

MULTIFREQUENCY STRATEGIES FOR THE IDENTIFICATION OF GAMMA-RAY SOURCES

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Abstract

More than half the sources in the Third EGRET (3EG) catalog have no firmly established counterparts at other wavelengths and are unidentified. Some of these unidentified sources have remained a mystery since the first surveys of the γ -ray sky with the COS-B satellite. The unidentified sources generally have large error circles, and finding counterparts has often been a challenging job. A multiwavelength approach, using X-ray, optical, and radio data, is often needed to understand the nature of these sources. This chapter reviews the technique of identification of EGRET sources using multiwavelength studies of the gamma-ray fields.

1. Introduction and historical overview

The discovery of point-like high energy sources in the γ -ray sky has been one of the most exciting results in the field of γ -ray astronomy, since the advent of the first satellites in the 1970s. These sources have included exotic and energetic objects such as active galaxies, powered by super massive black holes, pulsars, and powerful and mysterious γ -ray bursts, and have enabled us to explore some of the highest energy accelerators in the cosmos. But, perhaps the most mysterious and enigmatic

of the sources have been the “unidentified” γ -ray sources. As the qualifier suggests, these are objects in the γ -ray sky with no identifications or known counterparts at other wavebands. Some of the unidentified sources have remained so since the first surveys of the γ -ray sky carried out by the COS-B satellite in the 1970s. As described in Chapter 1 of this book, COS-B detected a total of 25 sources, of which only the pulsars, Crab and Vela, the molecular cloud ρ -Oph and the first extragalactic source, 3C 273 were identified (Bignami & Hermsen 1983). The remaining 21 sources in the 2nd COS-B catalog had no unambiguous counterparts at other wavebands. Figure 1 shows the COS-B skymap. As one of the first catalogs of γ -ray sources it represents a significant step in the field of γ -ray astronomy.

Following COS-B, the next major step in γ -ray astronomy came with the launch of the *Compton Gamma Ray Observatory* (CGRO) in 1991, when the on-board EGRET (Energetic Gamma-ray Experiment Telescope) instrument carried out improved surveys of the γ -ray sky, at relatively better angular resolution. EGRET’s success was tremendous, and a total of 271 point sources of high energy γ -rays above 100 MeV, were catalogued (Hartman et al. 1999). However, only a fraction of these sources were identified. The unidentified sources comprised the majority of the γ -ray point sources, some in fact being originally discovered by the COS-B satellite. The nature of these persistent γ -ray sources is an

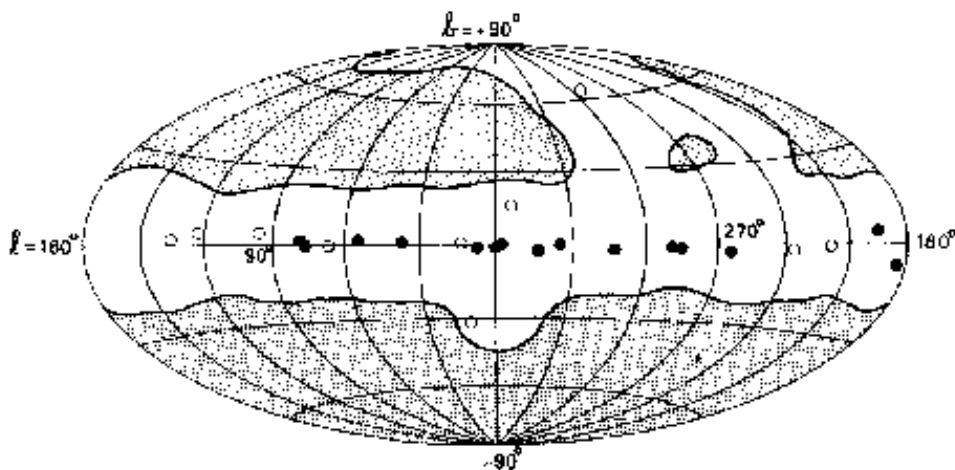


Figure 1. Point sources of γ -rays in the second and final COS-B catalog. Sources with flux brighter than $1.3 \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}$ are denoted with filled circles. Only the unshaded area represents the sky portion surveyed for point sources. Figure from (Swanenburg et al. 1981).

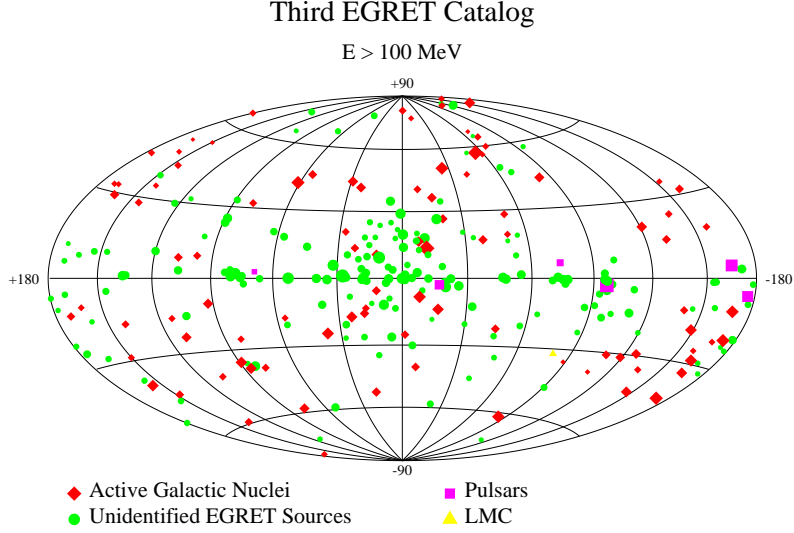


Figure 2. Point sources (from the Third EGRET Catalog) detected by EGRET at > 100 MeV. The size of the symbols are scaled according to source flux. The unidentified sources are shown as filled circles. Figure from (Hartman et al. 1999).

outstanding mystery in high energy astrophysics, in some cases almost three decades after their discovery. Figure 2 shows the point sources catalogued in the Third EGRET (3EG) catalog, detected above 100 MeV. The unidentified sources, shown as filled circles, constitute the largest class of the EGRET sources. Resolving the mystery of the γ -ray sources is a significant challenge across all wavebands in astronomy. A nice recent review of the current status in the quest for the identification of the high energy γ -ray sources is given by Caraveo (2002).

1.1 EGRET source sensitivity

It is important to point out that EGRET did not survey all regions of the sky with the same sensitivity. Figure 3 shows the sky exposure for EGRET above 100 MeV for the duration of the EGRET mission. The significance of detection S of a source with flux F is related to the exposure E and background B by $S \sim F\sqrt{E/B}$. Since the EGRET intensity map is dominated by strong diffuse emission along the Galactic plane (Hunter et al. 1997), the γ -ray source detection threshold is definitely higher in regions of low exposure or high diffuse radiation. Because of the larger systematic uncertainties in the EGRET analysis for the high intensity Galactic plane region, the 3EG catalog actually adopts two different and separate criteria for source detection thresholds. A source

is listed in the catalog if it is detected at 4σ or higher for $|b| > 10^\circ$, and 5σ or higher for $|b| < 10^\circ$. Because of the differences in source sensitivities, the EGRET catalog cannot be taken as a uniform sampling of the γ -ray sky, and this has to be taken into account in all source population studies.

1.2 Source distributions of the unidentified sources

EGRET measured the source location, the γ -ray light curve and the spectra of the individual γ -ray sources. Typical EGRET observations lasted for a period of about 2 weeks, although some observations were as short as a week, while others were as long as 3 to 5 weeks. EGRET's threshold sensitivity (> 100 MeV) for a single 2-week observation was $\sim 3 \times 10^{-7}$ photons $\text{cm}^{-2} \text{s}^{-1}$. Details of the EGRET instrument, and data analysis techniques are given elsewhere (Thompson et al. 1993; Hartman et al. 1999).

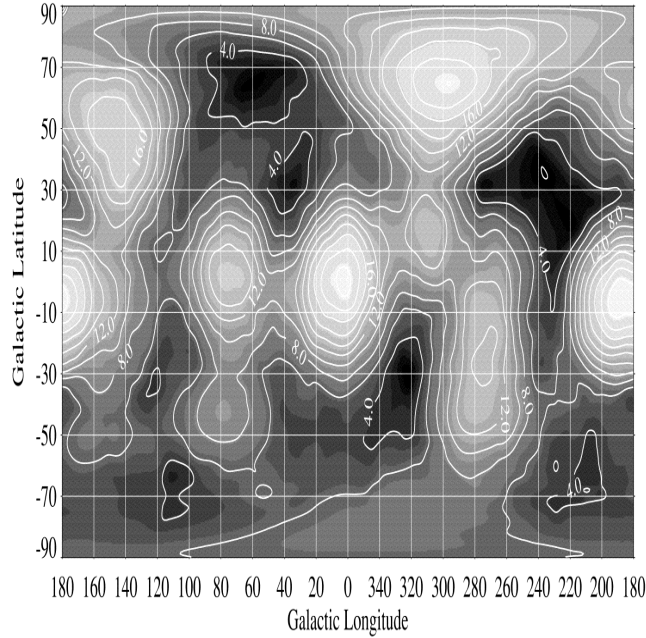


Figure 3. EGRET sky exposure in units of $10^8 \text{ cm}^2 \text{s}$ for photon energies > 100 for the sum of CGRO 1, 2, 3 and 4 (1991 April - 1995 October). The intervals of contour spacing are 2×10^8 .

Source distributions of the unidentified EGRET sources are often useful in understanding the overall properties of these sources, particularly in providing a constraint on the average distances or luminosities of the sources. One of the first studies of the unidentified source distributions as a function of Galactic latitude and longitude was carried out by Mukherjee et al. (1995), using the source lists available at that time. The unidentified Galactic sources were found to have an average distance between 1.2 and 6 kpc, and isotropic luminosities in the range $(0.7 - 16.7) \times 10^{35} \text{ erg s}^{-1}$. These results were in agreement with the earlier findings of Bignami & Hermsen (1983) for the COS-B data.

