X-RAY AND RADIO OBSERVATIONS OF BRIGHT GEV SOURCES

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Keywords: Pulsars, Pulsar Wind Nebulae, Supernova Remnants, Variable γ-Ray Emission, Wolf-Rayet Stars.

Abstract We present X-ray and radio studies of sources which are bright above 1 GeV ($F_{\gamma \text{GeV}} \geq 4 \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$). Only 11 out of $\sim 30$ of these γ-ray sources have been identified with lower energy counterparts: 5 blazars and 6 pulsars. Three of these pulsars are surrounded by radio pulsar wind nebulae (PWN), two of which are also seen as bright, extended X-ray synchrotron nebulae. The ASCA X-ray telescope has observed 28 of the bright GeV sources, revealing an excess of
Sources that are bright above 1 GeV are an important subset of the sources detected by \textit{EGRET}. Lamb and Macomb (1997) first noted that the \sim 30 sources with GeV fluxes $F_{\gamma \geq 1\text{GeV}} \geq 4 \times 10^{-8}$ ph cm$^{-2}$ s$^{-1}$ are tightly clustered along the Galactic plane (Figure 1), making up the majority of low-latitude \textit{EGRET} sources. 6 of the \sim 8 identified \gamma-ray pulsars are in this set but only a small fraction (5/\sim 80) of the known blazars are. The unidentified bright GeV sources are therefore good candidates for further pulsar identifications. Virtually none of them are likely to be background blazars seen through the Galaxy. Of special importance to our understanding of pulsar emission mechanisms is the number of these sources which are radio-quiet pulsars. Outer-gap models (Romani 1996) predict the majority of these sources should be pulsars whose \gamma-ray emission is beamed towards us, but whose radio emission is not. Polar-cap models (Harding 2000) predict relatively few such pulsars, making other source classes necessary. One such proposed class is supernova remnant (SNR) shocks, generally assumed to produce the majority of observed cosmic rays (eg. Berezhko & Völk 2000). Models of SNR predict hard, generically flat spectra in the GeV range (Baring et al. 1999). Other proposed source classes, such as colliding winds in massive binary systems (Eichler & Usov 1993) and isolated accreting black holes (Punsly 1999), have more tentative predictions of their \gamma-ray luminosity at GeV energies.

There are practical observational reasons to focus on the bright GeV sources among the Galactic source population of \gamma-ray sources. In general, the point spread function (PSF) of high energy \gamma-ray telescopes is roughly proportional to $E_{\gamma}^{-1/2}$. Observations of Galactic plane sources at energies below a few hundred MeV are plagued by source confusion...
and low signal-to-noise and will continue to be so in the GLAST era. If the energy dependence of the PSF is included in the analysis, sources with significant GeV emission can be more reliably localized and are less likely to be confused with background sources. A general steepening of the diffuse Galactic γ−ray emission (Hunter et al. 1997) above 1 GeV further helps the signal-to-noise ratio.

In this article, we present results of X-ray and radio studies of the bright GeV sources. We will first discuss the lower energy properties of the known and proposed source classes. We will then summarize the results of a recently completed 2–10 keV ASCA survey of nearly the entire sample (Roberts, Romani & Kawai 2001, hereafter RRK) and report on analysis of VLA and ATCA radio images of selected fields.

2. OBSERVATIONAL CHARACTERISTICS OF POTENTIAL LOWER ENERGY COUNTERPARTS

In general, when trying to find evidence of particle acceleration in the Galactic plane, one looks for evidence of non-thermal emission. In X-rays, it is necessary to observe at energies above ∼ 2 keV, both to see through the high absorption in the plane and to look for a hard power-law component of any emission. At radio wavelengths, one looks for a steep spectrum and high polarization. A high radio to infrared ratio is also a good indication of a non-thermal origin of radio emission. Blazars, young pulsars, and SNR can all show these characteristics allowing identification as potential γ−ray sources through a combination of their X-ray and radio emission.

