OG3.1-6

CONSTRAINTS ON THE GALACTIC DISTRIBUTION OF COSMIC RAYS FROM THE COS-B GAMMA-RAY DATA

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1. Introduction. The diffuse component of the galactic high-energy ($\gtrsim 50$ MeV) gamma rays results mainly from the interaction of CR nuclei (mostly protons with energies of a few GeV) and electrons (with energies up to several hundreds of MeV) with the nuclei of the interstellar gas (via the decay of π°-mesons and bremsstrahlung). An additional contribution is obtained from the interaction of CR electrons (with energies >1 GeV) with the interstellar photons (mainly in the optical and infrared range) through the inverse-Compton (IC) process. Gamma-ray astronomy therefore offers an excellent means to study the distribution of CR particles throughout the Galaxy, but it is essential to know the distribution of the target interstellar gas particles, the major constituents being atomic (HI) and molecular (H_2) hydrogen. Although large-scale mapping of the HI component had been performed using its characteristic 21-cm line, the numerous previous gamma-ray studies of the galactic CR distribution, using gamma-ray observations obtained by the SAS-2 and COS-B satellites, suffered severely from uncertainties in the galactic distribution of interstellar molecular hydrogen. Large-scale millimetre-wave surveys of the CO molecule covering more than half of the Milky Way, obtained with the Columbia 1.2m telescopes, are currently available and can be used to trace the H_2; the COS-B observations have sufficient resolution and sensitivity to constrain the relation between the integrated CO line intensity W_{CO} and the molecular-hydrogen column density $N(H_2)$ (Lebrun et al., 1983; Bloemen et al., 1984a).

The velocity information of the HI and CO observations is used as a distance indicator to ascertain the spatial distribution of the interstellar gas. Using this distance information, the galacto-centic distribution of the gamma-ray emissivity (the production rate per H atom) is determined for three gamma-ray energy ranges (70 MeV - 150 MeV, 150 MeV - 300 MeV, and 300 MeV - 5 GeV) from a correlation study of the gamma-ray intensity maps and the gas-tracer maps for selected galacto-centric distance intervals, taking into account the expected IC contribution and pointlike gamma-ray sources (details are given in Section 2). On the assumption that unresolved gamma-ray point sources do not contribute significantly to the observed gamma-ray emission, the gamma-ray emissivity is proportional to the CR density and, more specifically, the energy dependence can be used to study separately the distribution of CR electrons and nuclei: whereas the emission for the 300 MeV - 5 GeV range is dominated by π°-decay, the 70 MeV - 150 MeV range has a large electron bremsstrahlung contribution. For a complete description of the method and the results the reader is referred to Bloemen et al. (1985).

Bloemen et al. (1984b,c) applied such a method to the COS-B gamma-ray observations and HI 21-cm line observations of the second and third galactic quadrants alone (they showed that H_2 can be neglected in the outer Galaxy within the uncertainties of the analysis), and found evidence that the distribution of the CR electron density decreases beyond the solar circle while the density of the CR nuclei is approximately constant out to large (~20 kpc) galacto-centric distances.

2. Method. Skymaps of HI column densities, $N(HI)_i$, and integrated CO line intensities, $W_{CO,i}$, were constructed in four ($i = 1,2,3,4$) galacto-centric distance ranges (2 kpc $< R <$ 8 kpc, 8 kpc $< R <$ 10 kpc, 10 kpc $< R <$ 15 kpc, and $R >$ 15 kpc) and convolved with the energy-dependent COS-B point-spread function. We selected these four distance intervals because the angular distributions of the gas in each interval show distinct differences, which are needed to ascertain the contribution of the gas in each interval to the observed gamma-ray intensities. Similarly, determining the conversion factor between W_{CO} and $N(H_2)$ (i.e. the ratio $X = N(H_2)/W_{CO}$) requires distinct differences between the structures in the HI and CO maps. Due to the limited sky area that is covered by the CO observations, the following correlation analysis has been restricted to the first and second galactic quadrants and the Carina region ($270° < l < 300°$), and the latitude range $-4.5° < b < 6.5°$.

