XMM-NEWTON AND WIDE FIELD OPTICAL IMAGING TO CRACK THE MYSTERY OF UNIDENTIFIED GAMMA-RAY SOURCES

P.A. Caraveo¹, A. De Luca¹, ², N. La Palombara¹, R. Mignani³, E. Hatziminaoglou³, R. Hartman⁴, D.J. Thompson⁴, and G.F. Bignami⁵

¹Istituto di Astrofisica Spaziale e Fisica Cosmica, Via Bassini 15, I-20133 Milano, Italy
²Università di Milano Bicocca, Dipartimento di Fisica, Piazza della Scienza 3, I-20126 Milano, Italy
³ESO, Karl Schwarzschild Str. 2, D-85748 Garching bei München, Germany
⁴NASA GSFC, Greenbelt MD, USA
⁵Agenzia Spaziale Italiana, Via di Villa Graziodi, 23 I-00198 ROMA, Italy

ABSTRACT

The limited angular resolution of gamma-ray telescopes prevents the straight identification of the majority of the sources detected so far. While the only certified galactic gamma-ray emitters are associated with pulsars, more than 90% of the nearly 100 low latitude sources detected by EGRET on the GRO lack an identification. The best identification strategy devised over the years relies on the use of X-ray and optical data to single out possible counterparts, rating them on the basis of their extreme \( \frac{F_x}{F_{\text{opt}}} \). Here we describe a multicolor programme based on the EPIC mapping of selected EGRET sources complemented by the optical coverage of the same fields obtained through the Wide Field Imager (WFI) of the ESO 2.2 m telescope. The field of view of the WFI, comparable to that of EPIC, will allow to directly cross-correlate X and optical data speeding up significantly the selection of interesting candidates worth follow-up optical (and X-ray) studies.

Key words: Missions: XMM-Newton – multiwavelength astronomy–optical identifications

1. INTRODUCTION

The third EGRET catalogue (Hartman et al. 1999) of high energy gamma-ray sources contains 271 entries as opposed to the 25 listed in the COS-B one. The low latitude (\( b \leq 10^\circ \)), presumably galactic, sources went from 22 to 80, while the high latitude (\( b \geq 10^\circ \)), presumably extragalactic, ones jumped from 3 to 181, with blazars accounting for roughly half of them.

Surprisingly enough, EGRET has done very little to clarify the nature of the low latitude, mostly galactic, gamma-ray emitters. While their number increased fourfold, successful identifications remain at a meagre 10% level and rely only on the time signature of the gamma-ray photons, which unambiguously associates these sources with pulsars. In the remaining cases, both the poorer statistics and the uncertain positions of the gamma-ray sources have hampered “blind” periodicity searches, while the size of the gamma-ray error boxes (on average 1 sq deg) prevents a direct optical identification. For these reasons, the search for counterpart(s) has been pursued through the X-ray coverage of the fields followed by the optical study of each X-ray source.

Figure 1 summarizes the “zoom in” approach devised during the 20 year long chase which led to the identification of Geminga (Bignami & Caraveo 1999). The Einstein Observatory was used to image the gamma-ray error box of Geminga, one of the brightest gamma-ray source in the galactic plane, shown in the upper right panel together with the slightly fainter Crab pulsar. All but one of the four sources discovered by the Imaging Proportional Counter were readily optically identified (Bignami et al. 1983). The one lacking identification, 1E0630+178, was later observed with the High Resolution Imager which yielded a few square arcsec error box. This was the target of CFH, Palomar and the ESO 3.6m telescopes, eventually yielding the \( m_V \geq 25.5 \) G" as the candidate counterpart. This identification was later confirmed by the discovery of the source proper motion (Bignami et al. 1993) which was then used to improve the time solution of the gamma-ray photon (Mattox et al. 1996), providing a direct link between the bright gamma-ray source and its faint optical counterpart. The link between the X and gamma-ray behaviour was provided by the discovery of the pulsation in X-rays (Haipern & Holt 1992) followed by the confirmation in the gamma-ray domain. The lack of radio emission prompted Caraveo et al. (1996) to classify Geminga as a radio quiet neutron star, the first of its kind, characterized by a gamma-ray yield 1,000 times higher than the X-ray one, which, in turn, is 1,000 times higher than the optical one. Indeed, the identification procedure relies on the extreme \( \frac{F_x}{F_{\text{opt}}} \) value measured for Isolated Neutron Stars (INSs), 6 of which are known to be gamma-ray emitters (see e.g. Thompson 2001). Such a multicolor approach is now the standard method to search for the counterparts of EGRET gamma-ray sources.

