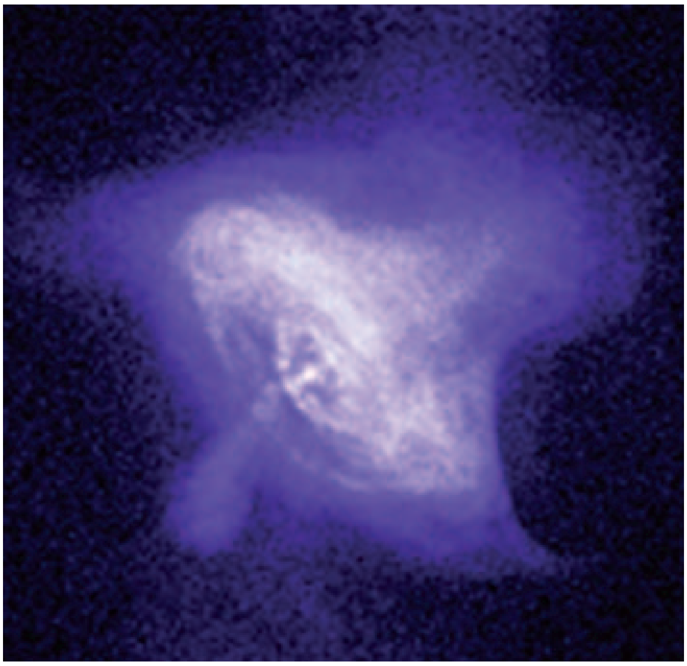


Figure 2. The Crab Nebula seen in visible light (left, courtesy of ESO) and X-rays (right, courtesy of NASA/CXC/SAO). The visible light image traces filaments of hot gas, which are a remnant of the stellar explosion. The X-ray emission comes from electrons spiralling in a strong magnetic field, and therefore the two images trace totally different components of this complex region

In X-ray astronomy, no such 'standard candles' are known. At best, in the 1960's and 70's, which represented the early years of X-ray astronomy's development, most instruments were pointed to the Crab Nebula as part of their calibration activity (Fig. 2). This is about the brightest object in the X-ray sky, and is believed to represent the remnant of a titanic stellar explosion in the year AD 1054. The spectrum of X-radiation given off by the remnant is assumed to have a simple form that decreases with energy by a simple power law. The instrument's response can be cross-checked against this assumption. Nevertheless, the inferred brightness and detailed physics behind these energy characteristics of the Crab have always been a little in doubt.

To compound the problem for modern observatories, their collecting power is now so much more enormous than previous instruments, that generally they are unable to observe the Crab Nebula in normal operating modes, because the brightness exceeds their ability to count the individual X-rays properly! The challenge therefore has been to devise a programme of observations of a wide variety of cosmic sources that is suitable for verifying ground-based measurements of the instruments or substituting for our inability to make representative measurements on the ground, and interpret the data in a manner suitable for science analysis.

Ground limitations

In principle, one could measure all the necessary properties on the ground before launch, but this usually proves difficult, and indeed was not possible for XMM-Newton for a number of diverse reasons:

(a) Lack of time – instrument completion is typically one of the last hardware phases in the mission development, such that waiting for several months for end-to-end calibration of the complete instrument would add a significant and expensive delay to the overall programme. In any case, to collect enough X-rays at representative brightnesses would take a huge amount of time.

(b) Replacement of flight units – late in the hardware delivery programme, a number of flight units had to be replaced due to unexpected failures, and spare detectors were eventually flown which were not calibrated to the depth and accuracy of the former intended flight units.

(c) Parallel beams – X-rays from cosmic sources illuminate the telescope entrance in essentially parallel beams. On the ground, the facilities for creating X-ray beams from tiny high-voltage vacuum tubes are implemented in very long test facilities, which are designed as much as possible to mimic flight conditions. However, even a small diversion of light rays from a point source prevents complete illumination of the entrance aperture.

(d) Changing knowledge – only on completion of the accelerated on-ground measurement programme was the detailed analysis of instrument performance made, and some subtle aspects revealed that with the benefit of hindsight more or different measurements were required to interpret accurately.

Special XMM challenges

XMM-Newton carries the largest-ever focusing X-ray mirrors. This is a key element of its spectroscopic performance, because astronomers need to collect as many photons as possible at all X-ray wavelengths. This inevitably means that any systematic misunderstanding in its collection efficiency becomes evident above statistical fluctuations much sooner than would be the case in smaller observatories.

