Using the ROSAT catalogue to find counterparts for unidentified objects in the first Fermi/LAT catalogue

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ABSTRACT
There are a total of 1451 gamma-ray emitting objects in the Fermi Large Area Telescope First Source Catalogue. The point source location accuracy of typically a few arcmin has allowed the counterparts for many of these sources to be found at other wavelengths, but even so there are 630 which are described as having no plausible counterpart at 80 per cent confidence. In order to help identify the unknown objects, we have cross-correlated the positions of these sources with the ROSAT All Sky Survey Bright Source Catalogue. In this way, for Fermi sources which have a possible counterpart in soft X-rays, we can use the much smaller ROSAT error box to search for identifications. We find a strong correlation between the two samples and calculate that there are about 60 sources with a ROSAT counterpart. Using the ROSAT error boxes we provide tentative associations for half of them, demonstrate that the majority of these are either blazars or blazar candidates, and give evidence that most belong to the BL Lac class. Given that they are X-ray selected and most are high synchrotron peaked objects, which indicates the presence of high-energy electrons, these sources are also good candidates for TeV emission, and therefore good probes of the extragalactic background light.

Key words: catalogues – surveys – gamma-rays: general.

1 INTRODUCTION

A key strategic objective of the Fermi mission is a survey of the sky at gamma-ray energies, making use of the large area and field of view of the Large Area Telescope (LAT) instrument (Atwood et al. 2009). The telescope allows the detection of sources with an angular resolution of about 0.6 (68 per cent at 1 GeV) and a point source location accuracy (PSLA) varying from around 1 to 6 arcmin, depending on the detection significance. In the first Fermi catalogue (Abdo et al. 2010a), comprising data from the initial 11 months of the science phase of the mission, there are 1451 objects listed, of which 821 have been associated with known sources at other wavelengths. These identified sources comprise both extragalactic and Galactic objects with the former including blazars [flat spectrum radio QSOs (quasi-stellar objects) (FSRQ) or BL Lacs], a few radio galaxies and four normal galaxies, white dwarfs and a few binaries. Some peculiar objects are also found but their associations are less secure. No plausible counterparts have been found for the remaining 630 objects and therefore these cannot yet be associated with any known class of gamma-ray emitting objects. The Fermi/LAT active galactic nuclei (AGN) catalogue (Abdo et al. 2010b, hereafter A1) lowers the confidence limit to 50 per cent for high latitude (|b| > 10°) sources and thereby provides possible counterparts for another 26 of these sources, and for 104 more there are potential associations (‘affiliations’) but with unquantified confidence.

Searching for counterparts of these new high-energy sources is a primary objective of the survey work but it is made very difficult by the large, with respect to other wavelengths, Fermi error boxes. This uncertainty in their locations means that a positional correlation with a known object is usually not enough to identify a Fermi source and instead a multi-wavelength approach, using X-ray, optical and radio data of likely counterparts must be used in order to understand their nature and to evaluate the likelihood of their association with the Fermi detections. Searches for X-ray counterparts are particularly useful in finding a positionally correlated, highly unusual object with the special parameters that might be expected to produce gamma rays. X-ray surveys are well suited for this type of search because they offer three great advantages: (a) they allow a full coverage of the Fermi error box; (b) they provide arcsec location accuracy and (c) they give information in an energy band quite close to that in which Fermi operates. Cross-correlation analysis using X-ray catalogues can therefore be a useful tool with which to

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restrict the positional uncertainty of the objects detected by Fermi and so to facilitate the identification process.

Herein, we report on the strong level of positional correlation between the unassociated Fermi sources and the ROSAT All Sky Survey Bright Source Catalogue leading to evidence for the association of a number of GeV sources with a soft X-ray counterpart, better positions for all correlated objects and hence the possibility of optical follow-up work. We find that most of these associations are with BL Lac or BL Lac candidates.

2 THE CROSS-CORRELATION

The ROSAT all-sky survey was performed in the period 1990 July to 1991 February with the X-ray telescope (XRT) and the Position Sensitive Proportional Counter (Pfeffermann & Briel 1986). The survey mapped 145 060 sources in the soft X-ray band (0.1–2.4 keV) from which the Bright Source Catalogue (RASSBSC-1.4.RXS), containing 18 806 RASS sources having a PSPC count rate larger than 0.05 count s$^{-1}$ and at least 15 source counts, was extracted (Voges et al. 1999). Many of these sources have been identified with objects expected to emit even at high energies, i.e. in the Fermi/LAT regime.

