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THE RADIAL DISTRIBUTION OF GALACTIC GAMMA-RAYS. I. EMISSIVITY AND EXTENT IN THE OUTER GALAXY

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ABSTRACT

A method is presented by which the radial distribution of galactic high-energy γ-rays (70 MeV–5 GeV) can be determined. It is shown that the γ-ray intensity for $R > R_\odot$ depends on N(H I) alone to within the uncertainties of the method. The kinematics of the H I are used to show that galactic γ-rays, and consequently cosmic-ray particles, are present in significant quantities to galactocentric distances of approximately 17 kpc. The γ-ray emissivity (70 MeV–5 GeV) at $R > R_\odot$ is found to be $(2.12 \pm 0.07) \times 10^{-26}$ photons H atom^{-1} s^{-1} sr^{-1}, within 15% of the local value, and the γ-ray luminosity (>100 MeV) of the Milky Way is $(1.3–2.5) \times 10^{42}$ photons s^{-1} ([1.6–3.2] $\times 10^{39}$ ergs s^{-1}). The H_2 mass at $R > R_\odot$ is found to be $< 3 \times 10^8 M_\odot$.

Subject headings: cosmic rays: general — galaxies: Milky Way — gamma rays: general — interstellar: matter — interstellar: molecules

I. INTRODUCTION

The diffuse component of galactic high-energy γ-rays ($\gtrsim 50$ MeV) has long been thought to be mainly the result of interactions between cosmic rays and the nuclei of interstellar gas (e.g., Fazio 1967 and Stecker 1971). Using the *COS B* data, Lebrun *et al.* (1982) and Strong *et al.* (1982) have shown that locally ($\lesssim 1$ kpc), the γ-ray intensity is correlated with the total gas column density along the same line of sight. If this correlation holds for the Galaxy as a whole, it is then possible to use the kinematics of the gas coupled with the rotation curve as a tracer for the locations of γ-ray production. This information can then be used to determine the radial distribution of the diffuse γ-rays.

In this paper, we show that beyond the solar circle, the γ-ray intensity is proportional to the H I column density alone within the uncertainties, and that the emissivity in the 70 MeV–5 GeV energy range is only about 15% lower than the local value. We then examine the radial distribution of the H I with which the γ-rays are correlated and show that a significant fraction of the γ-ray emission originates at large galactocentric distances, which implies that cosmic rays must be abundant in the outer Galaxy. The results are shown to warrant a more detailed analysis which will be the subject of a forthcoming paper (Bloemen *et al.* 1984).

II. THE CONTRIBUTION OF H_2 AT $R > R_\odot$

Using galaxy counts and *COS B* γ-ray data in the latitude range $10° < |b| < 20°$, Lebrun *et al.* (1982) and Strong *et al.* (1982) have shown that the γ-ray intensity is well correlated with the total column density of hydrogen nuclei $[N(\text{H I}) + 2N(\text{H}_2)]$ in the solar vicinity. The derived local emissivity ($\epsilon_\gamma = q_\gamma/4\pi$) in the energy range 70 MeV–5 GeV is 2.5×10^{-26} photons H atom^{-1} s^{-1} sr^{-1} with an uncertainty (which is mainly systematic) of about 25% (Strong *et al.* 1982). Since $I_\gamma = \epsilon_\gamma[N(\text{H I}) + 2N(\text{H}_2)] + I_B$, where I_γ is the observed *COS B* γ-ray intensity and I_B is the underlying isotropic background level, it is in principle possible to determine ϵ_γ in regions within 10° of the galactic plane from 21 cm and CO observations. There is, however, no complete CO survey of the galactic plane, and in any event, the derived H_2 column densities are generally thought to be uncertain by about a factor of 3.

Beyond the solar circle, however, the H_2 mass appears to be small compared to the H I mass. Estimates of the H_2 mass at $R > R_\odot$ have been given by Kutner and Mead (1981) to be 3×10^8 $M_\odot$ (with a possible upward correction of about a factor of 2 for scale height effects). Solomon, Stark, and Sanders (1983) have argued that the number of clouds between $R = 11$ kpc and $R = 15$ kpc is 12% of the number of clouds between $R = 3$ kpc and $R = 9$ kpc, with very few clouds beyond $R = 15$ kpc. Using Sanders's (1982) estimate of H_2 mass of 2.7×10^9 $M_\odot$ between $R = 2$ kpc and $R = 10$ kpc, one derives an approximate H_2 mass of 3×10^8 $M_\odot$ at $R > R_\odot$. For the H I, Henderson, Jackson, and Kerr (1982) derive a total H I mass for the Milky Way of 4.8×10^9 $M_\odot$, of which 80% lies beyond $R = R_\odot$. Thus for a typical line of sight in the second and third galactic quadrants, one expects $N(\text{H}_2)/N(\text{H I}) \approx 0.08–0.15$. On average, it is therefore expected that it is possible to ignore the molecular gas in obtaining γ-ray emissivities with uncertainties due to the H_2 contribution of $\sim 10\%$. However, because of the large uncertainties in the CO/H_2 conversion, and the disagreements among CO observers regarding the outer Galaxy results, we have made an independent check of the hypothesis that the H_2 can be ignored.

