The Life Cycle of XMM-Newton's 'Targets of Opportunity'

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The term 'Target of Opportunity' (ToO) is used in astronomy to identify unpredictable events whose study is of the highest scientific interest. For XMM-Newton a ToO is an astronomical event observable by its instruments, which cannot be predicted and scheduled on the time scale of one year, yet is scientifically significant enough to justify the interruption of the ongoing observing programme. Here we discuss the kinds of objects that are suitable for observation as ToOs with XMM-Newton, their scientific interest, and how they are incorporated into the overall observing schedule in terms of target selection and mission planning. What has been done so far and the preliminary results for a few ToO examples are then presented.

Introduction

The XMM-Newton (X-ray Multi-mirror Mission) observatory is the second Cornerstone of ESA's Horizons 2000 Scientific Programme. It offers astronomers simultaneous:

- high-throughput non-dispersive spectroscopic imaging
- medium-resolution dispersive spectroscopy
- optical-ultraviolet (UV) imaging and timing from a co-aligned telescope (the Optical Monitor, or OM instrument).

The three European Photon Imaging Cameras (EPICs) provide a large effective area over the energy range from 0.1 to 15 keV. Each of the two modules of the Reflection Grating Spectrometer (RGS) covers the energy range from 0.35 to 2.5 keV. Thus, XMM-Newton provides a unique opportunity for a wide variety of sensitive X-ray observations accompanied by simultaneous optical/UV measurements.

For XMM-Newton, ToO types of interest are Gamma-Ray Bursts (GRBs), supernovae, classical novae, X-ray transient binary stellar systems and X-ray transient Active Galactic Nuclei (AGN). 'Hot topics' in astrophysics, for example newly detected objects that are of high scientific interest, can be awarded discretionary time by the Project Scientist. Some of the scientific issues relating to potential ToO targets are:

- GRBs are extremely energetic events whose nature is still far from being understood. Current models claim either the coalescence of a binary system of compact objects (such as black holes, neutron stars and white dwarfs), or the collapse of a massive star (hypernova). Observational evidence discriminating against the various models should come with measurements of X-ray emission lines. X-ray lines would also provide an estimate of their distance and a diagnostic tool for both the nature of the central engine and its environment, thereby probing the early Universe.
- The X-ray emission from supernova explosions comes from the interaction of the shock wave with the interstellar matter. XMM-Newton observations of supernovae shortly after the expansion should provide spectra to test the models for the different types, and light curves to monitor the interaction between the shock wave and the interstellar matter.
- Classical novae are stellar systems formed by a white dwarf and a giant star, where the mass transfer from the giant to the dwarf generates nuclear explosions in the hydrogen-shell-burning white dwarf. They emit X-rays during outbursts via three different mechanisms: (a) luminous super-soft X-rays by the shell, (b) thermal X-rays (0.5 to 20keV) from shocks in the wind or the interaction between the ejecta and the circumstellar material, and (c) hard X-ray emission due to Compton degradation of radioactive decay, which was predicted but never detected. XMM-Newton observations can be used to understand the properties of the shocked nova shell and the composition of the hard X-ray emission, to detect the supersoft component and to test the theoretical model predictions.
- AGN is a term that refers to very energetic phenomena that occur in the cores of certain galaxies. They are suspected of containing super-massive black holes surrounded by accreting material moving so fast that it

becomes sufficiently hot to produce X-rays. XMM-Newton observations of AGN in either outburst or extremely low state would allow constraining of the physical characteristics of the central engine. Moreover, they will provide tools to separate the emission from the different components (such as the inner relativistic accreting gas or the outer cold material that reprocesses the primary radiation) and to understand the accretion events that trigger an outburst (such as tidal disruption of nearby objects). They could also provide tools to discriminate between the outburst of the AGN itself and the circumnuclear starbursts observed in many AGN.

The routine XMM-Newton mission planning

XMM-Newton as an observatory

XMM-Newton activities are prepared long in advance, with the process starting more than eighteen months before the actual observations are performed. At that time, the ESA Director of Science makes a public call for observing-time proposals and astronomers from all over the world can respond by submitting proposals for observations of carefully selected objects before the specified deadline. All of the proposals are technically evaluated and are then sent to the Observing Time Allocation Committee (OTAC) for independent peer review of their scientific merits. The OTAC selects the proposals, and the observations within a proposal, that should be performed, and assigns them a priority. In addition to this 'Open Time' programme, routine calibration observations are necessary to understand the responses of the instruments.

Based on the OTAC recommendations, it is the task and the responsibility of the Science Operations Centre (SOC), located at ESA's Vilspa facility near Madrid, to ensure that all are 'visited' for the approved time in the safest and most efficient way. Being efficient means minimising idle periods and the time spent making manoeuvres. There are some additional items specific to XMM-Newton:

- Whenever possible, the six on-board instruments should operate in parallel (even if this was not requested).
- The exposures for all instruments should start and end at the same time.
- It may be that for safety reasons some instruments have to remain closed.

