High-energy gamma rays and the large-scale distribution of gas and cosmic rays

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HIGH-ENERGY GAMMA RAYS AND THE LARGE-SCALE DISTRIBUTION OF GAS AND COSMIC RAYS

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ABSTRACT

The COS-B gamma-ray survey is compared with ^{12}CO and HI surveys in a region containing the Orion complex and in the outer Galaxy. The observed gamma-ray intensities in the Orion region (100 MeV<E<5 GeV) can be ascribed to the interaction of uniformly distributed cosmic rays with the interstellar gas. Calibration of the ratio between H_2 column-density and integrated CO line intensity resulted in the value: $(3.0\pm0.7)\times10^{20}$ molecules $cm^{-2}K^{-1}km^{-1}s$. In the outer Galaxy HI column-density maps in three galacto-centric distance ranges are used in combination with COS-B gamma-ray data to determine the radial distribution of the gamma-ray emissivity. A steep negative gradient of the emissivity for the 70 MeV-150 MeV range and an approximately constant (within $\sim$20%) emissivity for the 300 MeV-5 GeV range is found. The result is interpreted as a strong decrease in the cosmic-ray electron density and a near constancy of the nuclear component.

1. INTRODUCTION

The diffuse component of galactic gamma radiation in the energy band discussed in this paper (E>70 MeV) has long been interpreted to be mainly the result of the interaction of cosmic-ray (CR) electrons (via bremsstrahlung, the dominant process at low energies, $E \lesssim 150$ MeV) and CR nuclei (via π°-decay, dominant at higher energies, $E \gtrsim 300$ MeV) with the interstellar gas. The produced gamma-ray intensity, I_γ, can be formulated as follows:

$$I_\gamma = (q_\gamma/4\pi)\,[\,N(HI) + 2N(H_2)]\,, \qquad (1)$$

in which q_γ is the gamma-ray production rate per H atom and N is the

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column density of atomic hydrogen (HI) and molecular hydrogen (H_2) respectively. Therefore, gamma radiation is a tracer of the product of the CR density and the interstellar gas density. Gamma-ray measurements can provide a diagnostic of the CR density in regions where the interstellar gas is well traced at other wavelengths, as well as a diagnostic of the total gas content in cases where the CR density can be assumed to be equal to the value for the solar neighbourhood (local value, $\lesssim 1$ kpc). The latter has been verified at intermediate latitudes using galaxy counts as a total-gas tracer for the local interstellar medium [see e.g. Lebrun et al. (1982), Strong et al. (1982) and Lebrun and Paul (1983)]. A good correlation was found between gamma-ray intensities and total-gas column densities.

Sofar, the interstellar gas has been mapped on a large scale only for the atomic hydrogen component, using its characteristic 21-cm line. Large-scale surveys of molecular hydrogen are not possible and other molecules (especially CO) have to be used to trace this component. However, considerable ambiguity remains in the conversion of observed CO emission to H_2 column densities [see e.g. Lequeux (1981)]. Gamma-ray astronomy can provide new insight into this calibration problem.

In the actual comparison between measured gamma-ray intensities and atomic- and molecular-hydrogen column densities equation (1) becomes:

$$I_\gamma = (q_\gamma/4\pi)\,[N(HI) + 2XW_{CO}] + I_b, \tag{2}$$

where W_{CO} is the integrated temperature of the ^{12}CO 2.6-mm line (which is best mapped at the moment) and $X=N(H_2)/W_{CO}$ is the $N(H_2)$-to-W_{CO} conversion factor. I_b is the mainly instrumental background level. N(HI) and W_{CO} should be convolved with the energy-dependent point-spread function of the COS-B instrument (Hermsen, 1980) before making comparisons with the gamma-ray intensities. So, if the convolved distributions of N(HI) and W_{CO} show significant (and mutually different) structure, a multiple-linear regression method can be used to determine q_γ, X and I_b. In this paper a maximum-likelihood method, similar to that used by Lebrun et al. (1982), was applied on 1°x1° bins. We will concentrate on recent results obtained by the Caravane Collaboration for the COS-B gamma-ray satellite from the comparison of gamma-ray data with measurements at radio and millimetric wavelengths. The gamma-ray data used are those described by Mayer-Hasselwander et al. (1982), supplemented by later observations. HI column densities are determined from the Berkeley 21-cm line survey (Heiles and Habing, 1974; Weaver and Williams, 1973). The comparisons using ^{12}CO 2.6-mm line surveys are performed in collaboration with the Goddard Institute for Space Studies and Columbia University, who made the CO data available. For a detailed description and maps of the large-scale distribution of galactic gamma-ray emission see e.g. Mayer-Hasselwander et al. (1982) and Hermsen and Bloemen (1983), the latter together with large gamma-ray maps folded in the same volume.

2. THE ORION CLOUD COMPLEX

A region of the sky, away from the intense ridge of gamma radiation along the galactic plane, which is ideal to study eq. (2), is the region containing the nearby Orion cloud complex. Previous studies of one COS-B

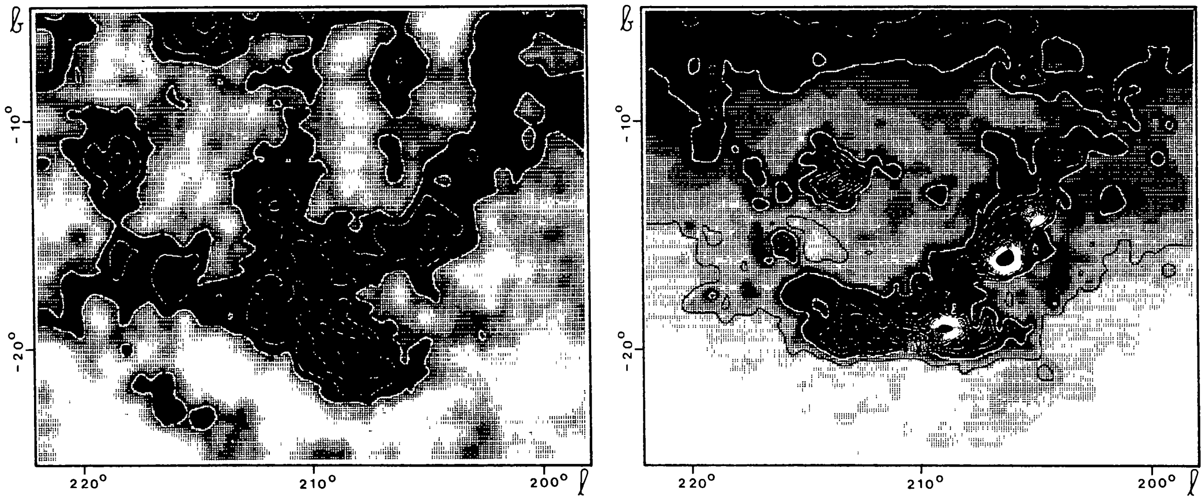

Figure 1: a) Observed gamma-ray intensities (100 MeV<E<5 GeV) in the Orion region. The isotropic background level ($\sim 5.5\times10^{-5}$ph cm^{-2}s^{-1}sr^{-1}) is not subtracted. Contour values: (12, 16, 20, ...)$\times10^{-5}$ph cm^{-2}s^{-1}sr^{-1}. b) Total gas column densities determined from N(HI) and integrated intensities W_{CO} of ^{12}CO-line emission at 2.6 mm, using the N(H_2)-to-W_{CO} ratio found in the present analysis. Contour values: (2, 4, 6, ...) 10^{21}H at cm^{-2}.

