The components of galactic $\gamma$-ray emission

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**Summary.** The $\gamma$-ray luminosity of the Galaxy has been determined to a fair degree of accuracy, and it is known to arise from several components. We group them into three classes. The strong discrete sources are defined by the acceptance criteria of the 2CG catalogue, and are mostly unidentified; however, population-type information (which can be derived from evolution constraints) and the observed gradient in galactocentric radius enables us to set their relative contribution at $\geq 34$ per cent. Normal radio pulsars (as opposed to very young objects like the Crab and Vela) are also expected to emit $\gamma$ rays; we propose that the conversion efficiency of $E$ to $L_\gamma$ be close to unity, and from the radio data derive a class contribution of $\sim 20$ per cent. The remainder is attributed to cosmic-ray interactions with the diffuse matter; no evidence is found for a positive correlation between the cosmic-ray and gas densities; indeed, the large $\gamma$-ray luminosity contributed by a Population I component (the 2CG sources) naturally explains the longitude profile of the $\gamma$-ray background, which initially prompted the correlation hypothesis.

1 Introduction

One of the major achievements of the *COS B* mission was the discovery of a number of discrete $\gamma$-ray sources. The first CG catalogue included 13 entries (Hermsen et al. 1977) and was followed by a second list of 29 sources (Wills et al. 1980). A more detailed analysis and more stringent acceptance criteria led to the compilation of the 2CG catalogue, which contains only 25 objects, but is free from spurious sources with a probability $> 98$ per cent (Hermsen 1980; Swanenburg et al. 1981). The 2CG catalogue, however, cannot be considered complete to the level of the weakest source, because of the non-uniform sensitivity level arising from the non-uniform background, and because of a spectral selection effect favouring hard sources.

An evaluation of the relative source contribution to the overall galactic $\gamma$-ray luminosity would provide indirect information on the contribution of cosmic rays, and, consequently, on the correlation between their distribution and that of the interstellar matter. Several attempts, under various hypotheses, resulted in estimates which vary from $\sim 20$ per cent
(Wolfendale 1980) to $\approx 40$ per cent (Bignami, Caraveo & Maraschi 1978) and up to 100 per cent (Coe, Quenby & Engel 1978). In this paper we will re-examine the problem in the light of recent observational results.

In assessing the contribution of the sources, however, one is limited by the lack of reliable information about their nature: the only identified galactic sources are 2CG 185 – 5 (= PSR 0531 + 21) and 2CG 263 – 2 (= PSR 0833 – 45), while for the others no firm counterparts have yet been recognized. Therefore we have to take into account the properties derived from the $\gamma$-ray data alone (Section 2). The situation is more promising for a subclass of sources: the $\gamma$-ray pulsars. Apart from the two objects mentioned — the only pulsars appearing in the 2CG catalogue — positive detection of $\gamma$-ray emission from ‘normal’ radio pulsars has been reported in the literature (see the review of Buccheri 1980) even if unquestionable evidence is yet to be produced. On the other hand, several theoretical models of pulsars allow for a relevant $\gamma$-ray emission (Salvati 1980), and such objects must be considered as possible $\gamma$-ray sources. By guessing the conversion efficiency from rotational energy loss to $\gamma$-ray luminosity, we are able to estimate from the radio data alone the pulsar contribution to the galactic $\gamma$-ray emission, as explained in Section 3.