Scheduling constraints

The orbit of the XMM-Newton observatory (Fig. 1) is the basis of every planning activity. It is highly elongated, from ca. 7000 km altitude at perigee to 114 000 km at apogee, and it takes almost 48 hours to complete one revolution around the Earth. In the lowest part of the orbit, the platform passes across the Earth's radiation belts, consisting of high-energy atomic particles that extend for about 40 000 km from the Earth. The radiation environment there is so intense that all of the instruments need to remain inactive, and if possible closed, since otherwise they would be seriously damaged. The spacecraft can, however, start manoeuvring to the next target shortly after its perigee passage and it is usually ready to start an observation as soon as the observing conditions for some of the instruments are fulfilled. At an altitude of 46 000 km (about 4 h after perigee passage), the RGS and OM instruments are ready for scientific exposures. Currently, the EPIC instruments are only exposed to the sky after the spacecraft has reached an altitude of about 60 000 km (7 h after perigee). Similarly, at the end of the revolution all the instruments are put into a safe configuration at 46 000 km altitude. This means that during every 48 h orbit, about 37 h are available for uninterrupted observations with the EPIC cameras and about 3 more hours with the RGS and OM detectors.

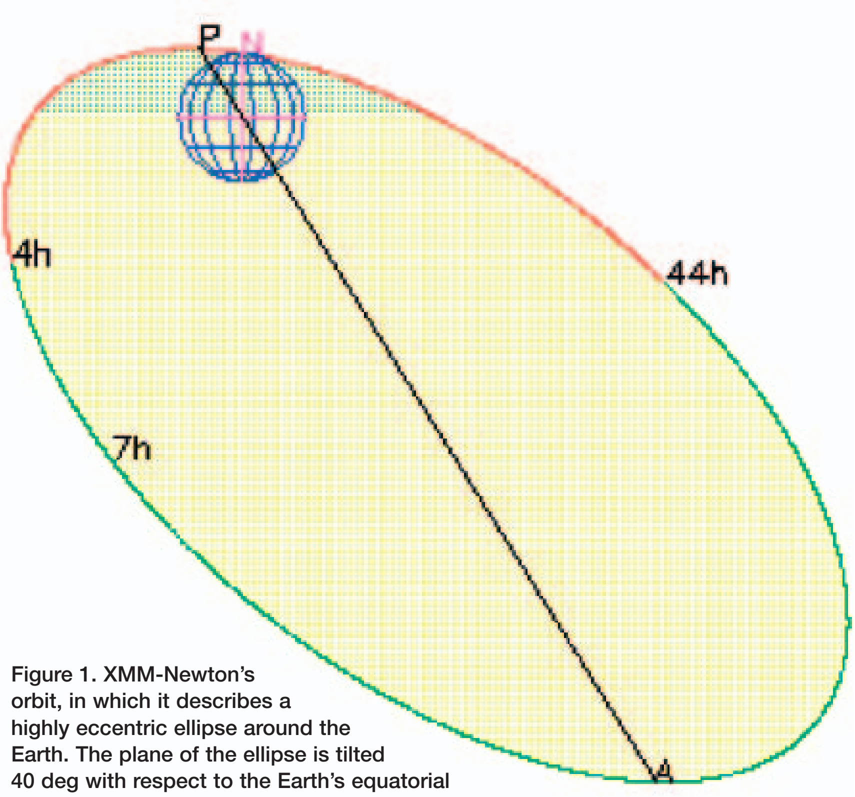


Figure 1. XMM-Newton's orbit, in which it describes a highly eccentric ellipse around the Earth. The plane of the ellipse is tilted 40 deg with respect to the Earth's equatorial plane. The fraction of the orbit that is above the Earth's equatorial plane (i.e. pointing to the North) is shadowed. At its maximum distance, or apogee (point A), the spacecraft reaches an altitude of 114 000 km before returning to its point of closest approach, namely 7000 km at perigee (point P). The duration of one orbit (its period) is very close to 48 h. The figure shows in red the fraction of the orbit that lies within the Earth's radiation belts. The green line shows the part of the orbit that is available for science. The time at which the EPIC observations can start (7 h after perigee passage) is also shown. With the spacecraft moving much faster at perigee than at apogee, this orbit offers the astronomers the possibility of long uninterrupted observations of close to 140 ks

There are more severe restrictions on the observations. The most important ones are related to the pointing constraints and are driven by either the instrument avoidance angles of bright objects, or the spacecraft requirements on the alignment with respect to the Sun, to ensure sufficient energy supply. The spacecraft solar aspect angle is limited to the 70 – 110 deg range. The angles with the Earth's limb and the Moon have to be larger than 47 and 22 deg, respectively. Major planets and Solar System objects have to be avoided for OM observations. In practice, only 34% of the sky is visible to XMM-Newton during a given orbital revolution, and even less at a given time within the revolution. The position of the Sun relative to the stars as seen by XMM-Newton changes during the year (in the same way as it changes for us on Earth!) and most of the sky can be visited for a few weeks only. Figure 2 shows, as an example, the sky that was visible during revolution number 221 (21-22 February 2001). In particular, the Earth's position in the XMM-Newton sky changes during the revolution, following the satellite path along its orbit. Therefore some visible objects