An additional novel feature of XMM-Newton is the simultaneous operation of all its instruments, pointing to and observing the same patch of sky. Observing an object with different instruments with their very different characteristics can in some senses aid the calibration by providing a crosscheck for each other. On the other hand, the general observer also wants to combine data from the different instruments for his/her own analysis and needs a very secure knowledge that the cross-calibration is reliable. For previous observatories, it was possible ignore cross-calibration difficulties under the assumption that the astronomical target had perhaps varied between different observations.

To maintain the greatest possible flexibility, the XMM-Newton instruments have been provided with different operating modes. For example, the CCD arrays of the EPIC camera can be programmed to read out restricted areas only of the focal plane in order to accommodate very bright objects. These cameras also have different filters that can be deployed in the focus to provide different amounts of visible-light-blocking capability, should the target happen to be a very bright visible magnitude star, which might swamp the X-ray signal, for example. The RGS instrument has the capability to select out a small portion of the spectrum and rapidly read out the data with high time resolution. Nevertheless, each and every operating mode needs to be calibrated with the appropriate accuracy, putting an additional burden on the development of the calibration database.

Early commissioning-phase activities

The spacecraft subsystems were declared to be commissioned in early spring 2000, at which point the long-planned sequence of observations of calibration and performance/verification targets was started. In reality this phase was also used to debug and tune a large range of ground-segment changes. This was necessary partly due to the accelerated launch date, which did not leave time for comprehensive testing of the ground software systems, and partly because of the usual array of unexpected instrument operation details that arise when new detector systems are deployed in orbit for the first time.

Early calibration activity was therefore performed in the context of a hectic cycle of instrument updates, observation re-planning, trouble-shooting the received data files, and updating of software. The modus operandum was generally that the data sets were sent to the hardware teams, who worked out new processing routines and associated calibration quantities, through improved understanding of the physics of the detectors. The ESA Science Operations Centre (SOC) team revised the data file formats, and co-coordinated changes in the science analysis software, which was being continually improved by the members of the Survey Science Consortium and ESA. Their software calls upon Current Calibration Files, which embody the latest calibration knowledge, and which in turn are maintained by the ESA SOC team, who were also responsible for near-real-time planning of updated sequences for the in-orbit operations.

By summer 2000, this hectic pace resulted in a large number of early science results being reported in a special issue of the journal *Astronomy and Astrophysics*. Thereafter the instrument teams and ESA staff started to plan special calibration observations to determine particular facets of the calibration knowledge that had been shown to be lacking by such science analysis. This required careful co-ordination to understand the deficiencies, define a target that would provide the required information, determine the detailed instrument setup needed for the observation, insert the sequences into the mission planning cycle, then on completion of the observation co-ordinate the analysis and interpretation. This planning cycle could be frustratingly long: sometimes the ideal target might be available in an accessible portion of the sky only months after its definition as an imperative observation. Even then, the time taken to understand the results and recode software might be a further impediment to instantaneous improvements.

Now the situation is a little more relaxed, so that we are driven by the requirements of the exciting new science that is enabled by XMM-Newton's amazing capabilities, but which also pushes the requirements for calibration knowledge still further. The ESA team has to respond to the requests from the scientists for further improvements by continuing the cycle of planning and executing the new observations, coordinating analysis and software changes.

In the following paragraphs, we review some of the important instrument parameters that have been explored in the calibration campaign, highlighting some of the complexities involved.

Astrometry

One of the most obvious properties of an astronomical object is its position in the sky. For