Figure 4 shows the latitude distribution of all the unidentified sources in the 3EG catalog. In terms of source counts, 90% of the EGRET sources at $b < 10^\circ$ are unidentified. At high latitudes, $b > 10^\circ$ where a large number of the EGRET sources are identified as blazars, the fraction of the unidentified sources is 50%. Gehrels (2000) and Grenier (2000) note that there is an excess of faint sources at mid-latitudes, $10^\circ < b < 30^\circ$ that are fainter and softer than the low latitude sources, on the average. It has been suggested that these mid latitude sources could possibly be associated with the Gould Belt structure (Gehrels 2000; Grenier 2000). Figure 4 (bottom) shows the longitude distribution of the unidentified sources in the 3EG catalog.

Log N -log S studies of EGRET sources are often useful in learning about the general characteristics of EGRET source populations. One of the first such studies was carried out by Ozel & Thompson (1996) for comparing unidentified EGRET sources and EGRET-detected AGN populations. Similarly, Reimer & Thompson (2001) have studied log N -log S distributions for 3EG sources. Population studies of EGRET sources, taking advantage of source distributions and correlations have been used to infer the nature of EGRET unidentified sources. We have not summarized these studies in this article, but we point to several review articles that describe these in some detail (Mukherjee, Grenier & Thompson 1997; Caraveo 2002).

1.3 Counterpart searches - challenges in the identification process

EGRET's better sensitivity and superior angular resolution in comparison to COS-B led to nearly a ten-fold increase in the number of γ -ray source detections over COS-B. However, this did not necessarily lead to an increase in the number of source identifications. The identification of the EGRET sources, particularly those close to the Galactic plane has proved to be challenging. The error box of the typical EGRET source

is large, $\sim 0.5^\circ - 1^\circ$, and identifications and counterpart searches on the basis of position alone has been difficult. This is further hampered for the low latitude sources by the presence of bright Galactic diffuse emission along the plane. Also, a lack of tight correlation between the γ -ray flux and other properties, like X-ray flux, core radio flux, etc., allows only the strongest sources to be identified on the basis of position alone.

Counterpart searches of γ -ray sources usually start with looking for “more of the same” kinds of sources. So far the identified sources fall into two major source classes: blazars and pulsars. Most of the blazar identifications are at high Galactic latitudes, where the source fields are less crowded, positions are better determined, and additional resources such as γ -ray flux variability, correlated with variability at radio or optical

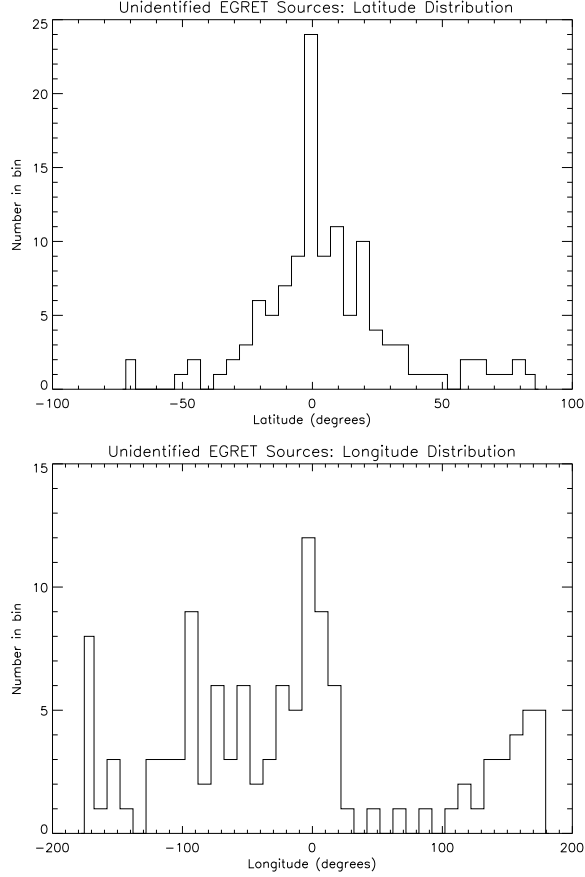


Figure 4. Distributions in (top) latitude and (bottom) longitude of all the unidentified sources in the 3EG catalog.

bands make the identifications more confident. All the pulsars detected by EGRET are at low latitudes. It is therefore quite likely that at least a fraction of the unidentified sources at $b < 10^\circ$ will belong to the pulsar class. In this case, a definite time signature will be needed in the γ -ray data, which was usually difficult in the case of EGRET data. Similarly, it is likely that a large fraction of the high latitude unidentified sources, with better source positions obtained in the future with GLAST, will turn out to be associated with blazars (see the chapter by Torres).

An “elusive template” for possibly another class of γ -ray source is provided by Geminga, the only radio-quiet pulsar in the EGRET data (see Caraveo, Bignami & Trümper 1996 for a review). Although Geminga is probably the nearest member of this class (see also discussion on 3EG J1835+59 below), it is possible that other candidates will be found in the era of GLAST. In fact, some of the fainter, mid-latitude EGRET sources (more local Galactic population) could be accounted for by Geminga-like pulsars (Gehrels et al. 2000).

For a γ -ray source that does not definitely belong to the blazar or pulsar category, a search for counterpart usually relies on one of two techniques. Generally, identifications of γ -ray sources are carried out using either the help of population studies or on a case-by-case basis relying on information based on multiwavelength observations. In the former, γ -ray source distributions and properties of populations of γ -ray sources are compared with properties of other source classes. In the latter case, error boxes of individual γ -ray sources are studied using information obtained at other wavebands. This chapter attempts to summarize the multiwavelength approach to the identification of γ -ray sources.

1.4 The multiwavelength approach

Studying the optical to X-ray data of 3EG unidentified sources has in several cases shed some light on the nature of the EGRET source. This approach has now been applied successfully to several of the EGRET sources. The first steps in this process usually involve the study of archival *ASCA* or *ROSAT* data of the EGRET fields, with a follow up of optical and/or radio observations of X-ray sources in the error boxes. One of the first exhaustive studies of this kind was carried out by Roberts, Romani & Kawai (2001) who presented a catalog of *ASCA* images in the 2-10 keV band of fields containing bright EGRET sources. Although time consuming, this “case-by-case” method has met with success in several cases. In the following we describe some of the individual cases, discussed in no particular order.

2. Blazars and EGRET unidentified sources

The majority of the identified EGRET sources are blazars (flat-spectrum radio quasars and BL Lac objects) - the only kinds of AGN that EGRET has detected with any measure of confidence. Mattox et al. (1997) and Mattox, Hartman, & Reimer (2001) have studied the statistical issues concerning the identification of EGRET sources with blazars, and have presented the probabilities of association of individual sources with blazars. In the 3EG catalog Mattox et al. (2001) find that 46 EGRET sources may be confidently identified with blazars, while an additional 37 are plausibly identified with radio sources.

The blazars seen by EGRET all share several common characteristics: they are radio-loud, flat spectrum sources, with radio spectral indices $0.6 > \alpha > -0.6$ (von Montigny et al. 1995). Most of the EGRET sources confidently identified with blazars are characterized by strong radio fluxes (> 500 mJy) at 5 GHz. EGRET blazars have a continuum spectrum that is non-thermal, and are characterized by strong variability and optical polarization. In counterpart searches of unidentified EGRET sources, the EGRET source is usually examined to see if it fits the blazar template. Here we describe multiwavelength studies of EGRET fields that have led to the identification of the EGRET source with a blazar.

2.1 A Blazar counterpart for 3EG J2016+3657

This is an example of a low-latitude EGRET source, 3EG J2016+3657, that was identified with a blazar behind the Galactic plane, B2013+370. Although rare, it is certainly not unexpected that several of the “Galactic” unidentified sources will turn out to be blazars, given the isotropic distribution the of γ -ray blazar population.

3EG J2016+3657 was identified after a detailed study was carried out of archival X-ray data, with follow-up optical observations of the the γ -ray error box (Mukherjee et al. 2000). The identification was soon confirmed by Halpern et al. (2001a) who concluded that B2013+370 was the most likely counterpart, after optical spectroscopic identifications of all soft and hard X-ray sources in the error circle of the EGRET source eliminated the other candidates. We discuss these results here in some detail in order to illustrate the multiwavelength “strategy” of the identification of 3EG sources.

3EG J2016+3657 & 3EG J2021+3719 are two sources in the Cygnus region probably associated with the unidentified COS-B source 2CG 075+00 (Pollack et al. 1985). The error circles of both 3EG J2016+3657 & 3EG J2021+3716 are covered by archival X-ray imaging observations with *ROSAT* (PSPC and HRI) and *ASCA*, as well as *Einstein* IPC (Wil-

son 1980). Figure 5 shows the *ROSAT* soft X-ray (0.2 – 2.0 keV) and HRI image of the region, along with the EGRET error circles. The X-ray point source positions, marked in the figure, derived from the *ROSAT* analysis were used to search for counterparts to the X-ray sources.

Halpern et al. (2001a) used the MDM 2.4 m and the KPNO 2.1 m telescopes to obtain a complete set of optical identifications of all X-ray point sources within the error circles of the two EGRET sources. It turns out that other than source # 1 and # 3 in figure 5, the other sources in the EGRET fields are either cataclysmic variables (CVs), or Wolf-Rayet stars or binary O stars, all unlikely to be γ -ray emitters. (Note, however, under some circumstances Wolf-Rayet binaries are expected to be significant gamma-ray emitters (e.g. Benaglia & Romero 2003). Possible high energy emission of early type binaries is also discussed in the chapter by Rauw in this book). The two sources of interest in the field are the supernova remnant (SNR) CTB 87 (source # 1) and the blazar-like radio source B2013+370 (source #3). Of the two the blazar B2013+370 was suggested as the most likely candidate. The other source, CTB 87, is too weak and too far away to be the likely candidate, and was therefore disfavored (see Halpern et al. 2001a; Mukherjee et al. 2000 for details. However, a revised distance to CTB 87 places it half as far as previously believed (Kotthes et al. 2003), which weakens this argument slightly.)