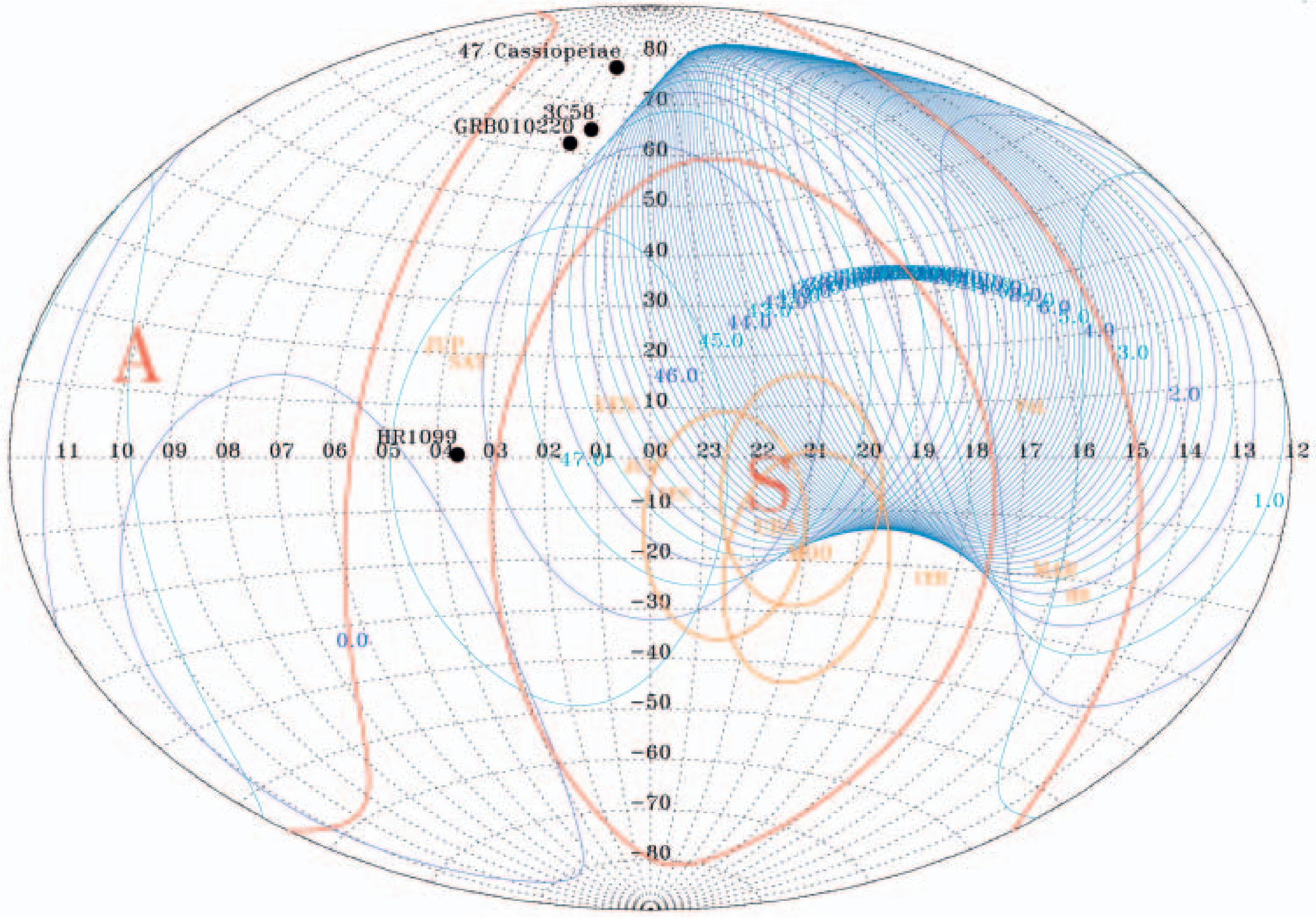


Figure 2. The projection of the sky as seen by XMM-Newton for revolution 221 (21-22 February 2001). The equatorial coordinates are shown in the centre (right ascension in hours goes horizontally, declination in degrees vertically) The Sun, Earth and Moon avoidance regions are shown in red, blue and orange, respectively. The Sun position is marked with an 'S'", the anti-Sun with an 'A'. Different Earth positions are shown and appear as deformed ellipses; the numbers close to the centres of these ellipses indicate elapsed time since the start of the revolution. Though these numbers cannot be read in part of the figure, they are used as an indication of the path followed by the Earth. The concentration of numbers at the top-right of the figure shows where the Earth is at XMM-Newton apogee, when the satellite is moving more slowly. It is also when the Earth's size projected on the sky is smaller, although this is not clearly seen here because of the projection effects. Only three different Moon positions (at the start, middle and end of the revolution) are shown. For this particular revolution, the Moon does not impose additional visibility constraints because it happens to be located in the Sun-avoidance region. However, a few days later when it is a bit higher and to the left (i.e. further to the North/West), it lies just inside the visibility window band. It should be noted that the Moon avoidance angle is larger for the Optical Monitor (OM). The positions of some major planets and asteroids are also indicated in orange. They should be avoided for observations with the OM. This is a revolution that was quickly re-planned to allow a ToO observation. The positions of the scheduled targets and the one that was removed from the schedule are shown. Note that it is just by chance that GRB010220 is very close to the second target in the schedule, 3C 58

are far enough from the Earth, while some others are only visible either at the start or end of the revolution.