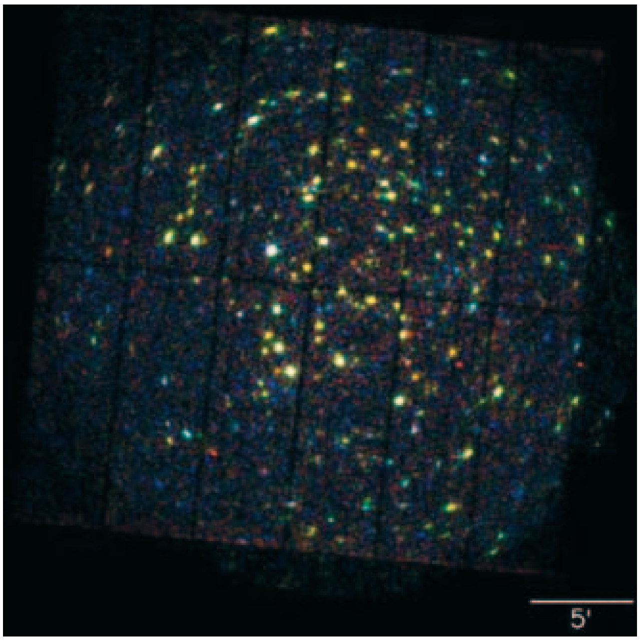


Figure 3. The XMM-Newton view of the stellar cluster known as NGC2516. The colours represent the temperature of detected stars. Yellow and red are probably from the relatively cool (millions of degrees!) stars, but the blue objects are likely to be emission from massive black holes residing in very distant galaxies in the background. The scale bar of 5 arcmin is equivalent to less than 1/5th the diameter of the full Moon

example, when we discover new objects, they are catalogued, so that follow-up at other wavelengths of light can be performed in order to characterise the objects better. Localising the positions with as high an accuracy as possible is important, so that large ground-based telescopes can zoom in to an accurate position without wasting valuable time searching for the correct candidate. In many typical XMM-Newton observations, about 100 objects, many of them never previously detected, might be imaged. The sharpness of XMM-Newton's telescopes, in principle, allows each of these to be centred to a precision of about 1 arcsecond (the width of a 1 Euro coin viewed at a distance of 5 km!). Such performance needs to be matched by the accuracy of the location of the cameras behind the bore sight of the telescopes, the relative location of all the camera readout devices within the camera, the pointing accuracy of the spacecraft star trackers and their relative alignment to the telescopes, etc. This accuracy has now been achieved by observing a number of selected fields containing enough bright point-like objects whose positions were previously known from other catalogues.

Figure 3 shows one of those special fields – a relatively nearby stellar cluster known as NGC2516. While more than 100 stars are precisely located in visible light, their association to the bright X-ray sources is not always secure. Some of the objects in this image may be background galaxies, and some of the true stellar X-ray sources rather dim in the optical. After very careful matching of different catalogues, we have satisfied the requirement of 1 arcsec accuracy. Now this target is observed several times a year to check for potential ageing effects, such as the carbon-fibre tube connecting mirrors to instruments being affected by bending as a result of out-gassing.

Wavelength scale

Identifying the precise energy of any of the bright emission lines of a spectrum can be very important. For example, the energies of different atomic species are precisely known from laboratory measurements, so identifying such features allows astronomers to make a census of atomic diagnostics to be measured. Due to motions within the target or to cosmological recession from our Solar System, the line energy might be changed due to the Doppler effect shifting the X-ray energies to shorter or longer wavelengths. By measuring