The integrated luminosity of our Galaxy can be evaluated directly from the observations by means of a simple deconvolution procedure, independent of the nature of the emission (Strong & Worrall 1976): above 100 MeV the value $L_\gamma = 1.3 \times 10^{42}$ photons s$^{-1}$ is generally accepted. We assume throughout an average photon energy $\langle E_\gamma \rangle = 250$ MeV, which corresponds to a Crab-like spectrum of number index $-2.1$ in the frequency range 100 MeV–1 GeV; in energy units, then, the galactic luminosity becomes $L_{\gamma G} = 5 \times 10^{38}$ erg s$^{-1}$. By subtracting the contributions of discrete sources and normal radio pulsars from this figure, we obtain the galactic $\gamma$-ray luminosity due to the interactions of the cosmic rays with the interstellar matter. The errors involved in such a procedure can also be evaluated, and it is easy to show that a significant upper limit can be found to the $\gamma$-ray contribution arising from diffuse processes. This result will imply, as shown in Section 4, that the interstellar gas and the cosmic-ray distributions are not positively correlated, ruling out interpretations of the galactic $\gamma$-ray emission such as those proposed a few years ago (see, e.g. Bignami & Fichtel 1974; Paul, Cassé & Cesarsky 1974; Stecker et al. 1975; Fichtel 1977), essentially in terms of diffuse mechanisms. A fortiori, the large contribution from discrete sources makes it impossible to deconvolve the data for the cosmic-ray density.

2 The contribution of strong sources

The contribution of the 2CG sources to the galactic $\gamma$-ray luminosity can be computed in two steps: first, the surface specific emissivity in the solar neighbourhood due to these sources, $\sigma_\alpha$, is evaluated, and is then integrated across the whole Galaxy according to a spatial distribution law.

The $\gamma$-ray sources are found to lie very close to the galactic equator ($|b| \approx 1^\circ.5$), and this enables us to perform both steps virtually without needing to know anything about the nature and intrinsic properties of the sources themselves.

As for their galactic distribution, we have assumed that they follow a typical Population I pattern, namely an exponential dependence of the surface density on the galactocentric distance $R$, with an $e$-folding length of the order of $R_1 = \alpha^{-1} = 2.2$ kpc, and inner and outer cut-offs at 5 and 15 kpc, respectively. There is, in fact, evidence in favour of this choice: the latitude distribution of the sources is so narrow that a 100–200 pc scale height seems to be required; a trace of spiral structure can also be recovered if the longitude-flux distribution is analysed according to certain simplifying assumptions (Panagia & Zamorani 1979). On the
other hand, it is easy to demonstrate that such an assumption is not critical to our aim. In fact, another possibility is an old disc population distribution without inner cut-off and an $e$-folding distance equal to $2a^{-1} = 4.4$ kpc; if a form factor is introduced — equal to the surface integral of either distribution, normalized to the density at the Sun’s position, and to a disc area of $\pi (15 \text{ kpc})^2$ — one finds the values of 1.43 and 1.33 for the old disc and Population I cases, respectively. The spread is certainly negligible with respect to the other uncertainties which affect the problem.

The evaluation of the local $\gamma$-ray surface emissivity arising from discrete sources is simple for an unbiased bidimensional population; there the sampled area is proportional to the intrinsic luminosity, hence the detected number will be proportional to the local density and to the intrinsic luminosity, that is, to $\sigma_\odot$. Let $n_\odot(L) \, dL$ be the local luminosity function per unit area of the galactic disc, and $N_{\text{obs}}$ the number of sources contained in a statistically complete sample down to a limiting flux $\phi$; then the emissivity in the solar neighbourhood is

$$\sigma_\odot = \int_0^\infty n_\odot(L) \, dL$$

(1)

and

$$N_{\text{obs}} = 2\pi \int_0^\infty dL \, n_\odot(L) \left( \frac{L}{4\pi \phi} \right)^{1/2} dr \, r = \sigma_\odot / 4\phi.$$  

(2)

We have neglected the thickness $h$ of the source distribution, which, at a certain luminosity $L$, is reasonable when the distance to the nearest source is much larger than $h$:

$$[n_\odot(L) L]^{-1/2} \gg h.$$  

(3)

For a well-behaved luminosity function, the relation (3) is most stringent for the smallest $L$; at any rate, it appears consistent with the observational data, from which typical distances of $\sim 2$ kpc are inferred (Hermes 1980).

