GAMMA RAYS FROM COSMIC RAYS

A.W. Wolfendale,
Physics Department, University of Durham, U.K.

It is shown that there is evidence favouring molecular clouds being sources of γ-rays, the fluxes being consistent with expectation for ambient cosmic rays interacting with the gas in the clouds for the clouds considered. An estimate is made of the fraction of the apparently diffuse γ-ray flux which comes from cosmic ray interactions in the I.S.M. as distinct from unresolved discrete sources. Finally, an examination is made of the possibility of gradients of cosmic ray intensity in the Galaxy.

1. INTRODUCTION

The nature and location of the sources of cosmic ray particles is one of the most important questions in contemporary cosmic ray physics. The reason for uncertainty is well known - the presence of the Galactic magnetic field causes particle trajectories to be torturous, and uncertain, for all but the most energetic particles. The first question to be asked is whether the bulk of the cosmic rays detected at the earth have come from sources within the Galaxy or outside it. For electrons, the answer is almost certainly the former because of the 'absorption' of most extragalactic electrons by the 2.7K radiation. For protons, however, there is still some uncertainty although it is often considered that our work on γ-rays from the Galactic anti-centre (Dodds et al., 1975) indicates that the bulk of the protons between 1 and 10 GeV are of Galactic origin and observations of anisotropies (see, for example, the summary by Kiraly et al., 1979) suggest a continuation of this type of origin to much higher energies.

The role of the γ-ray studies in this connection is that if those arising from particle interactions with the nuclei of the I.S.M. can be identified, and if the characteristics of the I.S.M. are known in detail then the intensity of particles can be determined at various locations in the Galaxy. Ideally one would hope to see the characteristic signature of γ's from π^o - mesons generated by protons near sources (S.N.R., pulsars ..., see, for example, Pinkau, 1975) but

G. Setti, G. Spada, and A. W. Wolfendale (eds.), Origin of Cosmic Rays, 309–319.

this condition has not yet been realised. Instead, attention has been directed towards searching for gradients of cosmic ray intensity in the Galaxy the detection of which would strongly suggest a Galactic origin for the particles.

Even this apparently modest goal is fraught with difficulties, however. These can be listed as follows: (i) with the poor angular resolution of contemporary detectors (a few degrees at the energies of interest here : 0.3 - 10 GeV), the contribution of unresolved discrete γ-ray sources is uncertain, (ii) the I.S.M. is not known in sufficient detail insofar as the column densities of the important H_2 component are not accurately known, (iii) most of the H_2 is in rather dense clouds and there is the possibility that some particles may not be able to penetrate them and (iv) although the electron to proton ratio at the earth is small, electrons are so efficient at producing γ-rays (and, furthermore the e/p ratio appears to be higher elsewhere than locally) that the important proton-contribution is hard to disentangle. Attention will be given to all these problems.

The form of the present paper is first to search for gas clouds which should give detectable γ-ray fluxes from ambient cosmic ray fluxes. The relevance of such detections as there are to the likely contribution of genuine discrete sources is then examined. Finally, a search is made for large scale cosmic ray gradients.

2. GAMMA RAYS FROM MOLECULAR CLOUDS

A test of several aspects of the diffuse γ-ray problem would be the observation of γ-rays from known molecular clouds, each with roughly the flux expected from the ambient cosmic ray flux acting on the known mass of the cloud. Preliminary estimates of the expected fluxes were made by Black and Fazio (1973); here, we make estimates using more recent I.S.M. data and compare with the observations from both the SAS II and COS B satellites.

Coverage of the sky in searches for 'large' molecular clouds is, of course, by no means complete and even for those clouds examined mass estimates are very imprecise. Most of our data have come from the survey by Blitz (1977) and Stark and Blitz (1978) but to this has been added data on ρ Oph (see our recent work, Issa et al., 1980a) on Cygnus X (Cong, 1978) and on the Galactic centre region (Scoville et al., 1974). Figure 1 gives a plot of the clouds referred to and also lines corresponding to particular γ-ray fluxes, integrated over the solid angle subtended by each cloud.

