THE PULSAR CONTRIBUTION TO THE DIFFUSE GALACTIC GAMMA-RAY EMISSION

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ABSTRACT

There is active interest in the extent to which unresolved γ-ray pulsars contribute to the Galactic diffuse emission, and in whether unresolved γ-ray pulsars could be responsible for the excess of diffuse Galactic emission above 1 GeV that has been observed by EGRET. The diffuse γ-ray intensity due to unresolved pulsars is directly linked to the number of objects that should be observed in the EGRET data. We can therefore use our knowledge of the unidentified EGRET sources to constrain model parameters like the pulsar birthrate and their beaming angle. This analysis is based only on the properties of the six pulsars that have been identified in the EGRET data and is independent of choice of a pulsar emission model.

We find that pulsars contribute very little to the diffuse emission at lower energies, whereas above 1 GeV they can account for 18% of the observed intensity in selected regions for a reasonable number of directly observable γ-ray pulsars (≈14). The latitude distribution of the diffuse emission caused by unresolved pulsars is narrower than that of the observed diffuse emission. While the excess above 1 GeV γ-ray energy is observed up to at least 6°–8° off the plane, the pulsar contribution would be small there. Thus, pulsars do significantly contribute to the diffuse Galactic γ-ray emission above 1 GeV, but they cannot be made responsible for all the discrepancies between observed intensity and model predictions in this energy range.

Subject headings: diffuse radiation — gamma rays: observations — pulsars: general

1. INTRODUCTION

A recent analysis of the diffuse Galactic γ-ray emission in the energy range from 30 MeV to 30 GeV (Hunter et al. 1997) indicated that the spatial structure and total intensity of the emission observed by EGRET can be well understood as the result of interactions between cosmic rays and the interstellar medium in addition to an isotropic extra-galactic background. The main emission mechanisms are π0 production and decay in inelastic collisions between cosmic-ray nucleons and thermal gas; bremsstrahlung of relativistic electrons in thermal gas; and inverse Compton scattering of ambient millimeter-wavelength, infrared, and optical photons by highly relativistic electrons. The limitation of these studies is the inability to separate truly diffuse γ-ray emission from that of unresolved discrete sources.

At energies above 1 GeV, the models predict only roughly 60% of the observed intensity. This effect is most significant in the Galactic plane but is not restricted to it. This discrepancy might be explained in two different ways. First, it may be that the Galactic cosmic-ray protons and/or electrons have a harder spectrum beyond 10 GeV than those observed in the solar vicinity. Second, there may be a number of unresolved point sources in the Galactic plane with appropriate spectra. The γ-ray spectrum of these sources would have to be harder than that of the Galactic diffuse emission below a few GeV and may roll over beyond a few GeV. The only known objects with such spectra are pulsars, especially Geminga-type pulsars.

The goal of this paper is twofold. We want to provide constraints on the general contribution of the most likely input from discrete sources—pulsars—to the diffuse Galactic γ-ray emission. We also want to find out whether unresolved pulsars can account for the observed excess at high γ-ray energies. Previous work has addressed the former problem (Bailes & Kniffen 1992; Yadigaroglu & Romani 1995; Sturmer & Dermer 1996) primarily on the basis of pulsar models, for which the input parameters are not always well known. Conversely, γ-ray data have been used to limit the emission from millisecond pulsars (Bhatia et al. 1997). Here we use a different strategy: instead of using models, we will base our analysis solely on the properties of the six pulsars observed by EGRET. Clearly, the main limitation of this approach is that the six objects are not necessarily representative of the whole population. The great advantage of our method, however, is that all spectral information can be taken into account. This will allow us to address whether pulsars can account for the observed excess at high γ-ray energies.

In general, older pulsars are less luminous and often exhibit spectral cutoffs at high γ-ray energies. Since the luminosity and spectral evolution provide the best parameters from which to estimate the contribution of pulsars to the diffuse γ-ray emission, we will derive the luminosity of an “ideal” pulsar as a function of its age and its observed energy directly from the EGRET data. Since this method will use the observed intensity of the pulsars at different energies, it will automatically account for the hard spectrum
and for possible cutoffs without using power-law fit results on individual data. We will simultaneously calculate the diffuse intensity due to pulsars and the numbers of directly identifiable objects. The latter provide a constraint on otherwise weakly determined parameters like the birthrate and the beaming angle of pulsars, since the diffuse γ-ray intensity due to unresolved pulsars scales almost linearly with the number of resolved pulsars.

