THE XMM-NEWTON SURVEY SCIENCE CENTRE SERENDIPITOUS SKY SURVEY: A PROGRESS REPORT

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Abstract

The XMM-Newton Survey Science Centre (SSC) is carrying out an X-ray sky survey based on the serendipitous content of the XMM-Newton EPIC images. The survey consists of an imaging programme and a core programme where large samples of serendipitous sources, both at high and low galactic latitudes, are identified by means of archival investigation, optical imaging and spectroscopy. Over 100 XMM-Newton target fields have been optically imaged in one or more filters and ~ 350 sources have so far been identified spectroscopically . In this paper we summarize the methodology, show examples of the follow-up data obtained and highlight a few results achieved to date.

Key words: Missions: XMM-Newton – X-rays: general – Galaxies: Active

1. Introduction

After two years of operation, XMM-Newton has proven to be a unique tool to carry out an X-ray serendipitous sky survey. Thanks to its very large collecting area (Jansen et al. 2001), moderate angular resolution and, especially, the large field of view of the EPIC cameras (Turner et al. 2001), XMM-Newton discovers 30-150 serendipitous X-ray sources in every EPIC full-window mode observation. The source content of the XMM-Newton serendipitous sky survey thus grows at a rate of $\sim 50,000$ sources per year of XMM-Newton operations.

One of the tasks of the XMM-Newton Survey Science Centre (SSC)[1] is to develop and carry out an identification and follow-up programme of the X-ray sources serendipitously discovered by XMM-Newton observations (the "XID" programme). An overview of this programme has been presented in Watson et al. (2001). The programme will eventually encompass the full database of XMM-Newton observations but is currently based on public fields and those fields where the Principal Investigator granted permission for the SSC to include the serendipitous content in the corresponding AO proposal. The serendipitous data included is the non-target content of XMM-Newton observations which are searched for sources and compiled to build-up large statistical samples.

The scientific goals of this survey include the detailed characterisation of the dominant X-ray source populations (e.g., AGN luminosity functions, absorption distribution and evolution; distribution of active coronal stars and accreting binaries throughout the Galaxy, etc.) and the discovery of new rare classes of sources. This requires the exploration of large samples of sources, which is possible with the XMM-Newton serendipitous sky survey.

[1] http://xmmssc-www.star.le.ac.uk

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In this paper we present the overall strategy and current status of the XID programme carried out within the SSC. Accompanying papers by Motch et al. (2002) and Della Ceca et al. (2002) discuss in more detail the XID galactic plane survey and the XID high galactic latitude survey at bright fluxes respectively.

2. The SSC identification and follow-up (XID) programme

The large size of the serendipitous sky survey makes it impossible to carry out a full spectroscopic identification of all sources. Instead the XID approach consists of using the X-ray information (source extent, hardness ratios) together with basic optical/infrared imaging information (colours, shape) to predict, in a statistical sense, the nature of the X-ray source. The key feature of this approach is to train this algorithm with significant spectroscopically identified samples of X-ray sources.

In practice this is being achieved by carrying out two distinct (but related) observational programmes: an *imaging programme* (see Sect. 3) aimed at obtaining optical and near-infrared images of XMM-Newton target fields, and a *core programme* (see Sect. 4) where significant samples of X-ray sources will be spectroscopically identified.

The large field of view of the EPIC cameras determines that the only efficient way to carry out the imaging programme is with large format CCD cameras and NIR arrays. The typical exposure time of XMM-Newton scheduled observations ($\sim 25-35$ ks) dictates the depth of the required optical/IR images. With that exposure time, sources as faint as $10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ in the 0.5-4.5 keV band are easily detected in the EPIC cameras with many fields going to significantly lower fluxes. From *ROSAT* experience, these sources will have counterparts $\sim 21^{\mathrm{mag}}$, or fainter if the harder response of XMM-Newton is able to uncover optically obscured objects. Limiting magnitudes $\sim 22-23^{\mathrm{mag}}$ can be reached with 2m-class telescopes (for imaging).