If the H_2 contributes significantly to the γ-ray emissivity, there should be a measurable difference between the locally determined emissivity (which includes the H_2 contribution) and the value found in the second and third quadrants determined from the 21 cm observations alone. Furthermore, the CO scale height is significantly smaller than the H I scale height outside the solar circle (Fich and Blitz 1983; Kulkarni, Blitz, and Heiles 1982). The γ-ray emissivity at $R > R_\odot$ should therefore show a latitude dependence, if the H_2

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contribution is significant, and if the H I alone is used to determine the γ-ray emissivity.

To determine the γ-ray emissivity at $R > R_{\odot}$, we use the *COS B* data in the longitude range covered by the Weaver and Williams (1973) H I survey in the second and third quadrants. Gamma-ray intensity maps have been derived from the *COS B* data base described by Mayer-Hasselwander *et al.* (1982), supplemented by later observations. The decrease in instrument sensitivity as a function of its lifetime in orbit has been taken into account by comparison of measured intensities from many selected regions along the galactic plane which were viewed at different epochs. An E^{-2} input spectrum, as derived for the diffuse emission in the solar neighbourhood (see, e.g., Lebrun *et al.* 1982), has been assumed when taking into account the energy dependence of the instrument response for the determination of the γ-ray intensities. The correction for the isotropic background emission (mainly instrumental) is left as a free parameter. Those regions where contamination from seven known pointlike γ-ray sources (Swanenburg *et al.* 1981) and known concentrations of molecules between $l = 107°$ and $l = 113°$ might affect the analysis are excluded. We analyse the remaining data in the longitude range $l = 95°$–$245°$ and the latitude range $|b| < 10°$.

The H I survey data are corrected to obtain the brightness temperature T_b (Williams 1973), and an optical depth correction is made assuming that the spin temperature is everywhere 125 K. The resulting data are convolved with the *COS B* point spread function (Hermsen 1980), and the H I survey of Heiles and Habing (1974) is used to obtain the contribution to the convolved maps from $|b| > 10°$. The H I data are binned in $4° \times 2°$ ($l \times b$) bins and compared to the *COS B* data along the same lines of sight.

The data are analyzed by comparing I_{γ} and N(H I) bin by bin in the energy ranges 70 MeV–5 GeV and 150 MeV–5 GeV. The results are presented in Figures 1*a* and 1*b*.

