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THE PULSAR CONTRIBUTION TO THE GALACTIC GAMMA-RAY EMISSION*

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ABSTRACT

Unresolved pulsars can produce a significant fraction of the total galactic γ-ray emission at energies greater than 100 MeV. Thus the observed variation of the γ-ray emission with galactic longitude can be understood without requiring a spatial variation of the cosmic-ray intensity in the Galaxy.
Subject headings: cosmic rays: general — galaxies: structure — gamma rays: general

I. INTRODUCTION

High-energy (>100 MeV) γ-ray observations (Fichtel *et al.* 1975) show a greater intensity variation with galactic longitude than would be expected from the decay of neutral pions produced by cosmic-ray interactions with the interstellar gas, using current models of the atomic and molecular gas distribution and assuming a uniform cosmic-ray intensity throughout the Galaxy. Thus it has been suggested (e.g., Bignami *et al.* 1975; Stecker *et al.* 1975) that the observations require an increased cosmic-ray intensity in regions of higher gas density and thus provide evidence of a galactic origin of cosmic rays. The alternative possibility that most of the observed γ-ray emission was produced by X-ray sources (Ögelman 1969) or by cosmic rays in the remnant nebulae of supernovae (Hayakawa and Tanaka 1970) has been considered but observational limits on γ-ray emission from these sources are much lower than that required.

The SAS-2 observations (Kniffen *et al.* 1974; Thompson *et al.* 1975) do, however, show that the enhanced emission from the direction of the Crab and Vela supernova remnants is predominantly pulsed, indicating that this emission comes directly from the remnant pulsars. This suggests that the direct contribution of pulsars to the galactic γ-ray emission should also be considered.

In this *Letter* we show that unresolved short-period pulsars could in fact produce a significant fraction of the galactic γ-ray emission at energies >100 MeV. We therefore find that the observed variation of the high-energy γ-ray emission with galactic longitude does not require a variation in cosmic-ray intensity and thus does not provide evidence of a galactic origin of cosmic rays.

II. GALACTIC GAMMA-RAY EMISSION

Before considering the pulsar contribution, we recalculate the cosmic-ray contribution using the more recent atomic and molecular hydrogen distributions of Gordon and Burton (1976), which are based on a re-evaluation of the 21 cm emission, considering the effects of saturation, and on extensive CO observations in the Galaxy.

Assuming a uniform cosmic-ray intensity throughout the Galaxy and an interstellar gas density $n(l, b, r)$ as a function of galactic longitude l, latitude b, and distance r, the differential γ-ray intensity per radian of longitude, dI/dl, is given by

$$\frac{dI}{dl} = \frac{q}{4\pi} \int d \sin b \int dr n(l, b, r) , \qquad (1)$$

where q is the yield of γ-rays produced by cosmic-ray interactions with the interstellar gas. The γ-ray yield $q \approx 1.6 \times 10^{-25} \gamma(>100 \text{ MeV}) \text{ s}^{-1}(\text{H atom})^{-1}$ (Higdon 1974) is principally from pion decay, but electron bremsstrahlung is also important.

The contributions to the γ-ray intensity dI/dl from cosmic-ray interactions with atomic (H I) and molecular hydrogen (H_2) were calculated separately and are shown in Figure 1, together with the SAS-2 observations (Fichtel *et al.* 1975) of the variation of high-energy (>100 MeV) γ-ray emission as a function of galactic longitude.

As can be seen, in the direction $80° < l < 260°$ the emission is consistent with that expected from this model. Note that the molecular hydrogen contribution as shown is only the spatially averaged value which ignores small-scale longitudinal variations resulting from the concentration of molecular hydrogen in a relatively small number of dense clouds. However, the observed longitudinal variation of the galactic emission between $270° < l < 80°$ cannot be accounted for by pion decay and bremsstrahlung γ-rays from cosmic-ray interactions with the interstellar gas assuming a uniform cosmic-ray intensity throughout the Galaxy, as was shown for similar distributions by Bignami *et al.* (1975) and Stecker *et al.* (1975).