In the core programme, the goal is to identify 3 samples of X-ray sources with ~ 1000 sources each, at flux limits $10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (bright sample), $10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (medium sample) and $10^{-15}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (faint sample). (Fluxes in the high galactic latitude core programme always refer to the 0.5-4.5 keV energy band, where the XMM-Newton + EPIC response is fairly flat and therefore converting from count rates to fluxes does not strongly depend on the spectrum of the sources.) In the galactic plane ($|\ b\ |< 20°$) the strategy is to select a number of fields representative of various galactic longitudes and latitudes, and then follow them up down to a 0.2-12 keV flux of $\sim 5-10\times 10^{-15}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. The reason for selecting the full band is that in this way we do not miss active coronal stars (which have a very soft X-ray spectrum) or other hard X-ray spectrum sources, including extragalactic AGN shining through the galactic plane.

The identification of X-ray sources in the core programme starts with an archival search using the CDS resources at Strasbourg, which produces a significant number of identifications, ranging from a few percent in the medium sample or galactic plane sample to 10-20 per cent in the bright sample.

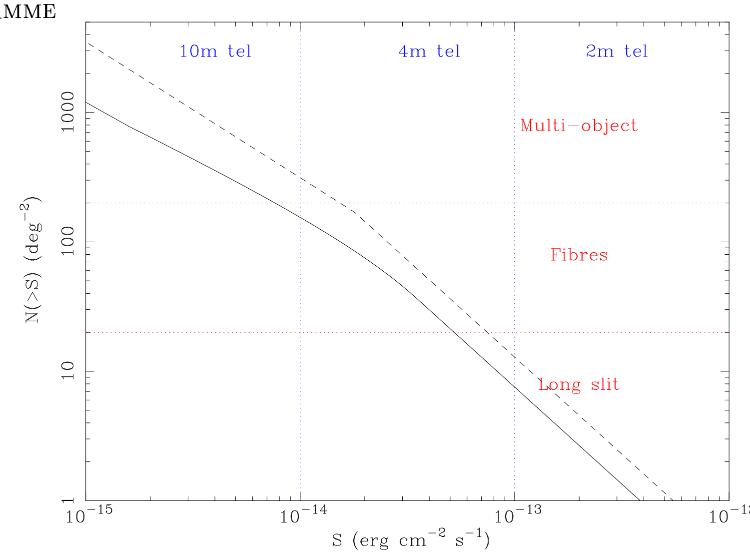

Figure 1. Expected source counts in the $0.5-4.5$ *keV band converted from ROSAT* $0.5-2$ *keV source counts (continuous line, Hasinger et al. 1998), using a photon spectral index of 2 and from the ASCA and Chandra* $2-10$ *keV source counts (dashed line, Ueda et al. 1999, Mushotzky et al. 2000), using a photon spectral index of 1.6*

The sources not previously identified are then observed spectroscopically. Fig. 1 illustrates the size of the telescope and type of spectrograph needed. At low sky density (bright sample), single slit spectrographs are the most efficient, and since many of the sources have a counterpart brighter than $\sim 19^{\mathrm{mag}}$, they can be observed with 2m class telescopes. Indeed there are fainter sources that require 4m class telescope observations. For the high galactic latitude medium sample and the galactic plane sample, the typical magnitude of the counterparts falls to $\sim 21-22^{\mathrm{mag}}$. This fact, coupled to the source density of $\sim 100\,\mathrm{deg^{-2}}$, calls for fibre spectroscopy on 4m class telescopes. Spectroscopic identifications of the faint sample are most efficiently carried out with multi-object spectrographs on 10m-class telescopes. As has already been noted in *ROSAT* deep surveys at faint flux levels, the optical counterparts become not only fainter but redder (Lehmann et al. 2001). This means that at faint fluxes infrared spectroscopy will finally be needed.

Table 1 lists the telescopes and instruments that have been used so far to carry out the XID programme. The vast majority of the nights used have been obtained through

Table 1. Telescopes and instruments used for imaging and spectroscopy in the XID programme.