Additional constraints are driven by scientific considerations. Examples of this are systems of two stars that should be observed at a given phase of their orbits; also multi-wavelength studies of variable objects that need co-ordination with other satellites or ground-based observatories; or variability monitoring projects that require a specific time lag between consecutive observations within the programme. Approved targets that, because of these different constraints, have short visibility periods are called 'critical targets'. Special care is needed to get all critical targets in the planning within their visibility windows.

Long- and short-term planning

The planning of XMM-Newton observations starts with the identification of all 'critical' objects and the time slots when they can be observed. The optimal date (usually the first possible) for each critical target is then 'reserved' in a long-term plan. The rest of the available time is filled with objects that are close to the critical ones, considering the assigned priorities. An observing plan is made public 3 months in advance, with half of the time left free. The detailed plan is prepared 3 to 4 weeks in advance. The SOC mission-planning group is responsible for the optimisation of the XMM-Newton scientific activities and creates a timeline, which is then passed to the Flight Dynamics group at ESOC in Darmstadt (D). Flight Dynamics checks that all the constraints are considered and introduces additional information for the manoeuvres. The final timeline (the actual telecommands and their execution dates and times) is generated at the Mission Operations Centre (MOC), which is also located at ESOC. The operations team at the SOC takes care of any additional manual commanding that is needed, though this is kept to a minimum to involve almost no significant manual routine intervention. It is therefore a team task that involves most of the groups at the SOC and MOC. The teams work in a close collaboration, which is one of the keys to the success of the entire project. As soon as one revolution is scheduled, the scientists that requested the scheduled observations are informed by electronic mail, and the scheduling details are made public via the XMM-Newton web site at Vilspa. The whole process can take 1 or 2 days for each revolution.

At this point, the nominal planning is complete and no changes would be introduced unless an unforeseen eventuality arises. A ToO alert is, by definition, one such eventuality.

Reception and scheduling of a ToO alert

The scientific value of many ToO observations increases significantly with decreasing reaction time. For example, a delay of 2 h in a GRB observation implies a 10% decrease in the expected flux. The procedure must therefore ensure the shortest possible reaction time for such observations after the request is received.

ToO alerts reach the SOC via the GCN (GRB Coordinates Network) circulars, or through the XMM-Newton SOC web site at Vilspa (which allows every astronomer to propose a ToO observation). Every incoming ToO alert is immediately checked by the SOC instrument operator on shift. There are three pre-defined selection criteria:

- Does the object require immediate reaction, like for example GRBs?
- Is the target visible for XMM-Newton during the current orbit?
- Are the target coordinates sufficiently accurate to allow an observation, i.e. would the target definitely be within the field of view?

If these three questions can be answered positively, then the SOC scientist on call is informed. He or she evaluates in detail the feasibility of the proposed observations (e.g. the earliest time at which the new target could be reached), the impact on the ongoing revolution (e.g. which observation(s) must be substituted), and the scientific expectations (e.g. expected flux and spectra). Based on this evaluation, the Project Scientist, who is always on call, decides whether 'to go' or 'not to go'. If he decides to go, the instrument and spacecraft operators are informed and one expert from the Flight Dynamics group is called at the MOC. The goal is to start the slew to the ToO within 4 h of the alert being received. The whole scheduling process described in the previous section, which under normal conditions requires from one to two and a half days, has to be done in 2 to 3 h.

This can only be achieved because all of those involved work as a team. Many tasks that are performed sequentially during routine scheduling are now done in parallel, or are pre-planned in advance. At the MOC, the flight dynamics are evaluated based on the new coordinates and the approximate starting time of the additional slews. The instrument operators carefully check the possibilities for interrupting ongoing observations and the time needed to swap timelines. The SOC scientist acts as mission planner. The observation of the ToO, i.e. instruments and modes, is prepared. Wherever possible observation templates, which have been prepared in advance, are used. The schedule for the current revolution is opened (without interrupting the ongoing satellite activities). One or more targets are removed from it and the ToO observation is fitted into the available slot. However, during all of this excitement, the security of the spacecraft and its instruments has absolute priority. A schedule generated in 2 to 3 h is not expected to be as optimised as a normally generated one. In this respect, ToOs are expensive, but the expected scientific results certainly justify paying the price.

After reception of the schedule generated at the SOC, the MOC generates the new version of the timeline. Half an hour before the time chosen for swapping the new timeline for the old one, the latter is interrupted and the spacecraft and instrument operators complete the ongoing observation manually. Immediately after the timeline swap, the spacecraft starts the slew to the position for the ToO. As a backup, the Flight Dynamics group and the spacecraft operators are ready to manually command the slew, which allows some flexibility in the procedure.


The XMM spacecraft

Once the slew has been completed and the ToO observation starts, more and more scientists arrive in the operations room. The excitement there increases with each extra minute of accumulated observing time. Do we see the target? Is it well centred in the field of view? Do we see emission lines? Is the target bright enough to get a spectrum in the RGS detectors? These are the questions that pervade the room and lead into the scientific analysis described below.

