UNIDENTIFIED EGRET SOURCES IN THE GALAXY

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Identifying γ-ray sources in the Galaxy is hampered by their poor localization, source confusion, and the large variety of potential emitters. Neutron stars and their environment offer various ways to power γ-ray sources: pulsed emission from the open magnetosphere and unpulsed γ rays from the wind nebula and from the cosmic rays accelerated in the supernova remnant. While the latter still awaits confirmation, new candidate associations bring forward the importance of $10^4$ yr old pulsars as GeV sources, with a diversity that will help constrain the acceleration mechanisms near the pulsar and in the wind. Theoretical interest in the γ-ray activity of X-ray binaries and micro-quasars has also been revived by the emergence of a subset of variable sources in the inner Galaxy and another one in the halo.

Only $\sim$80 of the 271 EGRET sources\textsuperscript{26} have been identified because of the large position uncertainty resulting from the poor angular resolution and the structured interstellar background. Irrefutable identifications with a flaring blazar or a pulsar are even fewer. Most identifications are blazars, based on spatial coincidence with a bright, flat-spectrum radiogalaxy. Their number agree with the total expected from the largely anisotropic distribution of all sources across the sky. So, nearly two thirds of the sources are hiding in our Galaxy, awaiting identification.

1. In the Galactic disc

A population of rather hard and steady sources is found at $|b| < 3^\circ$ along the Galactic plane, mostly in the inner Galaxy. Their average spectral index is $\bar{\gamma} = 2.09 \pm 0.02$ and 80% of them show no sign of time variability\textsuperscript{43}. The positional correlation with tracers of star formation, such as HII regions, pulsars, supernova remnants (SNR), and OB associations, points to an origin in or near active star-forming sites. The latest compilation\textsuperscript{40} yields combined probabilities for chance alignment with 23 OB associations and 26 SNRs below $10^{-3}$ and $10^{-5}$, respectively. Distances of 1 to 2.5 kpc for
the OB associations\textsuperscript{40} and of 1 to 4 kpc from the source spatial distribution imply luminosities $L_{>100 MeV,4\pi sr}$ of $(0.6-4) \times 10^{28}$ W.

The stable pulsars show a standard deviation in flux of 10-12% that is attributed to systematic uncertainties in the instrument performance. Unidentified sources are found to vary less at lower latitude\textsuperscript{34}. Yet, 17 sources along the Galactic plane exhibit a lower limit in flux standard deviation that is twice as large as the instrumental dispersion\textsuperscript{34}. These sources vary over months and are concentrated at $|l| \leq 55^\circ$, i.e. in the inner spiral arms. Distances of 5 to 8 kpc imply high luminosities $L_{>100 MeV,4\pi sr}$ of $(0.5-5) \times 10^{29}$ W that are typical of X-ray binaries and 10$^4$-yr-old pulsars. The latter are expected to be steady emitters, but variability over months is common in accreting systems. The large dispersion in spectral indices, ranging from 1.7 to 3.1, yields no further clue.

2. In the Gould Belt

The stable sources gathering at $3^\circ < |b| < 30^\circ$ significantly differ from those in the inner Galaxy. They exhibit softer spectra and lower fluxes with a distinctly steeper $\log(N) - \log(> S)$ distribution than near the plane\textsuperscript{18}. Their excess at mid latitudes points to a nearby origin and closely follows the trace of the Gould Belt around us. It is significantly better correlated with the Belt than with other Galactic structures\textsuperscript{21}. As a 30 to 40 Myr-old starburst region, 300 pc in radius, the Belt has recently produced nearby supernovae at a rate 3 to 5 times higher than the local Galactic one\textsuperscript{21}. As many as 45±6 persistent sources can be associated with the Belt, among which $\sim 10$ may be background sources in the Galactic disc. They have luminosities $L_{>100 MeV,4\pi sr}$ of $(0.3-8) \times 10^{26}(D/300\text{pc})^2$ W. Most error boxes lack suitable counterparts, but neutron star activity offers a promising prospect, in particular emission from Myr-old pulsars\textsuperscript{21,25}.

