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LETTER

Letter to the Editor

Gamma-ray sources as relics of recent supernovae in the nearby Gould Belt

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Abstract. The nearby, 30 to 40 Myr old, starburst region of the Gould Belt has formed numerous massive stars. Within its ∼300 pc radius, it produces core-collapse supernovae at an enhanced rate which is shown to be 75 to 95 Myr^{-1} kpc^{-2}, i.e. 3 to 5 times higher than the local Galactic rate, over the past and future few million years. A population of persistent, but unidentified, γ-ray sources has been recently singled out at medium latitudes above 100 MeV. Their distribution across the sky is shown to be quite significantly and better correlated with the tilted Gould Belt than with other Galactic structures. As many as 40 ± 5 sources are statistically associated with the Belt at $|b| > 5°$. It is therefore proposed that these sources are part of the Belt and are relics of the Belt supernovae in the form of million-year old pulsars. Their presence stresses how active the local medium is, heated, enriched and shaped by multiple recent explosions.

Key words: gamma rays: observations – stars: pulsars: general – stars: supernovae: general

1. Introduction

Above 100 MeV, EGRET has discovered ∼70 persistent, unidentified, sources at medium latitudes that clearly differ from the ∼40 sources seen close to the Galactic plane (Hartman et al. 1999): they are significantly softer, fainter, and have a steeper logN-logS function than at low latitudes (Gehrels et al. 2000). They have been tentatively associated with the local interstellar medium and the Gould Belt (Grenier 1997; Gehrels et al. 2000; Grenier 2000), but their nature remains a mystery. The likely candidates present in the Galactic disc, such as pulsars, supernova (SN) remnants, and OB associations, cannot account for so many sources off the plane. Interestingly, the starburst Gould Belt disc is tilted at $\sim 20°$ to the Milky Way and close enough for weak sources to be detected. Proposing an origin of the sources in the Belt however requires one a) to confront their spatial distribution with that of the Belt and other likely Galactic structures given strong observational biases; b) to evaluate the number of likely γ-ray emitters, i.e. compact stars, formed in the Belt in the recent past. Both aspects are analyzed below before discussing the possible nature of the sources.

2. Supernova rate in the Gould Belt

Our Galaxy produces on average $2.5^{+0.8}_{-0.4}$ SNe per century (Tammann et al. 1994), ∼85% of which arise from the core collapse of a massive star. This value and the stellar distribution in the Galaxy imply a local rate of 20 events Myr^{-1} kpc^{-2}, in reasonable agreement with the 29 progenitors Myr^{-1} kpc^{-2} found with masses > 8 $\mathrm{M}_\odot$ within 1 kpc from the Sun (Tammann et al. 1994). This region, however, includes the starburst Gould Belt with its 300 pc radius. Today, the Belt hosts 432 ± 15 progenitors with masses > 8 $\mathrm{M}_\odot$ (Comeron et al. 1994) and their maximum lifetime will imply a crude minimum rate $>$ 40 collapses Myr^{-1} kpc^{-2} in a few tens of Myr. Numerous explosions have lately occurred from the first generations of massive stars formed in the Belt. A recent-past rate can be inferred from the current stellar content of the Belt as a function of mass, for both short-lived and long-lived stars, given a few assumptions: 1) a stellar initial mass spectrum $dN/dM = a\,M^{\Gamma-1}$ with a range of indices $-2.0 \le \Gamma \le -1.1$ as measured in nearby OB associations (Scalo 1986; Massey et al. 1995); 2) lifetime estimates as modelled for stars with solar metallicity ($Z = 0.02$; Schaller et al. 1992; Meynet et al. 1994) and interpolated in mass; 3) a constant birth rate for simplicity; 4) a conservative mass threshold for collapse of 8 $\mathrm{M}_\odot$. Using this formalism, star counts were integrated in various spectral bands and scaled to the observed Belt star counts (Comeron et al. 1994) to eliminate the unknown birth rate and amplitude *a*.

