

# Unidentified 3EG gamma-ray sources at low galactic latitudes

G.E. Romero<sup>1,\*</sup>, P. Benaglia<sup>1,\*</sup>, and D.F. Torres<sup>2</sup>

<sup>1</sup> Instituto Argentino de Radioastronomía, C.C.5, (1894) Villa Elisa, Buenos Aires, Argentina

<sup>2</sup> Departamento de Física, UNLP, C.C.67, (1900) La Plata, Buenos Aires, Argentina

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**Abstract.** We present a study on the possible association of unidentified  $\gamma$ -ray sources in the Third EGRET (3EG) catalog with different types of galactic objects such as Wolf-Rayet and Of stars, supernova remnants (SNRs), and OB associations (considered as pulsar tracers). We have made use of numerical simulations of galactic populations of  $\gamma$ -ray point sources in order to determine the statistical significance of the positional coincidences. New constraints on pure chance association are presented for SNRs and OB associations. There is overwhelming statistical support for the hypothesis that some SNRs are  $\gamma$ -ray sources (we obtain probabilities of pure chance association  $< 10^{-5}$ ). OB star associations present higher, but still negligible probabilities ( $< 10^{-3}$ ). It is also shown that although massive stars present just marginally significant correlation with 3EG sources, there is a posteriori support for at least three candidates.

**Key words:** gamma rays: observations – stars: early-type – ISM: supernova remnants – stars: pulsars: general

## 1. Introduction

The existence of a galactic population of  $\gamma$ -ray sources is known since the days of the COS B experiment (Swanenburg et al. 1981). Montmerle (1979) showed that about 50% of the unidentified COS B detections lie in regions containing young objects, like supernova remnants (SNRs) and OB massive stars. He suggested that the  $\gamma$ -ray emission could stem from  $\pi^0$ -decays resulting from hadronic interactions of high-energy protons (or nuclei) and ambient matter. These protons would be locally injected by young stars in the SNR shocks where they would be diffusively accelerated up to high energies by Fermi mechanism.

Cassé & Paul (1980) argued that particle acceleration at the terminal shock of strong stellar winds alone could be responsible for the  $\gamma$ -ray sources without the mediation of the SNR shock waves advocated by Montmerle. Gamma-ray production in shocks generated by massive stars has been discussed since then, and from different points of view, by Völk & Forman

(1982), White (1985), Chen & White (1991a,b), and White & Chen (1992), among others.

Since 1991, with the advent of the Energetic Gamma Ray Experiment Telescope (EGRET) onboard the Compton satellite, the observational data on galactic  $\gamma$ -ray sources have been dramatically improved. Two of the previously unidentified COS-B sources, Geminga and PSR 1706-44, are now known to be pulsars. The detection of pulsed high-energy emission from other sources (there are seven  $\gamma$ -ray pulsars so far, see Thompson 1996 for a review) and the identification of Geminga as a radio quiet object have prompted several authors to explore the possibility that all unidentified low latitude sources in the Second EGRET (2EG) catalog (Thompson et al. 1995, 1996) are pulsars (with the exception of a small extragalactic component which is seen through the Galaxy). In particular, Kaaret & Cottam (1996) have used OB associations as pulsar tracers finding out a significant positional correlation with 2EG unidentified sources. A similar study, including SNRs and HII regions (these latter considered as tracers of star forming regions and, consequently, of possible pulsar concentrations), has been carried out by Yadigaroglu & Romani (1997), who concluded that the pulsar hypothesis for the 2EG sources is consistent with the available information.

However, recent spectral analyses made by Merck et al. (1996) and Zhang & Cheng (1998) clearly show that several 2EG sources are quite at odds with the pulsar explanation. Time variability in the  $\gamma$ -ray flux of many sources also argues against a unique population behind the unidentified galactic  $\gamma$ -ray detections (McLaughlin et al. 1996, Mukherjee et al. 1997, Tavani et al. 1998).

Sturmer & Dermer (1995) and Sturmer et al. (1996) have investigated the possible association of  $\gamma$ -sources with SNRs, finding significant statistical support for the idea that some remnants could be  $\gamma$ -ray emitters. Esposito et al. (1996) have shown that five 2EG sources are coincident with well-known SNRs and, more recently, Combi et al. (1998a) have detected a new shell-type SNR at the position of 2EGS J1703-6302, as well as an interacting compact HI cloud, through multiple radio observations, clearly demonstrating, in this way, that at least some EGRET detections are physically related to SNRs.

With the publication of the Third EGRET (3EG) catalog of high-energy gamma-ray sources (Hartman et al. 1999), which includes data from Cycles 1 to 4 of the space mission, new and

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Send offprint requests to: G.E. Romero

\* Member of CONICET

valuable elements become available to deepen the quest for the nature of the unidentified  $\gamma$ -ray sources. The new catalog lists 271 point sources, including 170 detections with no conclusive counterparts at other wavelengths. Of the unidentified sources, 74 are located at  $|b| < 10^\circ$  (this number can be extended to 81 if we include sources with their 95% confidence contours reaching latitudes  $|b| < 10^\circ$ ). This means that the number of possible galactic unidentified sources is now nearly doubled with respect to the 2EG catalog.

Can these new sources be associated with pulsars? How many sources could be ascribed to known SNRs? Is there new statistical evidence for the identification of some detections in the 3EG catalog with massive stars that generate very strong winds? In the present paper we investigate these questions in the light of the new  $\gamma$ -ray data of the 3EG catalog. We use numerical simulations (constrained by adequate boundary conditions) of  $\gamma$ -ray source populations to weight the statistical significance of the different levels of positional coincidences determined for diverse types of candidates such as individual massive stars (Wolf-Rayet and Of stars with strong stellar winds), SNRs, and OB associations.