Observatory	Telescope	Instrument	Use
ORM, La Palma	2.5m INT	WFC	optical imaging
		CIRSI	NIR imaging
	2.6m NOT	ALFOSC	long-slit spectroscopy
	3.5m TNG	DOLORES	long-slit spectroscopy
	4.2m WHT	AF2/WYFFOS	Fibre spectroscopy
		ISIS	long-slit spectroscopy
ESO	2.2m	WFI	optical imaging
Las Campanas	6.5m Magellan	LDSS2	multi-object spectroscopy
Hawaii/NAOJ	8m Subaru	FOCAS	Imaging and multislit spectroscopy

the AXIS[2] programme at the Observatorio del Roque de los Muchachos in the Canary Islands. About 85 nights, spread in the INT, NOT, TNG and WHT telescopes at that observatory have been allocated and used. Other programmes at the same observatory, a large number of nights at the ESO 2.2m telescope in La Silla to further the imaging programme in the southern hemisphere, and a limited number of nights in the Subaru and Magellan telescopes complete the resources we have used so far.

3. The imaging programme: A progress report

A large number of XMM-Newton target fields have been imaged in various optical and near-infrared colours. The full EPIC field (30 arcmin across) is imaged in a single exposure. For the INT imaging a set of filters has been selected to match closely the Sloan Digitized Sky Survey: u(RGO), g'(SDSS), r'(SDSS), i'(SDSS), and Z(Gunn) in the optical, plus the H filter in the infrared. The choice of a filter set close to SDSS filter system is intended to provide a way to apply photometric redshift techniques, at least for these objects where the optical light is not dominated by active nuclei. Galactic plane fields are also imaged in a narrow-band Hα filter in order to single out active objects. In the ESO 2.2m telescope, standard B, V, R, I and Z Johnson filters are used due to the unavailability of Sloan filters at that telescope. Table 2 summarizes the number of fields imaged so far in each band.

Images are inevitably obtained in a range of observing conditions, so some effort is being invested in quality control of these data. Fig. 2 shows the histogram of the seeing in which the INT/WFC images were obtained. The median seeing is around 1.3-1.5 arcsec.

Astrometric calibration of such wide field images is always a challenge, but the telescope distortion has been fairly well parametrized, producing very small residuals across the whole images. Astrometric calibration of the images is performed automatically, either using the APM catalogue or the USNO catalogue (more than 500 matches were typically found). Fig. 3 shows a histogram of the residuals in the astrometric calibration of the images. Except for a few outliers which arise primarily in short exposures of standard star fields for photometric calibration, the astrometry is good to typically 0.3 arcsec. We stress that this accuracy is comparable to the uncertainty in the positions of the stars in the input APM or USNO catalogues, so the calibration does not introduce any additional significant errors.

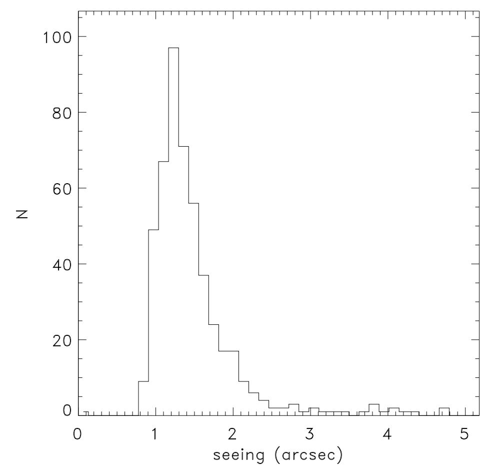

Figure 2. Histogram of seeing in the images obtained at the INT with the WFC instrument in a variety of filters.

To find candidate counterparts of X-ray sources, we typically use the i' (or I) band. The typical depth reached in the images is $i' \sim 22-24$ depending on air mass, moon, seeing, etc. Fig. 4 shows the resulting galaxy counts in an INT WFC optical image of the Lockman Hole region. The image was obtained in dark sky conditions on June 24, 2000 with a seeing of 1.2 arcsec. Although far from optimal, the limiting magnitude exceeds 23.5, almost 2 magnitudes deeper than the SDSS. Fig. 4 also demonstrates that

[2] AXIS: An XMM-Newton International Survey, see http://www.ifca.unican.es/~xray/AXIS

