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A Study of the Diffuse Galactic Gamma Radiation

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I. INTRODUCTION

Assuming cosmic rays pervade the Galaxy, they necessarily produced 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 or curvature radiation, but these processes are much less important then the others previously mentioned for the galactic diffuse radiation and will not be discussed here.

Extensive 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.) However, several recent devlopments make a reexamination and extension of this work worthwhile. These include the recently published 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 absorption radiation in the galaxy and, hence, the atomic hydrogen density in the inner galaxy, considerations related to the molecular hydrogen density normalization, recent results on molecular clouds, and improved theoretical calculations on the nucleon-nucleon source function. 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 will then be compared to the recently published COS-B high energy γ-ray results in section III.

II. DIFFUSE GALACTIC GAMMA RAY PRODUCTION

(a) Galactic Matter, Photon, and Cosmic Ray Distributions

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 (~ 0.12 kps in scale height for atomic hydrogen, but see specifically Kniffen, Fichtel and Thompson, 1977, for the model of scale heights used here) with the molecular hydrogen distribution apparently somewhat narrower (e.g., Gordon and Burton, 1976; Solomon and Sanders, 1980). Atomic hydrogen reveals its presence through the emission of the 21 cm line; however, there remains some uncertainty in the density of the inner galactic region related to 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 4 to 5 kps from the galactic center may be greater than previously estimated perhaps by a factor of 1/2. In this work the atomic hydrogen density distribution as a function of radius from the galactic center of Gordon and Burton (1976) was used, but modified so that the atomic hydrogen density in the inner region was increased by a factor of 1.5, and the closer densities were increased less in accordance with the amount of intervening matter. This density is also modulated for the galactic arms in a manner to be described later.

The density distribution of molecular hydrogen is measured less directly. At present, the best approach appears to continue to be 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 in terms of what is really desired makes the molecular hydrogen density distribution less certain than that of the atomic hydrogen. The average galactic radial distribution of molecular and atomic hydrogen deduced by Gordon and Burton (1976) does show reasonably 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 intenisty of molecular hydrogen is still quite uncertain. For the work here, the molecular hydrogen density normalization is treated as an adjustible parameter in the range from that estimated by Gordon and Burton (1976) to a factor of 0.4 smaller. The final value actually used was 0.6 smaller. It should be noted that the CO observations indicated that the great majority of the molecular hydrogen is in clouds. The recent 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 spacial distribution is difficult, on a broad scale the density profile is reasonably well known, even though details of arm structure are not always agreed on by all workers in the field. A general spiral pattern does appear to emerge. In addition to the 21 cm data the distribution 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 shown 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 Satigarius 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), and the matter density in the plane will be assumed to follow the pattern described by Kniffen and Fichtel (1981) relative to the arm to interam density ratio and the arm width.

For the photon distributions Kniffen and Fichtel (1981) using results of Bossé 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, source function for the Compton emission as a function of position in the galaxy. These will be used here.

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. Again, for the reasons described in the above works, 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 high of 0.6 kpc. This latter number 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 a relative reduction in the Compton contribution.

(b) Gamma Ray Source Function and Calculation of Prediced Intensities

The detailed calculations asscociated with the production of energetic γ rays through cosmic ray nucleons interaction 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. See, for example, Cavallo and Gould (1971), Stecker (1971), Badwar and Stephens (1977), and Morris (1982). The latter's work is based on the inclusion of substantial recent experimental work into a model of γ-ray production which requires momentum balance in the center of mass system. The predicted spectra are shown in Figure 1. The significance of the differences will become more apparent in the discussion of the experimental results in the next section.

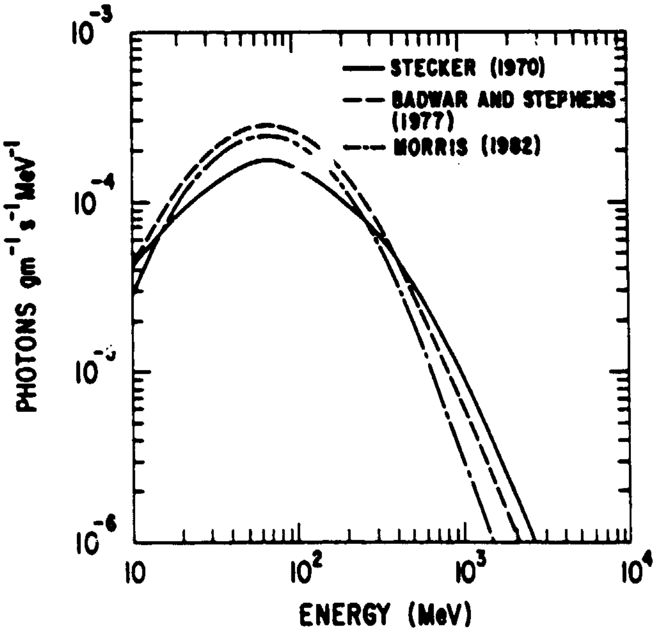


Fig. 1: Spectrum of the gamma-ray source function for cosmic ray nucleon, interstellar nucleon interations as a function of energy (Morris, 1982).