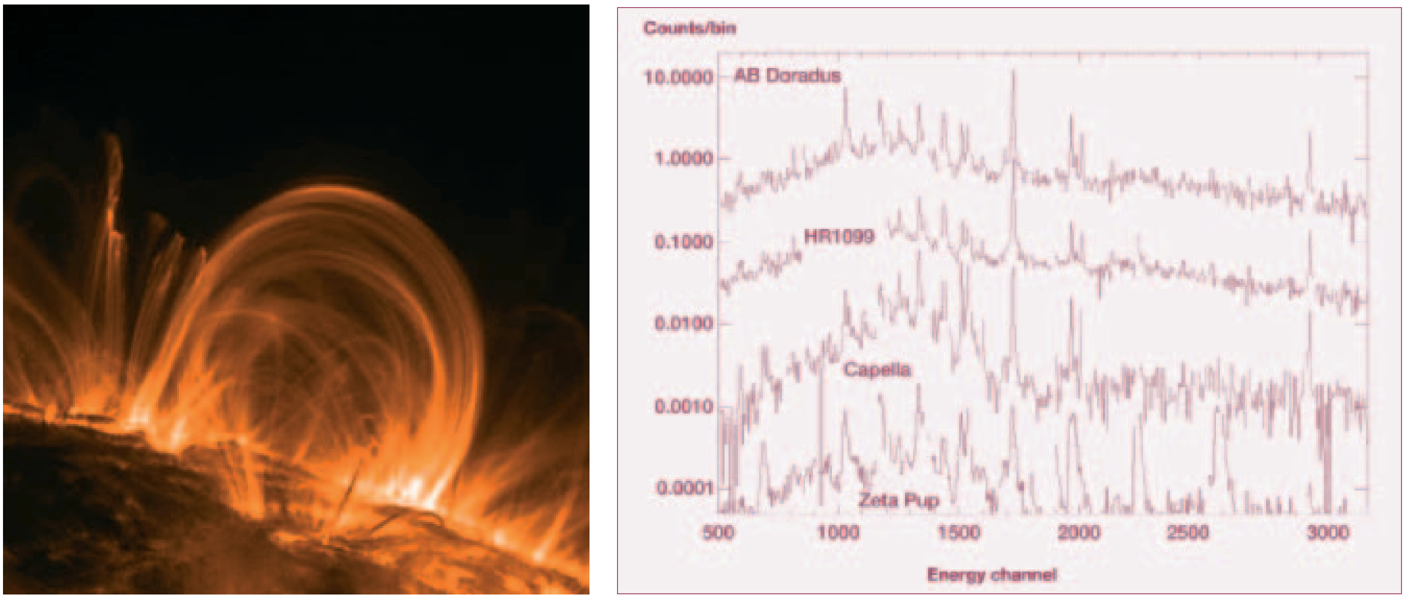


Figure 4. Solar coronal loop image from TRACE (courtesy of M. Aschwanden of Lockheed Martin Solar Astrophysics Lab.). X-ray emission on the Sun traces small flares originating in magnetic loops. We cannot see such structures directly even on the nearest stars, but the X-ray measurements allow us to measure the temperatures, sizes and motions of large active regions on many stars, in order to assess how these flares may differ between stellar types. The XMM-Newton RGS instrument observations of a number of such stars were compared to determine if the wavelength scale was stable (emission features in the right-hand panel stay in the same place)

these shifts precisely, the dynamical state of gas within an object might be measured.

The accurate wavelength scale has been determined by observing a number of well-known bright stars. These have been selected for the presence of very bright emission-line features at well-determined wavelengths.

PSF

The sharpness of images from a telescope is characterised by a parameter called the Point Spread Function, or PSF. Generally, the mirrors of optical observatories are made by accurate grinding and polishing of glass blanks. The same technology was used to fabricate the telescope in the Chandra Observatory, but for XMM-Newton the need to provide a large collecting area precluded launching the necessary equivalent of tons of figured glass. Instead, XMM-Newton's mirrors have been fabricated from thin foils of nickel into the correct shape (Fig. 5), but this inevitably meant that the focusing is not as sharp. It is important to measure this image quality, so that the astronomer can be sure whether an image of an object is truly extended, or if it is an intrinsic property of the mirror focusing. Furthermore, when measuring the amount of X-ray light detected from an object, a circle of interest can be drawn which excludes neighbouring sources, but then it is important to know precisely what fraction of detected light is within the circle.

Calibrating this quantity turns out to be far from trivial. A high signal-to-noise ratio is necessary to make an accurate measurement, but bright objects suffer from an important problem in the EPIC cameras: during the finite readout time (~seconds) of each image frame, more than one X-ray might fall on each picture element (pixel), so that it becomes impossible (for example) to discriminate between a pixel with a single X-ray photon with 2 kilovolts of energy or two photons of 1 kilovolt. In fact, for the brightest targets, the on-board electronics rejects events that are merged together in neighbouring pixels, so that a hole of reduced brightness of valid events is seen at the core of the image – an artefact known as pile-up (Fig. 6). Conversely, using faint sources to avoid pile-up limits the calibration, either through lack of time to build up the necessary image, or because the background of fainter stars confuses the clarity of the wings of the PSF.

To add complexity on top of complexity, the PSF is expected to vary significantly across the field of view and with X-ray energy. While a number of measurements were made to characterise the PSF in orbit, the approach adopted has been to use these to verify metrology measurements made on the mirror shells on the ground, and derive a model for expected performance in space.