Other characteristics of B2013+370 supports the identification with 3EG J2016+3657. B2013+370 has all the blazar-like characteristics of typical EGRET identifications - compact, extragalactic, non-thermal radio source, variable at optical and mm (90 GHz, 142 GHz) wavelengths, with a 5 GHz flux of ~ 2 Jy. The spectral energy distribution (SED) of 3EG J2016+3657 is characterized by a synchrotron peak at lower energies, a Compton peak at higher energies, with most of the power output in γ -rays and confirms the blazar nature of the source. All these observations suggest that 3EG J2016+3657 fits the blazar template, and that B2013+370 is the identification for the EGRET source.

2.2 3EG J2027+3429: Another blazar behind the Galactic plane?

3EG J2027+3429, also in the Cygnus region, has been recently suggested to be another blazar behind the Galactic plane. Using a multi-wavelength strategy, Sguera et al. (2003) have suggested the BeppoSAX X-ray source WGA J2025.1+3342, to be associated with the EGRET source. A search for X-ray counterparts in the EGRET error box using archival BeppoSAX data yielded several X-ray point sources, with WGA

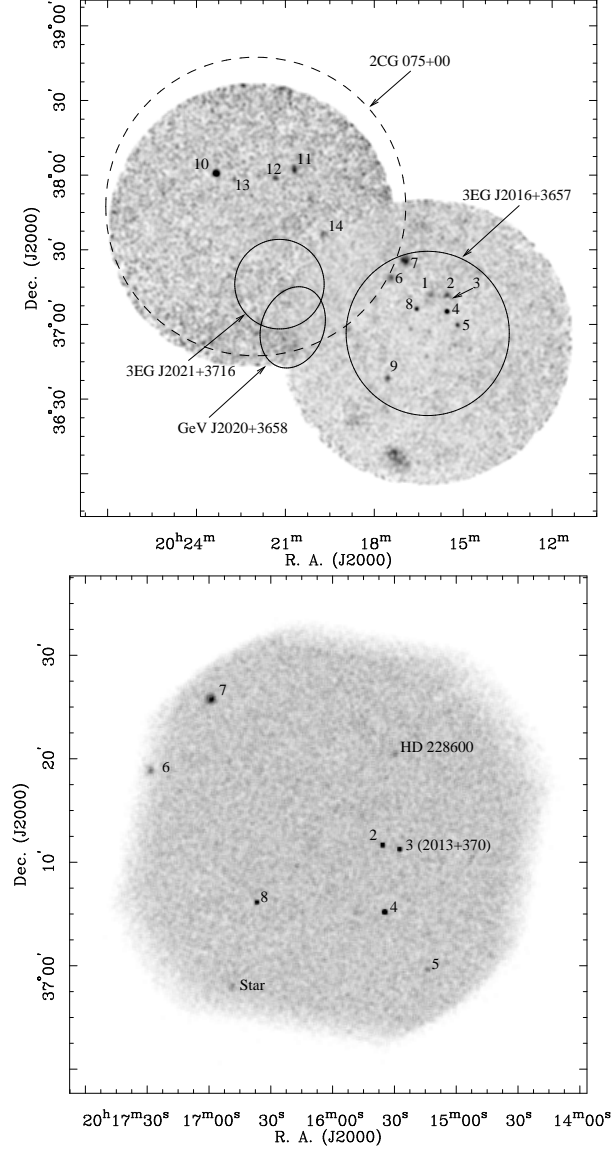


Figure 5. (Top) *ROSAT* soft X-ray image of 3EG J2016+3657 and 3EG J2021+3716. The circles for the two 3EG sources correspond to the $\sim 95\%$ confidence contours. The dashed circle corresponds to the COS-B source 2CG 075+00. The GeV Catalog source (Lamb & Macomb 1997) is also shown. The minimum detectable intrinsic flux for the *ROSAT* image was $6.5 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. (Bottom) *ROSAT* HRI X-ray image of the field around 3EG J2016+3657. The image shows the sources 2 and 3 (B2013+370) as clearly resolved point sources. Both figures are from Mukherjee et al. (2000).

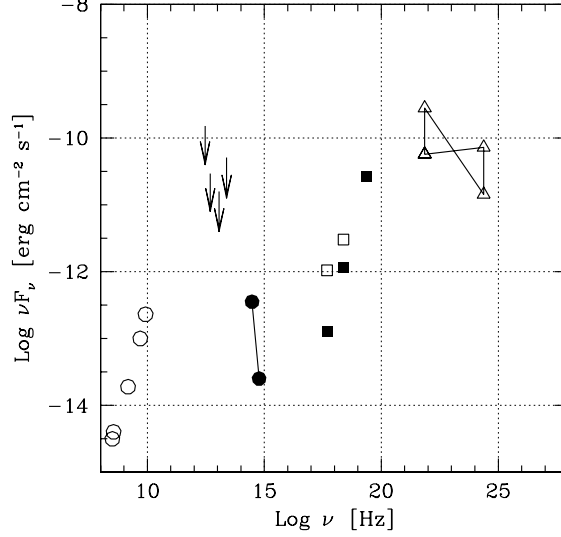


Figure 6. Spectral energy distribution (SED) of 3EG J2027+3429, assuming that it is associated with the X-ray source WGA J2025.1+3342. The symbols are as follows: open circles - radio, filled circles - optical, open and filled squares - BepoSAX, triangles - EGRET. The arrows correspond to IRAS upper limits. Note the synchrotron and inverse Compton humps characteristic of EGRET blazars. Figure from Sguera et al. (2003).

J2025.1+3342 being the strongest. WGA J2025.1+3342 is also highly variable at X-ray energies, and has a flat spectrum in the range 1-100 keV. A cross-correlation of these X-ray sources with radio catalogues found only two of the X-ray point sources in the EGRET error circle to be associated with radio sources, with WGA J2025.1+3342 being the brightest radio source. At radio wavelengths, the source was found to have a flat spectrum in the range 0.3-10 GHz, and is a bright, compact object. Optical observations of the source by Sowards-Emmerd et al. (2003) suggest that the spectrum has emission lines of the Balmer series, and is therefore a quasar at $z = 0.219$. All these characteristics point towards a blazar identification of 3EG J2027+3429. Figure 6 shows the SED of 3EG J2027+3429, assuming the identification is the correct one. The SED is typical of a low-frequency peaked blazar, with the synchrotron peak at mm/far IR range and the inverse Compton peak at γ -ray energies (Sguera et al. 2003). Once again, the analysis of archival radio, IR, optical and new X-ray observations has suggested an identification for an EGRET unidentified source. If correct, this is the second γ -ray blazar behind the Galactic plane, and is very likely not to be the last.

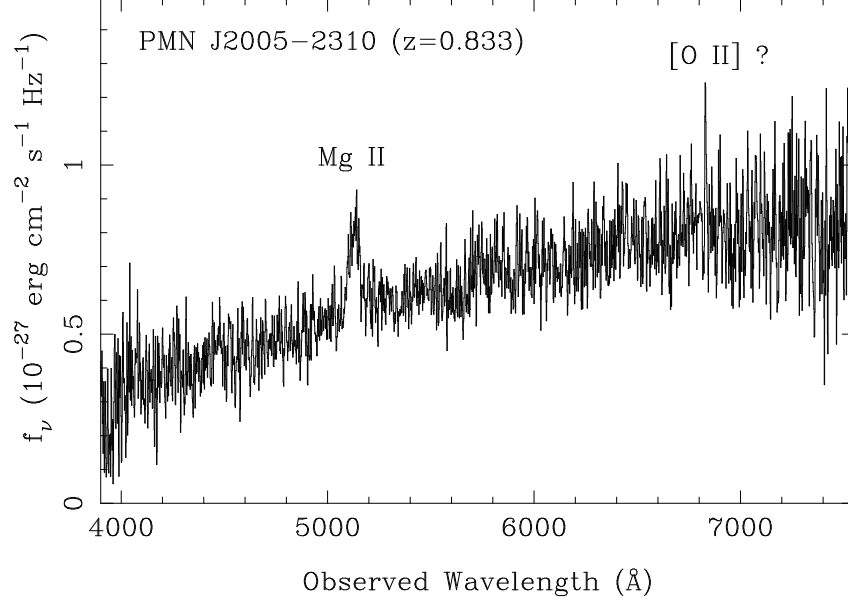


Figure 7. Spectrum of the optical counterpart of PMN J2005-2310, suggested as the counterpart of 3EG J2006-2321, from the KPNO 2.1 m. Analysis of archived radio, X-ray data together with optical spectroscopy and polarimetry of the region helped in the identification of the 3EG source. Figure from Wallace et al. (2002).

2.3 3EG J2006-2321: A blazar with a weak radio flux

Yet another blazar identification was made for the EGRET source 3EG J2006-2321 (Wallace et al. 2002), using a similar multiwavelength approach. The source was identified with the flat-spectrum radio quasar PMN J2005-2310, after a careful study of the field at radio, optical and X-ray energies. Its optical counterpart has $V = 19.3$ and $z = 0.833$. Figure 7 shows the spectrum of PMN J2006-2310 from KPNO 2.1 m. Interestingly, this source has a 5 GHz flux density of 260 mJy, which is the lowest of the 68 identified blazars in the 3EG catalog. Although this is atypical of most EGRET blazar identifications (bright, ~ 1 Jy, radio sources at 5 GHz), the identification is still plausible because the radio to γ -ray flux density ratio is comparable to the “confident” blazar identifications (see Figure 8 and the discussion in §2.4). As Wallace et al. rightly point out, other weaker EGRET unidentified sources are likely to be identified with low flux density radio sources in the future.