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 strong solar modulation. For the work here, the calculated source functions of Fichtel et al. (1976) based on the cross-sections of Koch and Motz (1959) will be used here.

The calculations associated with the production of Compton γ rays have been performed in some detail for the 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. The results presented here for the Compton radiation will be based on the source functions of Kniffen and Fichtel (1981).

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. The predicted variation with longitude for the various Compton components and the cosmic ray, matter interaction component are shown in Figure 2.

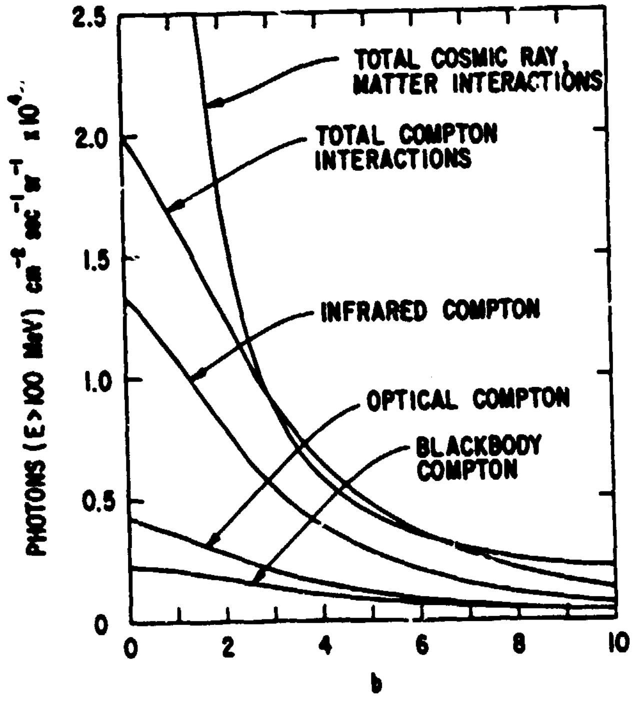


Fig. 2: Gamma ray photon intensity as a function of galactic latitude predicted by the model discussed here for the Compton components and the total cosmic ray, matter interaction component.

III. GAMMA RAY RESULTS AND THEIR INTERPRETATION

Based on the source functions, the matter distributions, and the assumptions just discussed, the expected γ-ray intensity has been calculated. The prediction of the γ-ray intensity with the molecular hydrogen assumed to be 0.6 that of Gordon and Burton (1976) is compared to the SAS-2 and COS-B longitude distributions in Figures 3 and 4 and to the energy spectrum in the galactic center region in Figure 5. Considering the uncertainty in the point