Figure 5. Close-up of an XMM-Newton Mirror Module. The 57 gold-coated thin nickel shells are concentrically stacked and fastened to spokes that help the shells maintain their correct positions. The nickel shells are about 1 mm thick, with a separation of about 4 mm between them

Energy redistribution

Naturally, it is important to understand the relationship between the energy of an incoming X-ray and the signal transmitted to the ground. For a variety of reasons some of the photons' energy absorbed by the detector may not be correctly registered: the absorption may be in a partially dead entrance layer; perhaps some of the energy might be lost during the process of transferring the minute electrical signals across the focal plane; or the amplification process adds some noise and uncertainty to the measurement. In order to calibrate this 'response function' we need to observe some X-ray emission with individual features isolated

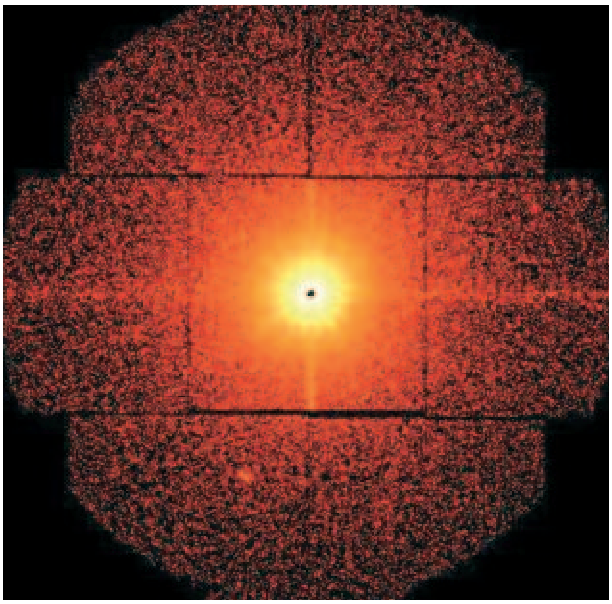
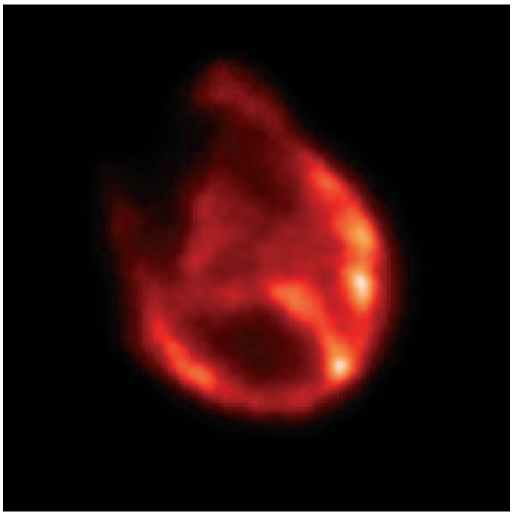


Figure 6. An image from XMM-Newton's EPIC camera, which shows some of the complexity involved in calibrating the mirror Point Spread Function (PSF) when observing a bright target. One of the brightest X-ray objects observed by XMM-Newton, it is probably a binary system comprising a normal low-mass star orbiting either a black hole or neutron star. Due to the piling up of many X-rays at the same position at the very core of the image, the onboard electronics cannot recognise valid signatures in that region and a 'hole' appears in the image. Radiating away from the centre are faint beams caused by the scattering of radiation from the supporting structures seen in Figure 5. Also, the whole image has a faint halo, which is caused by X-rays from the target scattering off interstellar dust grains in space – very interesting to astronomers, but certainly no help to the calibration scientist trying to understand the intrinsic focussing properties of the mirrors



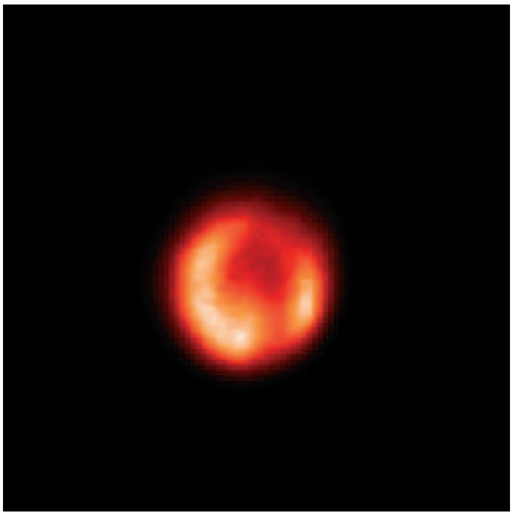
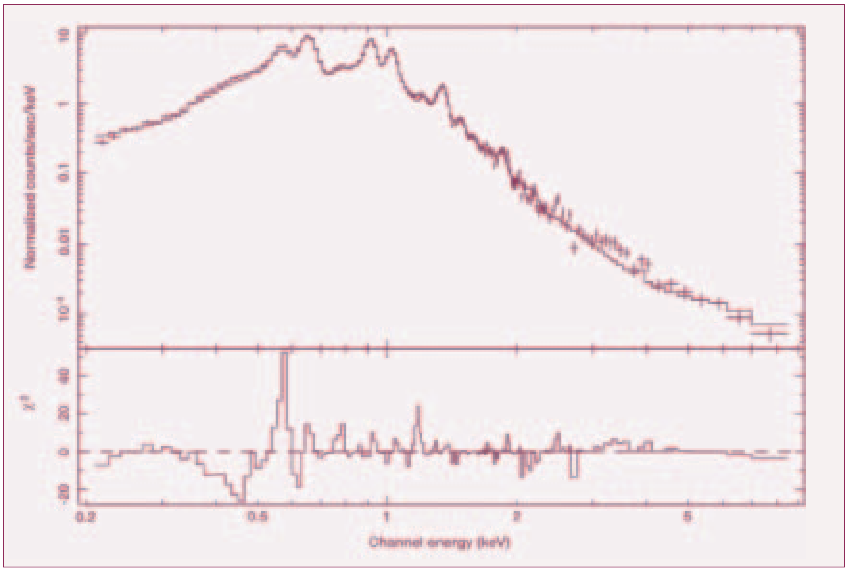


