The nature of the ASCA/INTEGRAL source AX J183039–1002: a new Compton-thick AGN?

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ABSTRACT

We report on the identification of the X/soft γ -ray source AX J183039–1002 detected with ASCA and INTEGRAL/IBIS. The source, which has an observed 20–100 keV flux of \( \sim 8.6 \times 10^{-11} \text{ erg cm}^{-2} \text{s}^{-1} \), is inside a diffuse radio supernova remnant (SNR) and is spatially coincident with a compact radio source. We analysed archival Chandra and XMM–Newton observations in order to identify the ASCA/INTEGRAL source. A point-like Chandra X-ray object was found to be positionally coincident with the compact radio source and within the error circle of the ASCA and INTEGRAL sources. Although the association of a compact radio/X-ray source with a radio SNR could be indicative of a pulsar wind nebula (PWN), the XMM–Newton X-ray spectrum is compatible with an absorbed, Seyfert-2 like active galactic nucleus, since it provides evidence for an iron emission line of \( \sim 1 \text{ keV} \) equivalent width; furthermore the X-ray source spectrum is similar to that of other Compton thick AGN where the \( \lesssim 2 \text{ keV} \) data are associated to a warm reflector and the \( \gtrsim 10 \text{ keV} \) one to a cold reflector.

Key words: X-rays: general – X-rays: individual: AX J183039–1002.

1 INTRODUCTION

A key strategic objective of the International Gamma Ray Astrophysics Laboratory (INTEGRAL) mission is a high energy survey of the Galactic plane and Centre (Winkler et al. 2003) in primis and of all the sky as a by-product of pointing observations. This makes use of the unique imaging capability of Imager on Board INTEGRAL Satellite (IBIS; Ubertini et al. 2003), which allows the detection of sources at the mCrab level, with an angular resolution of 12 arcmin and a point source location accuracy of typically 1–3 arcmin within a large (29' × 29' ) field of view. So far, several surveys produced from the IBIS/ISGRI data have been reported, the most complete being those of Bird et al. (2007) and Krivonos et al. (2007); both reported around 400 sources down to a flux level of a few mCrab above \( \sim 20 \text{ keV} \). A significant fraction (25–30 per cent) of the objects in these surveys have no obvious counterpart at other wavelengths and therefore cannot yet be associated with any known class of high energy emitting objects. Searching for counterparts of these new sources is of course a primary objective of the survey work, but it is made very difficult by the relatively large INTEGRAL error boxes. Cross-correlations with catalogues in other wavebands can be used as a useful tool with which to restrict the positional uncertainty of the objects detected by IBIS and therefore to facilitate the identification process. Observations at softer X-ray energies, where the positional accuracy is much better, have already proved an invaluable aid in the identification and classification process (Stephen et al. 2006; Masetti et al. 2008 and references therein), but the use of data at other wavebands, for example the radio, is also useful to help identify peculiar and interesting objects.

In this Letter, we report on the unusual nature of the ASCA/INTEGRAL source AX J183039–1002, located within diffuse radio emission and likely associated to a compact radio source. We use unpublished Chandra and XMM–Newton observations to localize and identify the X-ray counterpart of this high-energy emitter and to characterize its broad-band spectrum. We provide arguments for the identification of this X/gamma-ray source with either a new composite Supernova/PWN system or a background active galactic nucleus (AGN); this second option is however the more convincing on the basis of the source spectral characteristics.

2 THE ASCA/INTEGRAL SOURCE AX J183039–1002

AX J183039–1002 was first reported by Sugizaki et al. (2001) as an unidentified and faint X-ray source detected by ASCA...
during the Galactic plane survey. It was located at RA(J2000) = 18\(^\circ\)30\(^\circ\)39\(^\prime\) and Dec.(J2000) = −10\(^\circ\)02\(^\prime\)42\(\prime\) with a positional uncertainty of ∼3 arcmin. Its soft X-ray spectrum is well described (∝√ν) by an absorbed flat power law with Γ = 0.04\(^\pm\)0.07, N\(_H\) = (3.1\(^\pm\)3.4) \times 10\(^{22}\) cm\(^{-2}\) and an unabsorbed 0.7–10 keV flux of ∼2.3 \times 10\(^{-12}\) erg cm\(^{-2}\) s\(^{-1}\).

