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PULSAR AND DIFFUSE CONTRIBUTIONS TO THE OBSERVED GALACTIC GAMMA RADIATION

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With the aquisition of satellite data on the energy spectrum of galactic γ-radiation,[1,2] it has become clear that such radiation has a multicomponent nature.[3-7] In this letter, we make use of a calculation of the pulsar γ-ray emission spectrum together with a statistical analysis of recent data on 328 known pulsars to make a new determination of the pulsar contribution to galactic γ-ray emission. We then reexamine the contributions from diffuse interstellar cosmic-ray induced production mechanisms to the total emission and conclude that pulsars may account for a significant fraction of galactic γ-ray emission.

Models for the production of high energy γ-rays in the Galaxy have dealt primarily with diffuse emission processes, those which involve interactions between cosmic rays and interstellar matter. The major contributions are thought to come from electron bremsstrahlung and the decay of neutral pions produced in high energy proton collisions, with a small additional flux from Compton interactions. In determining the relative contributions of these processes from the shape of the observed γ-ray spectrum, the contribution of true point sources (as opposed to enhancements in the spatial distribution from diffuse processes) has been neglected, largely because the point source spectrum has been undetermined. At present, pulsars can give the best information on a true point source component of the galactic γ-ray flux.

We report here on the first calculation of a γ-ray production spectrum from pulsars in the Galaxy and on the implications of this point source contribution to the general interpretation of the observed galactic γ-ray spectrum. The details of this calculation, as well as a determination of the longitude and latitude profiles of pulsar γ-rays will be described elsewhere.[8] There have previously been estimates of the pulsar contribution to the observed galactic γ-ray flux,[9-11] using only 51 pulsars and very general assumptions about their γ-ray luminosities. There are now 328 known radio pulsars, all having independent distance determinations via their dispersion measures. The local density and galactic distribution can therefore be much better determined, assuming a value for the mean free electron density in the galactic plane. Pulsed γ-rays have been observed from the Crab (PSR 0531 + 21) and Vela (PSR 0833-45) pulsars by the SAS-2 satellite,[12,13] and the COS-B satellite.[14] The energy spectra of these sources have recently been determined in the range 50 MeV-2 GeV and they can both be fit with steep power laws of similar slope around -2.[15] Although these two young sources represent only a small fraction of the known pulsars, their emission testifies to the fact that some, and possibly all pulsars are γ-ray emitters at some stage of their evolution. Though these others may be individually below the present limits of detectability, the contribution of their γ-rays to the observed galactic emission could be significant, as has been previously suggested.[9]

We assume that the γ-ray emission above 100 MeV is produced by curvature radiation from primary particles which have been accelerated to high energies in the electric fields of the pulsar's magnetosphere. Some of these γ-rays are converted to electron-positron pairs in the strong pulsar magnetic field. The electric field induced perpendicular to the magnetic field by the star's rotation also contributes to the pair production rate and has a large effect on the optical depths in short period pulsars.[16] The shape of the numerically calculated spectra in this model depend on the initial energy of the primary particles and on the pulsar magnetic field strength and period.[17] For an initial energy of 1.5×10^4 GeV and a field strength of 10^{12} gauss, the resulting calculated spectrum for a pulsar period of .033 s reproduces the shape of the observed Crab pulsar spectrum. The observed 100 MeV flux from the Crab pulsar at 2 kpc is used to determine the normalization factor ($\sim 10^3$) which is the ratio of the primary particle density above the polar cap to the corotation charge density. Using this same normalization factor, primary particle energy, and magnetic field strength, the calculated spectrum for a period of .089 s. fits the observed Vela pulsar spectrum quite well.

It may be reasonable to assume, then, that these values of the parameters determining the spectrum are valid for all pulsar periods.