Years of multicolor efforts have yielded (so far) less than a dozen tentative identifications encompassing 4 energetic young radio pulsars, 3 Geminga-like radio quiet isolated neutron stars, 2 peculiar binary systems, 1 low latitude Blazar and few pulsars nebulae (see Caraveo 2001 for a review of the proposed identifications).
Attempts to associate the low latitude unidentified EGRET sources with different classes of galactic objects (see e.g. Romer et al. 1999; Gehrels et al. 2000) have not yielded, so far, gamma-ray source templates more appealing than the classical Isolated Neutron Star one. Thus, while not neglecting other possibilities, it is natural to assume that at least a fraction of the remaining low latitude sources are unidentified neutron stars.

Our EPIC-ESO programme, centered on two middle latitude EGRET sources, is precisely aiming at these objects.

2. INSs: radio-loud vs. radio-quiet

The search for neutron stars in gamma-rays started as soon as COS-B discovered the UGOs (Unidentified Gamma Objects, see Bignami & Hermsen 1983 for a review), but no new pulsar, after Crab and Vela, was unveiled. New searches have been spurred by the EGRET detections of four more pulsars (e.g. Thompson et al. 1996) but the lack of results, experienced at the time of COS-B, appears to be substantially unchanged. Dedicated radio searches (Niel & Sayer 1997), aimed precisely at the search for radio pulsars inside the error boxes of 10 of the brightest EGRET sources, yielded null results, showing that the straightforward radio pulsar identification is not the only possible solution to the enigma of the unidentified high-energy gamma-ray sources. This has been further strengthened by the work of Nel et al. (1996) who investigated 350 known pulsars, finding few positional coincidences but no significant gamma-ray timing signature for any of the pulsars in the survey. The recently released portion of the Parkes survey, encompassing 368 new pulsars, has been correlated to the EGRET error boxes, finding no more than 3 plausible pulsar candidates against a dozen of chance coincidences (Torres et al. 2001). With no gamma-ray instruments in operation, it is presently impossible to confirm these associations.

Indeed, gamma-ray astronomy does offer a remarkable example of an INS which behaves as a pulsar as far as X- and gamma-astronomy are concerned but has little, if at all, radio emission. As an established representative of the non-radio-loud INSs (see Caraveo et al. 1996 for a review), Geminga offers an elusive template behaviour: prominent in high energy gamma-rays, easily detectable in X-rays and downright faint in optical, with sporadic or no radio emission. Although the energetics of a Geminga-like object is not adequate to account for the very low latitude (presumably more distant) EGRET sources, the third EGRET catalogue contains several middle latitude sources which could belong to a local galactic population. In this case, their gamma-ray yield is certainly compatible with the rotational energy loss of a middle aged neutron star, like Geminga.

Thus, it makes sense to apply to these sources the two-step strategy devised during the 20 year long chase for Geminga (Bignami & Caraveo 1996), more recently also applied to pinpoint the candidate neutron star counterpart to the EGRET source 3EG J1835+5918 (Mirabal & Halpern 2001) as well as to few other EGRET sources (see Caraveo 2001). First of all, one has to start from a list of unidentified X-ray sources detected in the EGRET error boxes. Next step is to single out potential neutron star candidates taking advantage of their high $F_x/F_{opt}$ as a distinctive character and using multicolor information as a further handle to solve ambiguous cases, e.g., when more optical entries are compatible with the X-ray position.

3. Our XMM-ESO programme

3.1. X-ray side

Currently, we are focussing on two middle-latitude EGRET sources (3EG 0616-3310 and 3EG 1249-8330), selected on the basis of their relatively good positional accuracy, spectral shape, galactic location and lack of candidate extragalactic counterpart. EPIC (Turner et al. 2001; Strüder et al. 2001) is the ideal instrument to perform the X-ray coverage of the gamma-ray error boxes, since it offers good angular resolution ($\lesssim 6^\prime$ FWHM), coupled to high sensitivity in a broad energy range ($0.1\div 12$ keV) and good spectral resolution ($E/\Delta E \approx 20\div 50$), over a wide field of view ($\approx 15$ arcmin radius). Thus, each gamma-ray source error box, a circle of 30 arcmin radius, can be covered with four EPIC exposures. For a net exposure time of 10 000 s for each pointing, this yields an homogeneous coverage of about 1 square degree down to a 5σ detection limiting flux ranging from $\approx 7 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ to $\approx 2 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, depending on the source spectrum. Taking these values as reference, folded with the $LogN - LogS$ function for extragalactic sources (see e.g. Hasinger et al. 2001) and including an evaluation of the galactic contribution (see e.g. Guilout et al. 1990), we were expecting $\approx 100$ sources (mainly AGN and active stars), positioned to within 5 arcsec, in each EGRET error box. To quickly identify such a number of serendipitous sources, we had to devise an ad hoc optical strategy.