observation of the Orion complex (Caraveo et al., 1980, 1981) did reveal the cloud structure in gamma rays and did yield a total mass of the complex in agreement with independent radio-astronomical evaluations. Now all data are available to perform a three-parameter fit following eq. (2). The gamma-ray map of the region of the sky analysed is shown in Figure 1a for energies >100 MeV. For this analysis the high-energy range (300 MeV-5 GeV) is selected, since only for these energies the three parameters can be determined independently, exploiting the better angular resolution at high gamma-ray energies (HWHM $\sim$1°). The obtained value for the background level is consistent with other analyses of the same COS-B data base (e.g. Strong et al., 1982) and q_γ (300 MeV-5 GeV)/4π=(0.52±0.13)$\times10^{-26}$ph H at^{-1}s^{-1}sr^{-1}, in good agreement with the average local values determined by Strong et al. (1982) [(0.59±0.15)$\times10^{-26}$ph H at^{-1}s^{-1}sr^{-1}] using galaxy-count data at intermediate latitudes, and by Bloemen et al. (1984a and section 3) [(0.50±0.04) $\times10^{-26}$ph H at^{-1}s^{-1}sr^{-1}] from the radial distribution of the gamma-ray emissivity in the outer Galaxy. For the average N(H_2)-to-W_{CO} ratio is found X=(2.6±1.2)$\times10^{20}$molecules cm^{-2}K^{-1}km^{-1}s. Figure 1b shows the total mass distribution (HI plus H_2) using this conversion factor. It is verified that after convolution of the distribution in Figure 1b no significant differences exist between the structures in the convolved map and in Figure 1a.

For the energy range 100 MeV-5 GeV a three parameter fit is not possible, because after convolution with the broader COS-B point-spread function the N(HI) distribution resembles, over the largest part of the map, too closely the flat isotropic background level. Since in Caraveo et al. (1980, 1981) for E>70 MeV and above for E>300 MeV values for the CR density consistent with the local value are found, it seems reasonable to use the average local emissivity q_γ(100 MeV-5 GeV)/4π=1.7$\times10^{-26}$ph H at^{-1}

$s^{-1}sr^{-1}$ [derived from Bloemen et al. (1984a) and Strong et al. (1982)] as an input value for the analysis. Then a value for the conversion factor is obtained, consistent with the result for the 300 MeV-5 GeV range, namely $N(H_2)/W_{CO}=(3.0\pm0.7)\times10^{20}$ molecules $cm^{-2}K^{-1}km^{-1}s$, in which the error of 0.7 includes systematic uncertainties. Full details of the analysis are given by Bloemen et al. (1984b).

3. RADIAL DISTRIBUTION OF GAMMA RAYS AND COSMIC RAYS IN THE OUTER GALAXY

In the outer Galaxy no extensive millimetre-wave surveys have been completed yet. However, for this region Bloemen, Blitz and Hermsen (1984) have shown that the gamma-ray intensity is proportional to the HI column density alone to within the uncertainty of the analysis (the H_2 mass at $R>R_\odot$ they found to be $<3\times10^8 M_\odot$). Therefore the W_{CO} term can be deleted from eq. (2) and q_γ and I_b can be determined fitting the gamma-ray and N(HI) distribution. In addition, the kinematics of HI can be used to construct column-density maps in various galacto-centric distance ranges in the outer Galaxy. These maps can be used in combination with COS-B gamma-ray data to determine gamma-ray emissivities in these distance ranges. Bloemen et al. (1984a, details of the analysis are given in that paper) used the rotation curve of the outer Galaxy given by Blitz, Fich and Stark (1980) as modified by Kulkarni, Blitz and Heiles (1982) to determine distances beyond the