A further, more critical consistency check is on the distance to the detected sources; let $d = (L/4\pi \phi)^{1/2}$,

(4)

then equation (2) is not valid if the source distribution changes appreciably over distances of order $d$, or, a fortiori, if $d$ is larger than the distance to the edge of the Galaxy. The sources contained in the first COS B catalogue were distributed in galactic longitude in a statistically uniform way, which was reflected also in the log $N$—log $\phi$ relation, showing, after allowance had been made for the existing uncertainties, the theoretical slope $N \propto \phi^{-1}$. The 2CG catalogue, instead, exhibits a marked asymmetry between centre and antecentre regions, the former being much more crowded with bright sources than the latter. The log $N$—log $\phi$ curve still agrees with the theoretical expectation if the central objects are excluded from the sample; when they are included, however, the slope becomes steeper than $-1$, providing evidence for a source density enhancement toward the Galactic Centre (Bignami & Caraveo 1980). Clearly, $d$ is larger than the local scale for distribution changes, and this fact must be taken into account in order to evaluate the $\gamma$-ray source contribution.

We have thus introduced a spatial distribution function like that of Population I, as discussed above: the number of sources per unit surface and luminosity interval is expressible in the form

$$\frac{dN}{dL \, d\Sigma} \propto n(L) \exp \{ -\alpha R \},$$  

(5)
$d\Sigma$ being the surface element of the galactic disc, and $R$ the galactocentric radius

$$R = (R_o^2 + r^2 - 2R_o r \cos l)^{1/2},$$

(6)

with $r$ the distance from the Sun to the source, and $l$ the galactic longitude. We have expanded equation (5) up to the second order in $r/R_o$, and integrated it to obtain the numbers of detected sources inside and outside the solar circle, $N_I$ and $N_o$, respectively. The integrations with respect to $r$ out to $(L/4\pi \phi)^{1/2}$, and with respect to $L$ out to infinity, are exactly analogous to those in equation (2). Instead of giving $N_I$ and $N_o$ separately, we prefer to give $N_{\text{obs}} = N_I + N_o$, and the ratio $\xi = (N_I - N_o)/(N_I + N_o)$, since the former can be compared with the 'local' treatment of equation (2), and the latter, apart from being independent of $\sigma_o$, more clearly expresses the asymmetry between the centre and anticentre regions of the 2CG catalogue. We obtain therefore

$$N_{\text{obs}} = (\sigma_o/4\pi) \{ 1 + (1 - 1/\alpha R_o) (\sigma^2 d^2 / 8) \}$$

(7)

and

$$\xi = (4/3\pi) \alpha d \{ 1 + (1 - 1/\alpha R_o) (\sigma^2 d^2 / 8) \}^{-1},$$

(8)

with $d$ given by equation (4). In reality $d$ should be determined by means of a somewhat complicated expression involving the luminosity function, but we do not have enough information for even attempting a guess at the form of $n(L)$, and the only two equations which we can fit to the data are (7) and (8); thus, for the sake of simplicity, we will adopt a $\delta$ distribution, and $d$ will acquire the meaning of the distance out to which the sources are individually detectable.

A further delicate point is the choice of $\phi$. We cannot take the smallest detected flux, $1.0 \times 10^{-6}$ photon cm$^{-2}$ s$^{-1}$, because the background is highly non-uniform — as we have anticipated in the Introduction; specifically, it is more intense in a broad sector containing the Galactic Centre and substantially weaker in the anticentre. On the other hand, putting $\phi = 2.0 \times 10^{-6}$ photon cm$^{-2}$ s$^{-1}$ already reduces the sample to only 10 sources, due to the narrow dynamical range of the instrument. We have selected an intermediate value $\phi = 1.3 \times 10^{-6}$ photon cm$^{-2}$ s$^{-1}$, which does not blur the anisotropy in the longitude distribution, as discussed by Wills et al. (1980) and Hermans (1980); to be on the safe side, however, we have also explored the stability of the solution with respect to this parameter.

The last problem is how to include in our analysis the very bright source 2CG 263–02, corresponding the Vela pulsar; because of the small distance from the Sun (~ 500 pc), it can be considered as a 'local perturbation' to the sample, and it is not evident whether one should locate it inside or outside the solar circle. In our preferred solution we assume Vela to be half inside and half outside, but other approaches are also investigated.