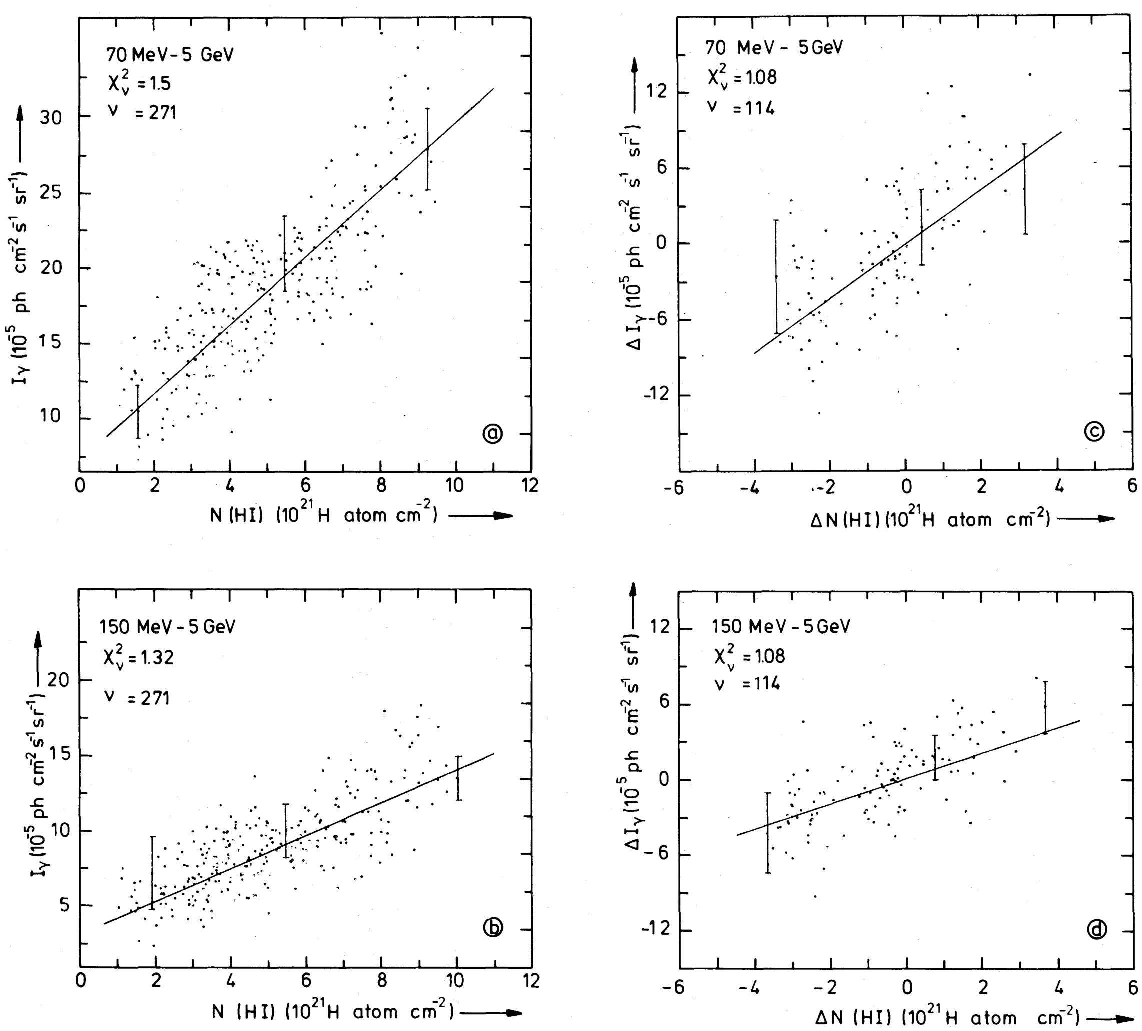

FIG. 1.—Comparison of γ-ray intensities and H I column densities in the second and third galactic quadrants for two energy ranges. Plots *a* and *b* show I_{γ} vs. N(H I) in $4° \times 2°$ ($l \times b$) bins. Plots *c* and *d* show ΔI_{γ} vs. ΔN(H I) [for definition of ΔI_{γ} and ΔN(H I), see text] in the same bin sizes. The statistical error bars given are characteristic for most points. The solid lines indicate the least squares fits to the data points, and their slopes correspond to the γ-ray emissivities in Table 1.