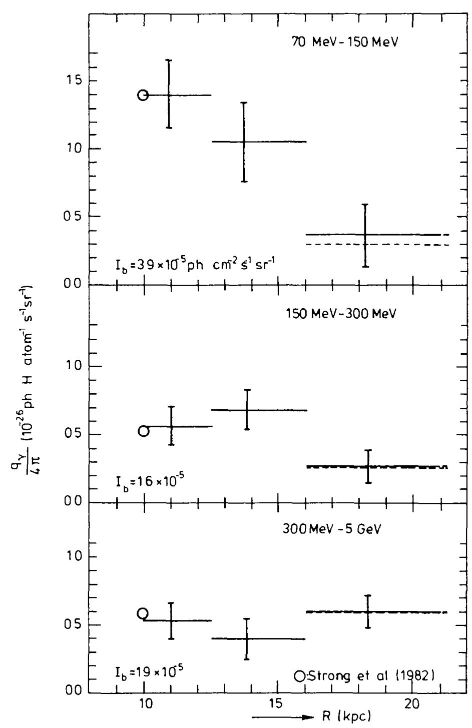

Figure 2. Radial distribution of q_γ in the outer Galaxy for three energy ranges. The resulting isotropic background levels I_b are given in the figures. The errorbars indicate formal 1σ errors. The dashed lines for R>16 kpc show the values of q_γ after correction for a π°-decay input spectrum.

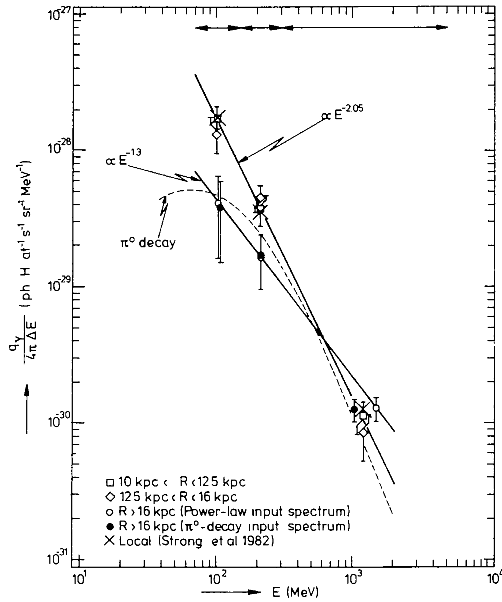

Figure 3. The gamma-ray emissivity spectrum for three distance ranges in the outer Galaxy. Formal (1σ) error bars are indicated. The used energy ranges are given at the top of the figure. Solid lines: power-law fits for R<12.5 kpc and R>16 kpc. Dashed curve: fit to a π°-decay spectrum (after Stephens and Badwahr, 1981).

solar circle. The analysis was performed in the longitude range covered by the Berkeley HI surveys for $95° < l < 245°$ and $|b| < 10°$. Gamma-ray intensity maps were derived in three energy ranges: 70 MeV-150 MeV, 150 MeV-300 MeV and 300 MeV-5 GeV. HI column-density maps have been constructed for the gas in three distance intervals: R<12.5 kpc (1), 12.5 kpc<R<16 kpc (2) and R>16 kpc (3).

The distribution of N(HI) in the three distance intervals is quite different. On a large scale this is due to the warp of the hydrogen layer, which is more pronounced for increasing galacto-centric distances [see e.g. Henderson, Jackson and Kerr (1982), Kulkarni, Blitz and Heiles (1982)]. On smaller scales the clumpiness of atomic hydrogen produces distinct differences in the distribution of N(HI) in the distance ranges selected. These differences in the projected distributions allowed the following two-dimensional correlation analysis. It was investigated which combination of gamma-ray emissivities in the three distance ranges best describes the observed gamma-ray distribution, using a relation of the form:

$$I_\gamma = (1/4\pi)\,[q_{\gamma,1}\,N(HI)_1 + q_{\gamma,2}\,N(HI)_2 + q_{\gamma,3}\,N(HI)_3] + I_b$$

where $N(HI)_1$, $N(HI)_2$, $N(HI)_3$ are the convolved HI column densities in the three distance ranges. A maximum-likelihood method, similar to that used in Section 2, was applied on 1°x1° bins to determine the three emissivities and I_b for each energy range. The resulting fit values show that the emissivity decreases with increasing R for the 70 MeV-150 MeV range, while the emissivity for high energies (300 MeV-5 GeV) remains approximately constant (within 20%) out to large distances (Figure 2). For the 70 MeV-

