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SUMMARY

The observed diffuse galactic γ radiation is compared to that predicted from galactic cosmic ray interactions with galactic matter and photons, assuming that on a broad scale the galactic cosmic rays in the plane are correlated with matter density. Recent considerations of the galactic diffuse matter distribution, particularly the molecular hydrogen, the galactic photon density, and a revised cosmic ray galactic scale height, are included. The predictions are compared to the observational γ-ray longitude distributions, the latitude distribution, and energy spectrum, including the recently reported COS-B satellite results, and the new COS-B background estimate. Considering the uncertainties, the agreement between the theoretical predictions and the γ-ray data seems generally reasonable, suggesting that the general concepts are likely to be correct. Both the results determined here alone and in conjunction with other work calculating source functions assuming only cosmic ray matter contributions indicate no necessity for a significant point source contribution to the diffuse γ radiation in the energy range being considered ($E_\gamma \gtrsim 10$ MeV). The intensity of the highest energy γ-rays ($E_\gamma >$ 300 MeV) could be explained entirely by cosmic ray matter and photon interactions, and, in fact, the relatively low intensity of those highest energy photons is of some concern in relation to the allowed range of the interstellar cosmic ray electron spectrum, if all of the diffuse γ radiation is to have this origin. Other possible explanations are a larger contribution of point sources at low energies, although the few observed γ-ray spectra of point sources would not suggest this, or an enhanced cosmic ray spectrum at low energies. The Compton contribution over most regions of the Galaxy is calculated to make a 10% to over 20% contribution to the diffuse γ radiation

depending on latitude and longitude; however, in the inner galaxy the contribution is smaller due to the effect of the Compton radiation itself on the parent cosmic ray electron spectrum.

Key Words: Gamma Rays, Galactic Structure, Cosmic Rays

I. INTRODUCTION

The γ-ray sky is dominated by radiation from the galactic plane, which is generally assumed to be the sum of diffuse radiation and point sources. The point source contribution would for the most part appear diffuse to the high energy γ-ray satellite instruments that have flown thus far because the angular resolution of these instruments for individual photons has been only one to a few degrees,or poorer, depending on energy.

The source of the true diffuse radiation has been assumed to be cosmic ray interactions since, assuming cosmic rays pervade the Galaxy, they necessarily produce high energy γ-rays as they interact with the interstellar matter and photons. The cosmic ray nucleon interactions give rise to γ rays primarily through the decay of π° mesons, giving a unique spectrum with a maximum at approximately 68 MeV. Cosmic ray electrons produce γ rays through bremsstrahlung, but with a markedly different energy spectral shape, one which decreases monotonically with energy. Cosmic ray electrons also interact with the interstellar starlight, optical and infrared photons, and the blackbody radiation through the Compton process. Finally, cosmic ray electrons can interact with magnetic fields giving rise to synchrotron radiation, but this process can be shown to be much less important than the others previously mentioned for the galactic diffuse radiation (e.g., Fichtel et al., 1976) and will not be discussed further here. Should the γ radiation due to cosmic ray interactions be dominant for the diffuse galactic emission relative to the contribution of point sources, the observations of the diffuse γ radiation together with other information should provide a better understanding of the general character of our galaxy than would otherwise be possible.

Substantial work has already been performed on the calculation of the source functions for these various γ radiations and the intensity to be expected in the vicinity of the solar system. (For a general review see Chapter 5 of Fichtel and Trombka, 1981.) There has also been a substantial number of attempts to correlate the γ radiation with the matter distribution (e.g., Fichtel et al., 1978; Issa et al., 1981; Strong et al., 1982; Arnaud et al., 1982; Lebrun and Paul, 1983; and Riley et al., 1983) with generally reasonable results. However, several recent devlopments make a reexamination and extension of this work worthwhile. These include the detailed results of high energy galactic γ-radiation obtained with the COS-B satellite (Mayer-Hasselwander et al., 1982), further evaluations of the 21 cm radiation in the galaxy, and hence the atomic hydrogen density distribution, additional CO line observations from which molecular hydrogen column densities are deduced, the high photon density estimate for the inner galaxy which affects the Compton radiation and the electron spectrum in this region, the current longer estimate of the galactic cosmic ray lifetime, further evidence supporting the galactic arm concept, and improved theoretical calculations on the nucleon-nucleon source function. It should be noted that the difficultry in normalizing the molecular hydrogen column density deduced from the CO measurements in an absolute manner remains a problem, but one which can at least be constrained.

An important assumption of this paper is that cosmic rays are correlated with matter on the scale of arms. Because of the complication that this assumption introduces, the reasons for believing it to be correct are reviewed again together with the new information supporting it. It is worth noting, however, that for galactic latitudes where the local contribution may be expected to dominate, $|b|$ greater than 10° or 15°, the cosmic ray density as a function of the local galactic position may not vary much. For this case, since the scale height of the cosmic rays is expected to be large compared to that of matter, a good approximation for the cosmic ray, matter interaction contribution to the γ-ray diffuse radiation is probably obtained by using a constant cosmic ray density, which allows the direct use of atomic and molecular hydrogen column densities. If the point source contribution is small and if account is taken of the Compton contribution, it should be possible to obtain a good agreement using the matter column densities directly as shown by Strong et al. (1982). It should also be possible to use this simplified approach successfully at intermediate longitudes (~ 60° to ~ 100° and ~ 250° to ~ 280°), where regions which are at galactic radii similar to the Earth are predominantly being viewed, as shown, for example, by Arnaud et al. (1982) and Lebrun et al. (1983) for the (60° < l < 100°) region. The developments related to the galactic matter distribution and γ-ray production will be considered in the next section and incorporated into the general γ-ray production calculation. The predictions of this work are compared to the recently published high energy γ-ray results in Section III, with the conclusions summarized in Section IV.

II. DIFFUSE GALACTIC GAMMA RAY PRODUCTION

(a) Galactic Matter Distribution

With regard to the matter, the relevant concern is the galactic diffuse matter in the form of atoms, molecules, ions and dust. The latter two are believed to be minor constituents and, hence, unimportant for γ-ray production through cosmic ray interactions. Hydrogen is the primary component of both the atomic and molecular matter. Helium and heavy nuclei add about 55% more to the γ-ray production. It is assumed these latter nuclei have a distribution in the galaxy similar to hydrogen, although little is known about them. Both atomic and molecular hydrogen are known to be confined to a narrow disk with the molecular hydrogen distribution generally having a smaller scale height (e.g., Gordon and Burton, 1976; Solomon and Sanders, 1980).

If it were true that the cosmic ray density were constant throughout the galaxy, it would only be necessary to know the column density of the hydrogen in order to calculate the diffuse galactic γ-ray emission (See, for example, Fichtel and Kniffen, 1974). However, if the cosmic ray density is variable, the product of the cosmic ray density and the matter density must be integrated over the line of sight in the galaxy, and hence, the matter distribution in the galaxy must be deduced. This point will be discussed further in Section II(c). It is worth noting now, however, that for the local region of the galactic disk, represented by $|b| \gtrsim 10°$, where the cosmic ray density in the plane varies slowly, and for regions where the Compton component variations are not too important, the galactic γ-rays themselves represent an indication of the galactic column density as a function of direction. Correlation studies of this type have been performed by Lebrun et al. (1982), Lebrun and

Paul (1982), Strong and Wolfendale (1981), and Strong et al. (1982), and their relationship to this work is discussed later.

Consider first the neutral atomic hydrogen. Its density as revealed by the 21 cm emission remains somewhat uncertain in the inner galactic regions because of uncertainty in the absorption correction. Recent work (e.g., Dickey et al., 1982; Thaddeus, 1982) suggests that the absorption had previously been somewhat underestimated and that the density in the region of 3 to 5 kps from the galactic center is probably greater than previously estimated perhaps by a factor of 1 1/2. In this work, the atomic hydrogen density distribution of Gordon and Burton (1976) as a function of radius from the galactic center was used, but modified so that the atomic hydrogen density in the innermost region was increased by a factor of 1.5, and the closer densities were increased less in accordance with the amount of intervening matter. In earlier work (Kniffen, Fichtel, and Thompson, 1977), a scale height of 0.12 kpcs had been used in the inner galaxy and a value gradually increasing from 0.12 kpcs in the outer galaxy. Recent work by Lockman (1982) has shown, however, that the effective scale height is about 3/2 times larger then previously believed because a relatively faint component of HI has been overlooked. Hence, the scale height used in this work is 0.18 kpcs for the galactic radius, R_{Gal}, less than that of the Sun (10.0 kpcs) and $[0.18 + 0.023 \times (R_{Gal} - 10.0)]$ kpcs for $R_{Gal} > 10.0$, with the increase beyond the solar circle being based on the work of Baker and Burton (1975). It is now believed that the scale height in the outer galaxy increases more rapidly than this (Kulkarni, Blitz, and Heiles, 1982), but the surface density, which is the relevant parameter when the total galactic plane contribution is considered, is still believed to be similar to earlier estmates. However, this larger scale height would imply a somewhat broader latitude distribution in the outer galaxy. The latter authors have also shown that the galactic disk extends to 30 kpc although, by that distance, the surface density has become quite small, of the order of 0.1 $M_\odot$ pc^{-2} compared to 6 $M_\odot$ pc^{-2} near the solar system. The density distribution used in this work is also modulated for the galactic arms in a manner to be described below.

The density distribution of molecular hydrogen is measured less directly. At present, the best estimate is obtained through the observations of the 2.6 mm spectral line of ^{12}CO, from which the distribution of cold interstellar matter is inferred. The nature of the interpretation of these measurements makes the derived molecular hydrogen density distribution less certain than that of the atomic hydrogen. The average galactic radial distributions of molecular and atomic hydrogen show clearly that the molecular hydrogen to atomic hydrogen ratio is larger in the inner galaxy than it is in the outer galaxy even if the absolute intensity of molecular hydrogen is still quite uncertain. The basic distribution of the density as a function of distance from the galactic center was taken from Robinson et al. (1983) and Gordon and Burton (1976) with the molecular hydrogen density normalization treated as an adjustable parameter. (It is interesting to note that the CO observations indicated that the great majority of the molecular hydrogen is in clouds. The work of Solomon and Sanders (1980) has, in fact, suggested that the interstellar medium is dominated by massive cloud complexes.)

Although the translation of the observations into a galactic spatial distribution is difficult, on a broad scale the density profile is reasonably well accepted. Even though there is no general agreement on details of arm structure, a general spiral pattern does appear to emerge. In addition to the 21 cm data, the distributions of continuum radiation (Landecker and

Wielebinski, 1970; Price, 1974), γ radiation (Bignami, et al., 1975), HIII regions (Georgelin and Georgelin, 1976), supernova remnants (Clark and Caswell, 1976), pulsars (Seiradakis, 1976), and infrared emission (Hayakawa et al., 1976) are all consistent with the existence of spiral structure in the galaxy. Until recently, it had not been clear whether molecular clouds were associated with spiral structure. However, now on the basis of a high sample survey and observations in both the first and second quadrants of the galactic plane, Cohen et al. (1980) have reported the existence of the molecular counterparts of the five classical 21 cm spiral rams segments in these quadrants, namely the Perseus arm, the Local arm, the Sagitarius arm, the Scutum arm, and the 4 kpc arm. Kutner and Mead (1981) have even identified arms through CO measurements in the outer galaxy. The specific spiral pattern that will be used here is that of Georgelin and Georgelin (1976). In regard to the particular choice, the spiral structure model recently developed by Robinson et al. (1983) based on a current well-sampled CO survey by these same authors shows "excellent agreement" with the Georgelin and Georgelin model. A five hundred parsec width is adopted for the arms. The excess of material in the arms is taken to be twice the local average density of matter not in the arms, unless the distance between the arms is less than the arm's width in which case it is proportionally smaller, based on recent considerations (Lockman, 1982, and Kulkarni, Blitz, and Heiles, 1982). In either case, the total matter is made to be consistent with the estimated column density, although this is practical only on a broad scale and not on a fine scale (of clouds, for example).

It is realized that the unfolding of the radio observations to obtain a spiral arm, or arm segment, matter distribution pattern is necessarily somewhat uncertain. However, if the theory is to incorporate properly the correlation of the cosmic ray density with the matter density on the scale of arms, it is necessary to have the density distibution and not just the column density. A reasonably accurate calculation of the γ-ray intensity does not require an exact galactic picture of the matter distribution because a good approximation will result if the mass is in approximately the right place, and reasonable care has been taken to verify that the arm width and mass ratios do, in fact, lead to column densities that are in agreement with the column densities deduced from observations on the average. Some fine details on the scale of clouds are lost.

(b) Galactic Photon Distribution

For the photon distributions, Kniffen and Fichtel (1981), using results of Boissé et al. (1982) on the infrared volume emissivity and a model of Bahcall and Soneira (1980) for the starlight distribution, obtained photon densities and, hence, a source function for the Compton emission as a function of position in the galaxy. These will be used here.

(c) Galactic Cosmic Ray Distribution

With regard to the cosmic ray distribution in the galaxy (see particularly Kniffen and Fichtel, 1981, and Fichtel et al., 1976), it will be assumed that the nucleonic cosmic ray composition and energy spectrum remain unchanged throughout the galaxy and that the electron spectrum changes only in a second order manner as the density changes, except at very high energies principally in the inner galaxy. The latter point will be discussed later in Section II(d). The cosmic ray density in the plane will be assumed to be proportional to the matter density on the scale of arms and, perpendicular to the plane, to have a Gaussian distribution with a scale height of 0.6 kpc. This value is based on the radio continuum measurements of Cane (1977) and the assumption that the galactic magnetic fields energy density and the cosmic ray energy density have the same scale height. This scale height for the cosmic rays is somewhat less than that used previously, and the primary effect is some reduction in the Compton contribution.

Since the assumption that the cosmic ray density is correlated with the matter density substantially complicates the calculation, it is worth reviewing why it is believed to be the case. The galactic cosmic ray pressure locally is about equal to the magnetic field and kinetic motion of matter pressures, and together they are as large as can be held by the local galactic matter. These conditions suggest that the cosmic ray density is as great locally as the galactic matter will allow. Further, the cosmic ray age determination suggests that this situation is the result of plentiful sources and leakage, not just chance accumulation to the maximum over time. Hence, excluding the possibility that the local conditions are anomalous, the most natural assumption is that the cosmic ray pressure is as great as it can be throughout the galaxy except possibly in the outer galaxy where sources or regions of further acceleration may be rare. (For a further discussion, see Chapter 5 of Fichtel and Trombka, 1981.) The assumption that the density varies on the scale of the arms is based not only on the natural scale of the arms, but on the scale height of cosmic ray electrons perpendicular to the plane ~ 600 kpcs and the theoretically suggested mean diffusion length in the plane (a few to several tenths of a kiloparsecs). Support for this assumption is obtained from the recent work showing that the cosmic ray electron intensity within the spiral arms is about a factor of 2 higher than between the arms (Webber, 1983)

It is ultimately the total gravitational mass that is relevant in considering the galactic attractive force needed to balance the expansive pressures of the cosmic ray gas, the magnetic fields, and the kinetic motion of matter, e.g., Parker (1966), and there is much more mass in the stars than in the diffuse matter. The assumption that the cosmic ray surface density is proportional to the diffuse mass surface density in particular was made because the distribution of the latter in our galaxy is better known. The observations of other galaxies indicate that the two populations are similar at least for $R_{Gal} \lesssim 15$ kpc, and the galactic magnetic fields which control the cosmic ray motion are generally believed to be correlated with the diffuse mass.

The combination of the simplifying assumption of step function matter arms and a similar cosmic ray distribution is recognized to be unrealistically sharp and leads to enhancements in the predicted γ-radiation from the direction of arms which are too sharply defined. However, the refinement of a smooth rise and fall would be difficult to implement, and this seems unwarranted at this time both on the basis of the limitations in the γ-ray data and the lack of knowledge of the matter arm profile.

(d) Gamma Ray Source Function and Calculation of Predicted Intensities

The detailed calculations associated with the production of energetic γ rays through cosmic ray nucleons interacting with interstellar matter including all the primary cosmic ray and interstellar matter components, all the secondaries and their decay products, the angular distribution, and the energy spectrum are very detailed and lengthly. These calculations have, however, been performed. Following the original work of Cavallo and Gould (1971) and Stecker (1971), Badhwar and Stephens (1977), Stephens and Badhwar (1981), and Morris (1982 and 1983) have used the substantial recent high energy physics experimental work to estimate the γ-ray production energy spectrum for cosmic rays interacting with interstellar matter. The spectral shapes calculated by Stecker (1973), Badhwar and Stephens (1977), and Morris (1982) with the corrections at high energies (Morris, 1983) are in fact very similar. The Morris (1983) work was used here, and the relevant values are given in Table I at the end of this section.

The cosmic ray electron, matter γ-ray production can be calculated using the bremsstrahlung cross-section formulas of Koch and Motz (1959). The predicted radiation in the region below about 10^2 MeV is uncertain even locally in our galaxy because the interstellar cosmic ray electron spectrum is not well known at low energies where the electron spectrum observed near the Earth has undergone significant solar modulation.

To consider the electron spectrum, it is necessary to look ahead to some of the γ-ray results. At present, the γ-ray spectral observations, particularly of COS-B, represent a concern independent of questions of the details of the matter density and distribution and of the variation of the cosmic ray density. Prior to the recently reported results of COS-B in the energy region above 300 MeV, the galactic γ-ray spectrum had been consistent with a galactic cosmic ray population consisting of the sum of cosmic ray nucleon spectrum and the electron energy spectrum observed at high energies (e. g., Protheroe, 1982), approximately 3.9×10^{-3} $E^{-2.3}$ electrons cm^{-2} sr^{-1} s^{-1} MeV^{-1} changing to a spectrum of the same form, but with a power law index of 2.1 to 2.3 at (2 to 3) $\times 10^3$ MeV (e.g., Kniffen and Fichtel, 1981, and Webber, 1982) in agreement with the interstellar electron spectral range set by radio observations (Cummings et al., 1973) and with current concepts of solar modulation (See also Webber, Simpson, and Cane, 1980). This combined spectrum changes little in shape with position in the galaxy whether one assumes a cosmic ray density proportional to matter or a constant cosmic ray density if the life-time is similar to what it is locally. (For a discussion of this point, see Fichtel et al., 1976.) If this spectrum is used, although there is good agreement in shape in the medium energy range (a few to 35 MeV) and over the 35 MeV to 300 MeV range, where results of SAS-2 and COS-B are available (e.g., Bertsch and Kniffen, 1983), the predicted intensity above 300 MeV exceeds that observed by COS-B. Lebrun and Paul (1983) have deduced a spectrum of the form $E_e^{-2.7}$ for the energy range below 1 GeV from the γ-ray data alone. A cosmic ray differential electron spectrum with the form $E_e^{-2.8}$ and a normalization below (somewhat more than a factor of two) that of the observed cosmic rays could be used with the cosmic ray nucleon spectrum to obtain agreement with the medium and high energy spectrum (Lavigne, 1982); however, in addition to its being inconsistent with the observed ratio of high energy cosmic ray nucleons to electrons, it is only marginally consistent with the electron spectrum deduced from radio data especially when one considers shape.

For this work, the observed high energy cosmic ray electron spectrum of 3.9 x 10^3 $E^{-2.8}$ electrons cm^{-2} sr^{-1} s^{-1} MeV^{-1} has been retained above 4000 MeV, and a spectrum of 324 $E^{-2.5}$ electrons cm^{-2} sr^{-1} s^{-1} MeV^{-1}, confined to agree with the spectral range deduced from radio measurements, has been used below that energy. As will be seen, the resulting spectral agreement with observation is fair, but not entirely satisfactory. It does not appear possible to obtain better agreement if one retains the constraints of not reducing the high energy electron spectrum below the locally observed value and staying within the bounds set by radio observations. (For a further discussion of the electron spectrum, see Webber, 1983) This general problem will be addressed further in the discussion section, particularly with respect to possible alternative explanations. However, it should be noted that if the threshold of the high energy range of 300 to 5000 MeV of COS-B were in fact only (30 to 50) MeV higher than quoted, the difficulty would not exist since the theoretically predicted intensity would then be (11 to 17) % lower. There is no reason known to the authors, however, to suspect such a correction is appropriate.

It should be noted that to obtain agreement at low γ-ray energies (Sacher and Schoenfelder, 1982) there has to be an increase in slope of the electron spectrum in the region below about 30 to 50 MeV, but this increase is permitted by the radio measurements, and it is not unreasonable that such a low energy electron component should exist, for example, as a result of stellar flares.

The calculations associated with the production of Compton γ rays have been performed in some detail for cases of astrophysical interest by Ginzburg and Syrovatskii (1965). Cosmic ray electrons interact with galactic starlight photons, for which the optical and infrared ranges are the important ones, and with the universal blackbody radiation. The source functions of these interactions are much smaller in the galactic plane than that for bremsstrahlung. However, the total contribution to the galactic γ radiation is significant because the cosmic ray and stellar photon scale height above the galactic plane are greater than those of the matter.

In early work, the bremsstrahlung and Compton spectra were calculated from the electron spectrum in a manner described by Fichtel et al. (1976), and it was shown that within the expected range of average mass densities over the galaxy, although the cosmic ray intensity might vary within a limited range according to the model, the spectral shape did not change in a significant manner. However, there are two new considerations, one related to galactic photon densities and the other to cosmic ray lifetime, which now enter the picture, and, although they do not effect the bremsstrahlung predictions, they do effect the predicted Compton radiation in the inner galaxy. Kniffen and Fichtel (1981) calculated the expected photon densities through the galaxies based on existing observations and found that they were much higher than anticipated. Particularly in the optical and infrared regions of the spectrum they ranged from 3 or 4 to 10 or more times their local value in the inner Galaxy ($R \lesssim 5$kpc). The significance of these estimated photon densities lies in the effect they have on the very high energy electron spectrum and hence the Compton radiation. In the γ-ray energy range of interest here there is no significant affect for bremsstrahlung which for cosmic ray like spectra arises very prominantely from electrons with energies in the range of one decade immediately above the γ-ray energy. The Compton radiation typically comes from much higher energy electrons.

To approach this point more quantitively, consider the quantity

$$\left(\frac{\tau_e}{E_e}\frac{dE_e}{dt}\right)$$

for synchrotron radiation, Compton radiation, bremsstrahlung, and ionization, where τ_e is the electron lifetime, and E_e is the electron energy. If this quantity approaches minus one for any region in the galaxy in the energy range of interest (for the purposes of this discussion $E_e \gtrsim 50$ MeV), the assumption of a nearly constant spectrum is not valid. With regard to bremsstrahlung and ionization there is no concern in this higher energy range (although for lower energies there is). Using the work of Fichtel et al. (1976), but a τ_e value of 1.5×10^7 years rather than the lower value they used to reflect the fact that current thinking places the lifetime of cosmic rays in the (1 to 2) $\times 10^7$ years range gives:

$$\left.\frac{\tau_e}{E_e}\frac{dE_e}{dt}\right|_{\text{synch}} \approx -1.6 \times 10^{-5} \left(\frac{B_\perp}{B_\perp\text{ (local)}}\right)^2 E_e, \tag{1}$$

where $B_{\perp\,(\text{local})}$ is assumed to be 3×10^{-6} gauss, and E_e is in MeV, and

$$\left.\frac{\tau_e}{E_e}\frac{dE_e}{dt}\right|_{\text{Comp.}} \approx -4.4 \times 10^{-5} \frac{\mu_{ph}}{\mu_{ph(\text{local})}} E_e \tag{2}$$

where $B_\perp$ is the perpendicular component of the magnetic field, E_e is in MeV, μ_{ph} is the photon density, and $\mu_{ph\,(\text{local})}$ is estimated to be 1.16 cm^{-3} for infrared, optical, and blackbody combined. Other contributions to the photon density are assumed to be small. Assuming the local electron energy spectrum to be in equilibrium, equation (2) shows clearly that in the inner galaxy where

$\mu_{ph} >> \mu_{ph(local)}$, for $E_e \gtrsim 2 \times 10^4$ MeV the cosmic ray electron intensity will be dramatically reduced, and for the energy range from approximately 0.4×10^4 MeV to 2×10^4 MeV the effect will be strong. Assuming $B_\perp^2$ is generally proportional to the mass, Compton radiation losses will dominate in the inner galaxy and synchrotron losses may be neglected for the first order consideration relevant here. The Compton radiation will itself be seen to be small compared to that from matter interactions.

For the energy ranges of particular interest here (70 MeV < E_γ ≤ 150 MeV), (150 MeV < E_γ ≤ 300 MeV), (E_γ > 100 MeV), and (300 MeV < E_γ ≤ 5000 MeV), the typical parent electron energies (although, in fact, there is a broad range in each size) are in the range from 0.4×10^4 MeV to 1.1×10^4 MeV for starlight, 1.6×10^4 to4.4×10^4 MeV for the infrared region, and 2.0×10^5 to 5.6×10^5 for the blackbody radiation. As a result, the electron spectrum will be sufficiently depressed in the inner galaxy in the relevant energy range such that there will be essentially no black black body and little infrared Compton radiation in this region. Even the starlight Compton radiation will be reduced to some degree. In the inner galaxy, were it not for this effect, the infrared Compton radiation would be twice or more that of the optical, and the blackbody Compton radiation would be about two-thirds that of the optical region. The net result is that the Compton contribution is quite small. This effect causes the center to anticenter diffuse galactic γ-ray emission ratio to be less than it would be if it did not exist.

The source functions obtained in this work are given in Table I. It is interesting to compare these values with those of other authors making direct comparisons of the γ-ray intensities to the matter column densities. Strong et al. (1982) obtain (1.40, 0.53, and 0.59) x 10^{-26} γ^{-1} (H Nuc)$^{-1}$ s^{-1} ster^{-1} for the three energy intervals (70-150) MeV, (150-300) MeV, and (300-5000) MeV for a sum of 2.52 x 10^{-26} γ (H Nuc)$^{-1}$ s^{-1} ster^{-1}, for $10° < |b| < 20°$, Issa et al. (1981 obtain 2.2 x 10^{-26} γ (H Nuc)$^{-1}$ s^{-1} ster^{-1} for $E_\gamma > 100$ MeV. For the sake of comparison, the numbers in Table 1 must be divided by 4 π to obtain q/4 π. Doing so, one obtains (0.88, 0.55, 0.53, 1.96, and 1.52) x 10^{-26} γ (H Nuc)$^{-1}$ s^{-1} ster^{-1} for (70 <E< 150), (150 <E< 300), (300 <E< 5000) (70 <E< 5000) and (E > 100) MeV, respectively. These latter values are generally lower as they should be, since they refer only to cosmic ray matter interactions to which Compton γ radiations and point source contributions are added, whereas the former values have knowingly ignored these contributions and attributed all the radiation to matter. For the (70 to 500) MeV region, the ratios of the above number are 0.78 and 0.92, and for the ($E_\gamma > 100$) MeV comparison, the ratio of the above numbers is 0.69. The average 0.80 would suggest a Compton and point contribution of typically 20%. For the highest energy interval, the two approaches lead to almost the same source function suggesting a minor contribution from point sources and Compton radiation.

In this work, the Compton contribution averaged over $|b| < 10°$ in these energy ranges varies from about 6% to about 14% of the radiation due to cosmic ray, matter interactions depending on the energy range and longitude, suggesting that essentially the entire galactic γ-ray diffuse radiation in this broad energy range can be explained by the sum of cosmic ray nucleon-nucleon interactions, bremsstrahlung, and Compton radiation, with little requirement for the addition of point sources. The ratios of the Compton radiation to that from the sum of the cosmic ray, matter interactions for several typical directions and energy intervals are given in Table II.

TABLE 1

Energy Range (MeV)	70-150	150-300	300-5000	> 100
Nucleon-Nucleon	3.4 $n_H r$	4.5 $n_H r$	5.6 $n_H r$	12.3 $n_H r$
Bremsstrahlung	7.9 $n_H r$	2.4 $n_H r$	1.2 $n_H r$	6.8 $n_H r$
Cosmic Ray, Matter	11.1 $n_H r$	6.9 $n_H r$	6.7 $n_H r$	19.1 $n_H r$
Compton Optical	0.26 $\mu_{vis} r$	0.12 $\mu_{vis} r$	0.13 $\mu_{vis} r$	0.38 $\mu_{vis} r$
Compton Infrared	0.44 $\mu_{IR} r$	0.20 $\mu_{IR} r$	0.22 $\mu_{IR} r$	0.65 $\mu_{IR} r$
Compton Blackbody	0.14 $\mu_{BB} r$	0.07 $\mu_{BB} r$	0.07 $\mu_{BB} r$	0.21 $\mu_{BB} r$

Gamma ray source functions in units of 10^{-26} γ-rays cm^{-3} s^{-1} for the energy range indicated. "n_H" represents the number of hydrogen nuclei per cm^3 either in atomic or molecular form. The matter source functions all include a correction for helium and heavier nuclei as described in the text. "μ_{vis}", "μ_{IR}", and "μ_{BB}" are the photon densities for the visible, infrared, and blackbody ranges, respectively. "r" is the ratio of the cosmic ray spectra to their local value if the spectra are unchanged. For the inner galaxy, the situation for Compton radiation is complex as explained in the text because of the high rate of energy loss of the parent electrons. The values of the "μ_i's" as a function of position in the galaxy are given in Kniffen and Fichtel (1981).

Given the source functions, the intensities in any direction are then calculated in a manner described, for example, by Fichtel and Trombka (1981) with consideration of the angular resolution of the instrument being taking into account where appropriate.

III. GAMMA RAY RESULTS AND THEIR INTERPRETATION

The predicted γ-ray intensities are compared to the SAS-2 and COS-B longitude distributions in Figures 1 and 2. It was noted earlier in this article that molecular hydrogen density normalization was left as an adjustable parameter. In earlier work (Kniffen, Fichtel, and Thompson and Kniffen and Fichtel, 1981) a normalization of 0.6 was used relative to Gordon and Burton (1976). This normalization is consistent with the independent analysis of radio data by Blitz and Shu (1980), and corresponds to a value of 1.3×10^{20} mol. cm^{-2} K^{-1} km^{-1} s^{1}. This value seemed again here to be about the best considering the various constraints set by the data in spite of the several new features. There were two competing affects in the new consideration. A higher value would have been indicated by the smaller arm to inner arm matter contrast (which has the effect of reducing the intensity because of the assumed correlation of the cosmic ray surface density with the matter surface density leading to a γ-ray intensity proportional to the square of the matter density) and the smaller Compton contribution due to the smaller scale height for cosmic rays assumed here relative to the earlier work. However, the relatively small diffuse galactic center γ-ray intensity reported by Mayer-Hasselwandeer et al. (1982) above 300 MeV dictates that the molecular hydrogen normalization factor be kept smaller.

TABLE II

ENERGY INTERVAL	l	b	Ratio of Compton Radiation to that Produced by Cosmic Ray, Matter Interactions
(70-150) MeV	0°	0°	.04
" "	0°	10°	.13
" "	90°	0°	.06
" "	90°	10°	.14
" "	170°	0°	.07
" "	170°	10°	.10
" "	290°	0°	.05
" "	290°	10°	.23
(150-300) MeV	0°	0°	.03
" "	0°	0°	.10
" "	90°	0°	.05
" "	90°	10°	.12
" "	170°	0°	.06
" "	170°	10°	.08
" "	290°	0°	.04
" "	290°	10°	.20
(300-5000) MeV	0°	0°	.03
" "	0°	10°	.09
" "	90°	0°	.05
" "	90°	10°	.12
" "	170°	0°	.06
" "	170°	10°	.08
" "	290°	0°	.04
" "	290°	10°	.20

Regarding specifically Figure 2 and the energy spectrum shown in Figure 3, there are two general comments. First, the Caravane collaboration has recently reanalyzed the combined instrumental and astrophysical isotropic γ-ray background (Strong, 1982). Whereas the background intensities for the (150-300) MeV and the (300-5000) MeV energy intervals are essentially unchanged from the values given by Mayer-Hasselwander et al. (1982), the (70-150) MeV background intensity is now estimated to be 4×10^{-5} photons $cm^{-2}s^{-2}$ $ster^{-1}$ rather than 3.2×10^{-5} photons $cm^{-2}s^{-1}ster^{-1}$. This change has been incorporated in Figures 2 and 4 by introducting a new "zero base". Second, in general, considering the difficulties and pioneering nature of the experiments, the agreement between the SAS-2 and COS-B data is remarkably good in terms of general intensity level, energy spectra, and relative distribution, as seen for example in Figs. 1, 2, and 3.

Considering the uncertainty in the point source contribution and the mass distribution, the agreement between the data and the predicted curves seems reasonably good especially when the sources noted in Figure 1 are taken into account, except for concern about the energy spectrum which was alluded to earlier.

There are some specific features to be noted in Figures 1 and 2. Notice that the edges of the Sagittarius and Crux arms at about 55° and 310° respectively mark the beginning of the higher intensity associated with the central region of that galaxy, and that further steps near 35° and 330° mark the edges of the Scutum and Norma arms. There appear to be increases at 75° and 285° associated with the local arm and the Carina arm respectively. The expected increase at 265° for the local arm is masked by the large increase due to the Vela pulsar.

The latitu distributions resulting from the model have been calculated taking into acco the COS-B instrument response. Figure 4 shows the predicted latitude distributions at longitudes near the galactic center, the anticenter and at two intermediate longitudes plotted together with the COS-B observations (Mayer-Hasselwander et al., 1982). The dashed line in the 70-150 MeV energy range again indicates the adjustd zero level on top of which the model predictions are plotted to account for the new higher background estimate (Strong, et al., 1982). In comparing with the observations, it should be remembered that the model makes no attempt to include contributions due to local clouds. The fits to the galactic center observations (1 = 350° to 10°) and in the intermediate range in the first quadrant $40^0 > 1 > 70^0$ are very good at medium and high energies. At (1=275° to 320°), the latitude dependence has the right shape, again indicating the radial distribution of the matter in the model is consistent with the γ-ray observations; there is a slight displacement from zero latitude at all energies in the observations (the "hat brim" effect) which the model does not attempt to reproduce. The anticenter result is also reasonable in these energy intervals considering the uncertainty of the γ-ray measurements and the gas distribution in that direction. In general, these results give confidence that the spatial distribution of the emission calculated from the model must be approximately correct. The predicted intensity in the 70-150 MeV range is somewhat low by an amount which appears to be independent of latitude and longitude. Since the shape of the distribution is in generally good agreement with the data in this energy range, except for this constant displacement, the presumption is that the difference is less likely to be due to an underestimated cosmic ray electron intensity in the 70-150 MeV range than to some unexplained background or nearly isotripic component. Otherwise, in consideration of the uncertainties involved, the overall agreement seems good.

It should also be mentioned that in the concept being presented here the arms on the far side of the galaxy make an important contribution for small ($|b| \lesssim 0.4°$) galactic latitudes. This feature results from the high energy γ-rays being essentially unattenuated as they pass through the galaxy to the Earth and the far side arm matter being largely concentrated in this small latitude interval. With future high resolution γ-ray measurements, these back side arms should appear as a narrow ridge superimposed on the broader ridge of the near side arms. If the mass density and photon density in the far side arms are similar to the near side arms, although the total intensity over the arm width will be lower by the ratio of the distances (not the distance squared because they are arms, not points), the peak intensities will be approximately the same since the distance factor is canceled by the area factor for a uniform density region in a given solid angle. Regions in longitude, not directly towards the center, but before the first arm tangents, e.g., ($5° \lesssim l \lesssim 15°$) would be ones in which to look for this effect. It should also be possible to identify tentatively very large far side molecular clouds if the majority of the molecular hydrogen is in large clouds.

It was noted earlier in section IId that the observed γ-ray energy spectrum presented a difficulty in terms of the cosmic ray spectra used here also having to agree with both the observed cosmic ray information and constraints placed on the cosmic ray electron spectrum by the radio data. It is seen that these constraints do permit fair agreement with the γ-ray data, but do not permit quite as steep a γ-ray spectrum as reported by Mayer-Hasselwander et al (1982) based on the COS-B data.

In section IIA, it was mentioned that for certain directions the cosmic ray density might be expected to be reasonably constant over that portion of the line-of-sight integration making a significant contribution to the

γ radiation and for these regions it would be possible to simplify greatly the calculation by assuming a constant cosmic ray density. Reference was given to some of the papers that had used this approach in that section. Somewhat more surprising perhaps is the good agreement that is obtained by assuming a constant cosmic ray density in the plane for the region ($10° < \ell < 100°$, $|b| < 10°$) and the COS-B data for the γ-ray energy interval 300 MeV < E < 5000 MeV as shown by Lebrun et al. (1983). There are, however, several factors which contribute. First, the relatively small percentage of the Compton component in the galactic center region compared to higher l values partially compensates for the stronger enhancement that would otherwise occur as l decreases due to an increased cosmic ray intensity. Second, in both the work here and that of Lebrun et al. (1983) the normalization of the molecular hydrogen density is treated as an adjustable parameter. Since the molecular hydrogen density is concentrated towards the galactic center, a large normalization value for molecular hydrogen is essentially the same as assuming a positive cosmic ray gradient towards the center in terms of the γ-rays produced. Lebrun et al. (1983) used 3.1×10^{20} molecules cm^{-2} k^{-1} s compared to the smaller value used here. Also, assuming an effective area of 47 cm^2 for COS-B, their deduced source function for cosmic ray interactions with matter for (300 MeV < E_γ < 5000 MeV) is 0.60×10^{-26} γ (H atom)$^{-1}$ s^{-1} sr^{-1} or 7.5×10^{-26} q (H atom)$^{-1}$ s^{-1}, a bit higher than the value of 6.7×10^{-26} γ (H atom)$^{-1}$ s^{-1} based on high energy particle physics results, but this difference is in the direction expected since ignoring the Compton radiation has the effect of raising the deduced source function. It can also be noted that the variation in the observed γ-ray intensity between 50° and 10° in l is less for 300 MeV < E_γ < 5000 MeV than in the other two COS-B energy ranges. This feature, if confirmed, may be due to a greater contribution of other sources at lower energy toward the direction of the inner Galaxy.

The constant cosmic ray assumption combined with the source functions based on high energy physics results predicts too large a diffuse γ-ray intensity in the anticenter direction by a ratio of about 4:3 to 3:2, as noted several times before, e.g., Houston and Wolfendale (1982). This result is expected, since as the matter density decreases in the outer galaxy, the cosmic ray density must also, since there is not then sufficient gravitational attraction to hold the local cosmic ray density.

This is an appropriate point to reiterate that there is also an unresolved point source contribution to the "diffuse" radiation measured by the SAS-2 and COS-B γ-ray instruments because of the limited angular resolution of these instruments. It is quite difficult to estimate this contribution; however, several factors suggest that point sources may not be a major contributor (see, for example, Cesarsky, 1980). These include the apparent near uniformity of the energy spectrum and the γ-ray luminosity of the galaxy and its distribution being about what would be expected from the diffuse sources. For the purpose of this paper, the reader is simply asked to keep in mind that there is some point source contribution yet to be determined which at least for the moment appears to be small.

IV. CONCLUDING REMARKS

It was the intent of this paper to determine if, in light of the recent developments, the calculation of the diffuse γ radiation including contributions from cosmic ray nucleon-nucleon interactions, bremsstrahlung, and Compton intensities leads to a reasonable agreement with the diffuse γ-ray results when using the current available estimates of the relevant interstellar parameters and certain specific assumptions. The two most important assumptions, beyond the acceptance of the interstellar matter and photon data used here and the interaction cross section information, are that the relevant components of the interstellar matter all lie in a common spiral pattern and that the cosmic ray density is proportional to the matter density on the scale of the spiral arms. These assumptions are supported by observations and theoretical considerations as described earlier. In general, the agreement between the theoretical predictions and the γ-ray data seems reasonable. For the present, more detailed refinements are inappropriate in view of the limitations imposed by the data and the limited knowledge related to some of the input parameters.

There are several further conclusions or suggestive implications which emerge. First, since the results obtained do suggest that the general concepts are reasonable, as γ-ray data of better angular accuracy and energy resolution and greater statistical weight become available, it should be possible to deduce the galactic cosmic ray and matter density distributions on a broad scale and even in relation to clouds with greater accuracy than has previously been possible. It may also be possible to detect the arms and even specific large clouds on the far side of the galaxy.

As with the earlier papers noted previously, the variation of the cosmic ray density with matter density on a broad arm scale seems consistent with the data. The anticenter region seems clearly to show a decrease in cosmic ray intensity, while the inner galaxy is consistent with an increase. At high latitudes and mid-longitudes where the cosmic rays are either local or would be expected to have characteristics similar to the local cosmic rays, agreement between observed γ-ray intensities and those predicted by a uniform cosmic ray distribution seem reasonable.

The observed energy spectrum is of some concern. The relatively small amount of galactic emission observed by the COS-B γ-ray instrument above 300 MeV places rather significant constraints on models of diffuse galactic emission. First, even assuming that essentially all of the galactic γ radiation above 300 MeV not clearly identified with point sources comes from cosmic ray interactions, a relatively steep cosmic ray electron energy spectrum, only marginally consistent with the spectrum deduced from radio observations, is still required to compensate for the value of the normalization for the molecular hydrogen (which is primarily concentrated in the inner galaxy) forced by the high energy γ-ray observations. There are several possible explanations for this situation:

1. Point sources account for the rest of the γ radiation in the lowest energy intervals. The few observed γ-ray source spectra are relatively hard like the diffuse spectrum, but these hard spectra sources may have been observed first for that very reason since the direction of the higher energy γ-rays can be measured more accurately. If the molecular hydrogen density is even lower, the point sources would become even more important. If the cosmic ray electron spectrum is closer to the modulated one, as some modulation theory would suggest, point sources at lower energies would also be more important. (It might be noted that if this is the explanation, the γ-ray emission spectrum in the outer galaxy, where point sources are presumably much less common, would be flatter than observed locally.)

2. The electron spectrum is quite steep and intense with the molecular hydrogen density being lower. The difficulties with this assumption are primarily related to constraints set by cosmic ray and radio data.

3. The diffuse galactic γ-ray intensity above 300 MeV derived from

the COS-B data is underestimated for some reason, or the threshold of the high energy interval is underestimated. It is only the intensity above 300 MeV which has forced these alternate considerations, and only a small correction in the energy threshold would eliminate the difficulty.

The Compton radiation is calculated to account for from 7% to 14% of the γ radiation in the plane ($|b| < 10°$) and for 8% to over 20% depending on energy at higher latitudes. In the central part of the galaxy its contribution is much smaller than it would be if the local electron energy spectral shape existed there; in this central region the high energy part of the electron spectrum from which the Compton radiation comes has itself been suppressed by the Compton radiation.

The Compton radiation appears then to account possibly for a major part of the approximately 20% difference between the calculation of source functions based on high energy physics results, as used here, and the observations or source functions calculated by other authors based on the simplifying assumption that only cosmic ray matter interactions are important for the production of the diffuse γ radiation. As a result, there is no compelling need to assume a large point source contribution (about 10% is quite compatible with the work here) although there is the suggestion that a more significant addition may be needed at lower energies than high energies, but there might also be an enhanced lower energy cosmic ray electron intensity which would account for this difference. There is the warning, however, that both this paper and the others treated the molecular hydrogen normalization as an adjustable parameter and only demanded it be within the fairly wide range allowed by other considerations. Even so, the agreement obtained with the γ-ray data when the molecular hydrogen contribution is added to the others which are not normalized adds credence to the hypothesis that the observed galactic diffuse radiation is primarily due to the interactions of cosmic rays with photons and matter.

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FIGURE CAPTIONS

Figure 1: The high energy E > 100 MeV γ-ray intensity as a function of longitude for $-10° < b < 10°$ from the SAS-2 data (Hartman et al., 1979) compared to the model discussed here.

Figure 2: Gamma ray intensity as a function of longitude averaged over the latitude range $-10° < b < 10°$ from 70 MeV - 150 MeV, 150 MeV - 300 MeV, and 300 MeV - 5000 MeV from the COS-B data (Mayer-Hasselwander et al., 1982) compared to the model discussed here shown by the solid line. The dashed line in the 70-150 MeV graph represents the new "0.0" line based on the revised background intensity for the COS-B data in this energy interval discussed in the text.

Figure 3: Energy spectrum of the galactic γ radiation for a region near the galactic center. The calculated spectra are based on the work described here. The solid curves give the sum of all components and the two principal components. The dot-dash curve includes an estimated correction for the increased energy loss by electrons in the inner galaxy. The 300 to 5000 MeV point of COS-B (Mayer-Hasselwander et al., 1983), which covers a large range in energy is plotted at an energy where the differential energy spectrum of the equivalent power law spectrum is equal to the integral intensity divided by the energy interval width. The Compton component shown as a lightly dashed line is seen to be small and uncertain because of the large effect of the Compton radiation on the parent electron spectrum in the galactic center region as discussed in the text. The COS-B data are those of Mayer-Hasselwander et al. (1982), and the SAS-2 data are those of Hartman et al. (1979).

Figure 4: Latitude distribution of the diffuse galactic γ radiation for three energy ranges and three longitude regions. The data are from the COS-B experiment (Mayer-Hasselwander et al., 1982); the solid lines are the unnormalized predictions of the model discussed in the text. The horizontal dashed lines in the lowest energy bin are the revised zero level, taking into account the more recent estimate of a higher background for the energy interval (Strong, 1982).

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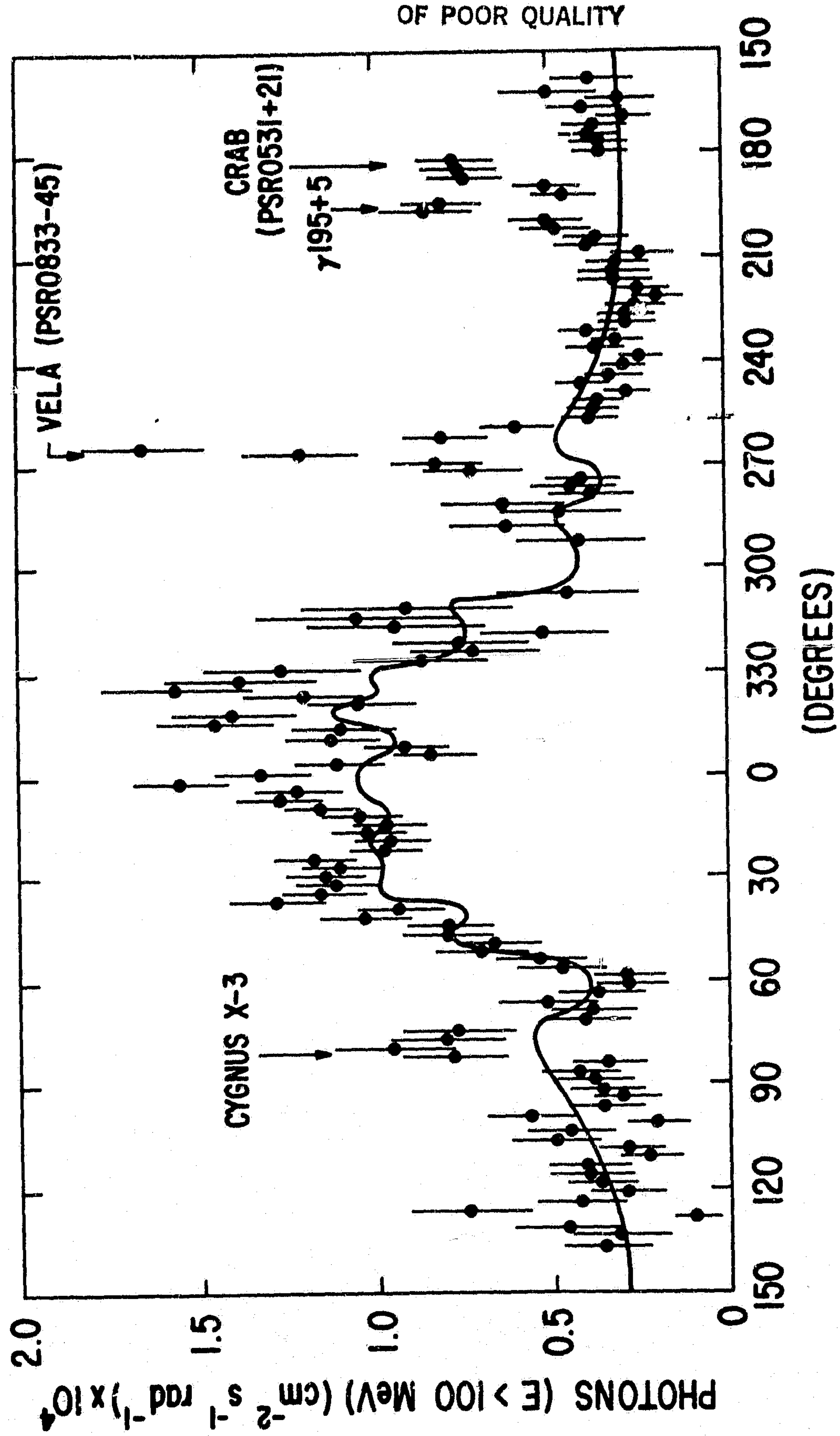
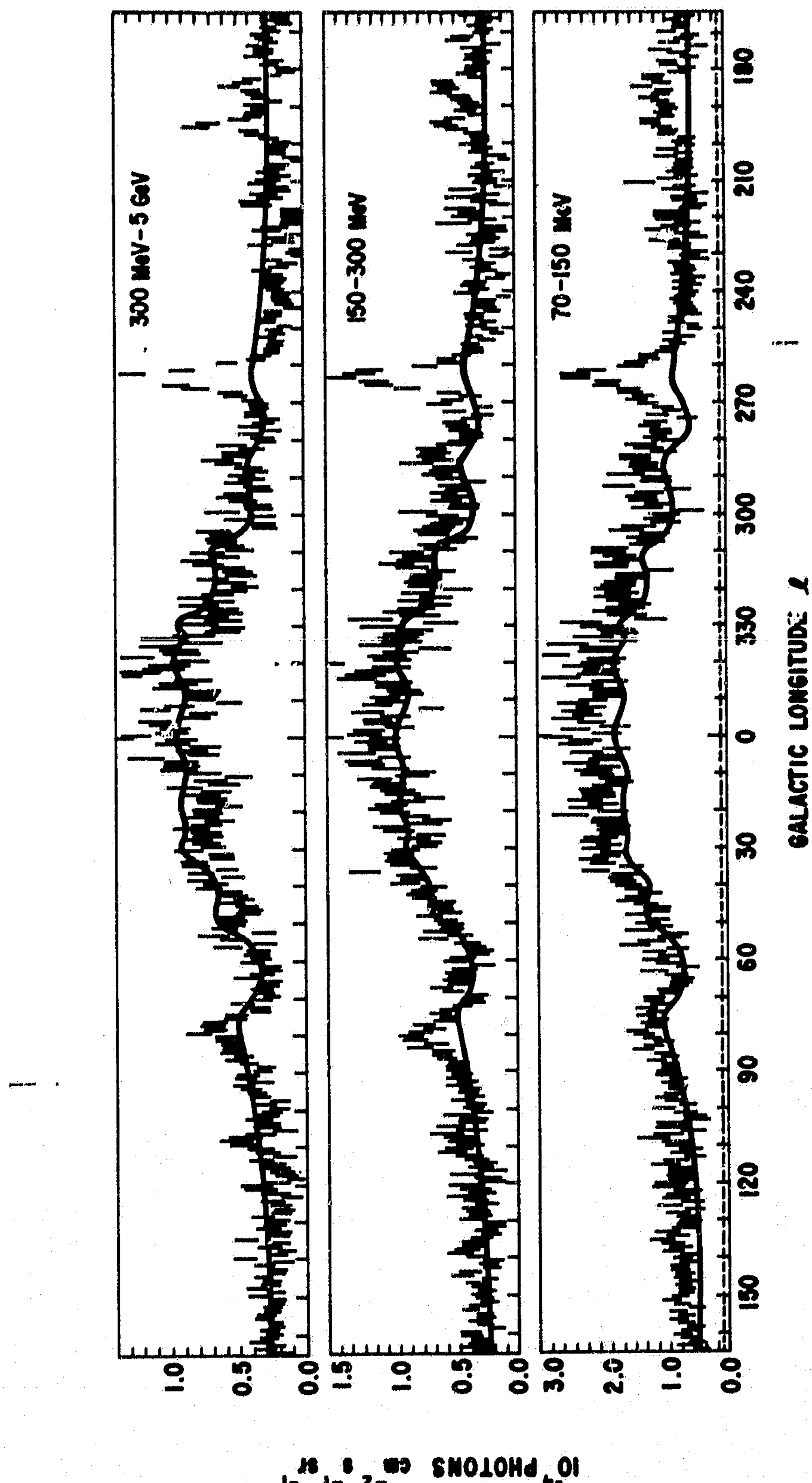