2.4 Blazars in the northern sky

The γ -ray blazar content of the northern sky was recently explored by Sowards-Emmerd et al. (2003), who used radio survey data to re-evaluate correlations of flat spectrum radio sources with the EGRET sources. This is similar to the approach traditionally used for the selection of blazar candidates in the past for EGRET sources (Hartman et al. 1999 in the 3EG catalog; Mattox et al. 2001). Sowards-Emmerd et al. additionally carried out follow-up optical spectroscopic observations with the Hobby Eberly Telescope (HET) to confirm the AGN candidate. This survey has resulted in the confirmation of the existing EGRET blazars and suggested blazar candidates for several 3EG unidentified sources in the northern sky. If confirmed, the association of 3EG sources at $b > 10^\circ$ with blazar-like radio sources is found to be 70%. Unlike previous associations of EGRET sources with bright, 1 Jy radio sources (Hartman et al. 1999), Sowards-Emmerd et al. have suggested plausible counterparts down to fluxes of ~ 100 mJy at 8.4 GHz. It is likely that in the future GLAST era, better multiwavelength follow-ups will result in the association of more γ -ray sources with weaker (< 100 mJy) radio sources. In that case, the really interesting question will be what is the nature of the “non-blazar” EGRET sources.

Another multiwavelength study of “lower confidence” γ -ray blazars in the 3EG catalog was carried out by Halpern et al. (2003), who identified optical counterparts of 16 3EG sources associated with blazars and obtained nine redshifts. In each of these cases very little optical information was previously available. Although the radio identification of EGRET sources are not flux limited, because of source confusion due to the large EGRET error circles, only the brightest radio sources (> 500 mJy) are secure identifications. Figure 8 compares the radio and γ -ray fluxes of the high confidence blazar identifications of Mattox et al. (2001) with that of the 16 3EG sources studied by Halpern et al. (2003). These 16 blazars have lower radio fluxes than the high-confidence blazar identifications, but are still plausible counterparts as they have the same radio to γ -ray flux ratios. It is likely that many of the unidentified 3EG sources are blazars with lower radio fluxes. In fact, this was the case for the AGN identification of 3EG J2006-2321 discussed earlier.

2.5 Blazars in the southern sky

On a smaller scale, Tornikoski et al. (2002) have carried out high frequency radio observations at 90 and 230 GHz of a dozen 3EG sources in the southern hemisphere that were tentatively identified as blazars in the 3EG catalog. These radio observations have confirmed 5 of the

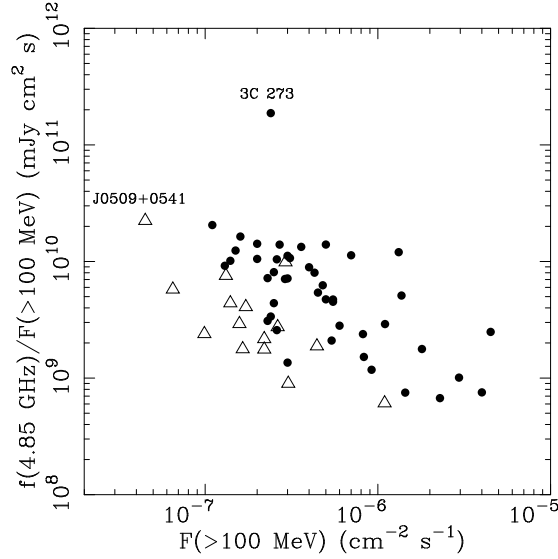


Figure 8. Ratio of radio (4.85 GHz) flux density to the peak γ -ray flux of the confident EGRET blazar identifications (circles) compared with that for the 16 3EG sources tentatively identified with blazars (triangles). Note that the marginally identified blazars are still plausible identifications, although they have lower radio fluxes, as they fall within the same radio/ γ -ray flux ratio. Figure from Halpern et al. (2003).

sources as blazars. An additional 4 unidentified EGRET sources have been identified as likely blazars, based on their activity at mm wavelengths.

3. EGRET sources and radio galaxies

Other than blazars, the only extragalactic sources to have been detected by EGRET are the radio galaxy Cen A, and the normal galaxy LMC. Radio galaxies are not known to be strong γ -ray emitters. In the 3EG catalog, Cen A (NGC 5128) is the only radio galaxy to be identified with an EGRET source at energies above 100 MeV (Sreekumar et al. 1999), and provides the first clear evidence that an AGN with a large-inclination jet can be detected at γ -ray energies above 100 MeV. This is unlike the EGRET blazars which are believed to have jets nearly aligned along our line-of-sight. Cen A's jet is offset by an angle of about 70° (Bailey et al. 1986; Fujisawa et al. 2000). Cen A is also a weak γ -ray source and has a derived γ -ray luminosity weaker by a factor of 10^{-5}

compared to the typical EGRET blazar. Cen A was probably detected by EGRET as it is the brightest and nearest radio galaxy ($z = 0.0018$, ~ 3.5 Mpc). Cen A was the only one of its kind in the 3EG catalog, until recent reports of a couple of other candidate radio galaxies to be identified with EGRET sources (see below). It is very likely that the detection of more radio galaxies by EGRET has been limited by its threshold sensitivity. If this is true then there exists the exciting possibility that instruments like GLAST, with much higher sensitivity, will detect more radio galaxies in the future.

3.1 3EG J1621+8203: The radio galaxy NGC 6251?

In an effort to investigate the nature of the EGRET source 3EG J1621+8203, Mukherjee et al. (2002) have again used a multiwavelength approach and examined X-ray images of the field from *ROSAT* PSPC, *ROSAT* HRI, and *ASCA* GIS, as well as radio and optical surveys with follow-up optical spectroscopic classification of active objects within the error ellipse of the EGRET source. Except for one, all X-ray sources in the EGRET error box were identified with ordinary QSOs or coronal emitting stars, all unlikely to be counterparts of the γ -ray source. The most notable object in the γ -ray error box is the bright FR I radio galaxy NGC 6251, which Mukherjee et al. (2002) have suggested as a plausible counterpart for 3EG J1621+8203.

As in the case of Cen A, 3EG J1621+8203 has a lower γ -ray luminosity (3×10^{43} ergs/s) than that of other EGRET blazars (typically 10^{45} to 10^{48} ergs/s). Compared to Cen A, NGC 6251 is much further away ($z = 0.0234$), which raises the question whether it is luminous enough to have been detected by EGRET. However, NGC 6251 is most likely still detectable by EGRET because of its smaller jet angle (45°) in comparison to that of Cen A (70°).

If 3EG J1621+8203 corresponds to NGC 6251, then it would be the second radio galaxy to be detected in high energy γ -rays. NGC 6251 is a notable candidate because of the possible link between FR I radio galaxies and BL Lac objects; FR I radio galaxies are hypothesized to be the likely parent population of BL Lac objects (Urry & Padovani 1995).

3.2 3EG J1735-1500: Another new radio galaxy

Yet another possible radio galaxy counterpart to an EGRET source was recently suggested by Combi et al. (2003) for 3EG J1735-1500. In this case, the NRAO VLA Sky Survey (NVSS) (Condon et al. 1998) was used to examine the radio sources within the 95% EGRET error

box. The radio galaxy J1737-15 was suggested as the most likely counterpart. Combi et al. noted, however, that another likely counterpart of 3EG J1735-1500 could be the flat-spectrum, compact weak radio source PMN J1738-1502, also located in the error box. The lack of a unique counterpart for an EGRET source, following a multiwavelength survey of the error box is not surprising. In fact, this illustrates the problems associated in the counterpart searches for EGRET sources, which typically have large $\sim 1^\circ$ error boxes. In this case, future observations with GLAST will help confirm the identification for 3EG J1735-1500.

4. Radio quiet isolated neutron stars

Caraveo (2002) has referred to isolated neutron stars (INS) as “elusive templates” for the identification of the γ -ray sources. Geminga is the best example of this source class in the EGRET catalog, and provides a template of characteristics that includes behavior as a pulsar at X-ray and γ -ray energies, but faint in optical wavelengths, with sporadic or no radio emission (see Caraveo, Bignami, & Trümper 1996 for a review). The question of whether there are other Geminga-like pulsars in the 3EG unidentified source catalog has often been raised. It has been suggested that perhaps Geminga-like sources could account for the weaker mid-latitude 3EG unidentified sources (Gehrels et al. 2000). On a case-by-case basis, the multiwavelength strategy has been used to suggest isolated neutron star counterparts to some EGRET sources. In fact, the identification of Geminga came after a successful multiwavelength campaign, carried out over a 20 year period (see Bignami & Caraveo 1996 for a review). We describe a few other recent examples below.

4.1 The case of 3EG J1835+5918

3EG 1835+5918 is the brightest and most accurately positioned unidentified EGRET source that has been persistently detected at high energy γ -rays (Nolan et al. 1996). 3EG J1835+5918 is located at high Galactic latitude at $l = 88.74^\circ$, $b = 25.07^\circ$, well away from the confusing diffuse emission. The source shows no strong evidence of variability (Reimer et al. 2000), and has a spectral index in the 70 MeV to 4 GeV range of -1.7 (Hartman et al. 1999). Despite its small error circle, 3EG J1835+5918 remained a mystery, and was the subject of several multifrequency studies (Reimer et al. 2000; Carramiñana et al. 2000; Mirabal et al. 2000; Reimer et al. 2001; Mirabal & Halpern 2001). No known flat-spectrum radio source was found in earlier searches of its error circle (Mattox et al. 1997). Its temporal and spectral variability indicate that it is more similar to pulsars than blazars. We present the steps towards the identi-

fication of 3EG J1835+5918 in some detail as a classic example of the use of the multifrequency strategy in the identification of EGRET sources.