What had been neglected, however, in previous studies was the contribution of unresolved pulsars to

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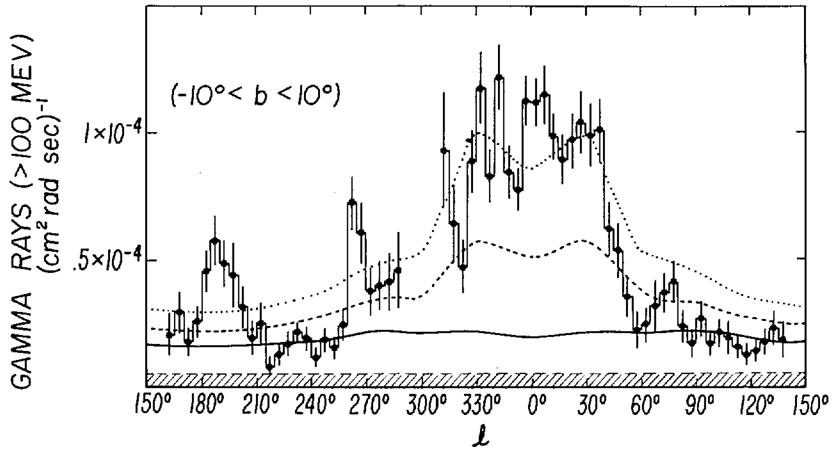

FIG. 1.—Gamma-ray intensity for energies >100 MeV, averaged over 5° intervals in galactic longitude l, and $\pm 10°$ of latitude centered on the galactic equatorial plane (Fichtel *et al.* 1975). The shaded area is the diffuse extragalactic component of 6×10^{-6} γ-rays cm^{-2} rad^{-1} s^{-1}. Also shown are the calculated emissions expected from cosmic-ray interactions with atomic hydrogen (*solid curve*), from this plus cosmic-ray interactions with molecular hydrogen (*dashed curve*), and from both of these plus pulsed γ-ray emission from pulsars (*dotted curve*). The calculated values for the latter two contributions are only spatially and temporally averaged values, and the expected present emission should show small-scale longitudinal variations because of the finite number of pulsars and molecular hydrogen clouds.

the γ-ray emission at $270° < l < 80°$, even though the important contribution of the Crab and Vela pulsars to the emission at other longitudes has been clearly recognized.

III. GAMMA-RAY EMISSION FROM PULSARS

The γ-ray emission from the Crab pulsar (PSR 0531+21) at a galactic longitude of 185° and the Vela pulsar (PSR 0833−45) at 264° are conspicuous features of the galactic γ-ray emission (Fig. 1). The bulk of the emission from these two sources is pulsed. The observed pulsed γ-ray intensity at energies >100 MeV from the Crab pulsar (Kniffen *et al.* 1974) is $2.2 \times 10^{-6} \gamma$ cm^{-2} s^{-1} and from the Vela pulsar (Thompson *et al.* 1975; Bennett *et al.* 1976) is apparently variable between 4.5×10^{-6} and $1.0 \times 10^{-5} \gamma$ cm^{-2} s^{-1}.

Of particular significance to this discussion is the fact that the pulsed emission from these two sources alone contributes 20 percent of the total γ-ray emission from the galactic disk in the longitude interval $80° < l < 270°$. The importance of these two resolved pulsars clearly suggests that other as yet unresolved pulsars may also make a significant contribution to the galactic γ-ray emission, especially in the region $270° < l < 80°$. Tentative identifications of two radio pulsars PSR 1747−46 and PSR 1818−04 as pulsed γ-ray emitters have recently been reported in this region (Ögelman *et al.* 1976).

To estimate the total contribution of pulsars to the galactic γ-ray emission we must first estimate how the high-energy γ-ray luminosity of a pulsar varies with age and how the pulsars are distributed in both age and distance in the Galaxy. The pulsed γ-ray luminosities determined from the SAS-2 observations of the Crab pulsar at a distance of 2 kpc and the Vela pulsar at 0.46 kpc are $\sim 1.0 \times 10^{39} f\gamma(>100$ MeV) s^{-1} and ~ 1 to $2 \times 10^{38} f\gamma(>100$ MeV) s^{-1}, respectively, where f is the fraction of the 4π sr solid angle swept out by the pulsar emission beam. This fraction f is also the probability of observing the pulsar from an arbitrary direction.