AX J183039−1002 was then reported as an IBIS source both by Bird et al. (2007) and Krivonos et al. (2007); here we use data collected in the third IBIS survey (Bird et al. 2007), which consists of all exposures from the beginning of the mission (2002 November) up to 2006 April. The total exposure on this region is ∼1.78 ms. ISGRI images for each available pointing were generated in various energy bands using the ISDC (INTEGRAL Science Data Center) off-line scientific analysis software version 5.1 (OSA 5.1; Goldwurm et al. 2003). The individual images were then combined to produce mosaics of the sky region of interest here to enhance the detection significance using the system described in detail by Bird et al. (2004, 2007). A clear excess is observed in the IBIS map with a positional uncertainty of 4.8 arcmin (90 per cent confidence level).

Our position is compatible with that reported by Krivonos et al. (2007) (note that their 2.1 arcmin error radius corresponds to 68 per cent confidence level). Fig. 1 shows the 20–40 keV image of the region surrounding AX J183039−1002 with superimposed both the INTEGRAL and ASCA error circles. The IBIS/ISGRI spectrum was obtained following usual procedures: fluxes were extracted from the location of the source in 10 narrow energy bands over the 17–100 keV range for all available pointings; a spectral pha file was then made by taking the weighted mean of the light curve obtained in each band. An appropriately rebinned rmf file was also produced from the standard IBIS spectral response file to match the pha file energy bins. Here and in the following, spectral analysis was performed with xspec v.11.3.2 package and errors are quoted at 90 per cent confidence level for one interesting parameter (Δχ\(^2\) = 2.71). A simple power law provides a good fit to the IBIS data (∝√ν) and a photon index Γ = 3.1\(^\pm\)0.9 (much steeper than the ASCA one) combined to an observed 20–100 keV flux of 8.6 \times 10\(^{-11}\) erg cm\(^{-2}\) s\(^{-1}\).

3 RADIO COUNTERPART

The Multi-Array Galactic Plane Imaging Survey (MAGPIS; Helfand et al. 2006) has mapped the region of interest here with a 20 cm sensitivity of 1–2 mJy and detected a compact source surrounded by diffuse extended emission (see Fig. 2 which is a MAGPIS extract). The compact source (G21.6329−0.00682) which is located at RA(J2000) = 18\(^\circ\)30\(^\circ\)38\(\prime\).9 and Dec.(J2000) = −10\(^\circ\)02\(^\prime\)46\(\prime\).4 (5 arcsec uncertainty) has an integrated 20 cm flux density of 5.13 ± 0.26 mJy, and is also detected at 6 cm with an integrated flux density of 1.89 ± 0.18 mJy (White, Becker & Helfand 2005). The diffuse emission (G21.6417+0.0000) around this discrete source has an integrated flux of 1.54 Jy at 20 cm and a diameter of 2.8 arcmin.

Comparison with mid-infrared images obtained with the Midcourse Space Experiment (MSX) (Price et al. 2001) allows us to discriminate between thermal and non-thermal sources: indeed high values of the radio-to-infrared flux ratio (20 cm versus 20 μm, where the source is generally not detected in the MSX) generally indicate non-thermal radio emission such as is produced in a supernova remnant (SNR; see, e.g. Fürst, Reich & Sofue 1987; Green 1989). This evidence together with the morphology of the diffuse radio emission (in this case almost a complete shell structure) and the detection of the source in the 90 cm images, led Helfand and co-workers to propose G21.6417+0.0000 as a high-probability SNR candidate.

The association of a hard X-ray source coincident with a radio point source and surrounded by a very low surface brightness radio shell is suggestive of a situation where a SNR harbours a classic young radio pulsar possibly together with its wind nebula (PWN). A displacement of the compact source with respect to the centre of the shell structure is not unusual, since many pulsars are born with high kick velocities which allow them to propagate through the shocked ejecta in the SNR interior (Gaensler & Slane 2006). Although the distance and age of G21.6417+0.000 are not well known, it is clear from its small angular size that it’s relatively small and young. If the compact source is a PWN, therefore, its offset from the centre of the shell would require an unusually large kick velocity. A way to know if our discrete radio source is a PWN is by means of its radio spectrum, which is expected to have a flat energy index 0.3 ≤ α ≤ 0.1 (defined by S\(_ν\) ∝ ν\(^{-α}\), Chevalier
formed with CIAO v.3.4 and CALDB v.3.2.4 to apply the latest gain sky region containing AX J183039 and from the Log probability should be considerably greater than much larger than 2.8 arcmin, therefore the ‘true’ chance association with an AGN to be about 5 per cent. This probability two objects detected within the

in Table 1.