The error circle of 3EG J1835+5918 has been the subject of intense multiwavelength study. Analysis of archival *ROSAT* HRI and PSPC as well as *ASCA* observations of the EGRET field yielded several point-like X-ray sources within the error circle of 3EG J1835+5918 (Mirabal et al. 2000; Reimer et al. 2001). Optical identifications of the X-ray sources were carried out independently by Mirabal et al. (2000) and Carramiñana et al. (2000). Most of the sources were found to be either radio-quiet QSOs or coronal emitting stars or a galaxy cluster. In addition, analysis of archival radio data (VLA, NRAO and WENSS) revealed only three sources within the 99% error contour of 3EG J1835+5918, all of which were fainter than 4 mJy at 1.4 GHz. The positions of the quasars and radio sources in the vicinity of the EGRET source are shown in figure 9 (Mirabal et al. 2000). Three of the interesting sources are individually marked in the figure: RX J1834.1+5913 is the brightest quasar in the EGRET error ellipse, VLA J1834.7+5918 is the brightest of the three weak radio sources within the EGRET error circle, and RX J1836.2+5925 is an object that does not seem to have an optical counterpart. No blazar-like radio sources were found in the vicinity of the EGRET source. The brightest neighbouring radio sources were steep-spectrum radio galaxies or quasars.

In fact, the broadband characteristics of 3EG J1835+5918 were examined to see if they fall within the multiwavelength parameters of the blazar class of sources seen by EGRET. Figure 10 (Mirabal et al. 2000) shows the radio, optical, X-ray and γ -ray fluxes of the sample of well-identified blazars in Mattox et al. (1997). For comparison, the fluxes of the brightest possible QSO counterpart, RX J1834.1+5913, and the most likely radio counterpart VLA J1834.7+5918 are also shown. A low energy synchrotron component and a high energy inverse Compton component is assumed. Note that both the candidates are found to lie at the faint end of the distribution, making it unlikely that 3EG J1835+5918 is a blazar.

RX J1836.2+5925, indicated in figure 9, is the most intriguing object within the error circle of 3EG J1835+5918. This object has no optical counterpart to a limit of $V > 25$ (Mirabal & Halpern 2001), and has been suggested as a radio quiet pulsar, and the most promising counterpart to the enigmatic γ -ray source 3EG J1835+5918 (Reimer et al. 2001; Mirabal & Halpern 2001). The ratio of the γ -ray flux above 100 MeV of 3EG J1835+5918 to the X-ray flux (0.12 - 2.4 keV) of RX J1836.2+5925 is similar to that of other similar candidates considered to be of pulsar origin (Reimer et al. 2001). The lack of an optical counterpart, and the

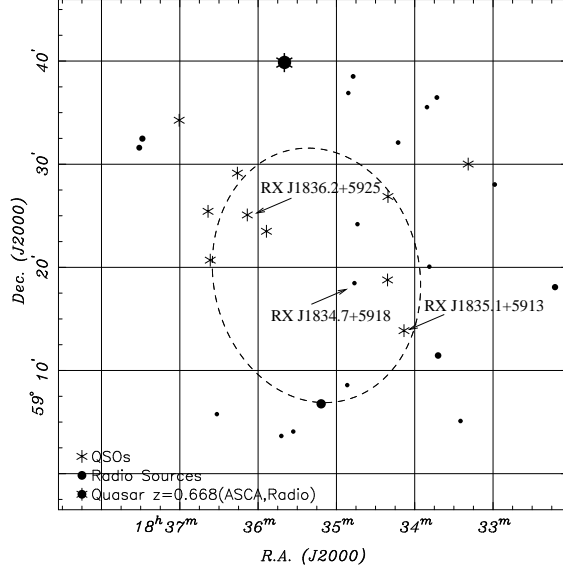


Figure 9. Quasars and radio sources within the error circle (shown with dashed lines) of 3EG J1835+5918. The positions of the three interesting objects, described in the text, are individually marked (Mirabal et al. 2000).

non-variability of the γ -ray source are all characteristic signatures for a radio-quiet pulsar.

Recently, Mirabal & Halpern (2001) have presented arguments that RX J1836.2+5925 is indeed a neutron star, and could be a nearby, rotation-powered radio-quiet γ -ray pulsar. Although its X-ray flux is at least 10 times fainter than that of Geminga, RX J1836.2+5925 is possibly older or more distant than Geminga, and the most likely counterpart of 3EG J1835+5918.

Using deep *Chandra* data, along with HST and radio observations of RX J1836.2+5925, Halpern et al. (2003) have presented further, conclusive evidence that an older, possibly more distant Geminga-like pulsar is responsible for the origin of γ -rays from 3EG J1835+5918. Figure 11 shows the *Chandra* ACIS-S spectrum of RX J1836.2+5925 with a fit that requires a two-component model: a thermal blackbody of $T_\infty \simeq 3 \times 10^5$ K with a power law component of photon index $\Gamma \simeq 2$. This non-thermal extension to the X-ray spectrum is characteristic of the EGRET pulsars and further supports the identification of the EGRET source.

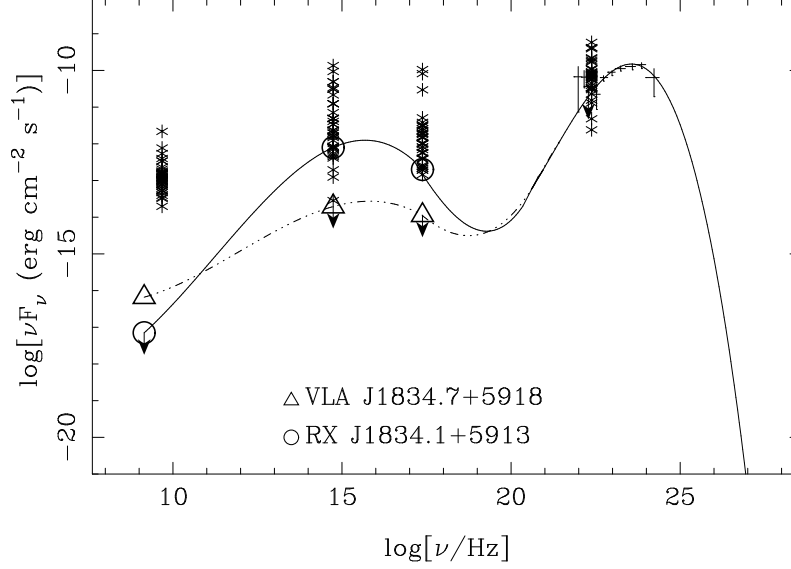


Figure 10. The broadband fluxes of EGRET blazars, as compiled from the literature, are shown as asterisks. The X-ray and radio data of the two most likely counterparts, RX J1834.1+5913 and VLA J1834.7+5918, if 3EG J1835+5918 were a blazar, are also shown. Note that the two candidates lie at the faint end of the distribution, making it unlikely that 3EG J1835+5918 is a blazar, at least with properties similar to other EGRET-detected blazars (Mirabal et al. 2000).

4.2 Other neutron star candidates

Two other examples of neutron star candidates are 3EG J0010+7309 (Brazier et al. 1998) and 2EG J2020+4026 (3EG J2020+4026) (Brazier et al. 1996). 3EG J2020+4026 is coincident with the γ -Cygni supernova remnant G78.2+2.1. Brazier et al. (1996) studied *ROSAT* PSPC data on this region, and found a single, point-like X-ray source in the EGRET 95% error contour, RX J2020.2+4026, the only plausible counterpart. The flux ratio at γ -ray and X-ray energies, F_γ/F_X was found to be ~ 6000 , similar to that of Geminga, and very different from non-pulsar sources. Brazier et al. suggested RX J2020.2+4026 as the counterpart of the EGRET source, and 3EG J2020+4026 as possibly a young pulsar. No radio source was found at the position of the X-ray source, and it is likely that the pulsar is Geminga-like.

3EG J0010+7309 (2EG J0008+7307) is a similar example of a possible pulsar/neutron star candidate. It has a smaller error box compared to most EGRET unidentified sources because it was clearly visi-

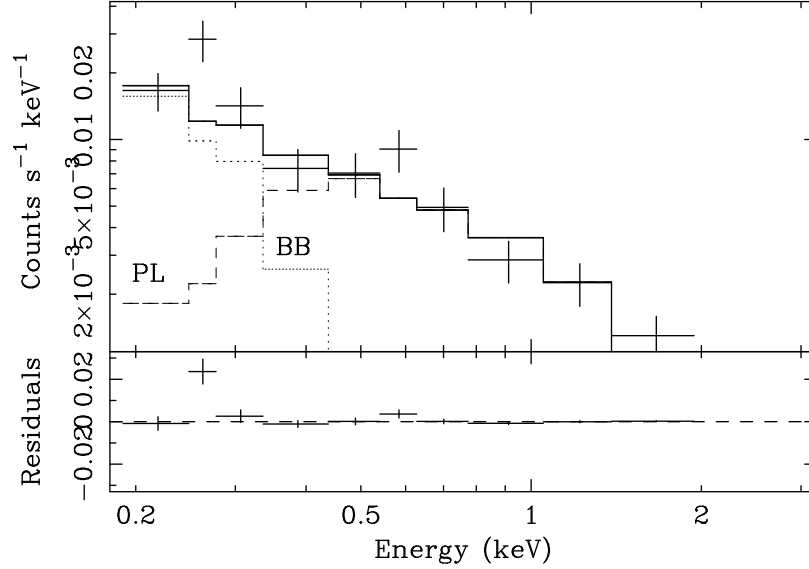


Figure 11. *Chandra* ACIS-S3 spectrum of RX J1836.2+5925, the neutron star counterpart of 3EG J1835+5918. Data shown as crosses; best fit model as a thick line, with contributions of a blackbody (BB) and power-law (PL) components. Difference between data and model is shown in the bottom panel. Figure from (Halpern et al. 2003).

ble above 1 GeV. The source is spatially coincident with the supernova remnant CTA 1. X-ray data (*ROSAT* and *ASCA*) of this region was studied by Seward et al. (1995) and Slane et al. (1997) and re-examined by Brazier et al. (1998) in some detail in an effort to identify 3EG J0010+7309. The small EGRET error contour encloses one *ROSAT* source, RX J0007.0+7302, which Brazier et al. (1998) suggest as the counterpart of the EGRET source. The X-ray source is believed to be a pulsar. No optical counterpart was found for the X-ray source, suggesting a neutron star nature of the source. No radio pulsed source was detected at the position of the X-ray source either. Brazier et al. (1998) suggest that the X-ray source is possibly a radio quiet pulsar.