The significant increase in birth rate obtained for stars <40 Myr confirms the Belt nuclear age and the validity of our simple formalism. SN yields of 21.4 ± 0.8, 24.1 ± 0.9, and 27.2 ± 1.0 per Myr were obtained for Γ indices of -2.0, -1.5, and -1.1, respectively, for a 40 Myr old Belt. The quoted error results from the uncertainty in the observed star counts. These estimates decrease by 15% with Belt age from 50 to 30 Myr. Truncating the mass spectrum at 60 or 120 $\mathrm{M}_\odot$, or choosing 10 $\mathrm{M}_\odot$ for the collapse threshold, has $< 10\%$ impact on the results. Given the uncertainties for the Belt age and Γ index (particularly at large masses), we infer a frequency of

Table 1. max-likelihood results and their 1σ errors for selected models against the 67 persistent unidentified sources

model	P_α[model|ISO]	$N_{\rm iso}$ $\|b\| > 2.5°$	$N_{\rm ani}$ $\|b\| > 2.5°$	$N_{\rm ani}$ $5° < \|b\| < 30°$	α
ISO=isotropic		67 ± 8			> -0.5
HAL=ISO+halo	10^{-4}	41 ± 7	26 ± 7	14 ± 4	> -0.15
GAL=ISO+thick Gal.	2×10^{-9}	0 ± 11	67 ± 11	39 ± 6	-1.90 ± 0.07
LOC=ISO+local Gal.	7×10^{-9}	0 ± 10	67 ± 10	38 ± 6	-1.90 ± 0.06
ISM=ISO+NH	2×10^{-13}	0 ± 6	67 ± 6	39 ± 4	-2.1 ± 0.3
BELT=ISO+Gould Belt	2×10^{-14}	12 ± 4	55 ± 4	47 ± 4	-2.2 ± 0.3

20 to 27 SNe per Myr and a rate of 75 to 95 Myr^{-1} kpc^{-2} which is 3 to 5 times the local Galactic one. This high rate is valid for the past few Myr. It is consistent with the power of 2.3×10^{51} erg Myr^{-1} kpc^{-2} required to maintain the local cosmic-ray density (Blandford & Ostriker 1980) for a standard SN-to-cosmic-ray energy conversion efficiency of a few percent (Drury et al. 1994). It is consistent with the presence, within the Belt, of four 0.1-1 Myr radio loops (Berkhuijsen 1973) and the Local Bubble. Thirteen radio pulsars from the Princeton catalogue are found at high latitudes with distances <1 kpc and age <2 Myr, but they are too few to show a correlation with the inclined Belt or with the Galactic plane. The narrow radio beams from many more may miss the Earth.

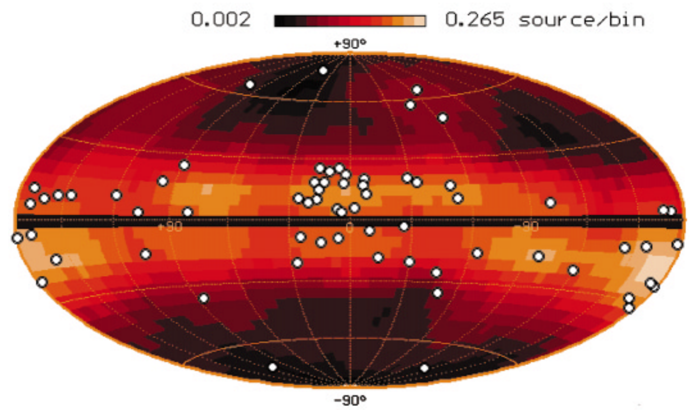

Fig. 1. visibility map, in Galactic coordinates, from the best fit "Iso+Belt" model, the Belt being traced by its young massive stars. The colour codes the number of sources detectable per bin in the EGRET survey. The 67 persistent, unidentified EGRET sources at $|b| > 2.5°$ are marked as white dots which closely follow the curved lane of Belt stars.