2. THE MODEL

2.1. The Intensity-Age Distribution of Pulsars

EGRET has identified six pulsars by their light curves. The differential γ-ray photon spectra of these sources have been measured by Fierro (1995) from pulsed analysis. The restriction to pulsed analysis neglects part of the possible unpulsed emission but allows us to obtain better spectra of the weak pulsars. The EGRET sensitivity is rather poor at unpulsed emission but allows us to obtain better spectra of the weak pulsars. The Fierro (1995) sensitivity is rather poor at the lowest energies, so we will concentrate on nine energy bands spanning 50 MeV to 10 GeV for which we have the observed photon flux \( S(E_i) \) of pulsar \( i \) in energy band \( E_i \). Analogous to the calculation for absolute brightnesses in optical astronomy, we multiply these fluxes by the square of the pulsar’s distance \( D_i \) to find fluxes we would observe from these sources if they were at unit distance. So in each of the nine energy bins we get the “absolute” γ-ray intensity and the age of the six pulsars from our data. The basis for our modeling is the assumption that pulsars exhibit a correlation between absolute intensity and age. The slope and normalization of this correlation may be different at different γ-ray energies. This correlation, which describes something of an ideal pulsar, will then be used to calculate the diffuse emission from unresolved pulsars together with the number of directly observable objects.

There is no physical necessity why such a correlation should exist. The best evidence comes from the data themselves: the \( \chi^2 \) sums we obtain indicate that a correlation is an appropriate description of the data. In reality, one should expect such a correlation to be noisy, i.e., that there is a probability distribution with a certain dispersion around the mean of the correlation, but in our case the limited number of degrees of freedom compels us to use the most simple correlation model, a power law:

\[
S_m(t, E_i) = 10^a \left( \frac{t}{10^4 \text{ yr}} \right)^{-b_k} \text{kpc}^2 \text{ cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}.
\]

This relation can be fitted to the data on the basis of weighted least squares for all energy bins. This is equivalent to assuming Gaussian errors in the measured luminosities. The kpc² part of the units comes from our choice for the distance normalization. The distance \( D_i \) and its uncertainty can be generally derived on the basis of the pulsar dispersion and rotation measure (Taylor, Manchester, & Lyne 1993) and only for extremely nearby objects like Geminga by parallax measurements (Caraveo et al. 1996). The age of pulsars can be estimated from the ratio of period and period derivative. The uncertainty of this measure of age is large, especially since pulsars often do not slow down solely by dipole radiation. We will use a factor of 2 for the age uncertainty \( \delta t_i \), except for the Crab pulsar, whose true age is taken with a nominal uncertainty of 10%.

Three sources of uncertainty have to be considered in the fit: uncertainties in intensity, in distance, and in age. While the intensity error can be assumed to follow a Gaussian probability distribution, both the errors in age and in distance appear in powers, so that their effective probability distributions are definitely not Gaussian. Furthermore, the way in which ages and distances are measured leads us to believe that a Gaussian probability function is not a fair description of the actual error distributions. The errors in these parameters are sometimes of the same order as the estimates, which clearly implies that their distributions are asymmetric. We can account for these effects and still use the \( \chi^2 \)-method if we assume that the error distributions for the logarithms of age and distance are Gaussian.

To account for the different uncertainty distributions in the three parameters, we have separated the \( \chi^2 \)-summation into three components. The total \( \chi^2 \) (eq. [2]) is derived by combining the contributions of the intensity (eq. [3]), the distance (eq. [4]), and the age (eq. [5]):

\[
\chi^2_i = \frac{1}{\chi_{i,1}^{-2} + \chi_{i,2}^{-2} + \chi_{i,3}^{-2}}, \tag{2}
\]

where

\[
\chi_{i,1} = \frac{S_m(t, E_i) - S(E_i)}{D_i^2 \delta S(E_i)}, \tag{3}
\]

\[
\chi_{i,2} = \frac{\log S_m(t, E_i) - \log S(E_i) - 2 \log D_i}{2 \delta \log D_i}, \tag{4}
\]

\[
\chi_{i,3} = \frac{\log S_m(t, E_i) - \log S(E_i) - 2 \log D_i}{b_k \delta \log t}. \tag{5}
\]

An example of how a power-law relation fits the pulsar data after distance normalization is shown in Figure 1, where all sources of uncertainty are included as vertical and horizontal error bars. The results of the fitting procedure are shown in Table 1, where the 1σ uncertainty of the fit parameters is estimated from the usual \( \chi^2_{\text{min}} + 1 \) condition.