5. Young pulsar candidates

The majority of the identified EGRET sources at low Galactic latitudes are pulsars. In view of this fact, pulsars are a natural template for counterpart searches for the Galactic plane 3EG sources (see Caraveo 2002 for a review). In fact, there have been several efforts for pulsar

searches at radio wavelengths (e.g. Nice & Sayer 1997; Nel et al. 1996). Other studies using Parkes data have yielded radio pulsar candidates for 3EG J1420-6038, 3EG J1837-0606 (D’Amico et al. 2001) and 3EG J1013-5915 (Camillo et al. 2001). Torres, Butt & Camilo (2002) have recently reported on a correlative study between the low latitude 3EG sources and the newly discovered pulsars in the Parkes multibeam radio survey (Manchester et al. 2001), confirming earlier studies, but not yielding any new counterparts. Other possible associations include PSR B1046-58 with 3EG J1048-5840 (Kaspi et al. 2000; Thompson 2001). Confirmation of γ -ray pulsars will only come from measuring the timing characteristics at γ -ray energies, and will be a priority for future γ -ray missions such as GLAST. Here we discuss a couple of individual cases where extensive multifrequency efforts have been utilized to suggest pulsar counterparts for 3EG sources.

5.1 3EG J2021+3716: The young radio pulsar PSR J2021+3651

This is a classic example of how multiwavelength studies of the EGRET field of 3EG J2021+3716 (GeV J2020+3658) was used to suggest a pulsar counterpart for the EGRET source. Along with 3EG J2016+3657, this source is possibly associated with the COS-B source 2CG 075+00. Both sources were discussed earlier in §2.1, where we described multifrequency studies leading to the identification of 3EG J2016+3657 with a blazar counterpart. Figure 5 shows the *ROSAT* PSPC data covering the error boxes of the two EGRET sources, as well as the contour of the COS-B source. Roberts et al. (2002) have recently reported on multiwavelength studies of GeV J2020+3658 in which they carried out a deep search for radio pulsations toward the unidentified *ASCA* source AX J2021.1+3651 in the error box of the EGRET source. AX J2021.1+3651 is one of the hard X-ray sources listed in the *ASCA* catalog of potential X-ray counterparts of GeV sources, a catalog resulting from X-ray studies of the EGRET fields (Roberts, Romani, & Kawai 2001). Figure 12 shows the *ASCA* GIS image of the γ -ray source region. Roberts et al. (2002) observed AX J2021.1+3651 with the Wideband Arecibo Pulsar Processor (WAPP) and discovered a new young and energetic pulsar PSR J2021.1+3651, which they argue is the counterpart to the EGRET source GeV J2020+3658. WR 141 is a Wolf-Rayet star also in the field of view. Figure 13 shows the 1.4 GHz pulse profile of PSR J2021+3651. The positional coincidence of the pulsar with GeV J2020+3658, the hard spectrum of the EGRET source, and its low variability, and the fact that Roberts et al. (2002) find high inferred spin-

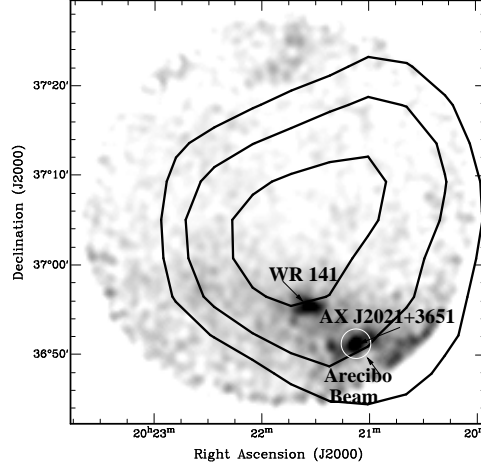


Figure 12. ASCA GIS image (2-10 keV) of the error box of the γ -ray source GeV J2020+3658. The contours correspond to 68%, 95% and 99% confidence levels. The position of the ASCA unidentified hard X-ray source, suggested as the counterpart of the EGRET source, is shown. The circle corresponds to the 3' Arecibo beam. Figure from Roberts et al. (2002).

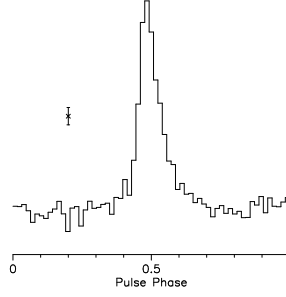


Figure 13. Pulsar profile of PSR J2021+3651 at 1.4 GHz. Figure from Roberts et al. (2002)

down luminosity for the pulsar strongly argue that the two sources are related. Confirmation of the identification will hopefully come in the future with GLAST observations.

5.2 The case of 3EG J2227+6122

3EG J2227+6122 is another source at low Galactic latitude ($l = 106.^\circ 5$, $b = 3.^\circ 2$) that was the subject of recent multiwavelength study (Halpern et al. 2001b). X-ray, radio, and optical observations of the EGRET field together point to the possibility that 3EG J2227+6122 is most likely a young, energetic pulsar, with an associated X-ray pulsar wind nebula (PWN), enclosed in a small non-thermal radio shell.

Figure 14 shows a composite *ROSAT* HRI image of the error circle of 3EG J2227+6122, showing 6 point-like X-ray sources within the EGRET 95% contour (Halpern et al. 2001b). All sources, except # 1 have optical spectroscopic identifications obtained using the KPNO 2.1 m telescope and Goldcam spectrograph, and are either bright K and M type stars, or emission-line stars. Source # 1, RX J2229.0+6114, also detected in

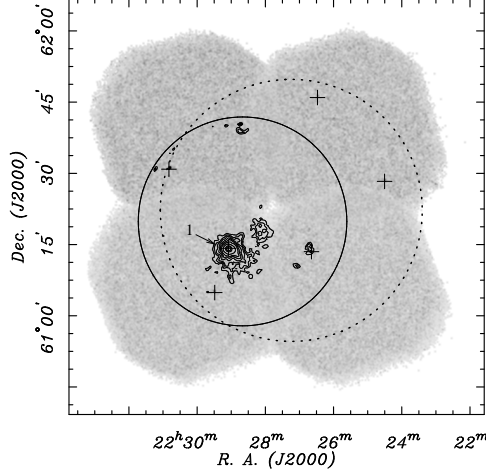


Figure 14. Composite ROSAT HRI image of the 3EG J2227+6122 field. The dashed circle corresponds to the 95% error contour of the EGRET source. Except for # 1, all the X-ray point sources (plus signs) are bright stars. # 1 is the only unidentified HRI source, and is coincident with a bright, hard source seen in the ASCA GIS image (contours). The solid circle corresponds to the ASCA GIS field. Figure from Halpern et al. (2001b).

the *ASCA* image of the region was found to have no optical counterpart. The contours in figure 14 correspond to the *ASCA* GIS image of the source AX J2229.0+6114. The X-ray source RX/AX J2229.0+6114 was found to have a non-thermal spectrum with a power law photon index $\Gamma = 1.51 \pm 0.14$.

Halpern et al. (2001b) obtained 20 cm (NVSS) and 6 cm (VLA) images of the error circle of the EGRET source. These images are shown in figure 15. Interestingly, they found that there was only one radio source that was coincident with an X-ray source in the field, and that was source # 1, RX J2229.0+6114 of figure 14. The radio source VLA J2229.0+6114 has an incomplete circular shell-like structure, with a high degree of linear polarization evident throughout the shell. Halpern et al. (2001b) have presented convincing arguments suggesting that VLA J2229.0+6114 and RX/AX J2229.0+6114 are associated with each other.

Recently, Halpern et al. (2001c) described further multiwavelength observations of the X-ray source RX/AX J2229.0+6114 with the *Chandra* imaging CCD array ACIS-I, and at radio frequencies, and reported on the detection of radio and X-ray pulsations at a period of 51.6 ms from the X-ray source. The *Chandra* image clearly shows a point source surrounded by diffuse emission. Halpern et al. note that this morphology,

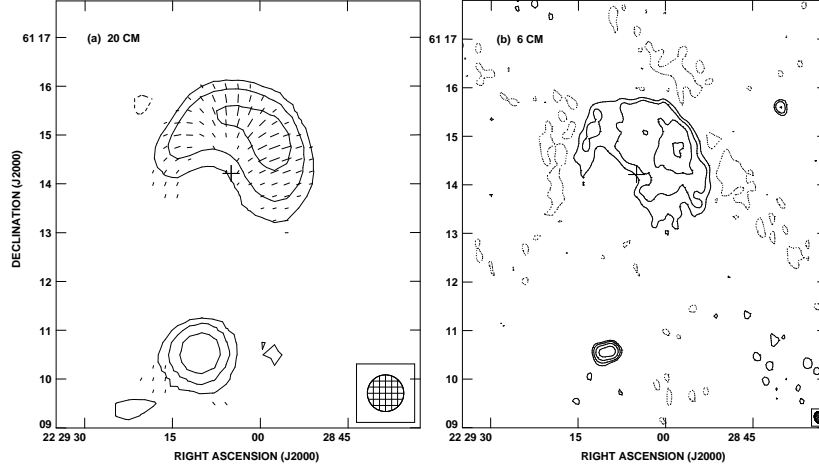


Figure 15. (Right) 20 cm NVSS map and (left) 6 cm VLA map, showing the shell-like radio source. The position of the X-ray RX J2229.0+6114 source is shown with a '+'. Notice the polarization vectors in the 20 cm NVSS map. Figure from Halpern et al. (2001b).

together with the non-thermal spectrum of the X-ray nebula indicates a “composite” supernova remnant, which they have called G106.6+2.9. Figure 16 shows the radio pulse profile of PSR J2229+6114 at 1412 MHz, observed with the Lovell radio telescope at Jodrell Bank in 2001 February. Following the radio pulsar discovery, Halpern et al. (2001c) searched the *ASCA* GIS data for X-ray pulsations. Their results, shown in figure 17, indicate a pulsed fraction of 22%.