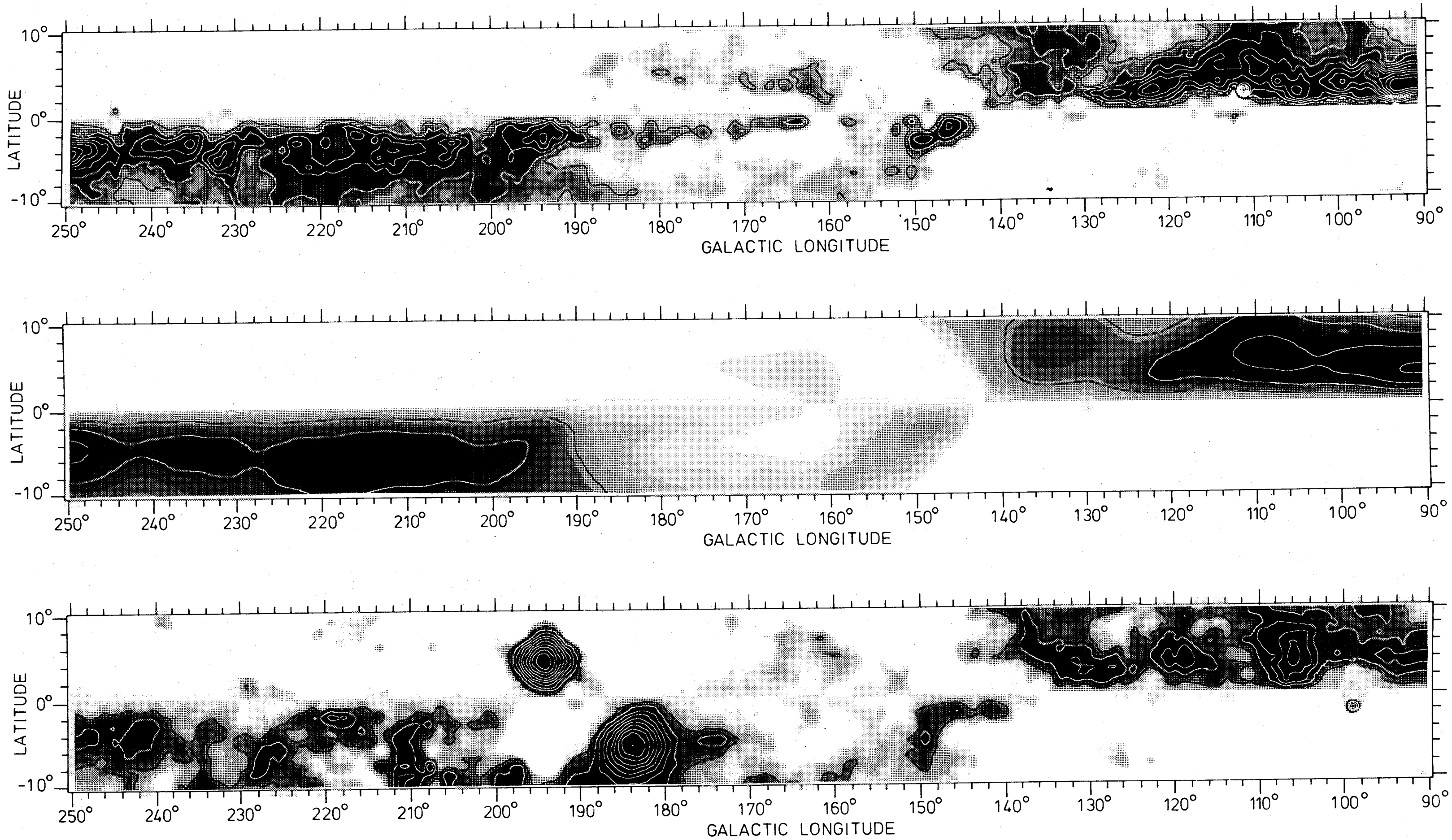

FIG. 2.—Two-dimensional maps of the differential H I column density ΔN(H I) (Figs. 2*a* and 2*b*) and the differential γ-ray intensity ΔI_γ (Fig. 2*c*) in the second and third galactic quadrants. For those positions where the differences are negative, the absolute values are indicated at the equivalent negative latitudes. (*a*) ΔN(H I). Contour values: (1, 2, 3, ...) $\times 10^{21}$ H atom cm^{-2}. (*b*) The same quantity, but after convolution of N(H I) with the point spread function of the *COS B* experiment for the energy range 70 MeV–5 GeV (contour values as in Fig. 2*a*). (*c*) ΔI_γ (70 MeV–5 GeV). Contour values: (4, 8, 12, ...) $\times 10^{-5}$ photons cm^{-2} s^{-1} sr^{-1}. The strong excesses at about (185, −6) and (195,4) correspond to two strong γ-ray point sources.

TABLE 1

GAMMA-RAY EMISSIVITY ϵ_γ IN THE SECOND AND THIRD GALACTIC QUADRANTS AND $|b| < 10°$, AS DETERMINED FROM THE COMPARISON OF I_γ WITH N(H I) AND FROM THE COMPARISON OF ΔI_γ WITH ΔN(H I)

	ϵ_γ (150 MeV–5 GeV) (10^{-26} photons H atom^{-1} s^{-1} sr^{-1})	ϵ_γ (70 MeV–5 GeV) (10^{-26} photons H atom^{-1} s^{-1} sr^{-1})
From I_γ vs. N(H I)	1.06 ± 0.05	2.12 ± 0.07
From ΔI_γ vs. ΔN(H I)	1.01 ± 0.11	2.11 ± 0.19
Local	1.12[a]	2.52[a]

NOTE.—The local γ-ray emissivities are those given by Strong *et al.* 1982.
[a] Strong *et al.* 1982 mention that these values have systematic uncertainties of about 25% (for comparison with our outer Galaxy emissivities, see text).

A good correlation is evident in the figures. The slope of the least squares fit defines ϵ_γ in both energy ranges, the values of which are given in Table 1. The offset of the fit defines the isotropic background emission in both energy ranges. The background levels resulting from the present analysis are consistent with the values determined by Strong *et al.* (1982) (using the same *COS B* data base).

Since the background level entered the analysis as a free parameter, one would like to verify that the derived emissivities are independent of the resulting background. This may be done by subtracting the data at negative latitudes from those at equivalent positive latitudes to provide a comparison between ΔI_γ and ΔN(H I), where Δ is the excess emission at positive latitudes. This analysis is made possible because of the large-scale warp of the hydrogen layer and has the additional advantage (discussed in § III) that the gas contributing to ΔN(H I) is, on average, at a larger distance than that contributing to N(H I). Using ΔI_γ and ΔN(H I) therefore provides a measure of ϵ_γ at relatively larger galactocentric distances. Plots of a bin by bin comparison of ΔI_γ and ΔN(H I) are given in Figure 1*c* and 1*d*. The resulting values of ϵ_γ are also given in Table 1. Figure 2 presents the two-dimensional maps of ΔI_γ and ΔN(H I), showing the good detailed correlation between these quantities.

The values in Table 1 show that the emissivities determined from N(H I) and ΔN(H I) are in good agreement in both energy ranges. Therefore the background level determined from the analysis of N(H I) is reliable. Because Strong *et al.* (1982) and the present analysis treat the *COS B* data in the same way, and because the background levels are found to be consistent in both analyses, a direct comparison of our results can be made to the local emissivity values. In the systematic uncertainties (~25%) mentioned by Strong *et al.* in determining the local values, about 15% were due to uncertainties in the derived background levels. The emissivity in the 150 MeV–5 GeV range is equal to the local value of 1.1×10^{-26} photons H atom^{-1} s^{-1} sr^{-1} given by Strong *et al.* In the energy range of 70 MeV–5 GeV the emissivity is ~15% lower than the local value of 2.5×10^{-26} photons H atom^{-1} s^{-1} sr^{-1}. Because of remaining uncertainties of ~10% in determining the local value, it is unclear whether the decrease in the 70 MeV–5 GeV emissivity is significant. If it is significant, the decrease is mainly due to a lowered (by ~30%) emissivity in the 70–150 MeV energy range. A detailed analysis of this point will be the subject of the second paper of this series. *In any event, the values in Table 1 show that the emissivities determined from the* H I *data are equal to or less than the local values, thus justifying the assumption that, on average, the contribution from* H_2 *can be ignored in the outer Galaxy.* On the other hand, a large γ-ray emissivity gradient would mask a dependence on H_2, but this can be checked by an analysis of the latitude dependence of the emissivity.