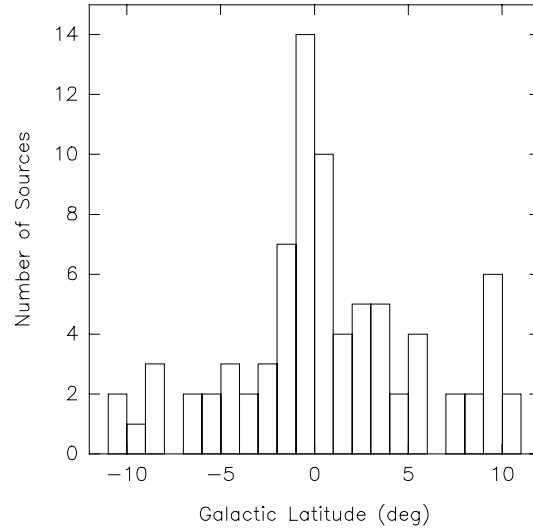
The contents of the paper are as follows. In the next section we describe the numerical procedure implemented for the analyses. Sects. 3, 4, and 5 deal with the possible association of unidentified 3EG sources with stars, SNRs, and star-forming regions considered as pulsar tracers, respectively. In Sect. 6 we present some further comments and, finally, in Sect. 7, we draw our conclusions.

## 2. Numerical simulations and statistical results

With the aim of finding the positional coincidences between unidentified 3EG sources at  $|b| < 10^\circ$  and different populations of galactic objects, we have developed a computer code that determines the angular distance between two points in the sky, taking into account the positional uncertainties in each of them. The code can be used to obtain a list of  $\gamma$ -ray sources with error boxes (here assumed as the 95% confidence contours given by the 3EG catalog) overlapping different kinds of objects, both extended (like SNRs or OB associations) and point-like (e.g. stars).

We ran the code with the 81 unidentified EGRET sources at galactic latitudes  $|b| < 10^\circ$  and complete lists of Wolf-Rayet (WR) stars, Of stars, SNRs, and OB associations. These lists were obtained from van der Hucht et al. (1988), Cruz-González et al. (1974), Green (1998), and Mel'nick & Efremov (1995), respectively. We have found that 6  $\gamma$ -ray sources of the 3EG catalog are positionally coincident with WR stars, 4 with Of stars, 22 with SNRs, and 26 with OB associations.

In order to estimate the statistical significance of these coincidences, we have simulated a large number of sets of EGRET detections, retaining for each simulated position the original uncertainty in its galactic coordinates. Specifically, in each case we have generated by computer 1500 populations of 81  $\gamma$ -ray sources through rotations on the celestial sphere, displacing a source with original coordinates  $(l, b)$  to a new position  $(l', b')$ .



**Fig. 1.** Distribution in galactic latitude of the 81 unidentified EGRET sources with positions at  $|b| < 10^\circ$  (within errors)

The new pair of coordinates is obtained from the previous one by setting  $l' = l + R_1 \times 360^\circ$ . Here,  $R_1$  is a random number between 0 and 1, which never repeats neither from source to source nor from set to set. Since we are simulating a galactic source population and not arbitrary sets at  $|b| < 10^\circ$ , we impose that the new distribution (i.e. each of the simulated sets) retains the form of the actual histogram in latitude of the unidentified 3EG sources, with  $1^\circ$  or  $2^\circ$ -binning. The histogram, for  $1^\circ$ -binning, is shown in Fig. 1.

In order to accomplish the mentioned constraint, we make  $b' = b + R_2 \times 1^\circ$ , and then, if the integer part of  $b'$  is greater than the integer part of  $b$  or if the sign of  $b'$  and  $b$  are different, we replace  $b'$  by  $b' - 1^\circ$ . Here, again,  $R_2$  is a random number between 0 and 1. This ensures that the new set of artificial positions preserves the actual histogram in latitude at  $1^\circ$ -binning. Similarly, a  $2^\circ$ -binning distribution can be maintained. Both sets of simulations provide comparable results.

The unidentified 3EG sources have, additionally, a non-uniform distribution in galactic longitude, showing a concentration towards the galactic center (see Fig. 2). This is basically an a posteriori result: a galactic population is not necessary compelled to follow such a distribution. If we impose on the simulated sets the observed distribution in longitude, probabilities of pure chance association will result naturally raised. When doing the simulations we have considered both cases: we made simulations of any kind of possible galactic populations adopting just constraints in  $b$ , and we made also simulations under the stronger hypothesis that just populations with the observed concentration towards the galactic center are possible. These latter results are useful because they provide an absolute upper limit for the pure chance overlapping probabilities between EGRET sources and the different types of known objects.

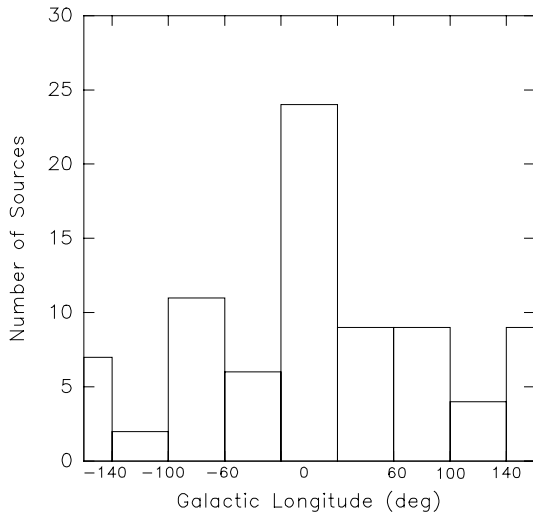
Once we performed 1500 simulations for each type of counterparts (a larger number of simulations do not significantly modify the results), we estimated the level of positional coin-

**Table 1.** Statistical results obtained from simulations with a random distribution in galactic longitude.

Object type	Actual coincidence	Simulated 1°-bin	Probability 1°-bin	Simulated 2°-bin	Probability 2°-bin
WR	6	2.3 ± 1.4	8.3 × 10 <sup>-3</sup>	2.1 ± 1.4	5.8 × 10 <sup>-3</sup>
Of	4	1.2 ± 1.1	1.5 × 10 <sup>-2</sup>	1.1 ± 1.0	5.9 × 10 <sup>-3</sup>
Assoc.OB	26	12.7 ± 3.1	1.2 × 10 <sup>-5</sup>	12.5 ± 3.1	9.8 × 10 <sup>-6</sup>
SNR	22	7.8 ± 2.5	1.6 × 10 <sup>-8</sup>	7.0 ± 2.4	5.4 × 10 <sup>-10</sup>

**Table 2.** Statistical results obtained from simulations constrained in both galactic latitude and longitude. The indicated binning interval is the binning of the preserved hystogram in galactic longitude.