An expression for the γ-ray luminosity can be derived by integrating the spectra calculated for different periods, P, and surface magnetic field strengths, B_{12} (in units of 10^{12} gauss). The best fit for the dependence of luminosity on these quantities gives:

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

The γ-ray luminosities and fluxes for the known radio pulsars have been calculated from equation (1) and compared to the upper limits obtained by SAS-2[18] and the sources in the COS-B catalog[19]. Eight pulsars have predicted fluxes above the point source detectability limit of COS-B but most are toward the galactic center where the diffuse background is high. Only two lie in the longitude range $90^0 < \ell < 270^0$ where the search is considered complete down to 1.3×10^{-6} cm^{-2} s^{-1}; however, they both lie just outside the latitude range of the search. Four pulsars have predicted fluxes above their SAS-2 upper limits, but exceed them by no more than the estimated uncertainties in either the measurements or the model.

In calculating these pulsar spectra and luminosities, it has been assumed that the magnetic field is a pure dipole and that the angle between the dipole axis and spin axis is 90^0, since we are concerned here with the collective properties of the pulsar population, and a random distribution of angles would give an average of 90^0. More details of the model are given in Reference 17.

If all pulsars produce pulsed γ-rays according to this model, then the local differential production spectrum will be,

$$q_{PSR}(E_\gamma) = \frac{D_\theta}{2h} \int_0^\infty I_\gamma(P,E_\gamma)\, \rho\,(P)\, dP,$$

where D_θ is the local surface density of pulsars which are beamed in our direction, h is their scale height above the plane, $\rho(P)$ is their period distribution and $I_\gamma(P,E_\gamma)$ is the γ-ray spectrum of an individual pulsar with period P. $I_\gamma(P,E_\gamma)$ is also directly proportional to surface magnetic field strength, so that q_{PSR} will be proportional to the average pulsar magnetic field strength. We take an average field of 10^{12} gauss, which is consistent with measured pulsar spindown rates. The derived local density and scale height depend on a determination of $\langle n_e \rangle$, the mean electron density in the galactic plane, which, through dispersion measure observations, fixes the pulsar distance scale. Unfortunately, the galactic distribution of n_e is not well known and is difficult to determine. There are several indications that n_e is not uniform throughout the galactic plane and that it does not have a simple exponential Z dependence[20, 21, 22], both of which have been previously assumed in determining pulsar densities. However, in view of the difficulties entailed in a detailed spatial modeling of n_e, given the present observational data, we choose to adopt the simple constant density model of Taylor and Manchester[23] which is sufficient for estimating the mean contribution from pulsars to the galactic γ-radiation. For $\langle n_e \rangle = .03\ \text{cm}^{-3}$, a value consistent with HI absorption distances to pulsars in local regions of the Galaxy[20], a statistical analysis of data on the 328 known pulsars gives $D_\theta \sim 480$ pulsars kpc^{-2} and $h_p \sim 325$ pc. The resulting γ-ray production spectrum per cm^{-3} is shown in Figure 1 along with the production spectra for the major diffuse processes calculated by Stecker,[6] assuming a local interstellar hydrogen density of 1 atom per cm^{-3}. This spectrum gives volume-averaged integral pulsar γ-ray production rates at 10 kpc of 2.2×10^{-26} photons cm^{-3} s^{-1} above 100 MeV and 4.6×10^{-26} photons cm^{-3} s^{-1} above 35 MeV. Although the calculated pulsar spectrum has been extrapolated below 100 MeV, the model does not accurately predict the low energy spectrum because the synchrotron radiation from secondary particles, which may extend to the γ-ray region, has not been included. This contribution would tend to steepen the spectrum and increase the estimated flux level below around 100 MeV.

The diffuse production spectra illustrated in Figure 1 have widely differing uncertainties. The pion production spectrum is least uncertain, since it primarily involves cosmic ray protons with energies in the 1-10 GeV range where uncertainties in determining galactic fluxes owing to solar modulation effects produce small uncertainties ($\leqslant$ 15 percent) in the total production rate.[25] Even the differential γ-ray source spectrum for $E_\gamma \leqslant$ 10 GeV is insensitive to the kinematical model chosen, as evidenced by the excellent agreement between calculations of Stecker,[24-26] Ganguli and Sreekantan,[27] and Badhwar and Stephens.[28]

The Compton production mechanism produces a small expected contribution in our region of the Galaxy, however, this process could be significant near the galactic center.[6] Since this component is small over most of the galaxy and various theoretical estimates[29,30] are in reasonable agreement with Figure 1, we conclude that little error in determining the total galactic flux is introduced via the Compton process.