Blazars are distinguished from other active galactic nuclei by being radio loud ($F_R \gtrsim 0.5$ Jy). They also have moderate X-ray emission
(\(F_X \gtrsim 10^{-13}\) ergs cm\(^{-2}\) s\(^{-1}\), Sambruna 1997) with hard power-law spectra (\(\Gamma \sim 1.7\)). It is therefore relatively easy to rule out a blazar identification for most of the unidentified sources by looking at single dish radio survey data. If there is no bright, point-like radio source, then the source is probably not a blazar. Blazars are quite variable at most wavelengths, including \(\gamma\)-rays, unlike the known pulsars and what is expected from SNR shells. Therefore, any variable \(\gamma\)-ray source that is not a blazar is likely to belong to a new class of objects.

Figure 2  **Left:** 4850 MHz radio image of the GeV blazar QSO 0208–512 from the PMN survey (Condon et al. 1991). The contours mark the 68%, 95%, and 99% confidence position regions. **Right:** 2-10 keV ASCA image of QSO 0208–512.

The known \(\gamma\)-ray pulsars can be placed in two rough categories. The youngest ones (Crab and Vela) have bright synchrotron X-ray and radio wind nebulae surrounding them which dominate the emission at lower energies. These pulsar wind nebulae (PWN) are a common feature of the youngest pulsars (\(\tau \lesssim 10^4\) years old). Older \(\gamma\)-ray pulsars, such as PSR 1055–52 and Geminga, appear as point sources in X-rays with a spectrum consisting of a soft thermal component (often highly absorbed) and a flat power law component (photon spectral index \(\Gamma \lesssim 2\), Halpern & Wang 1997). These have weak or no PWN, and will be referred to here as isolated pulsars. The known \(\gamma\)-ray pulsars have not been observed to be variable in studies of \(E \geq 100\) MeV \(\text{EGRET}\) emission (McLaughlin et al. 1996; Tompkins 1999). However, the Crab PWN appears variable to \(\text{EGRET}\) in the soft 70-150 MeV energy band (de Jager et al. 1996).

Supernova remnants are identified at radio wavelengths by having a shell type morphology, a steep radio spectrum, and significant polarization. They can also be distinguished from thermal radio sources, such as HII regions, by a high radio to infrared emission ratio (Whiteoak & Green 1996). PWN are distinguished in radio from SNR by having somewhat flatter spectra (energy spectral index \(\alpha \sim -0.3 \sim -0.1\)), somewhat
higher polarization fraction ($\sim 10 - 30\%$), and amorphous morphologies (Frail & Scharringhausen 1997). In X-rays, SNR can have either a shell or filled center morphology with thermal plasma spectra having strong emission lines. PWN tend to have featureless, hard power-law X-ray spectra with toroidal, bow-shaped, or jet-like morphologies. Since SNR are generally several parsecs across, they are not expected to vary on timescales observable by \textit{EGRET}, unless the $\gamma$-ray emission is highly localized.

3. **ASCA X-RAY SURVEY**

The images in this paper (unless otherwise noted) were made with the GIS instrument on the \textit{ASCA} satellite. They come from the \textit{ASCA} catalog of GeV sources (RRK) which covers about 85\% of the \textit{EGRET} 95\% error contours for 19 of the 20 bright unidentified GeV sources listed in LM97. In order to screen out stellar sources, which tend to be quite bright in soft X-rays but faint above 2 keV, 2–10 keV images that have been exposure corrected and smoothed are shown. Some images are composites from multiple pointings, and sometimes field edge artifacts appear from scattered light. The details of the image reduction and analysis can be found in RRK. A log N–log S comparison in the 2–10 keV band of the unidentified GeV source fields to the relation derived from the \textit{ASCA} Galactic Plane Survey ($|l| < 45^\circ, |b| < 0.4^\circ$, Sugizaki et al. 2001) shows a clear excess of sources with $F_{2-10\text{keV}} > 10^{-12}$ ergs cm$^{-2}$s$^{-1}$ (Figure 3).