3. At large scale height

Variable sources at $|b| > 3^\circ$ form a separate population with spectral, temporal, and spatial properties different from the persistent sources\textsuperscript{22}. It is unlikely that the difference be due to systematic biases in the instrument performance, the survey exposure, or the Galactic background. Average spectral indices of $2.25 \pm 0.03$ and $2.52 \pm 0.06$ were obtained for the persistent (p) and non-persistent ($\bar{p}$) sources, with a chance probability of $2 \times 10^{-7}$ of equal index\textsuperscript{22}. Average variability indices\textsuperscript{43} of $0.38 \pm 0.06$ and $0.95 \pm 0.18$ were obtained with a chance probability of $1.3 \times 10^{-4}$ of equal $\tau$. The $\bar{p}$
sources behave much like the variable EGRET blazars and the p sources show no or little variability\textsuperscript{34}. While the p sources gather along the Gould Belt, the \( \bar{p} \) sources are scattered within 60° around the Galactic center, with a 4 \( 10^{-8} \) probability of identical distribution. The 45 ± 9 \( \bar{p} \) sources are not isotropically distributed (4.7\( \sigma \)), but have a large scale-height \( z_{H} = 2.0^{+1.2}_{-0.6} \) kpc above the Galactic plane or a radial distribution in the halo equivalent to that of the globular clusters (Grenier, in prep.). Their location implies luminosities \( L_{>100MeV,4\pi sr} \geq 10^{28-30} \) W and ages of the order of \( 10^{9} \) yr.

4. Massive stars

Particles accelerated in the supersonic wind of massive stars, at the terminal shock or along the turbulent \( 10^{28-29} \) W wind, can up-scatter the stellar UV radiation field to produce \( \gamma \) rays. Yet, none of the numerous nearby O stars in the Gould Belt has been detected by EGRET\textsuperscript{21}. Binary systems of massive stars should be more efficient by providing ample UV target photons and a strong shock between colliding winds. Synchrotron radio emission has indeed been observed in several systems. The WR+O star system W140 has been proposed to explain the stable 3EG J2022+4317 source\textsuperscript{1} and the O+O+B system Cyg OB2 n°5 to account for half of the 3EG J2033+4118 flux\textsuperscript{2}. Collective acceleration from stellar winds and nearby supernova shocks, as in SNOBs\textsuperscript{35} or in superbubbles\textsuperscript{10}, could also produce extended \( \gamma \)-ray sources that EGRET could not resolve.

5. X-ray binaries and micro-quasars

In high-mass X-ray binaries, electrons accelerated at the shock between the pulsar and the stellar winds can shine up to TeV energies\textsuperscript{42,30} by up-scattering the stellar radiation. PSR B1259-63 has been extensively studied near periastron when TeV synchrotron emitting electrons are produced. But, the emission peak should occur at TeV energies, explaining the lack of EGRET detection\textsuperscript{30}. The association of SAX J0635+0533 with the hard and stable 3EG 0634+0521 source\textsuperscript{27} would offer a unique opportunity to study the early phase of a massive system hosting a young (1.4 kyr) and energetic (5 \( 10^{31} \) W) pulsar. Alternatively, if a transient accretion forms and rotates more rapidly than the pulsar, protons may be accelerated to TeV energies in the magnetosphere, near the null surface. Colliding further out with the disc, they would produce \( \pi^{0} \)-decay \( \gamma \) rays. This scenario could explain the soft, \( E^{-2.67^{+0.22}_{-0.22}} \), variable 3EG 0542+2610 source coincident with the X-ray transient A0535+26\textsuperscript{41}. 
In micro-quasars, energetic electrons in persistent jets can up-scatter accretion disc photons or stellar radiation to a few MeV for a low-mass companion and to GeV energies for a high-mass one, depending on the jet viewing angle\textsuperscript{19}. Synchrotron-self-Compton emission is fainter. Sporadic ejections would shine too briefly to account for EGRET sources. Tidal precession would cause variability on a few month timescale, so micro-quasars with high-mass companions have been proposed to explain variable sources in the inner Galaxy\textsuperscript{29}. The LS 5039 system\textsuperscript{37} is indeed seen toward 3EG J1824-1514, but the source is stable. Whether the low-mass systems can explain the variable halo sources is being explored.