their positions, detection significance and count rates are reported

we have also compared the
counterpart of AX J183039 1002 is about 2 \times 10^{-2} s^{-1},

of the likely counterpart of source N1 with the compact MAGPIS

image analysis in the 3–10 keV band: within the smaller

The spectrum of source N1 is instead very hard as a simple power-law model provides a flat spectrum ($\Gamma = -0.86$) and an unacceptable fit ($\chi^2/\nu = 87.8/45$). Residuals to this model show some curvature possibly due to intrinsic absorption. Addition of this extra component provides a fit improvement ($\chi^2/\nu = 40/45$), which is significant at the 99.99 per cent confidence level, a steeper spectrum ($\Gamma = 1.01^{+0.57}_{-0.38}$), a column density of $N_H = (11.4^{+3.9}_{-2.8}) \times 10^{22}$ cm$^{-2}$, and an unabsorbed 0.7–10 keV flux of $(3.2^{+4.0}_{-0.8}) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. The Chandra spectrum is compatible within errors with the ASCA one. The spectrum is quite flat (as found previously) and the column density exceeds largely the Galactic $N_H$ value: it points to a source able to emit from a few keV up to $\sim 100$ keV, constant in time and, as underlined before, able to produce emission also at radio frequencies.

| Source | RA (J2000)$^\dagger$ | Dec. (J2000)$^\dagger$ | S/N | Count Rate$^\ddagger$ |
|--------|----------------------|----------------------|-----|----------------------|
| N1     | 18 30 38.3           | -10 02 47.1          | 27  | 38.90 ± 1.50       |
| N2     | 18 30 37.1           | -10 02 45.4          | 4.7 | 1.25 ± 0.28        |

$^\dagger$1σ uncertainty on Chandra positions is 0.6 arcsec.

$^\ddagger$In units of $10^{-3}$ counts s$^{-1}$ in the 3–10 keV energy band.

4 CHANDRA OBSERVATION

On 2006 February 19, Chandra carried out an observation of the sky region containing AX J183039–1002. Data reduction was performed with CIAO v.3.4 and CALDB v.3.2.4 to apply the latest gain corrections. Subsequent filtering on event grade and exclusion of high background times resulted in a total exposure of 19.2 ks. In order to locate the source of hard X-/gamma-ray emission associated to the ASCA/IBIS object, we concentrate on the Chandra image analysis in the 3–10 keV band: within the smaller ASCA error box we detect two objects above a 3σ detection threshold; their positions, detection significance and count rates are reported in Table 1.

Fig. 3 is a cut-out of the 3–10 keV Chandra image, showing the two objects detected within the ASCA error box, together with the location of the compact MAGPIS radio source G21.63201–0.00682. It is evident from the figure that the Chandra observation further confirms the association of source N1 with the compact MAGPIS radio object and, purely for its brightness, also with the ASCA/IBIS source. The reduced positional uncertainty does not contain any optical/infrared counterpart for this Chandra source in the HEASARC archive and even in the DSS infrared image (see Section 6 for a discussion on the expected optical extinction).

To look for the possible presence of a PWN around source N1, we have also compared the Chandra PSF against that of the source but have found no evidence for it: object N1 is seen as point-like

by Chandra implying that a PWN is not present or, if present, is extremely compact.

The CIAO script psextract was then used to generate the spectrum, with appropriate background and response files, of both source N1 and N2; spectra were extracted using a radius of 5.6 arcsec, while background files were generated using a circular region of radius 100 arcsec. With a count rate of 0.119 counts/frame, the pile-up fraction is insignificant at less than 2 per cent. In all our fitting procedures, we used a Galactic column density, which in the direction of AX J183039–1002 is 1.52 × 10^{22} cm$^{-2}$ (Dickey & Lockman 1990).

The spectrum of source N2 is very soft with very few counts above 3 keV; when compared to the IBIS spectrum we have to assume a cross-calibration constant $\sim 3 \times 10^4$, implying that the extrapolation of the Chandra data predicts an IBIS flux far below that observed, a further indication that this source is not the counterpart of the ASCA/IBIS object.