To perform the correlation, instead of using the entire first year Fermi catalogue, we chose to use only those 630 which were listed as unassociated in order to keep the possibility of chance positional coincidences to a minimum. We used the standard statistical technique which has been employed very successfully to help identify sources found in the various INTEGRAL/IBIS surveys (Stephen et al. 2005, 2006, 2010). This consists of simply calculating the number of Fermi sources for which at least one ROSAT counterpart was within a specified distance, out to a distance where all Fermi sources had at least one ROSAT counterpart. To have a control group we create a list of fake ‘anti-Fermi’ sources. For every object in the Fermi list, we make a corresponding source in the fake list with coordinates mirrored in Galactic longitude and latitude (this mirroring was chosen due to the strong Galactic component evident in the LAT distribution), and the same correlation algorithm was then applied between this list and the ROSAT catalogue. Fig. 1(a) shows the results of this process. The lower solid curve is the ‘anti-source’ correlation, while the dashed line is that expected from chance correlations given the number of Fermi objects and the number of ROSAT sources. It is clear that, in this case, the number of correlations can be completely explained by chance. The upper solid curve, however, shows the number of associations for the Fermi unidentified sources, and demonstrates that a strong correlation exists.

Fig. 1(b) shows the difference in the number of associations between the true and fake data sets. The point at which the curve flattens off gives the total number of associations present in the data set, which is around 60. In this analysis we have not used the positional errors of either catalogue, but the shape of the curve should be compatible with the PSLA of Fermi as the uncertainty in the ROSAT position is negligible in comparison. By fitting a series of inverse Gaussians to the data we find the curve to be consistent with a combination of location errors varying between around 1 and 4 arcmin (dashed line in Fig. 1b), consistent with the range in errors quoted for the Fermi sources.

Clearly, even though there are around 60 true associations in the data set, we cannot search for counterparts for them all as we do not know exactly which sources are correctly identified as being correlated. At around 500 arcsec, all we know is that around 60 of the 77 correlations found will be correct. For this reason, we limit the correlation distance to 160 arcsec, where less than two false associations are expected, from a total of 30 sources with possible RASSBSC counterparts. In order to provide a rough estimate of the probability of association we note that the number of false sources is expected to be 1±1. This indicates that, given no other information, the likelihood of any one source being associated correctly is around 74 per cent. If we can assume that the extra information on X-ray source type allows us to assert that we know the identity of one chance alignment (1FGL J0841.4–3558, see below) then this probability will rise to over 90 per cent for any individual source in the list.

3 SEARCHING FOR COUNTERPARTS OF UNIDENTIFIED FERMI SOURCES

For the 30 Fermi sources which have a possible counterpart within 160 arcsec, Table 1 reports the Fermi name, ROSAT coordinates, both instruments’ error box radius as well as the distance of the ROSAT position from that of the Fermi/LAT location. The ROSAT uncertainty provides a smaller error box than Fermi by about an order of magnitude, and so allows an easier search for counterparts; furthermore in many cases XMMSlew (Saxton et al. 2008), XMM serendipitous (Watson et al. 2009) and/or Swift/XRT measurements

1 The Swift/XRT data analysis is performed using the standard procedure (see Landi et al. 2010 for details).
provide an even smaller error box and therefore an unambiguous source identification. In the following we discuss each individual ROSAT source in detail trying to provide when possible an indication of its nature and class (see the last two columns in Table 1). In particular, we use X-ray and radio data from the literature and/or archives to assess the object type and hence its association with the Fermi detection.

Historically, AGN were discovered by radio observations. Radio emission is often a way to recognize active galaxies, except at lower luminosities where star formation in galaxies can also stimulate radio production. Therefore, for bright objects, mere detection in radio provides support for the presence of an active galaxy, although contamination from Galactic sources may come from SNR, pulsars and micro-quasars. In some cases, the radio spectrum, morphology and loudness can help in discriminating between the above possibilities since a compact source with a flat spectrum which is radio loud is often indicative of a blazar-type AGN, i.e. those strongly correlated with emission in the GeV domain. So, while mere radio detection does not imply identification with an AGN, the combination of X (and even more gamma-ray) emission plus association with a loud, compact and flat spectrum radio source provides strong support (augmented if it is located away from the Galactic plane) for the extragalactic nature of an unclassified object and further suggests a blazar classification.

