PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

On the Nature of the Galactic 2CG $\gamma $-ray Sources [and Discussion]

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I. DISCRETE SOURCES

On the nature of the galactic 2CG γ-ray sources

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The identification of two γ-ray sources of the COS-B catalogue with radio pulsars is used as an important hint for the identification of the rest of the population.

The relevant distributions of γ-ray pulsars visible at the Sun within the limiting sensitivity of COS-B are derived on the following assumptions: (i) the γ-ray luminosity is a decreasing power law of the pulsar age, as indicated by current models; (ii) the scale height of pulsars at creation is equal to that of the supernova remnants; (iii) the pulsars' birth rate and spatial distribution are those published by Taylor & Manchester (1977).

As a preliminary result it is shown that 10 to 20 γ-ray pulsars may be visible from the Earth with distributional parameters not distinguishable from those of the 2CG γ-ray sources. We suggest therefore that a significant fraction of the unidentified galactic γ-ray sources are pulsars.

Introduction

Since the publication of the first CG Catalogue of γ-ray sources (Hermsen *et al.* 1977) much work has been done to identify the corresponding astronomical objects. One approach has consisted of selecting the galactic populations known to have distributional properties similar to those of the γ-ray sources. Owing mainly to the low statistical weight of the sample of sources available and to the existence of several galactic populations with similar distributional properties, this exercise cannot give a precise answer but only the conclusion that γ-ray sources are young with Population I spatial distribution (see, for example, Panagia & Zamorani 1979; Montmerle 1979).

From the observational side several searches have been directed to look for counterparts of the COS-B γ-ray sources, mainly in the radio and in the X-ray ranges. It is unfortunate that the size of the COS-B error boxes is so large as to prevent a unique identification unless supported by a recognizable signature independent of the spatial position, as for PSR 0531+21 and PSR 0833−45 for which the timing signature makes unquestionable their identification with the corresponding γ-ray sources.

Theoretically, a complication arises from the necessity of proposing *ad hoc* mechanisms for conspicuous production of γ-rays without the possibility of supporting experimental evidence.

Predictions of large fluxes of γ-rays from pulsars have been made by several authors (see, for instance, Cheng & Ruderman 1977; Hardee 1979; Salvati & Massaro 1979; Morini 1980); however, little attention has been devoted to explaining the γ-ray sources by pulsars. There are two main reasons. The first is that radio surveys have failed to detect fast pulsars (which could have sufficient rotational energy release), which leads to the conclusion that PSR 0531+21 and PSR 0833−45 could be exceptional cases. The second is due to a possible overestimate of the distances suggested for the COS-B sources (Hermsen 1980; Swanenburg *et al.* 1981), thus requiring intrinsic luminosities exceeding those derived for PSR 0531+21 and PSR 0833−45.

It is our opinion that the lack of fast pulsars observed in radio research is not a proof of their absence, considering the lower sensitivity level of the radio surveys for shorter periods.

On this basis and because the only two identified γ-ray sources are two radio pulsars, PSR 0531+21 and PSR 0833−45, we consider it natural to consider a correlation between pulsars and γ-ray sources. Similar work, but with the use of qualitative arguments, has been made in the past (D'Amico & Scarsi 1980; Buccheri 1980*a*). In this paper we present the preliminary results of a more quantitative approach in which the number and the distributional characteristics of the γ-ray pulsars visible from the Earth are derived from the spatial distribution of the radio pulsars published by Taylor & Manchester (1977) and from the available data about PSR 0531+21 and PSR 0833−45 in the γ-ray range.

The validity of the identification of a large fraction of γ-ray sources with pulsars is then discussed after comparison of the results with the distributional parameters of the γ-ray sources as published in the 2CG catalogue (Swanenburg *et al.* 1981; $E_\gamma > 100$ MeV).

The 2CG catalogue

The 2CG Catalogue (Swanenburg *et al.* 1981) lists 25 sources, 22 of them at galactic latitudes below 6°.

For two of the three high latitude sources there exists a suggestion of identification, 2CG 289+64 being associated with QSO 3C273 (Swanenburg *et al.* 1978; Bignami *et al.* 1981), and 2CG 353+16 with the ρ-Oph cloud complex (Bignami & Morfil 1980; Mayer-Hasselwander *et al.* 1980). It is not the aim of this paper to discuss the validity of these associations and their implication on the formulation of the physical mechanisms responsible for the observed γ-ray emission, given the completely different nature of the two objects. We address ourselves to the low latitude regions where presumably most of the sources are galactic.