The spectrum of source N1 is instead very hard as a simple power-law model provides a flat spectrum ($\Gamma = -0.86$) and an unacceptable fit ($\chi^2/\nu = 87.8/45$). Residuals to this model show some curvature possibly due to intrinsic absorption. Addition of this extra component provides a fit improvement ($\chi^2/\nu = 40/45$), which is significant at the 99.99 per cent confidence level, a steeper spectrum ($\Gamma = 1.01^{+0.57}_{-0.38}$), a column density of $N_H = (11.4^{+3.9}_{-2.8}) \times 10^{22}$ cm$^{-2}$, and an unabsorbed 0.7–10 keV flux of $(3.2^{+4.0}_{-0.8}) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$. The Chandra spectrum is compatible within errors with the ASCA one. The spectrum is quite flat (as found previously) and the column density exceeds largely the Galactic $N_H$ value: it points to a source able to emit from a few keV up to $\sim 100$ keV, constant in time and, as underlined before, able to produce emission also at radio frequencies.

5 XMM–NEWTON OBSERVATION

The Chandra N1 source has also been detected during the XMM Galactic plane survey (Hands et al. 2004) as XGPS–I J183038–100248. It is also reported in the 2nd Serendipitous Source Catalogue as 2XMM J183038.2–100246 (Watson et al. 2009; http://xmmssc-www.star.le.ac.uk); the source 0.2–12 keV flux is $\sim 2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (i.e. compatible with the ASCA/Chandra flux), with almost all counts coming from the

Figure 3. Cut-out of the Chandra 3–10 keV band image showing the two objects detected within the ASCA error box, together with the XMM–Newton 1.06 arcsec 1σ uncertainty as well as the location of the compact MAGPIS radio object.
hardest X-ray band (4.5–12 keV), again an indication of a flat 2–10 keV spectrum.

We have then analysed the spectrum of 2XMM J183038.2–100246, using its pipelined and reduced 2XMM catalogue data products available at the HEADAS archive. This observation was performed on 2003 September 13, for a total of 4335 s of exposure time with the EPIC-pn instrument.

The source was constant during the entire observation and its spectrum is poorly described by a simple absorbed power law (\(\chi^2/\nu = 62/19\)), at variance with that obtained by ASCA and Chandra. Excess counts are visible at low energies and around 6.4 keV (Fig. 4). A good description of the data (\(\chi^2/\nu = 12/14\)) is achieved with a model consisting of a blackbody (\(kT = 0.20 \pm 0.02\) keV), an absorbed power law \([N_H = (8.8 \pm 4.0) \times 10^{22} \text{ cm}^{-2}; \Gamma = 0.6 \pm 0.5]\) and an iron K\alpha line. Both these two extra features are required by XMM–Newton data, with a significance of 99.99 per cent for the blackbody component and 99.6 per cent for the line. This line is very little redshifted (\(z \leq 0.08\)) and has an equivalent width (EW) of \(\sim 1\) keV (\(\sigma = 0.4 \pm 0.2\) keV). Considering the errors on the line width and normalization given by the low statistics of the data, the EW could be significantly lower than 1 keV. If present, the broad line may be due to a blend of narrow lines (as often seen in Compton-thick AGNs; e.g. Matt et al. 2004).

Note that Chandra does not clearly detect the line. This is not surprising, since the effective area of ACIS in the Fe-K band is so small.

Finally, we combined the XMM–Newton data with the INTEGRAL one to obtain a broad-band spectrum over the 1–200 keV energy band. The model used to fit the XMM–Newton spectrum gives residuals in the IBIS data suggesting the presence of some curvature or a cut-off above 10 keV, which is immediately obvious also from the comparison between the X- and \(\gamma\)-ray photon indices. To describe the broad-band source spectrum and in view of the low statistical quality of the data, we have therefore replaced the absorbed power-law component with other simple models, like an absorbed broken power law or an absorbed cut-off power law; we have further fixed the cross-calibration constant C between XMM–Newton and IBIS to 1 in view of the non-variability of the source flux in the keV band given by comparing the ASCA, Chandra and XMM–Newton fluxes. We emphasize that the fit does not change considerably leaving C free to vary and in any case the large uncertainty on this parameter reaches as a lower boundary \(C = 1\). The first model gives the same parameters found when using XMM–Newton data alone, a break at 26 ± 5 keV where the hard power law steepens to \(\Gamma > 2.8\) \((\chi^2/\nu = 12/21)\). This fit is shown in Fig. 5. The second model, apart from the other parameters that do not change significantly, has \(\Gamma = 0.0 \pm 0.5\) with a cut-off energy at 14 ± 5 keV \((\chi^2/\nu = 18/22)\).

