PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The γ-ray Emissivity of the Local Interstellar Medium from Correlations with Gas at Intermediate Latitudes [and Discussion]

A. W. Strong, A. W. Wolfendale and H. Elliot

Phil. Trans. R. Soc. Lond. A 1981 **301**, 541-554
doi: 10.1098/rsta.1981.0132

Phil. Trans. R. Soc. Lond. A **301**, 541–554 (1981)
Printed in Great Britain

II. DIFFUSE γ-RAYS AND THE EXTRAGALACTIC COMPONENT

The γ-ray emissivity of the local interstellar medium from correlations with gas at intermediate latitudes

By A. W. Strong and A. W. Wolfendale, F.R.S.
Department of Physics, The University, Science Laboratories, South Road, Durham DH1 3LE, U.K.

A survey of recent studies of the correlation between γ-rays from latitudes $|b| > 10°$ and gas tracers is presented. Results for the ranges 35–100 MeV and above 100 MeV from the SAS-2 satellite, and for energies between 70 and 5000 MeV from the COS-B satellite, are used to obtain an estimate of the γ-ray emissivity spectrum for all forms of gas. Good agreement between the two experiments is found. A comparison is made between this spectrum (which is an average for a region some few hundred parsecs around the Sun) and that expected for recent estimates of the low energy electron spectrum in the local interstellar medium. If the pion-decay component is as expected for the demodulated interplanetary proton spectrum, then the electron spectrum must have a steep slope (differential index 2.8) below 1 GeV. If the pion contribution is smaller than expected, however, a flatter electron spectrum is allowable.

The presence of a component of γ-ray emission related to gas in molecular form is evident in both the SAS-2 and COS-B data. We discuss the correlation of the SAS-2 data with both components and show that the emissivities of each component can be independently determined. The longitude dependence of the emission is also discussed.

Finally, an examination of the γ-ray fluxes from specific dense clouds of molecular gas is made.

1. Introduction

Studies of cosmic γ-rays have as their objective the elucidation of the nature of the localized sources, and the distribution and other characteristics of the cosmic-ray particles whose interactions with the interstellar medium produce the diffuse γ-ray component. The present work relates to the diffuse component, and in particular we summarize studies that have been made by using data from the SAS-2 and COS-B satellites to determine the γ-ray emissivity spectrum within a few hundred parsecs of the Sun. In this context the work differs from many previous studies (e.g. our own work, Strong & Wolfendale 1978), which have usually referred to much larger regions of space.

The choice of data, both for γ-rays and gas tracers, is dictated by the following possible conditions and sources of error:

(*a*) availability of a 'total gas' tracer;
(*b*) presence of a point source contribution;
(*c*) presence of contributions from distances outside the local region, i.e. beyond about 500 pc;
(*d*) effect of purely geometrical correlations;
(*e*) adequate statistics.

Conditions (*b*) and (*c*) can be avoided by using only data for latitudes $|b| > 10°$. The only currently available tracer of total gas (atomic, molecular and ionized) which also covers large areas of the sky at high latitudes is the Lick galaxy count data (Shane & Wirtanen 1967), so that to satisfy (*a*) only the Northern celestial hemisphere can be used. Geometrical effects (due to our position in the Galaxy) can never be eliminated, but can be minimized by restricting the analysis to limited ranges of latitude. This, however, can conflict with (*e*) and so a compromise is necessary in the choice of region.

The general assumption for these studies is the relation

$$I_\gamma(E) = (q(E)/4\pi)\ \tilde{N}_{\mathrm{H}} + I_{\mathrm{b}}, \tag{1.1}$$

where $\tilde{N}_{\mathrm{H}}$ is the hydrogen column density convolved with the instrumental response, $I_\gamma(E)$ is the γ-ray flux, $q(E)$ is the γ-ray emissivity at energy E and I_{b} is the total background, which includes all contributions that are not correlated with N_{H}. The production from nuclei with $Z > 1$ (about 40% by mass) need not be considered until comparison with absolute predictions is made. This relation holds only for a uniform local cosmic-ray flux and for the case where this flux is the same inside and outside molecular clouds. To remove the latter restriction we may wish to generalize (1.1) to

$$I_\gamma(E) = (q_1/4\pi)\tilde{N}_{\mathrm{H\,I}} + (q_2/4\pi)\tilde{N}_{\mathrm{H_2}} + I_{\mathrm{b}}, \tag{1.2}$$

where q_1 and q_2 are the emissivities of the atomic and molecular components. (The 'E' has been dropped from $q(E)$ but it is to be understood that the q-values are functions of E.) The outcome of this work might be expected to be the demonstration that $q_1 = q_2$ thus indicating that there is an internal consistency in the relation between the various parameters describing the gas and the γ-rays (coupled with a complete penetration of the molecular gas by the cosmic rays).

The first detailed study of high-latitude γ-ray–gas correlations was made by Fichtel *et al.* (1978*a*) using the SAS-2 data and only 21 cm atomic hydrogen column densities ($N_{\mathrm{H}} = N_{\mathrm{H\,I}}$ in equation (1.1)), for latitudes $|b| > 12.8°$. The results of these authors are summarized in table 1 together with the other results to be considered later in this paper.

In addition to large-scale correlations a brief discussion will also be made of some specific restricted regions of dense gas which are present at latitudes $|b| > 10°$.

2. Galaxy counts as a total gas tracer

Since the work to be described in this paper has made extensive use of the Lick galaxy counts as a measure of total absorption along the line-of-sight, some account of this method is given here. The total gas column density is estimated from

$$N_{\mathrm{Ht}} = \frac{1.5 \times 10^{21}}{\gamma} \lg \frac{N_{\mathrm{g}}^0}{N_{\mathrm{g}}}\ \mathrm{cm}^{-2}, \tag{2.1}$$

where N_{g} is the number of SW galaxies per square degree. The best values for the parameters γ and N_{g}^0 for use in this type of work have been discussed in detail by Strong & Lebrun (1980), who conclude that $\gamma = 0.75$ and $N_{\mathrm{g}}^0 = 50$ are preferred. These values have been adopted in all determinations given in this paper (conversion of results to this system being made where necessary). The value of γ is smaller than that derived by other workers (Heiles 1976; Burstein & Heiles 1978) and the reader is referred to Strong & Lebrun for a full explanation of the reasons for the difference.