For this study, we inspect radio images taken from the NVSS (NRAO VLA Sky Survey; Condon et al. 1998) and the Sydney University Molonglo Sky Survey (SUMSS; Mauch et al. 2003). All sources which have a radio flux listed in Table 1 have a compact radio structure except for the case of the supernova remnant G043.3−00.2. A flat radio spectrum is often indicative of a blazar-type object: indeed in A1 the overall distribution is consistent with a flat spectral index ($\alpha = 0.08 \pm 0.32$). No difference is found between FSRQs and BL Lacs. Information on the radio spectrum of our sources (see Table 2) can be obtained from Specfind (Vollmer et al. 2010) which is a tool used to cross-identify radio sources in various catalogues on the basis of self-consistent spectral index as well as position. This allows the combination of data at different frequencies and the estimation of the source radio spectrum as $\log(S(\nu)) = a \times \log(\nu) + b$ where $S$ in expressed in Jy and $\nu$ in MHz. Flat spectrum sources are those with $a \geq -0.5$ Only four (1FGL J0137.8+5814, 1FGL J2056.7+4938, 1FGL J2329.2+3755 and 1FGL J1926.8+6153) of the 30 ROSAT sources had information about the spectral slope in the Specfind data base and all were found to have a flat radio spectrum. Indication of a flat spectrum in other sources can be found in the literature (Reich et al. 2000; Ribó et al. 2002; Tsvetysky et al. 2005; Jackson et al. 2007; Mahony et al. 2010a; Landi et al. 2010) or from archival radio data [taken from HEASARC and/or NASA/IPAC Extragalactic Data base (NED)] when available a radio loudness indication is also reported in the discussion of each individual source. The ROSAT flux, calculated in the 0.1–2.4 keV band, has also been estimated and listed in Table 2.

### Table 1. Unidentified Fermi sources with a possible RASSBSC counterpart: ROSAT position, identification and class.

| Fermi name | ROSAT coordinates | Error (arcmin) | ROSAT Fermi Distance (arcmin) | ID (NED) | Class |
|------------|-------------------|----------------|-------------------------------|----------|-------|
| 1FGL J0638.4+3716 | 19 42 46.3+10 33 39.0 | 0.23 | 1.7 | 0.25 | 87GB J194203.4+102612 | BL Lac |
| 1FGL J2146.6+3135 | 21 46 37.3+13 43 55.0 | 0.17 | 2.6 | 1.60 | NVSS J214637+134359 | BL Lac |
| 1FGL J2329.2+3755 | 23 29 14.2+37 54 15.0 | 0.15 | 1.1 | 1.16 | NVSS J232914+375414 | BL Lac |
| 1FGL J0908.8-2828 | 09 08 34.2+28 27 23.0 | 0.28 | 5.8 | 1.42 | 1RXS J090834.2+282723 | ? |

2 The Fermi error is the average of the semimajor and semiminor axes at 68 per cent while the ROSAT error is the 1σ radius.

3 Objects at low Galactic latitude, i.e. within ±10° of the Galactic plane.

| Fermi name | ROSAT coordinates | Error (arcmin) | ROSAT Fermi Distance (arcmin) | ID (NED) | Class |
|------------|-------------------|----------------|-------------------------------|----------|-------|
| 1FGL J0051.4-6241 | 00 51 17.7-62 41 54.0 | 0.20 | 2.5 | 1.43 | RBS 119 | BL Lac |

2 The Fermi error is the average of the semimajor and semiminor axes at 68 per cent while the ROSAT error is the 1σ radius.

3 Objects at low Galactic latitude, i.e. within ±10° of the Galactic plane.
### 4 THE INDIVIDUAL SOURCES

In the following, we provide detailed information on each individual source as available in the literature and in various archives, in the same order as in the tables (by correlation distance).

**1FGL J1942.7+1033.** This *ROSAT* source is identified with a radio object having very similar flux at 20 and 6 cm (around 100 mJy) and so is likely to be a flat spectrum source (Tsarevsky et al. 2005). The optical spectrum is featureless, which when combined with the detection at radio and X-ray frequencies, suggests that it is probably a new BL Lac type object located behind the plane of the Galaxy, and it is classified as such in NED.

**1FGL J1307.6–4259.** This X-ray emitter is still unidentified. The only secure radio detection is at 36 cm with a flux of 36 mJy; however it is possible that PMN J1307–4259 at a distance of 0.34 arcmin is also a radio counterpart of 1RXS J130737.8–425940 in which case its radio flux at around 6 cm is 53 mJy (Griffith & Wright 1993), again indicative of a flat spectrum source. The source location above the Galactic plane, its radio and X-ray emission all suggest that this is most likely an AGN; indeed it is listed as an affiliated source in the *Fermi* first AGN catalogue with an HSP SED class and hence could be a BL Lac candidate.

