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# Enhanced pulsar and cosmic-ray production in the Gould Belt ?


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## Abstract

We have investigated the spatial distribution at medium latitude of the unidentified, persistent sources from the 3rd EGRET catalogue. By persistent, we mean stable or variable sources that were significantly detected from the cumulated data between 1991 and 1995. Given the obvious biases in their distribution, due to the non-uniform sensitivity of the survey, the correlations of the sources with possible Galactic and extragalactic distributions point to an origin of 50 ± 8 persistent sources in the nearby Gould Belt.

Over the last few million years, we estimate that this star-forming expanding structure has produced 20 to 27 supernovae per Myr, a rate that is 3 to 5 times higher than the Galactic average. This value is based on the present stellar content of the Belt, standard stellar lifetimes, a range of initial-mass-function indices from –2.0 to –1.1, and a constant birth rate. The proposed conclusions are two-fold : 1) nearby $\gamma$-ray pulsars born in the Belt plus a few born in the Galactic plane may plausibly explain most of the EGRET sources correlated with the Belt ; 2) the cosmic-ray characteristics within a kpc from the Sun need to be investigated in the light of an enhanced production rate over the last few million years.


## 1 Supernova rate in the Gould Belt :

The structure of the nearby interstellar medium is dominated by the Gould Belt, an expanding ring (or disc) of stars and clouds, ~300 pc in radius, inclined by 15° to 20° onto the Galactic plane, which was created 30 to 40 million years ago (see Pöppel 1997, Lindblad et al. 1997). The Sun lies half a radius away from the Belt centre. The Belt is swarmed with young massive stars among which 305 ± 13 or 432 ± 15 are very likely supernova progenitors, with masses in excess of 10 and 8 $M_\odot$, respectively (Comeron et al. 1994). Standard stellar lifetimes imply a crude estimate of 42 $Myr^{-1}\ kpc^{-2}$ for the supernova rate in the Belt *in the near future*, i.e. 2 or 3 times the average Galactic rate. This rate was also high in the recent past from the collapse of the first generations of massive stars formed in the Belt. An estimate can be determined from the present stellar content of the Belt as a function of mass (or age), for both short-lived and long-lived stars, given a small set of assumptions : 1) a stellar initial mass spectrum $dN/dM \propto M^{\Gamma-1}$ with $-2.0 \leq \Gamma \leq -1.1$ as measured in nearby OB associations (Scalo 1986, Massey et al. 1995) ; 2) lifetime estimates with mass as modelled by Schaller et al. (1992) and Meynet et al. (1994) for solar metallicity ; 3) a constant birth rate in the Belt for simplicity ; 4) a mass threshold for collapse of 8 or 10 $M_\odot$. Detailed equations can be found in Grenier 1999 (G99). The observed star counts of Comeron et al (1994) in different mass intervals yield the collapse rates listed in Table 1.

**Table 1**: SNII rate per Myr in the 40 Myr old Gould Belt :

| Progenitor mass | $M > 8\ M_\odot$ | $M > 10\ M_\odot$ |
|---|---|---|
| $\Gamma = -2.0$ | 21.4 ± 0.8 | 21.5 ± 0.9 |
| $\Gamma = -1.5$ | 24.1 ± 0.9 | 23.8 ± 1.0 |
| $\Gamma = -1.1$ | 27.2 ± 1.0 | 26.4 ± 1.1 |

Within 10%, the estimates are insensitive to the Belt age from 30 to 50 Myr, or to the chosen mass threshold for collapse. Given the large uncertainty on the initial mass function, we infer that 20 to 27 supernovae per Myr have lately occurred in the Belt. It amounts to 70 to 100 SNe $Myr^{-1}\ kpc^{-2}$, i.e. 3 to 5 times the Galactic average. We are therefore surrounded by an active "starburst" region. *This high rate applies to the last few million years.* So, one would expect at least 2 or 3 nearby SN remnants with an age < $10^5$ yr to be seen in the radio and

ROSAT surveys, in good agreement with the known nearby loops. On a longer time scale, relics can be found in the form of pulsars. Bearing in mind their small beaming fraction, the Princeton catalogue includes as many as 13 radio pulsars with distances < 1 kpc and age < 2 Myr. They are seen at high latitudes, but are too few to show the signature of their origin in the inclined Belt or in the Galactic plane. The apparent distribution of some EGRET sources is, however, strongly reminiscent of the Belt geometry.

## 2 Spatial distribution of the unidentified EGRET sources :

The EGRET data above 100 MeV collected between April 1991 and October 1995 have been searched for point-sources to produce the 3rd EGRET catalogue (Hartman et al. 1999). Besides LMC and 6 $\gamma$-ray pulsars, the catalogue lists 67 (and 27) firmly (and tentatively) identified active galactic nuclei. The concentration of 38 sources along the Galactic plane attests their Galactic origin, a few kpc away, often toward OB associations sites that are likely to harbour compact stars (Mukherjee et al. 1997, Romero et al. 1999). To question the origin of the 126 unidentified sources scattered at higher latitude, particularly at $|b| \lesssim 30°$, their spatial distribution has been studied at $|b| > 2.5°$.