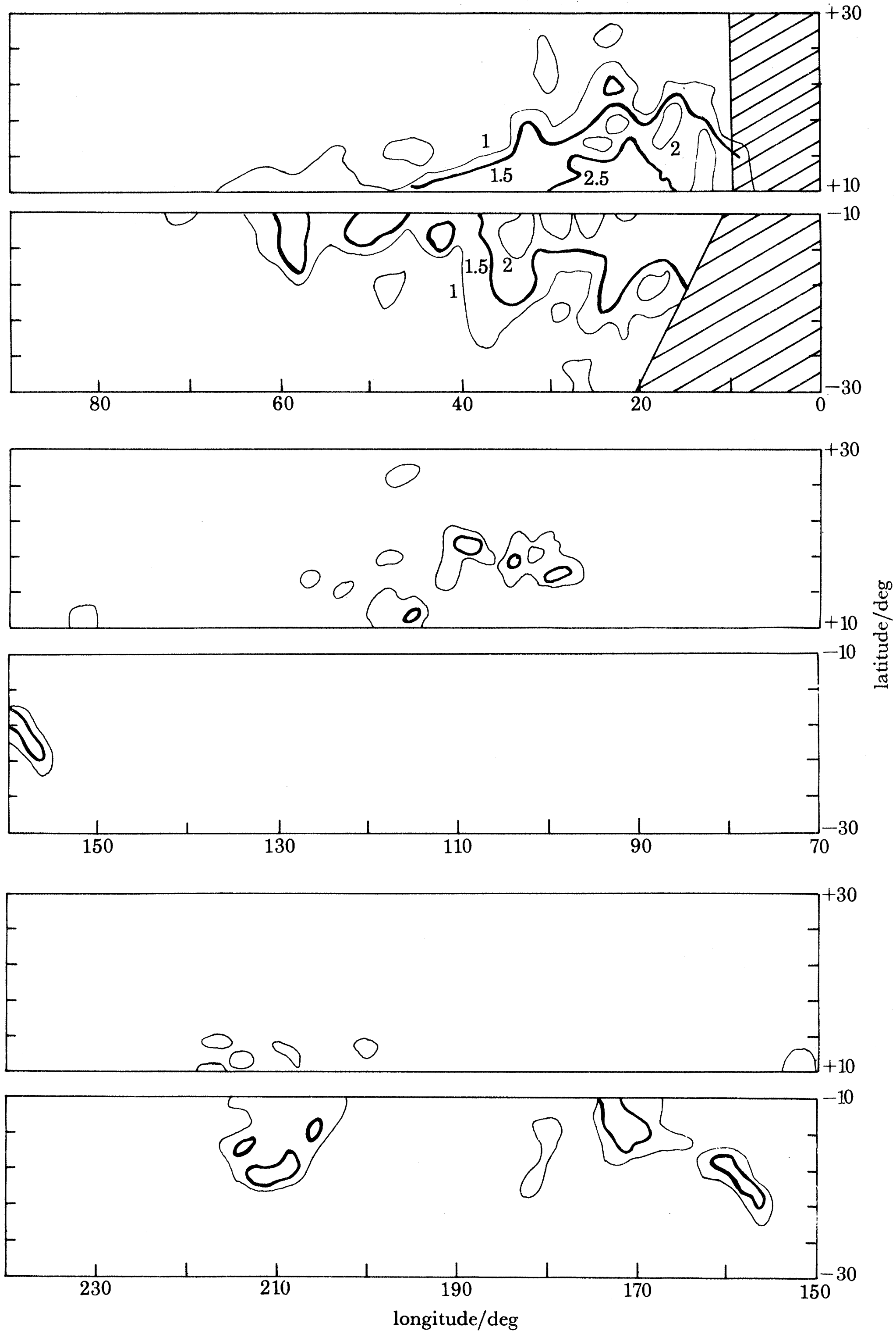


FIGURE 1. Distribution of molecular hydrogen column densities for $240° > l > 10°$ and $30° > |b| > 10°$ as derived from galaxy counts and atomic hydrogen column densities by Strong & Lebrun (1980). The contour interval is $5 \times 10^{20}\ cm^{-2}$ and the lowest contour is $1.0 \times 10^{21}\ cm^{-2}$.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

On the basis of (2.1) Strong & Lebrun give a map of molecular hydrogen column densities for $30° > |b| > 10°$ and $240° > l > 10°$. This is shown in figure 1. The map is derived by subtracting the atomic hydrogen column density (from 21 cm surveys) from the total column density. Because of possible variations in the gas : dust ratio, and the effects of galaxy clustering, equation (2.1) is at best a noisy estimate of total gas, and fine details in figure 1 are not significant. It does however illustrate the large-scale features of the distribution. The two large concentrations for $60° > l > 10°$ are of particular importance, the northern part being associated with Gould's belt. The southern part is referred to as 'region A' following Lebrun & Paul (1980) and Strong & Lebrun (1980). Other prominent features are the Orion clouds at $l \approx 210°$ and the Taurus clouds at $l \approx 170°$.

TABLE 1

reference	experiment	longitude deg	latitude deg	linear fit to	$(q/4\pi)/(10^{-26}\ s^{-1}\ sr^{-1}\ atom^{-1})$ 35–100 MeV	> 100 MeV	
Fichtel *et al.* (1978*a*)	SAS-2	0–360	$\|b\| > 12.8$	N_{H_I}	4.3 ± 1.5	3.0 ± 0.8	
Lebrun & Paul (1980)	SAS-2	0–360	$\|b\| > 10$	N_{H_I}	4.5 ± 0.3	3.5 ± 0.2	
			$\delta > -25$	N_{Ht}	3.0 ± 0.2	2.0 ± 0.15	
This work	SAS-2	0–240	$20 > \|b\| > 10$	N_{H_I}	$q_1 = 3.2 \pm 1.0$	$q_1 = 3.1 \pm 0.5$	
				N_{H_2}	$q_2 = 4.0 \pm 1.5$	$q_2 = 1.9 \pm 0.6$	
			$\delta > -25$	N_{Ht}	3.7 ± 1.0	2.6 ± 0.5	
assumed sensitive area (this table)†					40 cm²	59 cm²	
					70–150 MeV	150–300 MeV	300–5000 MeV
Lebrun *et al.* (1980)	COS-B	10–240	$20 > \|b\| > 10$	N_{H_I}	1.15 ± 0.17	0.76 ± 0.10	0.84 ± 0.08
			$\delta > -25$	N_{Ht}	1.45 ± 0.15	0.54 ± 0.07	0.46 ± 0.07
assumed sensitive area (this table)					25.1 cm²	41.1 cm²	47.0 cm²

assumed conversion for galaxy counts: $N_{Ht} = 2.0 \times 10^{21} \lg (50/N_g)\ cm^{-2}$.