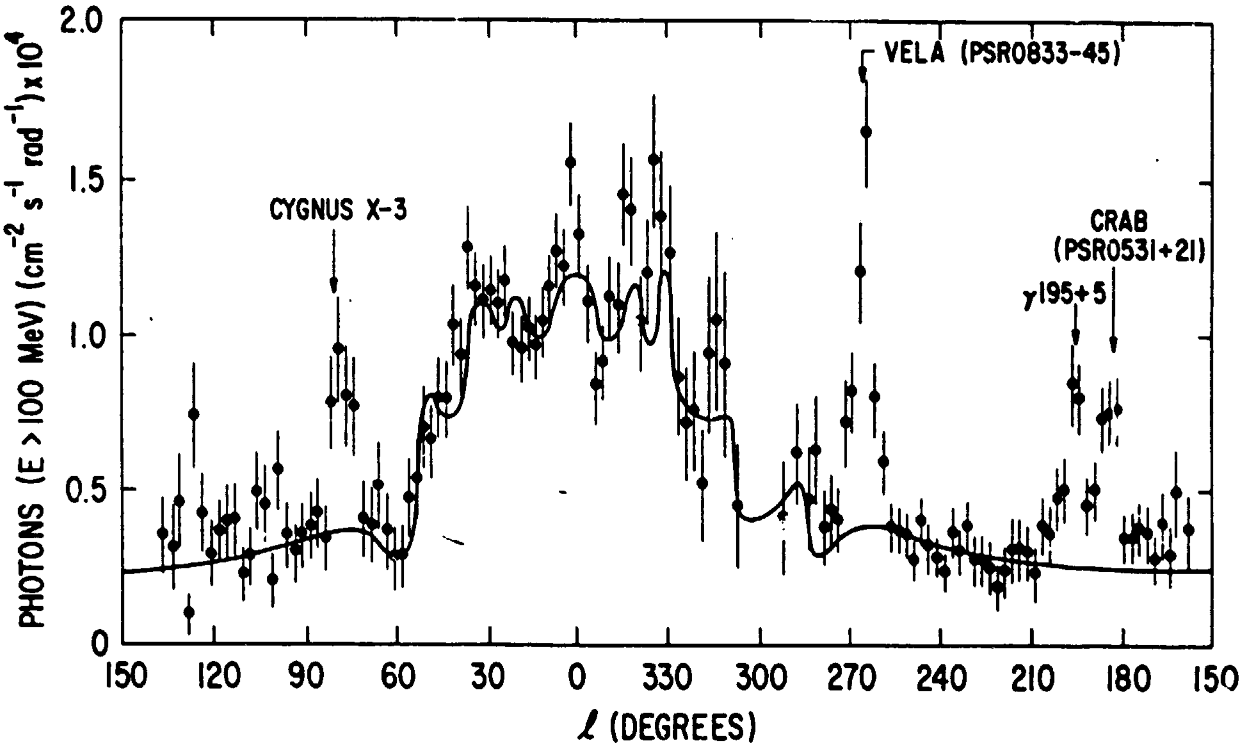


Fig. 3: The high energy E > 100 MeV γ-ray intensity as a function of longitude for -10° < b < 10° from the SAS-2 data (Hartman et al., 1979) compared to the model discussed here.

source contribution and the mass distribution, the agreement between the data and the predicted curves seems reasonably good. Regarding Figures 4 and 5, there are two comments. First, if the older cosmic ray nucleon source function of Stecker (1971) had been used rather than that of Morris (1982), the agreement in the 300 MeV to 5000 MeV energy interval would be quite poor with the theory predicting 1.7 to 2 times as many γ rays in the center than reported. If this older source function were correct, then either the cosmic ray nucleons play a relatively small role for some reason, or the measured high energy COS-B γ-ray intensity is too low. Even with the more recent nucleon-nucleon calculations, the >300 MeV intensity seen by COS-B is generally a bit lower than expected relative to the 70-150 MeV intensity. The most straightforward adjustment to the model to account for this posible difficulty would be an enhancement of the electron component coupled with a decrease in the normalization parameters for molecular hydrogen. The second

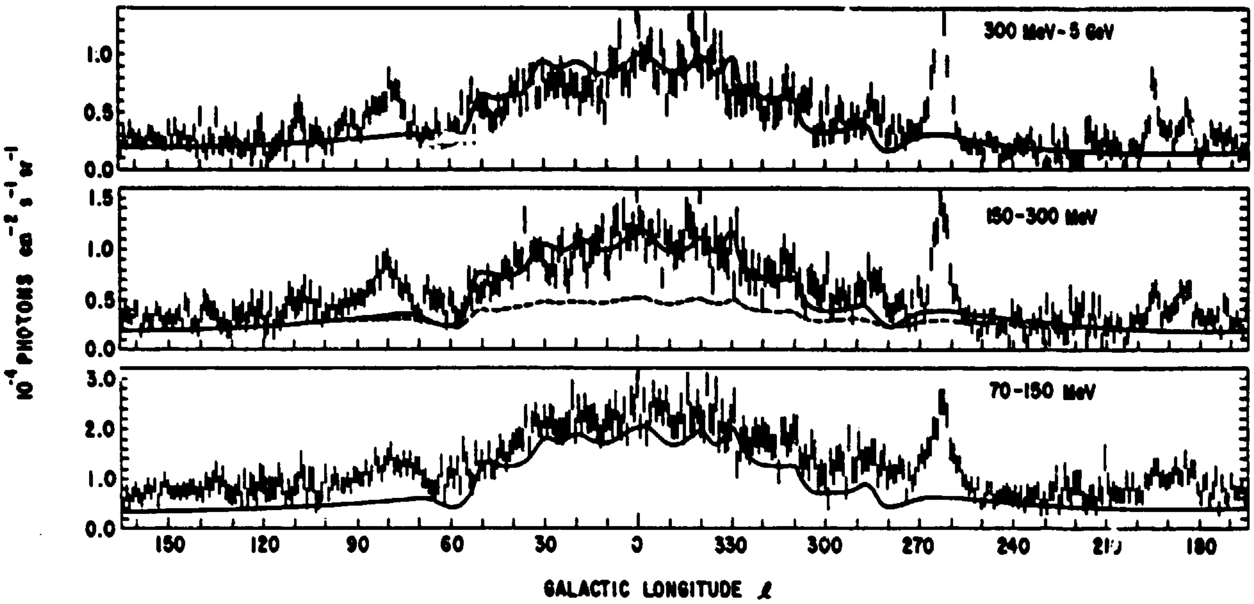
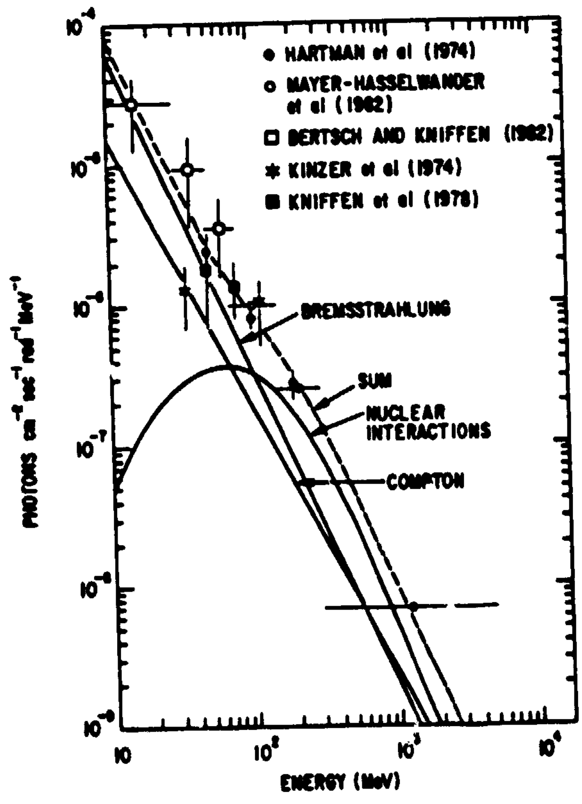