Object type	Actual coincidence	Simulated 20°-bin	Probability 20°-bin	Simulated 40°-bin	Probability 40°-bin
WR	6	4.2 ± 1.8	1.3 × 10 <sup>-1</sup>	3.5 ± 1.7	8.3 × 10 <sup>-2</sup>
Of	4	2.0 ± 1.3	2.9 × 10 <sup>-1</sup>	1.7 ± 1.2	5.4 × 10 <sup>-2</sup>
Assoc.OB	26	18.7 ± 3.1	8.4 × 10 <sup>-3</sup>	16.4 ± 3.1	1.0 × 10 <sup>-3</sup>
SNR	22	11.1 ± 2.6	2.2 × 10 <sup>-5</sup>	10.6 ± 2.6	1.1 × 10 <sup>-5</sup>

**Fig. 2.** Distribution in galactic longitude of the 81 unidentified EGRET sources with positions at  $|b| < 10^\circ$  (within errors)

cidences between each simulated set and the different galactic populations under consideration. From these results we obtained an average expected value of chance associations and a corresponding standard deviation. The probability that the observed association level had happened by chance was then evaluated assuming a Gaussian distribution of the outputs. The results of this study are shown in Table 1 (for simulations just constrained in  $b$ ) and in Table 2 (for simulations constrained in both  $b$  and  $l$ ). In these tables we list, from left to right, the type of object under study, the number of actual positional coincidences, the number of expected chance coincidences according to simulations with the indicated binning, the probabilities that the actual coincidences can be due to chance, and the similar results for simulations with a different binning.

From Table 1, it can be seen that there is a strong statistical correlation between unidentified  $\gamma$ -ray sources of the 3EG

catalog and SNRs (at  $\sim 6\sigma$  level) as well as with OB associations (at  $\sim 4\sigma$  level). Regarding the stars, we find that there is a marginally significant correlation with WR and Of stars ( $\sim 3\sigma$ ). Remarkably, the probability of a pure chance association for SNRs is as low as  $5.4 \times 10^{-10}$  according to the 2°-binning simulations ( $1.6 \times 10^{-8}$  for 1°-binning). For the stars, we obtain probabilities in the range  $10^{-2} - 10^{-3}$ , which are suggestive but not overwhelming.

When simulations constrained to follow the observed distribution of unidentified sources in both  $b$  and  $l$  are considered (Table 2), we see that SNRs still present quite negligible probabilities for pure chance overlapping with 3EG sources ( $\sim 10^{-5}$ ), whereas OB associations show marginally significant probabilities ( $\sim 10^{-3}$ ). The case for physical association of 3EG sources with stars is not compelling in this case (probabilities  $\sim 10^{-1}$ ), and must be supported by further a posteriori evidence.

In the next sections we explore these results in more detail.

### 3. Massive stars

The case for possible association of unidentified EGRET sources with WR stars was previously presented –using data from the 2EG catalog– by Kaul & Mitra (1997). In the former catalog, there are 37 unidentified sources at  $|b| < 10^\circ$ . Kaul and Mitra proposed, on the basis of positional correlation, that 8 of these sources could be produced by WR stars. Their analysis of the possible chance occurrence of these associations, which was purely analytic and assumed equiprobability for each position on the sky, yielded an a priori expectation of  $\sim 10^{-4}$ . Their results are notably modified when the 3EG catalog is considered. Changes in position and smaller positional uncertainties reduce the number of positional coincidences despite the remarkable increment in the number of sources. Additionally, a more rigorous treatment in the probability analysis has the effect of significantly enhance the possibility of chance association (see Tables 1 and 2).

**Table 3.** Positional coincidences with WR stars.

$\gamma$ -Source (3EG J)	$F_\gamma \times 10^8$ (ph cm <sup>-2</sup> s <sup>-1</sup> )	$\Gamma$	Star	$\Delta\theta$ (deg)	$r$ (kpc)	$v_\infty$ (km s <sup>-1</sup> )	$\log\dot{M}$ (M <sub>⊙</sub> yr <sup>-1</sup> )	$L \times 10^{-34}$ (erg s <sup>-1</sup> )	Other coincidences
0747-3412	16.3±5.0	2.22±0.18	WR 9 (B)	0.37	2.35	2200 <sup>a</sup>	-4.2 <sup>f</sup>	6.5±2.0	
1102-6103	32.5±6.2	2.47±0.21	WR 34	0.48	9.50	1200 <sup>b</sup>	-4.5 <sup>b</sup>		OB/SNR
			WR 35	0.30	9.58	1100 <sup>b</sup>	-4.3 <sup>b</sup>		
			WR 37*	0.45	2.49	2150 <sup>b</sup>	<-4.1 <sup>f</sup>		
			WR 38*	0.45	1.97	2400 <sup>a</sup>	<-4.2 <sup>f</sup>		
			WR 39*	0.51	1.61	3600 <sup>a</sup>	<-4.0 <sup>f</sup>	6.1±1.1	
1655-4554	38.5±7.7	2.19±0.24	WR 80	0.59	4.40	2000 <sup>c</sup>	-4.1 <sup>c</sup>	54.0±10.8	OB
2016+3657	34.7±5.7	2.09±0.11	WR 137 (B)	0.44	1.82	1900 <sup>d</sup>	-4.5 <sup>d</sup>	8.3±1.4	OB/SNR
			WR 138*	0.50	1.82	1500 <sup>b</sup>	-4.7 <sup>d</sup>		
2021+3716	59.1±6.2	1.86±0.10	WR 142*	0.15	0.95	5200 <sup>e</sup>	<-4.7 <sup>g</sup>	3.9±0.4	OB
2022+4317	24.7±5.2	2.31±0.10	WR 140 (B)	0.64	1.34	2900 <sup>d</sup>	-4.1 <sup>d</sup>	3.2±0.7	OB

a: Koesterke & Hamann (1995); b: Hamann & Koesterke (1998); c: Zubko (1995); d: Prinja et al. (1990); e: Polcaro et al. (1991); f: Leitherer et al. (1997); g: Abbott et al. (1986); (B) stands for “binary system”; \* indicates stars whose positional coincidence with 2EG sources was previously noticed by Kaul & Mitra (1997).