† Except for Fichtel *et al.* (1978*a*).

3. ANALYSES OF SAS-2 DATA

As mentioned in § 1, an extensive analysis of the correlations of the SAS-2 fluxes with atomic hydrogen was given by Fichtel *et al.* (1978*a*). With the publication of the tabulated SAS-2 data (Fichtel *et al.* 1978*b*) giving counts and exposure in two energy ranges (35–100 MeV and above 100 MeV), other studies have also been made. Here we report the work of Lebrun & Paul (1980) (L.P.) and of the authors of this paper (see Issa *et al.* 1980*a*). Table 1 summarizes the results, adjusted as mentioned above to a uniform conversion from galaxy counts to gas column density.

3.1. *Lebrun* & *Paul* (1980)

These authors used the SAS-2 data for latitudes $|b| > 10°$, the Lick galaxy counts as given by Seldner *et al.* (1977) and the Heiles & Habing (1974) 21 cm survey.

The fits were made by maximum likelihood, and results are given for $N_H = N_{H_I}$ and $N_H = N_{Ht}$ in equation (1.1). L.P. give the values in a form that allows the energy response of the SAS-2 detector to be explicitly included in comparison with theoretical spectra; for comparison with other work, in table 1 we give the emissivities for particular values of the sensitive area taken from Fichtel *et al.* (1978*b*) for $|b| < 10°$. This procedure is appropriate if the galactic-plane emission is dominated by the diffuse (i.e. non-source) component, as appears to be so. The

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

procedure is of course only justified if, as should be the case here, the isotropic component, with its steeper spectrum (Fichtel *et al.* 1978*a*), has been eliminated by fitting to equation (1.1). Conversion to other sensitive areas and spectra can be made if required.

Inspection of the L.P. results in table 1 shows that the use of N_{Ht} rather than $N_{\mathrm{H_I}}$ reduces the emissivity per atom by 30–40% for the ranges of l and b considered. Such a reduction would be expected if N_{Ht} and $N_{\mathrm{H_I}}$ were well correlated (25% is roughly the fraction of local gas in molecular form (Bohlin *et al.* 1978)).

Some information can be obtained about the shape of the electron spectrum from the results. L.P. (after the original suggestion by Fichtel *et al.*) conclude that a steep electron spectrum (differential index 2.8) below 1000 MeV is required to explain the low energy γ-ray spectrum in terms of bremsstrahlung, if the pion-decay component is as expected for the local directly observed proton spectrum (see also Cesarsky *et al.* 1978; Hartman *et al.* 1979). Some confirmation comes from the COS-B results as described later; other interpretations are also possible however (§ 6).

In a previous paper, Lebrun & Paul (1979) showed that the residuals of the SAS-2 γ-ray intensity with respect to a fit to $N_{\mathrm{H_I}}$ correlate strongly with residuals for a fit of lg N_{g} to $N_{\mathrm{H_I}}$, thus providing additional evidence for the component of γ-ray emission related to the non-atomic gas first noted by Puget *et al.* (1976).

3.2. *This paper*

3.2.1. *Method for testing* (1.2)

The presence of a large signal from molecular gas in the SAS-2 data suggests the possibility of testing the more general relation given in equation (1.2). To do this, we have used the likelihood function

$$L(q_1, q_2, I_{\mathrm{b}}) = \prod_{\mathrm{bins}} \frac{\exp(-AI_\gamma)(AI_\gamma)^{n_i}}{n_i!}, \tag{3.1}$$

where n_i is the number of γ-rays observed in the ith bin on the sky and A is the effective exposure for an assumed spectral shape within the energy range. The information about q_1 and q_2 available in the data is conveniently displayed in the form of contours of the maximum-likelihood ratio λ defined by

$$\lambda(q_1, q_2) = -2\ln\{\max_{I'_{\mathrm{b}}} L(q_1 q_2 I'_{\mathrm{b}})/\max_{q'_1 q'_2 I'_{\mathrm{b}}} L(q'_1 q'_2 I'_{\mathrm{b}})\}, \tag{3.2}$$

which is distributed under fairly general conditions as χ^2_2 (see Eadie *et al.* 1971) for two constraints (q_1 and q_2). This approach has several advantages: it shows clearly the effect of correlations between the 'independent' variables $N_{\mathrm{H_I}}$ and $N_{\mathrm{H_2}}$, and gives a reliable error estimate. If $N_{\mathrm{H_I}}$ and $N_{\mathrm{H_2}}$ form orthogonal sets the λ-contours will be ellipses with axes parallel to the q_1- and q_2-axes (or circles if $q_1 = q_2$) indicating that q_1 and q_2 can be separately estimated (though in general with differing accuracy).

The situation for a fit to N_{Ht} only is found by taking the line $q_1 = q_2$, as is apparent from equation (1.2). Similarly, putting $q_2 = 0$ gives the fit to $N_{\mathrm{H_I}}$ alone.

3.2.2. *Application to SAS-2 data*

The method has been applied to the region $20° > |b| > 10°$, $240° > l > 10°$, declinations greater than $-25°$ being chosen to correspond to the analysis of COS-B data by Lebrun *et al.* (see § 4), the same reasoning being used as in that paper for the choice of area. We also give results for the subregions of longitude $120° > l > 10°$ and $240° > l > 60°$. The latter is intended to test the effect of removing the extended regions of high absorption in the inner quadrant of the Galaxy mentioned in §2 (i.e. $10° < l < 60°$). Ideally, results should also be given for this region separately, but the statistical weight of the data is not good enough here, so we have chosen $120° > l > 10°$ as a compromise.