Example: scheduling GRB010220

An example of a revolution during which one of the two GRBs observed so far with XMM-Newton was targetted is illustrated in Figure 2. The figure shows a projection of the sky for XMM-Newton revolution 221, which started on 21 February 2001 at 6:38 (UT). The original plan for this orbit was to first spend 56 ks on 47 Cassiopeae, then 33 ks on 3C 58, and finally 47 ks on HR 1099. 47 Cassiopeae is an active cool star (a 'solar analogue'), but about 1000 times more luminous in X-rays than the Sun because of the presence of a close companion. 3C 58 is a point-like source at the centre of a supernova remnant, and almost certainly the youngest neutron star ever observed. HR 1099 is another cool star, much brighter in X-rays than 47 Cassiopeae, which is used to calibrate the RGS wavelength scale.

On 21 February at 4:30 (UT), an alert was sent by the X-ray BeppoSax satellite team. A GRB (GRB010220) had been detected on 20 February at 22:51 (UT) and it was visible with XMM-Newton, but the coordinates were only preliminary. A subsequent communication with the refined position reached the Vilspa SOC on the same date at 6:08 (UT). The error box was sufficiently small to fullfil the pre-selection criteria. Therefore, the ToO alert was triggered, the SOC scientist was called, and the Project Scientist approved the GRB observation. At this time, revolution 221 was just starting and so the EPIC cameras could observe about 7 h later (13:38 UT). The goal was therefore to be on target by 13:38 (UT). The requested exposure time was of the order of 40 ks. This was about the EPIC exposure time in the first observation scheduled in the original timeline, which by chance was close to the GRB position. The obvious way to re-plan the revolution was therefore to replace 47 Cassiopeae by GRB010220, leaving the two remaining observations unchanged.

Following the ToO implementation procedure described above, a new timeline was generated. In this case, the manoeuvre to the GRB was manually performed before the timeline swap. The observation was successful and X-ray emission from the GRB, though

already very weak, was detected. The results are outlined below.

Results of some ToO observations

The first XMM-Newton ToO observation was made as early as March 2000, during revolution 44. However, it was just after the end of the 'Commissioning Phase', and there was still some lack of knowledge of the instruments' performance. In addition, the target proved to be weaker than expected.

The next object in the XMM-Newton ToO list was a newly discovered high-redshift quasar, which was awarded discretionary time by the Project Scientist. The results are outlined below. It was followed by observations of a nova detected in the Large Magellanic Cloud (Nova LMC 2000). This nova was discovered on 12 July 2000 and first observed with XMM-Newton on 25 July. It is one example of a 'slow-reaction-time' ToO. Follow-up observations of the nova were requested to monitor its different phases. The third observation was performed on 29 March 2001 and analysis of the data received is still in progress. The first GRB observed with XMM-Newton was GRB001025, on 27 October 2000 at 0h (UT); though weak, X-rays were detected and an International Astronomical Union circular was published with the precise position as measured from the EPIC images. Another GRB and two binary systems have subsequently been observed. More details are given below.

X-ray binary systems

Quite recently, two binary systems have been observed as 'slow-reaction-time' ToO targets. Many X-ray binaries are transient. They are bright only occasionally (once every few months to tens of years) and briefly (between days and months) in comparison to the quiescent state. Such ToO observations enable the study of a wide dynamic range of luminosity states. In the X-ray-faint state, the optical emission is less affected by X-ray irradiation and the companion can be most easily studied, particularly if it is lighter than a few solar masses and intrinsically faint. The cause for the quiescent X-ray emission is not completely understood. Is there a different kind of less energetic accretion present, or does the emission relate more directly to the compact object? In the X-ray-bright state, the high-energy radiation enables detailed study of the compact object and its immediate neighbourhood. Because of the sensitivity of XMM-Newton's instruments, the platform is well-suited for studies at both ends of the flux scale if the X-ray binary is in our Galaxy. At low fluxes, the quiescent emission is easily detected. At high fluxes, X-rays may potentially reveal details about the chemical composition, density and morphology of the accreting matter, and relativistic effects close to the compact object may be detected. Transients in outburst necessarily have to be observed as ToOs, because the outburst times cannot be predicted.

SAX J1711.6-3808 is a new X-ray transient discovered on 8 February 2001 by the BeppoSax satellite and observed by XMM-Newton on 2 March. GRS 1758-258 is a well-known, very bright, black-hole-candidate, micro-quasar in the centre of our Galaxy. Although it is classified as a non-transient system, it suddenly moved into an extremely dim state between 21 and 27 February 2001, as detected by the RossiXTE satellite, providing a unique opportunity to study the low-state X-ray emission. It was observed by XMM-Newton on 22 March. Figures 3 and 4 show the EPIC and RGS images of this bright source; analysis of the observations is still in progress. GRS 1758-258 was observed previously with XMM-Newton, on 19 September 2000. At that time, its spectrum displayed the typical signature of an accretion disc around a black hole and the