**Table 4.** Positional coincidences with Of stars.

$\gamma$ -Source (3EG J)	$F_\gamma \times 10^8$ (ph cm <sup>-2</sup> s <sup>-1</sup> )	$\Gamma$	Star	$\Delta\theta$ (deg)	$r$ (kpc)	$v_\infty$ (km s <sup>-1</sup> )	$\log\dot{M}$ (M <sub>⊙</sub> yr <sup>-1</sup> )	$L \times 10^{-34}$ (erg s <sup>-1</sup> )	Other coincidences
0229+6151	37.9±6.2	2.29±0.18	HD 15629	0.30	1.9 <sup>a</sup>	2900 <sup>c</sup>	-5.8 <sup>c</sup>	10±1	OB
0634+0521	15.0±3.5	2.03±0.26	HD 46150	0.64	1.3 <sup>a</sup>	2900 <sup>c</sup>	<-5.9 <sup>c</sup>	1.8±0.5	OB/SNR
			HD 46223	0.63	1.6 <sup>a</sup>	2800 <sup>c</sup>	-5.8 <sup>c</sup>		
1410-6147	64.2±8.8	2.12±0.14	HD 124314	0.25	1.0 <sup>a</sup>	2400 <sup>d</sup>	-4.7 <sup>g</sup>	4.6±0.7	OB/SNR
2033+4118	73.0±6.7	1.96±0.10	Cyg OB2 5 (B)	0.27	1.8 <sup>b</sup>	1500 <sup>e</sup>	-4.43 <sup>e</sup>	17±1.5	OB
			Cyg OB2 11	0.24	1.8 <sup>b</sup>	2500 <sup>f</sup>	-5.2 <sup>h</sup>		

a: computed using  $M_v$  from Vacca et al. (1996); b: Humphreys (1978); c: Leitherer et al. (1997); d: Prinja et al. (1990); e: Conti & Howarth (1999); f: Biegging et al. (1989); g: Benaglia et al. (1999); h: computed as in Lamers & Leitherer (1993); (B) stands for “binary system”.

In Tables 3 and 4 we list the 3EG sources positionally coincident with WR and Of stars, respectively. As far as we are aware this is the first time that a statistical study of the correlation between Of stars and EGRET detections is carried out, despite that the possibility of  $\gamma$ -ray production in this kind of objects has been extensively discussed in the literature (e.g. Völk & Forman 1982). Of stars are the result of the evolution of massive O stars. They go through the Blue Super Giant (BSG) and Luminous Blue Variable (LBV) phases to end as WR stars and present spectral profiles that imply wind terminal velocities up to 3000 km s<sup>-1</sup> (e.g. Prinja et al. 1990). The wind velocities in these stars are considerably larger than the escape velocity, in such a way that important mass loss takes place (at the level 10<sup>-6</sup> – 10<sup>-5</sup> M<sub>⊙</sub> yr<sup>-1</sup>). The action of the Of stellar winds on the interstellar medium that surrounds the star creates bubbles of hot gas bounded by an expanding envelope of swept-up material, similar to what is found in WR stars (e.g. Benaglia & Cappa 1999). Gamma-ray emission can be then generated in these stars by processes similar to those invoked in the case of WRs (see below).

In the tables we provide, from left to right, the 3EG source name, the measured (summed over Cycles 1 to 4)  $\gamma$ -ray flux, the photon spectral index  $\Gamma$  ( $N(E) \propto E^{-\Gamma}$ ), the star name, the angular distance from the star to the  $\gamma$ -ray source best position,

the distance to the star, the terminal wind velocity, the mass loss rate, the expected intrinsic  $\gamma$ -ray luminosity assuming the star’s distance (the minimum one when there are more than one star in the field) and isotropic emission with average index  $\Gamma = 2$ , and, in the last column, any other positional coincidence revealed in our study.

From Table 3, it can be seen that most of the possible associations claimed by Kaul & Mitra (1997) are no longer viable ones. Just WR stars 37-39, 138, and 142 of their list stay after our analysis.

In order to compare Kaul and Mitra’s results with ours, it is worth remembering that when testing against positional coincidences they assumed an angular uncertainty of 1° for all EGRET sources. If we would make such an assumption, we would have found 20 positional coincidences in the 3EG catalog (i.e. 24.7% of the unidentified low-latitude sources). However, due to the new reduced EGRET errors, just 7% of these sources are now positionally consistent with WR stars, with a priori probabilities in the range  $\sim 10^{-3}$  – 10<sup>-1</sup> of being by chance. In addition, there are 4 sources with Of stars within their error boxes. The probability that these latter associations result just by chance is  $\sim 10^{-2}$  – 10<sup>-1</sup>.

Several mechanisms have been proposed to generate  $\gamma$ -rays in the vicinity of massive stars with strong winds. A compact  $\gamma$ -

ray source could be the result of  $\pi^0$ -decays which occur as a consequence of hadronic interactions between relativistic protons or nuclei, locally accelerated by shocks arising from line-driven instabilities in the star wind, and thermal ions (White & Chen 1992). The same embedded shocks can also accelerate electrons that could provide an additional source of (inverse Compton)  $\gamma$ -ray emission through the upscattering of stellar UV photons (Chen & White 1991a). Synchrotron losses of these energetic electrons can produce observable nonthermal radio emission, as detected in several massive stars (e.g. Abbott et al. 1984).

A different region where the  $\gamma$ -rays might be generated is at the interface between the supersonic wind flow and the interstellar medium. There, the terminal shock can reaccelerate ions up to high energies and, if sufficient concentration of ambient matter is available (e.g. small clouds or swept-up material), nuclear  $\gamma$ -rays copious enough to be detected could be produced (Cassé & Paul 1980). Völk & Forman (1982) have argued that stellar energetic particles lose too much energy in the expanding wind to be efficiently accelerated at the terminal shock, in such a way that local injection (e.g. from a nearby star) is required. However, White (1985) showed that the shocks embedded in the highly unstable radiatively driven winds can be responsible for much higher initial energies and partial reacceleration of the particles during the adiabatic expansion, so isolated massive stars could be also efficient  $\gamma$ -ray emitters if they present sufficiently strong winds.