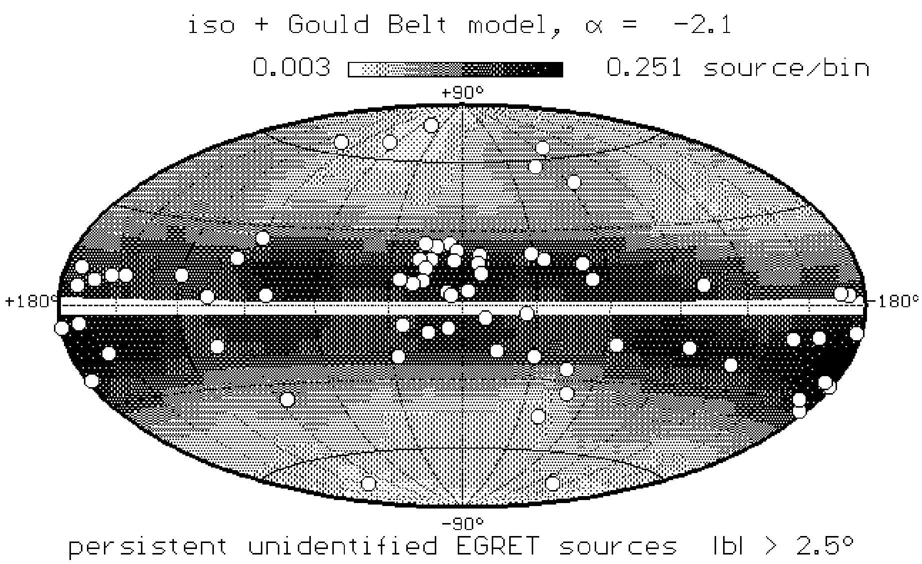
Many sources appear to be highly variable. To concentrate on the statistically firmest sources, we selected the 69 sources that passed the detection threshold using the cumulated data from phase 1 to 4. To remind the reader of this selection, we call them “persistent” sources since they were detected over a 4-yr time span. Persistent is not synonym of constant flux. They could have brightly flared only once. It can be noted, however, from the variability measurements presented by W. Tompkins (1999) that the persistent sources are often stable or moderately variable, so their name.

Their apparent distribution on the sky strongly depends on the non-uniform sensitivity of the EGRET survey, which varies with exposure, the structure of the underlying interstellar emission, and the source luminosity function (Grenier 1997, G99). The latter being unknown, it has been parametrized as a power-law of index $\alpha$. A statistical analysis had been developed to take these biases into account and test the correlation between the observed distribution and linear combinations of well-known distributions over the whole sky. The degree of freedom in $\alpha$ is essential since the contrast in longitude and latitude varies greatly for sources remaining visible to different distances according to $\alpha$. The detection threshold used to predict source counts in a given (l, b) bin varies with the local exposure and the Galactic+extragalactic intensity exactly as in the 3rd EGRET catalogue. The unidentified source distribution has thus been confronted to various populations or combinations of populations, among which 1) an isotropic distribution ; 2) a homogeneous population of sources in a spherical Galactic halo with a radius of 20 kpc ; 3) sources uniformly distributed in longitude in the “local Galactic disc” with any scale height z ; 4) sources spread in a “thick Galaxy” with a radial scale length of 9.3 kpc and a scale height of 0.4 kpc, typical of the radio pulsar population (Lyne et al. 1985) ; 5) sources distributed in the interstellar medium as mapped in HI, CO for $H_2$, or both $HI+2H_2=NH_{TOT}$ ; 6) sources in the Gould Belt as traced by the column-density of young nearby OB stars of spectral type < B4. These distributions hopefully cover the various possible sites harbouring $\gamma$-ray sources to be seen at medium latitudes : at extragalactic distances, in the Galactic halo, in a thick Galactic plane, and locally, in the plane or in the inclined Gould Belt. At $|b| > 2.5°$, the interstellar maps are dominated by local clouds associated with the Gould Belt. So, the distributions used in 5) and 6) provide independent ways to trace the Belt across the sky.