The value for the emissivity has been taken to be $\frac{q}{4\pi}(E_\gamma > 100 \text{ MeV}) = 2.2 \times 10^{-26} s^{-1} H \text{ atom}^{-1}$ following our detailed analysis (Issa et al., 1980a). For those clouds within about 1 kpc of the sun, this q-value

https://doi.org/10.1017/S0074180900074763 Published online by Cambridge University Press

should be appropriate but further afield significant differences might well occur due to cosmic ray gradients.

The γ-ray data from the SAS II satellite are those tabulated by Fichtel et al. (1978a) and the COS B results come from Wills et al. (1980), this paper giving fluxes of detected 'sources' with $I_\gamma > 10^{-6}$ $cm^{-2}s^{-1}$, and from the flux contours of Mayer-Hasselwander et al. (1980).

The comparison of observed γ-ray intensities with prediction is rather difficult due to uncertainty in the contribution to the γ-flux from other regions not necessarily associated with the complex in question. This problem is particularly acute for the extended sources in Cygnus, Perseus and Orion, but we make the attempt nevertheless.

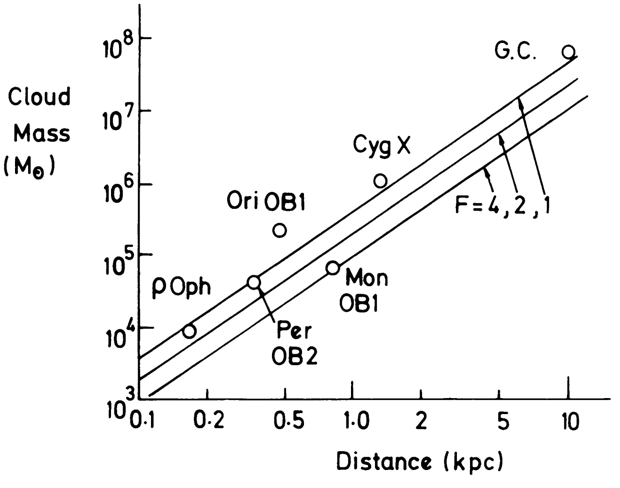

Figure 1. Estimated masses of molecular clouds versus approximate distance from the sun. The lines represent predicted γ-ray fluxes of $10^{-6}cm^{-2}s^{-1}(E_\gamma > 100$ MeV) for the ambient cosmic ray particle fluxes of FX the local particle flux with F=1, 2 and 4. Only those clouds (from the references used) which lie above the line with F=4 are included. The references are given in the text.

ρ Oph. This cloud complex is particularly useful, being at a comparatively high latitude where confusion caused by background effects should be small. In addition the cloud is expected to be comparatively inert (i.e. it probably does not contain discrete γ-sources).

Issa et al. (1980a) have considered this cloud in detail and they conclude that there is reasonable consistency between observation and expectation for I_{CR} being close to the local value. Figure 2 shows the value of F = I_{CR} (ρ Oph)/I_{CR} (local) needed (Note - the adopted value of I_γ is somewhat less than the COS B flux : 0.75 cf $1.1 \times 10^{-6} cm^{-2} s^{-1}$, because the SAS II upper limit was ∿ 0.7 x $10^{-6} cm^{-2} s^{-1}$). As ρ(Oph) is only ≃ 160 pc away, we would expect F ≃ 1.

Per OB2. This cloud is situated in the region of ℓ ≃ 160° and b ∿ - 17° and has high gas column densities extending over about 5° in ℓ and 8° in b. Unfortunately this region is outside the published COS B coverage and it is necessary to fall back on the SAS II data. The cloud does not show up in the energy range 35-100 MeV, but for E_γ>100 MeV a finite excess flux appears (the data were binned in 3.4° bins of latitude for the longitude range 155 - 165°). The excess corresponds to a flux of (1.4 ± 0.7) $10^{-6} cm^{-2} s^{-1}$, in reasonable agreement with what we expect for F = 1 (Figure 2).

