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# DIFFUSE GAMMA RADIATION

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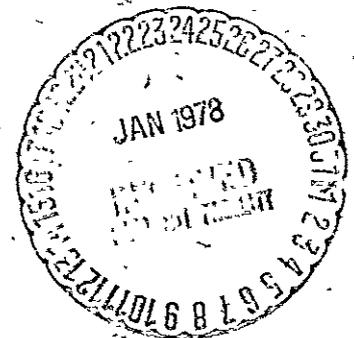
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C. E. FICHEL  
G. A. SIMPSON  
D. J. THOMPSON

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## Diffuse Gamma Radiation

C. E. Fichtel, G. A. Simpson\*, and D. J. Thompson  
NASA/Goddard Space Flight Center, Greenbelt, MD 20771

### ABSTRACT

An examination of the intensity, energy spectrum, and spatial distribution of the diffuse  $\gamma$ -radiation observed by SAS-2 away from the galactic plane in the energy range above 35 MeV has shown that it consists of two components. One component is generally correlated with galactic latitudes, the atomic hydrogen column density as deduced from 21 cm measurements, and the continuum radio emission, believed to be synchrotron emission. It has an energy spectrum similar to that in the plane and joins smoothly to the intense radiation from the plane. It is therefore presumed to be of galactic origin. The other component is apparently isotropic, at least on a coarse scale, and has a steep energy spectrum. No evidence is found for a cosmic ray halo surrounding the galaxy in the shape of a sphere or oblate spheroid with galactic dimensions. Constraints for a halo model with significantly larger dimensions are set on the basis of an upper limit to the  $\gamma$ -ray anisotropy.

The features of the galactic component of the  $\gamma$ -radiation and conclusions which can be inferred from the data are: (1) A linear correlation between both the 35 MeV  $< E < 100$  MeV and the  $> 100$  MeV  $\gamma$ -ray intensity and the radio continuum radiation as measured at 150 MHz. (2) For  $|b| > 12.8^\circ$ , a linear correlation between the  $\gamma$ -ray intensity in the same two energy ranges and the deduced atomic hydrogen column

\*NAS-NRC Postdoctoral Research Associate.

density. (3) For  $|b| < 12.8^\circ$  and  $60^\circ < \ell < 300^\circ$ , a correlation between the  $\gamma$ -ray intensity and the atomic hydrogen column density deduced from the 21 cm emission, but with less  $\gamma$ -radiation than would be expected from the linear extrapolation based on data for  $|b| > 12.8^\circ$ . (The magnitude of the decrease suggests that both the cosmic ray density and the molecular-to-atomic hydrogen ratio decrease beyond the local region,  $< 0.5$  kpc, for galactic radii larger than that for the solar system, although the possibility that only one of these two components decreases dramatically cannot be excluded.) (4) For  $300^\circ < \ell < 60^\circ$ , a  $\gamma$ -ray intensity from the galactic plane above that suggested by a linear extrapolation based on data for  $|b| > 12.8^\circ$ . (5) An energy spectrum of the high latitude  $\gamma$ -rays which is similar to that from the central galactic plane and hence has a substantially larger intensity in the 35 MeV to 100 MeV range than that expected from most current estimates of the interstellar cosmic ray electron spectrum. If this 35 MeV to 100 MeV excess emission is interpreted as being due largely to cosmic ray electron bremsstrahlung, a significant enhancement in the low energy (35 MeV to several hundred MeV) cosmic ray electron spectrum over previously assumed spectra is implied. If the excess is attributed to Compton radiation, the electron intensity at  $> 50$  GeV must be substantially higher than current measurements at the earth suggest. (No enhancement is necessary for the 1 to 30 GeV range, so there is not necessarily a conflict with the radio continuum observations.)

The "isotropic" component was found to have the following properties:

(1) an energy spectrum which is quite steep, with a  $2.85^{+0.50}_{-0.35}$  differential

power law index for a best fit straight line between 35 MeV and  $\sim 150$  MeV, (2) an intensity above 35 MeV of  $(6.3 \pm 1.4) \times 10^{-5}$  photons  $\text{cm}^{-2} \text{ster}^{-1} \text{s}^{-1}$ , and (3) an extrapolated intensity at 10 MeV which agrees well with the diffuse "isotropic" intensity measured at low energies. Relatively few theoretical models are consistent with the combination of the observed spectral shape, the intensity, and the lack of strong anisotropy, and those are not entirely free of other difficulties.