Table 2. Number of XMM-Newton target fields imaged in each filter.

u	B	g'	V	R	r'	I	i'	Z	Hα	H	Total
38	12	64	21	37	81	23	70	60	9	16	107

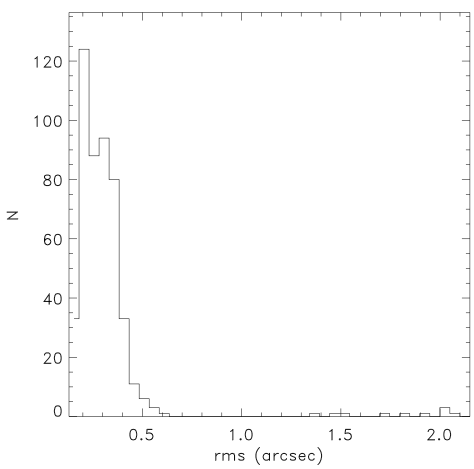

Figure 3. Histogram of rms deviations in the astrometric fit to INT WFC images.

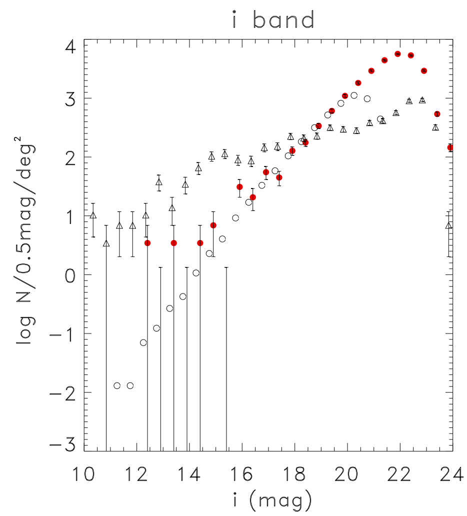

Figure 4. Optical counts in an INT WFC image of the Lockman Hole in the i-band (red points). The triangles represent stellar objects and the hollow circles are from the SDSS galaxy counts.

the photometric calibration is in excellent agreement with the Sloan photometry. A careful examination shows the photometry to be good to better than 0.1^{mag} for the vast majority of fields. A public release of optical images and optical image source catalogues for XMM-Newton target fields in the public archive is planned for early 2002.

4. The core programme: A progress report

Identification of the various core programme samples start by locating candidate counterparts within the X-ray error-circle. Candidate counterparts are normally considered if either the optical source falls within 5 statistical errors in the X-ray source position or within 5 arcsec from the X-ray source. This last value takes into account possible systematic residuals in the astrometric solution of the X-ray data.

The above criteria have proved to be appropriate for medium sample (and indeed the bright sample) work at high galactic latitude: 90 to 95% of the X-ray sources brighter than $2\times10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ have a candidate counterpart, and for about 3/4 of them the candidate is unique. These fractions decrease when approaching the galactic plane: on the one hand some of the X-ray sources are extragalactic shining through significant obscuration and also the star density grows, so multiple candidate counterparts are the rule at $\mid b \mid \sim 0-10°$. We have found that the depth of the optical images is appropriate for the majority of the X-ray sources in a typical XMM-Newton exposure time of $\sim 20-30$ks.

4.1. High galactic latitude identifications

At $\mid b \mid > 20°$ the archival and spectroscopic identification of sources is a highly efficient task as the number of counterparts per X-ray source is 1, most of the time. At the time of writing this paper, we have a total of 308 identifications at various depths. The breakdown is as follows: 176 Broad-Line Active Galactic Nuclei (BLAGNs), which include Seyfert 1s and QSOs; 42 Narrow-Line Emission Galaxies (NELGs), which include Seyfert 2s as well as starburst galaxies; 2 BL Lacs; 20 sources identified with absorption line galaxies (some of which might be clusters); and 68 stars of various classes, a significant fraction of which are Me stars.

Fig. 5 shows the Luminosity-redshift space spanned by the extragalactic sources in this sample. A simple X-ray power-law spectrum with photon index $\Gamma = 1.7$ has been used to apply the K-correction and a cosmological model with $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_{\mathrm{matter}} = 1$ and $\Lambda = 0$ has been assumed.