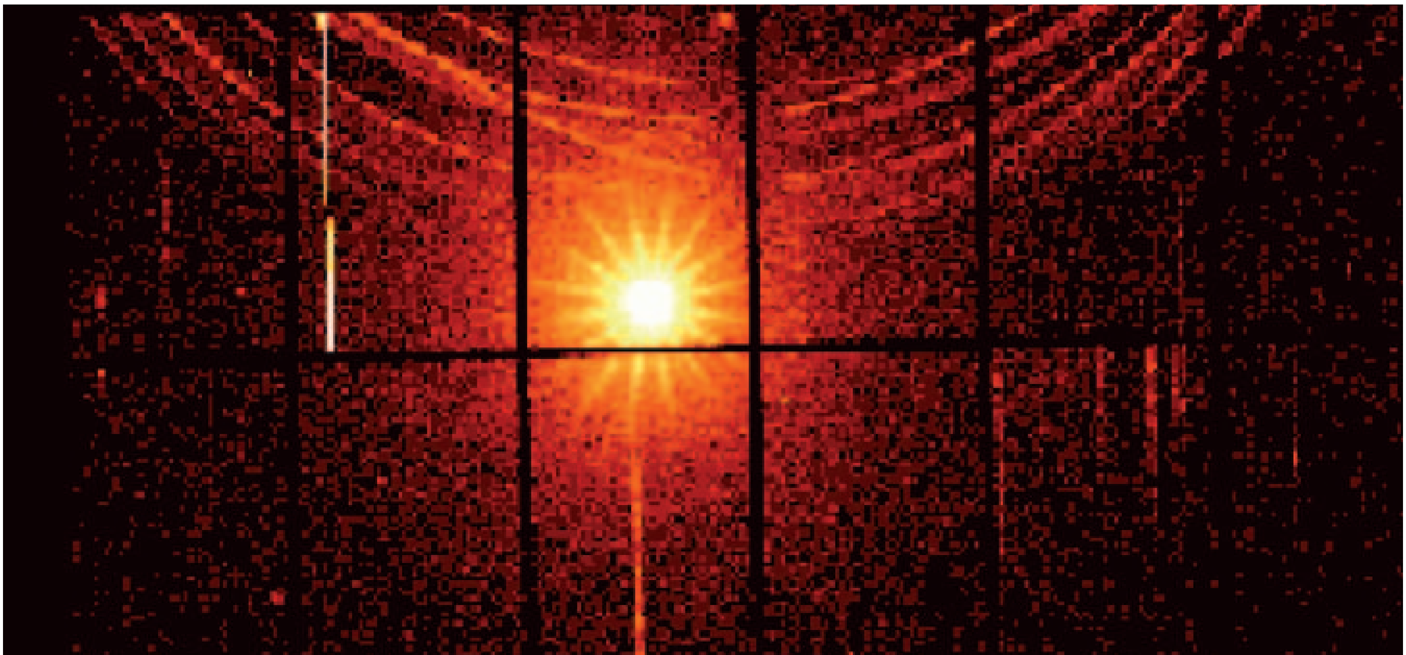


Figure 3. EPIC p-n image of GRS 1758-258. The sharp arcs that appear in the upper part of the image are caused by single mirror reflections of photons, possibly from GX 5-1, which is outside EPIC's field of view