The situation is quite different in the case of electron bremsstrahlung. The curve shown in Figure 1 for this component was determined using a conservative "standard" cosmic ray electron spectrum[31]. However, the electron spectrum cannot be easily determined from cosmic-ray data owing to large solar modulation effects. Theorists have thus had much leeway in invoking large electron fluxes to account for discrepancies in both the spectrum and intensity of the observed galactic γ-rays with "standard" predictions[32, 33]. Indeed, the spectral data have even been used to speculate on drastic fluctuations in both electron and proton fluxes in the Galaxy[34] although, in our view, inherent systematic errors as well as statistical errors in the spectral data make such a radical analysis unwarranted.

The calculated pulsar contribution, as presented here, has clear implications for analyzing the total galactic spectrum. Pulsars contribute a soft power law flux component similar to that expected from electron bremsstrahlung. In addition, the pulsar component as estimated in Figure 1 is as large as the "standard" bremsstrahlung component.

It is also expected that the pulsar contribution to the total galactic flux should be roughly independent of galactic longitude except in the outer Galaxy. The argument is as follows. We have used the longitude and distance data for the full sample of observed pulsars, together with corrections for selection effects, to determine the radial distributions of pulsars in both the northern ($0^{\circ} < \ell < 180^{\circ}$) and southern ($180^{\circ} < \ell < 360^{\circ}$) Galactic longitudes. The results for the inner Galaxy ($R \leqslant 8$ kpc) are strikingly similar to the distributions of total γ-ray emissivity determined previously.[6] Thus, the ratio of pulsar to total emissivity (i.e., the fraction of the flux from the pulsar component) should be roughly constant with longitude, for longitudes within 60° of the Galactic center. This fraction is calculated to be 15 to 20 percent above 100 MeV (as derived from both Figure 1 and a comparison of the longitude distribution of pulsar and observed γ-ray emission[8] using the data in Figure 2.) It can easily be of the order of 50 percent at lower energies (see Figure 1), obviating the need to invoke large low energy electron fluxes to explain the shape of the observed γ-ray spectrum.

The latitude distribution of pulsar γ-ray emission will be narrow but will extend somewhat beyond b = 10° (Ref. 8). Pulsars may therefore be able to account for some of the flux observed at galactic latitudes above 10° [25,26]. According to the model, the younger pulsars are the strongest γ-ray emitters. They are also more confined to the galactic plane[27]. Thus, the pulsars at high b have a higher mean age and are weaker. This would be consistent with the lack of observed point sources at high b.

We therefore conclude that the integrated flux from distant γ-ray emitting pulsars may provide an important fraction of the low to medium energy galactic γ-ray flux (although a smaller fraction of the flux above 100 MeV) and the inclusion of the pulsar component in analyzing the galactic γ-ray spectrum supports a coherent integrated relationship with galactic cosmic-ray theory as previously discussed[28-42].

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FIGURE CAPTIONS

Figure 1--Differential production spectra for pulsars and the major diffuse processes. The π^0, bremsstrahlung and Compton spectra are from Stecker[6,26] and the total spectrum includes the pulsar contribution. SAS-2 and COS-B data points for the longitude range $355^0 < l < 15^0$ are also shown.[1,3] The left and right hand scales refer to the theoretical production rates at 10 kpc from the galactic center and the observed γ-ray flux, respectively.

Figure 2--Surface density of pulsars[8] and γ-ray surface emissivity[6] plotted against galacto-centric radius for northern and southern halves of the Galaxy.