To determine the latitude dependence, the data are analyzed as above for each latitude and the results are plotted in Figure 3. As before, the results are plotted separately for I_γ and ΔI_γ as well as for the two energy ranges we have analyzed. Figure 3 shows that there is no significant increase in the γ-ray emissivity at low latitudes. We therefore conclude that to within 7% (2 σ; Fig. 3*a*), molecular hydrogen can be ignored as a source of γ-rays in the outer Galaxy. Thus, on average, the γ-ray intensities in the outer Galaxy are shown to be dependent on N(H I) only. Since most of the H_2 in the outer Galaxy at $R > 11$ kpc is within $\pm 4°$ of the plane (see the catalog of Blitz, Fich, and Stark 1982), and ϵ_γ does not change at higher latitudes, the H_2 mass at $R > R_\odot$ cannot be more than $\sim 3 \times 10^8 M_\odot$.

In principle, the emissivities given in Table 1 should be corrected for a contribution from inverse Compton γ-rays and the small contribution from H_2. Kniffen and Fichtel (1981) and Sacher and Schönfelder (1983) have shown that although the inverse Compton effect may be significant in the inner Galaxy, it is small ($\lesssim 10\%$) for $R > R_\odot$ compared to the contribution from the cosmic-ray–matter interactions. For the contribution of γ-rays originating from H_2, a limit of ~7% has been given above for the outer Galaxy. Inclusion of these effects will negligibly change the tabulated emissivities because the low-energy photon field and the H_2 gas would have to be spatially well correlated with the H I. Since the correlations are probably fairly poor, we expect that the lower bound of the values given in Table 1 will only be lowered by a few percent.

III. THE RADIAL DISTRIBUTION

The good correlation between the γ-ray intensities and the H I column densities in the outer Galaxy, with the average ϵ_γ along the line of sight close to the local value, indicates that the γ-ray distribution must be strongly coupled to the H I distribution (at least for γ-rays in the 150 MeV–5 GeV range). The velocity information available from the 21 cm line can be used to determine the radial H I distribution, which, because of the near constancy of ϵ_γ will be very

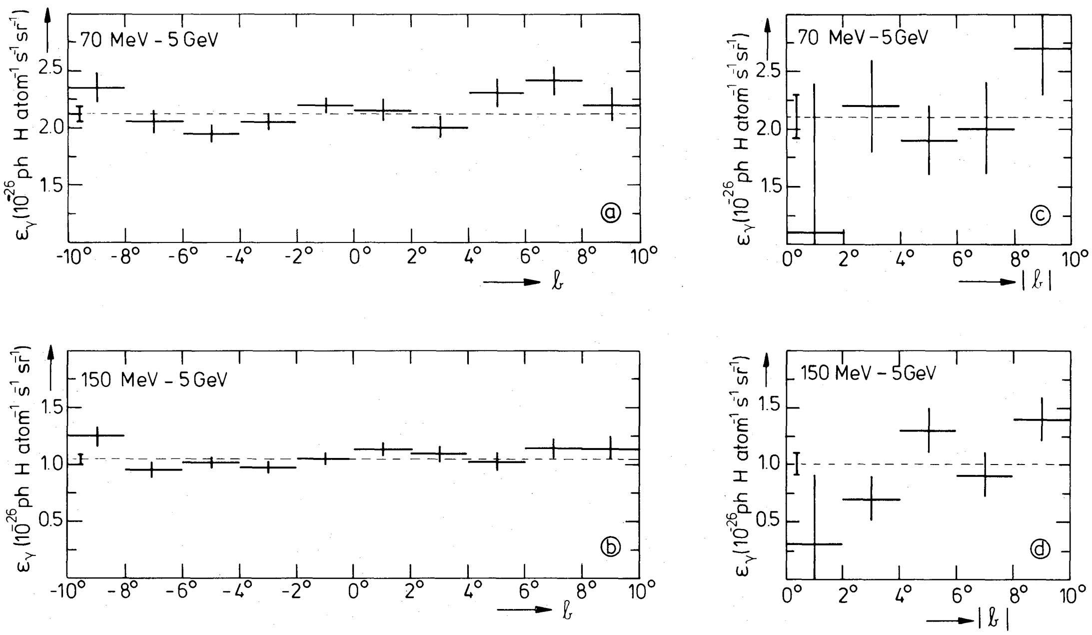

FIG. 3.—Gamma-ray emissivities ϵ_γ as a function of galactic latitude in the second and third galactic quadrants for the two energy ranges. Plots *a* and *b* show the results obtained by a comparison of I_γ and N(H I). Plots *c* and *d* present the results from the comparison of ΔI_γ and ΔN(H I). The dashed lines indicate the γ-ray emissivities for the total latitude range ($|b| < 10°$) given in Table 1.

similar to the radial γ-ray distribution. We use the rotation curve of the outer Galaxy of Blitz, Fich, and Stark (1980) as modified by Kulkarni, Blitz, and Heiles (1982) to determine distances beyond the solar circle.