The 21 cm data used here are from the Berkeley survey (Weaver & Williams 1973, 1974) integrated on the assumption of a uniform spin temperature of 120 K.

Figure 2*a* shows the $\lambda(q_1, q_2)$ contours for $\lambda = 1.0$ (corresponding to 67% confidence of 1σ) for $100 > E > 35$ MeV and $E > 100$ MeV, for the various regions of l and b.

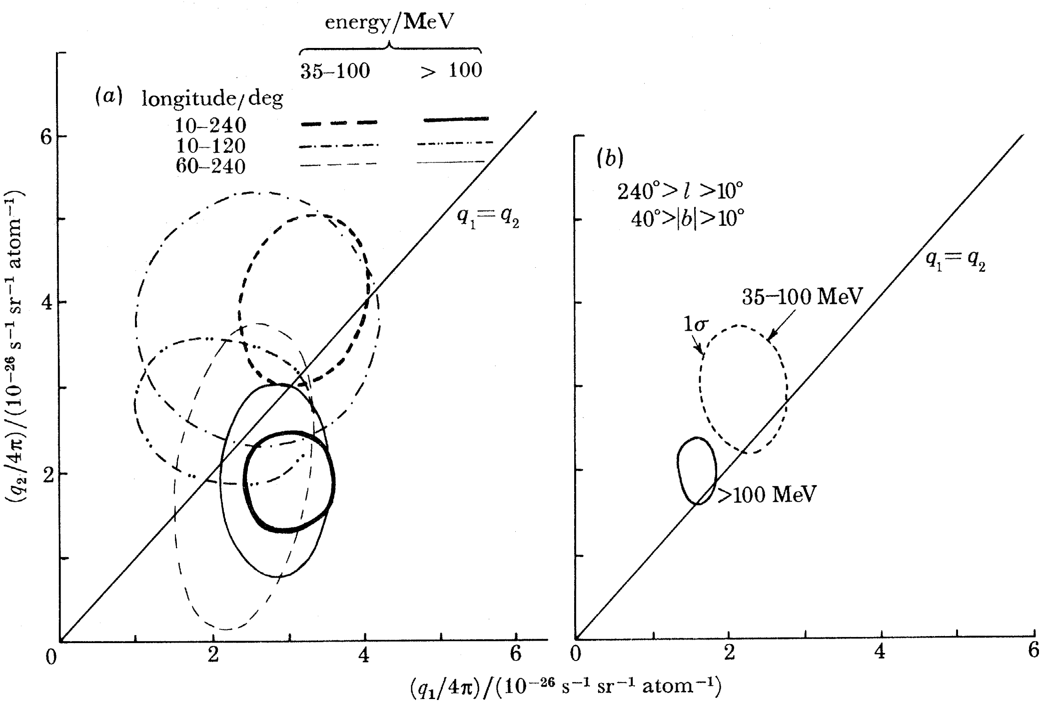


FIGURE 2. Contours of λ (q_1, q_2) (defined in the text) for SAS-2 data showing allowable ranges of q_1 and q_2 for longitudes $240° > l > 10°$, $240° > l > 60°$ and $120° > l > 10°$ and latitude range (*a*) $20° > |b| > 10°$ and (*b*) $40° > |b| > 10°$. The line of $q_1 = q_2$ gives the fit to N_{Ht} alone.

3.2.3. *Discussion*

The most important result is that the HI and H_2 'signals' are clearly separated in both energy ranges and in each region. As discussed above, the effect of correlations between N_{HI} and N_{H_2} is displayed clearly in the q_1–q_2 plots; in the present case, the HI and H_2 column densities are evidently sufficiently 'orthogonal' as seen from the solar vicinity to allow independent determination of q_1 and q_2. The accuracy of the q_2-determination is however very poor for the divided regions, but improves when the whole region is taken.

A feature that cannot be ignored is the apparent difference in spectral shape between q_1 and q_2; there is a trend for q_2/q_1 to be larger for $35 > E > 100$ MeV than for $E > 100$ MeV. This is of little significance by itself ($q_2/q_1 = 1.0$ is consistent with all the data, as can be seen from figure 2), but the effect is in the same direction as that seen in the COS-B data at higher energies (Lebrun *et al.* 1980). However, as described in § 3.2.4 the effect seems to be mainly

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

from the range $60° > l > 10°$, and is probably not a general property of the local interstellar medium. Further, on extension of the analysis to $|b| = 40°$, the effect disappears (figure 2*b*).

Our values of q_1 and q_2 are summarized in table 1 for comparison with L.P.; as described in §3.1, a common system for assumed sensitive-area and galaxy-count calibration has been used, so that any differences are due to the nature of the fits and the regions used. Exact agreement is not expected because of these differences; within the quoted errors (larger for our work because of the narrower range of latitude) the values are consistent, and we may be reasonably confident in proceeding to a comparison with theoretical spectra.

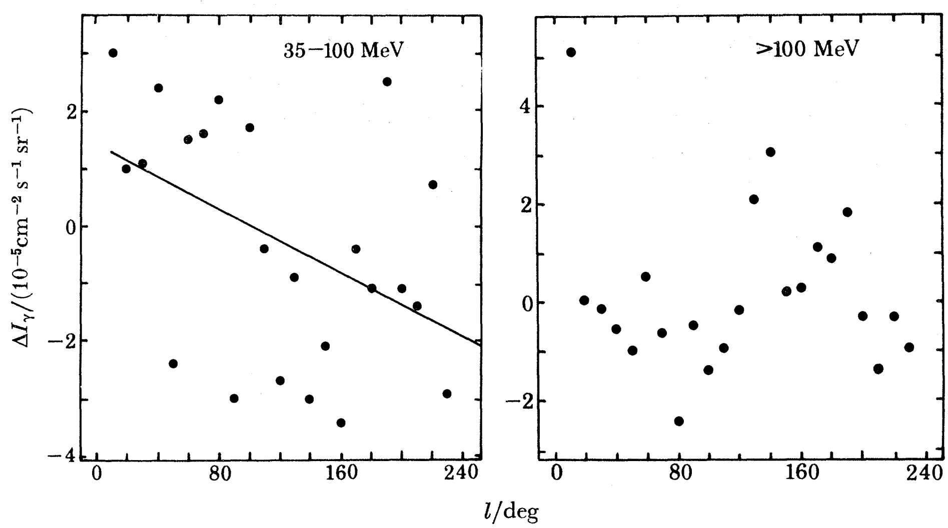


FIGURE 3. Distribution of residuals from the fit to equation (1.2) for SAS-2 data as a function of longitude. Latitude range is $20° > |b| > 10°$.