These observations leave very little doubt that the EGRET source 3EG J2227+6122 is indeed the young and energetic 51.6 ms X-ray/radio pulsar PSR J2229+6114. Further confirmation will be possible after the launch of *GLAST* and if direct pulsations are observed at γ -ray energies.

6. Other source classes

Multiwavelength studies have led to the tentative identification of EGRET sources with counterparts from some other source classes. For example, EGRET sources have long been associated with supernova remnants (SNRs), and there are several examples of positional coincidences between EGRET sources and SNRs (see Torres et al. 2003b for a review). Examples are IC 443 (GeV J0617+2237), W 28 (GeV J1800-2328), among others.

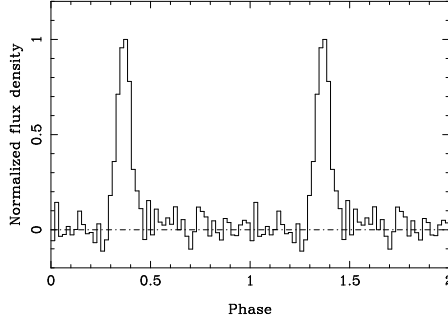


Figure 16. Radio pulse profile of PSR J2229+6114 at 1412 MHz observed with the Lovell radio telescope at Jodrell Bank. Figure from Halpern et al. (2001c).

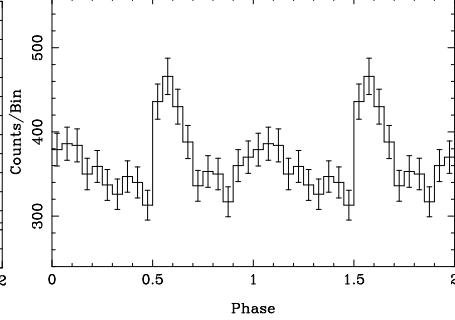


Figure 17. X-ray pulse profile of PSR J2229+6114 in the 0.8-10 keV band from ASCA GIS. Figure from Halpern et al. (2001c).

Similarly, there have been at least a couple of examples where a particular EGRET source has been associated with a microquasar. Paredes et al. (2000) have suggested that the microquasar LS 5039 is the counterpart to the EGRET source 3EG J1824-1514. The unidentified EGRET source 3EG J1828+0142 has been suggested as a possible Galactic microblazar, following multifrequency studies at X-ray and radio energies (Butt et al. 2002). Several authors have suggested that some variable γ -ray unidentified sources in the Galactic plane could be interpreted as microquasars (e.g. Paredes et al. 2000; Romero 2001; Kaufman-Bernado, Romero, & Mirabel 2002). It is possible that microblazars are a “new” class of γ -ray sources - further confirmation will come after more such sources are identified at γ -ray energies in the future.

In a few cases EGRET sources have been identified with peculiar binary systems, following a multiwavelength study of the EGRET error box. Two possible examples are 3EG J0634+0521 (2CG 135+01) associated with the binary system of a compact object and a Be star companion, SAX J0635+0533 (Kaaret et al. 1999), and 3EG J0241+6103, associated with the periodically variable radio/Be/X-ray/ source GT 0236+610/LSI +61°303 (Bignami et al. 1981). Another example is the possible association of 3EG J0542+2610 with the Be/X-ray transient A0535+26 (Romero et al. 2001). The gamma-ray production mechanism proposed in this case, based on the magnetosphere model of Cheng & Ruderman (1989), could explain emission from other variable EGRET sources in the plane.

The possible association of the variable radio star LSI +61°303 with the COS-B γ -ray source 2CG 135+01, was first noted by Bignami et al. (1981), who described the Einstein X-ray identification of the source. EGRET observations of 2CG 135+01 (3EG J0241+6103), a prominent unidentified source near the Galactic plane, were presented by Tavani et al. (1998). LSI +61°303 was the subject of a multiwavelength investigation at radio, optical, infrared and hard X-ray/ γ -ray frequencies, in order to confirm the association of the with the γ -ray source (Strickman et al. 1998). Although there was no conclusive proof of the identification, this is an intriguing association.

The second such example is the case of 3EG J0634+0521, associated with the hard spectrum X-ray source, SAX J0635+0533, discovered in the error box of the EGRET source (Kaaret et al. 1999). Optical observations of SAX J0635+0533 in the V band showed a counterpart with broad emission lines, and the colors of an early B type star. Subsequent discovery of pulsations at a period of 33.8 ms from the SAX source further strengthens the association (Cusumano et al. 2000). Figure 18 shows the pulse profile obtained by analyzing the SAX data. The pulsations were suggested to be due to a neutron star in a binary system with a Be companion. A definitive proof of the association with the EGRET source will require detection of periodicity in the EGRET source.

Several studies have suggested that some variable 3EG sources are associated with pulsar wind nebulae (see Roberts, Gaensler, & Romani 2002 for a review). X-ray and radio studies of pulsar wind nebulae (PWN) suggest that several of these sources are associated with unidentified EGRET sources. One example is that of GeV J1417-6100 (3EG J1420-6038), the error box of which coincides with the Kookaburra radio

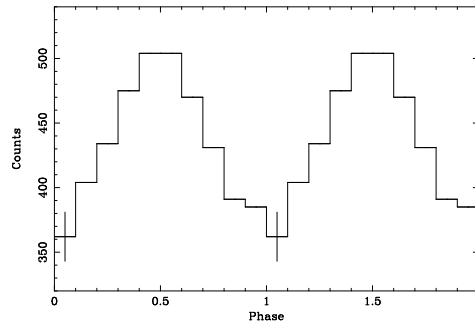


Figure 18. X-ray pulse profile of SAX J0635+0533, associated with the EGRET source 3EG J0634+0521. The X-ray source is believed to be X-ray binary, emitting γ -rays. Figure from Cusumano et al. (2000).

complex, within which are two extended hard X-ray sources (Roberts et al. 1999). Figure 19 shows the image of GeV J1417-6100 in X-rays (Roberts et al. 2001), with the two X-ray sources indicated. Figure 20 shows the radio 20 cm image of the region, showing the Kookaburra Nebula and the location of the Rabbit Nebula at the edge of the Kookaburra complex. One of the two hard X-ray sources in the field (AX J1420.1-6049) was recently found to contain the 68 ms radio pulsar PSR J1420-6048 (D’Amico et al. 2001), suggesting that the source is an X-ray and radio PWN. Recently Roberts, Romani & Johnston (2001) have presented multiwavelength X-ray, radio, and infrared observations of the pulsar and the surrounding nebula. PSR J1240-6048 is a possible counterpart of the γ -ray source. Roberts, Gaensler & Romani (2002) name a few other variable EGRET unidentified sources associated with PWN, GeV J1825-1310, GeV J1809-2327, suggesting that some variable EGRET 3EG sources may be PWN. Another possible example is that of 3EG J1410-6147. Doherty et al. (2003) have presented radio continuum, HI and X-ray (*Chandra*) observations of this field recently. The EGRET source could be a PWN, near the pulsar PSR J1412-6145, but the association is not definite.

7. Studies of EGRET unidentified sources at TeV energies

A new window for the observations of unidentified EGRET sources is now available at energies above 300 GeV by using imaging atmospheric Cherenkov (IACT) detectors, and at lower energies (~ 100 GeV), solar array experiments like STACEE and CELESTE. IACTs have the advantage of superior sensitivity and angular resolution. IACTs have successfully detected high energy γ -ray emission from both Galactic & extragalactic objects at energies above 300 GeV (see Ong 2003 for a review of the experiments and recent results). The Whipple 10 m telescope has been used to observe several unidentified EGRET sources in the past (Buckley et al. 1997), but none was detected. Recently, Fegan (2001) reported on the upper limits of a selected number of EGRET unidentified sources observed with Whipple.