![Figure 3](image.png)

\textit{Figure 3} The \textit{ASCA} 2–10 keV log N–log S distribution of X-ray sources found in the 95\% error contours of unidentified GeV sources (RRK) compared to the \textit{ASCA} Galactic Plane Survey (Sugizaki et al. 2001).
3.1. PREVIOUSLY KNOWN SUPERNova REMNANTS

There are five well observed SNR coincident with bright unidentified GeV sources. The X-ray images tend to be dominated by thermal plasma emission which falls off rapidly above 2 keV. Therefore, 4–10 keV contours on the 2–10 keV image can reveal a hard, power-law spectral component which is evidence of particle acceleration. W44 (GeV J1856+0115) and CTA 1 (GeV J0008+7304) both contain hard emission coincident with the GeV source (Figure 4). However, the hard source in W44 is a PWN associated with the young pulsar PSR B1853+01 (Har rus, Hughes, & Helfand 1996), while the emission in CTA 1 is a suspected PWN associated with the X-ray pulsar candidate RXJ0007.0+7302 (Slane et al. 1997). This suggests the GeV emission is related to the pulsars and not the SNR shell.

IC443 (GeV J0617+2237) and W28 (GeV J1800−2328) also have regions of hard X-ray emission, but in these cases the emission is not well correlated with the EGRET positions derived from GeV photons (Figure 5). The two regions of hard X-ray emission in the southern portion of the IC443 ASCA field, one of which now appears to be a pulsar with PWN (Keohane et al. 2001), have previously been suggested as sites of shock acceleration producing GeV emission (Keohane et al. 1997). The newer GeV based position seems to exclude this. W28 is coincident with the young pulsar PSR B1758−23. However, the high dispersion measure distance of 13.5 kpc (Kaspi et al. 1993), although admittedly...
unreliable, suggests the pulsar is not associated with the remnant or GeV J1800–2328.

Figure 5 Left: SNR IC443 / GeV J0617+2237. Right: SNR W28 / GeV J1800–2328.

GeV J2020+4023 is well located near the center of the γ Cygni SNR shell. Despite very extensive observations with ASCA, there is no obvious X-ray emission associated with the γ-ray source. Therefore, none of the SNR associated with GeV sources show evidence of X-ray shock emission consistent with the GeV position which can not be attributed to a young pulsar.

Figure 6 Left: 2-10 keV image of SNR γ Cygni / GeV J2020+4023. Right: GeV J1025−5803 with the WN5+0 binary star 1E1024.0−5742. At the edge of the image is a colliding wind system in the RCW49 HII region.
3.2. MASSIVE BINARIES

Colliding winds in massive binary systems are potential sources of γ-ray emission (Mücke & Pohl 2001), and it is interesting to note any candidates among the bright GeV sources. There are two Wolf-Rayet + O star binary systems: 1E1024.0−5742 consistent with GeV J1025−5809 and WR141 consistent with GeV J2020+3658. Neither can be considered a very strong candidate. 1E1024.0−5742 is outside the somewhat large 95% positional contour. WR141 is well within the positional contour, but so is a second, equally bright hard point source. These two sources in GeV J2020+3658 are embedded in diffuse X-ray emission with a somewhat steep (photon index $\Gamma \sim 2.5$) spectrum, suggestive of a thermal SNR. However, a 20 cm observation of the field with the VLA in D array shows no bright radio nebula (Figure 7).

![Figure 7](image)

Figure 7 **Left:** GeV J2020+3658 in X-rays, showing WR 141 and the second hard source embedded in diffuse X-rays. **Right:** 20 cm VLA image of GeV J2020+3658 field with X-ray as light contours.

GeV J0241+6102 is consistent with the peculiar radio emitting Be-star/X-ray binary LSI+61 303. This source has been the subject of much study (cf. Strickman et al. 1998), but the nature of the compact object in the system is still uncertain. Although the γ-ray source is moderately variable, the variations have not been correlated with any known time scales of LSI+61 303. With the latest EGRET positional determination, the source now lies just outside the 95% confidence contour.