**1FGL J0648.8+1516.** This *ROSAT* detection is also reported in the first *XMM–Newton* slew survey catalogue as XMMSL1 J064847.6+151626; the smaller XMMSlew error box allows the unambiguous identification of this (and the *ROSAT*) source with the galaxy 2MASX J06484763+1516248 which is still unclassified in NED. This galaxy is radio detected at 6 and 20 cm with a flux of 67 and 64 mJy (see NED photometric data base) and has a flat radio spectrum (Mahony et al. 2010a); the source was also reported as a radio-loud AGN first by Brinkman et al. (1997) and later by Laurent-Muehleisen et al. (1997). The 0.2–12 keV flux is 6.5 × 10⁻¹² erg cm⁻² s⁻¹. Recently, the source has been observed with VERITAS and found to be a source of very high energy photons (Ong & Paneque 2010). There are four *Swift*/XRT observations of this source: the spectrum from each can be fitted with an absorbed power law with purely Galactic $N_H$ giving a photon index which...
ranges from 2.15 to 2.78 (typical error ±0.1). The 0.2–12 keV flux also varies within a wide range (2.16–0.76 × 10 −11 erg cm −2 s −1). All these properties suggest that the X-ray source is the likely extragalactic counterpart of the Fermi object, probably a blazar at low Galactic latitudes.

1FGL J1353.6–6640. This source also has a counterpart in the XMMSlew catalogue (XMMSL1 J135340.5–663958) which provides a restricted error box, a secure identification with VASC J1353–66 and a 0.2–12 keV flux of 3.9 × 10 −12 erg cm −2 s −1. Tsarevsky et al. (2005) report that this source has a featureless optical spectrum and a flat radio spectrum which together with the detected X-ray and radio emission leads these authors to suggest that it is probably a new BL Lac type object behind our galaxy despite the marginal detection of a small proper motion.

1FGL J0137.8+5814. The ROSAT position is compatible with an XMM source (2XM J013750.3+581410) serendipitously detected in the field of PSR B0136+57 which is around 11 arcmin away. It has a 0.2–12 keV flux of 1.8 × 10 −12 erg cm −2 s −1. This source is also associated with an INTEGRAL object first reported by Krivonos et al. (2007) in their all-sky hard X-ray survey and also listed in the fourth IBIS catalogue (Bird et al. 2010). It is relatively bright in radio; has a flat spectrum between 6 and 82 cm (Vollmer et al. 2010) and is radio loud (Brinkman et al. 1997; Laurent-Muehleisen et al. 1997). The optical spectrum is featureless, indicating that this is another BL Lac object (Bikmaev et al. 2008).

1FGL J0604.2–4817. This source also has a counterpart in the XMMSlew catalogue (XMMSI1 J060408.5–481712) which provides a much better position and a 0.2–12 keV flux of 7.1 × 10 −12 erg cm −2 s −1. In this case the source has also been observed by Swift/XRT; the observed spectrum is a simple power law absorbed by the Galactic column density (N H = 3.64 × 10 20 cm −2) and having a photon index Γ = 2.3 ± 0.1; the 0.2–12 keV flux of 5.6 × 10 −12 erg cm −2 s −1 is slightly lower than that measured by XMM during slews, suggesting variable X-ray emission. The source is located at high Galactic latitude and has a counterpart in the SUMSS catalogue with a 36 cm flux of 32 mJy. All these properties suggest an AGN nature. Indeed, the source appears in the Fermi AGN catalogue as an affiliated source with no further information; however recently it has been classified as a BL Lac on the basis of its optical spectrum (Mahony et al. 2010b).

1FGL J0506.9–5435. This ROSAT source has also an XMMSlew counterpart (XMMSL1 J050658.2–543503) which is associated with the source RBS 621, classified in NED and SIMBAD as a BL Lac object; the source is also a Fermi AGN affiliation although with no optical or SED class. RBS 621 is fairly bright in X-rays with a 0.1–12 keV flux of 9.5 × 10 −12 erg cm −2 s −1 while the only radio detection of the source is at 36 cm with a relatively low flux of 18 mJy.

1FGL J1304.3–4352. The Fermi source was also detected by EGRET as 3EG J1300–4406, and it is listed as an affiliation in the first year AGN catalogue with no further information. The ROSAT detection is quite strong and is localized 4:2 south-west of the radio galaxy Centaurus A; it has a radio counterpart in the SUMSS survey with a 36 cm flux of around 44 mJy. The X and radio detection together with the high Galactic latitude indicate that 1FGL J1304.3–4352 has an extragalactic origin and hence a tentative AGN classification.

1FGL J1823.5–3454. This source was previously detected by Einstein and ASCA but with large error boxes. Within the ROSAT positional uncertainty lies the radio source NVSS J182338–345412, detected at 20, 36 and possibly 6 cm (Wright et al. 1994) with a flux of 132, 155 and 148 mJy, respectively; it is also characterized by a flat radio spectrum (Mahony et al. 2010a). Despite the location on the Galactic plane the detection in radio, X and gamma-ray frequencies as well as the flat radio spectrum hints at an AGN seen through the Galactic plane.