To establish the radial distribution of the H I, we ask within what distance does 25%, 50% and 75% of the H I emission lie, and produce maps of these distances for both N(H I) and ΔN(H I). These maps are presented as Figures 4 and 5. The longitude range 165°–195° is excluded because one cannot obtain reliable kinematic distances.

A number of conclusions may be drawn from these maps regarding the H I distribution and consequently the γ-ray distribution. (1) The maps show that the distances are strongly latitude dependent which implies that emission near the plane tends to sample gas and γ-rays at larger distances than does the higher latitude emission, a result which has long been known. (2) ΔN(H I) samples gas and γ-rays at larger distances than N(H I) at a given l, b. The reason is that the maps of ΔN(H I) subtract the component of the relatively local distribution that is symmetric with respect to the galactic plane. The warp in the H I plane becomes more pronounced at larger galactocentric distances (see, e.g., Kulkarni, Blitz, and Heiles 1982); thus the asymmetric emission component at large distances is preferentially mapped by ΔN(H I). (3) About $\frac{1}{4}$ of the H I and γ-ray emission is found to be emitted from regions between $R \approx 14$ kpc and $R \approx 17$ kpc near the galactic plane. *The diffuse component of the galactic high-energy γ-ray emission therefore extends to very large galactocentric distances. Since ϵ_γ is nearly constant and nearly equal to the local value, the cosmic-ray density must be large and nearly equal to the local value at distances as large as 14–17 kpc from the galactic center.* In a recent study Schlosser and Feitzinger (1983) claim incorrectly that the major part of the γ-ray emission in the second and third quadrants is produced in the local spiral arm (for remarks on their analysis see Bloemen, Blitz, and Hermsen 1983). (4) The maps show a longitude dependence of the distance from which a given percentage of the emission originates in the sense that larger distances tend to occur at larger longitudes. This effect is caused by the spiral structure of the outer Milky Way which is best seen in the H I surface density plots of Kulkarni, Blitz, and Heiles (1982).

With regard to point (3) above, it is necessary to keep in mind that the remaining uncertainties of ~10% in the local emissivities of Strong *et al.* (1982) lead to uncertainties in the ratio of outer-Galaxy-to-local emissivities of ~10%. These ratios are 0.95 ± 0.10 for the 150 MeV–5 GeV range and 0.84 ± 0.09 for the 70 MeV–5 GeV range. In the most extreme case, one finds an average emissivity in the outer Galaxy which is 75% of the local value. We cannot exclude this possibility with the present analysis; such a lowered emissivity would imply that the distances within which 25%, 50%, and 75% of the γ-ray production is located are somewhat overestimated in the galactic plane. However, we point out that the close correlation between the γ-ray intensities and H I column densities shown in Figures 1 and 2 requires that any emissivity decrease be monotonic and smooth, as opposed to abruptly cutting off at some distance R. This can only be true if the production rate of γ-rays is still substantial at large R, validating the conclusion that the production of γ-rays is significant at distances of 14–17 kpc from the galactic center.

IV. THE GAMMA-RAY LUMINOSITY OF THE MILKY WAY

The diffuse component of the galactic γ-ray luminosity can be determined from mass estimates of the gas content of the Galaxy and the γ-ray emissivity. Since a small decrease