3.2.4. *Distribution of residuals with longitude*

The region of space covered by this analysis (some few hundred parsecs around the Sun) is small on a galactic scale, but the fact that the Sun may be on the edge of an interarm spur, and the presence of local irregularities, mean that there could be a longitude dependence of the emissivity. Furthermore a halo component could be present which would also cause a longitude variation.

Any general trend of emissivity with longitude will show up in the spatial distribution of residuals from the fit to equation (2.1). Figure 3 shows this distribution for both energy ranges, for bins 30° wide in l and for $10° < |b| < 20°$. For $E > 100$ MeV, no trend is apparent and the residuals appear random. For $35 < E < 100$ MeV, however, there is an excess of emission for $l < 60°$, apparently indicating a steeper spectrum for Gould's belt.

There are several possible causes of this result. One is that there is a significant halo contribution, since this would be expected to be greatest in the inner Galaxy. In this case the apparent difference between q_1 and q_2 is no more than an artefact of a fortuitous correlation between Gould's belt and the halo. However the effect is restricted to positive latitudes while a halo contribution would be expected to be symmetrical about the galactic plane. An alternative is that there are steep-spectrum sources associated with Gould's belt. Finally there remains the possibility that q_2/q_1 is a function of energy.

4. Analysis of COS-B data: Lebrun *et al.* (1980)

Lebrun *et al.* (1980) give the results of a study of COS-B data in three energy ranges: 70–150 MeV, 150–300 MeV and 300–5000 MeV. The criteria for selection of the area of sky as outlined in §1 led to the use of the region $20° > |b| > 10°$, $240° > l > 10°$, declination $> -25°$. Only photons detected at less than 18° from the detector axis were used. The analysis was made by the same method as outlined for L.P. in §3.1. Results for $N_H = N_{HI}$ and $N_H = N_{Ht}$ are given, and these are summarized in table 1. The Heiles & Habing (1974) and Berkeley 21-cm surveys were used for N_{HI}. The analysis used a $1° \times 1°$ binning and the maximum-likelihood technique described in §3.2, in this case for 1-constraint (λ distributed as χ_1^2).

The values of the derived slopes of the γ-ray–gas correlation can be used together with the spectral response curves given by Lebrun *et al.* to compare any predicted spectrum with the data. For our presentation of results in table 1, we give the emissivities for an *assumed* spectral shape of E_γ^{-2} within each range of E_γ. Since the overall shape does seem to agree well with such a spectrum, the procedure is justified *a posteriori*, although it is not unique.

Lebrun *et al.* conclude that:

(*a*) the quality of the fit to N_{Ht} is better at all energies than the fit to N_{HI} alone;

(*b*) a strong correlation of γ-ray residuals and N_{Ht} residuals with respect to N_{HI} is found, as for the SAS-2 data;

(*c*) from an analysis in terms of pion-decay and bremsstrahlung components, the local electron spectrum has the form

$$92\,E^{-2.8}\ [\mathrm{m^{-2}\,s^{-1}\,sr^{-1}\,GeV^{-1}}] \tag{4.1}$$

with E in GeV for the appropriate energy range (100–1000 MeV roughly).

It should be noted that conclusion (*c*) depends on an assumption about the pion-decay contribution. A further discussion on this point is given in §5.

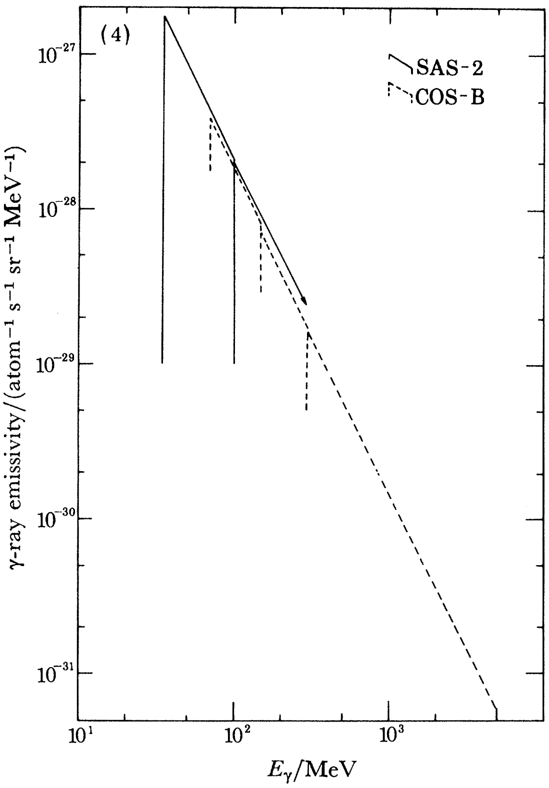
5. The local γ-ray emissivity spectrum for 50–1000 MeV

The results referred to already can be used to determine the emissivity spectrum of γ-rays at intermediate latitudes. For this spectrum we use the correlation of I_γ with N_{Ht} (although there is the problem described above of the apparent steeper spectrum of q_2 which means that the situation is not as simple as this presentation might suggest). The virtue of the N_{Ht} spectrum is that it should be free of localized source contributions and is appropriate to the local region. Figure 4 gives a composite spectrum from the SAS-2 and COS-B results. Each 'segment' is plotted under the assumption of an E_γ^{-2}-spectrum for that energy band. A consistent picture is evident, with good agreement between the SAS-2 and COS-B results in the region of overlap. The whole spectral range may be represented to sufficient accuracy by the formula

$$q(E_\gamma)/4\pi = 3.5\ 10^{-24}\ E_\gamma^{-2.12}\ [\mathrm{s^{-1}\,sr^{-1}\,atom^{-1}\,MeV^{-1}}]$$

with E_γ in MeV. The energy range covered is approximately $50 > E > 1000$ MeV (outside this range, although this relation is consistent with the data, it should clearly be used with caution).

