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GALACTIC GAMMA-RAY EMISSION FROM RADIO PULSARS

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ABSTRACT

Using both the polar cap and outer gap models of pulsar gamma-ray emission, the pulsars' contribution to the Galactic gamma-ray emission is derived. A Monte Carlo technique is used to model the Galactic pulsar population, and their contribution to the Galactic gamma-ray emission is found to depend strongly upon their birth properties, which remain controversial. The "standard model" of radio pulsar evolution suggests that the majority of the observed gamma-ray emission originates from radio pulsars. However, other models of the Galactic pulsar population, which have pulsars being born with periods near $0^{s}.5$, suggest that the contribution is much smaller. For any model, the majority of this emission arises from pulsars *currently unknown as radio pulsars.* This result holds for both the polar cap, and outer gap models, and suggests that the pulsar contribution to the Galactic gamma-ray emission might be much higher than previous calculations have suggested. The result can be inverted to place limits upon the Galactic distribution of radio pulsars and their birth properties. If pulsars are the predominant source of Galactic gamma-rays, then their mean initial field strengths and periods must be $\lesssim 10^{12}$ G and $\lesssim 20$ ms, respectively. Although the number of known pulsars detectable by the *Compton Gamma Ray Observatory* (*Compton*) is only expected to be $\lesssim 10$, there may be many more observable as point sources either undetectable as radio pulsars due to beaming effects, or simply below the detection threshold of previous radio pulsar surveys. Deep radio observations of all *Compton* point sources is therefore recommended. It is found that the millisecond pulsars may also contribute significantly to Galactic gamma-ray emission, although population estimates, and the validity of gamma-ray emission models at millisecond pulsar periods and field strengths require confirmation.

Subject headings: Galaxy: stellar content — gamma rays: observations — pulsars: general

1. INTRODUCTION

One of the great surprises of both pulsar and gamma-ray astronomy has been the unlikely union of the two fields. Yet over 20 years after the discovery that PSR 0531+21 emitted gamma rays at the pulsar period, only it and the Vela pulsar stand as confirmed gamma-ray emitters. Suggestions of several other sources near the limiting threshold of sensitivity of observation, lends optimism to the expectation that, with the quantum leap in sensitivity that has become available with the launch of *Compton*, many more gamma-ray pulsars will be detected. Coordination has been established with radio astronometers in both the northern and southern hemispheres to provide contemporary period and period derivative determinations of candidate pulsars, necessary for the analysis of the gamma-ray data with their relatively limited statistics.

A second aspect of gamma-ray pulsars is the speculation that several of the unidentified gamma-ray sources (Hermsen et al. 1977) may be pulsars. These pulsars may not have been detected in radio observations because of beaming effects, or the reduced sensitivity to short-period pulsars of radio pulsar surveys (Dewey et al. 1984). Short-period pulsars are believed to be the most likely gamma-ray emitters. Indeed, the short-period pulsars detected in surveys since the last gamma-ray satellite measurements (Clifton & Lyne 1986; Johnston et al. 1992) are prime candidates to be observed with *Compton* (Kniffen 1990; Mattox 1990; Thompson 1990; Taylor 1990).

The third aspect most relevant to this work is the contribution of gamma-ay emitting pulsars, most of them unidentified at either radio or gamma-ray frequencies because of either beaming or sensitivity effects, to the overall Galactic gamma-ray emission. This emission was the basis of the first unambiguous detection of extraterrestrial gamma-rays (Clark, Garmire, & Kraushar 1968). Predicted in advance of the first gamma-ray observations (Pollack & Fazio 1963; Stecker 1969) it is believed to be dominated by gamma rays produced in the interactions of Galactic cosmic-ray nucleons and electrons with the gas and dust. Information on this possibility is important to the study of the origin of cosmic rays. The limitation in these studies is the inability to separate diffuse gamma-ray emission from that of unresolved discrete sources owing to the limited angular resolution inherent in current gamma-ray observations. The observations to be obtained by *Compton* will probably still not resolve the question.

In an attempt to put constraints on the discrete source contribution to the Galactic diffuse gamma-ray emission, this work provides an analysis of the contributions from the most likely input from unresolved discrete sources—that due to pulsars. Although previous work has addressed this problem, Higdon & Lingenfelter (1976), Strong, Wolfendale, & Dahanayake (1977), and in particular Harding (1981b), more recent observational and theoretical information, and a different approach to the pulsar distribution question, allows us to make an estimate of the pulsar contribution to the Galactic gamma-ray emission which is free from many of the simplifying assumptions used in previous studies. The method employed here is to develop a Monte Carlo simulation of the radio pulsar population. The pulsars are generated with a set of initial physical parameters and allowed to evolve in the model galaxy.

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A snapshot is then taken of the pulsar population and their individual gamma-ray luminosities, and hence fluxes, derived from gamma-ray models. By varying the birth parameters of radio pulsars over acceptable limits, this allows us to explore their potential contribution to the Galactic gamma-ray emission. This approach gives a much better estimate of the true uncertainty in the pulsars' contribution to the Galactic gamma-ray emission. Indeed, using the polar cap model of Harding (1981a), and the standard model of pulsar evolution, Lyne, Manchester, & Taylor, (1985, hereafter LMT), our calculations suggest that radio pulsars could be the dominant source of Galactic gamma-ray emission.

The plan of this paper is as follows: in § 2 we determine the critical parameters which affect the integrated gamma-ray flux over the lifetime of a radio pulsar. A description of the method used to derive the Galactic gamma-ray emission is given in § 3, and the results presented in § 4. Finally, in § 5, we discuss our results and present our conclusions.