We thus have $N_{\text{obs}} = 15$, $\xi = 0.67$, and from equations (7) and (8) we obtain $d = 5.8$ kpc and $\sigma_o = 1.8 \times 10^{35}$ erg kpc$^{-2}$ s$^{-1}$. This value of $\sigma_o$ corresponds to a total contribution from discrete sources $L_{\gamma S} = 1.7 \times 10^{38}$ erg s$^{-1}$, i.e. 34 per cent of the overall emission $L_{\gamma G}$. The luminosity of the individual sources would be around $2.1 \times 10^{36}$ erg s$^{-1}$, giving a number of 80 sources in our Galaxy.

If Vela is dropped from the sample, $N_{\text{obs}} = 14$ and $\xi = 0.71$, which lowers $L_{\gamma S}$ to $1.3 \times 10^{38}$ erg s$^{-1}$; note, however, that now the discriminant of equation (8) is negative, so that there is no real solution for $d$, and we have taken the value of 7 kpc, which corresponds to the null discriminant.

The present sample, though doubled with respect to the first catalogue, is not so rich as to limit statistical uncertainties. If, for instance, we were to choose $\phi$ a bit lower, say $1.2 \times 10^{-6}$ photon cm$^{-2}$ s$^{-1}$, we should add only one object with the consequent small variation of $\xi$.
from 0.67 to 0.69, but the source contribution would be curtailed to $1.4 \times 10^{38}$ erg s$^{-1}$. On the contrary, by assuming $\phi = 1.1 \times 10^{-6}$ photon cm$^{-2}$ s$^{-1}$, we would obtain $N_{\text{obs}} = 17$ and $\xi = 0.59$, and $L_{\gamma S}$ would rise up to $2.0 \times 10^{38}$ erg s$^{-1}$.

Indeed, the range of values spanned by our solution, because of marginal adjustments in the input data, is a measure of the internal consistency of the method, and provides a lower limit for the error, to which further uncertainties can only add. It follows $L_{\gamma S} = (1.7 \pm 0.35) 10^{38}$ erg s$^{-1}$.

Finally, we stress that the weakest source detected in the longitude interval $300^\circ - 360^\circ$ is at the high flux level of $1.8 \times 10^{-6}$ photon cm$^{-2}$ s$^{-1}$, hence the effective number of sources at the selected limiting flux of $1.3 \times 10^{-6}$ photon cm$^{-2}$ s$^{-1}$ should be certainly greater than that used in our analysis. This fact would imply an increase in $N_{\text{obs}}$ and $\xi$, and a larger value of $a_0$; we thus have to consider the estimated fraction as a lower limit to the source contribution.

3 The contribution of pulsars

Radio pulsars are a very special class of sources, because of their time signature: the search for $\gamma$-ray pulsars, in fact, can be carried out only if high quality radio data are available on the period $P$ and its first derivative $\dot{P}$ (Buccheri et al. 1977). The status of observations has been recently assessed by Buccheri (1980): the Crab and Vela pulsars are the only two well observed objects in the class, and are also two of the brightest sources in the $\gamma$-ray sky, included in the 2CG catalogue. Under a certain point of view these pulsars may be considered as ‘atypical’ because of short $P$, large $\dot{P}$, and large $\dot{E}$. As for ‘normal’ radio pulsars, PSR 1747 – 46 and PSR 1818 – 04 were detected by SAS 2 (Ögelman et al. 1976; Thompson et al. 1976), but the former is still under analysis by the COS B team, at variance with the latter which has been explicitly questioned (Kanbach et al. 1977). Also, PSR 0740 – 28 and PSR 1822 – 09, of which positive detection has been reported (Pinkau 1979), must be treated with caution, pending the solution of an apparent conflict between radio and $\gamma$-ray data (Buccheri 1980). Search for $\gamma$-ray emission from other radio pulsars is in progress by the COS B team (Buccheri & Sacco, private communication).