4. MULTI-WAVELENGTH STUDIES OF GEV SELECTED FIELDS

A crucial component in further categorizing the sources is γ-ray variability. Tompkins (1999) has measured the variability of all the sources
listed in the third *EGRET* catalog (Hartman et al. 1999) using the \( \tau \equiv \sigma_F/\mu_F \) statistic, where \( \sigma_F \) is the standard deviation of the measured fluxes from different viewing periods and \( \mu_F \) is the mean flux from all viewing periods. Note this is a measure of how variable a source is rather than the usual \( \chi^2 \) test of how inconsistent the source is with a constant model (cf. McLaughlin et al. 1996). In Figure 8 we plot all 28 sources in RRK the \( \tau \) value versus \( -\alpha_{X\gamma} \equiv -(1 + \log(F_{\gamma}/A_X)/6) \), a broadband energy ‘spectral index’ where \( F_{\gamma} \) is the photon flux above 1 GeV (equivalent to the power-law normalization at 1 GeV for a source with photon index \( \Gamma = 2 \)) and \( A_X \) is the 1 keV X-ray power law normalization in photons GeV\(^{-1}\) cm\(^{-2}\). In fields with more than one X-ray source, the \( -\alpha_{X\gamma} \) values are derived from the brightest source consistent with being the GeV source, and can therefore be considered an upper limit. The plot is split into regions of high and low variability, and, from left to right, X-ray faint, moderate, and bright. The dotted line represents the systematic uncertainty in the \( \tau \) measurement, which is consistent with no variability.

![Figure 8](image_url)  
*Figure 8* \( E \geq 100 \) MeV variability index \( \tau \equiv \sigma_F/F \) versus the X-ray to \( \gamma \)-ray “spectral index” \( -\alpha_{X\gamma} \) assuming the brightest non-thermal X-ray source consistent with the GeV source as the counterpart. Dashed lines denote regions of high and low variability, and from left to right X-ray faint, moderate, and bright. The dotted line is the level of variability due to systematic errors.
The only X-ray bright sources are the Crab nebula and possibly the source near the Galactic center. Vela is the only X-ray moderate pulsar, due to its PWN. The isolated pulsars are X-ray faint. All the identified GeV pulsars are consistent with no variability ($\tau = 0.1$, the systematic variability of $EGRET$), and the blazars are significantly variable. Four GeV sources in this sample are not in the 3EG catalog, and so were not measured for variability by Tompkins. These are shown along the bottom.

4.1. ISOLATED PULSAR CANDIDATES

There are three unidentified sources in the X-ray faint, low variability category which also contains the isolated pulsars. One is the source in SNR $\gamma$–Cygni. Since there are only weak upper limits on the non-thermal emission in W28 and IC 443, the $\gamma$–ray sources positionally coincident with these SNR may also fall in this category. The other two sources are GeV J1835+5921 and GeV J1837–0610. GeV J1835+5921 is the only high latitude source among the bright unidentified GeV sources, and has been extensively studied by Mirabal et al. (2000). Through X-ray, optical and radio studies, they identify every source in the field and find a single faint X-ray source whose ratio of X-ray to optical luminosity is consistent with a neutron star identification.

The field of GeV J1837–0610 contains one hard X-ray point source in the ASCA image (Figure 9) and faint diffuse emission. A 20 cm VLA D array image shows a faint ring surrounding the X-ray emission with a very bright HII region along one edge. This is suggestive of an old SNR interacting with the molecular cloud. However, the dynamic range requirements caused by the HII region make accurate spectral measurements of the ring difficult. Also in the field is the young (characteristic age of 34,000 yr) pulsar PSR J1837–0604 recently discovered by the Parkes Multibeam Survey (D’Amico et al. 2001). The dispersion measure distance to the pulsar of 6.2 kpc is consistent with the distance to the molecular cloud.

GeV J2035+4214 is in the X-ray moderate category and was not in the 3EG catalog and so was not measured by Tompkins for variability. The X-ray image (Figure 10) shows three sources: two hard point sources and a softer diffuse source. In the VLA 20 cm image it can be seen that one of the point sources is associated with a double-lobed radio galaxy. The other is embedded in the bright, nearby ($\lesssim 1$ kpc) molecular cloud DR17. The intensity of the brightest features of the molecular cloud make it difficult to determine if the dim region near the X-ray source has a different spectrum from the rest of the cloud. A some-
Figure 9  **Left:** GeV J1837−0610 in 2-10 keV X-rays, with the position of the young pulsar marked.  **Right:** 20 cm VLA image of GeV J1837−0610 field with X-ray contours.

what speculative possibility for the emission from GeV J2035+4214 and GeV J1837−0610 is that shock accelerated particles from an old SNR (whose diffuse thermal X-ray emission we still see) are interacting with the molecular clouds, causing the GeV emission. However, the interpretation as isolated pulsars may be more conservative.