2.2. The Fraction of Unresolved Pulsars

For each source, we can define a critical distance up to which the source can be detected directly and beyond which...
it would contribute to the diffuse emission. The true γ-ray flux threshold of the EGRET data has a rather awkward distribution on the sky. This is partly caused by the structure of the Galactic background emission and partly by the uneven exposure. In addition to this, the broad point-spread function of EGRET causes point sources to enhance the background over regions of around $10^{-2}$ sr, so that the yet detected sources already shadow more than 10% of the sky.

Monte Carlo simulations have shown that the significance of detection for an isolated EGRET source for the energy selection $E > 100$ MeV is adequately represented as

$$S = aF_s \sqrt{F_E/B_s},$$

where $F_s$ is the source flux in units of $10^{-8}$ cm$^{-2}$ s$^{-1}$, $E_s$ is the exposure in units of 10$^2$ cm$^2$ s, $B_s$ is the intensity of background emission in the region of the source in units of $10^{-5}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$, and $a = 0.08$ is an empirically determined constant (Mattox et al. 1996a). With the standard thresholds of 5 $σ$ for $|b| \leq 10^\circ$ and 4 $σ$ outside the Galactic plane, we can use equation (6) to calculate the sensitivity threshold $F_s$ for each viewing direction. To determine $E_s$, we have summed the exposure of all viewing periods of phases 1–4, corresponding to observations between 1991 April and 1995 September. The background intensity is the sum of the diffuse Galactic emission (Hunter et al. 1997), the external background (Sreekumar et al. 1997), and the point-spread functions of all greater than 5 $σ$ excesses that have been found in a maximum likelihood search (Mattox et al. 1996a) in the summed data of phases 1–4.

The sensitivity threshold $F_s$ corresponds to the integrated flux above 100 MeV. Thus the critical distance up to which a pulsar can be detected directly must be calculated as

$$X_{\text{max}}(l, b, t) = \sum_{k=3}^n S_k(t, E_k) \delta E_k / F(l, b) \text{ kpc},$$

where $\delta E_k$ is the width of the energy bin $E_k$. It can be expected that out of the Galactic plane $X_{\text{max}}$ generally exceeds the line of sight through the Galactic disk, so that all pulsars would be detectable by EGRET. Thus, only in the Galactic plane can pulsars contribute to the diffuse γ-ray emission.

### 3. The Contribution to the Diffuse Emission

The mean velocity of nearby pulsars is $\sim 450$ km s$^{-1}$ (Lyne & Lorimer 1994), and pulsars thus typically travel over a distance of 1 kpc in 2 million years. This is much larger than the vertical scale height, but it is considerably smaller than the radial scale length of the spatial distribution of pulsar birth locations (Paczyński 1990). Thus the vertical distribution of pulsars will strongly depend on their age, and the radial distribution will remain basically unaffected. It is straightforward to show that the pulsar trajectories are not strongly influenced by the gravitational potential of the Galaxy, except for the innermost kiloparsec around the Galactic center. The potential gradients in vertical direction change the mean pulsar velocity only at the percent level over 1 million years. The radial gradients in the plane are balanced to first order by the Galactic rotation.

We may thus parameterize the normalized spatial distribution of pulsar birth locations in cylindrical coordinates $(r, z)$ as

$$\rho(r, z, t) = \frac{0.0435 \exp \left(-|z|/z_c\right)}{z_c r_r^2 \cos(r/r_c)},$$

where the cosh term accounts for the Galactocentric gradient. The normalized spatial distribution of pulsars at time $t$ is then derived by integration over the three-dimensional distribution of pulsar birth velocities $P(v)$ (Lyne & Lorimer 1994) as

$$\rho(r, z, t) = \frac{0.0218}{z_c r_r^2 \cos(r/r_c)} \times \int_1^\infty dx \int_0^{\infty} dv P(v) \exp \left(-\frac{|z + v_{\text{ext}}|}{z_c}\right).$$