The results presented here are fully described and discussed in G99. The values relevant to the short discussion below are summarized in Table 2 and the best fit is shown in Figure 1. The goodness of fit to the observed source distribution on the sky very significantly increases in two steps, first by allowing the sources to follow a broad Milky Way, and even more when allowing the sources to follow the inclined geometry of the clouds or stars in the Belt. On the contrary, the best fit to the sample of EGRET active galactic nuclei is the isotropic one (G99). The Belt extends up to ~500 pc from the Sun. So, the significant correlation with the Belt suggests a distance of a few hundred parsecs for a large majority of the unidentified sources, a closeness that is confirmed by the equivalent goodness of fit achieved by the ‘iso+local disc’ and ‘iso+thick Galaxy’ models : no contrast in longitude is detected that would require a

**Table 2**: max-likelihood parameters and 1σ errors for selected models : source counts, $N_{ISO}$ and $N_{ANI,}$ in the isotropic and anisotropic components for different $|b|$ intervals, luminosity index α, and chance probabilities $P_\alpha[2|1]$ that a random fluctuation of model 1 yields as good a fit as model 2, with α left free.

| | $N_{ISO}$ $|b| > 2.5°$ | $N_{ANI}$ $|b| > 2.5°$ | $N_{ANI}$ $2.5°<|b|< 30°$ | α | $P_\alpha$[model\|iso] |
|---|---|---|---|---|---|
| iso = isotropic | 69.0 ± 8.3 | | | > -0.5 | |
| hal = iso + halo | 42 ± 8 | 27 ± 7 | 16 ± 4 | > -0.15 | $10^{-4}$ |
| gal = iso + thickGalaxy | 0 ± 11 | 69 ± 13 | 49 ± 9 | -1.90 ± 0.06 | $10^{-8}$ |
| loc = iso + local disc | 0 ± 10 | 69 ± 12 | 50 ± 9 | -1.90 ± 0.06 | $5\ 10^{-8}$ |
| NH = iso + $NH_{TOT}$ | -1.4 ± 4.9 | 70 ± 10 | 49 ± 7 | -2.15 ±0.25 | $3\ 10^{-12}$ |
| belt = iso + Gould Belt | 15 ± 5 | 54 ± 8 | 51 ± 8 | -2.1 ± 0.4 | $7\ 10^{-13}$ |
| $P_\alpha[2|1]$ | $P_\alpha$[gal\|hal] = $10^{-4}$ | $P_\alpha$[belt\|hal] = $6\ 10^{-9}$ | $P_\alpha$[belt\|loc] = $10^{-5}$ | | |




typical distance of a few kpc. Very few extragalactic sources seem to be present in the unidentified sample, at most a score of them, while twice as many appear to be linked to the Belt. All four galactic models under test yield a total of 50 ± 8 sources in our vicinity. Beyond their closeness, the significant improvement in the fit between the Milky Way fits on one hand (*gal* and *loc* models) and the Belt fits on the other (*NH* and *Belt* models), with a chance probability $P_\alpha$ of $10^{-5}$ between the two, strongly suggests an origin in the inclined Belt system for a large fraction of the sources.

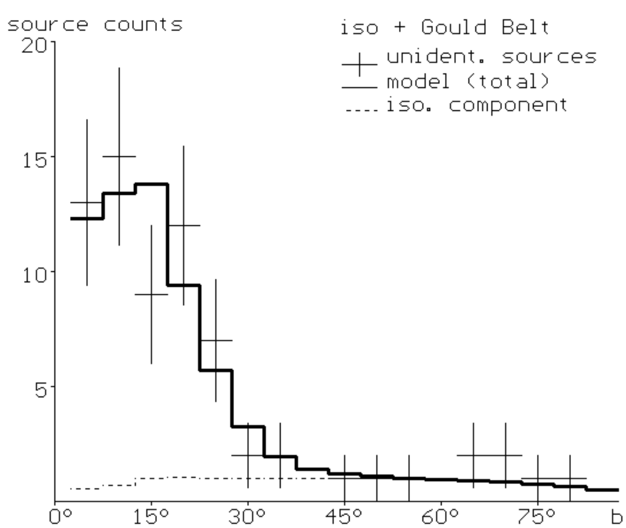



**Figure 1** : persistent unidentified EGRET sources plotted a) in l and b against the source counts predicted from a combination of an isotropic population and a Gould Belt one as traced by its young massive stars (both altered by the non-uniform survey sensitivity); b) in a latitude profile