Table 1 lists the 22 low latitude sources by interval of longitude. Their distributional properties have been discussed by Hermsen (1980) and Swanenburg *et al.* (1981). We want to stress here that the value of 2 kpc derived in the references quoted above is an estimate for the 'typical' distance of the γ-ray sources, i.e. the distance around which most of the sources are concentrated, while 7 kpc is an estimate of the maximum distance. This implies that the typical luminosity of the 2CG sources is around 4×10^{35} erg s^{-1}† while 2×10^{36} erg s^{-1} must be considered as an upper limit.

As for the completeness of the sample, we know that it is not complete at the level of the minimum detected flux, especially in the most intense regions near the galactic centre. However, on the basis of the flux distribution shown in table 1 and taking into account the typical errors on the fluxes themselves, we can estimate as 1.4, 1.2 and 1.0×10^{-6} ph cm^{-2} s^{-1} for the three longitude intervals respectively, the limiting fluxes for which the sample can be considered reasonably complete.

With this choice and by using the simplifying assumption that all the objects belong to the same population, the distributional properties of the sample can be conveniently described by the following parameters:

N = 19, the size of the sample;

$R_{\mathrm{i/o}}$ = 0.58, the ratio between the number of sources in the longitude interval $300° < l < 60°$

(inner galaxy) and that in $60° < l < 300°$ (outer galaxy) as an index describing the longitude distribution;

$I_\phi = 0.9$, the ratio between the number of sources with flux greater than 2×10^{-6} ph cm^{-2} s^{-1} and the rest, as an index describing the flux distribution;

$\langle|b|\rangle = 1.6°$, the average latitude of the sample.

Table 1. Low latitude 2CG sources flux distribution

longitude intervals/deg	source	flux/(10^{-6} ph cm^{-2} s^{-1})	
0–60, 300–360	2CG 013+00	1.0	
	2CG 054+01	1.3	
	2CG 359−00	1.8	
	2CG 036+01	1.9	
	2CG 342−02	2.0	
	2CG 311−01	2.1	
	2CG 006−00	2.4	
	2CG 356+00	2.6	
	2CG 333+01	3.8	
60–120, 240–300	2CG 095+04	1.1	
	2CG 065+00	1.2	
	2CG 075+00	1.3	
	2CG 288−00	1.6	
	2CG 078+01	2.5	
	2CG 284−00	2.7	
	2CG 263−02	13.2	Vela pulsar
120–240	2CG 121+04	1.0	
	2CG 135+01	1.0	
	2CG 218−00	1.0	
	2CG 235−01	1.0	
	2CG 184−05	3.7	Crab pulsar
	2CG 195+04	4.8	

The γ-ray pulsars

The luminosity function

Two pulsars, PSR 0531+21 (the Crab pulsar) and PSR 0833−45 (the Vela pulsar), have been identified as γ-ray emitters, and detailed studies of their observational features have been published recently (see, for example, Buccheri 1980*b*, and references therein). For two other pulsars, PSR 0740−28 and PSR 1822−09, uncertainty in identification arises from a discrepancy found between the radio and the γ-ray periods. We shall not consider these last two here.

In the 2CG Catalogue the Vela pulsar appears as the brightest source in the sky with a measured flux of 13.2×10^{-6} ph cm^{-2} s^{-1} corresponding to a luminosity of 3.95×10^{38} ph s^{-1} above 100 MeV if the beaming factor is neglected. The Crab pulsar has the fourth highest flux of the catalogue with $\phi = 3.7 \times 10^{-6}$ ph cm^{-2} s^{-1}, corresponding to an intrinsic luminosity of 1.77×10^{39} ph s^{-1} on the same assumptions. If the pulsar birth rate is high enough there will exist other pulsars within a range of ages including those of Crab and Vela, and extending up to a value T_γ defining the cut-off age of the γ-ray emission.

† 1 erg s^{-1} = 10^{-7} W.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

In the following, for simplicity, we shall assume that the γ-ray luminosity of pulsars is a decreasing power law of their age up to T_γ, and zero beyond, which is consistent with current pulsar theories (see, for example, Ruderman & Sutherland 1975):

$$L(t) = at^{-\alpha} \text{ ph s}^{-1}, \tag{1}$$

where t is the characteristic age $P/2\dot{P}$, P and $\dot{P}$ being the pulsar period and its derivative.