3EG 0241+6103 has long been associated\textsuperscript{31} with the radio source LSI $+61.5\,303$ which is known for its radio flares after periastron, its mildly relativistic jet and the 4-yr precession of its disc\textsuperscript{33}. But the EGRET variability does not correlate with the radio phase and the COMPTEL flux is stable. So, the association is unclear.

6. Pulsars and their wind nebulae

Hard and stable sources are often related to pulsars following the characteristics of the 7 young and energetic EGRET pulsars. But older, fainter pulsars may behave differently. Pulsar wind nebulae (PWNe), confined by the interstellar pressure or by the ram pressure from the pulsar motion, have also emerged as potential candidates up to TeV energies as in the Crab, Vela, and PSR J1709-4429 nebulae. 7 EGRET sources coincide with PWNe. In particular, PSR J1048-5832 shows unpulsed GeV emission possibly arising from the wind nebula\textsuperscript{28}.

Six of the 9 radio pulsars with highest $E/D^2$ rank are seen in $\gamma$ rays, indicating a close relationship between the onset of high-energy showers and coherent radio emission. Population studies using the characteristics of the $\gamma$-ray beam from the polar cap and the outer gap models, as well as the radio beam properties, show that pulsars likely dominate the unidentified source population at low latitude\textsuperscript{20,44}. Polar-cap and outer-gap pulsars can account for $\sim$60\% and $\sim$100\% of the stable sources, respectively. The two models predict different source counts and distinct ratios of radio-loud to radio-quiet $\gamma$-ray pulsars because of different beam apertures, a tighter correlation between the radio and $\gamma$-ray beams above the polar cap, and very different evolutions with age. The polar cap (or outer gap) simulations yield 13 (or 10) radio-loud and 2 (or 22) radio-quiet pulsars above the EGRET sensitivity\textsuperscript{20,44}. These differences and the detection of older pulsars
will serve as important diagnostics for modelling the pulsed emission.

Pulsars also largely contribute to the Gould Belt sources\(^{21,25}\) because of the enhanced supernova rate. Vela and Geminga are the first two examples of Belt pulsars. Off-beam emission is expected in polar cap models, due to high-altitude curvature radiation from primary electrons. This widely beamed emission is softer and fainter than on-beam emission, much like the Belt sources. Evolving neutron stars born in the expanding Belt over the last 5 Myr, using both on and off beams with free apertures and luminosities reflecting the \(L_\gamma \propto \dot{E}^{1/2}\) relation observed for the known pulsars, shows that enough pulsars remain visible to retain the Belt spatial signature and to account for half of the Belt sources. They are quite older, thus fainter, than the pulsars detectable in the Galactic plane (1.5 Myr vs. 0.35 Myr) and many would be radio quiet (Perrot et al., in preparation).