2. GAMMA-RAY PRODUCTION FROM PULSARS

The pulsars' contribution to the total gamma-ray flux is determined by their Galactic distribution, and individual gamma-ray luminosities. Over the lifetime of a radio pulsar, some fraction of the initial rotational kinetic energy will be liberated in the form of gamma rays. In this section it is our aim to determine what pulsars will be the most prolific gamma-ray emitters. In all models of gamma-ray emission from radio pulsars, the gamma-ray luminosity depends upon some function of the magnetic field strength and spin period, the evolution of which is determined by the initial period and magnetic field strength, and the field decay time scale. Therefore the integrated gamma-ray luminosity throughout the life of an individual pulsar is determined by its birth properties, as is that of the population as a whole.

Only a minute fraction of a radio pulsar's spin-down luminosity is converted to observable radio emission. For most pulsars this fraction is less than 10^{-6}. However, the fraction of energy liberated in gamma rays is much higher, and depending upon asumptions made about beaming, for the Crab and Vela pulsars is of the order 0.1%–1%. In other radio pulsars the efficiency may be even higher, but their energy output is insufficient to place meaningful limits using the *SAS 2* and *COS B* data. With only two pulsars detected as gamma-ray point sources, constraints on gamma-ray emission models are poor. At short periods, most models predict the same order of magnitude for the gamma-ray luminosity L_γ, as the polar cap model of Harding (1981a):

$$L_\gamma(>100\ \text{MeV}) = 1.2 \times 10^{35} B_{12}^{0.95} P^{-1.7}\ \text{photons s}^{-1}\ , \quad (1)$$

where B_{12} is the magnetic field strength in units of 10^{12} *G* and *P* is the spin period of the pulsar in seconds. This law was derived from the observed flux of the Crab pulsar, and at 100 MeV is consistent with the flux of the Vela pulsar, and the upper limits obtained for almost all of the remaining pulsars observed by *SAS 2* (Harding 1981a). When one considers that the distances to individual pulsars are uncertain by a factor of ~ 2, the model is adequate.

The outer gap model of Cheng, Ho, & Ruderman (1986a, b), has pulsars with Vela-like periods and magnetic fields radiating ~ 1% of their spin-down luminosity in gamma-rays. For those with the parameter $\eta = B^{-2}P^5 < 10^{3/2}$ that of Vela, the fraction of energy liberated in gamma rays is proportional to η, and rises to unity for $\eta \sim 100$ times that of Vela. In their model, the gamma-ray luminosity of a Vela-like pulsar is therefore

$$L_\gamma(>100\ \text{MeV}) = 0.01\, \frac{4\pi^2 I \dot{P}}{P^3} \Big/ (100\ \text{MeV})\ \text{photons s}^{-1}\ , \quad (2)$$

where $\dot{P}$ is the period derivative and I the moment of inertia of the pulsar. In the remainder of this paper we will use the polar cap model to illustrate some of the features of the problem. We do not feel that the situation with regard to the gamma-ray emission from pulsars is sufficiently well defined to make one model clearly applicable to the exclusion of others, and for the same reason a dual development is not warranted.

Harding showed that if equation (1) holds, the efficiency with which pulsars produce gamma radiation (n_γ) can be expressed in terms of the period and magnetic field strength in units of 10^{12} G and other variables expressed in cgs units as follows:

$$n_\gamma = \frac{2.0 \times 10^{31}}{4\pi^2 I} B_{12}^{0.95} \frac{P^{1.3}}{\dot{P}}\ . \quad (3)$$

Using the standard equation relating the period derivative to the magnetic field strength (Manchester & Taylor 1977),

$$B^2 = \left(\frac{3Ic^3}{8\pi R^6}\right) P\dot{P}\ , \quad (4)$$

and assuming a moment of inertia of 10^{45} g cm^2 and a neutron star radius R, of 10^6 cm, the efficiency can be written as a function of the magnetic field strength and period P, in seconds as follows:

$$n_\gamma = \frac{20}{4\pi^2} B_{12}^{-1.05} P^{2.3} \quad (5)$$

and hence find the period P_n, at which a pulsar reaches a level of efficiency n_γ:

$$P_n = \left(\frac{4\pi^2 n_\gamma}{20} B_{12}^{1.05}\right)^{1/2.3}\ \text{s}\ . \quad (6)$$

A simpler consequence of equation (5) is the increase in efficiency as the pulsar ages. Clearly the gamma-ray efficiency cannot exceed unity, and hence equation (5) must break down at some period.

The characteristic age of a pulsar is defined to be $\tau = P/(2\dot{P})$. It is close to the true age if the magnetic field strength is constant, and the initial period is small compared to the current period. The characteristic age τ_n at which a pulsar reaches the level of efficiency of gamma-ray production n_γ, is therefore:

$$\tau_n = P_n/(2\dot{P}_n) = 12.8 n_\gamma^{0.87} B_{12}^{-1.087}\ \text{Myr}\ . \quad (7)$$

Hence, most radio pulsars will not approach 100% gamma-ray efficiency until they have characteristic ages 10 Myr or greater. The integrated gamma-ray luminosity $G(n_\gamma, P_0, B)$ over the lifetime of a pulsar, if it ceases gamma-ray production when the efficiency reaches n_γ and has an initial period P_0 and a magnetic field strength B_{12}, can be obtained by integrating equation (1) from the characteristic age at birth until τ_n. If we write the period as a function of time t, as follows:

$$P^2 = P_0^2 + \frac{16\pi^2 R^6}{3Ic^3} B^2 t \quad (8)$$

then

$$G(n_\gamma, P_0, B) = \int_{P_0/(2\dot{P}_0)} 1.2 \times 10^{35} B_{12}^{0.95} P^{-1.7}\, dt \propto \frac{1}{B_{12}^{1.05}} \times \left\{\left[P_0^2 + 0.97B_{12}^2\left(\frac{-P_0^2}{2B_{12}^2} + \frac{0.90n_\gamma^{0.87}}{B_{12}^{1.09}}\right)\right]^{0.15} - P_0^{0.3}\right\}. \quad (9)$$