Figure 10  **Left:** GeV J2035+4214 in X-rays.  **Right:** 20 cm VLA image of GeV J2035+4214 field showing the bright molecular cloud DR17.

### 4.2. CANDIDATE PULSAR WIND NEBULAE

The most intriguing sources are the X-ray moderate, high variability sources. There are four in this category, not including blazars. In addition, the source containing LSI+61 303 is on the high variability border, and the source inside CTA 1 shows evidence of variability. One of the
four high variability sources is the PWN in W44 associated with PSR B1853+01. A second, GeV J1825−1310, is near the young pulsar PSR B1823−13. However, the ASCA image of the field (Figure 11) reveals a previously unknown, hard spectrum ($\Gamma \sim 2.2$) X-ray nebula. The other two variable sources also contain X-ray nebula, and are discussed in detail in the following sections.

![Figure 11](image)

*Figure 11* GeV J1825−1310 at 2-10 keV. The X-ray nebula is well centered with the young pulsar PSR B1823−13 to the south. The excess emission near where the four pointings join is from G18.1-0.2, a probable SNR in the Sharpless 53 HII cluster (Kassim et al. 1989), which is also consistent in position with the nearby softer $\gamma$-ray source 3EG J1823−1314.

**The Kookaburra and the Rabbit.** GeV J1417−6100 is another X-ray moderate high variability source that has been the subject of much recent study (Roberts & Romani 1998; Roberts et al. 1999; Case & Bhattacharya 1999; Roberts 2000; D’Amico et al. 2001). The region contains the Kookaburra radio complex, within which are two extended hard X-ray sources and two hard point sources (Figure 12). One of the point sources is coincident with a weak, variable radio source, and is likely to be a Seyfert galaxy. The other point source appears variable, and may also be a Seyfert, although there is no radio counterpart. The Kookaburra complex itself consists of a mostly thermal shell, with two wings extending to the north and south which, from comparison to infrared images and some excess polarization, may be non-thermal. At the edge of the shell, near the southern wing, is a moderately bright radio nebula known as the Rabbit.
The Rabbit is spectrally distinct from the shell, and a significant source of polarized flux (Roberts et al. 1999). The morphology of the polarized flux is doubly peaked (Figure 13). Spectral tomography of the Rabbit suggests the polarized region has a spectral index of $\alpha_r \sim -0.3$, typical of a PWN. The brighter extended X-ray source is coincident with the Rabbit, and in the SIS image seems to contain a point source at the location of the upper polarization peak. The X-ray spectrum and morphology is also suggestive of a PWN, although detailed spatial structure is impossible to determine with the broad PSF of ASCA.

The Parkes Multibeam Survey recently discovered a very energetic young ($\dot{E} \sim 10^{37}$ ergs/s) pulsar, PSR J1420–6048, coincident with the second extended X-ray source in the upper wing of the Kookaburra (
D’Amico et al. 2001). Folding the X-ray data at the radio period yields a marginal detection of an X-ray pulse. The detection is somewhat supported by the pulsed flux being consistent with the ASCA PSF, while the unpulsed flux has a significantly broader radial profile (Roberts et al. 2001). While several of the young objects in the region are at a distance of \( \sim 2 \) kpc, the dispersion measure and X-ray absorption towards the pulsar suggest a greater distance of \( \sim 8 \) kpc. Such a distance may be problematic for an ID as the GeV source, although it should be noted that dispersion measure distances can be quite unreliable in complex regions such as this one.

The upper wing of the Kookaburra has a strange rectangular shape reminiscent of SNR 3C 397 (Dyer & Reynolds 1999). There is no associated infrared flux seen by IRAS at 60 microns or the MSX mission at 8.3 microns. This, along with a suggestion of excess polarization in the ATCA radio maps, suggests a SNR ID. However, the radio spectral index measurements of the entire wing are currently too ambiguous to be certain, although the region immediately around PSR J1420–6048 is consistent with there being a small radio PWN (Roberts et al. 1999).