The a posteriori analysis of our association results show that three stars are of special interest as possible counterparts of EGRET sources: WR 140, WR 142, and Cyg OB2 No.5. The first one is a binary system composed of a WC 7 plus an O4-5 star. The region of stellar wind collision seems to be particularly suitable for producing high energy emission. Eichler & Usov (1993) have studied the particle acceleration in this system concluding that it should be a strong  $\gamma$ -ray source. Based on observational data on WR 140, they predicted a  $\gamma$ -ray luminosity in the range  $5 \times 10^{32} - 2.5 \times 10^{35} \text{ erg s}^{-1}$ , in good agreement with the measured EGRET flux from 3EG J2022+4317 and the distance to the system (see Table 3).

The second promising star, WR 142, is one of the five WR stars which present strong OVI lines without being associated with planetary nebulae. The large Doppler broadening of all spectral lines reveals the existence of a very high wind velocity of  $\sim 5200 \text{ km s}^{-1}$ , which doubles what is usually observed in WR stars (Polcaro et al. 1991). The identification of WR 142 with the COS-B source 2CG 075+00 was proposed in Polcaro et al.'s (1991) paper, where they considered the  $\gamma$ -ray production in the strong stellar wind. In the 3EG catalog the star position is consistent with the source 3EG J2021+3716. If the star is responsible for the observed  $\gamma$ -ray flux, its intrinsic luminosity would be  $\sim 3 \times 10^{34} \text{ erg s}^{-1}$ , which is of the order of what is expected from White & Chen's (1992) hadronic model for isolated stars.

Finally, the binary system Cyg OB2 No.5 seems to be another interesting candidate for producing  $\gamma$ -rays. Usually considered as a contact binary formed by two O7 I stars (e.g. Torres-Dodgen et al. 1991), recent observations suggest that the sec-

ondary star in this system would be of spectral type B0 V–B2 V (Contreras et al. 1997). Variable radio emission was detected by several authors (e.g. Persi et al. 1990), with timescales of  $\sim 7$  years. A weak radio component of nonthermal nature has been observed with the VLA at a separation of  $\sim 0.8''$  from the main radio source, which is thermal and coincident with the primary optical component (Contreras et al. 1997). The radio variability in Cyg OB2 No.5 has been interpreted in terms of a colliding wind model by Contreras et al. (1997), who suggested that the weaker radio component is not a star but a bow shock produced by the wind collision. In this shock, electrons can be locally accelerated up to relativistic energies, yielding the synchrotron radiation that constitutes the secondary nonthermal source. Additionally,  $\gamma$ -rays are generated through inverse Compton losses in the UV radiation field of the secondary (Eichler & Usov 1993). The same Fermi mechanism that accelerates the electrons should also operate on protons, providing a source of energetic ions that could contribute with higher energy  $\gamma$ -ray emission, as in the case involving WR stars. For strong shocks, the test particle theory predicts that the relativistic protons will have a differential energy spectrum given by  $N(E) \propto E^{-2}$ . The  $\pi^0$ -decay  $\gamma$ -rays resulting from  $p-p$  collisions should conserve the shape of the original proton spectrum, in such a way that at energies above 100 MeV the photon spectral index would be  $\Gamma \sim 2$ , as observed by EGRET.

#### 4. Supernova remnants

Possible correlation between SNRs and unidentified EGRET sources, on the basis of two dimensional positional coincidence, has been proposed since the release of the first EGRET (1EG) catalog. Sturmer & Dermer (1995) suggested that some of the unidentified sources lying at galactic latitudes  $|b| < 10^\circ$  might be associated with SNRs: of 37 detections, 13 overlapped SNR positions in the 1EG catalog. However, their own analysis showed that the statistical significance was not too high as to provide a strong confidence. Chance association was just  $1.8\sigma$  away from the obtained result. Using the 2EG catalog, Sturmer et al. (1996) repeated the analysis, and showed that 95% confidence contours of 7 unidentified EGRET sources overlapped SNRs, some of them appearing to be in interaction with molecular clouds. Similar results were independently reported by Esposito et al. (1996), although neither of them assessed the chance probability of these 2EG-catalog findings. Considering the 1EG catalog, 35% of the unidentified sources were positional related to SNRs. This drop to 21.8% in the 2EG catalog, and is currently about 27%. One important point to take into account when evaluating these differences is not only to consider the evolution of the EGRET catalog but also that of the supernova remnant Green's catalog. At the time of the first studies by Sturmer & Dermer (1995), the supernova catalog contained 182 SNRs. This grew up to 194 in 1996, and currently it lists 220 remnants.

In Table 5 we show the 3EG sources that are positionally consistent with SNRs listed in the latest version of Green's catalog. From left to right we provide the  $\gamma$ -ray source name, the measured flux, the photon spectral index  $\Gamma$ , the SNR identifi-