In our analysis we have considered only normal radio pulsars, using the radio data alone, which are well established, and a method which does not give any particular relevance to Crab and Vela. It will be seen that — as far as $\gamma$-ray emission is concerned — the objects considered in this section are quite distinct from the strong sources of Section 2; they are definitely less luminous, much more numerous, and possibly distributed with a different law, so that there is no danger of double-accounting. Crab and Vela might represent a link between the two classes, hence the need — in calibrating the $\gamma$ luminosity versus the radio one — of a procedure where their role is not overwhelming; our results would remain unchanged if these two objects were excluded from the sample, which would not be the case, for instance, with Higdon & Lingenfelter (1976).

To relate the $\gamma$-ray emission to the radio properties we need an assumption on the conversion efficiency from rotational energy to $\gamma$-ray energy (Buccheri et al. 1978). It was noted that this efficiency is larger in PSR 0833 – 45 than in PSR 0531 + 21, and must become of order unity in the other normal pulsars if their detection is definitely confirmed. In the (controversial) case of PSR 1822 – 09, the formal value of the efficiency is substantially larger than 1, even if a $\gamma$ beaming factor is allowed for; this might indicate a moment of inertia larger than the canonical value (see below). It was found convenient to order the sample according to the spin-down time-scale: along the sequence, the efficiency increases as a power law with index between 1 and 2, until it saturates at about the maximum value at times larger than $10^5$ yr. Also on the theoretical side there are reasons why the gap responsible
for the γ-ray energetics should increase as the pulsar slows down, until it swallows the whole magnetosphere (Ruderman & Sutherland 1975).

A controversial point is whether the efficiency remains so high once and for all; that is, whether the γ-ray turn-off occurs before the radio turn-off or at the same time. We will adopt the latter hypothesis; in any case, the rotational energy loss is positively correlated with the radio luminosity, and anticorrelated with the "apparent age": because of this, and because of the slope of the radio luminosity function, the low-luminosity, long-aged pulsars affect the results only through a logarithmic term. We thus assume that the main body of the radio pulsars' class, with possibly a few statistically irrelevant exceptions, radiate their rotational energy entirely in the form of γ photons.

Having connected the γ-ray emission to the basic physics of the pulsar, we only need the basic pulsar parameters which are contained in the radio data: the actual γ-ray observations do not enter into the calibration process, neither do the related selection effects, and especially the intricate question of the γ-ray beaming factor.

We have included in our sample all pulsars for which both $\dot{P}$ and DM (dispersion measure) distances are available: 81 of these are found in Taylor & Manchester (1975), and 21 more values of $\dot{P}$ are taken from Manchester et al. (1978) and Gullahorn & Rankin (1978). Note that $P$, the flux density at 400 MHz and the distance are those of Taylor & Manchester (1975) for all the 102 entries. From the above data one computes the rotational energy loss $\dot{E} = L_\gamma$ with the canonical value for the moment of inertia $I = 10^{45} \text{g cm}^2$, the spin-down age $P/2\dot{P}$, and the luminosity indicator $\mathcal{L}$ in mJy kpc$^2$, which is the independent variable consistently used by Taylor & Manchester (1977) in analysing the pulsars' distribution.

A plot of $\dot{E} = L_\gamma$ versus $\mathcal{L}$ would already exhibit the anticipated correlation. However, the period $P$ does not correlate very strongly with $\mathcal{L}$, nor does $P^{-3}$, which appears in the definition of $\dot{E}$. It is simpler and adequate for our purposes to take $L_\gamma$ proportional to $\dot{P}$

$$L_\gamma = 1.42 \times 10^{32} \dot{P}_{15} \text{ erg s}^{-1},$$

(9)

where $\dot{P}_{15} = \dot{P}/10^{-15}$, and the proportionality constant includes $\langle P^{-3} \rangle$. The calibration is then performed on the $\dot{P} - \mathcal{L}$ plot shown in Fig. 1. The two oblique lines are the envelopes of slope +1 to the populated portion of the diagram: in other words, they are the extremal lines of $L_\gamma$, which, according to equation (9), may be written as

$$L_{\gamma \text{max}} = 6.7 \times 10^{32} \mathcal{L},$$

(10a)

$$L_{\gamma \text{min}} = 3.2 \times 10^{28} \mathcal{L}.$$  

(10b)

We have also included a horizontal boundary at the $\dot{P}$ of PSR 0531 +21, corresponding to $L_\gamma = 6 \times 10^{34} \text{ erg s}^{-1}$.