3.2. The optical side

Given the range of $F_x/F_{opt}$ values characteristic for the known classes of X-ray sources (see, e.g. Krautter et al. 1999), we ought to reach $V \approx 25$ in the optical follow-up in order to be able to discard most non-INSs identifications. Thus, although useful for a first filtering, the available Digital Sky Surveys are not deep enough for our purpose: dedicated optical observations are needed. However, the expected EPIC yield prompted us to seek an approach different from the one-by-one philosophy used so far to identify the few sources detected by previous X-ray telescopes in each gamma-ray error box. It is apparent that without a “massive” approach to the identification work the optical side is bound to become the bottleneck of our a multiwavelength chain. Our optical work should
be aimed at dozens of faint objects distributed over about 1 sq deg. A dedicated, deep, multicolour optical survey of our fields must be the starting point for the real identification work. This is why we have decided to rely on the WFI of the 2.2 m as the optical complement of our EPIC coverage of EGRET sources. The WFI large field of view (33 × 34 arcmin), directly comparable to the EPIC one, will allow to cross correlate directly X and optical data speeding up dramatically the identification work.

3.3. The state of the art

The XMM/EPIC observation campaign of the two EGRET error boxes was completed in November 2001. The optical data are now being collected at the ESO 2.2m telescope (Period 68). The analysis of the X-ray data is currently in progress, using the XMM-Newton Science Analysis System (XMM-SAS) v5.2.

Unfortunately, we discovered that space weather was not favourable during 2 of our 8 pointings. These observations (1 per EGRET error box) were badly affected by high particle background episodes (the so-called soft proton flares, see XMM Users’ Handbook) and we were forced to reject up to 80% of the integration time.

We ran a preliminary source detection over the broad energy band 0.3-8 keV, which gathers almost all the usable X-ray events from celestial sources. About 130 sources per EGRET error box were found and their fluxes, computed using a simple Geminga-like spectrum (a black body with $kT=0.1$ keV and a $N_h$ of order 5) were found and their fluxes, computed from X-ray events from celestial sources. About 130 sources per EGRET error box were found and their fluxes, computed using a simple Geminga-like spectrum (a black body with $kT=0.1$ keV and a $N_h$ of order 5) were found and their fluxes, computed using a simple Geminga-like spectrum (a black body with $kT=0.1$ keV and a $N_h$ of order 5) were found and their fluxes, computed using a simple Geminga-like spectrum (a black body with $kT=0.1$ keV and a $N_h$ of order 5). Figure 2 shows the EPIC mosaic of the field of 3EG 1249-8330. The detected sources are marked with little circles. The South West observation clearly shows the dramatic effect of flaring particle background. A more sophisticated source detection analysis is currently under way. Following Baldi et al. (2001) particular care is now devoted to create a background map which properly reproduce the background fluctuations on small spatial scales, a crucial step in order to assess the reality and the significance of our sources.

As a first screening to filter out obvious non-INS identifications, we take advantage of the available optical catalogues to cross correlate our lists of sources (the position of which is known within 5 arcsec). Our starting point is the extended version of the recently released Guide Star Catalogue 2 (GSC2), an all-sky, multi-epoch and multicolor optical catalogue based on photographic surveys carried out between 1953 and 1991 (McLean et al. 2002-in preparation). The GSC2 provides color information in at least three photographic passbands (roughly corresponding to $B$, $R$ and $I$) down to $B \sim 22$ and morphological classification at a ~90% confidence level for objects in our latitude range and brighter than $B \sim 19$. To extend our color coverage to the infrared ($J$, $H$ and $K$) we use the updated release of the 2 Micron All Sky Survey (2MASS) catalogue.