**Table 5.** Positional coincidences with supernova remnants.

$\gamma$ -source (3EG J)	$F_\gamma$ ( $10^{-8}$ ph cm $^{-2}$ s $^{-1}$ )	$\Gamma$	SNR	$\Delta\theta$ (deg)	Size (arcmin)	Type	Other coincidences
0542+2610	14.7 $\pm$ 3.2	2.67 $\pm$ 0.22	G180.0-1.7	2.04	180	S	
0617+2238	51.4 $\pm$ 3.5	2.01 $\pm$ 0.06	G189.1+3.0	0.11	45	S	OB
0631+0642	14.3 $\pm$ 3.4	2.06 $\pm$ 0.15	G205.5+0.5	1.97	220	S	
0634+0521	15.0 $\pm$ 3.5	2.03 $\pm$ 0.26	G205.5+0.5	2.03	220	S	Of/OB
0824-4610	63.9 $\pm$ 7.4	2.36 $\pm$ 0.07	G263.9-3.3	1.71	255	C	OB
0827-4247	42.6 $\pm$ 7.4	2.10 $\pm$ 0.12	G260.4-3.4	1.04	60 $\times$ 50	S	
0841-4356	47.5 $\pm$ 9.3	2.15 $\pm$ 0.09	G263.9-3.3	2.28	255	C	
1013-5915	33.4 $\pm$ 6.0	2.32 $\pm$ 0.13	G284.3-1.8	0.65	24	S	
1102-6103	32.5 $\pm$ 6.2	2.47 $\pm$ 0.21	G290.1-0.8	0.12	19 $\times$ 14	S	WR/OB
1410-6147	64.2 $\pm$ 8.8	2.12 $\pm$ 0.14	G312.4-0.4	0.23		S	OB/Of
1639-4702	53.2 $\pm$ 8.7	2.5 $\pm$ 0.18	G337.8-0.1	0.07	9 $\times$ 6	S	OB
			G338.1+0.4	0.65	15	S	
			G338.3+0.0	0.57	8	S	
1714-3857	43.6 $\pm$ 6.5	2.30 $\pm$ 0.20	G348.5+0.0	0.47	10	S	
			G348.5+0.1	0.50	15	S	
1734-3232	40.3 $\pm$ 6.7	–	G355.6+0.0	0.16	6 $\times$ 8	S	OB
1744-3011	63.9 $\pm$ 7.1	2.17 $\pm$ 0.08	G359.0-0.9	0.41	23	S	
			G359.1-0.5	0.25	24	S	
1746-2851	119.9 $\pm$ 7.4	1.70 $\pm$ 0.07	G0.0+0.0	0.12	3.5 $\times$ 2.5	S	
			G0.3+0.0	0.19	15.8	S	
1800-2338	61.3 $\pm$ 6.7	2.10 $\pm$ 0.10	G6.4-0.1	0.17	42	C	
1824-1514	35.2 $\pm$ 6.5	2.19 $\pm$ 0.18	G16.8-1.10	0.43	30 $\times$ 24		OB
1837-0423	19.1	2.71 $\pm$ 0.44	G27.8+0.6	0.58	50 $\times$ 30	F	
1856+0114	67.5 $\pm$ 8.6	1.93 $\pm$ 0.10	G34.7-0.4	0.17	35 $\times$ 27	S	
1903+0550	62.1 $\pm$ 8.9	2.38 $\pm$ 0.17	G39.2-0.3	0.41	8 $\times$ 6	S	
2016+3657	34.7 $\pm$ 5.7	2.09 $\pm$ 0.11	G74.9+1.2	0.26	8 $\times$ 6	F	WR/OB
2020+4017	123.7 $\pm$ 6.7	2.08 $\pm$ 0.04	G78.2+2.1	0.15	60	S	OB

cation, the angular distance between the best  $\gamma$ -ray source position and the center of the remnant, the size of the remnant in arcminutes, the SNR type (S for shell, F for filled-centre, and C for composite), and other positional coincidences found in our study. The table contains 22 possible associations with an a priori probability of being purely by chance completely negligible ( $\leq 10^{-5}$ ). It is important to remind that this list is formed entirely of positional coincidences with currently catalogued SNRs. However, the diffuse galactic disk nonthermal emission, originated in the interaction of the leptonic component of cosmic rays with the galactic magnetic field, is veiling many remnants of low surface brightness. Recent observational studies using filtering techniques in the analysis of radio data have revealed many new SNR candidates that are not included in Green's catalog (e.g. Duncan et al. 1995, Jonas 1998, Combi & Romero 1998, Combi et al. 1998b, 1999). If these candidates were included in our analysis a larger number of associations would have resulted.

The intrinsic  $\gamma$ -ray luminosity of SNRs, stemmed from interactions between cosmic rays reaccelerated at the supernova shock front and swept-up material, is expected to be rather low (Drury et al. 1994). However, if a cloud is near the particle acceleration site, the enhanced nuclear cosmic rays from the shock can “illuminate” the cloud through  $\pi^0$ -decays yielding a compact  $\gamma$ -ray source (Aharonian et al. 1994). Such scenario has

been recently studied by Combi et al. (1998a) in relation with the source 3EG J1659-6251 (previously 2EGS J1703-6302).

## 5. OB associations

In Table 6 we list the unidentified 3EG sources that are positionally coincident with the OB associations in the catalog by Mel'nik & Efremov (1995). Our results can be compared with the similar work by Kaaret & Cottam (1996). Using the 2EG catalog, they have already found a statistically significant correlation: 9 of the unidentified 2EG sources have position contours overlapping an OB association and other 7 lie within  $1^\circ$  angular distance. These results are totally compatible with ours. Here, we find 26 superpositions out of 81 unidentified 3EG sources (32%),  $2.4\sigma$  away from what is expected from pure chance association (or  $5\sigma$ , if we consider the results listed in Table 1). The mean angular separation between the centroid of the OB association and the EGRET source is  $1.5^\circ$ , although most sources are at angular distances of less than  $1^\circ$ .

The differences between both methods of analysis are worth commenting. In particular, we decided, for completeness, to keep the nearby association Sco 2A despite its proximity. Any pulsar traced by it must have a negligible proper velocity in order to be consistent with its angular size, but its existence cannot be ruled out only on a priori grounds. To calculate the chance