With $\tau_{\text{p}}^{-1}$ as the birthrate of γ-ray pulsars and $\epsilon$ as the fraction that radiates in our direction, we can determine the number of directly detectable pulsars by integration over the line of sight, solid angle, and age,

$$N_{\text{det}} = \frac{\epsilon}{\tau_p} \int_0^{\tau_{\text{p}}} dt \int d\Omega \int_0^{X_{\text{max}}} dx x^2 \rho(r, z, t),$$

as well as the diffuse emission of unresolved pulsars,

$$I_{\text{diff}}(E_k) = \frac{\epsilon}{\tau_p} \int_0^{\tau_{\text{p}}} dt \int d\Omega \int_0^{X_{\text{max}}} dx x^2 \rho(r, z, t) S_{\text{m}}(t, E_k),$$

where

$$z = x \sin b, \quad r = \sqrt{r_C^2 + x^2 \cos^2 b - 2r_C x \cos b \cos l}.$$
only weakly on age; the age effects the number of directly observable objects \( N_{\text{det}} \) nearly as much as the predicted emission of unresolved pulsars \( I_{\text{dif}} \). In addition, a larger \( t_{\text{max}} \) would require extrapolation too far beyond the range of pulsar ages for which we have data. As we will see below, \( t_{\text{max}} \) does have a strong influence on the latitude distributions of observable pulsars as well as of the pulsar contribution to the Galactic diffuse emission.

The parameters used here, \( \tau_p^{-1} = 0.01 \, \text{yr}^{-1} \) and \( \epsilon = 0.15 \), imply that around 14 pulsars should be detectable by EGRET, which is to be compared with a total Galactic population of \( t_{\text{max}} \tau_p^{-1} \epsilon = 2400 \) pulsars that radiate in our direction. Since six are already identified, this would mean that another eight unidentified sources are actually pulsars. Considering the integrated intensity above 100 MeV in this example, pulsars would cause 10% of the observed intensity in the Galactic center direction and about 3% in the anticoncenter direction. Pulsars contribute very little off the plane. In direction \( l \approx 0^\circ \) and \( b \approx 8^\circ \), we obtain around 1%, so that integrated over the sky pulsars provide only a few percent of the observed diffuse emission, which is consistent with earlier estimates based on pulsar emission models. This is also true for the emission at higher \( \gamma \)-ray energies.

We have compared the latitude distribution of the observed diffuse emission above 1 GeV with what our model predicts for the pulsar contribution. The result is given in Figure 4, where we show the distribution of the diffuse intensity at energies above 1 GeV as averages over longitude. We find that pulsars contribute strongly only very close to the plane, where the lines of sight are long, but the observed emission does fall off much less rapidly with latitude than the emission of unresolved pulsars. Also, the observed spectral discrepancy above 1 GeV appears to extend to latitudes \( |b| \gtrsim 5^\circ \) (Hunter et al. 1997).

If we would allow for higher pulsar ages, e.g., \( t_{\text{max}} = 5 \times 10^6 \, \text{yr} \), the latitude distribution of the emission of unresolved pulsars would approach that of the observed emission. However, for the same number of directly observable pulsars, only around 6% of the observed diffuse emission above 1 GeV would be caused by unresolved pulsars, as shown by the dotted line in Figure 4. In our study, the
beaming fraction $\epsilon$ is taken to be a constant. Any physical variation of $\epsilon$ in the regime of observed pulsar ages ($10^3$–$10^7$ yr) should be accounted for by our fit parameters $y_k$ and $b_k$. Any variations of $\epsilon$ at higher pulsar ages cannot be accounted for. The fact that no pulsar with rotational age of 1 Myr or higher has been observed indicates strongly that $\gamma$-ray emission of pulsars ceases at ages of roughly 1 Myr. Note that for $t_{\text{max}} = 5 \times 10^6$ yr more than 50% of all observable pulsars in our model would be older than 1 Myr. Hence the results we present for a high $t_{\text{max}}$ serve to demonstrate basic behavior rather than to provide a realistic estimate.

Many of the observable pulsars should be located at higher latitudes. We expect 58% of pulsars at $|b| \gtrsim 6^\circ$ (74% in the case of $t_{\text{max}} = 5 \times 10^6$ yr) and 31% at latitudes $|b| \gtrsim 14^\circ$ (53% in the case of $t_{\text{max}} = 5 \times 10^6$ yr).