In view of the uncertainty in the mechanism of γ-ray emission, we simply assume that the γ-ray luminosity of a pulsar as a function of its age, $L(t)$, is proportional to its rate of rotational energy loss, dW/dt. Then differentiating the rotational energy with respect to the rotation period P, we see that

$$L(t) \propto dW/dt \propto P^{-3} dP/dt \, .$$

This is quite similar to the $P^{-3.25} dP/dt$ dependence of the γ-ray luminosity derived by Sturrock (1971), if we assume a predominantly dipole radiation loss for the pulsar so that $dP/dt \propto P^{-1}$. Since the maximum luminosity is associated with the shortest periods, an exponent of -3 is a more conservative estimate.

We thus define

$$L(t) \equiv f L_* P^{-3} dP/dt \, , \qquad (2)$$

where L_* is the normalization constant for the particular pulsar. For the Crab pulsar, which has an observed luminosity of $\sim 1.0 \times 10^{39} f\gamma(>100$ MeV) s^{-1}, a period of 0.0331 s, and dP/dt of 4.23×10^{-13}, $L_* = 9 \times 10^{46} \gamma(>100$ MeV) s^2; while for the Vela pulsar, taking a luminosity of $\sim 2.0 \times 10^{38} f\gamma(>100$ MeV) s^{-1} a period of 0.0892 s, and dP/dt of 1.25×10^{-13}, $L_* = 1.2 \times 10^{48} \gamma(>100$ MeV) s^2. Even higher values for L_* could be expected from the tentatively identified pulsars PSR 1747−46 and PSR 1818−04, but because of uncertainties in their identification and distances we will not consider them in this calculation.

Recent observations (Hulse and Taylor 1974, 1975) of the spatial distribution of pulsars in the longitude ranges $170° \lesssim l \lesssim 210°$ and $35° \lesssim l \lesssim 75°$ show that they are much more numerous in the inner part of the Galaxy than in the outer part. These observations show a markedly reduced density of pulsars at distances greater than 8–10 kpc from the galactic center. Although the entire radial distribution of the pulsar population is not known, qualitatively similar distributions within the observational uncertainties have been found for supernova remnants (e.g., Ilovaisky and Lequeux 1972) and carbon monoxide (Burton *et al.* 1975). Since the CO distribution is the best determined, we assume that the spatial distribution of pulsars in the Galaxy is proportional to that of CO molecules.

Assuming that the pulsar density distribution, $D(l, b, r)$, normalized to a volume integral of unity, is proportional to the CO density distribution of Gordon and Burton (1976), we calculate the total γ-ray emission from pulsars. We define the rate of pulsar formation in the galaxy as $1/\tau_s$, where τ_s is the mean time between formation of pulsars. We thus replace the product of the γ-ray emissivity and the gas density in equation (1) by the corresponding function for pulsar sources,

$$qn(l, b, r) \to \frac{1}{\tau_s} \int_0^\infty L(t) D(l, b, r) dt\,.$$

Using $L(t)$ from equation (2), and noting that $P = P_0$ at $t = 0$, we obtain

$$qn(l, b, r) \to \frac{fL_* D(l, b, r)}{\tau_s} \int_{P_0}^\infty P^{-3} dP = \frac{fL_* D(l, b, r)}{2\tau_s P_0^2}\,, \quad (3)$$

where $fL_*/2\tau_s P_0^2$ is the total pulsar γ-ray luminosity in the Galaxy.

We find that the difference between the observed γ-ray emission in the longitude range $270° < l < 80°$ and that expected from cosmic-ray interactions with the gas can be accounted for by pulsar emission, if the total galactic γ-ray pulsar luminosity is $\sim 4 \times 10^{41} \gamma$ (>100 MeV) s^{-1}. This is about half the galactic luminosity produced by cosmic-ray interactions. The longitudinal distribution of the combined γ-ray emission from pulsars and cosmic-ray interactions with the gas is shown as the dotted curve in Figure 1. The calculated emission from the pulsars represents only spatially and temporally averaged values, since the expected emission should come from a relatively small number of sources. The Crab and Vela pulsars are presently emitting roughly half of the time-averaged emission predicted within the longitude range $80° \lesssim l \lesssim 270°$.