The above analysis assumes, following Harding (1981a), that the beaming factor f, that is, the fraction of the solid angle into which the gamma rays are directed, is only 1 sr [i.e., $f = 1/(4\pi)$]. This is almost certainly not the case, as in both the Crab and Vela pulsars the gamma-ray beam is wider than the radio beam. In most models of radio pulsar emission such as Lyne & Manchester (1988), the beaming fraction of short-period pulsars is close to unity. Therefore the beaming fraction of gamma-ray pulsars is almost certainly closer to unity than $1/(4\pi)$. For the remainder of this paper the assumed gamma-ray beaming fraction will be 1.0. This makes radio pulsars more efficient gamma-ray emitters by a factor of 4π than equation (5) suggests and radically increases the estimated pulsar contribution to the Galactic gamma-ray emission. It also changes the constant preceding n_γ in equation (9) from 0.90 to 0.10.

The integrated gamma-ray luminosity of a pulsar $G(n_\gamma, P_0, B)$ is plotted in Figure 1 against each of the three parameters n_γ, P_0, and B. The dependence of $G(n_\gamma, P_0, B)$ upon the efficiency at which gamma-ray production ceases, n_γ is now explored. With only two pulsars detected at gamma-ray luminosities, n_γ is poorly determined. In Figure 1, $G(n_\gamma, P_0, B)$ is plotted as a function of n_γ for a pulsar born with a period of 10 ms and a magnetic field strength of 10^{12} G. As can be seen

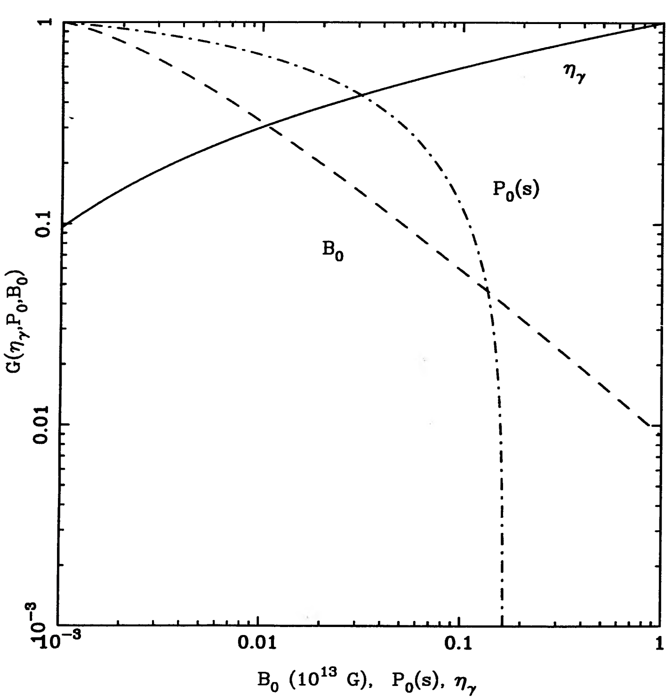

FIG. 1.—Integrated gamma-ray luminosity of a radio pulsar over its lifetime [$G(\eta_\gamma, P_0, B)$], as a function of the three variables η_γ, P_0, or B_0 shown on an arbitrary scale. The initial period (P_0), efficiency at which gamma-ray production ceases (η_γ), and initial magnetic field strength (B_0) are set to 0.01 s, 0.1 and 10^{12} G, respectively, unless they are the variable being plotted.

from the figure, the number of gamma-rays produced by the pulsar has a fairly weak dependence upon the efficiency at which the gamma-ray production ceases. The number of gamma rays produced if gamma-ray production continues until $n_\gamma = 1.0$ is only ~ 4 times that if it ceases when $n_\gamma = 0.01$. Unfortunately, the value of n_γ is unknown, and so our estimate of the gamma-ray emission from pulsars is going to be uncertain by at least a factor of 2 due to our ignorance of n_γ alone.

$G(n_\gamma, P_0, B)$ is also plotted as a function of initial period for a pulsar with a 10^{12} G field and a cutoff in its gamma-ray production when $n_\gamma = 0.1$. Over recent years there has been much discussion in the literature about the initial spin period of radio pulsars (e.g., Narayan 1987; Stollman 1987; LMT), but we will defer discussion of this important point until § 5. At short ($\lesssim 100$ ms) periods, $G(n_\gamma, P_0, B)$ is only weakly affected by the initial period. A 10^{12} G pulsar with a 1 ms initial period provides only ~ 6 times the number of gamma rays that a pulsar with a 100 ms initial period does, even though its energy content at birth is *four orders of magnitude higher*. At first this may seem counterintuitive, especially when considering equation (1), which has a strong inverse power-law dependence on period. However, this is a consequence of the reduced efficiency at short periods (eq. [5]), and the much greater fraction of its life that a pulsar spends at long periods. If pulsars are born with extremely long periods of more than ~ 0.5 s, then they have already reached the high-efficiency regime where gamma-ray production may have ceased. If this is the case, they will not provide a very significant contribution to the Galactic gamma-ray emission. Clearly the initial period distribution of radio pulsars is crucial to their contribution to the Galactic gamma-ray emission.