The adoption of an exponent -2.0 in deriving figure 3 from table 1 is therefore at least consistent with the data, although the representation is not necessarily unique. In principle we should iterate to obtain continuity of the spectrum; however, this is already almost achieved on the above assumption. For the COS-B data, the effect on the emissivity at the centre of the energy range is at worst 20 % for a spectral index change of 0.5.



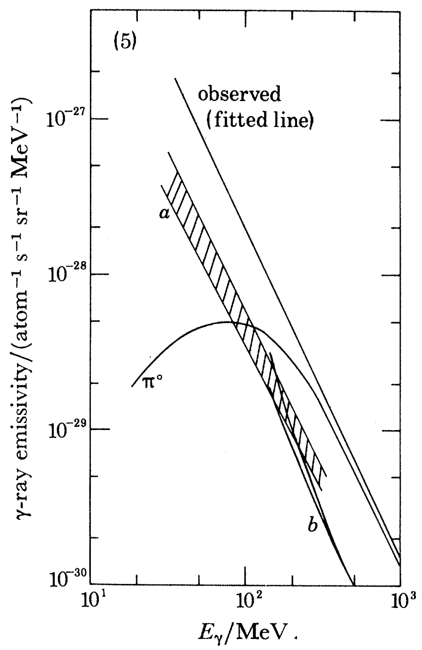


FIGURE 4. Composite γ-ray emissivity spectrum for total gas based on SAS-2 and COS-B results from table 2. An exponent of −2.0 has been assumed for each energy band indicated.

FIGURE 5. Comparison of experimental emissivity spectrum for the local interstellar medium with the predicted emissivity for pion-decay (from Badhwar & Stephens 1977) and from bremsstrahlung for electron spectra given by (*a*) Webber *et al.* (1980) and (*b*) Strong & Wolfendale (1978). These electron spectra are chosen to agree with the demodulated interplanetary flux at 1 GeV.

6. Relation to the local spectrum of electrons and nuclei

The work summarized above gives the absolute emissivity per atom; previous analyses have had to rely mainly on spectral shape with uncertain normalization. The problem of interpretation is thereby (in principle at least) simplified.

In figure 5 we compare $q(E_\gamma)$ with the theoretical predictions: the pion-decay emissivity is taken from Badhwar & Stephens (1977) for the demodulated interplanetary spectrum of nuclei. Bremsstrahlung predictions are taken from Webber *et al.* (1980) and our own earlier work (Strong & Wolfendale 1978) for two values of the assumed optical depth at 1 MHz. For the latter it should be stressed that the lack of knowledge of a precise value for the magnitude of the magnetic field precludes accurate knowledge of the magnitude of the local electron spectrum below 1 GeV and in turn the bremsstrahlung contribution in figure 5. Rather it is the *shape* of the electron spectrum that is determined from radio data although here too difficulties arise

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

below 500 MeV because of the uncertain correction for optical depth. In this paper we have used the usual normalization to the interplanetary demodulated spectrum near 1 GeV. The predicted spectra are about a factor 3 below the observed emissivity at 70 MeV and a factor 2 at 100 MeV (the minimum energy for which radio data are of use).

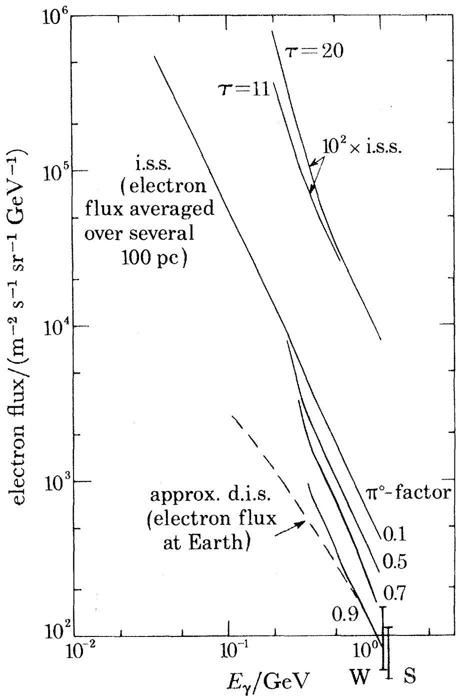


FIGURE 6. Electron spectra derived from the γ-ray emissivity spectrum for various pion-decay contributions. The curves are labelled with the fraction of pion component relative to that shown in figure 5. The electron flux at the Earth derived by Webber *et al.* (1980) and by Strong & Wolfendale (1978), both using direct measurements and indirect analyses (by way of the positron flux), are indicated by W and S respectively. The extension to lower energies in the latter work is indicated by a dotted line. The $\tau = 11$ and $\tau = 20$ lines show the shape of the interstellar electron spectrum derived from radio data (see text).

It has to be stressed that the above two comparisons depend on the assumption that the pion-decay contribution is close to that for the demodulated interplanetary spectrum of nuclei. If we are prepared to relax this condition then it is of course possible to fit the γ-emissivity spectrum with a flatter electron spectrum, more in accord with the shape derived by Webber *et al.* (1980) and by Strong & Wolfendale (1978) for more reasonable values of low frequency absorption. In the extreme case of a negligible pion contribution, the spectral shape is in fact the same as that of Webber *et al.* (1980) (index 2.14). In this case we have to demand that the interstellar electron spectrum for $E_\gamma > 1$ GeV be a factor 6 above the demodulated interplanetary value. An intermediate solution is to invoke some steepening of the electron spectrum as well as some reduction in the pion contribution from its 'nominal' value, as proposed by Strong *et al.* (1978) and Strong & Wolfendale (1978). This still appears a reasonable solution. An enhanced electron intensity at 1 GeV relative to the interplanetary value would help to explain the well known problem of the absolute intensity of the local interstellar synchrotron emissivity at frequencies below 100 MHz, if the effective magnetic field is of order 0.2 nT as indicated by pulsar rotation measures. An enhancement of the electron spectrum by a factor of about 5 is required for consistency with the synchrotron emissivity (Strong *et al.* 1978).