**Table 6.** Positional coincidences with OB associations.

$\gamma$ -source (3EG J)	$F_\gamma$ ( $10^{-8}$ ph cm $^{-2}$ s $^{-1}$ )	$\Gamma$	OB Assoc.	$\Delta\theta$ (deg)	$r$ (kpc)	Size (deg)	$L$ ( $10^{34}$ erg s $^{-1}$ )	Other coincidences
0229+6151	37.9±6.2	2.29±0.18	Cas 6	1.44	2.01	0.95	11.1 ± 1.6	Of
0617+2238	51.4±3.5	2.01±0.06	Gem 1	2.07	1.34	1.94	6.7 ± 0.4	SNR
0634+0521	15.0±3.5	2.03±0.26	Mon 2A	1.27	1.63	0.84		Of/SNR
			Mon 1B	1.27	1.48	0.60	2.4 ± 0.6	
0824-4610	63.9±7.4	2.36±0.07	VELA 2	4.75	0.49	4.14	1.1 ± 0.1	SNR
0848-4429*	20.1±7.7	2.05±0.16	VELA 1B	1.62	1.41	1.00	2.3 ± 1.7	
1027-5817*	65.9±7.0	1.94±0.09	Car 1A	1.17	2.40	0.80		
			Car 1B	1.98	2.14	1.61	21.8 ± 2.3	
1048-5840*	61.8±6.7	1.97±0.09	Car 1B	1.78	2.14	1.61	20.5 ± 2.2	
			Car 1E	1.72	2.64	1.55		
			Car 1F	0.72	2.76	0.55		
1102-6103	32.5±6.2	2.47±0.21	Car 1-2	1.17	2.62	0.56		WR/SNR
			Car 2	3.15	2.16	2.54	10.1 ± 3.0	
1308-6112	22.0±6.1	3.14±0.59	Cen 1B	1.15	1.76	0.44	5.0 ± 1.3	
			Cen 1D	1.46	1.87	0.75		
			Sco 2A	8.89	0.16	8.18	0.04 ± 0.01	
1410-6147	64.2±8.8	2.12±0.14	CLUST 3	1.12	1.51	0.76	10.6 ± 1.4	Of/SNR
1420-6038*	44.7±8.6	2.02±0.14	CLUST 3	1.08	1.51	0.76	7.4 ± 1.4	
1639-4702	53.2±8.7	2.5±0.18	Ara 1A A	1.95	1.59	1.39	9.8 ± 1.5	SNR
			NGC 6204	2.11	1.94	1.55		
1655-4554	38.5±7.7	2.19±0.24	Ara 1A B	1.13	1.35	0.47	5.1 ± 1.0	WR
1718-3313	18.7±5.1	2.59±0.21	Sco 4	1.84	1.23	1.30	2.0 ± 0.6	
1734-3232	40.3±6.7	–	Tr 27	1.63	1.31	1.14	5.0 ± 0.8	SNR
1809-2328*	41.7±5.6	2.06±0.08	Sgr 1B	0.47	1.94	0.31	11.3 ± 1.7	
1823-1314	42.0±7.4	2.69±0.19	Sct 3	1.45	1.48	1.16	6.7 ± 1.2	
1824-1514	35.2±6.5	2.19±0.18	Sct 3	1.68	1.48	1.16	5.6 ± 1.0	SNR
1826-1302*	46.3±7.3	2.00±0.11	Sct 3	1.62	1.48	1.16	7.3 ± 1.2	
2016+3657	34.7±5.7	2.09±0.11	Cyg 1,8,9	5.49	1.17	4.94	3.4 ± 0.6	WR/SNR
2020+4017	123.7±6.7	2.08±0.04	Cyg 1,8,9	5.10	1.17	4.94	12.3 ± 0.6	SNR
2021+3716	59.1±6.2	1.86±0.10	Cyg 1,8,9	5.24	1.17	4.94	5.9 ± 0.7	WR
2022+4317	24.7±5.2	2.31±0.19	Cyg 1,8,9	5.66	1.17	4.94	2.4 ± 0.5	WR
2027+3429*	25.9±4.7	2.28±0.15	Cyg 1,8,9	5.71	1.17	4.94	2.9 ± 0.1	
2033+4118	73.0±6.7	1.96±0.10	Cyg 1,8,9	5.22	1.17	4.94	7.2 ± 0.7	Of
2227+6112*	41.3±6.1	2.24±0.14	Cep 2 B	4.06	0.77	3.60	1.8 ± 0.2	

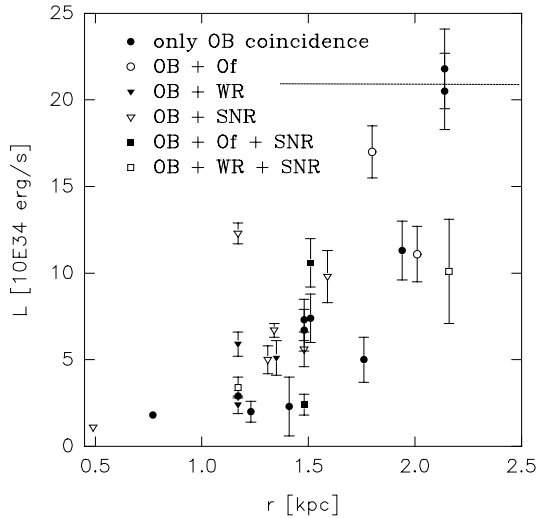
\* Pulsar candidate?.

superposition probability Kaaret and Cottam studied EGRET sources just within  $[-5^\circ, 5^\circ]$  in galactic latitude (only 25 sources of the total 129 unidentified ones present in the 2EG catalog), and generated sample locations using two Gaussian distributions, in longitude and latitude, with central value and deviation provided by the actual positions of the unidentified sources. They also used a galactic model to map the gas distribution. This procedure yields almost the same results that we show in Table 1 (chance association probability around  $10^{-5}$ ). Interestingly, despite all EGRET sources changed their positions from the 2EG to the 3EG catalog and a significant number of new detections has been added, the percentage and the confidence level of the positional coincidences remains almost the same. When we consider, instead, our simulations constrained in both  $b$  and  $l$ , the probability of pure chance overlapping raises in two orders of magnitude with respect to Kaaret & Cottam's results, but it is still negligible ( $\sim 10^{-3}$ ).

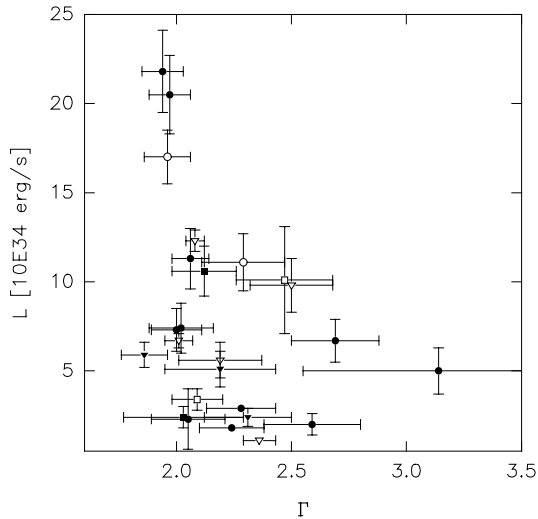
All known  $\gamma$ -ray pulsars are young objects ( $\leq 10^6$  yr) with spectral indices smaller than 2.15 (Crab's) and a trend for spectral hardening with characteristic age (Fierro et al. 1993). From Table 6, if we consider just sources coincident *only* with OB associations and exclude the three sources with very steep indices (3EG J 1308-6112, 3EG J 1718-3313, and 3EG J 1823-1314), we get  $\langle \Gamma \rangle = 2.07$  and  $1\sigma = 0.12$  for the 8 remaining EGRET sources. These are the most promising candidates for pulsar associations. We have marked them with a star symbol in Table 6.