The next step is to investigate the distribution of points within the boundaries, in order to expand the radio luminosity function $n(\mathcal{L}) \, d\mathcal{L}$ into a bivariate function $n(\mathcal{L}, L_\gamma) \, d\mathcal{L} dL_\gamma$. In fact, the diagram is far too wide for a naive interpretation in terms of a one-to-one correspondence between $L_\gamma$ and $\mathcal{L}$. The counts per logarithmic $\mathcal{L}$ interval are consistent with the expected value of a uniform distribution. This is important, since in a disc population the sampled area is proportional to $\mathcal{L}$, therefore the uniformity of a logarithmic histogram implies a true luminosity function close to $\mathcal{L}^{-2}$; Taylor & Manchester (1977) give $n(\mathcal{L}) \propto \mathcal{L}^{-2.12}$ for the whole sample, and we may be confident that our subsample is random with respect to $\mathcal{L}$, and is described by a similar law.

The situation for $L_\gamma$, however, is not so clear, and the presence of some structure is apparent; the hypothesis of a uniform distribution which we use must be considered only a working one. This, together with the absence of any bias on $L_\gamma$ and the form of the radio
Figure 1. Double logarithmic plot of $\dot{P}$ (in units of $10^{-15}$), versus the radio luminosity indicator $\mathcal{L}$ (in units of mJy kpc$^{-2}$). The crosses are single pulsars, the asterisks indicate several pulsars falling within the same resolution element; Crab and Vela are circled. The lines which enclose the populated strip have slope +1 (see text).

The luminosity function, force us to take
\begin{equation}
  n(\mathcal{L}, L_\gamma) = C \mathcal{L}^{-2.12} L_\gamma^{-1},
\end{equation}
where the normalization is found by integrating between $L_{\gamma_{\text{min}}}$ and $L_{\gamma_{\text{max}}}$, and by comparing with Taylor & Manchester's (1977) $n(\mathcal{L})$
\begin{equation}
  C = \frac{350}{\ln (6.7 \times 10^{32}/3.2 \times 10^{28})} = 35.
\end{equation}

A straightforward integration within the boundaries discussed before yields the local $\gamma$-ray luminosity per kpc$^2$ due to the pulsars whose radio beam sweeps past the Earth, $6.95 \times 10^{34} \text{erg s}^{-1}\text{kpc}^{-2}$. $L_{\gamma_{\text{pul}}}$ is obtained after multiplying by: (i) the reciprocal of the radio beaming factor, of order 5 (Taylor & Manchester 1977), since the invisible radio pulsars did not go into the normalization; (ii) the area of the galactic disc, times the form factor 1.38 describing the increase toward the centre for an intermediate population; (iii) a bandwidth factor $w$, which indicates the fraction of the total power appearing in the useful window 100 MeV–1 GeV. The precise computation of $w$ would require detailed information on the pulsar spectrum; if the slope is approximately $-2$, the dependence on the low- and high-energy cut-offs $E_{\gamma_{\text{max}}}$ and $E_{\gamma_{\text{min}}}$ is very weak, and only logarithmic in the limiting case. A pulsed X-ray emission seems to be a peculiarity of PSR 0531 + 21, so that $E_{\gamma_{\text{min}}} \geq 300 \text{keV}$; and only PSR 0833 – 45 is observed well beyond 1 GeV; so we take $w = 0.28/\ln \{E_{\gamma_{\text{max}}}/1 \text{Gev}\}(300 \text{keV}/E_{\gamma_{\text{min}}})$.