1FGL J1227.9–4852. This ROSAT source coincides positionally with XSS J12270–4859 classified as a cataclysmic variable and detected up to high energies by INTEGRAL (Bird et al. 2010). Its classification has been questioned recently by de Martino et al. (2010) as the broad-band characteristics suggest that it might be a low-mass X-ray binary system. Both types of systems are still to be proven emitters of MeV–GeV photons and so the association is still uncertain. We note, however, that XSS J12270–4859 is by far the brightest source in the Fermi error box and as such this ROSAT association still deserves some attention.

1FGL J1643.5–0646. The counterpart of this ROSAT object is most likely the galaxy 2MASX J16432892–0646190, which is still unclassified; it has a counterpart in the NVSS survey with a 20 cm flux of 28 mJy. No other information is available for this source so it is difficult to assess what type of AGN it may be without optical follow up observations. We note, however, that the source is listed in the sample of Fermi AGN affiliations with an HSP SED class, which suggests that it is probably a BL Lac candidate.

1FGL J0838.6–2828. Close to this ROSAT detection we find the XMMSlew object XMMSL1 J083842.9–282657 with a 0.2–12 keV flux of 6.9 × 10 −12 erg cm −2 s −1; the two objects are possibly associated given that the distance between the two is compatible with the error boxes of the two detections. Within the more refined XMMSlew position we do not find any radio counterpart for this object which is located close to the Galactic plane: both these circumstances exclude an extragalactic nature for this source and hence suggests an uncertain classification.

1FGL J0051.4–6242. The ROSAT source has a hard X-ray counterpart in a bright Swift/XRT source identified as RBS 119; this object is classified both in NED and SIMBAD as a BL Lac source. The Swift/XRT spectrum is a simple power law absorbed by the Galactic column density (N H = 1.7 × 10 20 cm −2) and with a photon index Γ = 2.5 ± 0.1; the 0.2–12 keV flux is 5.8 × 10 −12 erg cm −2 s −1. The source is reported in the SUMSS survey with a 36 cm flux of 43 mJy. Also, this source is listed in the first year AGN catalogue as an affiliation but with no further information.

1FGL J0131.2+6121. Within the ROSAT error box lies 87GB 012752.4+610507, known in radio to exhibit a relativistic one-sided jet and also to show a slightly negative or close to zero spectral index (Ribó et al. 2002). Indeed, the source flux at 6 and 20 cm frequencies is 22 and 19 mJy, respectively (Gregory & Condon 1981). The source has also been reported as a radio-loud AGN both by Brinkman et al. (1997) and by Laurent-Muehleisen et al. (1997). The optical spectrum displays a featureless continuum heavily absorbed at shorter wavelengths (Martí et al. 2004). All this observational evidence points to a blazar interpretation for this source, most likely of the BL Lac class.

1FGL J2056.7+4938. The ROSAT position is compatible with a Swift/XRT source also listed in the XMMSlew Survey as XMMSL1 J205642.7+494004. This source is also associated with an INTEGRAL object, IGR J20569–4940, first reported by Krivonos et al. (2007) in their all-sky hard X-ray survey and then listed in the fourth IBIS catalogue (Bird et al. 2010). The X-ray and radio properties of this X/gamma-ray object are fully discussed in Landi et al. (2010): in X-rays the source is relatively bright and variable (flux in the range 8–19 × 10 −12 erg cm −2 s −1) while in radio it has a flat spectrum and is radio loud. It has been proposed by Paredes, Ribó &
Marti (2002) as a micro-quasar candidate given its location close to the Galactic plane, but a blazar classification is more likely given the characteristics of the broad-band emission.

**1FGL J2146.6−1345.** This ROSAT object has a counterpart only in the NVSS survey with a 20 cm flux of 22.5 mJy. No other information is available for this source except that it is located at high Galactic latitudes; this together with the radio and X-ray detections strongly suggests that it is most likely an AGN. Here too, we note that the source is listed in the sample of Fermi AGN affiliations with an HSP SED class, again suggestive of a BL Lac candidate.

**1FGL J1544.5−1127.** This source has a detection in the XMMSlew survey (XMMSL1 J154439.8−112806/XMMSL1 J154439.4−112754) and has also been observed by Swift/XRT. The XMMSlew survey reports two detections at different epochs with a significantly different flux of 3.5 and 11 × 10^{-12} erg cm^{-2} s^{-1}. The XRT spectrum is well fitted with an absorbed power law having Γ = 1.5 ± 0.1 and a Galactic column density of 12.5 × 10^{20} cm^{-2}; in this case the 0.2–12 keV flux is around 4 × 10^{-11} erg cm^{-2} s^{-1}, i.e. close to that found in the first XMMSlew survey detection. The source is clearly variable in X-rays but has no detection so far in radio despite coverage by the NVSS of this sky region. The location of the source at high Galactic latitude suggests an extragalactic origin, but the lack of a radio counterpart is intriguing and follow-up optical observations are necessary to establish the nature of this X-ray source.