We investigated which combination of gamma-ray emissivities, q_{ij} ($j = 1,2,3$ corresponds to the 70 MeV - 150 MeV, 150 MeV - 300 MeV, and 300 MeV - 5 GeV ranges), best describes the observed gamma-ray distributions, $I_{\gamma,j}$, assuming a relation of the form:

$$I_{\gamma,j} = \{ \sum_{i=1}^{4} \frac{q_{ij}}{4\pi}.(N(HI)_i + 2Y_j.W_{CO,i}) \} + I_{IC,j} + I_{b,j}.$$

The term enclosed by braces represents the intensities that originate from CR collisions with atomic and molecular hydrogen, the term $I_{IC,j}$ represents the modelled (small) IC contribution (Bloemen, OG3.1-2), and $I_{b,j}$ is the total isotropic gamma-ray background, including the (dominant) instrumental background. The parameters Y_j are equal to the ratio X, independent of energy, if CR particles are not excluded from, or concentrated in, molecular clouds. Pollock et al. (1985) have shown that some gamma-ray point sources are present in the first quadrant; these have been included in our model as described by Pollock et al.

We applied a likelihood analysis on 1°x1° bins to determine the values and formal statistical uncertainties of the parameters q_{ij}, as well as of Y_j and $I_{b,j}$. Starting from the general model with these six parameters for each energy range, we tested (using the likelihood-ratio) whether various simpler models with fewer parameters (i.e. constant emissivity distributions as a function of R, identical Y_j values

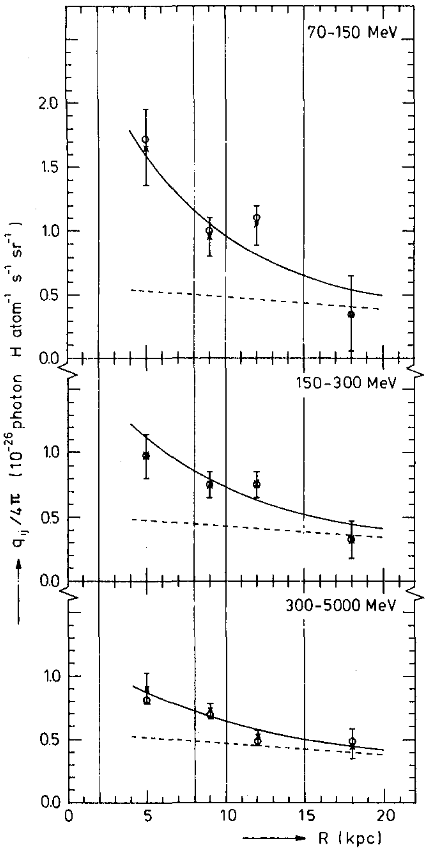


Figure 1: Galacto-centric distribution of the gamma-ray emissivity for three energy intervals j. The crosses, together with statistical 1σ error bars, indicate the fit values for selected distance ranges i (indicated by the vertical lines) without any constraints. The circles are the emissivity values when the values of Y_j are forced to be identical. The full curves represent the emissivity distributions $q_j(R)$ in the case of exponential distributions for the CR electrons and nuclei. The dashed curves indicate the π°-decay contribution from the CR nuclei (f = 1).

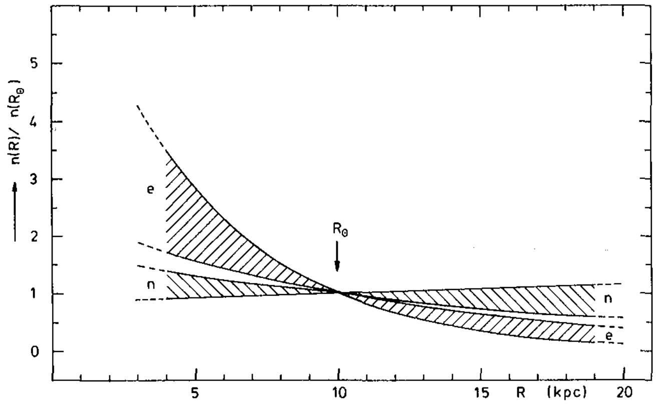
and/or identical emissivity distributions for each energy range) give significantly worse fits to the data.