Two examples of sources identified are shown: a NELG at $z = 0.238$ with 0.5-4.5 keV luminosity $\sim 1.1\times10^{44}\,\mathrm{erg\,s^{-1}}$

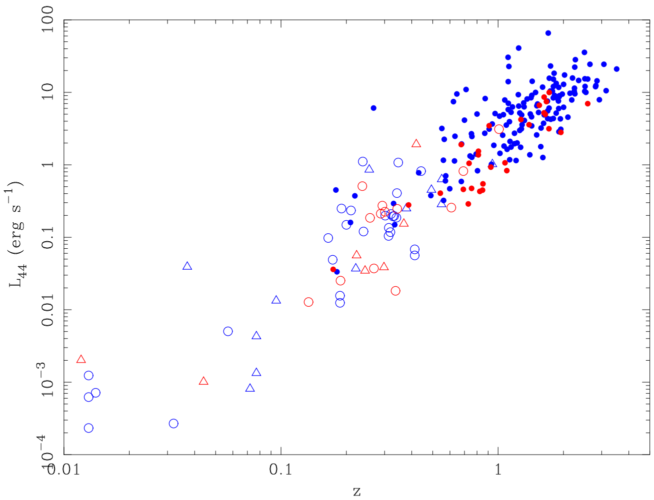

Figure 5. Luminosity-redshift relation for the identified extragalactic sources. Filled circles are BLAGN, empty circles are NELGs and triangles are Galaxies/Clusters. Blue symbols are firm identifications, and red ones have some sort of uncertainty, e.g., uncertain redshift or width of emission lines.

and a high redshift QSO ($z = 3.518$) with luminosity $\sim 2.1 \times 10^{45}\,\mathrm{erg\,s^{-1}}$. The images (i'-band) show the position of the X-ray source with its statistical error circle, and the label A is at the centre of the optical source. Spectra were taken with the AUTOFIB/WYFFOS2 fibre spectrograph in the 4.2m WHT telescope.

4.2. The galactic plane

The number of X-ray sources successfully identified in the galactic plane survey is smaller than at high galactic latitude. The reason is twofold. First, a significant (and maybe dominant even at $b \sim 0°$) fraction of the X-ray sources are expected to be extragalactic, but the optical absorption within the Galactic ISM is large enough to make the counterpart undetectable in our imaging. The second reason that makes X-ray source identification difficult in the Galactic plane is the density of stars, which means that the number of candidate counterparts for each X-ray source is large. The number of spectra that need to be taken in order to ensure a plausible identification is typically 2 or 3 at $b \sim 0°$. Using Hα imaging will help to single out objects with prominent Hα lines, but we find evidence that, as XMM-Newton goes deeper than *ROSAT*, we are finding active stars with weaker Balmer emission lines.

So far the vast majority of sources identified are active coronal stars. Qualitatively, what we find is very similar to the population sampled by *ROSAT*, but more distant. Only one accreting binary (SS397, Motch et al. 2002) has been identified so far. This object is in fact is a good candidate for the long sought after Be+white dwarf accreting binary systems. We refer to Motch et al. (2002) for a more complete account on the status of the galactic plane survey.