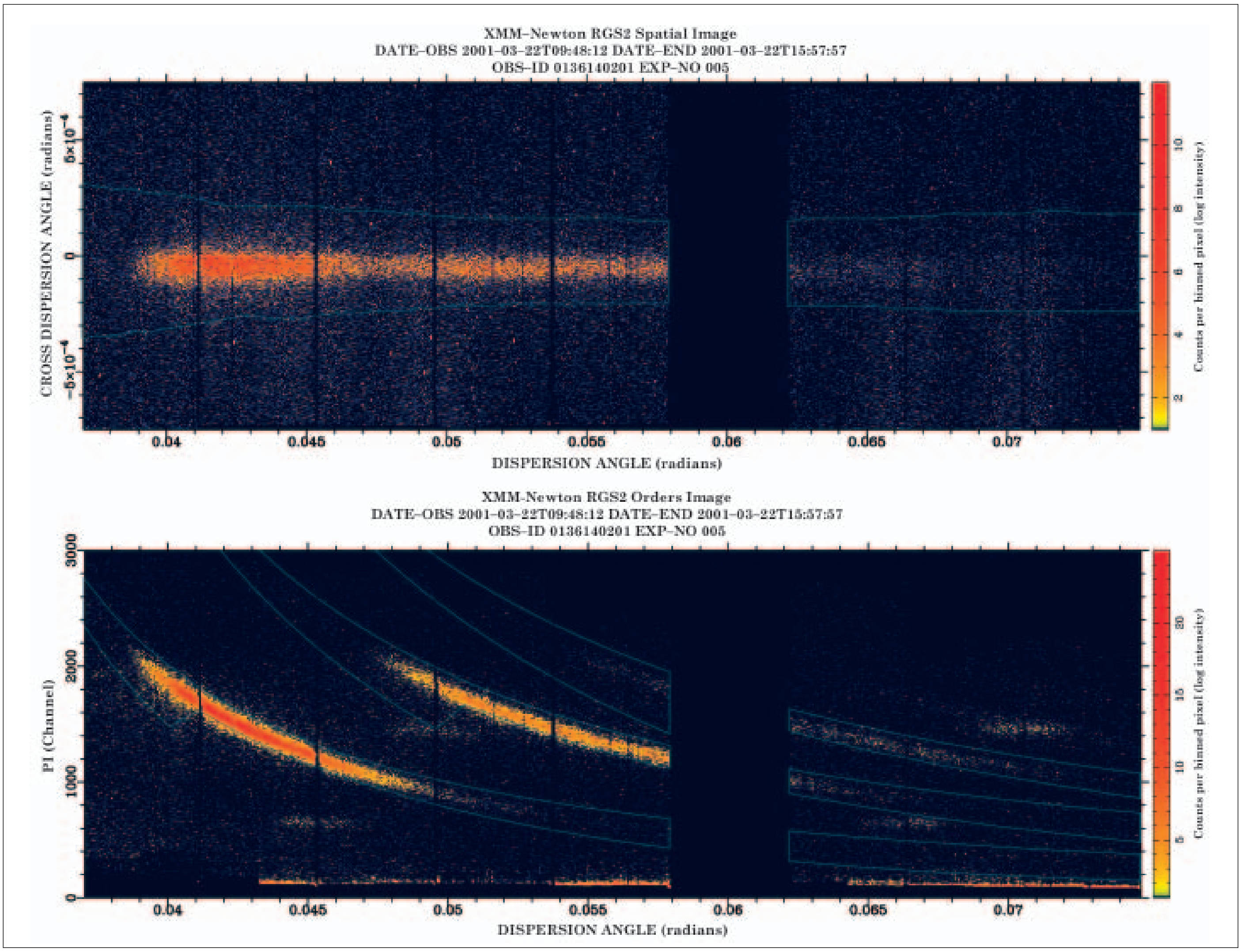


Figure 4. RGS data for GRS 1758-258. The dispersion axis runs horizontally, with shorter wavelengths (higher energies) to the left. The top panel shows the image of the dispersed light on the detector (the spatial, or cross-dispersion direction is along the vertical axis). The bottom panel shows the CCD's intrinsic energy on the ordinates, used to separate photons reflected, in first and second order, from the gratings. The lack of photons at long wavelengths is the result of the high absorption that the GRS 1758-258 photons suffer on their way to the Earth from the centre of the Galaxy

first indications of a transition state (more details are given in the ESA Science web pages). The comparison of the source spectrum in two different states promises even more valuable results.