Fig.1



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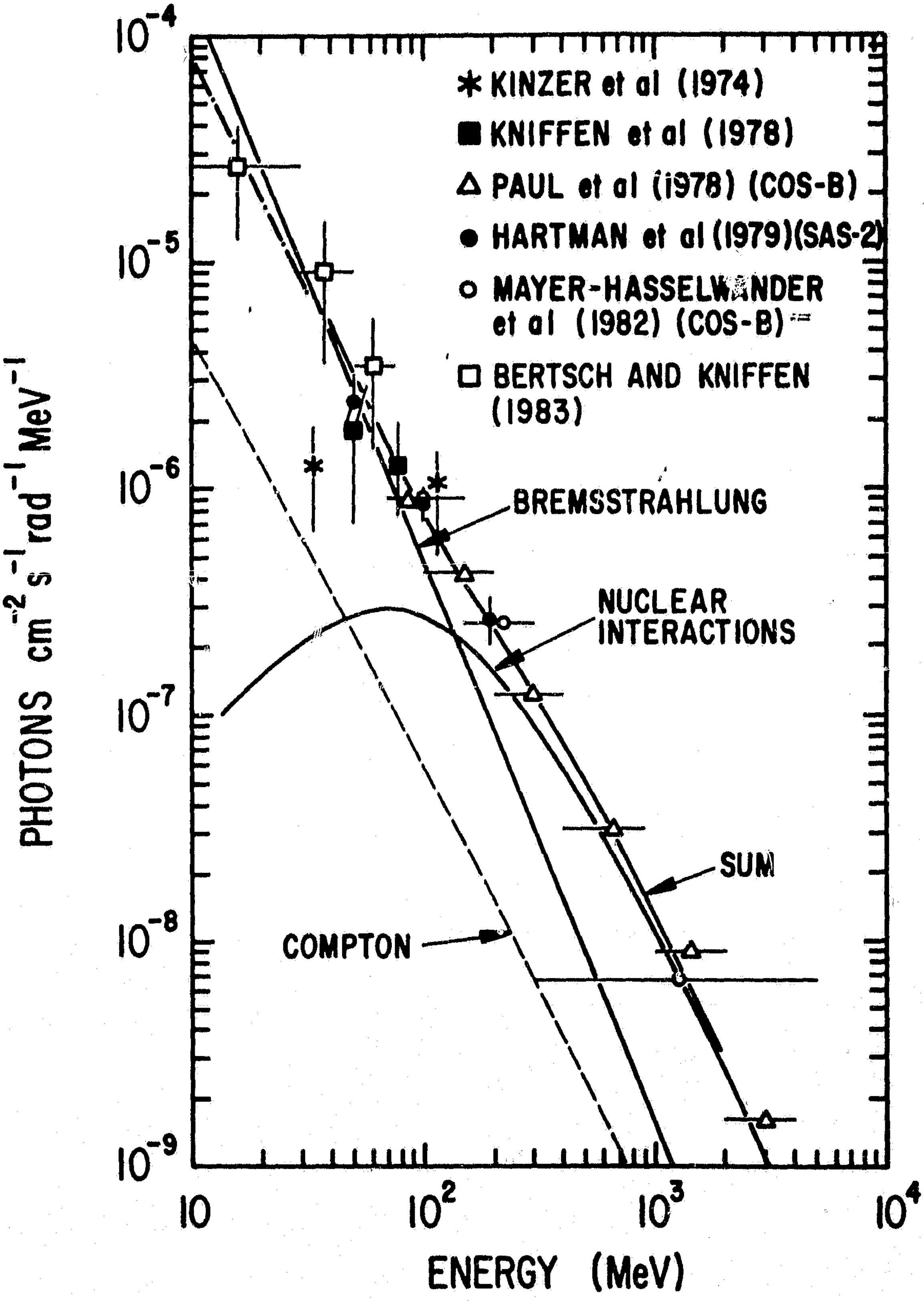

Fig.3

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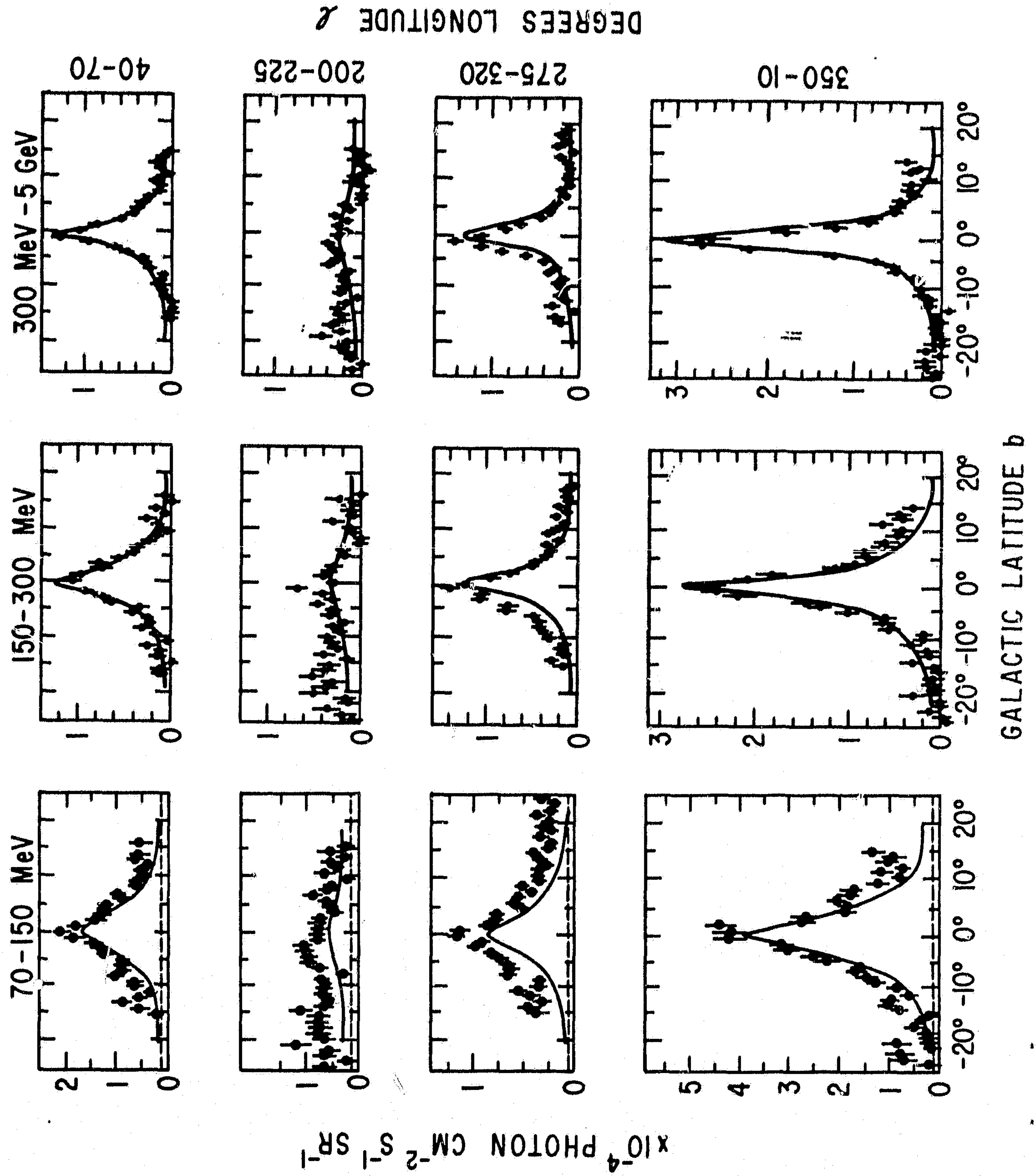

Fig. 4