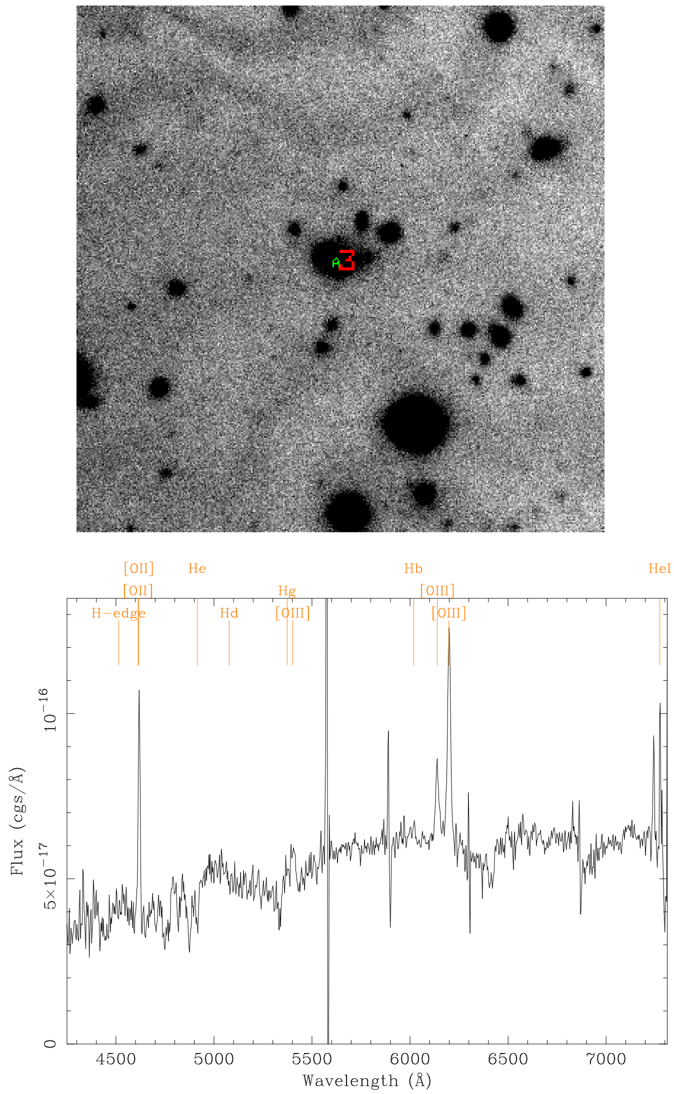

Figure 6. Optical image (i'-band, 2 arcmin length, top is North and left is East) and spectrum of a NELG at $z = 0.238$ with luminosity $\sim 1.1 \times 10^{44}\,\mathrm{erg\,s^{-1}}$.

5. Highlights and future projects

The Bright Serendipitous Survey, with flux limit of $\sim 10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, is discussed in detail in Della Ceca et al. (2002) and we refer to that paper for details. There are several results emerging from the early phases of that study, including the fact that stars have a distinctive X-ray colour $HR_2 = [C(2.0-4.5) - C(0.5-2.0)]/[C(2.0-4.5) + C(0.5-2.0)] < -0.8$. This sample of course grows at a very slow rate ($\sim$1.8 sources per EPIC exposure), so it will still take a considerable time to complete a large sample at this flux limit.

A first small complete compilation of 29 X-ray sources in the Medium Sensitivity Sample, brighter than 2×10^{-14}