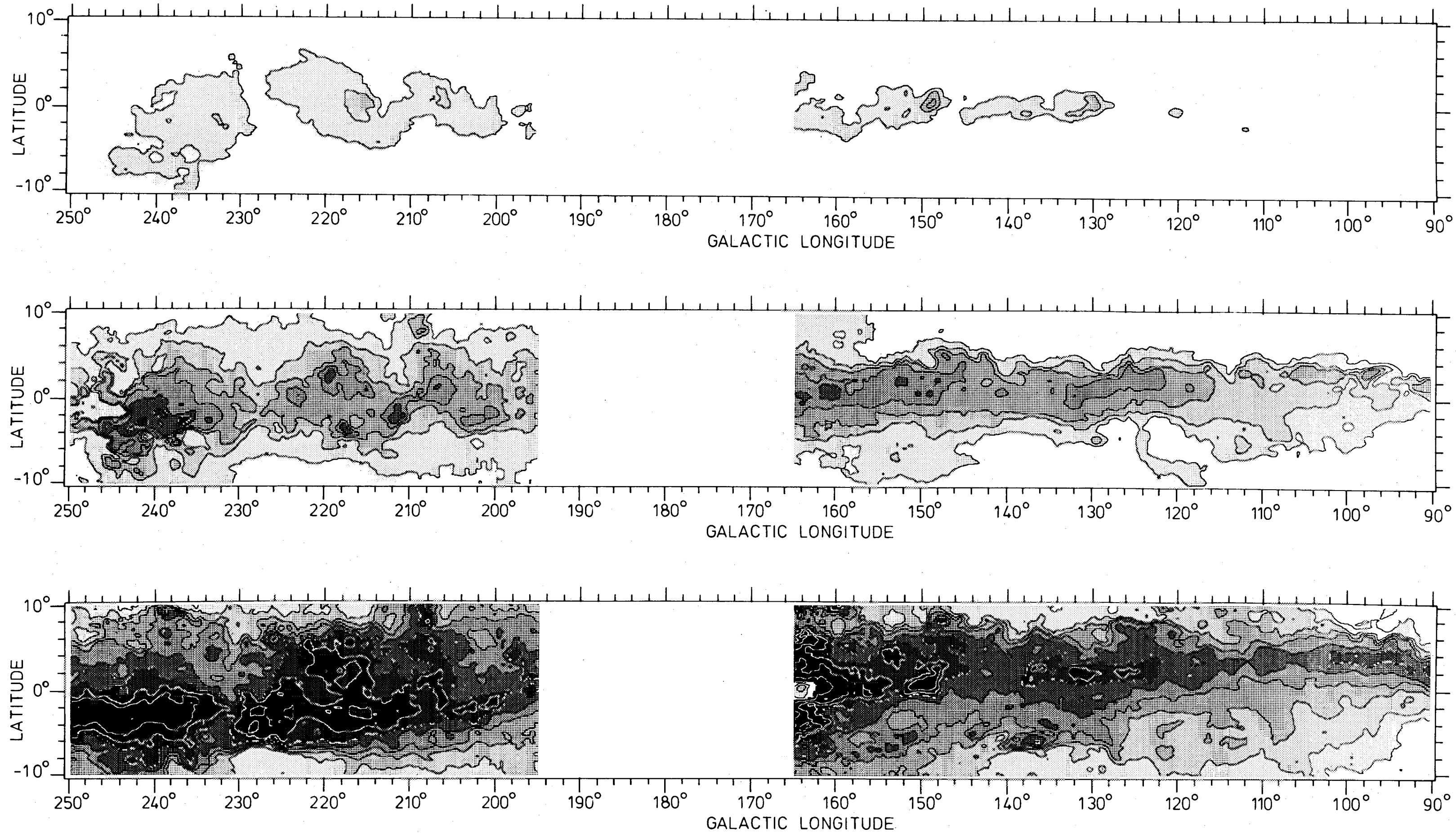

FIG. 4.—Two-dimensional maps of the galactocentric distances within which 25%, 50%, and 75% respectively of the total H I column density is located. The longitude range 165°–195° is excluded because in this range one cannot obtain reliable kinematic distances. Contour values: (11, 12, 13, ...) kpc.