3. Gamma-ray sources in the Gould Belt

The distribution on the sky of a subset of the unidentified EGRET sources is strongly reminiscent of the tilted Gould Belt. The subset includes all *persistent* sources at $|b| > 2.5°$ from the 3rd EGRET catalogue, i.e. those detected with a significance $> 4\sigma$ ($> 5\sigma$ at $|b| < 10°$) using the cumulative data from April 1991 to October 1995. Sources listed as likely artifacts were discarded. The 67 sources thus selected are displayed in Fig. 1. 80% of them show no time variability, the others are only moderately variable (Tompkins 1999). Strong biases due to the instrument exposure and the bright interstellar background does influence their apparent spatial distribution. To assess their correlation with various structures, a maximum-likelihood test was applied that takes these biases into account (Grenier 1997). An important degree of freedom is the unknown luminosity function $dN/dL \propto$ L$^\alpha$ of the parent sources. The flatter the function, the sharper the longitude and latitude profiles of any Galactic population because more sources remain visible to large distances. This effect being quite strong, α was kept as a free parameter over a wide range of values: $-2.5 < \alpha \leq 0$. EGRET exposure maps above 100 MeV for the 4.5-year survey (Hartman et al. 1999), the observed isotropic background of $(2.1 \pm 0.3) \times 10^{-5} \gamma$ cm^{-2} s^{-1} sr^{-1}, and the interstellar background model (Hunter et al. 1997) of the EGRET survey were used to model the source visibility in $5°$ by $5°$ bins across the sky.

To allow for possible extragalactic sources among the unidentified ones, linear combinations of an isotropic and a Galactic component were tested (and nicknamed as in Table 1). The choice of Galactic distributions cover the various sites likely to display sources at mid latitudes: 1) sources uniformly distributed in a spherical Galactic halo, 20 kpc in radius; 2) sources uniformly distributed in longitude in the "local Galactic disc" with *any* exponential or gaussian scale height; 3) sources spread in a "thick Galaxy" with a gaussian radial scale length of 9.3 kpc and an exponential scale height of 0.4 kpc, typical of radio pulsars (Lyne et al. 1985); 4) sources distributed in the interstellar medium as mapped by the NH=N(HI+2H$_2$) column-densities (Grenier 1997); 5) sources in the Gould Belt as traced by the column-densities of stars with spectral type < B3, fitted from the Yale Bright Star catalogue data according to the function $N_*(l, b) \propto$ exp(-0.5*sin$^2[b - b_*(l)]$/sin$^2\delta$), with the resulting width $\delta = 12.0° \pm 0.4°$ and median latitude $b_*(l)$ of the star distribution displayed in Fig. 1. Distributions 4) and 5) provide independent ways to trace the Belt through its young stars as well as its clouds since the latter dominate the interstellar maps at medium latitudes.

The reliability of the analysis was checked by applying it to the 67 active galactic nuclei discovered by EGRET and spread over the sky. For them, an isotropic distribution indeed yields the best fit and no Galactic component, however large in scale height, is detected: the maximum log-likelihood value remains constant within 0.1 for all the models tested in Table 1. 67 ± 8 sources are attributed to the isotropic component, 0 ± 6 to the local Gal., thick Gal., NH, or Belt components. The 9 $\pm$ 16 sources attributed to a halo component are not significant. The luminosity index of the parent population is $\alpha = 1.7 \pm 0.3$.

Results obtained for the 67 unidentified sources are displayed in Table 1. Modelled source counts in the isotropic and anisotropic components, $N_{\rm iso}$ and $N_{\rm ani}$ respectively, were summed over the given latitude intervals. The probability $P_\alpha[2|1]$ is determined from the log-likelihood increase between two models, with α left free. It is the chance probability that a random fluctuation from model 1 yields as good a fit as model 2. The dramatic improvement in the fit for any Galactic model over a pure isotropic population shows that over $\sim$50 sources have a Galactic origin. The fit improves very significantly from a spherical halo to a flatter Galactic distribution, $P_\alpha[\rm GAL|HAL] = 2 \times 10^{-5}$, and even more so with the tilted geometry of the Belt clouds or stars, $P_\alpha[\rm BELT|HAL] = 2 \times 10^{-10}$. The good quality of the BELT fit is illustrated in Fig. 1 & 2. The fact that the LOC and GAL models yield equally good fits implies a large fraction of *nearby* sources: no contrast in longitude is detected that would require distances of a few kpc to the sources. Observed source counts are indeed equivalent in the centre and anticentre quadrants in Fig. 1. Not only are the sources local, the significant likelihood increase between the LOC and BELT fits, with a chance probability $P_\alpha[\rm BELT|LOC] = 3 \times 10^{-6}$, gives strong support to their origin in the inclined Belt system. On the other hand, the sources at $|b| > 5°$ were shown to be distinctly fainter and softer than those at lower latitudes and a subset of $\sim$20 were pointed out along the Belt (Gehrels et al. 2000). Together these findings provide compelling evidence that a distinct population of 20 to 40 EGRET sources belong to the Gould Belt. Based on their spatial distribution only, they could be as numerous as 40 $\pm$ 5 at $|b| > 5°$. The luminosity index of their parent population is $\alpha = 2.2 \pm 0.3$.