By using the Crab and Vela data we obtain

$$\ln a = 41.35 \pm 0.31, \quad \alpha = 0.68 \pm 0.10,$$

where the errors account only for the statistical errors in the measured fluxes. Differences between characteristic ages and real ages could result in a systematic error in the luminosity law, but it is not taken into account here.

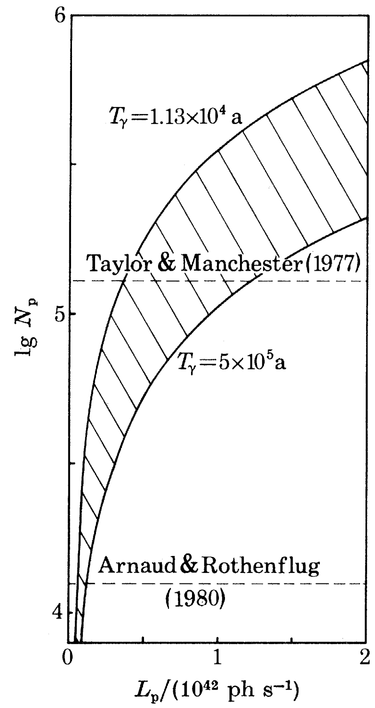

FIGURE 1. Relation between the number of observable radio pulsars N_p and their contribution L_p to the total γ-ray luminosity of the Galaxy for cut-off ages greater than the Vela age and less than 5×10^5 a (shaded area).

An estimate for the value of the γ-ray pulsar lifetime can be found by integrating equation (1) up to a T_γ to reach the total luminosity L_p contributed by pulsars above 100 MeV. From the equality

$$(N_p/T_r)\int_0^{T_\gamma} L(t)\,dt = L_p \tag{2}$$

we obtain

$$T_\gamma^{(1-\alpha)} = L_p(1-\alpha)\,T_r/(aN_p), \tag{3}$$

where T_r is the active radio lifetime and N_p is the total number of observable radio pulsars in the galaxy.

As shown in equation (3) the value of T_γ depends on the values of N_p, T_r and L_p. On the other hand, to accord with the experimental data we require T_γ to be greater than 1.1×10^4 a (the age of Vela) and less than 5×10^5 a, to exclude the cases where the pulsar luminosity, as given by equation (1), exceeds the pulsar braking power $\dot{E} = 10^{45}\dot{P}/4\pi^2P^3$.

Figure 1 shows the dependence of N_p on L_p for T_γ in the range discussed above and for $T_r = 4 \times 10^6$ a as suggested by Taylor & Manchester (1977), hereafter called T.M. In the same figure are shown for comparison the values $N_p = 1.3 \times 10^5$ as suggested by T.M. and $N_p = 12500$ as suggested by Arnaud & Rothenflug (1980). The two values depict two completely different energetic situations, the latter allowing only for a very low total γ-ray pulsar luminosity L_p. We think that this is too drastic a possibility which has to be very carefully checked before acceptance. We note here that the observed longitude distribution of radio pulsars is not well fitted with the model proposed by Arnaud & Rothenflug (1980); a different choice of the adopted parameter values might perhaps correct this fit. We also note incidentally that the other values quoted for N_p in the literature are comparable with or even higher than those published by T.M. In what follows we shall use the value $N_p = 1.3 \times 10^5$, for which values for L_p up to 1.2×10^{42} ph s^{-1} are allowed.

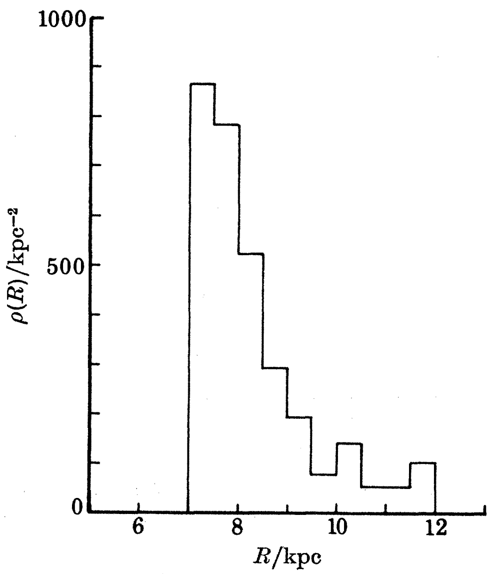

FIGURE 2. The galactocentric distribution of pulsars used for the analysis; after Taylor & Manchester (1977).