**1FGL J0848.6+0504.** Once again the ROSAT source has an XMMSlew counterpart (XMMSL1 J084840.1+050617) with a 0.2–12 keV flux of 3.4 × 10^{-12} erg cm^{-2} s^{-1}; it is associated with the radio source FIRST J084839.6+050618, which has a quite low 20 cm flux of around 2 mJy and is the counterpart of SDSS J084840.20+050611.9, classified as a galaxy in NED. Taken all together the source properties suggest that we are dealing here too with an AGN.

**1FGL J2329.2+3755.** Also this ROSAT object has a counterpart in the radio band having 6, 20 and 92 cm fluxes of 22, 16 and 19.8 mJy, respectively, suggestive of a flat spectrum source (Vollmer et al. 2010). The location at high Galactic latitude suggests an extragalactic origin further confirmed by the radio and X-ray detection. The source is in fact listed in the sample of Fermi AGN affiliations with an HSP SED class, again indicative that it may be another BL Lac.

**1FGL J1926.8+6153.** This ROSAT object has an association with an XMMSlew source, XMMSL1 J192650.6+615446, which is identified with 87GB 192614.4+614823, a well-known radio source which is still unclassified. The XMMSlew catalogue reports a 0.2–12 keV flux of 2.3 × 10^{-12} erg cm^{-2} s^{-1}. The source has also a detection by Swift/XRT. The XRT spectrum is well fitted by an absorbed power law having Γ = 2.6 ± 0.4 and 0.2–12 keV flux of 5.8 × 10^{-12} erg cm^{-2} s^{-1}; the measured absorption N_H = 5.2 × 10^{20} cm^{-2} is purely Galactic. The X-ray flux is clearly variable while the various radio detections provide evidence for a flat spectrum source as found by Specfind (see also Jackson et al. 2007). The location of the source at high Galactic latitudes together with the X-ray and radio properties suggests an AGN classification. Indeed, the source, listed among the Fermi AGN affiliations, is optically classified as a BL Lac and further characterized as an HSP object.

**1FGL J2042.2+2427.** Once again, this ROSAT source has an XMMSlew counterpart (XMMSL1 J204206.1+242653) associated with the galaxy 2MASX J20420606+2426518, classified in NED as a BL Lac. The 0.2–12 keV flux is 1.7 × 10^{-12} erg cm^{-2} s^{-1}; it is radio loud with 6 and 20 cm fluxes of 52 and 70 mJy, respectively (Griffith et al. 1990), and hence can be defined as a flat spectrum source (see also Reich et al. 2000 and Jackson et al. 2007). It is listed as an affiliation in the Fermi AGN catalogue where it is optically classified as a BL Lac and further characterized as an HSP object.

**1FGL J0841.4−3558.** The ROSAT source is probably the X-ray counterpart of the star HIP 42640 (SIMBAD name) of spectral type F2V, unlikely to be a gamma-ray emitter in the Fermi catalogue. This could well be a chance positional alignment, one of which is expected given the number of objects in the sample analysed in this work.

**1FGL J1910.9+0906.** This ROSAT source is most likely associated with the supernova remnant G043.3−00.2 (also known as Was49B). The X-ray source is slightly extended and encompasses almost the entire extension of the remnant. Supernovae are also found to be associated in some numbers with GeV emission (Abdo et al. 2010a) although it is not clear at the moment how many SNR not hosting a pulsar are Fermi emitters.

**1FGL J0054.9−2455.** This X-ray source has a radio association in the NVSS with an object having a 20 cm flux of 24 mJy. The source has been associated with the UV excess source 2MASS J00544675−2455291, which displays a continuous spectrum with no lines. In SIMBAD, it is catalogued as a white dwarf, but the radio emission and the high latitude location suggest that it could also be an extragalactic object. Indeed, the source is present in the Fermi AGN catalogue as an affiliated object having no optical class but an HSP SED. This source also appears in the recent catalogue of Fermi detections above 100 GeV (Neronov, Semikoz & Volyk 2010). The above information suggests that it might be another BL Lac.

**1FGL J1933.3+0723.** This source, located close to the Galactic plane, has a radio detection at 6 and 20 cm with a flux of 94 and 104 mJy (Becker, White & Edwards 1991), which implies a flat spectrum source. No other information is available, but the radio properties and the X-ray emission could be taken as evidence that it is another case of an AGN behind our galaxy.

**1FGL J1553.5−3116.** This ROSAT object has a detection in both the NVSS and in the SUMSS with a 20 and 36 cm flux of 156 and 139 mJy which indicates a flat radio spectrum. The high latitude location as well as the X-ray and radio emission clearly indicates that this is an AGN. Indeed, the source, listed among the Fermi AGN affiliations, is optically classified as a BL Lac and further characterized as an HSP object.