4. DISCUSSION

The dominant contribution of unresolved pulsars to the diffuse $\gamma$-ray emission is above 1 GeV, where in the direction of the Galactic center around 18% of the total observed emission could be provided with approximately 14 directly observable objects. Approximately 30 pulsars would have to be directly observable to account for 100% of the discrepancy between model predictions and the observed spectrum in this direction. This seems unreasonable since only few of the unidentified EGRET sources show the typical pulsar-like $\gamma$-ray spectrum (Merck et al. 1996). Furthermore, studies of known radio pulsars have led to constraining upper limits for pulsed emission for most of them (Thompson et al. 1994; Nel et al. 1996).

A few pulsars are positionally coincident with unidentified EGRET sources, but it is unclear whether the $\gamma$-ray emission is caused by the pulsar, the supernova remnant, or any other nearby system. A deep search for radio pulsars in the error boxes of 19 unidentified EGRET sources has been performed recently (Nice & Sayer 1997). Though data were taken at three different frequencies to minimize selection effects, no new pulsars were found. So the detectable, but not yet detected, pulsars would have to be either radio-quiet or located in active regions like SNOBs (Montmerle 1979) that would impede the radio detection by their high and possibly variable dispersion measures. It is interesting to see that roughly 10 unidentified EGRET sources can be associated with supernova remnants (SNRs) and/or OB associations (Sturner & Dermer 1995; Kaaret & Cottam 1996; Yadigaroglu & Romani 1997). However, SNRs only live for around $10^7$ yr, so that preferentially young pulsars would be expected to be associated with them, whereas the bulk of the observable pulsars should be old. From our modeling we expect 24% of the observable pulsars to be at an age less than $10^7$ yr and 76% older than this (for $t_{\text{max}} = 1.6 \times 10^6$ yr). Therefore we should not assume that too many young pulsars are hidden in regions of high electron density without having a corresponding number of old pulsars. It thus seems reasonable that a only a few $\gamma$-ray pulsars are hidden radio pulsars.

It is also possible that there is a substantial number of radio-quiet but $\gamma$-ray–loud pulsars. Though an extensive search for $\gamma$-ray pulsars among the brightest unidentified EGRET point sources has obtained only upper limits to date (Mattox et al. 1996b), the spatial and flux distributions of unidentified EGRET sources have been reported to be compatible with the majority of them being pulsars (Yadigaroglu & Romani 1997). If these were all Geminga-like, the corresponding unresolved sources would contribute strongly to the diffuse emission above 1 GeV. Since our analysis is based on the observed properties of mainly radio-loud pulsars, any basic difference in the $\gamma$-ray emission properties between radio-loud and radio-quiet objects would severely effect the predictions and leave us without a reliable tool to estimate numbers. This would be true even if the recent detection of weak pulsed radio emission from Geminga can be confirmed (Kuzmin & Losovsky 1997).

Nevertheless, the small fraction of unidentified EGRET sources that indicates pulsar-like or Geminga-like $\gamma$-ray spectra (Merck et al. 1996) argues strongly against the bulk of unidentified sources being pulsars. Also, a substantial fraction of the unidentified EGRET sources in the Galactic plane appears to be variable, which makes the identification of all unidentified sources with pulsars even more unlikely (McLaughlin et al. 1996).

5. CONCLUSION

In total, we think that around 14 directly observable pulsars, of which six are already identified, is a reasonable number, and that the calculated contribution of unresolved pulsars can thus be taken as a serious estimate. The main systematic uncertainty in our study is definitely that the six identified pulsars may not be a representative sample. On the other hand, we do not need to base our study on a theoretical model that may or may not be a fair description of nature.

We find that pulsars contribute very little to the diffuse emission at lower energies, whereas above 1 GeV they can account for 18% of the observed intensity in selected regions. This seems insufficient to explain the discrepancy between observed intensity and model predictions based on cosmic-ray interactions in this regime. We also find that pulsars contribute mainly close to the plane, where the lines of sight are long, but the observed emission does fall off much less rapidly than this. Also, the observed spectral discrepancy between the data above 1 GeV and the predictions of cosmic-ray models seems to extend to latitudes $|b| \gtrsim 5^\circ$ (Hunter et al. 1997). Thus there must be additional effects playing a role for the observed diffuse $\gamma$-ray emission above 1 GeV.

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