The spatial distribution

To use consistent data we shall assume that the probability of finding a γ-ray pulsar at galactocentric distance R follows the galactocentric distribution published by T.M. This is shown in figure 2.

As for the z-distribution, we shall use the simple model in which the probability of a pulsar being created at a height z above the galactic plane follows a Gaussian law with scale height h_0 constant over the whole galaxy. A similar assumption, but with h_0 varying with the galactocentric distance R, is made by Arnaud & Rothenflug (1980); owing to the purpose of our analysis we have neglected such variation.

The last ingredient of our model is the assumption that pulsars are runaway objects escaping from their birthplaces with high velocities. In particular, for simplicity, we will neglect any component of the velocity parallel to the galactic plane and assume that after creation pulsars escape transversely to the galactic plane with a fixed velocity v_z with equal probability in the two opposite directions. This schematization allows us to derive the following formula:

$$h(t) = [h_0^2 + (\tfrac{1}{2}v_z t)^2]^{\frac{1}{2}} \qquad (4)$$

giving the average distance from the galactic plane for all pulsars having ages less than t. From this relation and using the values published by T.M. for the radio lifetime ($T_r = 4\times10^6$ a) and for the scale height of all radio pulsars with known characteristic ages ($h(T_r) = 260$ pc), we can obtain a relation between the scale height at creation, h_0, and the migration velocity, v_z, which is shown in figure 3.

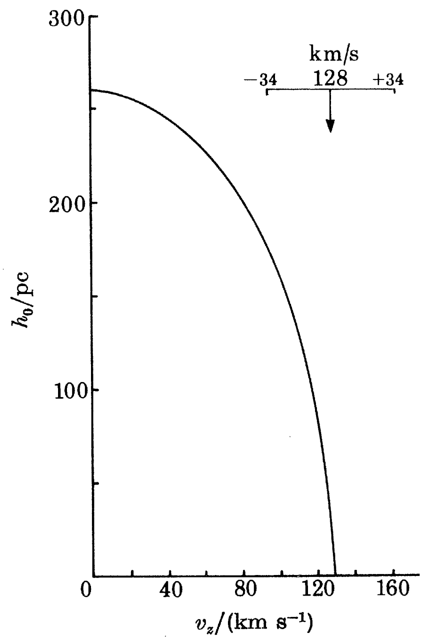

FIGURE 3. Scale height of pulsars at creation, $[h^2(T_r)-(\frac{1}{2}v_z T_r)^2]^{\frac{1}{2}}$, derived by assuming $T_r = 4\times10^6$ a and $h(T_r) = 260$ pc, in terms of the migration velocity.

We observe from this figure that the pulsar scale height at creation is critically dependent on the assumed migration velocity and becomes low in the range of measured proper motion velocities reported by T.M. In the following we will assume that $v_z = 125$ km s^{-1} which corresponds to a scale height at creation of 48 pc, comparable with the average scale height of the supernova remnants as published by Guibert *et al.* (1978).

Analysis and results

Within the assumptions discussed above, the number, dn, of pulsars per unit surface of the galactic disk, dσ, per unit age, dt, per unit distance from the galactic plane, dz, is written as

$$\mathrm{d}n \propto [\mathrm{e}^{-(z-v_z t)^2/(2z_0^2)} + \mathrm{e}^{-(z+v_z t)^2/(2z_0^2)}]\,\mathrm{d}z\,\mathrm{d}t\,\rho(R)\,\mathrm{d}\sigma, \qquad (5)$$

where $z_0 = (\frac{1}{2}\pi)^{\frac{1}{2}} h_0$.