Finally, $G(n_\gamma, P_0, B)$ is plotted as a function of the initial magnetic field strength for a pulsar with an initial period of 10 ms and $n_\gamma = 0.1$. If the polar cap model holds over a reasonable magnetic field range, then short-period, weak-field pulsars are the most prolific gamma-ray pulsars. Again this may seem rather counterintuitive. However, when one considers that the efficiency is inversely proportional to the magnetic field strength (eq. [3]) and that a 10^{12} G pulsar has the same rotational kinetic energy as a 10^3 G pulsar with the same period, the issue is not which pulsar has the greater gamma-ray luminosity, but which is the more efficient converter of spin-down energy to gamma-ray emission.

In summary, the integrated gamma-ray emission from a radio pulsar throughout its lifetime is critically dependent upon its initial birth properties. Provided that the peak of the initial period distribution is less than ~ 100 ms, our ignorance of its precise value will affect, but not by many orders of magnitude, our computation of the pulsars' contribution to the galactic gamma-ray emission. The initial magnetic field strength is also an important factor, although one upon which there is generally more agreement among authors. The value of efficiency at which pulsar gamma-ray emission ceases is uncertain, but it will not affect our computations by a large factor. The most important conclusion is that short-period, weak-field pulsars, such as the 37 ms pulsar in the supernova remnant CTB80 (Kulkarni et al. 1988), produce many more gamma rays throughout their lifetime than their high-field counterparts such as the Crab and Vela pulsars. This has important consequences for the Galactic gamma-ray emission from radio pulsars, especially if the radio luminosity is correlated in some way with magnetic field strength. If this is the case, then low-field pulsars will be relatively weak radio sources, and underrepresented in the observed sample of radio pulsars. They will however, be the most prolific gamma-ray sources.

3. THE MODEL

In order to place limits on the Galactic gamma-ray emission, a model of the Galactic pulsar population is required which is consistent with the radio observations. There have been numerous recent studies of the pulsar population, e.g., LMT, Narayan (1987), Stollman (1987), Emmering & Chevalier (1989, hereafter EC), and Narayan & Ostriker (1990). Consensus has yet to be reached on several issues, among them the initial spin period, magnetic field decay time scale, and luminosity law of radio pulsars. However, all of these studies require that the birthrate of pulsars be much lower than the estimates of a decade ago, mainly due to the improved distance model of LMT, which is common to most of the studies. Therefore, the Galactic population of pulsars is much lower than previously used in studies of the pulsar contribution to the Galactic gamma-ray emission, such as Harding (1981b), and one might expect the Galactic gamma-ray emission to be correspondingly lower. Scaling Harding's results by the generally accepted reduction in the pulsar population of ~ 10 predicts that the pulsars' contribution to the total Galactic gamma-ray emission will only be of order a few percent (although if one uses a more generous beaming factor than was assumed in Harding (1981b), the implied fraction is more like 20%).

We have chosen to concentrate on the models of EC and LMT. These models both provide good fits to the observed distribution of radio pulsars with a single population, but possess different initial period and magnetic field distributions, which were identified in § 2 as the most crucial parameters affecting gamma-ray emission.

The description of the birth, life, and death of radio pulsars presented by LMT is often referred to as the standard model of radio pulsar evolution (e.g., Dewey 1989). The majority of radio pulsar studies base at least some of their assumptions on this paper. LMT took the results of four major pulsar surveys and derived the underlying distributions of various quantities using iterative and theoretical techniques, among them, the spatial, period, and magnetic field distribution of radio pulsars in the galaxy.

EC adopted a different approach, in which they generated a large number of pulsars in a model galaxy by using a reasonable distribution function for the pulsars at birth and letting them evolve assuming magnetic dipole breaking and a field decay time scale of 5 Myr. Each pulsar was assigned a radio flux, based upon its period, magnetic field strength and distance. After taking into account several selection effects, including interstellar scattering, and sky background temperature, its flux was compared with the limit of surveys which observed the location of the pulsar. If it was greater than the flux limit, it became "detected" and was added to an inventory of pulsars which were later compared with the actual pulsars. The initial period, magnetic field, and several parameters affecting the luminosity of the pulsars were adjusted until a good fit to the radio observations was obtained.

A method very similar to that used by EC is employed here to determine the pulsar's contribution to the Galactic distribution of gamma rays. A large number of pulsars are generated using the distribution functions of the best-fitting model of EC. A gamma-ray flux is then assigned to each pulsar using equation (1) and the pulsar distance. In this way, the total gamma-ray flux from pulsars in the galaxy can be estimated, and some measure of the number of point sources associated with radio pulsars. By using a Monte Carlo simulation, one also obtains some idea of the distribution expected from a random distribution of point soures. For comparison, the radio pulsar luminosity law assumed by LMT is also considered.

A more detailed description of the model is now presented. In all, 5×10^5 pulsars were produced, with a random age between 0 and 25 Myr to model the assumed birthrate of one pulsar every 50 yr (see LMT; Narayan 1987). The initial distribution of the pulsars in galactocentric radius was taken to be a Gaussian, with a standard deviation of 5.66 kpc, following Narayan (1987). An exponential, with a scale height of 100 pc was used for the initial z-height, and the location of the pulsars were calculated from a simple linear relation connecting the initial position, velocity, and age. The initial velocity of the pulsars was assumed to be a Gaussian with a standard deviation of 70 km s^{-1} in each of three perpendicular directions. A Gaussian distribution of initial magnetic field strength in the log was assumed, and an exponential field decay time scale. The initial period distribution of pulsars was also assumed to be Gaussian in log P_0(s). The period was calculated assuming that the magnetic field decayed exponentially with an e-folding time of τ from

$$P^2 = P_0^2 + B_0^2 \tau \left(\frac{8\pi^2 R^6}{3Ic^3}\right)(1 - e^{-2t/\tau}) , \qquad (10)$$

where t is the age of the pulsar and the subscript 0 refers to the pulsar's initial parameters. The pulsar's radio flux was chosen from a Gaussian distribution in the log with a mean of

$$\log L_m = \gamma + \alpha P + \beta \dot{P} \qquad (11)$$

and a standard deviation of 0.8 in the log in the standard units of mJy kpc^2. The same values of α, β, and γ as those used in the EC and LMT were adopted.