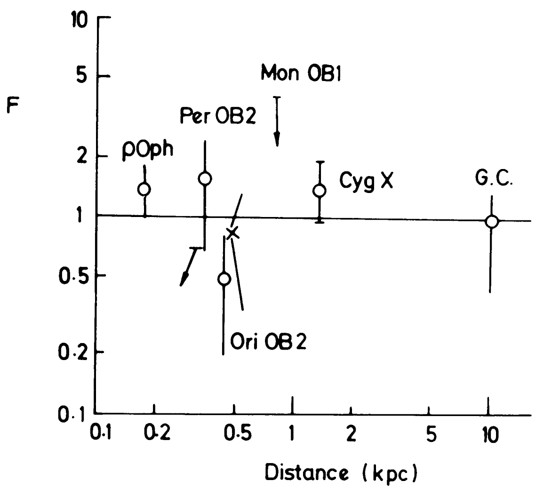

Figure 2. Enhancement factor for cosmic ray flux, F, versus distance of cloud from the sun for the clouds given in Figure 1. Vertical error bars correspond to E_γ>100 MeV and oblique error bars to γ's in the range 35 - 100 MeV.

Ori OB 1. This complex should show up in γ-rays in the region ℓ : 202° - 217°, b : -14° to -22°. Again, it is outside the COS B range and we have searched for it in the SAS II records. There is evidence for an excess in both energy ranges: the corresponding fluxes are (1.7 ± 0.8)$10^{-6} cm^{-2} s^{-1}$ for 35 - 100 MeV and (1.0 ± 0.5) $10^{-6} cm^{-2} s^{-1}$ for E_γ>100 MeV. These fluxes are a little less than we expect for F = 1 but not significantly so (see Figure 2).

Mon OB 1. This cloud is a 'long shot' in that it would require F≃4 for detection. There is no COS B 'source' in this position and the SAS II data show no significant excess; an upper limit of F∿4 is therefore indicated. The nearest COS B 'source' is at ℓ = 195.1°,

$b = 4.5^{o}$ and is bright ($I_{\gamma} = 4.8 \times 10^{-6} cm^{-2} s^{-1}$); it is too far away to be identified with OB1 but it is interesting to note that there is a deficit of galaxy counts close by, at $\ell \simeq 196^{o}$, $b \simeq + 6^{o}$, which may indicate the presence of a dense rather concentrated gas cloud which might account for this strong source.

Cygnus-X. The cloud complex marked 'Cyg-X' in Figure 1 comprises many clouds in the general direction of $\ell \sim 80^{o}$, $b \sim 0^{o}$. In an earlier paper (Protheroe et al., 1979a) we examined this region in some detail using quite extensive COS B data (E_{γ}>100 MeV) and a brief resumé will be given here. The complex has been investigated in CO by Cong (1978) and this author estimates that the total mass of some 78 clouds in the range, ℓ : 75^{o} to 85^{o}, $|b|<4^{o}$ is $\sim 10^{6} M_{\odot}$ and the distance range is 1 - 2 kpc. Protheroe et al. have derived column densities of H_2 from the CO results and combined these with the column densities of H from Weaver and Williams (1973) to predict the γ-ray flux. They give the longitude distribution of γ-ray flux for $|b|<6^{o}$ and show that, with $q/4\pi = 1.8 \times 10^{-26} s^{-1}$ there is rough agreement. In fact, as the authors point out, a higher cosmic ray intensity would give a better fit. Inspection of the longitude plot indicates $F \simeq 1.7 \pm 0.4$ and if $q/4\pi$ is increased to the presently adopted value, $2.2 \times 10^{-26} s^{-1}$, F is reduced to 1.4 ± 0.5.

It is likely that the 'sources' quoted by Wills et al. at $\ell = 75.0^{o}$, $b + -0.5^{o}$ ($1.3 \times 10^{-6} cm^{-2} s^{-1}$) and $\ell = 77.8^{o}$, $b = 1.5^{o}$ ($2.5 \times 10^{-6} cm^{-2} s^{-1}$) are due to clouds within the complex. With a mass of $10^{6} M_{\odot}$ and an effective distance of 1.3 kpc the expected net flux is $1.6 \times 10^{-6} cm^{-2} s^{-1}$, to be compared with the measured $3.8 \times 10^{-6} cm^{-2} s^{-1}$, i.e. we require $F \simeq 2.4$. The values, 1.5 and 2.4, are, understandably, not very different.

Galactic Center. The situation with respect to the flux of γ-rays from the G.C. region is confused. SAS II saw quite a respectable peak and Wolfendale and Worrall (1977) used the data to show that the flux above 100 MeV from within a few degrees of the G.C. was $\simeq 6.7 \times 10^{-6} cm^{-2} s^{-1}$. The COS B results appear to indicate a smaller source ($1.8 \times 10^{-6} cm^{-2} s^{-1}$) at $\ell = 359.5^{o}$, $b = -0.5^{o}$. However there is another source within 5^{o} ($2.6 \times 10^{-6} cm^{-2} s^{-1}$) at $\ell = 356.5^{o}$, $b = + 3^{o}$ and the summed intensity of $4.4 \times 10^{-6} cm^{-2} s^{-1}$ is not too far from that of the SAS II peak.

We are impressed by the evidence for the ring of molecular clouds round the G.C. subtending an angle of radius $\simeq 1.5^{o}$ at sun (Kaifu et al., 1972 and many other references). The mass is very uncertain but here we adopt the range $(4-10) 10^{7} M_{\odot}$ quoted by Scoville et al. (1974) and treat this as a conventional cloud complex penetrated by the ambient cosmic ray flux (although we are mindful of the many problems in this region - the likelihood of genuine discrete sources, excess radiation density causing enhanced inverse Compton emission, etc.).

Adoption of the one source (359.5°, -0.5°) as being due to the ring gives F = 0.9 ± 0.5 (Figure 2).

Discussion of results on molecular clouds. The preceeding results give support to the idea that some, at least, of the so-called γ-ray sources are molecular clouds irradiated by the ambient cosmic ray flux and this is a feature which supports our contention that it is possible to derive information about the distribution of cosmic rays from an analysis of the diffuse flux in general.

The majority of the clouds in Figures 1 and 2 are near enough to the sun for $F \simeq 1$ to be expected (or at least for us to expect $F \lesssim 2$) and this is observed. The exception is the molecular ring at the G.C., where F might have been expected to be very high. Indeed, it is possible that the cloud mass is grossly over-estimated, in which case F can be large, but it is also possible that the magnetic field configuration is such that the cosmic rays generated there cannot escape (Wolfendale and Worrall, 1977). If this is the case then the injection rate will be much higher than locally to give the measured γ-ray flux. Our earlier estimate was an injection rate higher by a factor of 100; use of the new COS B data and the greater mass gives an enhancement factor of $\sim$ 20.

3. GAMMA RAYS FROM DISCRETE SOURCES

Many attempts have been made to determine the fraction of the flux (f) from both resolved and unresolved discrete sources and estimates have varied from about 10% to near 100%. Such a spread is inevitable in view of the lack of identification of most of the apparent sources.

In an earlier work (Protheroe et al., 1979b) we examined the catalogue of 13 sources then available and used various arguments to determine values of f (for E_γ>100 MeV) for various assumptions about the distribution of γ-ray sources in the Galaxy. The values derived were as follows: uniform slab model, $f \simeq 0.33$; distribution similar to that of X-ray sources, $f \simeq 0.19$; distribution similar to that of pulsars, $f \simeq 0.18$. The new catalogue of Wills et al.(1980) contains 29 sources of which 18 have $I_\gamma > 1.3 \times 10^{-6} cm^{-2} s^{-1}$ and represent a complete sample over a fraction of the Galactic plane ($90^\circ < \ell < 300^\circ$). Riley et al. (1980) have analysed the new data using the uniform slab model and conclude that $f \simeq 0.25$; a similar result appears for the inner Galaxy ($300^\circ < \ell < 90^\circ$) although here the method is not very accurate.

It seems likely that the value of f for the outer Galaxy is no higher than 0.25 and, if the distribution of source emissivity follows that of cosmic ray-induced emissivity throughout the Galaxy (a reasonable assumption), this value will pertain to the Galaxy as a whole.

The value of f will be somewhat of an overestimate because of the fact that some of the observed discrete sources are irradiated molecular clouds. Examination of the sources of Wills et al. which have $|b|>1.0^{\circ}$ and $I_{\gamma}>1.3 \times 10^{-6}cm^{-2}s^{-1}$ shows 6 not associated with known clouds, 3(+2?) with clouds and 2 with SNR; in this region the visibility of clouds is probably reasonable so this means that probably $\sim$ 30% of the 'local' sources are irradiated clouds (of course, the uncertainty is considerable).

Riley et al. have used the data on the latitude distribution of sources to give a local source density of $\simeq$ 1.5 kpc^{-2} for 'equivalent' sources with emission $5 \times 10^{38}\gamma$'s s^{-1} above 100 MeV (corresponding to a flux of $1.0 \times 10^{-6}cm^{-2}s^{-1}$at 2 kpc). If 30% are clouds and if the distribution of genuine discrete sources follows roughly that of γ-emission in general the total Galactic flux will be $\sim$ $2 \times 10^{41}\gamma$'s s^{-1} above 100 MeV. This can be compared with the total emission of $\sim 1.3 \times 10^{42}\gamma$'s s^{-1} (Strong and Worrall, 1976) i.e. f $\simeq$ 17%.

It is useful at this stage to make a stock-taking of the various emission components. Prerequisites are a knowledge of the radial distribution of the densities of H and H_2 and that of the cosmic ray intensity. There are many permutations of these parameters but one which we prefer is as follows. For $I_{CR}(R)$ we take a distribution a little less rapid than that of SNR, viz $I_{CR}(R)/I_{CR}(\text{local}) \simeq 1.5$ at R = 3 kpc, 2.0 at R = 5 kpc, 1.6 at R = 8 kpc and 0.6 at R = 12 kpc. The H distribution is that given by Gordon and Burton (1976), the total mass of H in the Galaxy being $2 \times 10^{9}M_{\odot}$. There is a problem with the Gordon and Burton H_2 distribution in that the densities are rather high. There are several reasons why densities just one half of those quoted are preferred: the formaldehyde analysis by Few (1979) gives such values, the local H_2 density measurements of Savage et al. (1977) lead to surface densities about 1/3 those of G and B and the ratio of CO to H_2 densities in molecular clouds may well be about twice the G and B value. Adopting the above parameters we find the following emission components: H_2 : 6×10^{41}; H : 5×10^{41} and discrete sources, 2×10^{41} (all in γ's s^{-1} above 100 MeV).

If a division of this order is accepted for the time being, we can proceed to analyse the large scale gradients by neglecting the source contribution to the measured fluxes (with the exception of those from the CRAB and VELA, which are subtracted).

4. LARGE SCALE COSMIC RAY GRADIENTS

As was remarked in the Introduction, a demonstration of cosmic ray gradients in the Galaxy can be regarded as a first step along the road to identifying the sources of cosmic ray particles. Although there is no direct proof that protons, as distinct from electrons, are contributing to the γ-ray flux by way of π°-production there is circumstantial evidence from the spectral shape (e.g. Stecker,

1971) and insofar as the exponent of the γ-ray spectrum does not vary much with longitude (Hartman et al., 1979) it does seem that a gradient of 'cosmic ray intensity' would indicate a gradient of proton intensity (particularly at 'high' γray energies; $E_\gamma \gtrsim 100$ MeV).

Our method of studying gradients is by way of an examination of the γ-ray emissivity, q, as a function of position in the Galaxy. Many studies have been made of the relationship between γ-intensity and column density of gas (usually, the C.D. of atomic hydrogen N_H). The q value determined from the usual relation $I_\gamma = (q|4\pi)N_H + I_b$ is clearly the average along the line of sight and is roughly representative of the q-value at the median value of N_H. More recent analyses (e.g. Protheroe et al., 1979a; Lebrun and Paul, 1979) have included the effect of molecular hydrogen and these analyses are continuing.

A problem occurs in that N_{H2} is only known in very restricted regions and in what follows q-values related to N_H will be of main concern. The SAS II results will be used because of their current availability.

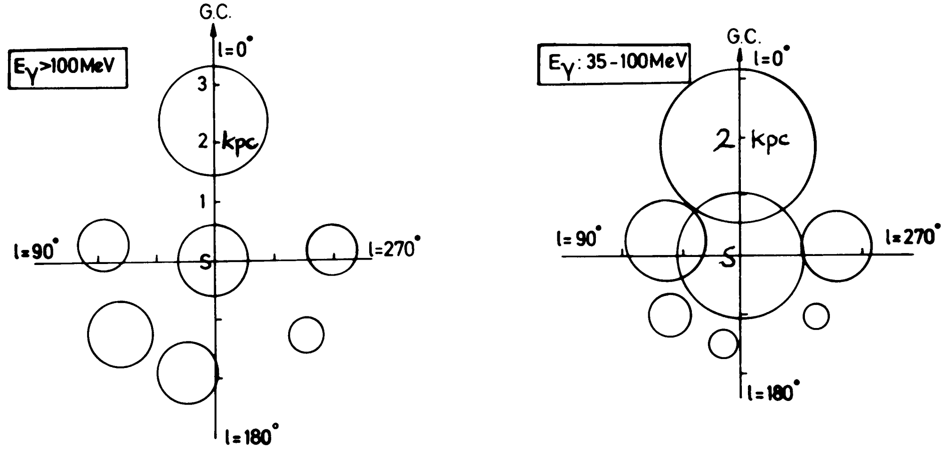

Figure 3. q-values at the median positions in the Galaxy. The radius of each circle is proportional to q. S = Sun's position.

Fichtel et al. (1978b) have made a comprehensive study of I_γ vs N_H using the N_H values of Daltabuit and Meyer (1972) and Heiles (1975) and have derived overall q-values. We have used their plots for individual ℓ- and b- ranges to derive appropriate q-values. The latitude distribution for each ℓ-range chosen has been used, together with the z-dependence of the gas, to determine the median linear distance appropriate to the q-values. An independent analysis has also been made of the q-values by taking the tabulated intensities of Fichtel et al. (1978a) together with the column densities of

Weaver and Williams (1973) and making a maximum likelihood fit to the I_γ, N_H expression. Finally, the q-values for the two methods have been averaged and the results are given in Figure 3. It should be remarked that the 'local' values are for 'high' latitudes ($|b|$: 12.8^o - 30^o) and thus correspond to a radius of $\simeq$ 500 pc round the earth.

The q-values given in Figure 3 can be used to make estimates of the likely cosmic ray gradients in the region of a few kpc from the sun although it must be remarked that there are some systematic errors present. One reason is that the q-values are over estimates because of the effect of molecular hydrogen and this overestimate is a function of both ℓ and b. The point is that there is some correlation between the column densities of H and H_2 (if only for geometrical reasons). Issa et al. (1980b and later work) find that the factor of overestimation, f, is $\simeq$ 1.22 for E_γ > 100 MeV, ℓ : 10^o - 240^o and $|b|$: 10^o - 51^o. The overestimate will be larger at small latitudes but here the necessary H_2 data are sparse. An analysis of COS B and SAS II results for the Cygnus region, where H_2 data are available, indicates that, for $|b|<15^o$, $f_o \simeq 1.5$. Corrections have not been applied here for this effect for two

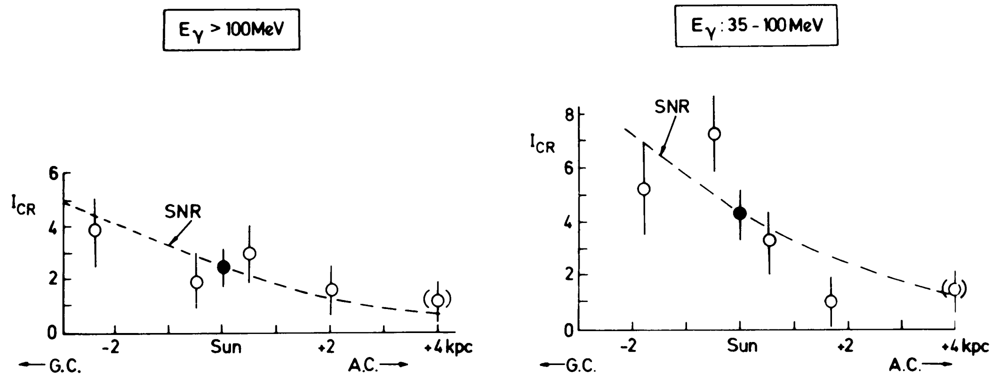

Figure 4. Very approximate values for the inferred 'cosmic ray intensity', I_{CR} (some combination of electrons in the range 100 MeV-1 GeV and protons etc. in the range 1-10 GeV) as a function of position in the Galaxy along the line ℓ=0, 180^o. Considerable averaging has been carried out. The points in parentheses are very approximate, having been derived from a subset of the γ-ray data (with $|b|<5.6^o$). The intensity units are arbitrary. The line marked SNR is the surface density of supernova remnants from the work of Kodaira (1974). The graph gives evidence for a gradient of the cosmic ray intensity (somewhat similar to that of SNR).

https://doi.org/10.1017/S0074180900074763 Published online by Cambridge University Press

reasons: (a) the values of f_o are not accurately known, (b) there is some measure of compensation as regards C.R. gradient because, due to the narrower thickness of the H_2 layer, the distance from the sun of the main producing layers is smaller than adopted. Later work will need to examine this problem, however.

Figure 4 shows the q-values, now designated as cosmic ray intensities, plotted as a function of radial distance from the sun, using average values from Figure 3 together with the dependence of q on ℓ at high latitudes ($|b|>12.8^o$). The results are necessarily imprecise at this stage but there does seem to be evidence for a gradient of cosmic ray intensity in the local region of the Galaxy both for electrons (E_γ:35-100 MeV) and what is probably a roughly equal mixture of electrons and protons (E_γ>100 MeV).

4. CONCLUSIONS

The foregoing can perhaps be regarded as an optimistic assessment of the role of γ-ray Astronomy in giving information about the distribution of cosmic rays in the Galaxy. As has been mentioned, a number of serious problems cause worry - notably uncertainty concerning the contribution to the γ-ray flux from discrete sources and uncertainties regarding the properties of the I.S.M. Doubtless a situation can be envisaged in which the bulk of the γ-rays are generated by electrons and the γ-rays then give no information at all about the proton component. However, it would be necessary to increase the e/p ratio considerably away from the sun and to keep protons (and presumably electrons) out of contact with the I.S.M. Such shielding might be possible in the inner Galaxy, where so much of the gas seems to be in dense clouds, but in the outer Galaxy shielding is unlikely. It is in the outer Galaxy too that an underestimate of the discrete source flux would increase rather than reduce the gradient.

In conclusion, then, the γ-ray evidence (particularly that away from the Galactic center) still seems to point to a Galactic origin for low energy cosmic rays. A reasonable case can be made for particle production in SNR (Figure 4) but any other sources having a similar distribution in the Galaxy would also be acceptable. A necessary consequence of SNR production would be that diffusive motion would be small by Galactic standards. If other evidence favoured much greater diffusive displacements then bigger source distribution gradients would be indicated. Considerable production at the Galactic Centre might not be ruled out.

ACKNOWLEDGEMENTS

The work described was carried out by the author's research group, comprising Dr. A.W. Strong, Dr. M.R. Issa and Dr. P.A. Riley and himself; he is very grateful to his colleagues for their

https://doi.org/10.1017/S0074180900074763 Published online by Cambridge University Press

considerable efforts. He also thanks colleagues in the COS B collaboration for helpful comments.

REFERENCES

Black, J.H., and Fazio, G.G.1 1973, Ap. J. Lett. 185, L7.
Blitz, L., 1977, Proc. Gregynog Workshop on Giant Molecular Clouds, Ed. P. Solomon.
Cong, H., 1978, Ph.D. dissertation, Columbia University (NASA Technical Memorandum 79590).
Daltabuit, E., and Meyer, S., 1972, Astr. Astrophys., 20, 415.
Dodds, D., Strong, A.W., and Wolfendale, A.W., 1975, Mon. Not. Roy. Astr. Soc. 171, 569.
Few, R.W., 1979, Mon. Not. Roy. Astr. Soc. 187, 161.
Fichtel, C.E., Hartman, R.C., Kniffen, D.A., Thompson, D.J., Ogelman, H.B., Turner, T., and Ozel, M.E., 1978a, NASA Tech. Mem. 79650.
Fichtel, C.E., Simpson, G.A., and Thompson, D.J., 1978b, Ap. J., 222, 833.
Gordon, M.A., and Burton, W.B., 1976, Ap. J., 208, 346.
Hartman, R.C., Kniffen, D.A., Thompson, D.J., Fichtel, C.E., Ogelman, H.B., Turner, T., and Ozel, M.E., 1979, Ap. J. 230, 597.
Heiles, C., 1975, Astron. Astrophys. Suppl. 20, 37.
Issa, M.R., Strong, A.W., and Wolfendale, A.W., 1980a (in the press).
Issa, M.R., Strong, A.W., and Wolfendale, A.W., 1980b (in the press).
Kiraly, et al., 1979, Rivista del Nuovo Cimento, 2, 1.
Kodaira, K., 1974, Publ. Astr. Soc. Japan, 26, 255.
Mayer-Hasselwander, H.A. et al., 1980, Proc. 9th Texas Symp. "Annals of the New York Academy of Sciences" (in the press).
Lebrun, F., and Paul, J.A., 1979, Proc. 16th Int. Cosmic Ray Conf., Kyoto, 12, 13.
Pinkau, K., 1975 "Origin of Cosmic Rays", Ed. J.L. Osborne and A.W. Wolfendale (D. Reidel Publ. Co.) 335.
Protheroe, R.J., Strong, A.W., and Wolfendale, A.W., 1979a, Mon. Not. Roy. Astr. Soc., 188, 863.
Protheroe, R.J., Strong, A.W., Wolfendale, A.W., and Kiraly, P., 1979b, Nature, 277, 542.
Riley, P.A., and Wolfendale, A.W., 1980 (in the press).
Savage, B.D., Bohlin, R.C., Drake, J.F., and Budich, W., 1977, Ap. J. 216, 291.
Scoville, N.Z., Solomon, P.M., and Jefferts, K.B., 1974, Ap. J., 187, L63.
Stark, A.A., and Blitz, L., 1978, Ap. J., 225, L15.
Stecker, F.W., 1971, Cosmic Gamma Rays, Mono. Book Co., Baltimore.
Strong, A.W., and Worrall, D.M., 1976, J. Phys. A., 9, 823.
Weaver, H., and Williams, D.R.W., 1973, Astron. & Astrophys. Suppl. 8, 1.
Wills, R.D. et al., 1980, Non Solar Gamma Rays (COSPAR) Ed. R. Cowsik and R.D. Wills, Pergamon Press, 43.
Wolfendale, A.W., and Worrall, D.M., 1977, Astron. Astrophys. 60, 165