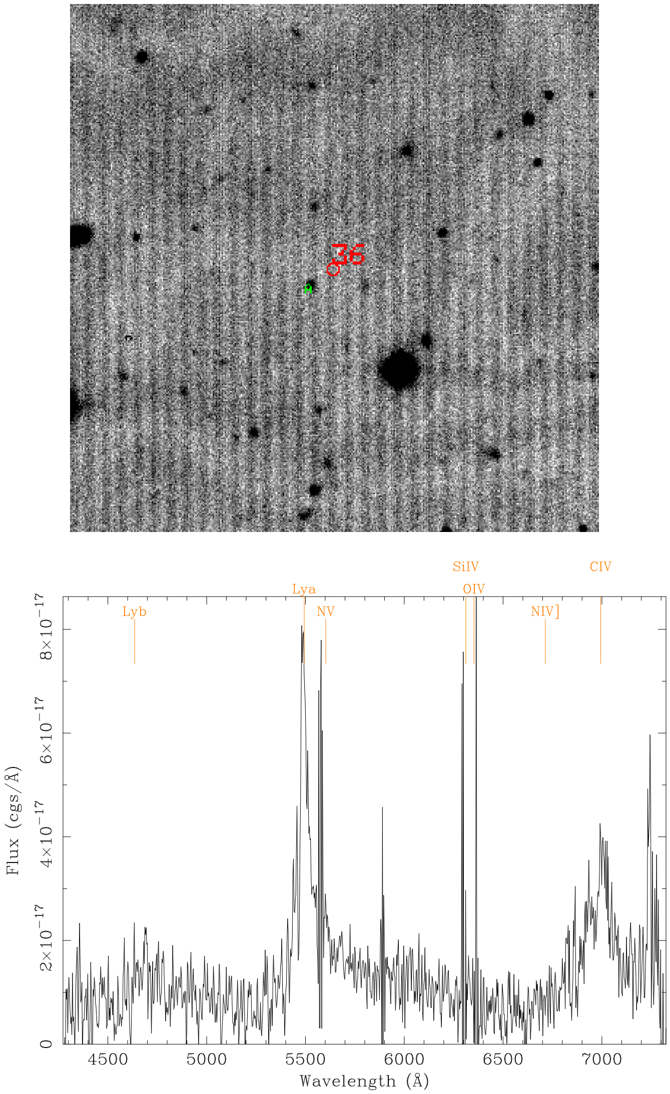

Figure 7. Optical image (i'-band, 2 arcmin length, top is North and left is East) and spectrum of a QSO at $z = 3.518$ with luminosity $\sim 2.1 \times 10^{45}\,\mathrm{erg\,s^{-1}}$.

$\mathrm{erg\,cm^{-2}\,s^{-1}}$ has been presented in Barcons et al. (2002). Among the conclusions of that paper, we found that the spectrum of BLAGNs is steeper at low energies than at the high energy end, going from $\Gamma = 2$ in the *ROSAT* band to $\Gamma = 1.6$ above 2 keV. We also found that NELGs have optical colours similar to those of early type galaxies, but X-ray selected BLAGN almost invariably have similar colours to those from the SDSS optically selected QSOs (Richards et al. 2001). Within the next few months we expect to have an unbiased sample of 100-200 Medium Sensitivity Survey sources, with a very high fraction identified. Combining this with the Bright Sample Survey results we should be able to define the AGN luminosity function and its evolution to $z \sim 2.5 - 3$, both for Broad-Line and Narrow-Line AGN. Reaching higher redshifts and testing whether or not there is a decline in the number density of high-z QSOs will require substantial progress in the identification of Faint Survey sources, work that has just started, mostly with the Subaru telescope.

Broad Absorption Line (BAL) QSOs also deserve a comment. We found 2 of these objects in the complete sample of 29 sources brighter than $2 \times 10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ in 0.26 deg^2, both of them in the same field (separated 5.8 arcmin) and at redshifts $z = 1.82$ and $z = 1.9$. BAL QSOs represent about 10% of the BLAGN in that small sample, in keeping with optically selected BLAGNs. However, BAL QSOs have been elusive as we have expanded the size of the survey. Although we have several other BAL QSO candidates, we have only confirmed one additional candidate at $z = 1.9$. Although we are not dealing with complete samples, it is intriguing that all 3 confirmed BAL QSOs identified so far reside at a very similar redshift. Of course, at $z < 1$ only low ionisation BALs would be found as both the CIV $\lambda\lambda 1548, 1550$ and the CIII] $\lambda 1909$ lines fall below the atmospheric cutoff. But we do find many QSOs with $1 < z < 2.5$ and all 3 BALs lie in a very narrow z range. That will deserve further exploration when we have a larger Medium Sensitivity Survey sample.

Clusters of galaxies deserve special comment. The XMM-Newton Pipeline products do not yet include a check on the extent of the X-ray sources. We have now started a pilot study to detect and identify clusters, using the Magellan telescope for the spectroscopy of the optical candidates. About 1 cluster per EPIC field seems to be present in high galactic latitude XMM-Newton fields. In fact, some of the X-ray sources that we have classified tentatively as "Galaxies" may actually be clusters with a prominent dominant galaxy. Work is in progress to identify a sizeable sample of these objects.

Work is also being started on the multi-band X-ray properties of various classes of objects. The relation between X-ray source populations selected in different energy bands is an important point as noted by the HELLAS2XMM team (see, e.g., Baldi et al. 2001). With the large samples involved here, we are making progress on the definition of bivariate flux distributions (e.g., 2-dimensional source counts in the 0.5-2 and 2-10 keV bands).

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