**GeV J1809–2327; A New PWN.** The final X-ray moderate, high variability GeV source in the sample is GeV J1809–2327. The ASCA image (Figure 14) shows an extended nebula centrally peaked with several smaller peaks to the south. The nebula has a power-law spectrum (\( \Gamma \sim 2.2 \)), with the central peak being slightly harder. The smaller peaks are softer and are coincident with massive young stars. Oka et al. (1999) mapped the CO emission in the region and noted that the X-ray emission is surrounded by molecular gas in the Lynds 227 dark nebula. 20cm and 6cm VLA imaging of the region shows two nebulae (Roberts, Gaensler, & Romani 2001) consistent with the GeV source. The southern one seems to be a thermal molecular cloud which is also seen in the MSX 8.3 micron image (Figure 15). The northern source, coincident with the central peak of the X-ray nebula, has a non-thermal spectrum (energy index \( \alpha \sim -0.4 \)) and is significantly polarized. These properties, along with its shape, suggest a PWN identification.

A short Chandra ACIS image (Figure 15) resolves the various point sources (Romani et al. 2001), and shows that the stellar sources are coincident with the middle, thermal cloud. The hard central peak of the X-ray nebula is coincident with a point source at the edge of the PWN candidate. There is a small trail of emission leading back towards the center of the radio nebula. This strongly supports the identification of the X-ray/radio nebula as a PWN.
5. SUMMARY

X-ray and radio studies of *EGRET* error contours have proven to be quite fruitful. There are now strong candidate low-energy counterparts for the majority of bright Galactic sources of GeV emission. *GLAST* should be able to make positive identifications of most of these sources. In the particular case of the two X-ray nebulae in the Kookaburra, *GLAST* would be able to distinguish between them even if both were sources of GeV emission (Roberts 2000). Although there are several massive colliding wind binary systems and SNR coincident with GeV sources, neither source class makes a convincing case for copious emission above a GeV. However, it should be noted that 100 MeV and above error ellipses around the SNR in this sample are much larger and often
shifted from the GeV position. There are several other SNR coincident with sources in the 3rd EGRET catalog that have significantly steeper spectra than the sources in this sample. If SNR are, as a class, steep spectrum (photon index $\Gamma > 2$) $\gamma$-ray sources, then current models of SNR emission and cosmic-ray production may have to be revised.

Isolated $\gamma$-ray pulsars (without bright X-ray PWN) seem to be non-variable, and several new candidates for this older population of pulsars have been found. Looking at the total numbers of isolated pulsars and candidates, roughly half seem to be radio pulsars. X-ray pulse searches of the radio-quiet candidates with Newton-XMM could prove successful.

With a strong radio PWN candidate counterpart for GeV J1809$-2327$, 3 of the 4 X-ray moderate, high variability GeV sources in this flux-limited sample have now been shown to contain likely PWN which emit in both radio and X-rays (the other two being the Kookaburra/Rabbit and PSR B1853+01). The fourth, GeV J1825$-1310$, contains a candidate X-ray PWN which has yet to be carefully imaged in radio. With the addition of the source coincident with the likely PWN in CTA 1, also apparently variable, there is a strong case for synchrotron nebulae being able to produce high-energy ($E > 100$ MeV) $\gamma$-rays. Noting the apparent soft $\gamma$-ray variability of the Crab nebula, only the Vela pulsar exists as a counterexample. The variability studies of Tompkins (1999) were sensitive to timescales on the order of a few months. This is roughly the synchrotron cooling timescale of the X-ray emission. The presence of a strongly emitting $\gamma$-ray nebula would hinder pulse searches of these sources, since it would significantly reduce the pulse fraction in these sources. Therefore, even with the greater sensitivity of GLAST, it may be necessary to find pulsations at X-ray or radio wavelengths before $\gamma$-ray pulsations can be detected in these sources.

**Acknowledgments**

We would like to thank V. Kaspi for useful discussions and comments. MSER acknowledges support from the Québec Merit Fellowship Program. BMG acknowledges the support of NASA through Hubble Fellowship grant HF-01107.01-98A. The National Radio Astronomy Observatory Very Large Array is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The Australia Telescope is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. This work made use of several on-line resources, including Skyview and W3Browse from the High Energy Astrophysics Science Archive Research Center a service of the Laboratory for High Energy Astrophysics at NASA/GSFC and the High Energy Astrophysics Division of the SAO, as well as the NASA/IPAC Infrared Science Archive.
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