Fig. 4: Gamma ray intensity as a function of longitude averaged over the latitude range -10° < b < 10° from 70 MeV - 150 MeV, 150 MeV - 300 MeV, and 300 MeV - 5000 MeV from the COS-B data (Mayer-Hasselwander et al., 1982) compared to the model discussed here shown by the solid line and a constant cosmic ray density distribution model shown by the dashed line.

Fig. 5: Energy spectrum of the galactic γ radiation for a region near the galactic center. The calculated spectra are based on the work of Kniffen and Fichtel, (1981) modified to include the recent nucleon-nucleon calculations of Morris (1982). The COS-B data are those of Mayer-Hasselwander et al. (1982), and the SAS-2 data are those of Hartman et al. (1979).



comment is that, although the intensities for the center and the sources (195,5), PSR 0531+21, PSR 0833-45 measured with the SAS-2 and COS-B instruments are in good agreement with each other, the COS-B instrument appears to see a somewhat larger (about 25%) anticenter diffuse intensity. The SAS-2 instrument, which sees the lower diffuse intensity, had essentially no background; the very small extragalactic isotropic background is not substracted in Figure 1. In the case of COS-B, which sees the higher diffuse intensity, the background estimated by the COS-B collaboration has been subtracted.

The latitude distribution predicted by the model taking into account the angular resolution of the COS-B instrument generally agrees well with the COS-B observations up to latitudes of about eight degrees. Beyond this point the data tends to exceed the predictions of the model. An alternative description is that there is a small constant difference at all latitudes. This difference is consistent with the apparent excess in the COS-B data deduced from the longitude distribution just discussed.

A constant cosmic ray density, as might be predicted in the universal cosmic ray model, predicts a rather small γ-ray intensity from the central region. The dashed curve in Figure 4 refers to a model identical to the one just discussed except that the cosmic rays are assumed to be constant. Hence, if contrary to theoretical expectations, the cosmic ray density should be uniform, a relatively large point source contribution would be needed in the galactic center region.

It should be mentioned that there is also an unresolved point source contribution to the "diffuse" radiation measured by the SAS-2 and COS-B γ-ray instruments since the limited angular resolution of these instruments does not permit the separation of point sources. 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 uniformity of the energy spectrum just discussed and, as will be seen, 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 is assumed to be small, but not zero.

IV. CONCLUDING REMARKS

Considering the uncertainty in the point source contributions and the differences between the SAS-2 and COS-B data due presumably to the more limited statistics of the SAS-2 data and the need to subtract a substantial and necessarily somewhat uncertain background from the COS-B data, the agreement between the theoretical predictions and the γ-ray data seems quite reasonable. It should be noted that, 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. At present, detailed refinements to the model being discussed here seem inappropriate; however, when more detailed information exists, as it may soon, on the location of the large molecular clouds and especially the close ones, a further pursuit of the problem might be worthwhile.

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