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An assessment of models for the γ-ray flux from the Galactic plane

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Abstract. An assessment is made of five models for the production of Galactic γ rays, all of which involve the interaction of cosmic ray protons with neutral hydrogen. Conflict with either the γ ray or radio data is found in four cases. The remaining model, in which the intensity of cosmic rays of energy of a few GeV is correlated with the matter distribution in the Galaxy, gives rough agreement with the experimental data at present available but it does not conform with the idea that cosmic rays should originate in young Galactic objects. A completely satisfactory model has yet to be found.

1. Introduction

In the previous paper (Strong 1975, to be referred to as I), an analysis was made of the γ-ray observations in the Galactic plane at present available from the OSO-III and SAS-II satellites. The object of the analysis was to obtain the best estimate for the radial variation of γ-ray emissivity in the Galaxy, and of the uncertainties in the resulting emissivity distribution. It was shown that there is evidence for the emissivity being higher in a region some 3–8 kpc from the Galactic centre than elsewhere. We now turn to the discussion of some possible models for the form of the distribution and endeavour to choose between them. Finally we indicate the types of measurements needed in future experiments.

The energy spectrum of the γ radiation in the Galactic plane (GP) above 100 MeV is consistent with a mainly π^0-decay origin, the π^0 mesons being derived from cosmic ray–gas nucleus interactions, with perhaps 30% of a steeper component in the Galactic centre (GC) direction (Stecker *et al* 1974). The fact that the density of interstellar gas (mainly hydrogen) falls somewhat with increasing distance from the sun towards the GC means that the cause of the increased emissivity is an increase in cosmic ray density. A proviso is that the gas is indeed mainly neutral hydrogen (the component which has been most studied); if large amounts of molecular hydrogen (or other molecules) were discovered having a density which increased towards the GC then the conclusion of an increased cosmic ray density could be reversed. The implications of high molecular densities will be examined elsewhere.

The apparent observation of an increase in cosmic ray density towards the GC is a very important point in the controversy as to whether cosmic rays are of Galactic or extragalactic origin. If the increase is confirmed then this indicates that at the energies of relevance here ($\simeq$ 1–10 GeV) the cosmic rays are largely of Galactic origin (or at least that they gain the bulk of their energy within the Galaxy).

The correlation of emissivity with the distribution of HII in the Galaxy shown in I supports the ideas put forward since it is possible that the cosmic rays themselves are responsible for the ionization (Stecker *et al* 1974), although it should be stated that the ionization would be caused very largely by cosmic rays of energy much lower than those considered here.

Accepting that there is an increase in cosmic ray density, it may be due to one or more of the following:

(*a*) an increase in the number of cosmic ray sources towards the GC;
(*b*) an increase in the containment time of the particles;
(*c*) a large-scale acceleration mechanism, operative towards the GC.

Models based on these possibilities will be discussed individually in the following sections. A summary of the models and their parameters is given in table 1.

Table 1. Summary of π^0 models.

Model	$w = \dfrac{\text{emissivity at } R}{\text{emissivity at sun}}$ proportional to:	z dependence of CR variation	k
SNR sources	$n_H \times$ SNR surface density from Ilovaisky and Lequeux (1972)	$\exp(-\lvert z\rvert/90)$, with z in pc	2
Sources ∝ total matter distribution	$n_H \times \exp\left(\dfrac{10-R}{2 \cdot 44}\right)$ with R in kpc following the matter distribution given by Perek (1962)	Assumed wide compared to hydrogen width	1·5
Field containment	$n_H \times B^2$ $B \propto e^{-R^2/100}(1-e^{-R^2/4})$ with R in kpc (Thielheim and Langhoff 1968)	Assumed wide compared to hydrogen width	2
Gas containment model	n_H^2, with n_H from Bignami and Fichtel (1974)	As n_H	1·5
Acceleration model	$\left(\dfrac{R}{R_0}\right)^8 \exp 8\left(\dfrac{R-10}{5}\right)$ with R in kpc, from Stecker *et al* (1974) (for $R < 10$) and constant for $R > 10$	Assumed wide compared to hydrogen width	1

In what follows the emissivity and resulting longitude distribution of γ rays will be examined for the models in turn and comparison will be made with the experimental data referred to in I. At this point it is necessary to reiterate the fact that the experimental data comprise a combination of results from two experiments (OSO-III and SAS-II); the data are of different accuracy and for the SAS-II experiment the results used do not represent the final data (further analysis is continuing—Fichtel 1974, private communication).

An additional test of the models is provided by the synchrotron radiation from the electron component and this will be discussed.

2. Models involving π^0 production

2.1. Method of calculation

In the models discussed in this paper it is a sufficient approximation to take the neutral hydrogen density in the GP, n_H, as a function only of distance R from the GC (see figure 1), and of z from the plane. For $0 < R < 8$ kpc we take the summary of recent observations given by Puget and Stecker (1974), and for $R > 8$ kpc that of Westerhout (1970). The distribution in z is assumed to be Gaussian with a fullwidth at half-height of 270 pc for $R < 10$ kpc, and increasing linearly for $R > 10$ kpc to 1200 pc at $R = 15$ kpc.

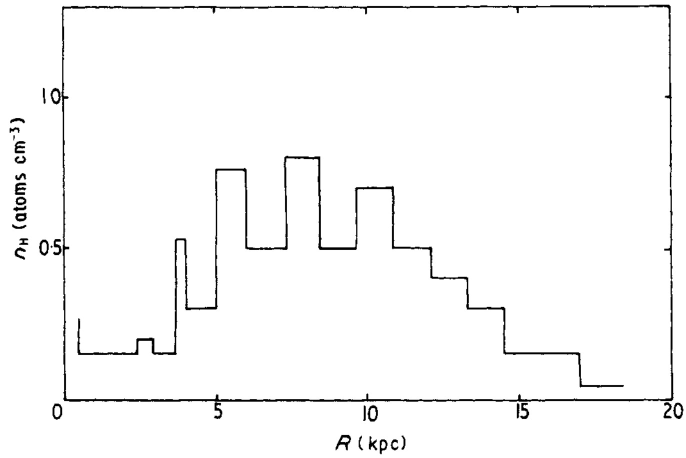

Figure 1. The adopted distribution of neutral hydrogen (in atoms cm^{-3}) as a function of radial distance (in kpc) from the GC. The distribution is taken from the summary of recent data by Puget and Stecker (1974) and Westerhout (1970); it is very similar to that given by Mezger (1973).

This approximates to the distribution given by McGee and Milton (1964). Line fluxes as a function of Galactic longitude, $j(l)$, are calculated for a rectangular response between $b = -10°$ to $+10°$, this being roughly the response and range of the experimental detectors. Using the yield of γ rays of energy above 100 MeV per hydrogen atom for the local cosmic ray intensity given by Stecker (1973) the line flux (measured in cm^{-2} s^{-1} rad^{-1}) follows as:

$$j(l) = \frac{1{\cdot}3 \times 10^{-25} n_0}{4\pi} k \int_{-10°}^{+10°} \int_0^{\infty} w(\rho, l, b) \, d\rho \, db \qquad (1)$$

where n_0 is the neutral hydrogen density near the sun, ρ is the distance from the sun,

$$w = \frac{I_{CR}(l, b, \rho)}{I_0} \frac{n_H(l, b, \rho)}{n_0}$$

is the emissivity at (l, b, ρ) relative to that at the sun and k is a normalizing factor which may also be considered a correction for other gas components (assuming that they have the same radial dependence as that of neutral hydrogen) and the possibility of the experimental CR flux not being typical of the solar region (see note added in proof). The normalization is made for the anticentre region.

2.2. Models involving a non-uniform source distribution

2.2.1. Supernovae. It is known that supernovae remnants (SNR's) contain large amounts of energy in the form of relativistic particles which may have originated in the supernova event or may be being injected continuously by the central pulsar. SNR's are therefore an obvious first choice for Galactic cosmic rays. The possible identification of Vela X as a source of γ rays (Fichtel 1974) supports the idea of a general correlation with SNR's. Further, Ilovaisky and Lequeux (1972) have used the radio observations of Landecker and Wielebinski (1970) to derive a radial distribution of emissivity at 150 MHz and find that it resembles that of SNR's (although the emissivity as a function of Galactic latitude is wider than that of the SN themselves). In figure 2 we compare the relative radio emissivity ϵ_ν given by these authors with the relative γ-ray emissivity from I—the distributions are not too dissimilar suggesting that a tenable model might be one in which cosmic rays (protons and electrons) which have escaped from SN shells produce the observed γ rays and radio quanta.

According to Ilovaisky and Lequeux (1972) the distribution of supernova remnants is fairly flat out to a galactocentric distance $R \simeq 8$ kpc, falls between 8 and 12 kpc and gives very few beyond 12 kpc. The z distribution is well approximated by the factor $\exp(-|z|/90)$, with z in parsecs. Figure 3 shows the expected relative emissivity, $w(R)$ (binned as in I), and the longitude distribution of γ-ray intensity, $j(l)$, on this model for cosmic ray production being proportional to SNR density and lifetime independent of radius. A value of $k = 2$ has been adopted (a not unreasonable value).

Comparison with experiment shows that the distribution of $j(l)$ is rather too wide and gives a rather small peak compared with the observations, although it must be stressed that the distribution of SNR's is based on limited statistics and has had important corrections for selection effects, so that we cannot completely rule out this explanation at present.

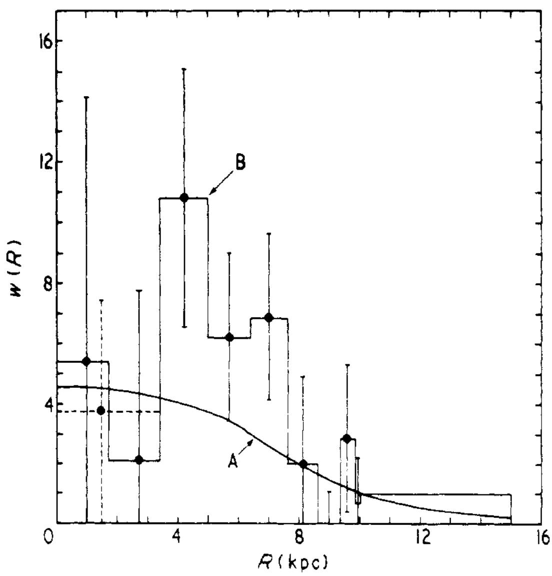

Figure 2. Comparison of the relative radio emissivity, ϵ_ν (curve A), from the work of Ilovaisky and Lequeux (1972), and the γ-ray relative emissivity (curve B) derived by Strong (1975).

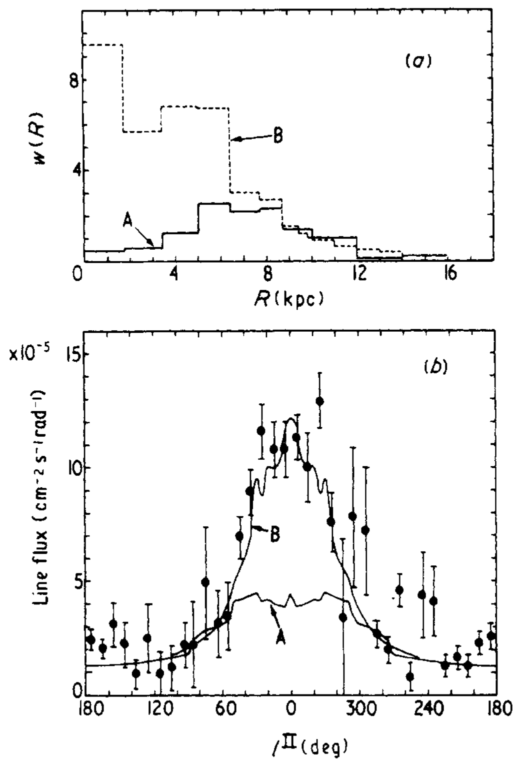

Figure 3. (*a*) Relative emissivities $w(R)$ for models in which the CR flux is proportional to the SNR density (curve A) and the total mass density (curve B). (*b*) The corresponding predicted line fluxes of γ rays above 100 MeV together with the summarized experimental fluxes from I (note, the experimental data are composite OSO-III–SAS-II results; there have been some small changes to SAS-II intensities resulting from further analysis: C E Fichtel, private communication). See Strong (1975) for a discussion of the OSO-III–SAS-II combination procedure.

2.2.2. Source density proportional to matter density. An alternative possibility is that sources of cosmic rays follow the general increase of matter density towards the GC. The mass model of Perek (1962) predicts an exponential variation of total density such that the central density is 60 times that at the sun. Figure 3 shows $w(R)$ and $j(l)$ for cosmic ray production proportional to matter density and $k = 1{\cdot}5$. There is quite good agreement with experiment, the lack of any large peak in the centre being due to the drop in hydrogen density for $R < 3{\cdot}5$ kpc.

This model is of course not in accord with the idea that cosmic rays (CR) originate in young objects, since the increase in matter density is mainly due to older populations. However, the agreement with experiment is sufficiently striking that such a model should be investigated further.

2.3. Models involving variable containment time

2.3.1. Variable Galactic field. So far we have considered the containment time to be constant, independent of position in the Galaxy, and the source density as the variable. Alternatively we can assume that the CR source distribution is fairly uniform in the

Galaxy and that the distribution of CR may be related to a variation in their containment time; such a situation could result from a variable Galactic magnetic field, *B*. Strong *et al* (1973) used the field model of Thielheim and Langhoff (1968) to predict the γ-ray distribution, and this is shown in figure 4 for the case where the CR flux is proportional to B^2, such a variation being expected to hold if the particles can be contained up to a pressure equal to that of the field (Parker 1971). Inspection of figure 4 shows that the prediction is a reasonable fit to experiment within the, as yet, rather large experimental errors.

If the electrons have a similar distribution to that of protons, however, then, since $\epsilon_\nu \propto B^4$ approximately, there will be a predicted increase in ϵ_ν towards the GC much larger than that derived by Ilovaisky and Lequeux. In this model we therefore require that the e/p ratio in sources (or the ratio of e sources to p sources) decreases towards the GC, which, although not impossible, seems unlikely.

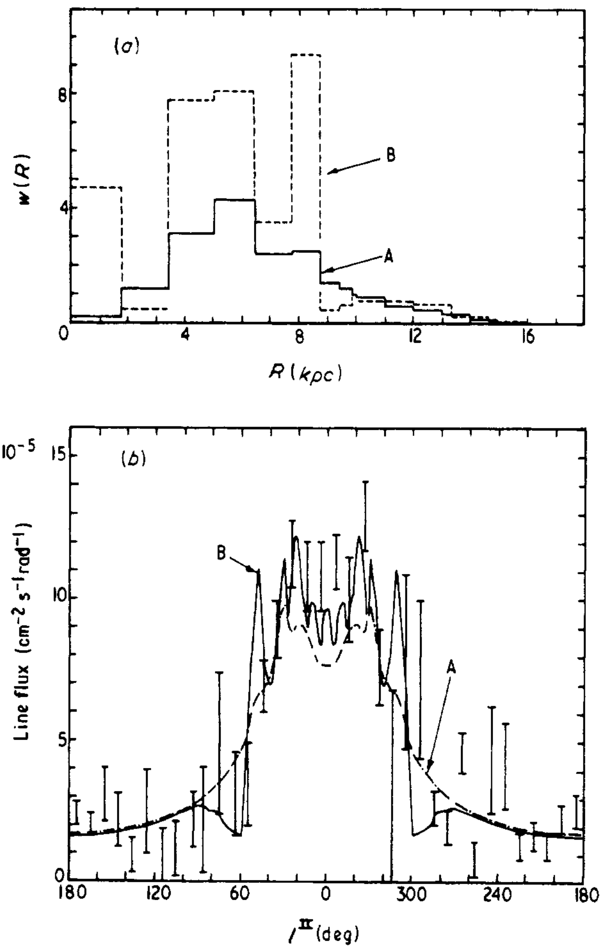

Figure 4. (*a*) Relative emissivities $w(R)$ for the models in which the containment of cosmic rays is proportional to the square of the magnetic field (curve A—see § 2.3.1) or for a correlation of containment with gas density (curve B—see § 2.3.2 and table 1). (*b*) The corresponding predicted line fluxes of γ rays above 100 MeV together with the experimental fluxes (see caption to figure 3 for details).

2.3.2. Correlation of containment with gas density. An alternative suggestion has been made by Bignami and Fichtel (1974) who assume that the CR density is proportional to the gas density, n_H, and use the arm/interarm density contrast of 5:1 predicted in the density-wave theory for spiral structure of Roberts and Yuan (1970). Our calculation of $j(l)$ using their model is also shown in figure 4(*b*). As pointed out in I the assignment of a large proportion of the observed flux to the nearby Sagittarius arm does not seem consistent with the observations: peaks are predicted at $l \simeq 50°$ and 310° which the OSO-III data do not appear to confirm. This is best seen by comparing the predicted $w(R)$ distribution shown in figure 4(*a*) with that for $l = 0$–$90°$ shown in figure 2. The Sagittarius arm is predicted to show up strongly despite the 10° bin size, whereas no such effect appears in figure 2.

2.4. *A model involving the large-scale acceleration of cosmic rays*

Stecker *et al* (1974) have proposed an increased CR flux associated with the large-scale radial gas motions observed at $R \simeq 5$ kpc. While we now feel (I) that there is no evidence for a peak in emissivity as dramatic as that given in this paper or the later paper by Puget and Stecker (1974), the model is still attractive. In view of the emissivity being tailored to fit the γ-ray distribution, $j(l)$, comparison of 'observed' and 'expected' intensities is not meaningful. However, an examination of the expected synchrotron radiation is very relevant. We would expect an enhancement of electrons as well as protons for an acceleration model of the type proposed, and in the calculations which following the e/p ratio is assumed to be constant. The relative increase in γ-ray and radio emissivities, q_γ and ϵ_ν, can be estimated, using $q_\gamma \propto K n_H$ and $\epsilon_\nu \propto K B^{(\gamma+1)/2}$, where the electron spectrum is assumed equal to $K E_e^{-\gamma}$. We have $n_H \propto \eta$, $K \propto \eta^{(\gamma-1)(\Gamma-1)+1}$ and $B \propto \eta^{2(\Gamma-1)}$, where η is the compression factor. For a relativistic gas $\Gamma = \frac{3}{2}$ for a one-dimensional compression perpendicular to a uniform field, and $\Gamma = \frac{4}{3}$ for a compression of a tangled field. Writing $\epsilon_\nu \propto q_\gamma^\beta$, it follows that

$$\beta = \frac{2\gamma(\Gamma-1)+1}{(\gamma-1)(\Gamma-1)+2} = \begin{cases} 1\cdot29 & \text{for } \Gamma = \frac{3}{2} \text{ and } \gamma = 2\cdot6 \\ 1\cdot08 & \text{for } \Gamma = \frac{4}{3} \text{ and } \gamma = 2\cdot6. \end{cases}$$

Since the compression will tend to align the field perpendicular to the direction of compression, it is reasonable to take $\Gamma = \frac{3}{2}$. The radio intensity in the plane, $I_\nu(l)$, will then be given by:

$$I_\nu(l) = \text{constant} \int_{-\Delta b/2}^{\Delta b/2} \int_0^\infty (w(l, b, \rho))^\beta \, d\rho \, db.$$

The calculations have been made for a beamwidth $\Delta b = 3°$ and the form of $w(l, b, \rho)$ from Stecker *et al* (1974), assuming acceleration to occur in a region of the thickness of the Galactic disc. The resulting distribution is shown in figure 5, normalized to the anticentre region to compare with the summary by Price (1973) at 150 MHz. The predicted peak is seen to be much too large and broad to agree with the observations. Even if $\beta = 1$ a considerable excess is predicted towards the GC.

Therefore a reduction in the e/p production ratio towards the GC seems to be a prerequisite for a model of this type, as in the 'increasing field' model of § 2.3.1. Such behaviour cannot be ruled out of course but the introduction of an additional *ad hoc* assumption makes the model less attractive.

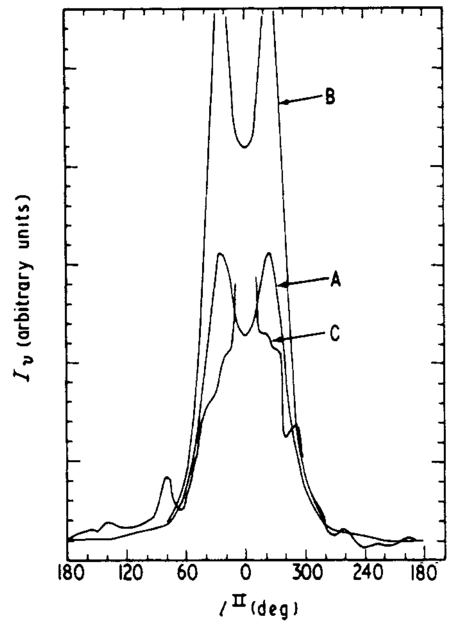

Figure 5. Intensity of radio emission around the GP expected in the large-scale acceleration model of Stecker *et al* (1974) in the case where $\epsilon_\nu \propto \epsilon_\gamma^\beta$ with $\beta = 1$ (curve A) and $\beta = 1{\cdot}3$ (curve B) (see § 2.4). Comparison is made with the observations at 150 MHz by Price (1973) (curve C). All the data refer to a beamwidth of $\Delta b = 3°$ around $b = 0°$.

3. Contribution from inverse Compton scattering

3.1. Constant electron density

The possibility that a significant part of the observed γ-ray flux towards the Galactic centre arises from inverse Compton scattering (ICS) of electrons on starlight has been discussed by Cowsik and Hutcheon (1971). A rapid increase in emissivity towards the GC is a consequence of the distribution of starlight, taken to follow that of stellar matter as given by Perek (1962). Cowsik and Hutcheon included the effect of secondary electrons produced in proton–gas interactions, taking the gas density to increase as $1/R$. This increase does not appear to be in agreement with current observations however (see figure 1)—except for the narrow spike for $R < 0{\cdot}5$ kpc—so we have assumed that the secondary electron component is everywhere small compared with the primary component.

In the present calculations the stellar mass density is taken to increase exponentially to a maximum at $R = 0$ of 60 times the local value, in agreement with the composite model from Perek (1962, figure 42). The $1/R^3$ dependence used by Cowsik and Hutcheon gives a much more rapid increase for $R < 5$ kpc. As a result of these differences in model we find that ICS contributes less to the observed γ-ray flux (assuming a constant CR density) than Cowsik and Hutcheon claimed.

The emissivity for ICS from an electron differential spectrum $j_e(E_e) = KE^{-\gamma}$ on an isotropic photon field of energy density W_{ph} is given by:

$$q_{ICS}(>E_\gamma) = 4\pi \,.\, \tfrac{2}{3}\sigma_T W_{ph}(m)^{1-\gamma}(\tfrac{4}{3}\bar{\epsilon}_{ph})^{(\gamma-3)/2} K \frac{E_\gamma^{-(\gamma-1)/2}}{(\gamma-1)/2}. \qquad (4)$$

(after Ginzburg and Syrovatsky 1964) where $\bar{\epsilon}_{ph}$ is the mean photon energy ($=2{\cdot}7\,kT$ for a black body distribution), σ_T is the Thomson cross section and m the electron mass. Note that the dependence on $\bar{\epsilon}_{ph}$ is very weak, the important quantity being the energy density.

Putting $\bar{\epsilon}_{ph} = 1{\cdot}4$ eV (corresponding to 6000 K) and $\gamma = 2{\cdot}6$ we get:

$$q_{ICS}(>100\,\text{MeV}) = 1{\cdot}8\times10^{-39}\,KW_{ph} \qquad \text{cm}^{-3}\,\text{s}^{-1}. \tag{5}$$

For electron energies of interest here, $E_e \simeq 3$ GeV, experiments give values of K in the range $1{\cdot}5$–$4{\cdot}4\times10^{12}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{eV}^{-1}$ (using data summarized by Meyer 1971). Estimates of W_{ph} vary from $0{\cdot}13\,\text{eV cm}^{-3}$ (Stecher and Milligan 1962) to $0{\cdot}45\,\text{eV cm}^{-3}$ (Allen 1973, Zimmerman 1964). We wish to obtain the upper limit to the CS contribution and hence use the larger of these values. Using also the larger value for K we find for the local emissivity:

$$q_{ICS}(>100\,\text{MeV}) = 3{\cdot}5\times10^{-27} \qquad \text{cm}^{-3}\,\text{s}^{-1}. \tag{6}$$

This is to be compared with the local π^0 contribution:

$$q_{\pi^0}(>100\,\text{MeV}) = 1{\cdot}3\times10^{-25}\,n_H \qquad \text{cm}^{-3}\,\text{s}^{-1}$$

(Stecker 1973) so that for $n_H = 0{\cdot}5\,\text{cm}^{-3}$, $q_{ICS}/q_{\pi^0} = 0{\cdot}05$. The ICS contribution is thus negligible locally, but if the starlight density increases by a factor 60 towards the GC, ICS would dominate the emissivity there. On this model $W_{ph} \simeq 30\,\text{eV cm}^{-3}$ near the GC so the lifetime of a 3 GeV electron is about 3×10^6 years. Therefore there may be a significant attenuation of the spectrum towards the GC, depending on the containment time of electrons. Again, to obtain an upper limit we take the case of no attenuation. Figure 6 (curve A) shows the expected longitude distribution for γ rays assuming

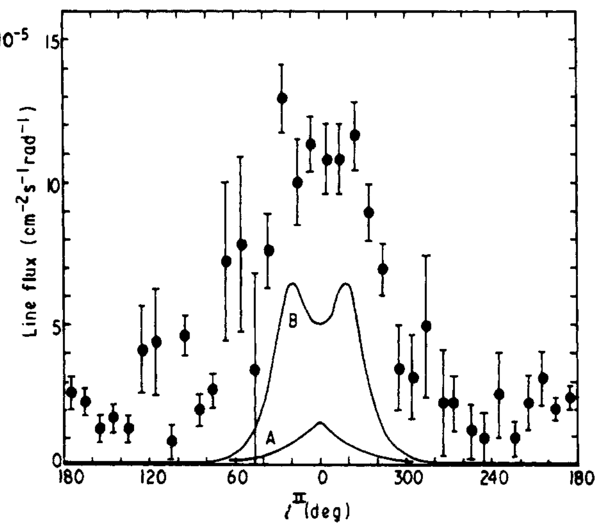

Figure 6. Contributions from inverse Compton scattering to the line flux of Galactic γ rays above 100 MeV for: a constant CR flux (curve A); a CR flux increasing as in the acceleration model of Stecker *et al* (1974) (curve B). The starlight energy density is assumed to increase in the same way as the matter density and have a value of $0{\cdot}45\,\text{eV cm}^{-3}$ in the vicinity of the solar system. The experimental fluxes (full circles) are those referred to in the caption to figure 3.

constant K, starlight density proportional to matter density on the Perek model, a fullwidth of the electron distribution of 500 pc, and q_{ICS} from equation (6). The maximum contribution comes from the GC direction and is there only about 5% of the total flux observed. Hence if the cosmic ray electron component is uniform in the Galaxy we expect the spectrum to be almost entirely that of decay π^0 at all longitudes. This is important since it shows that, provided a significant ICS component is confirmed, an increase in gas density can be ruled out as the cause of the enhanced emissivity.

3.2. *Variable electron density*

In models involving increased cosmic ray fluxes, the electron component might, as stated before, be expected to vary in the same way as the proton component. Each of the models can be taken in turn.

For the supernova model (§ 2.2.1) as with the case of π^0 production on this model the contribution from ICS is not significant; it is in fact not much greater than the contribution for a uniform CR distribution (figure 6, curve A).

With an electron source density proportional to matter density (§ 2.2.2) there is a big peak in the predicted distribution of $j(l)$ towards the GC. This peak would have been detectable experimentally and its non-detection shows that such a model is untenable.

Finally there is the model put forward by Stecker *et al* in which the large-scale acceleration mechanism is important. The idea of significant electron fluxes appears to be particularly valid in this case because both electrons and protons would be expected to be accelerated. If we disregard the limits set on the electron flux in § 2.4 and assume a constant p/e ratio, then the ICS contribution is as shown in figure 6 (curve B). (The contribution will be less by a factor of about three if the electron flux is limited for consistency with the radio data.) The distribution in $j(l)$ is seen to be wider than for the case of constant electron distribution because of the increased 'emissivity' in the region around 5 kpc and it is interesting to note that the distribution is consistent with a 30% contribution to the integrated flux above 100 MeV from ICS over the whole central region, for which there is some slight experimental evidence (see § 1). It is important to note that future precise measurements of the energy spectrum of the γ rays as a function of b and l should give information on the respective contributions from the π^0 and ICS components. For example, figure 6 shows that the spectrum in the region of 10–100 MeV should be flatter for $300° > l > 60°$ than for $300° < l < 60°$ where ICS with its steep spectrum becomes important.

4. Conclusions

With the proviso about non-detected gas in the Galaxy referred to in § 1 it can be concluded that there is evidence for an increase in CR density towards the GC. The density appears to be highest in the region of $3 \lesssim R \lesssim 8$ kpc; there is no evidence for a very high CR density very close to the GC. The latter conclusion is particularly valid for the electron component where a detectable flux of γ rays from ICS interactions would be measured close to $l, b = 0$ if electrons were numerous there.

With the present experimental accuracy in $j(l)$ a distinction between the models with source density proportional to mass density (§ 2.2.2), containment proportional to B^2 (§ 2.3.1), gas containment (§ 2.3.2) and the acceleration hypothesis (§ 2.4) is difficult. Figures 3 and 4 show that with only slightly improved accuracy it should be possible to determine which of the three first mentioned models is preferable. The gas containment model predicts a much sharper fall off of $j(l)$ with l in the regions $l \simeq 60°$ and 300° than the others. The spikes in that model should also be readily detectable.

As has been remarked, if the electron/proton ratio is constant over the Galaxy then the consequent predicted intense synchrotron radiation for the B^2 and acceleration models precludes them but the constancy of e/p is very problematical. If the constancy of the e/p ratio were to be confirmed from some other type of measurement then the model in which the CR source density varies as the star density would appear to be quite a strong candidate. Although the predicted ICS contribution (from electrons on starlight photons) is then too high for l and b close to zero (see § 3.2) it is possible that diffusion away from the plane would cause a sufficient reduction and broadening, in b, to give the required 30% (approximately) contribution.

Finally, concerning the future measurements, a precise determination of the distribution of γ-ray intensity as a function of latitude, $j(b)$, would be useful. The results of some preliminary calculations by the present authors are shown in figure 7. The most important ingredient is the z dependence of the various parameters; the values chosen are those indicated in table 1. The best experimental measurements of $j(b)$ made so far are those with SAS-II (Fichtel 1974) which indicate an approximate Gaussian

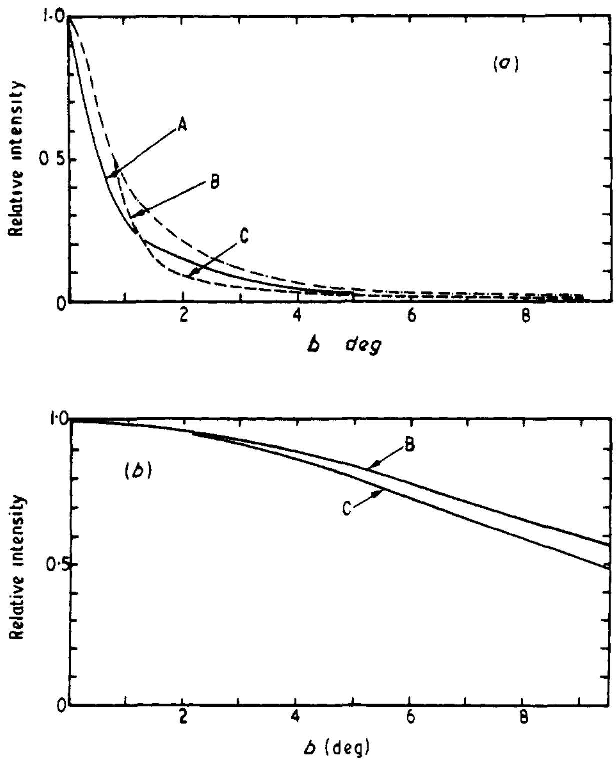

Figure 7. Variation of predicted γ ray line flux with Galactic latitude, normalized at $b = 0$. The nomenclature is as in table 1. Curve A, gas containment model; curve B, mass density model; curve C, acceleration model. (*a*) $-10° < l < 10°$; (*b*) $190° > l > 170°$. The γ rays have energy above 100 MeV and arise from π^0 decay. The calculations are to be regarded as preliminary in so far as the Galaxy has been assumed to be regular and symmetrical and specific features (such as spurs) have not been included.

distribution with standard deviation of 4·5°, for $E_\gamma > 100$ MeV and $330° < l^{II} < 30°$. However the inaccuracies in γ-ray directions have a standard deviation of $3{\cdot}5° \pm 1{\cdot}5°$ so that all that can be said at present is that the true standard deviation is probably less than about 3·5°. Some of the uncertainty in the SAS-II $j(b)$ distribution arises from technical problems which are currently being solved so that it may be possible to derive more precise experimental distributions rather soon.

Acknowledgments

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Note added in proof. Very recent observations by Solomon and Stecker (1974) indicate that large amounts of molecular hydrogen may exist near $R = 5$ kpc. The possible range of densities is from 0·7 to 5 molecules cm^{-3}. If the density is in the upper part of this range the interpretation of the γ-ray data will have to be modified (this possibility has been discussed by Dodds *et al* 1974 and by Solomon and Stecker 1974). The present paper treats the case where the density of molecular hydrogen is near the lower limit of the range given above.

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