Since the γ-ray problem has essentially only one unknown element, namely the magnitude of the pion contribution, it is possible to derive the set of interstellar electron spectra implied by the data as a function of this quantity. In figure 6 we show the differential electron spectrum derived after various fractions of the Badhwar & Stephens (1977) pion-decay spectrum (their middle curve) have been subtracted from $q(E_\gamma)$. Figure 6 also shows the demodulated interplanetary intensities derived from a variety of data by Webber *et al.* (1980) and Strong & Wolfendale (1978), and an approximate energy spectrum back to 100 MeV from the latter work.

The spectral shapes between 200 and 1000 MeV from the anti-centre low frequency radio data for optical depths at 1 MHz of 11 and 20 (Strong & Wolfendale 1978) are shown in the inset to figure 6. Since the τ (1 MHz) = 20 spectrum is almost compatible with the γ-ray data and this value of τ is considered to be plausible (though at the upper limit of reasonable optical depths) it is unfortunately not possible to rule out any of the spectra of figure 6 at present. However, the spectrum obtained by using the 'nominal' local pion-decay contribution also agrees with the demodulated interplanetary electron spectrum at 1 GeV which is certainly a strong argument in favour of this situation.

For the reasons previously outlined, we suggest instead that the most economical overall hypothesis is an electron spectrum flatter than given by (4.1), enhanced by a factor of a few above the demodulated interplanetary value at *ca.* 1 GeV, together with a pion contribution one-half its 'nominal' local value or less.

At this stage it can be remarked that our earlier analysis (Strong & Wolfendale 1978) of the γ-ray flux from the galactic plane, as distinct from high latitudes, gave a similar result. That work used spectral *shapes* as distinct from absolute intensities and no doubt can also be criticized on the grounds of possible contamination by discrete sources, but it does give support for the higher interstellar electron fluxes.

Another argument favouring an increased electron flux at all energies between 100 and 1000 MeV, and a smaller pion-decay component than expected, it that it avoids the up-turn in electron flux required at 300 MeV, which appears physically unreasonable. A pion-decay contribution of half the usual value would not require this up-turn.

A description of models of cosmic-ray origin and propagation that would meet these requirements is outside the scope of this paper, but it can be remarked that the idea is in the spirit of our earlier suggestions (see, for example, Dodds *et al.* 1975; Issa *et al.* 1980*a*) of gradients of cosmic-ray intensity in the Galaxy. Our previous work has related to larger regions of space than considered here; perhaps the position of the Sun with respect to the local spiral arm causes some of the variations.

7. Gamma-rays from discrete molecular clouds at $|b| > 10°$

The question of the contribution of γ-rays from molecular clouds to the flux in the galactic plane is important. Particularly significant is the extent to which individual clouds, or clouds accidentally near coincident in line of sight, when irradiated by the ambient cosmic ray flux, can give γ-ray profiles that simulate discrete sources. Only if the contribution to the γ-ray flux in the plane from genuine discrete sources (pulsars, supernova remnants, ...) is small can the data be used to examine the way in which the cosmic ray flux varies from place to place in the Galaxy.

Issa & Li Ti-pei (this symposium) have shown that perhaps 40% of the so-called discrete sources are irradiated molecular clouds. Here we examine those few local clouds that extend above our latitude limit of $|b| = 10°$.

This subject is still in its infancy because not only are there problems with low γ-ray fluxes of poor angular resolution but there are also considerable uncertainties in the masses of the individual clouds.

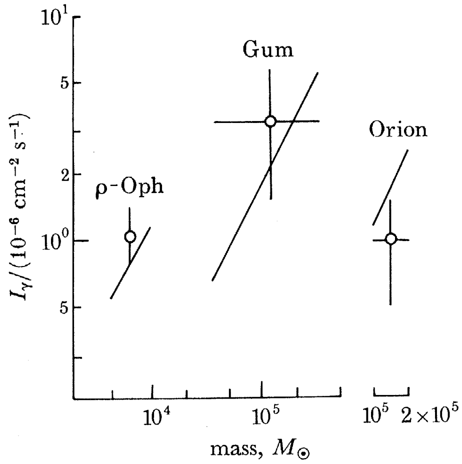


FIGURE 7. Observed and expected γ-ray fluxes from the direction of the molecular clouds named. The sources of data on the measured fluxes are: ρ-Oph (Issa *et al.* 1980*a*; analysis of both COS-B and SAS-2 results), Gum and Orion (our own analysis of SAS-2 data). The masses of the clouds are not well known – the ranges of uncertainty are indicated. For the Gum nebula we include only latitudes $b < -6°$ to avoid confusion from the Vela pulsar. In the predictions we assume that the cosmic ray flux in the cloud is the same as that locally.

TABLE 2. ADOPTED PROPERTIES OF LOCAL MOLECULAR CLOUD COMPLEXES

complex	mass $M_\odot$†	distance pc	angular range used‡	remarks
ρ-Oph (comparatively inert)	$5 \times 10^3 - 1 \times 10^4$	160	7° × 7°	an excellent candidate for study with γ-rays but mass is uncertain
Orion (very active: OB stars, flare stars.)	$1 \times 10^5 - 2 \times 10^5$	450	15° × 8°	might expect some enhancement in cosmic ray flux.
Gum (ionized gas)	$4 \times 10^4 - 3 \times 10^5$	400	25° × 10°	only that part with $b < -6°$ used because of confusion from Vela

† 'Mass' includes atomic, molecular and ionized components.
‡ Angular range is wider than object because of need to allow for imperfect resolution of γ-ray telescopes.

Figure 7 gives the result of a preliminary analysis by using the SAS-2 data with $E_\gamma > 100$ MeV, and table 2 gives basic data about the cloud complexes. The values in the table come from many sometimes discordant, sources and are intended to bracket the true value. The clouds were chosen as those that have big enough values of M/r^2 to be expected to be visible in γ-rays. The conclusion that can be drawn is that there is no reason, so far at least, to suspect that there are discrete γ-ray sources in the clouds, or sources of cosmic rays in or near the clouds that would increase the ambient cosmic ray flux in the clouds appreciably. We are particularly struck by the fact that there are many flare stars embedded in the Orion cloud complex (325 in the region centred on the Trapezium, according to Gurzadyan (1980)) – stars that might have been expected to act as important sources of γ-rays or particles – whereas the flux of γ-rays from the Orion complex as a whole is, if anything, below expectation for cosmic ray irradiation.