The radio beaming fraction of the pulsars was calculated using the equations given in EC for the Lyne & Manchester (1988) model. In this model, short-period pulsars have a much greater beaming fraction than long-period pulsars. The probability that a given radio pulsar was detected was equal to its beaming fraction.

The gamma-ray flux of all pulsars was recorded, along with those which met the detailed radio selection criteria outlined in EC, which was based upon the work of Narayan (1987). For our purposes we only considered the four major surveys where the bulk of pulsars was discovered. The total flux was integrated over $b = \pm 10°$ and plotted in comparison with the *SAS 2* data. A histogram of the fluxes of all pulsars was then formed to see how many of the pulsars are likely to be detectable as point sources by *Compton* and how many are already known as radio pulsars. The subset of the gamma rays from "detected" radio pulsars was also plotted. For a complete description of the details of the radio pulsar simulation see EC and references therein.

4. RESULTS

In Figure 2 the total gamma-ray flux, integrated over $|b| \leq 10°$, is plotted in comparison with the *SAS 2* data for the model of EC. The solid region represents the gamma-ray contribution from pulsars which satisfied the radio selection criteria. This model suggests that the pulsar's contribution to the Galactic gamma-ray emission is only a few percent, in broad

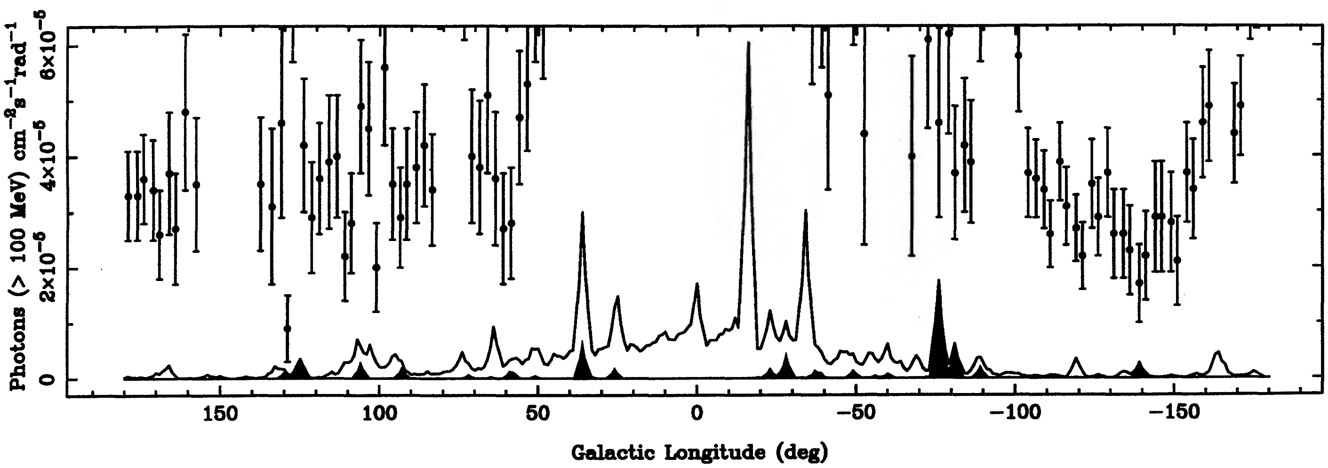

FIG. 2.—The contribution of radio pulsars to the Galactic gamma-ray flux using the polar cap model of Harding and the distribution of radio pulsars deduced by EC. The data is integrated over $|b| \leq 10°$ and plotted in comparison with the *SAS2* data. The solid region represents the contribution from radio pulsars which would have been detected in the radio by one of the four major pulsar surveys (see text).

agreement with the scaled results of Harding (1981b). The distribution is strongly peaked toward the center of the galaxy, suggesting that the bulk of the pulsar gamma-ray emission is not produced locally. However, in some respects, this model is unsatisfactory, as it does not predict any strong peaks in the Galactic gamma-ray emission such as those that are observed for the Crab and Vela pulsars. This is due to the large initial spin periods of radio pulsars used in the simulation [log $(P) = -0.39$].

The other model under consideration is that of LMT. In their model, radio pulsars are born with lower fields (log $B_0 = 11.88$ G) than EC (log $B_0 = 12.38$ G) and are assumed to be rotating infinitely quickly at birth. High-field pulsars born with such short periods quickly evolve to longer periods and hence such an assumption did not affect LMT's calculations. In our model we assumed that the mean period of pulsars at birth was 20 ms, near that of the Crab pulsar. The field decay time scale derived by LMT was 9.1 Myr. The results for this model are plotted in Figure 3 and suggest that the pulsars' contribution to the Galactic gamma-ray flux is of the same order as that observed by *SAS 2*. This is a result of the shorter initial rotation period of pulsars in the LMT model and their lower initial field strengths. Short-period, low-field pulsars were identified in § 2 as the most prolific gamma-ray emitters. Other processes, such as cosmic-ray interactions with the interstellar medium are known to contribute significantly to the Galactic gamma-ray emission (Stecker 1990). However, we suggest that there is considerable uncertainty in these estimates, and therefore that pulsars could easily contribute $\sim 50\%$ of the observed emission.

