X-RAY LINE–EMITTING OBJECTS IN XMM–NEWTON OBSERVATIONS: THE TIP OF THE ICEBERG

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Received 2004 September 10; accepted 2004 October 26; published 2004 November 1

ABSTRACT

We present preliminary results from a novel search for X-ray line–emitting objects (XLEOs) in XMM–Newton images. Three sources have been detected in a test-run analysis of 13 XMM–Newton observations. The three objects found are most likely extremely absorbed active galactic nuclei characterized by a column density NHI ∼ 1024 cm−2. Their redshift has been directly determined from the X-ray data, by interpreting the detected emission line as the 6.4 keV Fe line. The measured equivalent width of the X-ray line is, in all three cases, several keV. This pilot study demonstrates the success of our search method and implies that a large sample of XLEOs can be obtained from the public XMM–Newton data archive.

Subject headings: galaxies: active — galaxies: nuclei — surveys — X-rays: galaxies

1. INTRODUCTION

Both active galactic nuclei (AGNs) and clusters of galaxies are known to exhibit, under the right circumstances, a prominent emission line in their spectrum. In the case of AGNs, the strongest line in the 2–10 keV range is the “neutral” Fe Kα line at 6.4 keV (Mushotzky et al. 1993). In “classical” optically type 1 AGNs, where both the continuum and the Fe-emitting region are viewed directly, the equivalent width (EW) of the Fe line is small and typically less than 200 eV (e.g., Nandra & Pounds 1994). On the contrary, in the case of optically type 2 AGNs, the unification scheme predicts that obscuring material (a molecular torus?) near the active nucleus blocks the direct view to the central engine. In these cases, if the “line-emitting” material is exposed to a stronger continuum than the one detected by the observer, we should observe very large EWs (Krolik & Kallman 1987). For example, according to the modeling presented in Levenson et al. (2002), EWs up to 10 keV are expected in the case of the most extreme Compton thick (NHI > 1024 cm−2) deeply buried AGNs.

Furthermore, it is now clear and well established that the classification of galactic nuclei based only on their optical spectrum provides an incomplete description of their nature (e.g., Vignali et al. 1999; Della Ceca et al. 2002; Maiolino et al. 2003) and that X-ray data are fundamental for the recognition and classification of galactic nuclei (see, among others, Severgnini et al. 2003 and references therein). For example, studies of active objects at IR and X-ray wavelengths indicate a concomitant AGN and starburst activity (Fadda et al. 2002), which seems to happen in a high-density medium (NHI > 1024 cm−2) characterized by high dust extinction of the UV optical flux and strong photoelectric absorption of the soft X-rays. For these objects, a detailed investigation around the iron line at 6.4 keV seems to be at the moment the only way to find evidence of the presence of an AGN (see, e.g., Della Ceca et al. 2002). The existence (and the census) of such optically elusive AGNs may have profound implications on the cosmic X-ray background synthesis models as well as on our understanding of the accretion history versus the stellar history of the universe. As already discussed and emphasized by Levenson et al. (2002), the prominent Fe Kα line, which seems to be a very common feature of very obscured AGNs, “can be exploited to find more of them.”

The second class of extragalactic objects known to exhibit a prominent iron line (the “ionized” Fe Kα line at 6.7 keV) in their X-ray spectrum are clusters of galaxies. X-ray–selected cluster surveys in the ROSAT era, based on the source extent (e.g., the ROSAT Deep Cluster Survey [RDCS]; Rosati et al. 1995, 1998) have led to routine identification of clusters out to z = 0.85, with only a few examples at higher redshift (see Rosati et al. 2002 and references therein). The search proposed here has the potential for finding clusters of galaxies up to a redshift of 1.6, thanks to their 6.7 keV ionized Fe Kα line. Indeed, this line is clearly detected in the X-ray spectra of RDCS 1252.9–2927 (Rosati et al. 2004), a massive cluster at z = 1.24. We are aware, however, that since the EW of the Fe line is smaller in clusters of galaxies than in absorbed AGNs, the search for clusters of galaxies through their emission lines could be more difficult and/or less efficient than the search for heavily absorbed AGNs.

The unprecedented combination of high throughput (∼600 cm2 effective area in the ∼2.3–5.0 keV energy band) and high energy and spatial resolution (100 eV FWHM at 3 keV and ≲15′, respectively) offered by the ESA XMM–Newton X-ray telescope (just the one mirror module with the European Photon Imaging Camera [EPIC] pn detector) has convinced us of the possibility of searching the sky in a novel way, to discover weak X-ray sources whose emission is mainly concentrated in line flux. Without a dedicated detection technique, these sources, X-ray line–emitting objects (XLEOs), would be hard or impossible to find because their line emission is usually diluted within the typical broad energy interval of the X-ray images (a few keV). Even when detected also by “standard” techniques, as is the case of the three sources presented in this Letter (the X-ray brightest candidates among those found from the test-run analysis of 13 XMM–Newton images), these sources would remain indistinguishable (unless very bright) from the other thousands of serendipitous sources because of their very limited number of photons. None of the usual diagnostic diagrams (hardness ratios, Fα/Fγ, etc.) have the capability of clearly separating these sources from the multitude of generic serendipitous sources. Even an automated standard X-ray spectral analysis of a huge number of serendipitous sources will probably fail to identify them since the paucity of counts will force a rather large binning over the energy axis.
2. METHOD OF ANALYSIS