The number of objects detectable at the Sun within the limiting sensitivity of COS-B is computed by integrating equation (5). This integral, on the assumption of symmetry with respect to the galactic plane, and between the two longitude intervals 0–180° and 180–360°, is written as

$$N = K\int_0^{\pi} \mathrm{d}l \int_0^{T_\gamma} \mathrm{d}t \int_0^{\infty} [\mathrm{e}^{(-(z-v_z t)^2/(2z_0^2))} + \mathrm{e}^{(-(z+v_z t)^2/(2z_0^2))}]\,\mathrm{d}z \int_0^{D_t} D\rho(R)\,\mathrm{d}D, \qquad (6)$$

where

D is the distance, from the Sun,
l is the galactic longitude,
$D_t = [L(t)/4\pi\phi_0(l)]^{\frac{1}{2}}$ is the maximum distance at which a pulsar of age t is visible at the Sun with flux greater than $\phi_0(l)$,
$R = [R_0^2 + D^2 - z^2 - 2R_0 \cos(l)\,(D^2 - z^2)^{\frac{1}{2}}]^{\frac{1}{2}}$ is the galactocentric radius,
$R_0 = 10$ kpc is the assumed distance between the Sun and the galactic centre
$K = 2/T_r z_0 \pi$ is a normalization constant such that $N = 1.3 \times 10^5$ for $\phi_0(l) \to 0$.

TABLE 2.

active radio lifetime, T_r	4×10^6 a
migration velocity, v_z	125 km s^{-1}
scale height for radio pulsars, $h(T_r)$	260 pc
number of observable radio pulsars	1.3×10^5
galactic luminosity above 100 MeV for pulsars	7.5×10^{41} ph s^{-1}

TABLE 3.

active γ-ray lifetime, T_γ	5.5×10^4 a
total number of γ-ray pulsars	1777
number of visible γ-ray pulsars	13
inner–outer ratio, $R_{i/o}$	0.794
flux distribution index, I_ϕ	1.64
average latitude, $\langle\lvert b\rvert\rangle$	2.28°
average luminosity	3.8×10^{38} ph s^{-1}
average distance	2.3 kpc
scale height	48 pc
average age	1.2×10^4 a

The calculations have been made numerically by subdividing the whole range of age into ten equal logarithmic intervals. During the calculation the relevant distributions concerning the detectable γ-ray pulsars were derived for purposes of comparison with those of the 2CG sources.

Table 3 shows the results of the calculations under the assumptions summarized in table 2. Several comments on the results are necessary:

(i) The value of $\langle\lvert b\rvert\rangle$ is strongly dependent on the chosen values for v_z and $h(T_r)$ and is less sensibly affected by the variation of the other parameters. The agreement with the value of $\langle\lvert b\rvert\rangle$ for γ-ray sources is then better if pulsars are postulated to have low scale height at creation.

(ii) The average age and luminosity of the detectable γ-ray pulsars are close to those of the Vela pulsar which, in our hypothesis, can be considered as a typical γ-ray source. This is in rough agreement with the typical luminosity of 4×10^{35} erg s^{-1} estimated for the 2CG sources.

(iii) In figure 4 is plotted the latitude distribution of the detectable γ-ray pulsars. It shows a long tail, which is reflected in the large standard deviation. A small sample of objects randomly taken from such a distribution could show an average value for b in error by up to 1°. Typical distances derived for such a sample could be in error by as much as 1 kpc.

(iv) Figure 5 shows the distribution of distances of the detectable γ-ray pulsars. The difference between the expected distance (2.3 kpc) and that where most of the sources are concentrated is evident from the marked asymmetry of the distribution. This is consistent with our interpretation of the meaning to be attributed to the distance range of 2–7 kpc derived for the COS-B sources.

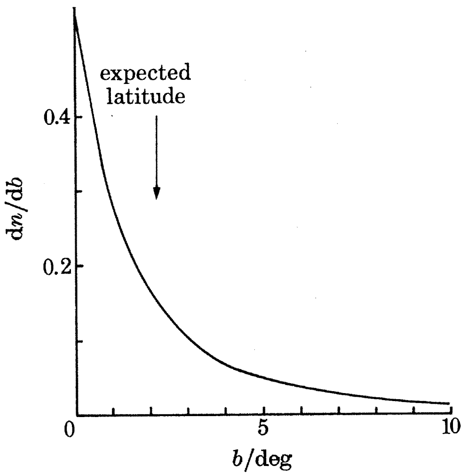

FIGURE 4. Latitude distribution of the detectable γ-ray pulsars for the conditions given in tables 2 and 3; σ = 2.4.