One surprising feature, is the relatively small fraction of the gamma-ray emission resulting from "observed" radio pulsars in both models. This is more pronounced in the LMT model, where the luminosity of a radio pulsar is independent of its period, a crucial factor in determining the gamma-ray luminosity. But even with the steep negative power law dependence of radio luminosity upon period in EC's model ($L_{\rm radio} \propto P^{-1.6}\dot{P}^{0.64}$), the fraction of the gamma rays eminating from observed pulsars was only $\sim 10\%$. Given that the integrated gamma-ray flux from the Crab and Vela pulsars is a few percent of the total observed between $\| b \| \leq 10°$, we conclude that the pulsar contribution to the Galactic gamma-ray flux is probably very significant.

The radial distribution of pulsars we used was a Gaussian fit to the pulsar radial density histogram of LMT by Narayan (1987). However, the pulsar population of the inner galaxy

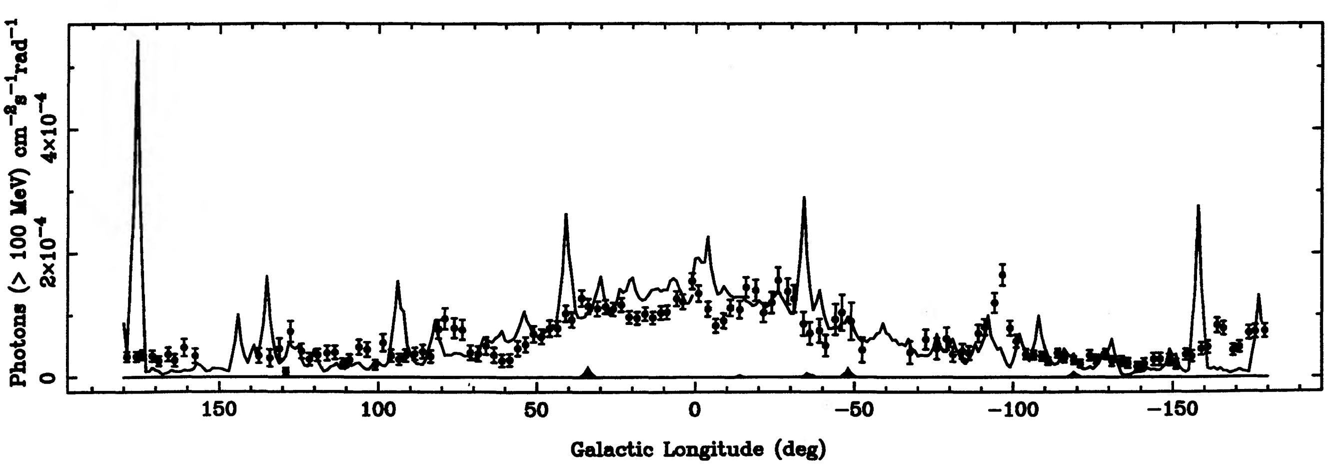

FIG. 3.—As for Fig. 2, but using the properties of radio pulsars as derived by LMT

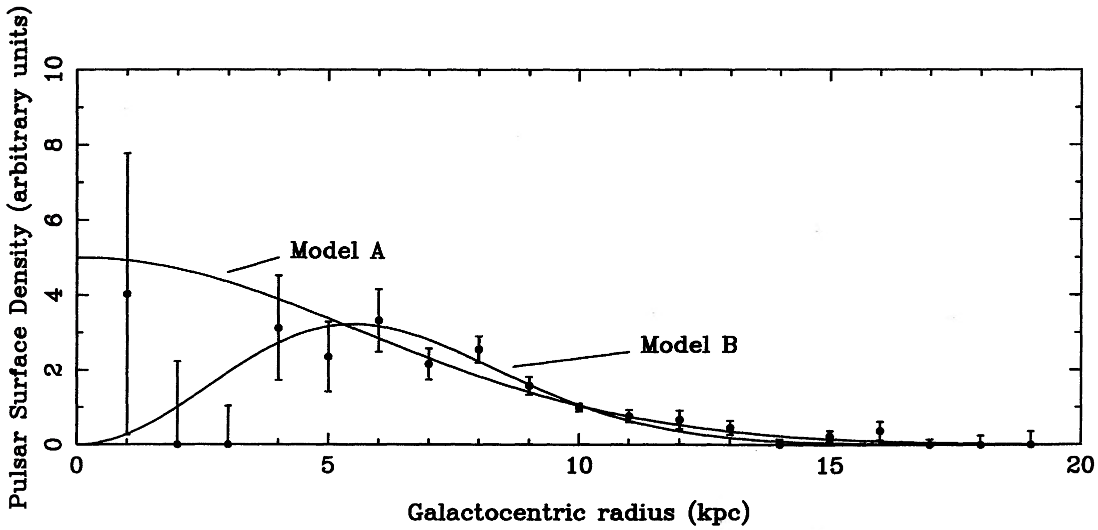

FIG. 4.—The derived surface distribution of radio pulsars by LMT, and two potential fits. The first (model A) is by Narayan (1987) in which he fitted a simple Gaussian to the data. Another plausible fit to the data (model B) is also given.

cannot be accurately probed by low-frequency surveys, such as those considered by LMT. Indeed the uncertainties on their derived radial distributions mean that the pulsar content of the inner galaxy is largely unknown. It is therefore entirely conceivable that the pulsar birthrate does not rise monotonically all the way to the Galactic center, but, like the distribution of supernova remnants (Leahy & Wu 1989), and CO (Robinson et al. 1984), peaks between 4 and 6 kpc. Stecker (1977) demonstrated that various other quantities also peak at this distance. If we adopt a radial distribution function which falls off after 4 kpc such as that presented in Figure 4, it remains consistent with the derived distribution of radio pulsars by LMT. We now take this radial distribution function, described in Figure 4 as model B, and the pulsar model of LMT and produce another Monte Carlo simulation. In this simulation, the birthrate of pulsars was decreased by 30% to keep the pulsar birthrate in the vicinity of the Sun constant. The results of this model are presented in Figure 5 and also provide a good fit to the *SAS 2* data. From this we conclude that radio pulsars could easily be the dominant source of Galactic gamma rays, although other mechanisms undoubtedly contribute.