**1FGL J1841.9+3220.** In this case, the ROSAT source is also detected by XRT on Swift, which allows the location uncertainty to be restricted and the X-ray spectral characteristics to be studied. The smaller XRT error box allows an identification with the radio source RGB J1841+323. The XRT spectrum has a good fit with an absorbed power law having Γ in the range 2.1–2.5 and a Galactic column density of 8.4 × 10^{20} cm^{-2}; the 0.2–12 keV flux is in the range 1.6–1.9 × 10^{-12} erg cm^{-2} s^{-1}. The available 6 and 20 cm fluxes of 14 and 20 mJy (Laurent-Muehleisen et al. 1997) suggest that the radio spectrum might be flat; RGB J1841+323 has also been reported as a radio-loud AGN first by Brinkman et al. (1997) and later by Laurent-Muehleisen et al. (1997). Finally, it is listed in the Seoul National University Bright Quasar Survey (Lee et al. 2008), which is the base for the NED classification as a QSO candidate and hence a probable blazar-type object. The source is listed among the Fermi AGN affiliations with the same association proposed here and with an HSP SED class, which indicates that it may be a BL Lac rather than a Flat Spectrum Radio Quasar.

**1FGL J1419.7+7731.** This ROSAT detection is also a radio emitter with a 20 cm flux of 8 mJy. An optical observation of the source
indicates that it is a weak point-like object with an extremely blue continuum (Zickgraf et al. 2003); the source is also listed in the Million QSO catalogue (http://quasars.org/milliquas.htm). Again, the high latitude location, radio and X-ray emission, and optical properties indicate that it is an AGN.

**1FGL J2323.0–4919.** This *ROSAT* source is still unidentified and has no detection in radio to date. At a distance of around 0.7 arcmin, i.e. outside the *ROSAT* error circle, we find an XMM-Slew survey source, XMMSL1 J232254.4–491624 which has a positional uncertainty of around 5 arcsec and a 0.2–12 keV flux of 2.6 × 10⁻¹² erg cm⁻² s⁻¹. Within the XMM-Slew error circle, there is also a radio source listed in the SUMSS with a 36 cm flux of 28.3 mJy. Although the error circles of the two X-ray sources do not match, it is still possible that the *ROSAT* and XMM-Slew detections are the same. This source is also listed between the *Fermi* AGN affiliations but is wrongly identified with the galaxy APMUKS(BJ) B232010.42–493502.4, which is not associated to the *ROSAT* and/or XMM-Slew detections. The source is located at high Galactic latitudes, is likely an X-ray emitter and possibly also a radio source which all together suggest an AGN nature.

**1FGL J0223.0–1118** Here too the *ROSAT* object has an association with an XMM-Slew source, XMMSL1 J022314.7–111735, which is identified with NVSS J022314–111737, a radio object not yet optically classified; it is associated with the galaxy 6dF J022314.3–111738 at redshift 0.042, but the optical spectrum is of too poor quality to allow a proper classification. The XMM-Slew catalogue reports a 0.2–12 keV flux of 1.97 × 10⁻¹² erg cm⁻² s⁻¹, while the NVSS provides a radio detection of 14 mJy at 20 cm. The source is clearly an AGN in the local Universe.

### 5 DISCUSSION

The first result of this work is that a number of likely X-ray counterparts to *Fermi* sources have been found. Statistically, there should only be around one chance alignment which is probably that of 1FGL J0841.4–3558 given the type of the X-ray source. The majority of the associations are of extragalactic nature while only two or three cases (an SNR; a binary system and maybe a micro-quasar) are Galactic. Of the extragalactic objects many are BL Lac or BL Lac candidates, i.e. objects that are expected to have GeV emission. In other cases the source may be radio loud or radio flat, characteristics that are often common to AGN emitting in the *Fermi* band (see Table 2 and the previous section).

Some information on the nature of the *Fermi* sources can also be gained from the GeV properties as reported in the *Fermi* catalogue; for each source of interest here Table 2 provides the *Fermi* 1–100 GeV flux, power-law photon index, curvature index and variability index. For example, both curvature and variability index can be used to discriminate between source types: as shown in fig. 11 of Abd et al. (2010a) one can clearly separate the pulsar branch located at large curvature and small variability indices from the blazar branch which is found at large variability and small curvature indices. Using these parameters and following the broad division adopted by Abd and co-workers, we conclude that all extragalactic objects in Table 1 are compatible with being blazars; the few exception are 1FGL J1942.7+1033, 1FGL J1227.9–4852 and 1FGL J1910.9+0906 which are border-line objects. The last two are indeed non-blazar-type objects while 1FGL J1942.7+1033 despite its location in the diagram is most likely a BL LAC given its broad-band properties (see the previous section).