## 3 Discussion :

Various scenarii are discussed in G99 as to the nature of these objects, but many fail to reproduce the data : unresolved gas clumps would be too massive to escape the radio and IR surveys, nearby binary systems would be too bright in X rays, isolated old neutron stars accreting interstellar gas would be too few and fail to reach the γ-ray luminosity, accreting black holes would have enough luminosity but an $L_\gamma/L_X$

ratio clearly at variance with the data unless non-thermal acceleration of protons is advocated, no spatial coincidence with O stars, WR stars or RSCVns has been reported. In the absence of more compelling counterparts, pulsars are left as plausible candidates. ~9 pulsars migrating away from the Galactic plane would be seen at medium latitude (Yadigaroglu & Romani 97). To observe another 30 to 40 pulsars born in the Gould Belt would require a product of their beaming fraction, $\Delta\Omega/4\pi$, by their maximum age of the order of 1.5, for instance $\Delta\Omega/4\pi = 0.5$ over 3 Myr. $\Delta\Omega/4\pi$ varies from 0.1 to 1.0 with models and age. A value of 0.5 is on the high side, as well as ages up to 3 Myr compared to the oldest age of 0.5 Myr seen in $\gamma$ rays so far. Yet, one should bear in mind the consequences of the extreme closeness of the Belt pulsars with respect to the remote Galactic pulsars identified so far. The $\gamma$-ray luminosity, $L_\gamma$, scales with the spin-down power, $\dot{E}$, as $L_\gamma \propto \sqrt{\dot{E}}$ over 4 decades (Thompson et al. 1997). Extrapolating the faintest known pulsar, Geminga, for half a decade, to $\dot{E} = 10^{27}$ W, therefore to $L_\gamma \sim 6\ 10^{25}$ W over 1 sr, a pulsar 10 times as old as Geminga, i.e. ~ 3 Myr old, would remain easily detectable by EGRET up to 500 pc. An even fainter pulsar, seen at angles grazing the main beam in order to increase the detection efficiency, would remain visible. In fact, given its possible birth locations, Geminga can be considered as the first example of a Gould Belt pulsar. Past a few million years, pulsar migration would erase the characteristic signature of the Belt across the sky. The Belt geometry is being revisited using Hipparcos data and the CO Columbia survey (Perrot & Grenier). Preliminary simulations show that the signature is preserved over a few million years despite the large, but random, pulsar velocity at birth of 450 km/s (Lyne & Lorimer 1994).

The average power required to maintain the cosmic-ray density in the Galaxy is $\sim 10^{44}$ J Myr$^{-1}$ kpc$^{-2}$ for a grammage $\lambda$ of 6-9 g cm$^{-2}$. The enhanced supernova rate in the Belt is consistent with this power if one assumes a typical SN-to-cosmic-ray energy conversion efficiency of a few percent as advocated by Drury et al. (1994). Our position inside a moderately active “starburst” region, as suggested by this high supernova rate and the possible link between the resulting compact objects and persistent EGRET sources, may shed a different light on the cosmic ray characteristics in our neighbourhood. We intend to investigate possible consequences on the local density, spectra, secondary-to-primary ratios, and degree of anisotropy from freshly injected particles in the Belt environment. The very low anisotropy recorded at $E < 10^{14}$ eV and the consistency between the local-gas emissivity above 100 MeV, $q_\gamma = (1.81 \pm 0.07)\ 10^{-26}\ \gamma\ \mathrm{at}^{-1}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$, and the average along the solar circle, $q_\gamma = (1.65 \pm 0.03)\ 10^{-26}\ \gamma\ \mathrm{at}^{-1}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$, indicate that diffusion should rapidly dissipate the signature of the Belt geometry. Yet, the derivation of the solar circle value is greatly biased by the local clouds (Strong & Mattox 1996). A 40% emissivity increase has been measured towards Ophiuchus where the Belt rim is closest to the Sun, but it could also be due to the line of sight crossing the old loop I remnant (Hunter et al. 1994).

## 4 References:


Comeron F. et al. 1994, A&A, 286, 789

Drury L O’C., Aharonian F.A., Völk H.J. 1994, A&A, 287, 959

Grenier I. A. 1999, submitted to A&A

Grenier I. A. 1997, 2nd Integral Symp., ESA/SP 382, 187

Hartman R. C. et al. 1999, ApJS, in press

Hunter, S. D. et al. 1994, ApJ, 436, 216

Linblad P.O. et al. 1997, Hipparcos, ESA/SP 402, 507

Lyne A.G., Manchester R.N., Taylor J.H. 1985, MNRAS, 213, 613

Lyne A.G., Lorimer D.R. 1994, Nature, 369, 127

Massey P. et al. 1995, ApJ, 454, 151

Meynet G. et al. 1994, A&AS, 103, 97

Mukherjee R., Grenier I.A., Thompson D.J. 1997, 4th Compton Symp., AIP 410, 394

Pöppel, W. 1997, Fund. of cosmic physics, 18, 1

Romero G.E. et al. 1999, submitted to A&A

Scalo, J. M., 1986, Fund. of cosmic physics, 11, 1

Schaller G. et al. 1992, A&AS, 96, 269

Strong A.W., & Mattox J.., 1996, A&A, 308, L21

Thompson D.J. et al. 1997, 4th Compton Symp., AIP 410, 39

Tompkins W. 1999, Stanford PhD thesis

Yadigaroglu I. & Romani R. 1997, ApJ, 476, 347