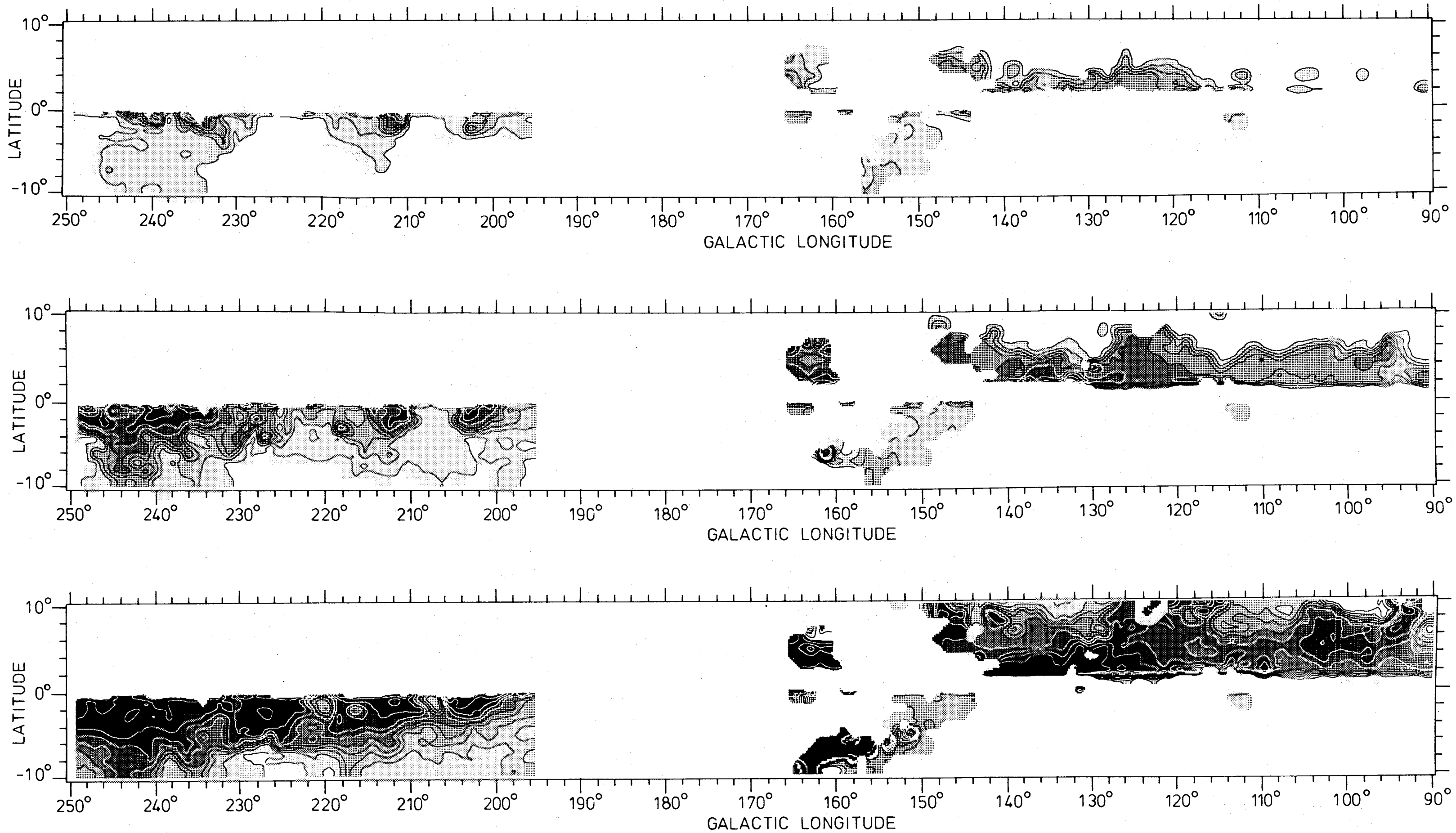

FIG. 5.—Two-dimensional maps of the galactocentric distances within which 25%, 50%, and 75% respectively of the differential H I column density $\Delta N(\text{H I})$ is located. The distances are only indicated for those positions where the difference $\Delta N(\text{H I})$ is larger than 15% of the total H I column density. For those positions where the differences are negative, the distances are indicated at the equivalent negative latitudes. Contour values: (11, 12, 13, ...) kpc.

of the γ-ray emissivity (70 MeV–5 GeV) seems to be present in the outer Galaxy, the luminosity has been determined separately for $R < R_\odot$ (using the local emissivities; see Table 1) and for $R > R_\odot$ (using the emissivities determined in this paper).

Henderson, Jackson, and Kerr (1982) derived a total H I mass of the Galaxy of $4.8 \times 10^9\ M_\odot$ of which about 80% is situated beyond the solar circle. Using a conversion factor $N(^{13}CO)/N(H_2) = 1 \times 10^{-6}$, Sanders derived a total H_2 mass for $R < 2$ kpc of $5 \times 10^8\ M_\odot$ and for 2 kpc $< R < R_\odot$ of $2.7 \times 10^9\ M_\odot$. The H_2 mass for $R > R_\odot$ is derived by Kutner and Mead (1981) and can also be estimated from the results of Solomon, Stark, and Sanders (1983) (see § II). In both cases a value of $\sim 3 \times 10^8\ M_\odot$ is obtained. Dickman (1978), however, proposes an $N(^{13}CO)/N(H_2)$ conversion factor which is about 2.5 times larger, thus reducing the total H_2 mass of the Milky Way by about a factor of 2.5.

Using the uncertainties in the H_2 mass mentioned above, a 10% uncertainty on the H I mass and the uncertainties in the γ-ray emissivities given in Table 1, the γ-ray luminosity of the Milky Way is determined to be $(1.8–3.2) \times 10^{42}$ photons s^{-1} for the energy range 70 MeV–5 GeV and $(0.9–1.5) \times 10^{42}$ photons s^{-1} for the 150 MeV–5 GeV range, *of which ~50% originates outside the solar circle.* An interpolation of the emissivities in the two energy ranges investigated yields a galactic luminosity of $(1.3–2.5) \times 10^{42}$ photons s^{-1} in the 100 MeV–5 GeV range, corresponding to $(1.6–3.2) \times 10^{39}$ ergs s^{-1} if an $E^{-1.8}$ power-law spectrum is assumed. These values are somewhat higher than the value $(1.2–1.5) \times 10^{42}$ photons (>100 MeV) s^{-1} derived by Caraveo and Paul (1979) and 2×10^{42} photons (70 MeV–5 GeV) s^{-1} derived by Mayer-Hasselwander *et al.* (1982) from unfoldings of the *SAS 2* and *COS B* γ-ray distributions, respectively.

V. CONCLUSIONS

For $R > R_\odot$:

1. The γ-ray intensity is proportional to N(H I) only, and $N(H_2)$ can be ignored to within the uncertainties of our analysis.
2. The γ-ray emissivity is independent of latitude to within 7%, which implies an upper limit of $3 \times 10^8\ M_\odot$ to the mass of H_2 in the outer Galaxy.
3. The γ-ray emissivity in the energy range 70 MeV–5 GeV is found to be only about 15% lower than the local value. If this result is statistically significant, it appears to be due to a gradient in the 70 MeV–150 MeV range (~30%).
4. About 25% of the γ-ray intensity originates from distances 14 kpc $< R <$ 17 kpc.
5. The density of cosmic rays is large and nearly equal to the local value at distances up to about 17 kpc from the galactic center. If the 30% decrease in the emissivity of the low-energy γ-rays is significant, then a gradient in the cosmic-ray electron density is required.
6. The γ-ray luminosity of the Milky Way is $(1.3–2.5) \times 10^{42}$ photons s^{-1} at energies above 100 MeV.

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