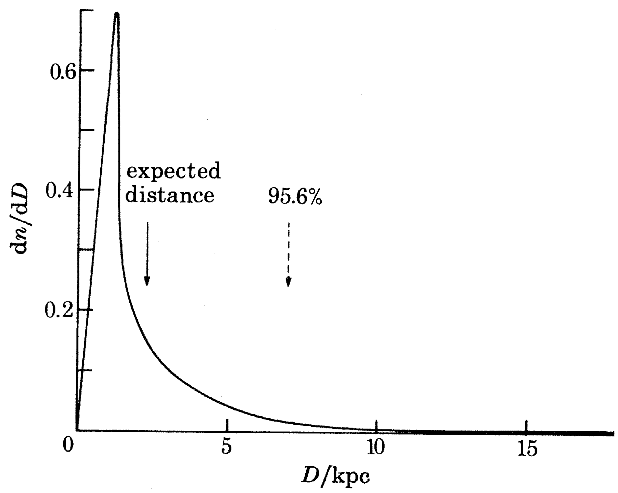

FIGURE 5. Distribution of distances for the detectable γ-ray pulsars for the conditions given in tables 2 and 3.

TABLE 4.

input parameters	range of allowed values
$\ln a$ = 41.49	(41.35 ± 0.31)
α = 0.65	(0.68 ± 0.10)
$N_p = 1.66 \times 10^5$	$(1.3 \pm 0.4) \times 10^5$
$L_p = 1.37 \times 10^{42}$ ph s^{-1}	($< 1.5 \times 10^{42}$ ph s^{-1})
$T_\gamma = 2.8 \times 10^4$ a	$(1.13 \times 10^4 / 5 \times 10^5)$ a

(v) The number of detectable γ-ray pulsars is strongly dependent on the value chosen for L_p. Small adjustments of the other parameters are sufficient to fit the other distributional data of the 2CG sources. This is demonstrated in table 4 which shows the values of the input parameters needed to be able to see from the Earth 19 γ-ray pulsars with distributional parameters equal to those of the 2CG sources within the chosen sensitivity limits. It is realized that the values of a, α and N_p are within the statistical errors derived from the experiments. It is also seen that the total energy release required to explain all the observed sources by pulsars is compatible with the total galactic luminosity as given by Caraveo & Paul (1979) and is in agreement with the total luminosity derived for γ-ray sources (Bignami *et al.* 1978; Salvati & Massaro 1981).

Conclusions

In the light of the preliminary results of our work, as presented in this paper, young radio pulsars seem the most probable counterparts of the galactic γ-ray sources. This derives principally from the fact that the only two positively identified γ-ray sources are radio pulsars and that their distributional properties are comparable with those of the 2CG sources.

It is remarkable that the eventual timing signature in the γ-ray data provides us with a valid check for source identification. This is not possible for the other classes of objects such as molecular clouds proposed as counterparts for the γ-ray sources on the basis of the positional coincidence of the ρ-Oph complex with 2CG 353+16 and of the recently announced γ-ray observation of the Orion cloud complex (Caraveo *et al.* 1980).

As further evidence for the association of γ-ray sources with radio pulsars we note the possible presence of young supernova remnants near the COS-B γ-ray sources (Lamb 1978; Van den Bergh 1979).

We suggest therefore that the detected γ-ray sources are mainly pulsars with possibly some molecular clouds (for their contribution to the galactic luminosity see, for example, Wolfendale 1980). This reduces perhaps the mystery that has recently grown up around γ-ray sources but, on the other hand, increases the interest in pulsars as new experimental effort becomes necessary to clarify their behaviour, especially during the early evolutionary stage.

We wish to thank Professor L. Scarsi and Dr E. Massaro for encouragement and discussions.

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Discussion

F. G. Smith, F.R.S. (*The Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, East Sussex BN27 4TQ, U.K.*). The total number of γ-ray sources in the Galaxy can presumably be estimated from the distribution of the known sources in latitude and longitude. It would be dangerous to assume that this distribution is the same as that for pulsars.

R. Buccheri. It is not possible to estimate the total number of γ-ray sources from the longitude and latitude distributions alone. Spatial and luminosity distributions play a fundamental role in the estimate of this number which can vary widely depending on them.

On this basis and considering that the only two surely identified γ-ray sources are pulsars we do not see why it is dangerous to assume also that the unidentified sources are pulsars and to use the pulsars' spatial distributions.

Finally, the results obtained widely justify the assumptions made.