The required galactic luminosity of $fL_*/2\tau_s P_0^2 \sim 4 \times 10^{41} \gamma(>100$ MeV) s^{-1} is quite consistent with current estimates of the initial periods and birthrates of pulsars. The range of $L_* = (0.9\text{–}12) \times 10^{47} \gamma(>100$ MeV) s^2, deduced from the Crab and Vela pulsars, gives a range of $\tau_s P_0^2/f \sim (1\text{–}15) \times 10^5\ s^{-3}$. Probably the best determination of f is that of Roberts (1976), who finds $f = 0.25$, based on the analysis of the radio pulsar periods and pulse widths. Since the γ-ray pulse widths for the Vela and Crab pulsars are comparable to their radio pulse widths (Bennett *et al.* 1976), we would also expect this value of f to hold for γ-ray emission. Assuming the same detection probability f, Gunn and Ostriker (1970) and Seiradakis (1976) estimate the galactic pulsar birthrate τ_s^{-1} to be one every 25 to 30 yr. Using an f of 0.25 and τ_s of 30 yr, the above range of $\tau_s P_0^2/f$ gives a range of $0.005 < P_0 < 0.02$ s. This is almost identical to $0.0055 < P_0 < 0.014$ s estimated by Ruderman (1972).

Thus we see that the difference between the observed high-energy emission at $270° < l < 80°$ and that expected from cosmic-ray interactions with the gas could simply be the result of the combined emission of all pulsars, if their average P_0 and L_* lie anywhere between the limiting combinations of an L_* comparable to that of the Vela pulsar with P_0 of 0.020 s and an L_* comparable to that of Crab pulsar with P_0 of 0.005 s. In the first limit we see that the bulk (90%) of the γ-ray emission would come from those pulsars with periods less than or equal to two-thirds that of the Vela pulsar. If pulsar ages are proportional to P^2, these pulsars would have ages $\lesssim 5500$ yr, and thus there should be nearly 200 such pulsars in the Galaxy. About 50 of these should be observable from the Earth for $f = 0.25$. Of these roughly 40 should lie between $270° < l < 80°$, and be the principal contributors to the emission from that region.

At the other extreme, if the characteristic luminosity of most pulsars is like that of the Crab pulsar and $P_0 = 0.005$ s, then the bulk of their γ-ray emission comes from those pulsars with periods less than or equal to half that of the Crab pulsar. Such pulsars should have ages $\lesssim 230$ yr, and thus we would expect only about eight in the Galaxy. Although most of these would lie between $270° < l < 80°$, only a quarter of them would be observable at the Earth, and thus only a couple of pulsars would be the principal contributors to the apparent excess emission. This latter extreme is clearly ruled out by the wide longitudinal distribution of the observed emission. But all possibilities with L_* at least twice that of the Crab pulsar, which would permit half a dozen or more pulsars to contribute to the bulk of the emission excess, are quite compatible with the observations. The observed small-scale variations of the intensity with longitude within the range $270° < l < 80°$ may not be entirely statistical but may in fact result from the emission of the few strongest pulsar sources, as is the case with the Crab and Vela pulsars at other longitudes.

IV. CONCLUSION

We have shown that short-period pulsars, emitting pulsed high-energy γ-rays with luminosities comparable to that observed from the Crab and Vela pulsars, are expected to produce a substantial fraction of the observed galactic γ-ray emission at energies >100 MeV. Only a few such pulsars have been detected at radio frequencies because of observational difficulties. At present only the γ-ray emission from the Crab and Vela pulsars has been unambiguously resolved, but further observation with greater angular and temporal sensitivity should be capable of resolving γ-ray emission from as yet undiscovered pulsars. Since variations in γ-ray emission on time scales of the order of a year are observed (Greisen *et al.* 1975; Bennett *et al.* 1976) from the Crab and Vela pulsars, significant time variations may also be expected in the galactic γ-ray emission from the region $270° < l < 80°$.

Finally, when the contribution of the pulsars to the galactic γ-ray emission is considered, the observed longitudinal dependence does not necessarily require any spatial variation of the cosmic-ray density. Thus until the contribution of discrete sources is fully understood, the longitudinal variation of the γ-ray emission cannot be regarded as evidence of either large-scale cosmic-ray gradients in the Galaxy or a galactic origin of cosmic rays. Clearly, more sensitive observations are required.

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