The idea is based on the extension to the energy axis of the usual source detection techniques that are typically restricted to the spatial coordinates. The selected energy range (2.3–5.2 keV) implies that the sources discovered will have a redshift in the interval 0.3–1.7, when we consider that the most prominent X-ray line is typically the iron line. The energy range chosen minimizes variations in the effective area (there is a sharp change below ∼2 keV, due to the Au M edge). As a consequence, no strong or sudden variations are expected in the background (cosmic + instrumental + source continuum) across the energy range considered. It will be interesting at some point to extend the line search to the largest possible range so as to sample from “local” to z ∼ 5 objects.

A detailed discussion of the detection algorithm and of its performance will be given in V. Braito et al. (2005, in preparation). In the interest of clarity, we briefly summarize here the basic properties of our search. Each XMM-Newton image (data cube) has been raster-scanned with a three-dimensional detection cell of 50″ × 50″ × 200 eV. The step of the scan is half a cell width, in both the spatial axis and in the energy axis. At each (X, Y)-position, counts in the energy range 2.1–5.4 keV are considered and binned in 200 eV bins. This range is one bin larger, on each side, than the range of interest for the line detection. The background level along the energy axis is then determined, after an iterative process to remove the possible presence of an excess due to a line, with a quadratic fit to the data. For the purpose of line detection, the source continuum, if present, is treated as background. Candidate XLEOs are then flagged if a particular energy bin in the range 2.3–5.2 keV contains a number of counts such that their probability of being a fluctuation of the estimated background level is smaller than ∼10^{-5}.

3. RESULTS FROM THE TEST RUN

We have test-run the above algorithm on a small number of data sets, 13, in order to assess its success rate and to fine-tune the various critical parameters (e.g., cell size in both spatial and energy dimensions, background determination, threshold for XLEO candidate flagging, etc.). Only the EPIC-pn data have been used. We have chosen the XMM-Newton test observations among those at high Galactic latitude, with an exposure time in the range from ∼1.5 × 10^4 s to 4.5 × 10^4 s. Of the candidates found during the test run, we present here the three most significant ones, which are also characterized by the highest continuum. The three candidates were flagged because of the detection of 9 counts in the energy bin 3.7–3.9 keV (1.4 counts expected), 7 counts in the bin 4.5–4.7 keV (0.7 counts expected), and 10 counts in the bin 4.6–4.8 keV (1.2 counts expected), respectively (see inset in Figs. 1a–1c).

With respect to the statistical significance of the lines, we would like to stress the following. In the energy bin where the line is detected, the probability that the excess seen is a random noise fluctuation is 1.6 × 10^{-5}, 8.9 × 10^{-4}, and 5.8 × 10^{-3} for the three sources, respectively. This is computed as the probability of observing 9, 7, and 10 counts (or more) when 1.4, 0.7, and 1.2 counts are expected. However, one should also consider the number of energy bins (14) and of the spatial cells searched. Although we have raster-scanned the whole image (but have ignored cells affected by gaps and edges), in analyzing the preliminary results of our search we conservatively considered here only those XLEO candidates coincident with an X-ray source, unambiguously detected by other
means (i.e., standard XMM Science Analysis System). Indeed, these three sources were independently found by the standard detection algorithm used to produce the 1XMM source catalog (XMM-Newton Serendipitous Source Catalogue, ver. 1.0.1)\(^2\) and are listed there. Thus, given that there are ~600 sources in the set of images used at the brightness level considered, the number of trials is ~14 × 600 and the resulting total number of false detections expected is ~0.1. Furthermore, we can adopt the X-ray positions reported in the 1XMM catalog since they are significantly better than those produced by our algorithm.

For all three sources, we did go back to the XMM-Newton data to extract the broadband spectrum, estimating the background from a nearby, source-free region. Apertures of 20\(^\circ\), 20\(^\circ\), and 25\(^\circ\) radius were used to extract the source counts, and of 23\(^\circ\) (because of the closeness to an intrachip gap), 40\(^\circ\), and 50\(^\circ\) radius for the background counts. When possible (XLEO J153241–082906 and XLEO J220425–015123), data from the MOS detectors were also used in order to maximize the available statistics and have contributed to the determination of the values given in Table 1. In the interest of clarity, however, the MOS data have not been plotted in Figure 1.

Inspection of the distribution of the resulting net counts reveals a rather weak continuum, the possible emission line that prompted the detection, and an excess of counts at high energies. All three sources seem to be characterized by an X-ray spectrum consisting of a two-component model: a “leaky absorbed” power-law continuum plus an emission line. This is typical of absorbed AGNs and thus suggests that these three sources are indeed AGNs. Although this is not the first time that an AGN is recognized as such and classified directly from the X-ray data (e.g., AX J2254+1146; Della Ceca et al. 2000), to our knowledge, it is the first time that this happens beyond the local universe.