Figure 7. With the powerful imaging capability of XMM-Newton it is possible to view these Super Nova Remnants (SNRs) even in our neighbouring galaxy (100 000 light years away). The panel below shows the spectrum recorded by the EPIC camera and the ratio between a model for this spectrum and the real measured data. This provides a measure of how well the energy response of the camera is known (or more likely in this case how much detailed knowledge of the plasma physics of these remnants remains to be established)



in X-ray energy. Part of this can be done with an internal radioactive source, but it has limited energy range. Therefore, we supplemented the measurement with observations of some bright supernova remnants, with rather different characteristics than the Crab Nebula. In the neighbouring galaxies to the Milky Way, known as the Magellanic Clouds, are two well-known and rather bright remnants in which the X-ray emission is produced by a hot tenuous gas. This gas cools by radiating most of the energy in the form of X-ray lines. Observing these lines provides a very useful method of determining the response across a wide range of the X-ray spectrum.

Background

Not all of the information we need has been derived from deliberately scheduled observations of particular targets, and to minimise the amount of precious observing time spent on calibration the SOC team has made ingenious use of existing data sets, by carefully examining lots of Guest Observer images to extract useful supplementary information. One example is the compilation of data that represents the detector background.

In addition to the required X-ray data of every cosmic field, there is an unwanted and annoying background signal that must be accounted for or subtracted from the desired signal. Often the observer can find a portion of image near his or her target of interest that is apparently devoid of X-ray emitting objects. Any signal in this ‘empty’ region is assumed representative of the background in the image area of the desired target, and can therefore be subtracted out. However, there are many occasions when this procedure cannot be followed, for example when the target of interest covers a large fraction of the field of view.

To facilitate such observations, we have developed a template set of data that contains no bright sources, but also equivalent to a very much longer exposure time than normal observations so that statistical errors will be negligible. Needless to say, with the power of XMM-Newton’s telescopes, no portion of the true sky appears without some sources of reasonable brightness. Therefore, we resorted to selecting a number of ‘deep field’ observations with no obvious central target, removed all data from the brightest objects in each field, and then co-added all the remaining data together, so that the locations with missing data were filled in and faint source locations diluted by the other fields (Fig. 8).

These methods allowed us to save nearly half a million seconds of observing time that would otherwise have been dedicated to special calibration observations, and furthermore produce a quality that is not obtainable under normal conditions. Nevertheless, for these data to be trustworthy, the calibration scientists have to take great pains to establish the effect of