The outer gap model of pulsar gamma-ray emission (Cheng, Ho, & Ruderman 1986a, b) was found to give very similar distributions to that of Harding's polar cap model, with a slight dc offset of no more than a factor of ~ 2, depending upon the exact initial conditions of the simulation. It also exhibited the same tendency for the emission to rise as the initial period and magnetic fields of radio pulsars decreased. That the two models should give very similar results is not that surprising, as they are consistent with the observed fluxes of the Crab and Vela pulsars, and both exhibit an increase of efficiency of gamma-ray production with weaker initial magnetic field strengths.

Figure 6 shows a histogram of the gamma-ray fluxes of model pulsars greater than 10^{-6} photons cm^{-2} s^{-1} as predicted by the LMT model and the model B pulsar radial distribution function. The solid region represents those pulsars which satisfy the radio selection criteria. The *COS B* satellite identified 13 point sources with gamma-ray luminosities greater than 10^{-6} photons cm^{-2} s^{-1} (Hermsen et al. 1977). The model of LMT predicts that there should be ~ 30 pulsars with such fluxes, which appears a little high, although these lie

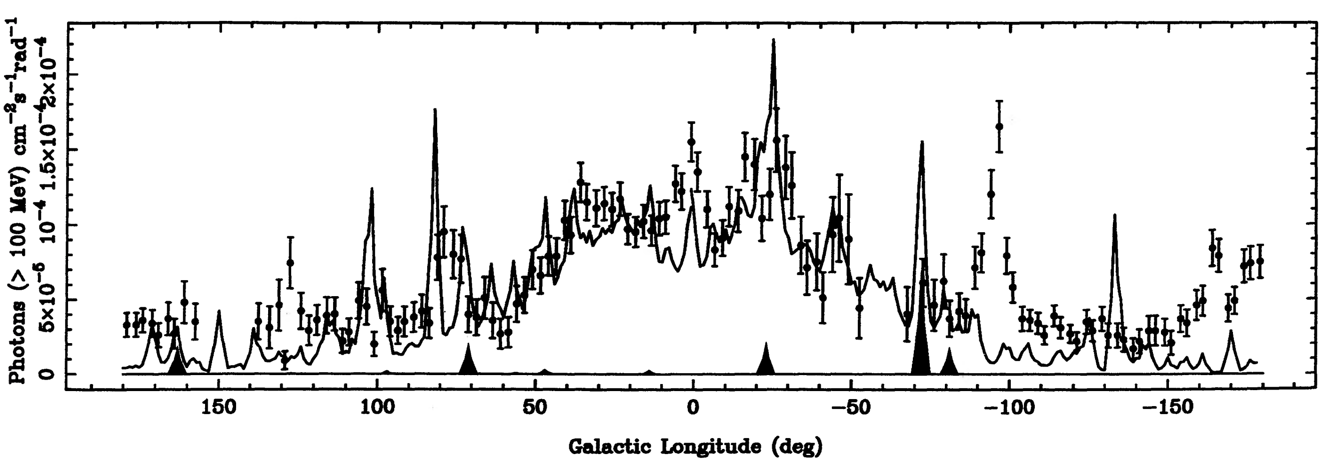

FIG. 5.—As for Fig. 2 but using the properties of radio pulsars as derived by LMT, and the radial distribution of radio pulsars described in Fig. 4 as model B

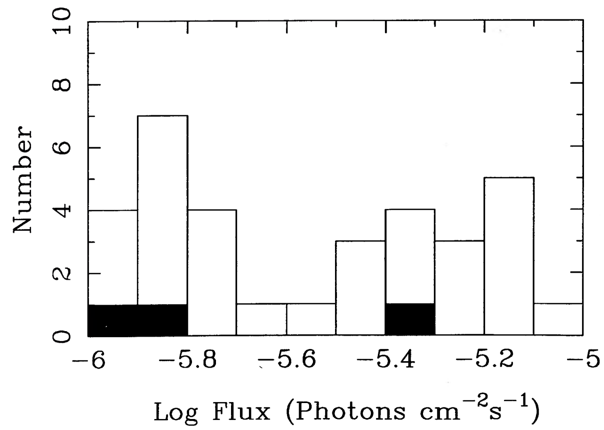

FIG. 6.—Distribution of the gamma-ray fluxes of pulsars, as predicted by the polar cap model of Harding, and the description of pulsars by LMT with the "model B" radial distribution function shown in Fig. 4. The shaded region represents those pulsars which would have been detected by one of the four major pulsar surveys.

almost exclusively within a few degrees of the Galactic plane and hence would have been difficult to resolve with the *COS B* satellite. All point sources with a gamma-ray flux greater than 6.3×10^{-7} photons cm^{-2} s^{-1} should be detectable by EGRET anywhere in the galaxy and hence the prediction of this model will be able to be tested in the near future. The interesting result here is that even among the brightest gamma-ray pulsars there is a large number which do not satisfy the radio selection criteria. It is possible therefore, that EGRET will detect some point sources that are pulsars, but that have not yet been detected in the radio. One might argue that the gamma-ray source Geminga is such a pulsar, either too weak, or too scattered to be detected as a radio pulsar, or simply beaming in the wrong direction. This highlights the importance of radio observations of gamma-ray point sources detected with *Compton*.