4. Nature of the sources

With luminosities L_γ of 1 to 15×10^{26} W over 4π sr at 500 pc (for E^{-2} spectra), the sources cannot be unresolved gas clumps irradiated by the local cosmic-ray flux: the required mass of $\sim 10^4$ $M_\odot$ at 500 pc cannot have escaped the radio and IR surveys, even when considering radio beam dilution from unresolved clouds (Grenier 1997). Nor can they be slow (<20 km/s), old neutron stars, accreting gas from a dense cloud: they are at least 10^{2-3} times too rare (Grenier 1997) and the maximum Bondi-Hoyle accretion power of $\sim 2 \times 10^{25}$ W that results from the formation of a surrounding HII region by the neutron star UV radiation, is 10 times too low (Blaes et al. 1995). The accretion power reached for fast (>200-400 km/s), highly magnetized (10^{12} G) neutron stars with long periods in the intercloud medium (10^{-3} H cm^{-3}), though increased by Kelvin-Helmholtz instabilities in the shocked gas, is also orders of magnitude too low (Harding & Leventhal 1992). Isolated accreting black holes with masses of 10 $M_\odot$ (Colpi et al. 1986) and 35 $M_\odot$ (Dermer 1997) have been proposed, but they would be too rare in the Belt: for mass progenitors > 25 $M_\odot$ (Timmes et al. 1996), black holes are 3 to 9 times fewer than neutron stars for Γ indices

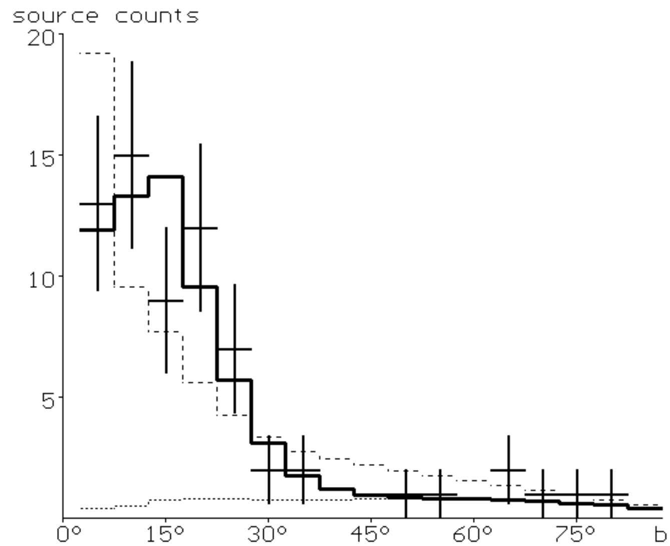

Fig. 2. latitude profiles of the persistent unidentified EGRET sources (crosses), of the best fit "Iso+Belt" model (thick line), and of the isotropic contribution to this model (dotted line). The "Iso+Local Gal." model (dashed line) yields a significantly poorer fit ($P_\alpha[\rm BELT|LOC] = 3 \times 10^{-6}$) with systematic deviations from the data over wide latitude bands.