The final outcome for $L_{\gamma_{\text{pul}}}$ is
\begin{equation}
  L_{\gamma_{\text{pul}}} = 1.0 \times 10^{38} \text{erg s}^{-1} = 0.20 L_{\gamma G}.
\end{equation}

Under the assumption that the region above the horizontal boundary, and up to the $L_{\gamma_{\text{max}}}$ line, were populated as well as the rest of the diagram (the points there would be young pulsars hidden by some selection effect on $P$), equation (13) would be changed into \begin{equation}
  L_{\gamma_{\text{pul}}} > 1.6 \times 10^{38} \text{erg s}^{-1} = 0.32 L_{\gamma G}.
\end{equation}
By the same internal consistency arguments used in Section 2, we attribute to the best estimate of equation (13) an error $\Delta L_{\gamma \text{ pu}} = \pm 0.5 \times 10^{38} \text{ erg s}^{-1}$ (see also Strong, Wolfendale & Dahanayake 1977).

4 Diffuse processes

The total contribution to the $\gamma$-ray luminosity of our Galaxy arising from 2CG-like sources and normal radio pulsars can be easily computed by adding together the results of Sections 2 and 3; we obtain the value of $(2.7 \pm 0.6) \times 10^{38} \text{ erg s}^{-1}$. The remaining fraction of $(2.3 \pm 1.2) \times 10^{38} \text{ erg s}^{-1}$ (an error of 20 per cent has been attributed to the total $L_{\gamma G}$) must be due to different mechanisms, such as the interaction of the cosmic rays with the interstellar gas.

Above 100 MeV, $\pi^0$ decay is the dominant process: current estimates of the $\gamma$-ray source function in the solar vicinity, $q_{\gamma \odot}$ (i.e. the number of $\gamma$ photons produced per hydrogen atom and second by cosmic rays), indicate that this process alone is responsible for a fraction of about 75 per cent (Fichtel et al. 1976), and therefore we will neglect other mechanisms without introducing large errors.

We cannot use the emission profile in galactic longitude due to the integrated contribution of $\gamma$-ray sources and pulsars because, after subtracting the latter from the observed one, the remaining data would be affected by errors so large as to make meaningless any conclusion on $\pi^0$-emissivity and cosmic-ray distributions. However, it is possible to obtain some indication on the correlation between high energy particles and interstellar matter by means of integral quantities, as explained in the following.

The total luminosity of the Galaxy due to $\pi^0$-decay can be written as

$$L_{\pi} = \langle E_\gamma \rangle q_{\gamma \odot} \int f n_g dV,$$

where $\langle E_\gamma \rangle$ is the average photon energy, $n_g$ the density of the interstellar gas, and $f$ the ratio of the cosmic-ray intensity to the local value. By introducing the average value of this quantity, weighted with the gas distribution

$$\langle f \rangle = \frac{\int f n_g dV}{\int n_g dV} = \frac{\langle m_p/M_g \rangle}{\int n_g dV},$$

we can put equation (15) in the simple form

$$L_{\pi} \sim (M_g/m_p) \langle E_\gamma \rangle \langle f \rangle q_{\gamma \odot},$$

where $m_p$ is the proton mass, and $M_g$ the total mass of the interstellar gas. The average photon energy $\langle E_\gamma \rangle$ depends on the spectral shape, and, adopting the same assumption as in Section 2, one has $\langle E_\gamma \rangle = 250 \text{ MeV}$; $M_g$ can be estimated from radio measurements and turns out to be $10^{22} \text{ g}$ (Gordon & Burton 1976; Mezger 1978)*; for $q_{\gamma \odot}$, finally, we have taken the value of $1.2 \times 10^{-25} \text{ s}^{-1}$ from Badhwar & Stephens (1977). We are thus able to evaluate $\langle f \rangle$: in fact, inserting in equation (17) for $L_{\pi}$ the value found above, it immediately follows $\langle f \rangle = 0.77 \pm 0.40$. Such a figure is a first indication that the cosmic rays and the interstellar gas are not positively correlated.