Table 1. radio pulsars coincident with EGRET sources. v notes variable sources

| source | sp. index | pwn | pulsar J | \(D_{\text{NE}2001}\) kpc | age kyr | \(E\) \(10^{28}\)W | \(L_{\gamma,\text{sr}}/E\) |
|--------|-----------|-----|----------|----------------|---------|----------------|----------------|
| 1013-6915 | 2.32 ± 0.13 | pwn | 1016-5857 | 7.6 | 21 | 25.9 | 0.08 |
| 1014-5705 | 2.23 ± 0.2 | | 1015-5719 | 5.0 | 39 | 8.27 | 0.05 |
| 1102-6103 | 2.47 ± 0.21 | | 1105-6107 | 4.9 | 63 | 24.8 | 0.06 |
| 1410-6147 | 2.12 ± 0.14 | pwn | 1412-6145 | 7.7 | 51 | 1.24 | 4.0 |
| 1410-6147 | 2.12 ± 0.14 | | 1413-6141 | 9.9 | 14 | 5.65 | 1.0 |
| 1420-6038v | 2.02 ± 0.14 | pwn | 1420-6048 | 5.6 | 13 | 104 | 0.03 |
| 1639-4702 | 2.5 ± 0.18 | | 1637-4642 | 5.0 | 41 | 6.40 | 0.15 |
| 1714-3857 | 2.3 ± 0.2 | | 1715-3903 | 4.1 | 117 | 0.689 | 1.0 |
| 1824-1514 | 2.19 ± 0.18 | | 1825-1446 | 5.0 | 195 | 0.412 | 1.7 |
| 1837-0423v | 2.71 ± 0.44 | pwn | 1838-0453 | 7.9 | 52 | 0.827 | 9.9 |
| 1837-0606 | 1.82 ± 0.14 | | 1837-0604 | 6.3 | 34 | 20.0 | 0.08 |
| 1856+0114v | 1.93 ± 0.1 | pwn | 1856+0113 | 3.1 | 20 | 4.30 | 0.08 |
| 2021+3716 | 1.86 ± 0.1 | pwn | 2021+3651 | 12.1 | 17 | 33.8 | 0.18 |
| 2227+6122 | 2.24 ± 0.14 | pwn | 2229+6114 | 7.2 | 10 | 225 | 0.04 |

The sample of radio pulsars has more than doubled since the end of EGRET, but it was not possible to search back for pulsations in the \(\gamma\)-ray data. Out of 1412 pulsars in the ATNF catalogue, 36 coincide with unidentified sources, but only the 14 listed in Table 1 exhibit \(\gamma\)-ray luminosities over 1 sr below or close to the pulsar spin-down power \(\dot{E}\), allowing for some distance uncertainty. The candidate counterparts span similar ages of \(10^4 - 10^5\) yr and \(\dot{E}\) of \(10^{28} - 30\) W than the known \(\gamma\)-ray pulsars, but they are much more distant and notably softer. The larger distances result in large \(L_{\gamma,\text{sr}}/\dot{E}\) efficiencies well in excess of the observed \(L_{\gamma,\text{sr}} \propto \dot{E}^{1/2}\) relation, unless their beams are much narrower or the pulsed fraction is low.

PSR J2229+6114, second only to the Crab in \(\dot{E}\), is a compelling iden-
tification for the stable EGRET source. Were it not, one should explain an unprecedented flux ratio $f_\gamma/f_X > 10^4$. Coincident with a soft COMPTEL source, its spectral distribution would peak in the MeV band as in Vela. It also produces an X-ray jet and an equatorial wind which powers a compact, bow-shock like PWN. PSR J1016-5857 is surrounded by an X-ray wind nebula and its radio wake may extend to the SNR G284.3-1.8 at 3 kpc. Its efficiency at this distance would compare with that of the $\gamma$-ray pulsars PSR J1709-4429 and J1048-5832 of equivalent age and $\dot{E}$. PSR J1420-6048, in the Kookaburra nebula, may be as close as 2 kpc. Its efficiency would be reasonable, but the source variability suggests the PWN may be active in $\gamma$ rays. The nearby Rabbit plerion could also contribute to the flux. A pulsar origin of 3EG 1837-0423 is unlikely because of the pulsar weakness and the source variability. The plerion in G27.8+0.6 offers an alternative. Error boxes are crowded: there is a bright ASCA source near PSR J1837-0604, the bright WR 141 star near PSR J2021+3651, and 3 SNRs toward 3EG 1639-4702. Coincidences with other famous SNRs are discussed below. Both PSR J1412-6145 and J1413-6141 can hardly produce the $\gamma$-ray flux, even at a distance a few kpc. PSR J1412-6145 is the likely progenitor of G312.4-0.4, but too weak to explain the wind-like nebula