3. Results and discussion. Figure 1 shows the resultant radial emissivity distributions. Since neither the two emissivity values outside the solar circle, nor the two values inside, can be determined entirely independently, these radial distributions have to be judged carefully. The likelihood-ratio hypothesis testings showed: (1) a gamma-ray emissivity gradient as a function of galacto-centric radius is required for the integral 70 MeV - 5 GeV range, (2) the gamma-ray model displays an energy dependence, (3) this energy dependence can be accounted for fully by an energy-dependent emissivity gradient (so energy-independent Y_j values) that is strongest for low energies, (4) it can less satisfactorily be ascribed to different emissivity spectra of HI and H_2 (i.e. different Y_j values). The ratio $X = N(H_2)/W_{CO}$ was found to be $(2.75 \pm 0.35) \times 10^{-26}$ mol. cm^{-2} K^{-1} km^{-1} s, and additional tests showed that X is constant throughout the Galaxy, within uncertainties. This X value is independent of excitation and abundance effects, which have plagued previous determinations. It should strictly be regarded, however, as an upper limit if a population of unresolved galactic gamma-ray sources distributed like CO exists. The resultant H_2 mass is equal to the HI mass for $2 \text{ kpc} < R < 10 \text{ kpc}$, namely $0.9 \times 10^9\ M_\odot$.

Assuming exponential distributions $e^{S(R-R_\odot)}$ ($R_\odot = 10$ kpc) for the CR electrons (e) and nuclei (n), the total gamma-ray emissivity at galacto-centric radius R can be written as:

$$q_j(R) = e^{S_e(R-R_\odot)}.\{q_j(R_\odot)-f.q_{\pi^\circ,j}\} + e^{S_n(R-R_\odot)}f.q_{\pi^\circ,j},$$

where the parameters $q_{\pi^\circ,j}$ are the local π°-decay gamma-ray emissivi-



f	S_e (kpc^{-1})	S_n (kpc^{-1})
1.2	$-0.18\,^{+0.04}_{-0.03}$	$-0.04\,^{+0.015}_{-0.015}$
1.0	$-0.16\,^{+0.05}_{-0.03}$	$-0.02\,^{+0.015}_{-0.03}$
0.8	$-0.14\,^{+0.05}_{-0.03}$	$0.00\,^{+0.015}_{-0.05}$

Figure 2: Radial CR-density distributions of the form $e^{S(R-R_\odot)}$*, for CR electrons (e) and nuclei (n). The hatched areas encompass* $0.8 \leq f \leq 1.2$ *and 1σ uncertainties for* S_n *and* S_e*, that is* $-0.21 < S_e < -0.09$ *kpc*$^{-1}$ *and* $-0.055 < S_n < +0.015$ *kpc*$^{-1}$*. Note that within these areas* S_e *and* S_n *are not independent: a stronger electron gradient implies a stronger gradient for the nuclei (see table, presenting* S_e *and* S_n *for different f values).*

ties (we estimated these values from the work of Stephens and Badhwar (1981), based on the demodulated proton spectrum near the earth) and f is an energy-independent scaling factor, because the demodulated proton flux may not be typical for the local interstellar medium. Considering a range of possible f values ($0.8 \leq f \leq 1.2$), we applied a likelihood analysis to determine the values of the local emissivity values $q_j(R_\odot)$, and of S_e and S_n. Note that we did not fit the emissivity distributions shown in Figure 1; our method allows for the dependencies mentioned above (for details see Bloemen et al., 1985). The resultant values of S_e and S_n are given in Figure 2 and the corresponding emissivity distributions are included in Figure 1. The total local gamma-ray emissivities $q_j(R_\odot)$ were found to be independent of the f value chosen and are consistent with the improved local emissivities determined at medium latitudes (Strong et al., OG3.1-3); the implications for the local electron spectrum are discussed by Strong (OG3.1-7). The CR electron gradient is required, but the results are consistent with a constant density of CR nuclei on a galactic scale. The quoted CR gradients could be affected by a population of unresolved galactic gamma-ray sources.

The gradient in the distribution of the CR electrons confirms their galactic origin. The exponential scale length of the CR nuclei distribution from the present analysis is at least 15 kpc; this is much larger than for the type of objects generally considered as candidates for CR sources (e.g. supernovae and pulsars, both having a scalelength of ∿5 kpc (Kodaira, 1974; Lyne et al., 1985)). The gradient of the CR nuclei, if it exists, is so weak, that on the basis of gamma-ray observations, it can no longer exclusively be claimed that CR nuclei (with energies of several GeV) are produced in the Galaxy. If the latter is the case, and if they are produced by objects like pulsars and supernova remnants, then the CR distribution does not seem to reflect the distribution of the CR sources.

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