150 MeV range the likelihood was found to reduce by a factor of about 10 when a constant emissivity is assumed.

Figure 3 presents the resulting gamma-ray emissivity spectrum for the three distance ranges. There is a clear hardening of the spectrum for increasing galacto-centric distances outside the solar circle. The best power-law fits are indicated in the figure. For R>16 kpc, the spectrum is equally well fitted by a π°-decay spectrum and is thus the first measurement of a diffuse gamma-ray spectrum significantly different from the local gamma-ray spectrum and consistent with the π°-decay spectrum.

These results can be interpreted as 1) a decrease of the density of cosmic-ray electrons with energies up to several hundreds of MeV, such that at large ($\sim$18 kpc) galacto-centric distances the electron density is approximately zero, and 2) a near-constancy of the density of cosmic-ray nuclei with energies of a few GeV, out to large distances [see Bloemen *et al.* (1984a) for a detailed discussion].

The variation of the electron component is consistent with low-frequency radio-continuum observations [e.g. at 30 MHz Webber *et al.* (1980) and at 408 MHz Phillips *et al.* (1981)]. The results confirm a galactic origin of electrons with energies up to several hundreds of MeV. For cosmic-ray nuclei with energies of a few GeV either confinement in a large halo or an extra-galactic origin is suggested by the data.

REFERENCES

Blitz, L., Fich, M., and Stark, A.A.: 1980, in *Interstellar Molecules*, ed. B. Andrew, Reidel, Dordrecht, p.213

Bloemen, J.B.G.M., Blitz, L., and Hermsen, W.: 1984, Ap.J., in press

Bloemen, J.B.G.M., et al.: 1984a, Astron. Astrophys., submitted

Bloemen, J.B.G.M., et al.: 1984b, Astron. Astrophys., in prep

Caraveo, P.A., et al.: 1980, Astron. Astrophys., 91, L3

Caraveo, P.A., et al.: 1981, *Proc. 17th Int. Cosmic Ray Conf.*, Paris, 1, p.139

Heiles, C., and Habing, H.J.: 1974, Astron. Astrophys. Suppl. 14, p.1

Henderson, A.P., Jackson, P.D., and Kerr, F.J.: 1982, Ap. J. 263, p.116

Hermsen, W.: 1980, Ph. D. Thesis, University of Leiden, The Netherlands

Hermsen, W. and Bloemen, J.B.G.M.: 1983, in *Southern Galactic Surveys*, eds. F.P. Israel and W.B. Burton, Reidel, Dordrecht, p.65

Kulkarni, S.R., Blitz, L., and Heiles, C.: 1982, Ap. J. Letters 259, L63

Lebrun et al.: 1982, Astron. Astrophys. 107, p.390

Lebrun, F., and Paul, J.A.: 1983, Ap. J. 266, p.276

Lequeux, J.: 1981, Comments on Astrophysics, 9, p.117

Mayer-Hasselwander, H.A., et al.: 1982, Astron. Astrophys. 105, p.164

Phillipps, S., et al.: 1981, Astron. Astrophys. 98, p.286

Stephens, S.A., and Badwahr, G.D.: 1981, Astrophys. and Space Science 76, p.213

Strong, A.W., et al.: 1982, Astron. Astrophys. 115, p.404

Weaver, H., and Williams, D.R.W.: 1973, Astron. Astrophys. Suppl. 8, p.1

Webber, W.R., Simpson, G.A., and Cane, H.V.: 1980, Ap. J. 236, p.448

DISCUSSION printed after Cesarsky's Review Paper in Section II4.