It is possible to specify further these considerations. $\langle f \rangle$ can be computed $a$ priori for a given gas distribution and assuming a relation between $f$ and $n_g$. For instance, if a simple power dependence is adopted

$$f = (n_g/n_0)^{\beta}$$

* See, however, the critical review by Blitz & Shu (1980).
with the obvious constraint $f = 1$ at the Sun position, one can determine a correspondence between $\beta$ and $\langle f \rangle$. An example is reported in Table 1 for the gas distribution derived by Gordon & Burton (1976); equation (18) has been used only inside the solar circle, whereas in the region 10–15 kpc $f$ has been set equal to 1. This correction is necessary because, for $\beta < 0$, equation (18) would imply an abnormal increase of the cosmic-ray density toward the periphery of the Galaxy, which disagrees with the observations of the galactic non-thermal radio background; we recall that a similar assumption has already been made in deconvolving the distribution of the observed $\gamma$ rays (Strong & Worrall 1976).

We see that $0.4 \leq \langle f \rangle \leq 1.2$ implies $-1.5 \leq \beta \leq 0.25$, but assuming $\beta = 1$, i.e. a definite enhancement of the cosmic-ray density in the densest gas structures, would result in the unacceptable value $\langle f \rangle = 2.7$.

5 Discussion

As we have shown in Sections 2 and 3, $\gamma$-ray sources and normal radio pulsars might be responsible for a fraction $\geq 50$ per cent of the whole galactic luminosity. Our estimate is in reasonable agreement with the results of Bignami et al. (1978) and Hermsen (1980). The novelty of our analysis is that it takes into account the asymmetry in the longitude distribution, which is a strong indication that the density of $\gamma$-ray sources has a gradient toward the Galactic Centre. This introduces a scale length, enabling us to deduce a typical luminosity ($\sim 2 \times 10^{36}$ erg s$^{-1}$) and the total source number ($\sim 80$).

A further point is the nature of the 2CG sources: the narrow $b$-distribution suggests a young population, but it is still unknown what objects they are, and if they belong to one and the same class. Several possible associations have been proposed, such as supernova remnants, plemions, young pulsars, dense interstellar clouds, . . . , but none has been firmly established. When more information on the nature of the $\gamma$-ray sources is available and a luminosity function estimated, it will be possible to use a better value of $\langle L \rangle$ in equation (4), and to improve the accuracy of $\sigma_\beta$.

As for the normal radio pulsars, the crucial point is to ascertain the level of the $\gamma$-ray emission. At present it is necessary to introduce some working hypothesis based on phenomenological and statistical considerations, such as the direct proportionality between $L_\gamma$ and $\dot{P}$. On the other hand, it is not possible to rule out this class of sources because they are very numerous and can give a non-negligible contribution, even if the intrinsic luminosity of the single pulsar may be low.
The final remark is on the relevance of cosmic rays for the galactic \( \gamma \)-ray emission. The idea that photons above 50 MeV might originate from \( n^0 \)-decay was suggested in the early works by Hayakawa (1952) and Morrison (1958), and has been the leading objective of \( \gamma \)-ray astronomy before the \textit{COS B} discovery of discrete sources. Our result indicates that cosmic rays can account for \( \lesssim 50 \) per cent of the total emission, and this is compatible with a rather uniform distribution of high energy particles throughout the Galaxy. On the other hand, every proposed interpretation in terms of cosmic-ray gradients requires that the contribution from discrete sources be a marginal one, typically less than 20 per cent (Wolfendale 1980). We stress, however, that in the region \(-60^\circ < l < +60^\circ\) the resolved sources (with the stringent criteria imposed by the \textit{COS B} collaboration) already account for \(~17\) per cent of the total \( \gamma \)-ray emission measured from the same region (Hermsen 1980). The conclusion that \( \gamma \)-ray sources play a fundamental role seems inescapable.

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References


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