A recent exciting news was the detection of what might be the first unidentified “TeV” source in the Cygnus region. This source was detected serendipitously by the HEGRA CT-System (Aharonian et al. 2002) in observations originally devoted to the EGRET unidentified source 3EG J2033+4118 and Cygnus X-3 and is known as TeV J2031+4130. The error circle of TeV J2033+4130 overlaps that of the EGRET unidentified source, but the two are not necessarily related. Figure 21 shows

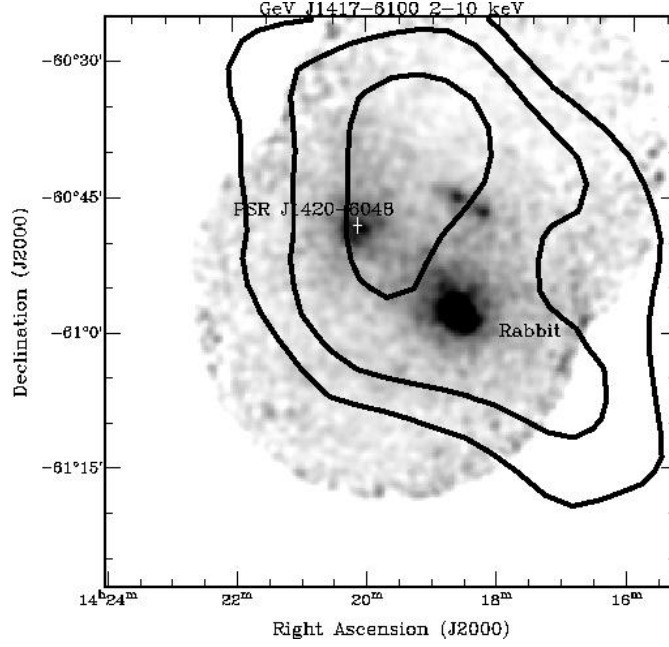


Figure 19. ASCA image of GeV J1417-6100 showing the two extended hard X-ray sources. Figure from Roberts et al. (2001).

an X-ray image taken with *ROSAT* PSPC in the energy range 0.2–2.0 keV, covering the field of 3EG J2033+4118/TeV J2032+4130. This TeV/EGRET field was the subject of recent multiwavelength study, with the intent of searching for a counterpart for the TeV source (Mukherjee et al. 2003; Butt et al. 2003). Most of the brighter X-ray point sources in Figure 21 were observed optically and identified spectroscopically to be a mix of early and late-type stars, unlikely to be counterparts of the γ -ray source (Mukherjee et al. 2003).

Recently, in August 2002 *Chandra* made a 5 ks director’s discretionary observation (Butt et al. 2003) of the field of TeV J2032+4130. Figure 22 shows the *Chandra* image of TeV J2032+4130, with the brightest point sources marked (Mukherjee et al. 2003). Optical imaging observations of these sources show that they are mostly stars, or in some cases non detected, probably AGNs that are highly absorbed by the Galactic ISM. Mukherjee et al. (2003) draw attention to source # 2 in figure 22, the brightest X-ray source in the *Chandra* image, and a transient that is missing from the *ROSAT* image of the region. The hard X-ray spectrum, rapid variability, and red optical/IR colors of this object suggest that it is a distant, quiescent X-ray binary system. It is too early to

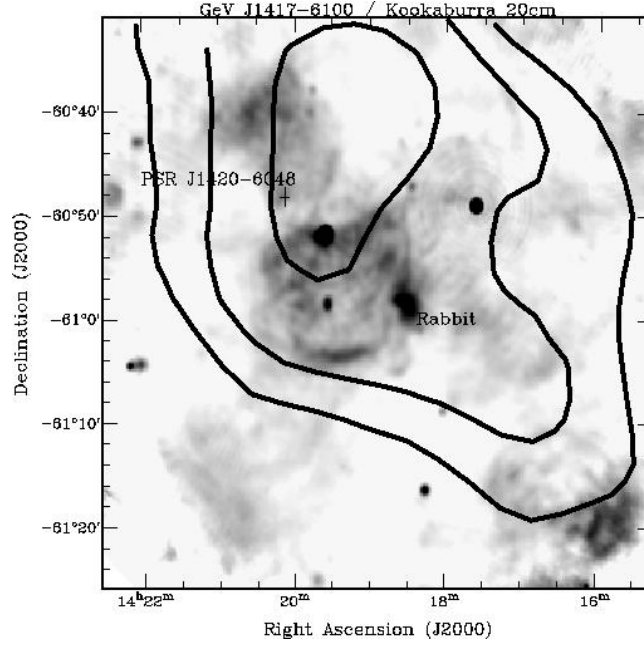


Figure 20. 20 cm ATCA image of GeV J1417-6100, showing the Kookaburra Nebula. The locations of the pulsar PSR J1420-6049 and the Rabbit Nebula are indicated. Figure from Roberts et al. (2001).

tell whether this X-ray source is associated with the γ -ray source. It is possible that TeV J2032+4130 is an extended source. In this case the TeV emission would not necessarily be centered on any point source counterpart at other wavelengths. Aharonian et al. (2002) have hypothesized two possible origins for extended TeV emission. One is that TeV emission could arise from π^0 decay resulting from hadrons accelerated in shocked OB star winds and interacting with a local, dense gas cloud. The other is inverse Compton TeV emission in a jet-driven termination shock, either from an as-yet undetected microquasar, or from Cyg X-3. Butt et al. (2003) have also presented a *Chandra*/VLA follow-up of TeV J2032+4130, and have argued that the TeV source is an extended one that is not detected yet in radio or X-ray. Future observations with *Chandra* and GLAST as well as by IACTs will help resolve the nature of this source.

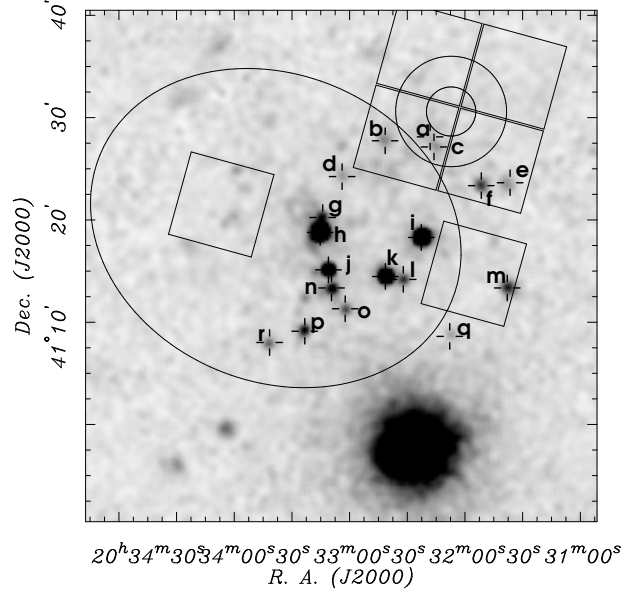


Figure 21. *ROSAT* PSPC X-ray image of the error circles of 3EG J2033+4118/TeV J2032+4130. The ellipse is the 95% uncertainty location of 3EG J2033+4118 from Mattox et al. (2001). The small circle is the 1σ uncertainty of the centroid of TeV J2032+4130, and the large circle is the estimated Gaussian 1σ extent of the TeV emission (Aharonian et al. 2002). The bright source is Cyg X-3. The properties of the marked sources are described in Mukherjee et al. (2003). The squares are the fields of view of the CCDs in the subsequent *Chandra* observation (see Figure 4). Figure from Mukherjee et al. (2003).

7.1 Summary and future directions

One of the most intriguing questions raised by EGRET has been the nature of its unidentified sources. Resolving the mystery of the unidentified EGRET sources remains a daunting task, even after much study. We have presented a selective review of some recent work done towards understanding the nature of the unidentified EGRET sources using a multiwavelength approach. This strategy of identification, although a systematic method, is a time consuming process requiring detailed multifrequency studies of EGRET fields. It is, however, a promising method, and has yielded several new source identifications in the past decade. The identification process is hampered by the large error boxes of EGRET sources. In the future, with smaller γ -ray error circles promised by GLAST, this strategy should secure more confident

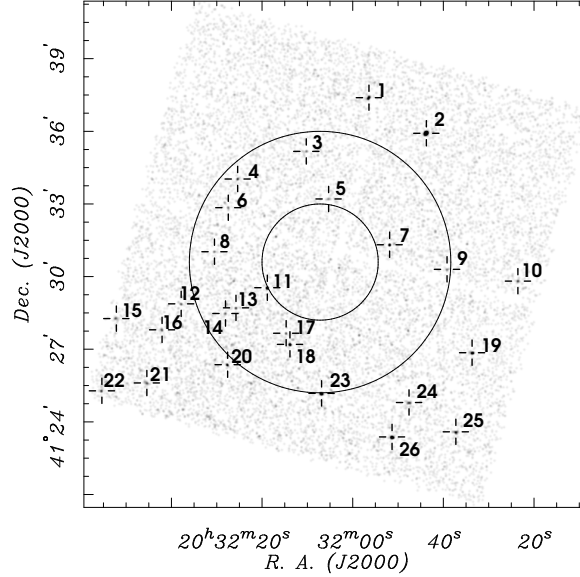


Figure 22. *Chandra* ACIS-I image of the field of TeV J2032+4130. The properties of the numbered sources are given in Mukherjee et al. (2003). The small circle is the 1σ uncertainty of the centroid of TeV J2032+4130, and the large circle is the estimated Gaussian 1σ extent of the TeV emission (Aharonian et al. 2002). The brightest *Chandra* source #2 was not detected in *ROSAT* images. Figure from Mukherjee et al. (2003).

source identifications. Future observations with GLAST or AGILE will also enable us to determine γ -ray source positions more accurately, and perhaps search for pulsations directly in the γ -ray data.

Although progress has been made in the identification of individual EGRET sources, both by looking at the sources as a group and by doing follow-up multifrequency observations on a case-by-case basis, the majority of the EGRET (3EG) sources remain unidentified. It is possible that there may be a new class of γ -ray emitters, yet to be identified, made up of several of the EGRET sources. In the interim before GLAST or AGILE, several of the unidentified EGRET sources will continue to be observed above 250 GeV by ground-based instruments like VERITAS, as well as by the new generation low-threshold ground-based Cherenkov detectors like STACEE (Covault et al. 2003) and CELESTE (Nuss et al. 2003), sensitive to energies as low as 50 GeV. In the future, unidentified 3EG sources are likely to be studied not only by satellite-based experiments like GLAST, but also by next generation ground-based detectors

like VERITAS (Ong et al. 2003), MAGIC (Martinez et al. 2003), HESS (Hofmann et al. 2003) and CANGAROO (Ohishi et al. 2003). Detection of very high energy γ -ray emission from unidentified 3EG sources with ground-based atmospheric Cherenkov telescopes is likely to open an exciting new chapter in the study of these sources.

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