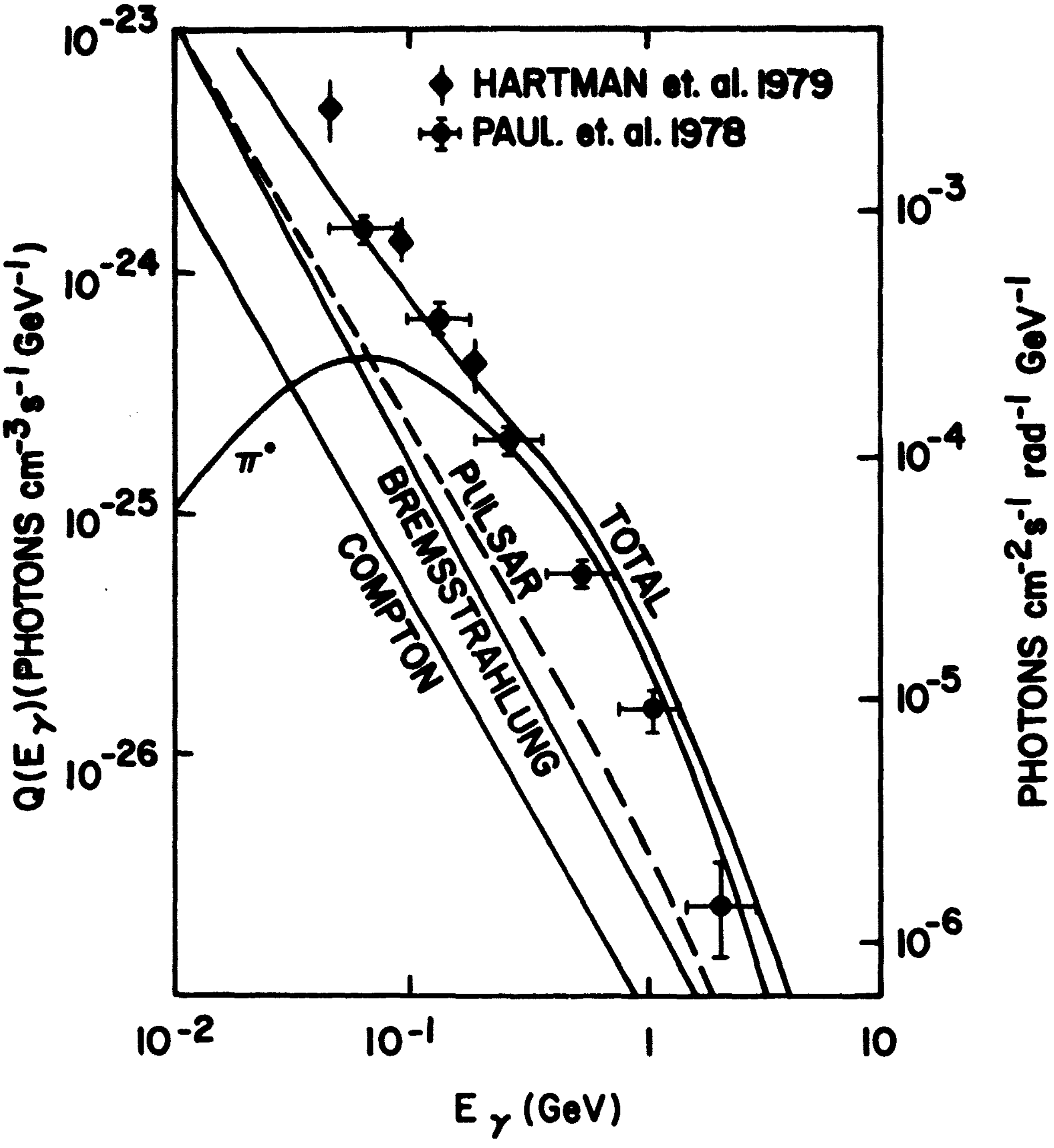
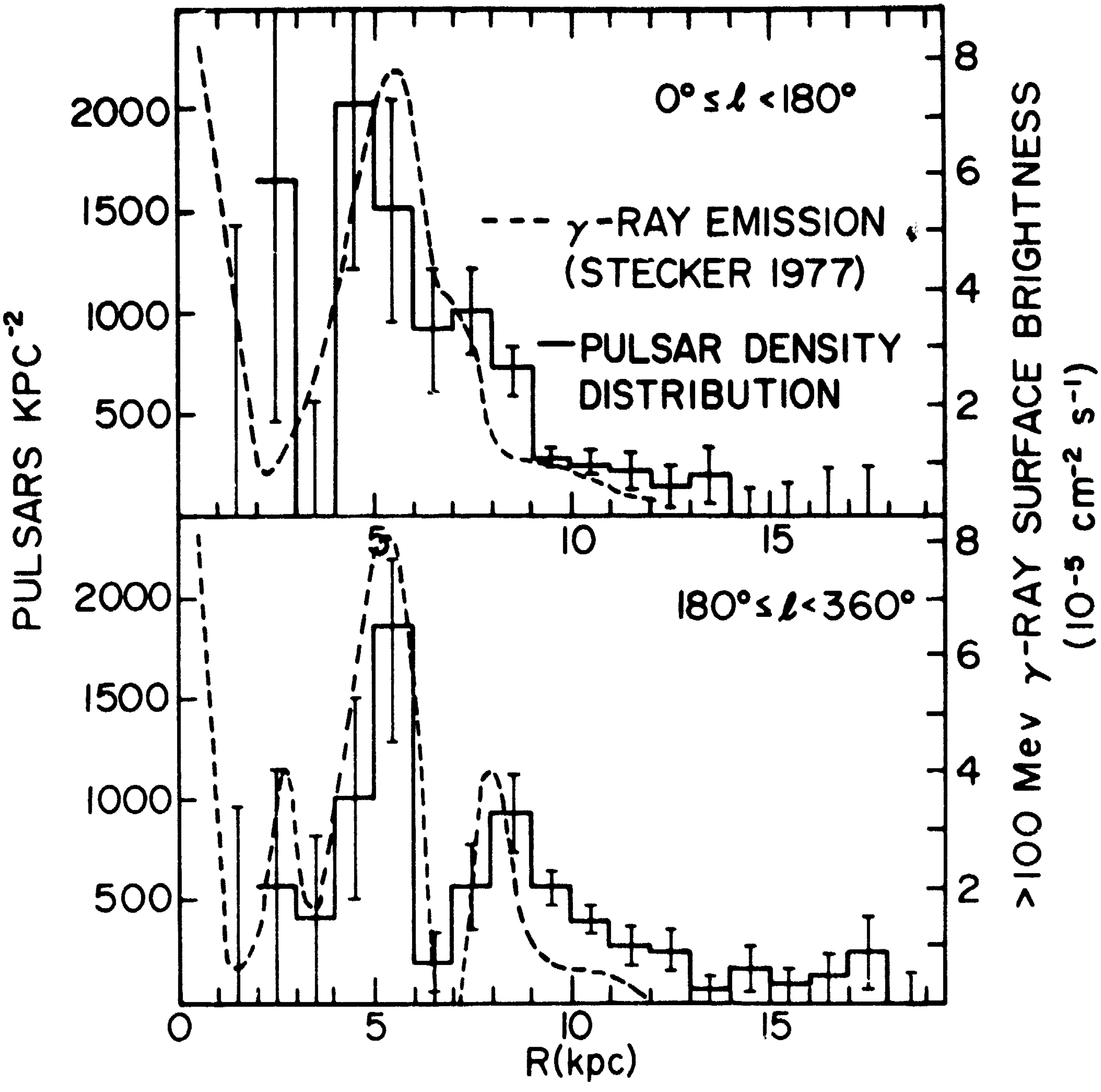

HARTMAN et. al. 1979
PAUL. et. al. 1978
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$Q(E_\gamma)$ (PHOTONS $cm^{-3} s^{-1} GeV^{-1}$)
PHOTONS $cm^{-2} s^{-1} rad^{-1} GeV^{-1}$
π°
COMPTON
BREMSSTRAHLUNG
PULSAR
TOTAL
10^{-2}
10^{-1}
1
10
E_γ (GeV)

Figure 1



0° ≤ l < 180°
γ-RAY EMISSION (STECKER 1977)
PULSAR DENSITY DISTRIBUTION
180° ≤ l < 360°
PULSARS KPC⁻²
>100 Mev γ-RAY SURFACE BRIGHTNESS (10⁻⁵ cm⁻² s⁻¹)
R(kpc)
0
5
10
15
500
1000
1500
2000
2
4
6
8

Figure 2