Over the last decade a new class of pulsars, referred to as the millisecond pulsars, have come into prominence (Backer et al. 1982; Taylor & Stinebring 1986). They are all characterized by very short periods, and weak magnetic fields $\sim 10^9$ G. It is perhaps unlikely that equation (1) holds over four orders of magnitude in B, but if it should, then the millisecond pulsars would be strong gamma-ray emitters. Early estimates of the population of millisecond pulsars in the galaxy similar to the 5.3 ms pulsar PSR 1855+09 suggested that the Galactic population could be as high as 10^5 (Kulkarni & Narayan 1988). Although more recent estimates of this pulsars' distance and further pulsar surveys have lead to a downward revision of the number of millisecond pulsars with such luminosities, the total population of millisecond pulsars could still be very large (Johnston & Bailes 1991). The gamma-ray efficiency predicted by equation (1) is less than unity and hence still plausible. However, we found that when we placed 10^5 1855+09-like pulsars in our model galaxy, the predicted gamma-ray flux was twice that of the *SAS2* limits. All that we can really conclude from this is that there is sufficient energy in the millisecond pulsars to contribute significantly to the Galactic gamma-ray flux. Bhattacharya & Srinivasan (1991) have independently reached similar conclusions. *Compton* observations of the millisecond pulsars should provide limits on their gamma-ray emission, which will enable a more accurate estimate of their contribution to the Galactic gamma-ray flux.

5. DISCUSSION AND CONCLUSIONS

In this study we have tried to show that the uncertainties in the birth properties of radio pulsars mean that the pulsars' contribution to the Galactic gamma-ray emission could approach 100% or be as low as a few percent. The most crucial factor is the initial spin period of radio pulsars. At present this is the topic of much debate among the pulsar community, see for example (Vivekanand & Narayan 1981; Narayan 1987; Stollman 1987; Chevalier & Emmering 1986; EC; LMT). Whether or not all radio pulsars can be born with periods of a few tens of milliseconds depends upon their radio luminosities. There are only a handful of strong-field pulsars with periods of less than 100 ms, and as such the luminosities of such "normal" pulsars are only poorly determined. The problem is that radio pulsars are born with short initial periods and high magnetic field strengths and spend only a relatively small fraction of their lives near their birth periods. By fitting to the luminosities of observed radio pulsars, Prószyński & Przybycień (1984) determined a power-law luminosity function for radio pulsars the form of which is given in equation (11). The power-law index on period, was close to -1, and as such, suggests that short-period pulsars are very bright. If this is so, then there is a marked deficit of them in the galaxy (Narayan 1987), and the mean initial period of pulsars greater than ~ 100 ms rather than of order 10 ms. However, if the luminosity function of pulsars flattens at short periods, then it is entirely conceivable that all pulsars can be born with short periods.

Gamma-ray observations of pulsars may be able to contribute to this problem. If the gamma-ray luminosity law of pulsars can be established, then limits on the initial periods of radio pulsars may be able to be placed. For instance, we can already say that if Harding's gamma-ray luminosity law holds, then the mean initial period of radio pulsars must be greater than ~ 20 ms if the mean initial field strength of radio pulsars is less than $\sim 10^{12}$ G. Caution here must be expressed as to the realization of this aim, as the radio pulsar luminosity law is still the subject of considerable debate, even though there are now over 500 radio pulsars with measured fluxes. Whether or not the gamma-ray luminosity law can be established with only a handful of gamma-ray pulsars seems questionable, although the fraction of the spin-down luminosity liberated in the form of gamma rays is considerably greater than that in radio emission. There is some hope therefore, that the deviation around any gamma-ray luminosity law may be less than that for radio pulsars.

Our approach to the problem has been quite different than the previous study of Harding (1981b). Harding took the observed period distribution of radio pulsars and calculated the mean gamma-ray luminosity of pulsars using this distribution of periods and a magnetic field strength of 10^{12} G. The main problem with this approach is that the observed distribution of pulsars does not accurately reflect the true distribution of pulsars (see, for example, Narayan & Ostriker 1990). This is because the observed pulsars are selected on the basis of their radio flux, and as a result we tend to observe only those pulsars in the high-luminosity tail of the luminosity distribution. If the radio luminosity of pulsars is some function of magnetic field strength and period (as is quite likely) then this approach could lead to very large systematic errors, the magnitude of which can be disguised. Harding did attempt to correct for the biases involved in radio pulsar surveys, but the method she adopted gives a poor estimate of the true errors involved. Furthermore, the beaming fraction of gamma-ray pulsars assumed by Harding was essentially 1 sr, much smaller than the width of the gamma-ray beam in the Crab and Vela pulsars would suggest.

In conclusion, we have shown that the radio pulsar contribution to Galactic gamma-ray emission could be very significant. The fact that known pulsars make up a few percent of the total gamma-ray observed by *SAS 2*, and that our simulations demonstrate that currently known radio pulsars are only ever expected to emit a small fraction of the gamma rays that are received at Earth, indicates that the fraction of the observed gamma-ray emission that originates from radio pulsars could well be over 50%. We look forward to *Compton* observations of radio pulsars to help place tighter limits upon the pulsar gamma-ray emission law, and their contribution to the Galactic gamma-ray emission, both of which at present are quite uncertain.

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