In the following discussion we concentrate only on those objects that are likely to be extragalactic and so exclude the three sources which are Galactic or spurious (1FGL J1227.9–4852, 1FGL J1910.9+0906 and 1FGL J0841.4–3558) but leave 1FGL J2056.7+4938 as it could well be a blazar behind the Galactic plane. To go deeper in our understanding of the nature of the *ROSAT–Fermi* associations, we can use the gamma-ray photon index to discriminate between BL Lac and FSRQs. From fig. 12 in A1, we see the latter have a lower limit to the *Fermi* photon index of 2, while that for BL Lac objects peak around this value with a range from about 1.2 to 2.7. Of the 27 extragalactic sources, 16 have a photon index below this critical value and so must be strongly suspected to be BL Lacs. Furthermore, there are another seven objects which have a steeper spectrum but have already been optically classified as BL Lacs; therefore in total we have at least 23 objects which probably belong to this class. Similarly, the intensity of the GeV emission suggests a preference for BL Lac objects among our sample, since the log of the *Fermi* flux reported in Table 2 is always below −8.0. (see fig. 10 in A1). Finally, if we plot the 0.1–2.4 X-ray flux versus the flux density at 20 cm for those objects which have both values, we find that their location in this diagram is again in the region populated by BL Lac objects (see fig. 5 of A1).

Thus, it seems that the cross-correlation using the *ROSAT* bright source catalogue tends to select associations with *Fermi* sources that are BL Lac type AGN. To test this finding, we can use the same statistical correlation method but on the sample of *Fermi* objects that are classified in the first catalogue as blazars (bzq and bzb). There are 573 such sources in the *Fermi* list, with almost the same number of objects in each of the two classes (51 per cent BL Lac). Again, the correlation is strong with 181 associations within 300 arcsec. Of these objects, the overwhelming majority (137) are with those already identified as BL Lac sources. The selection effect towards BL Lac when using the *ROSAT* bright source catalogue is likely related to the SED of these objects compared to FSRQ. In the widely adopted scenario of blazars, a single population of high-energy electrons in a relativistic jet radiate from the radio/FIR to the UV-soft X-ray by the synchrotron process and at higher frequencies by inverse-Compton scattering of soft-target photons present either in the jet [synchrotron self-Compton (SSC) model], in the surrounding material [external Compton (EC) model], or in both (Ghisellini et al. 1998 and references therein). Therefore, a strong signature of the blazar nature of a source is a double-peaked structure in the SED, with the synchrotron component peaking anywhere from infrared to X-rays and the inverse-Compton extending up to GeV or even TeV gamma-rays. Among blazars, BL Lacertae objects are the sources with the highest variety of synchrotron peak frequencies, ranging from the IR-optical to the UV-soft-X bands (called low or high energy peak BL Lacs, respectively; see Padovani & Giommi 1995). The X-ray selection discussed herein should favour objects peaking at high energies, i.e. in the X-ray band: indeed nine objects discussed in the previous section and affiliated to the *Fermi* AGN catalogue are also classified as HSP AGN. Given their high synchrotron peak energies, which flag the presence of high-energy electrons, these extreme BL Lacs are also good candidates for TeV emission as the Compton peak is expected in this energy range. One source in our sample, 1FGL J0648.8+1516, has already been detected by VERITAS in the TeV range while another, 1FGL 0054.9–2455, has been seen above 100 GeV. The interest in these extreme TeV blazars is driven by the possibility of obtaining information both on the acceleration processes of charged particles in relativistic flows and on the intensity of the extragalactic background light which...
absorbs the flux from high-energy sources (Mankuzhiyil, Persic & Tavecchio 2010).

6 CONCLUSIONS

We have shown that, as expected, there is a strong correlation between the Fermi survey source list and the ROSAT All Sky Survey Bright Source Catalogue, finding that there should be about 60 sources common to both lists. By placing a maximum correlation distance of 160 arcsec in order to minimize chance associations we have a sample of 30 objects in which only 1 ± 1 should be by chance alignment. We can use the ROSAT error box to help find optical counterparts for these sources, which in all cases is sufficiently small to allow the identification of one single object. Most of the associations are of extragalactic nature, with only a few being Galactic. We have also shown that this cross-correlation analysis appears to preferentially select BL Lac objects. These X-ray selected objects are often HSP BL Lacs and are therefore good candidates for TeV emission. Clearly, only optical spectroscopy of the ROSAT counterparts can confirm this suggestion, but cross-correlation with other catalogues may provide a different selection criterion and hence different source types.

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