The two fits are equally acceptable and can be used to describe in a phenomenological way the source spectrum, i.e. a low-energy blackbody together with an absorbed flat power law steepening at around 10–30 keV and a low-redshift iron line.

6 WHAT TYPE OF SOURCE IS AX J183039–1002?

AX J183039–1002 is certainly a broad-band emitter over the 1–100 keV band; it is also a weak and compact radio source sitting inside or behind a possible SNR. No optical source is present within the restricted Chandra error box down to a limiting \(M_v\) magnitude of \(\sim 20–21\); this suggests either that the source is weak or heavily obscured. Outside the Chandra positional uncertainty we find a Deep Near Infrared Survey of the Southern Sky (DENIS) and a Two-Micron All-Sky Survey (2MASS) object at 1.1 and 2.6 arcsec angular distance, respectively. Both have similar near-infrared magnitudes \((J = 15.8\) and \(K = 13)\) and compatible RA and Dec. within the respective positional errors so that they can be assumed to be the same source. While the DENIS position is compatible within errors with the Chandra one, the 2MASS location is too offset from the X-ray one to claim a match; the positional accuracy of the 2MASS catalogue is \(\leq 1\) arcsec, which combined with the Chandra uncertainties provides at most an angular distance of 1.6 arcsec, smaller than the observed one. The mismatch is however not too big and could be explained by a difference in object centroids, due for example to the source shape (as expected in an extended source like a galaxy) or to the source proper motion (as typical of a galactic source). We therefore assume that the DENIS/2MASS source could be the near-infrared counterpart of AX J183039–1002.

The overall morphology of the source suggests two possible scenarios: a PWN associated to the SNR or a background AGN. In the

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1 http://heasarc.gsfc.nasa.gov/W3Browse/xmm-newton/xmmssc.html
first case, the source would be a very unusual pulsar/PWN system from the radio and X-/soft gamma-ray spectral characteristics. For example, the soft X-ray spectral index of a PWN is usually around 1.5–2 (Kargaltsev & Pavlov 2008), softer than the ASCA and Chandra spectra. Furthermore, the photon index $\Gamma > 2.8$ observed in the IBIS band is significantly higher than the usual values for the INTEGRAL PWNe, that cluster around $\Gamma \sim 2.2$ (Dean et al., in preparation). The alternative possibility that we are dealing with a magnetar is disregarded on the basis of the stable 2–10 keV flux over the years and the shape of the high energy emission (typically IBIS sees a hard tail in this type of sources; Kuiper et al. 2006).

In the second, more likely, case, we would deal with a heavily absorbed AGN (a type-2 Seyfert?) with an extremely low exponential cut-off energy. The radio flux and spectral index would be compatible with the range of values found in other INTEGRAL selected AGN, which are almost invariably associated with radio sources (Mushotzky 2004). In this case, the spatial coincidence between a background AGN and a SNR is fortuitous. But the more conclusive evidence for the association with a heavily absorbed AGN comes from the XMM–Newton spectrum, that shows a strong iron line and is reminiscent of a Compton-thick AGN. We have phenomenologically fitted the source spectrum with simple models, like a blackbody and broken power law. From a comparison with other similar sources in the literature (e.g. NGC 1068, Matt et al. 1997; see also Maiolino et al. 1998) we can associate the low-energy blackbody-like component with a warm reflector, and the high-energy component as a cold reflector coming from the inner torus. The ultimate solution to this puzzle will only come from detailed radio observations; hopefully it will not be long before AX J183039−1002 is definitely properly classified. If the heavily absorbed nature of this source is confirmed, this brings to five the number of candidate Compton-thick AGN in the third IBIS catalogue, besides the seven confirmed sources, i.e. about 20 per cent of the total sample of type-2 active galaxies so far detected (Bird et al. 2007).

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