Radio-quiet pulsars are also promising candidates, but blind searches for pulsation have failed. The bright 3EG 1835+5918 source displays striking "Geminga-like" properties, i.e. a stable $E^{-1.73\pm0.07}$ spectrum cutting off at 4 GeV, a faint soft X-ray counterpart with no optical or radio emission, and a flux ratio $f_X/f_\gamma > 300$ typical of neutron stars. Its luminosity $L_{\gamma,1sr} = 4.6 \times 10^{26} (D/1\text{ kpc})^2$ W would be 10 times larger than Geminga. 3EG J0010+7309 also exhibits a stable $E^{-1.58\pm0.18}$ spectrum cutting off at 2 GeV and an X-ray counterpart with no optical emission. The 1.7 $10^{29}$ W compact keV nebula observed inside the CTA1 remnant could indeed be powered by 20 kyr radio-quiet pulsar. A third case of a radio-quiet pulsar was proposed in $\gamma$ Cygni.

Another candidate PWN has been found toward the variable, $E^{-2.06\pm0.08}$ source 3EG 1809-2328. GeV electrons irradiating the nearby cloud would not explain the variability timescale of months. Up-scattering of the ambient radiation field from the nearby OB association or the nebular synchrotron emission largely fail to explain the source. The $L_{>100\text{MeV},1sr} = 8.8 \times 10^{26}$ W luminosity is typical of a $10^{4-5}$ yr-old pulsar, but not the variability. So, this source is extremely puzzling.

Old millisecond pulsars have become attractive counterparts since the discovery of pulsed $\gamma$ rays $\leq 300$ MeV from PSR J0218+4232. The
identification is based on the alignment of the X-ray, γ-ray, and radio pulsed profiles. The soft emission peaks in the MeV range and is stable. The distance of 5.7 kpc in the halo implies a luminosity $L_{\gamma} > 100\, \text{MeV}, 1\text{sr} = 1.6 \times 10^{27} \, \text{W}$ and a 7% efficiency that both the polar-cap and outer-gap models can explain because the weak surface field ($B = 8.5 \times 10^{4} \, \text{T}$) is compensated by a very compact magnetosphere. Yet, both models fail to reproduce the spectral distribution. Whether ms pulsars can explain the equally soft, but variable halo sources remains an open question.

7. Supernova remnants

Supernova shocks accelerate particles to very high energies in a highly non-linear way. When the particle energy density becomes significant, the gas is more compressible, the acceleration rate and the post-shock density increase, and the temperature drops. So, both thermal X rays and γ rays shed light on cosmic-ray acceleration. TeV electrons are clearly revealed by synchrotron X rays, but interpreting the γ rays in terms of electron and proton emission critically depends on the highly uncertain magnetic field at the shock and in the remnant. Electron emission dominates for a compressed $B \sim 1 \, \text{nT}$, as in G347.3-0.5\textsuperscript{17}. Proton emission may prevail for non-linear amplification of $B$ up to 10-100 \text{nT} by the cosmic rays, as in Cas A\textsuperscript{4} and SN 1006\textsuperscript{3}.

Coincidences between EGRET sources and famous SNRs, such as IC443, W28, W44, γ Cygni, CTA1, and G347.3-0.5, have been reported, but the origin of the emission is not clear. In IC443, the 3EG 0617+2238 error box clearly exclude the X-ray pulsar and its plerion. It points to the shell center where no peculiar activity may explain the stable $E^{-2.01 \pm 0.06}$ source which does not seem to pulse\textsuperscript{12}. A $10^{4} M_{\odot}$ cloud may serve as target to the freshly accelerated cosmic rays\textsuperscript{9}. Cloud irradiation is also proposed for 3EG J1714-3857, which lies towards a $3 \times 10^{5} M_{\odot}$ cloud next to the G347.3-0.5 shell\textsuperscript{8}, and for sources found on the rim of old nearby radio shells at medium latitudes\textsuperscript{13,14}. In W44, electrons pervading a cloud or up-scattering the SNR radiation can reproduce the γ-ray flux\textsuperscript{16}. But the source coincides with PSR J1856+0113 and its bow-shock PWN that shines in synchrotron up to keV energies. The source spectrum is typical of a pulsar, but not its variability. So, the PWN offers an attractive alternative.

In short conclusion, γ-ray data with finer angular precision and ample statistics to search for variability and pulsation are desperately needed!
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