The preliminary results on local molecular clouds thus point to the importance of gas in this form as a target for cosmic ray nuclei and electrons, as do our earlier analyses (§§3,4).

The increased understanding of the behaviour of cosmic rays in gas in the intersteller medium adds confidence to our previous claims for gradients in the intensities of both electrons and nuclei over galactocentric distances in the range 7–13 kpc (Dodds *et al.* 1975; Issa *et al.* 1980*a*, 1980*b*; Wolfendale 1980).

All of the above is not to be taken as indicating that there is complete certainty about the conclusions. There are still some unexplained features, such as the apparent rapid fall-off of q_2 with increasing energy and the longitude dependence of emissivity. The apparent need for a cosmic ray intensity *below* ambient (§7) is also surprising. Improved data on both γ-rays and interstellar-medium gas properties are needed.

8. Conclusions

The absolute local γ-ray emissivity in the range 35–1000 MeV is now well established as a result of coordinated work on the SAS-2 and COS-B data sets. There is good agreement between the results obtained by using galaxy counts as a measure of total gas, and this allows comparison with theoretical estimates to be made with confidence. The importance of non-atomic (mainly molecular) gas has been established by both experiments.

We are pleased to acknowledge extensive discussion with and the cooperation of the Caravane Collaboration for the results described in this paper. We are also grateful to F. Lebrun and J. Paul for communicating results on their SAS-2 data analysis. We also thank Dr M. R. Issa for making many of the calculations on which §3.2 is based.

References (Strong & Wolfendale)

Badhwar, G. D. & Stephens, S. A. 1977 *Proc. 15th Int. C. R. Conf.* vol. 1, p. 198.
Bohlin, R. C., Savage, B. D. & Drake, J. F. 1978 *Astrophys. J.* **224**, 132.
Burstein, D. & Heiles, C. 1978 *Astrophys. J.* **225**, 40.
Cesarsky, C. J., Paul, J. A. & Shukla, P. G. 1978 *Astrophys. Space Sci.* **59**, 73.
Dodds, D., Strong, A. W. & Wolfendale, A. W. 1975 *Mon. Not. R. astr. Soc.* **171**, 569.
Eadie, W. T., Drijard, D., James, F. E., Roos, M. & Sadoulet, B. 1971 *Statistical methods in experimental physics*, pp. 230–232. Amsterdam: North Holland.
Fichtel, C. E., Hartman, R. C., Kniffen, D. A., Thompson, D. J., Ögelman, H. B., Tümer, T. & Özel, M. E. 1978*b* *NASA tech. Memor.* 79650.
Fichtel, C. E., Simpson, G. A. & Thompson, D. J. 1978*a* *Astrophys. J.* **222**, 833.
Gurzadyan, G. A. 1980 *Flare stars*. Oxford: Pergamon Press.
Hartman, R. C., Kniffen, D. A., Thompson, D. J., Fichtel, C. E., Ögelman, H. B., Özel, M. E. & Tümer, T. 1979 *Astrophys. J.* **230**, 597.
Heiles, C. 1976 *Astrophys. J.* **204**, 379.
Heiles, C. & Habing, H. J. 1974 *Astron. Astrophys. Suppl.* **14**, 1.
Issa, M. R., Riley, P. A., Strong, A. W. & Wolfendale, A. W. 1980*b* (In preparation.)
Issa, M. R., Riley, P. A., Strong, A. W. & Wolfendale, A. W. 1980*c* *Nature, Lond.* **287**, 811.
Issa, M. R., Strong, A. W. & Wolfendale, A. W. 1980*a* *J. Phys.* G (In the press.)
Lebrun, F., Bignami, G. F., Buccheri, R., Caraveo, P. A., Hermsen, W., Kanbach, G., Mayer Hasselwander, H. A., Paul, J. A., Strong, A. W. & Wills, R. D. 1980 *Astron. Astrophys.* (Submitted.)
Lebrun, F. & Paul, J. A. 1979 *Proc. 16th Int. C. R. Conf.* **12**, 13.
Lebrun, F. & Paul, J. A. 1980 *Astrophys. J.* (Submitted.)
Puget, J. L., Ryter, C. E., Serra, G. & Bignami, G. F. 1976 *Astron. Astrophys.* **50**, 247.
Seldner, M., Sieber, B., Groth, E. J. & Peebles, P. J. E. 1977 *Astr. J.* **82**, 249.
Shane, C. D. & Wirtanen, C. A. 1967 *Publs Lick Obs.* **22**, 1.
Strong, A. W. & Lebrun, F. 1980 Preprint.

Strong, A. W. & Wolfendale, A. W. 1978 *J. Phys.* G. **4**, 1973.
Strong, A. W., Wolfendale, A. W., Bennett, K. & Wills, R. D. 1978 *Mon. Not. R. astr. Soc.* **182**, 751.
Weaver, H. & Williams, R. W. 1973 *Astron. Astrophys. Suppl.* **8**, 1.
Weaver, H. & Williams, R. W. 1974 *Astron. Astrophys. Suppl.* **17**, 251.
Webber, W. R., Simpson, G. A. & Cane, H. V. 1980 *Astrophys. J.* **236**, 448.
Wolfendale, A. W. 1980 In *The origin of cosmic rays.* 94th I.A.U./I.A.U.P.A.P. Symp., Bologna.

Discussion

H. Elliot, F.R.S. (*Blackett Laboratory, Imperial College, London SW7 2BZ, U.K.*). The γ-ray luminosity of the gas clouds depends, of course, on their accessibility to cosmic rays as well as on the matter density within them. It seems not inconceivable that such clouds could have internal magnetic fields that are largely independent of the external interstellar field due, for instance, to rotation of the cloud. Such internal fields could significantly restrict the entry of cosmic rays and I wonder if anything at all is known about the strength and topology of the fields within the clouds?

A. W. Wolfendale. A little is known about field strengths but virtually nothing about topology, particularly in the dense regions where most of the mass resides. Dr Strong's argument concerning the good correlation of γ-ray flux with molecular gas in general (derived from galaxy counts) suggests to me that cosmic ray exclusion is not significant.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES