MULTIWAVELENGTH SEARCHES OF UNIDENTIFIED EGRET SOURCES

N. MIRABAL[1], J. HALPERN[1], R. MUKHERJEE[2], E. GOTTHELF[1] & F. CAMILO[1]
[1] *Astronomy Department, Columbia University, 550 West 120th Street, New York, NY 10027*

[2] *Dept. of Physics & Astronomy, Barnard College, Columbia University, New York, NY 10027*

3EG J1835+5918 is the brightest of the so-called unidentified EGRET sources at intermediate galactic latitude (l,b)=(89,25). We obtained complete radio, optical, and X-ray coverage of its error box, discovering a faint ultrasoft X-ray source in the ROSAT All-Sky Survey. Deep optical imaging at the location of this source, as pinpointed by an observation with the ROSAT HRI, reveals a blank field to a limit of $V > 25.2$. The corresponding lower limit on f_X/f_V is 300, which signifies that the X-ray source 3EG J1835+5918 is probably a thermally emitting neutron star. Here we report on recent *Chandra* and *HST* observations that strengthen this identification. 3EG J1835+5918 may thus become the prototype of an hypothesized population of older pulsars, born in the Gould belt, that can account for as many as 40 local EGRET sources. In addition to 3EG 1835+5918, we review the ongoing multiwalength effort by members of our group to study other unidentified EGRET sources using X-ray, optical, and radio data.

1 Introduction

One important achievement of the EGRET mission was the discovery of 273 persistent high-energy (> 100 MeV) γ-ray sources [1], of which 93 are likely or possibly identified with blazars, 9 with rotation-powered pulsars, one with the radio galaxy Cen A, and one with the LMC. This leaves more than one half the sources in the Third EGRET catalog without firm counterparts at other wavelengths. Many difficulties attend the identification of EGRET sources close to the Galactic plane, but even at high Galactic latitude, the large error circles and the lack of a tight relation between γ-ray flux and other properties such as X-ray flux and core radio flux prevent all but the brightest counterparts from being identified securely on the basis of position alone.

Of the unidentified sources, approximately one third lie within $|b| \leq 10^{\circ}$ along the Galactic plane. This excess of low-latitude sources must comprise a Galactic population that is either similar to the already identified γ-ray pulsars [2], or represents an entirely new class of γ-ray emitters associated with the disk population. The shapes of radio pulsar beams as determined by the rotating vector model [3] demand that a fraction of young radio pulsars are *not* visible from Earth. The clear differences between the broad observed γ-ray beam patterns and the narrow radio pulses implies that γ-ray emission is probably visible from a more complete range of directions than are the radio beams. In addition to the Galactic plane population, it is speculated [4] that as many as 40 of the steady, unidentified EGRET sources located at intermediate Galactic latitude are a population of older pulsars associated with the Gould Belt, an inclined, expanding disk of star formation in the solar neighborhood that is $\approx 3 \times 10^7$ yr old. The identification of Geminga as the first radio quiet pulsar [5] provides what might be the prototype for several of the remaining unidentified Galactic sources.

In spite of several γ-ray identifications, the nature of the majority of EGRET source remains mysterious. A multiwavelength survey using X-ray, optical, and radio data, is possibly the best available approach to determine the nature of unidentified sources. This technique has been used recently to find likely identifications for several EGRET sources, such as 3EG J2227+6122 [6], 3EG 1835+5918 [7], and the COS-B field 2CG 075+00, which overlaps with two EGRET sources 3EG J2016+3657 and 3EG J2021+3716 [8]. The possible discovery of new counterparts and envisioned applications of γ-ray pulsar properties [9] have motivated the search for additional EGRET identifications. However, the absence of obvious counterparts also admits the possibility that there is another population with characteristics unlike that of the identified EGRET sources yet to be discovered. A number of alternative γ-ray emitters have appeared in literature [10,11,12]. In the long term the advent of the next generation of high-energy γ-ray missions *INTEGRAL*, *AGILE* and *GLAST* will be able to explore the latter possibility. But prior to the new missions we have decided to take advantage of refined multiwavelength techniques and attempt detailed searches for counterparts of unidentified EGRET sources. Here we present recent results of multiwavelength work on two unidentified sources: 3EG J1835+5918 and 3EG J1621+8203.

2 3EG J1835+5918: The Next Geminga

3EG J1835+5918 is the brightest of the so-called unidentified EGRET sources at intermediate Galactic latitude $(\ell, b) = (89^\circ, 25^\circ)$, and the one with the smallest error circle, $12'$ radius at 99% confidence. It shows no evidence for long-term variability [13]. Its spectrum can be fitted by a relatively flat power law of photon index –1.7 from 70 MeV to 4 GeV, with a turndown above 4 GeV. Such temporal and spectral behavior is more consistent with a rotation-powered pulsar than a blazar, which is the other major class of EGRET source. However, observations find no radio pulsar in this field to an upper limit of 1 mJy at 770 MHz [14]. No radio-source candidate has been found for 3EG J1835+5918, either Galactic or extragalactic.

We performed an exhaustive search for a counterpart of 3EG J1835+5918, including deep radio, X-ray, and optical surveys, as well as optical spectroscopic classification of every active object within *and outside* its error ellipse [7]. In summary, we identified all but one of the *ROSAT* and *ASCA* sources in this region to a flux limit of approximately 5×10^{-14} erg cm^{-2} s^{-1}, which is 10^{-4} of the γ-ray flux. None of the identified sources are plausible γ-ray candidates. The only unidentified source is RX J1836.2+5925 that has no optical counterpart. RX J1836.2+5925 was the brightest X-ray source within the EGRET error ellipse (see Figure 1), with a flux of 1.6×10^{-13} erg cm^{-2} s^{-1}. Most important is the fact that this source falls on a blank optical field to a limit of $R > 24.5$ and $V > 25.2$ (Figure 2). Our upper limit on the optical flux from RX J1836.2+5925 implies that its ratio of X-ray-to-optical flux f_X/f_V is greater than 300, an extreme that is seen only among neutron stars.

As part of our survey, we discovered in the *ROSAT* All-Sky Survey that RX J1836.2+5925 was first detected a decade ago as a soft X-ray source [15]. These archival *ROSAT* PSPC photons provide the only X-ray spectral information, since the pointed *ROSAT* observations were obtained with the HRI, and the source was not detected in the *ASCA* images. Although only 22 photons were detected by the PSPC, they *all* fall at energies below 0.4 keV. In summary we have detected a soft X-ray, radio-quiet source, lacking a supernova remnant and with a high X-ray to optical flux. This is exactly what one would expect for thermal emission from the surface of an older neutron star. If fitted by a blackbody model, such a pulse-height distribution is consistent with $T \leq 5 \times 10^5$ K, but it is also dependent upon the unknown intervening column density. If we assume $1 \times 10^{20} < N_{\rm H} < 3 \times 10^{20}$ cm^{-2}, the bolometric flux corresponding to an assumed $T = 5 \times 10^5$ K is in the range $(1.5 - 5.7) \times 10^{-13}$ erg cm^{-2} s^{-1}. This is 10–40 times fainter than Geminga. Thus it is either more distant than Geminga ($d > 160$ pc [5]), or cooler ($T < 5 \times 10^5$ K [16]). But a cooling neutron star of age $< 10^6$ yr should not be *too* distant, because

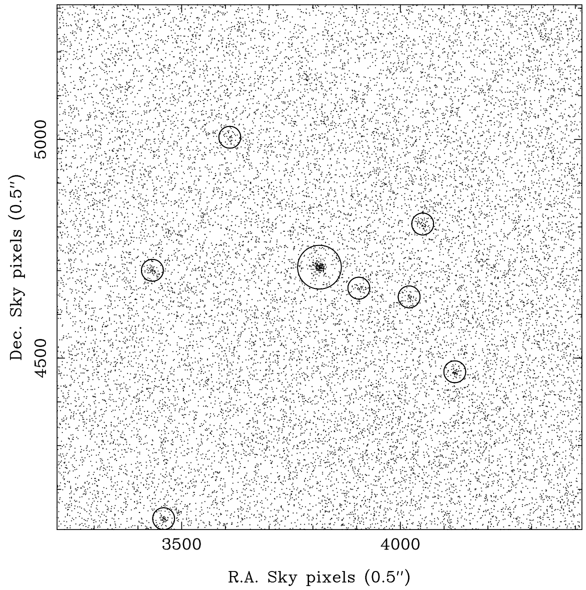

Figure 1: A $10' \times 10'$ portion of the *ROSAT* HRI image centered on the location of the brightest, unidentified X-ray source RX J1836.2+5925(*large circle*) in the error circle of 3EG J1835+5918.

to place it > 400 pc above the Galactic plane at $b = 25°$ would require a kick velocity at birth of > 500 km s^{-1}. A reasonable upper limit on the distance is therefore 1 kpc, which allows an isotropic γ-ray luminosity of $6 \times 10^{34}\,(d/1\,\mathrm{kpc})^2$ erg s^{-1}, comparable to the spin-down power $I\Omega\dot{\Omega}$ of Geminga (3.3×10^{34} erg s^{-1}).

Recently we have obtained coordinated observations of RX J1836.2+5925 using the *Chandra* ACIS and *HST* STIS instruments [17] to strengthen its identification as a neutron star by measuring its precise coordinates and using its X-ray spectrum and optical colors to address the physics of the source. The preliminary results show that the best-fitted X-ray spectrum requires two components, a soft thermal component previously suggested [15] as well as a hard tail that can be parametrized as a power law which is the expected signature of a neutron star [17]. Deep optical imaging with *HST* STIS reveals a blank field at the refined position of RX J1836.2+5925 to a limit of $V > 28.5$, corresponding to an extreme $f_X/f_V > 6000$ ratio. In addition new radio observations using the Jodrell Bank 76 m Lovell telescope at a frequency of 1400 MHz find no radio pulsar to a flux density upper limit of ≈ 0.1 mJy. At a distance of 1 kpc, which represents a reasonable upper limit for this source, the luminosity is then ≤ 0.1 mJy kpc^2. For comparison Geminga has a luminosity upper limit of 0.06 mJy kpc^2 (cf. IAUC 5532). These limits are fairly sensible and would make RX J1836.2+5925 one of the faintest radio pulsars if pulsations are ever found. Summarizing, all the evidence thus far is consistent with an older or more distant version of the Geminga pulsar. In the near future, it is important to look for X-ray pulsations from this object with *Chandra* or *XMM-Newton* to confirm it as a pulsar. A pulsar detection of RX J1836.2+5925 might be feasible with a long observation using the *Chandra* High-Resolution Camera if RX J1836.2+5925 has a period $P \geq 50$ ms.

The further identification of properties such as proper motion and distance should also serve greatly to test the association of this EGRET source with the Gould Belt. In particular, although some neutron stars might have been born in the Gould Belt, it is possible that for high kick velocities the neutron star distribution is broader than the Gould belt itself, as neutron stars travel to the outskirts of the Gould belt.

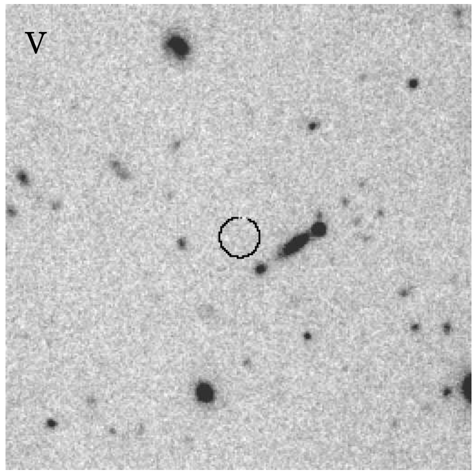

Figure 2: Zoom-in on a deep optical image from the MDM 2.4m at the location of the unidentified X-ray source RX J1836.2+5925. Seeing was $0''.8$, and the 3σ upper limit is $V > 25.2$. The field is $70''$ across, and the *ROSAT* HRI error circle is $3''$ in radius. The X-ray astrometry was calibrated using the optical positions of six well-identified X-ray sources surrounding this field from Figure 1.

3 3EG J1621+8203: An EGRET source coincident with NGC 6251

3EG J1621+8203 [18] was originally detected [1] with a flux above 100 MeV of 1.1×10^{-7} photon cm^{-2} s^{-1}. Its γ-ray spectrum can be fitted by a power law of photon index -2.27 ± 0.53. In spite of uncertainties, such spectral index is slightly steeper than the typical EGRET γ-ray blazar. An examination of existing catalogs finds no radio-loud, flat-spectrum radio source within its error box. However, no radio counterpart search was carried out for this source [19], as it is in a region of sky not covered by the 5 GHz Green Bank survey. 3EG J1621+8203 is a rather "weak" MeV source with a large error ellipse of semi-major axis a=1° and semi-minor axis b=0.7° which makes the unique identification with a counterpart a difficult task. An X-ray observation covering most of the error ellipse of 3EG J1621+8203 was carried out with the *ROSAT* PSPC instrument. Figure 3 shows the PSPC image ovelaid by the 1.4 GHz radio map of the same region. Complementary X-ray coverage of the periphery of the error ellipse was obtained with additional pointings using the *ROSAT* HRI and *ASCA* GIS instruments. Several X-ray sources fall within the error ellipse of 3EG J1621+8203. Using a multiwavelength approach we have been able to identify a number of active sources in the field with coronal emitting stars, radio-quiet QSOs and one with a galaxy cluster. The identifications are based mainly on a combination of catalog searches and optical imaging/spectroscopy of the X-ray positions.

An interesting source located within the error ellipse of 3EG J1621+8203 is the FR I radio galaxy NGC 6251. This source corresponds to the core and jet present in the 1400 MHz radio map (labels B1 through B5 in Figure 3). The highly extended jet has been observed at different scales and its inner structure has been resolved close to the core using VLBI maps [20]. NGC 6251 is an intriguing object because of the possible link between BL Lac objects and FR I galaxies [21]. It is believed that BL Lac objects correspond to jets aligned with the line of sight. However it appears that the general properties of BL Lac objects are similar to FR I galaxies [21]. Thus FR I galaxies could correspond to BL Lac with jets at non-zero viewing angles.

In the 3EG catalog, Cen A (NGC 5128) is the only radio galaxy candidate not belonging to the EGRET blazar class at energies above 100 MeV [22]. It is also the prototype of FR I galaxies and happens to be the brightest and nearest radio galaxy (z = 0.0018, $\sim$ 3.5 Mpc). Cen A

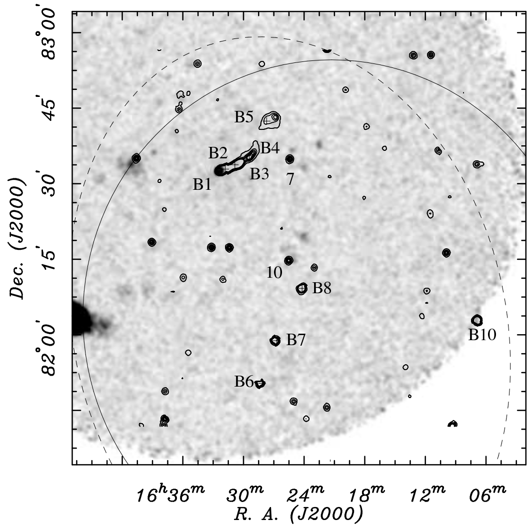

Figure 3: Contours of 1400 MHz sources in the field of 3EG J1621+8203 superimposed on the ROSAT PSPC image.

shows a jet that is oriented about 70° to our line of sight. Its derived γ-ray luminosity is weaker by a factor of 10^{-5} compared to the typical EGRET blazar. The low γ-ray luminosity and its radio properties might be evidence that Cen A is a misaligned BL Lac.

NGC 6251 shows some characteristics consistent with a BL Lac object. It has a flat-spectrum extended emission and inner radio core within uncertainties [23]. Moreover its radio luminosity is comparable to the average of EGRET blazar luminosity. Similar to Cen A, 3EG J1621+8203 is also less prominent in γ-ray luminosity by a factor of $10^2 - 10^5$ than the typical EGRET blazar. At an inclination angle of 45 degrees to our line of sight [24], the luminosity of NGC 6251 whose jets are pointed away from our line-of-sight is expected to be less than the total amount of scattered energy, F_1, of an aligned jet. We can write the total scattered energy as a function of the viewing angle [25]:

$$F_1(s, \mu_s^*) = D^{3+s}(1 - \mu_s^*)^{(s+1)/2}, \tag{1}$$

where the γ-ray flux seen by the observer is due to the scattered inverse Compton emission of ambient low energy photons by highly relativistic particles in the jet. Particles are assumed to be electrons and positrons distributed in energy as a power-law with a spectral index of s, μ_s^* is the cosine of the angle between the jet axis and the direction to the observer, and D is the Doppler factor of the blob, defined as $D = \Gamma^{-1}(1 - \beta\mu_s^*)^{-1}$, where βc is the bulk velocity of the plasma.

Figure 4 shows the decrease in scattered energy as a function of viewing angles, corresponding to two typical values of Lorentz factors (Γ) seen in blazars. This decrease could account for the discrepancy in γ-ray luminosities. Thus Cen A and NGC 6251 could correspond to BL Lac objects with jets at different viewing-angles. The increased sensitivity of future γ-ray missions may discover this new interesting class of objects associated with FR I galaxies and provide a crucial observation to test unification models for AGN.

Acknowledgments

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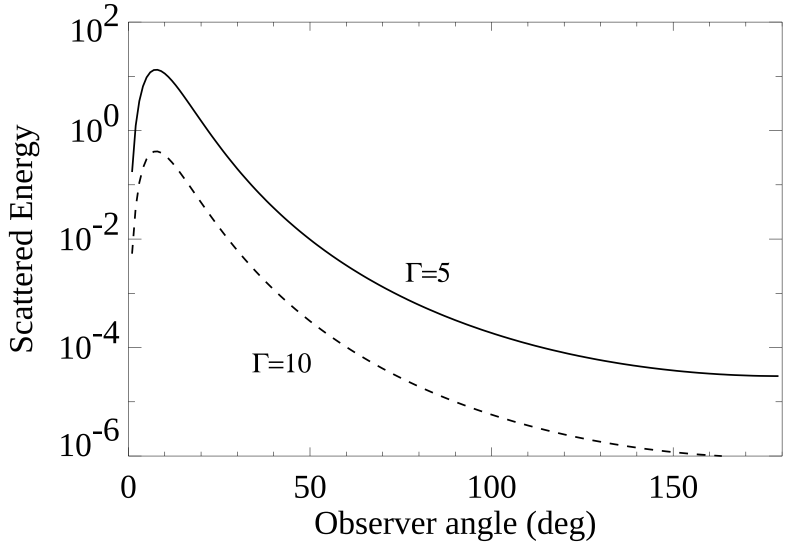

Figure 4: Decrease in the observed emission from a blazar as a function of jet orientation with respect to the observer.

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