After the cross correlations, the color catalogues are combined and used as input for the object classification procedure, with the morphological classification from the GSC2 as a further aid. For this, we apply the automatic algorithm developed by Hatziminaoglou, et al. 2000, which fits model fluxes, simulated from template spectral libraries, to the observed ones through a $\chi^2$ minimization technique. The reliability of this method has been tested successfully by Hatziminaoglou, et al. 2002 for the classification of the objects detected in the Chandra Deep Field South. Finally, the properties of the X-ray sources (e.g. hardness ratios, spectra) will be compared with the classifications of their candidate optical counterparts and identifications evaluated through a decision tree.

The whole procedure will be then repeated for the remaining, non identified, EPIC sources, using deeper optical catalogues extracted from the WFI data. The observations (in $UBVRI$) are now being carried out in Service Mode by the 2.2m team. So far, only the field of 3EG 0616-3310 has been observed, with an area coverage of $\sim 25\%$.

Of course, only the availability of the multicolor optical data from WFI will allow us to perform the final step of our identification chain.

4. Conclusions

The identification of gamma-ray sources, both individually and as a population, rests on multiwavelength observations. The programme we are pursuing at X-ray and optical wavelengths will yield, in a relatively short time, candidate counterparts worth follow-up investigations. Moreover, we plan to make available the complete catalog of the sources detected in our 1.6 sq. deg medium galactic latitude survey.

Acknowledgements

This work is supported by the Italian Space Agency (ASI).

References

Baldi, A. et al., 2001, ApJ 564, 190
Bignami, G.F. and Hersen W., 1983, Ann. Rev. Astr. Astrophys., 21, 67
Bignami, G.F., Caraveo, P.A. and Lamb, R.C., 1983, ApJ 272, L9
Bignami, G.F., Caraveo P.A. and Mereghetti, S., 1993, Nature 361, 704
Bignami G.F. and Caraveo P.A. 1996, Ann. Rev. Astr. Astrophys., 34, 331
Caraveo P.A., Bignami G.F., Trümper J.A. 1996, Astr. Astrophys. Rev., 7, 209
Caraveo, P.A., 2001, Gamma 2001 (AIP Conf. Proc. 587, New York),ed. S. Ritz, N. Gehrels, C. R. Shrader, p. 641
Gehrels, N. et al., 2000, Nature 404, 363
Guillout, P. et al., 1996, A&A 316, 89
Halpern, J.P. & Holt, S.S., 1992, Nature 357, 222
Hartman, R.C. et al. 1999 ApJ Suppl. 123, 79
Hasinger, G. et al. 2001, A&A 365, L45
Hatziminaoglou, E., Mathez, G. and Pelló, R., 2000, A&A 359, 9
Hatziminaoglou, E. et al. 2002, A&A - in press (astro-ph/0201028)
Krautter, J. et al., 1999, A&A 350, 743
Mattson, J.R., Halpern, J.P. and Caraveo, P.A, 1996, Astron.Astroph.Suppl.Ser. 120, 77
Mirabal, N. and Halpern, J.P., 2001, ApJ 547, L137
Nel H.I. et al. 1996 Ap.J., 465, 898
Nice D.J. and Sayer R.W. 1997 Ap.J., 476, 261
Romero, G.E., Benaglia, P. and Torres, D.F., 1999, A&A 348, 868
Strüder, L. et al., 2001, A&A,365, L18
Thompson, D.J. et al., 1996, ApJ 465, 385
Thompson, D.J. 2001, High Energy Gamma-Ray Astronomy (AIP Conf. Proc. 558, New York), ed. F. A. Aharonian, H. J. Völk, p. 103
Torres, D.F., Butt, Y.M. and Camilo, F., 2001, ApJ 560, L155
Turner, M.J.L. et al., 2001, A&A 365, L27
XMM-Newton Users' Handbook v. 2.0, Ehle, M. et al. eds.
Figure 1. From upper right to lower left: sketch of the 20 years-long identification chain which led to the identification of Geminga. The gamma ray source, discovered by SAS-2 and positioned by COS-B (upper right), was investigated using both the low and high resolution instruments on board the Einstein Observatory (center panel). The few arcsec error radius of the most promising source was imaged at length by CFH, 5m Hale, and ESO telescope yielding the candidate optical counterpart $G^\prime$ (upper left panel). $G^\prime$ was then studied with the HST (lower left panel).
Figure 2. EPIC mapping of the error box of 3EG 1249-8330. North is up, East is left. The detected sources, marked with circles, are more than 130. The lower right pointing is the one affected by flaring background. The reduction of the fraction of good observing time is evident.