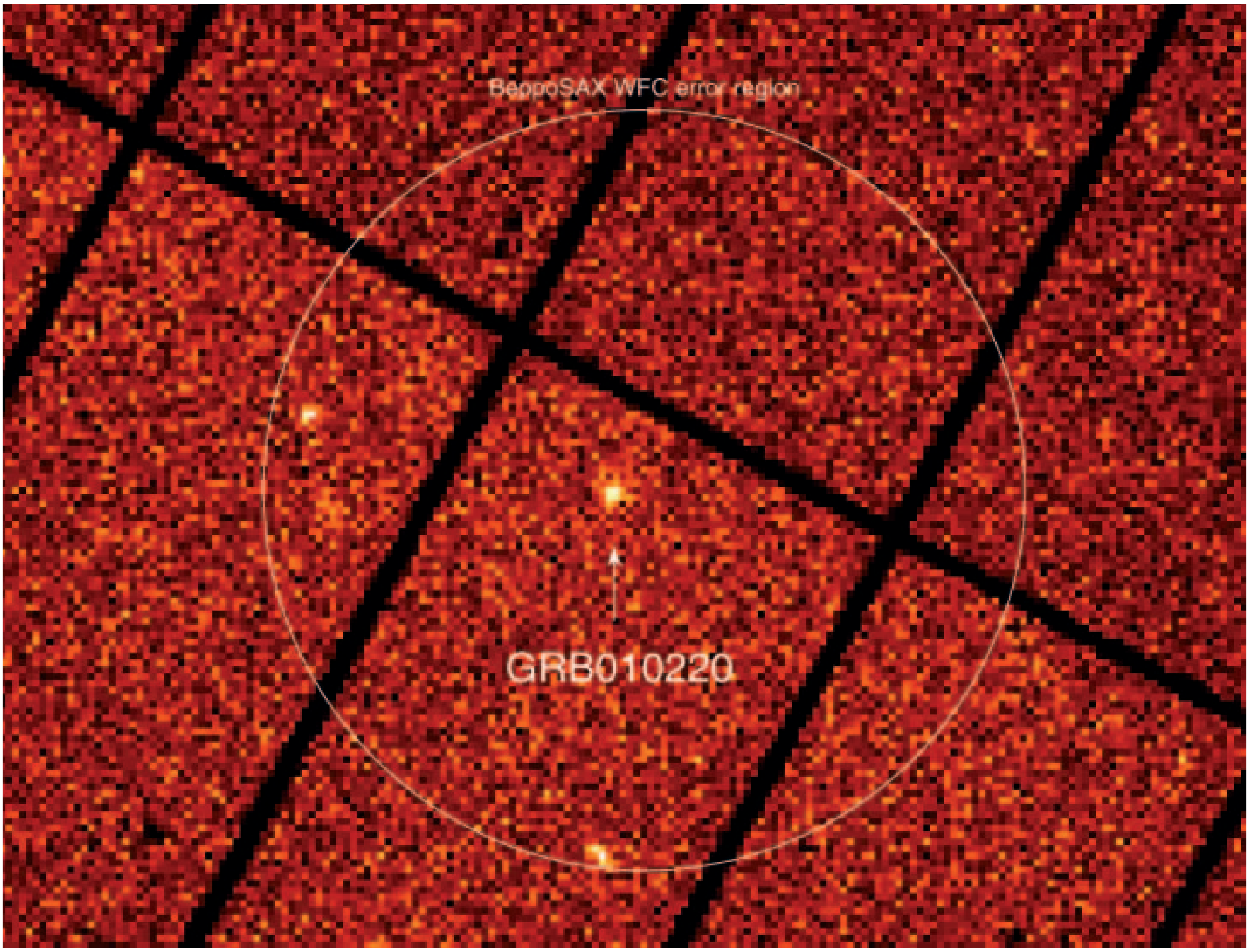
A high-redshift quasar

The most distant known celestial object at the time of observation, the quasar SDSJ1024-0125, was observed by XMM-Newton on 28 May 2000. Discovered in the Sloan Digital Survey, SDSJ1044-0125 has a redshift of z = 5.80, which corresponds to an age of only one million years after the Big Bang. The XMM-Newton observation yielded a statistically significant detection in the EPIC p-n camera in about 32 ks of exposure time. As exciting as the discovery of X-ray sparkles from the farthest reaches of the Universe was for the scientist team, it was also a source of puzzlement. If SDSSJ10.24-0125 would have an optical to X-ray luminosity ratio similar to objects of the same class, the X-ray flux should have been about two orders of magnitude higher. A possible explanation for this unexpected X-ray faintness is significant X-ray absorption. Intriguingly enough, that would fit with the idea that ancient quasars are preferably embedded in dusty environments, possibly due to regions of intense nuclear star formation, which are cleared up during subsequent phases of the quasar evolution. Alternatively, SDSSJ1024-0125 could represent an early stage of the quasar evolution, when the potential well required to produce their immense output energy was still in the process of being formed. The XMM-Newton observation was unable to discriminate between these competing scenarios. Nonetheless, it underlines the ability of the spacecraft's scientific payload to investigate these remote phenomena at the origin of the baryonic age in our Universe.

Gamma-ray bursts

Research in the field of GRBs has undergone an impressive acceleration in recent years. In parallel with the advances in our understanding of these huge explosions in the far Universe, new areas of investigation are being opened by the incoming data. The unprecedented capabilities of XMM-Newton will prove crucial in addressing some of the most important issues in the field. After the distance-scale determination, the study of afterglows of GRBs

Figure 5. EPIC p-n image of the field of GRB010220, the position of which is well within the BeppoSax error region



has allowed a fairly good understanding to be achieved of the radiation mechanisms in terms of a fireball model. There is evidence that at least some GRBs are the result of the explosion of a massive progenitor in a star-forming region. The latter scenario is supported by the discovery of iron lines and edges in the X-ray spectrum of five GRBs. The data are still sparse, and we still have to understand whether those lines are a common feature of GRBs, and whether we are missing them in other events because of a lack of sensitivity or because they fade away shortly after the burst. This is an area in which XMM-Newton's combination of high throughput, high spectral resolution and rapid reaction time can hardly be surpassed by other experiments, provided that a moderately bright afterglow is observed.

So far, XMM-Newton has observed two GRBs (GRB001025, GRB010220), finding a candidate afterglow in both cases, but one too dim for significant search into iron features. Nonetheless, the case of GRB010220 is of particular interest for another feature: the time decay connecting the early X-ray emission, observed by BeppoSax, with the Newton-XMM data point, taken 15 h after the GRB, is very steep – actually one of the steepest ever observed. Such behaviour is usually connected with either a collimated fireball or with an expansion in a very dense medium, typical for example of star-forming regions. Figure 5 shows an EPIC p-n image of this GRB.

Both old and new mysteries wait to be unveiled, and the key observation leading to their solution can be just around the corner. What is the origin of GHOSTs (GRB Hiding Optical Source Transient) or dark GRBs, i.e. events without optical afterglows (but with X-ray afterglows)? If GRBs are indeed associated with massive progenitors and therefore lie in regions of star formation, it is likely that in a large fraction of events the optical emission is heavily absorbed by dust. However, we cannot exclude the possibility that these events are GRBs at $z > 5$, such that optical photons are absorbed by the Lyα forest. BeppoSax has also revealed the existence of another new class of events, the so-called 'X-ray flashes', or 'X-ray-rich GRBs'. In these events, the bulk of the energy is not produced in gamma-rays, but in X-rays. An extremely intriguing possibility is that these phenomena occur in very distant galaxies ($z > 10$). Finally, very little is known about short GRBs, i.e. events lasting less than 1 s, since no counterpart has been so far identified. It is speculated that they may be produced by mergers of two neutron stars, which should result in very short bursts. No counterpart/afterglow has so far been identified at any wavelength for the last two classes of object. Here, the high sensitivity and rapid reaction time of XMM-Newton can be decisive in solving these mysteries.

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