of -1.1 & -2.0, respectively. Moreover, the luminosity $L_\gamma/L_{\rm X}$ ratios $\gg 50$ observed assuming statistically 1 or 2 faint ROSAT source in an EGRET error box, are clearly at variance with p-p interactions in the accretion flow (Colpi et al. 1986), unless non-thermal acceleration is advocated (in micro-quasar jets?). These luminosity ratios are also at variance with standard accreting binary systems. I found no spatial coincidence with a WR star or the numerous O stars at mid latitude despite their highly supersonic winds with kinetic powers of 10^{28-29} W. Eight pulsars are known in γ rays, 7 bright young ones at kpc distances in the Galactic disc, and a faint, older one inside the Gould Belt (Geminga). So, the present sample is strongly biased to high luminosity and youth. The stability of most of the Belt sources (Tompkins 1999, Gehrels et al. 2000) is consistent with a pulsar origin. Born with large velocities (Lyne & Lorimer 1994), Galactic pulsars rapidly migrate away from the plane to mid-latitudes. The outer gap model (Yadigaroglu & Romani 1997) for beamed emission predicts that 4-5 Galactic pulsars should be detectable at $|b| > 5°$ in contrast with the 40 $\pm$ 5 sources associated with the Belt. Similarly, the wide-beam comptonized polar-cap model (Sturner & Dermer 1996) predicts 1-2 Galactic pulsars detectable at $|b| > 10°$ as opposed to 25 $\pm$ 5 sources linked to the Belt. These discrepancies cannot be resolved by increasing the Galactic pulsar birth rate by more than 30% for fear of overproducing sources at low latitude (Yadigaroglu & Romani 1997), nor by using larger scale heights or velocities which are not supported by the radio data.

Given the enhanced SN rate in the Belt and its inclined geometry, I propose that the sources associated with the Belt be relics of Belt supernovae in the form of few Myr old pulsars. Detecting 20 to 40 Belt collapsed stars as EGRET sources requires the product of the beaming fraction $\Delta\Omega/4\pi$ and pulsar age be of order 1-1.5, for instance $\Delta\Omega/4\pi = 0.5$ over 2 or 3 Myr. $\Delta\Omega/4\pi \sim 0.1$ is predicted for the main polar-cap beam (Thompson et al. 1997), and values of 0.1-0.6 are possible for the outer-gap fan beam depending on pulsar age (Romani 1996). Yet, one should bear in mind the extreme closeness of the Belt objects. The γ-ray luminosity, L_γ, scales with the spin-down power, $\dot{E}$, as $L_\gamma \propto \dot{E}^{1/2}$ over 4 decades in $\dot{E}$ (Thompson et al. 1997). Extrapolating from the faint Geminga for only half a decade, to $\dot{E} = 10^{27}$ W $\Longrightarrow L_\gamma \sim 6 \times 10^{25}$ W over 1 sr, suggests that a pulsar 10 times as old as Geminga, i.e. 3-Myr old, remains easily detectable by EGRET out to 500 pc. Furthermore, the recorded γ-ray lightcurves show that 10 times fainter emission is detected off the main peaks over large phase intervals. This side emission from a 3 Myr old pulsar would remain detectable by EGRET up to 350 pc, thus largely increasing the detection probability $\Delta\Omega/4\pi$. Recent polar cap simulations indicate that 4-5 times as many off-beam sources as on-beam ones would be detectable above 100 MeV at a given distance (Harding & Zhang 2001), therefore up to 350 pc for side emission. In this case, the population of Belt neutron stars born in the last 2-3 Myr may account for the Belt γ-ray sources. It may also explain the scarcity of bright on-beam-like sources off the Galactic plane. The softness of side emission ($|\gamma|$ = 1.8 to 2.5) may also explain the soft average spectral index $|\overline{\gamma}| = 2.25 \pm 0.03$ measured for the Belt sources as opposed to that of $|\overline{\gamma}| = 1.74 \pm 0.02$ obtained the 5 on-beam pulsars in the Galactic plane. Preliminary simulations show that the Belt spatial signature is preserved over at least 2 Myr despite rapid migration. So, given our present understanding of pulsar γ-ray emission, the hypothesis that the Gould Belt sources be powered by pulsars, mostly off-beam pulsars, is quite plausible. If true, the Belt pulsars would considerably broaden our understanding of photon-particle cascades inside their magnetospheres to older and lower-luminosity objects at various aspect angles. The radio beam being apparently much narrower than the γ-ray beam, at least in one dimension, one would expect a majority of radio-silent pulsars among the Belt sources. The spectral criterion $|\gamma| < 2$ often adopted to search for γ-ray pulsars may not be valid for nearby objects. The next generation telescope, GLAST, to be launched in 2005, will be able to detect their periodicity in the γ-ray signal, if any. As supernova relics, the Belt sources would bring useful constraints on the initial star mass spectrum at large masses and on the abundance of explosive nucleosynthesis products in supernova remnants.

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