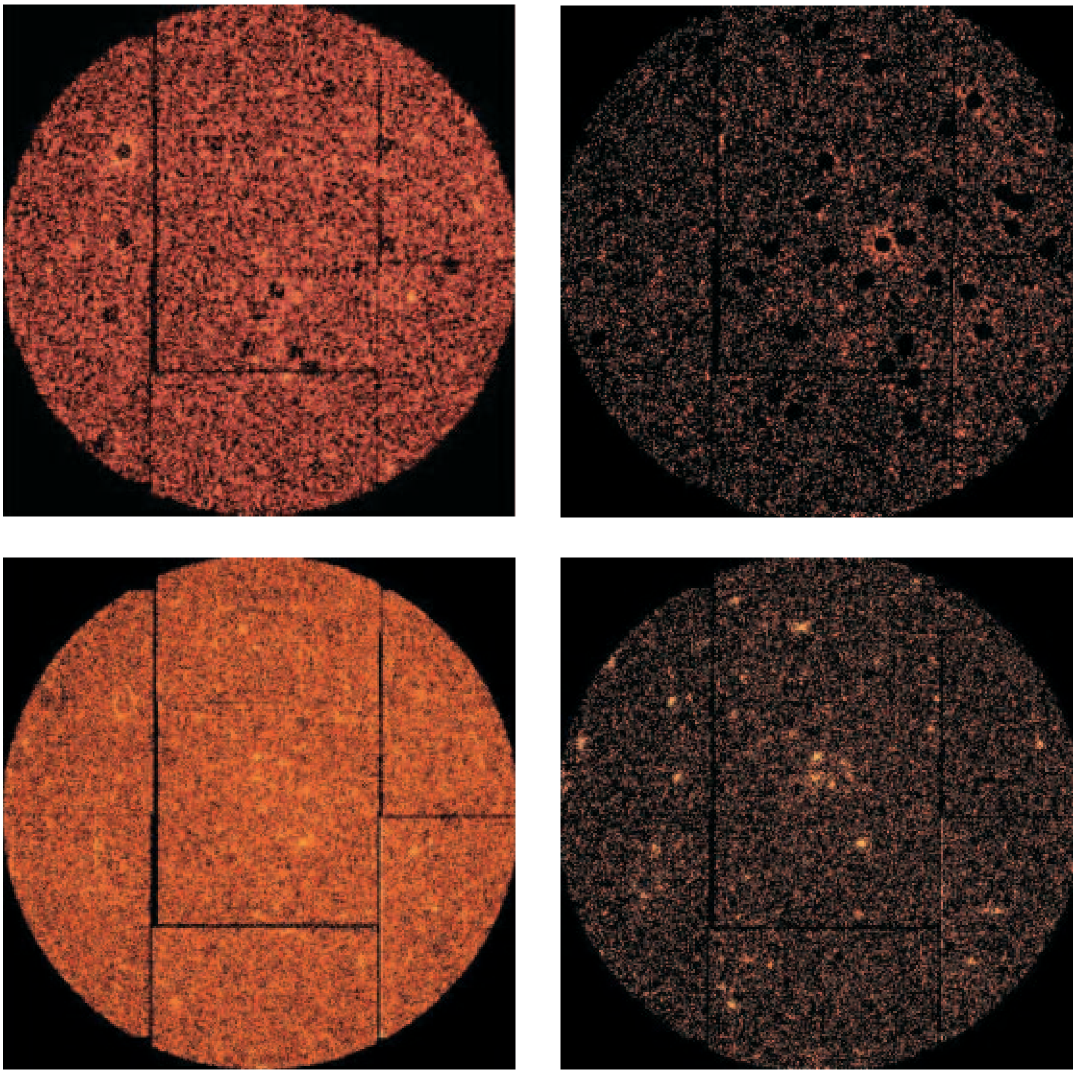


Figure 8. Different fields are combined together to make an artificial star field for background analysis. Clockwise from the top left, three fields from the true sky were selected. In the first two, some holes are just visible where bright sources have been removed. In the third field, some remnant low-level faint sources are still visible, but after adding many such fields together a rather smooth averaged field remains (bottom left)

the various selection criteria on other users' analysis, and provide detailed explanations and caveats or recipes for their use. Otherwise, there is a danger that the average scientist with no detailed knowledge of the instruments may jeopardise his/her analysis with erroneous application.

Conclusion

The status of all these and other calibration measurements were reported at the New Visions conference. Most participants were grateful for the chance to have a thorough review of this existing knowledge. It gave them an up to date snapshot that allowed them to judge whether their scientific interpretations were valid, and to see what areas of concern might need to be accounted for. In most cases, the existing calibration accuracies were shown to match or exceed the specifications laid out by the XMM-Newton Mission Science Team more than six years ago. What became clear, however, is that a number of exciting new science areas that are being enabled by the unique capabilities of XMM-Newton are actually demanding still higher calibration accuracy. Inevitably, this is an on-going process of improving knowledge and development that continually presses the XMM-instrument teams to refine the calibration information year by year, so that this activity will continue with a high priority.

Acknowledgement

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