In Figures 1a–1c, we report the X-ray spectrum of the three sources and the distribution of the total counts (insets) in the three-dimensional cells, which has led to the line detection. From the position of the emission line, and assuming that it is due to cold Fe at 6.4 keV, it is possible to derive, directly from the X-ray data, the redshift of the sources. The values are reported in Table 1, where the basic X-ray properties of these three sources are summarized. We stress that the values derived should be considered as indicative given the very low statistics involved (the three sources have on the order of 50 net counts each in the EPIC-pn detector). In the fitting procedure, we did not apply Occam’s razor; rather, we have assumed a reasonable model (see above) and determined a set of values that well describe the data. This is why no formal errors are quoted on the derived quantities.

Inspection of deep optical material reveals the presence of one to two candidates consistent (on positional ground) with being the optical counterparts of the X-ray sources. Their magnitudes are in the range 22.0–23.5. Considering, for each X-ray source, the brightest candidate, the resulting log \(F_X/F_{\text{opt}}\) are in the range ~1.2–1.8. These values are typical of absorbed AGNs (see, among others, Fiore et al. 2003 and Della Ceca et al. 2004) and thus further support our proposed identifications. Optical spectroscopy is of course needed to validate these results and has been proposed, together with follow-up XMM-Newton observations.

4. DISCUSSION

The results presented here are very preliminary. We have no doubts about the reality of the sources, and we are confident on the presence of the X-ray emission line in the source spectra. Three objects are too few to derive “general properties.” Also, we still have to determine the complex visibility function of our novel algorithm, the volume investigated for a given line luminosity/EW, the sensitivity of our search as a function of the spectral characteristics of the sources (continuum slope, intrinsic \(N_{\text{H}}\), iron density, etc.), and their redshift. Once this is obtained and a larger sample is assembled, it will be possible to derive volume densities, population properties, and more general conclusions.

This said, and with the caveat of the low statistics and unquantified selection effects, we would like to note a few things:

1. All three objects found are most likely AGNs in, or close to, the Compton thick regime. They have resulted from the analysis of 13 XMM-Newton observations. This initial success rate is very encouraging since quite a large sample can be readily assembled using the hundreds of suitable XMM-Newton observations already available from the ESA archive. If follow-up studies confirm that the three objects found are indeed AGNs absorbed by a column density of \(~10^{24}\) cm\(^{-2}\) and more, then we have a formidable tool to find and study these AGNs.

2. For the brightest XLEOs, characterized by a detectable continuum, it will be often possible to recognize the nature of the object and to determine its redshift directly from the X-ray data, especially in cases like the ones reported here of absorbed AGNs.

3. The redshifts of the three objects found (0.64, 0.45, 0.42) are in the middle to low part of our window (0.3 ≤ \(z\) ≤ 1.7). To understand whether this is primarily due to selection effects or whether it reflects an intrinsic distribution requires a detailed mapping of the visibility function of our algorithm.

4. No cluster has been found in this test run. It is not clear at this point whether this result is meaningful. A space density

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\(^2\) See http://xmmssc-www.star.le.ac.uk/newpages/xcat_public.html.
of $\sim 15$–20 clusters per square degree (with $z > 0.3$) and with an X-ray flux greater than $8 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ (0.5–4.0 keV) has been reported (S. Andreon 2004, private communication). It is not obvious, however, how this limiting flux compares with our detection threshold based on a line contrast; neither is known the fraction of clusters with a prominent (detectable) emission line. To attack this issue, we plan to run our algorithm on a number of XMM-Newton observations known to contain high-redshift clusters of galaxies.

To conclude, prompted by the power of the XMM-Newton mirror module plus the EPIC-pn detector, we have developed a novel algorithm to search X-ray data cubes ($X$, $Y$, $E$) for XLEOs. A test run on a dozen XMM-Newton observations has proven this search extremely successful, yielding the discovery of three sources, most likely highly absorbed AGNs ($N_{\text{H}} > 10^{24}$ cm$^{-2}$), and allowing a crude, but direct, determination of their redshift from the detected X-ray line. If these findings are confirmed by a more extensive analysis and by follow-up studies of the candidate objects, we have unlocked the doors to the long-sought large sample of highly absorbed, Compton thick AGNs, a key to the cosmic X-ray background synthesis models. Also, it is possible that other rarer objects will be detected, as the volume searched increases.

The idea of searching for line-emitting objects in X-ray images dates back to 1993, when one of us (T. M.), during a conference by Professor Y. Tanaka, was impressed by the quality of the X-ray spectra provided by the ASCA Solid-State Imaging Spectrometer, the first large field-of-view, solid-state, X-ray detector flown. Unfortunately, ASCA lacked the throughput and the angular resolution necessary to make the search for XLEOs feasible, and we had to wait for about 10 years to convert the idea into a successful experiment. We thank S. Andreon, L. Maraschi, and A. Wolter for useful suggestions and stimulating discussions. P. S. acknowledges a research fellowship from the Istituto Nazionale di Astrofisica (INAF).

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