## 6. Further comments

In Fig. 3 we show a plot of the  $\gamma$ -ray luminosity (assuming isotropic emission) of the unidentified sources coincident with OB associations against the estimated distance to the associations. By using different symbols we indicate whether there are additional positionally coincident objects for each  $\gamma$ -ray



**Fig. 3.** Luminosity versus distance for unidentified 3EG sources coincident *only* with OB associations (black filled dots) and with OB associations *and* other objects (remaining symbols). The horizontal line marks the luminosity of Vela pulsar. Isotropic emission has been considered in all cases.



**Fig. 4.** Luminosity versus photon spectral index for unidentified 3EG sources coincident with OB associations. Isotropic emission is assumed in all cases. Symbols are as in Fig. 3.

source. The solid horizontal line represents the luminosity of Vela pulsar. A similar plot of luminosity versus photon spectral index  $\Gamma$  is shown in Fig. 4. The first plot shows that the luminosity distribution of this subset of 3EG sources is consistent with the observed distribution for  $\gamma$ -ray pulsars when emission into  $4\pi$  sr is assumed (see Kareet & Cottam 1996). Fig. 4 shows, however, that not all sources superimposed to OB associations present the spectral signature expected from pulsars: they should concentrate in the left-upper corner of the frame. There, two sources clearly differentiate from the rest: 3EG J1027-5817 and 3EG J1048-5840. They have luminosities similar to Vela’s and hard spectra with  $\Gamma < 2$ , which make them good candidates for  $\gamma$ -ray pulsars. Their average spectral index

$\langle \Gamma \rangle = 1.95 \pm 0.09$  is consistent with the index observed in Geminga ( $\Gamma_{\text{Gem}} = 1.86 \pm 0.04$ )

The identification of 3EG J1048-5840 (formerly 2EG J1049-5847) with a pulsar (PSR B1046-58) was already proposed by Zhang & Cheng (1998), who showed that its  $\gamma$ -ray spectrum is consistent with the predictions of outer gap models. In addition, these authors also suggested that 3EG J1823-1314 (2EG J1825-1307) could be the pulsar PSR B1823-13. This latter identification must be now rejected in the light of the new determination of the spectral index of the  $\gamma$ -ray source in the 3EG catalog,  $\Gamma = 2.69 \pm 0.19$ , which is too steep for a pulsar.

Regarding 3EG J1027-5817, no known radio pulsar is found within its 95% confidence contour. It could be a Geminga-like object or the effect of the combined emission of a pulsar and a weak SNR in Car 1A-B (the 3EG catalog notes that it is a possible case of multiple or extended source).

Some of the low luminosity sources in Fig. 3 might be yet undetected SNRs, whereas the sources with the steepest indices could be background AGNs (Grenier 1997). A simple extrapolation of the high latitude population of  $\gamma$ -ray blazars shows that about 10 of this sources should be detected throughout the Galaxy within  $|b| < 10^\circ$  (Yadigaroglu & Romani 1997). Most of them, however, should belong to the group of 43 3EG sources for which we have found not positional coincidences with any known galactic object. This set of sources has an average value of galactic latitude  $\langle |b| \rangle = 5.8 \pm 3.3$ , which suggests a significant extragalactic contribution.

Finally, we want to mention two interesting additional possibilities to explain some 3EG sources: isolated Kerr-Newman black holes (Punsly 1998a,b) and isolated standard black holes accreting from the diffuse interstellar medium (Dermer 1997). In Punsly’s model, a bipolar magnetically dominated MHD wind is driven by a charged black hole located in a low density region (otherwise it would discharge rapidly). The wind forms two leptonic jets which propagate along the rotation axis in opposite directions, as it occurs in AGNs. Self-Compton losses provide  $\gamma$ -ray luminosity in the range  $10^{32} - 10^{33} \text{ erg s}^{-1}$  for a  $7-M_\odot$  black hole with a polar magnetic field of  $\sim 10^{10}$  G. If such an object is relatively close ( $\sim 300$  pc), it could appear as a typical unidentified EGRET source with  $\Gamma \sim 2.5$ .

In the case of isolated black holes accreting from a diffuse medium, a hole with mass of  $10 M_\odot$  and a velocity of  $10 \text{ km s}^{-1}$  can produce a  $\gamma$ -luminosity  $\sim 7 \times 10^{33} \text{ erg s}^{-1}$  in a medium with density of  $0.1 \text{ cm}^{-3}$  (Dermer 1997). Changes in the particle density can result in  $\gamma$ -ray flux variability, as observed in several unidentified sources. None of these  $\gamma$ -sources based on black holes can be ruled out at present, and their observational signatures at other wavelengths seem to be worth of careful search.

## 7. Conclusions

We have studied the level of two-dimensional positional coincidences between unidentified EGRET sources at low galactic latitudes in the 3EG catalog and different populations of galactic objects, finding out that there is overwhelming statis-



tical evidence for the association of  $\gamma$ -ray sources with SNRs and significant evidence for the association with OB star forming regions (considered as pulsar tracers). Additionally, there is marginal support for the association with early-type stars endowed with very strong winds, like Wolf-Rayet stars and Of stars. A posteriori analyses of the star candidates show that there are at least three systems (WR 140, WR 142, and Cyg OB2 No. 5) which are likely  $\gamma$ -ray sources. Several sources positionally coincident with OB associations are probably pulsars, like 3EG J1048-5840 and similar sources with hard spectra. Besides, there are 43 3EG sources for which we have not found any positional coincidence with known objects. This set of sources could include undetected low-brightness SNRs in interaction with dense and compact clouds, some Geminga-like pulsars, and, perhaps, a new kind of galactic  $\gamma$ -ray sources, like Kerr-Newman black holes or isolated black holes accreting from the interstellar medium.

The main conclusion to be drawn is that there seems to exist more than a single population of galactic  $\gamma$ -ray sources. Pulsars constitute a well established class of sources, and there is no doubt that under certain conditions some SNRs are also responsible for significant  $\gamma$ -ray emission in the EGRET scope. Both isolated and binary early-type stars are likely to present high-energy radiation strong enough to be detected by EGRET in some special cases. We propose that, in addition to the well-known WR stars 140 and 142, the Cyg OB2 No. 5 binary system could be a strong  $\gamma$ -ray source, the first one to be detected involving no WR stars. The large number of unidentified EGRET sources free of any positional coincidence with luminous objects also encourage further studies to find whether there exist a population of exotic objects yet undetected at lower wavelengths.

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