Key words: galaxies: Milky Way - galaxies: structure -  
gamma rays: general

## I. INTRODUCTION

There is substantial interest in the diffuse  $\gamma$ -radiation from regions away from the galactic plane because of the several possible origins of this radiation, some involving important cosmological implications and others relating to the nature of our Galaxy. The possible explanations of this radiation include emission from normal or extraordinary galaxies of various types, interactions of the universal black body radiation and cosmic rays (either primordial or from galactic leakage), primordial black hole emission, particle-antiparticle interactions at the boundaries of superclusters of matter and antimatter resulting from the baryon symmetric big bang theory, as well as various galactic models involving primarily bremsstrahlung and Compton radiation. These latter theories would in general suggest a variation of intensity with galactic latitude.

A large number of experiments have been conducted in an attempt to study the diffuse radiation. At low  $\gamma$ -ray energies, the situation

is rather unclear, in part due to the background problem which has been encountered in this energy range. At intermediate energies (from about 8 to 35 MeV), the most serious difficulty is probably the lack thus far of an adequate exposure opportunity outside the Earth's atmosphere. At higher energies ( $E > 35$  MeV), which is the range to be considered here, the Second Small Astronomy Satellite (SAS-2) has now provided data which confirm the existence of a diffuse high latitude  $\gamma$ -radiation (Fichtel, Kniffen, and Hartman 1973) first suggested by the OSO-3  $\gamma$ -ray data (Kraushaar et al. 1972).

In a letter summarizing the initial analysis of the entire SAS-2 data set Fichtel et al. (1977) showed that when the existing SAS-2 high energy data were summarized over galactic longitude, there was a strong variation with galactic latitude. For the region  $10^\circ \leq |b| \leq 90^\circ$ , it was shown that the summed data were consistent with an expression of the form  $C_1 + C_2/\sin |b|$ , corresponding to an isotropic component plus a galactic disk component. The ratio  $C_1/C_2$  was larger at 35-100 MeV than at energies above 100 MeV indicating that the apparently isotropic component on a coarse scale had a steeper energy spectrum than the galactic component. The galactic component intensity joined smoothly to the more intense region along the plane reported earlier (Fichtel et al., 1975) and had a similar energy spectrum.

In this paper, a substantially more detailed analysis of the diffuse radiation is performed along with a comparison to relevant data at other wavelengths, including the 21 cm emission from atomic hydrogen, the radio continuum radiation (a large portion of which is

believed to be synchrotron radiation), and the limited ultraviolet and radio information on the local molecular hydrogen. It is found that there are indeed two quite distinct components to the diffuse radiation, one which shows a good correlation with the galactic matter distribution and the synchrotron radiation, and the other, having a much steeper energy spectrum, which appears to be isotropic at least on the scale that it could be examined here. The galactic component is interpreted in terms of its implications for both the local and more distant regions of the galaxy. The apparently isotropic  $\gamma$ -radiation is then discussed particularly with regard to the constraints placed on possible models by the steep energy spectrum, the intensity, and the upper limit on the anisotropy.

## II. OBSERVATION AND ANALYSIS

The principal data sources are: (1) the  $\gamma$ -ray sky survey of SAS-2, in the energy intervals  $35 < E < 100$  MeV and  $E > 100$  MeV to be discussed in this paper, (2) the 21 cm summaries of Daltabuilt and Meyer (1972), Heiles (1975), and Burton (1976) which provide a measure of the atomic hydrogen column density, and (3) the 150 MHz synchrotron radiation survey of Landecker and Wielebinski (1970). In addition, to estimate the molecular hydrogen component, the results of the Copernicus ultraviolet survey of Savage et al. (1977) and the recent radio survey of the CO emission line analysis by Gordon and Burton (1976) are used.

The SAS-2  $\gamma$ -ray telescope is a 32-level thin plate digitized spark chamber. A detailed description of the instrument is given by Derdeyn et al. (1972). The entire SAS-2 celestial  $\gamma$ -ray data set, which was

collected during the period from November 1972 through June 1973, has now been analyzed in accordance with procedures described by Fichtel et al. (1975). The analysis used the detailed sensitivity, angular response function,  $\gamma$ -ray arrival direction accuracy determination, energy measurements, and energy resolution function (for determining the true energy spectral shape) determined in the extensive calibration outlined in that paper, as well as extensive (> 80%) rescans of the  $\gamma$ -ray event films to search for possible inefficiencies and selected earth albedo measurements during the satellite's history to check for possible changes in detector performance. Figure 1 shows the region of the sky covered by the complete SAS-2  $\gamma$ -ray observations. Notice that a full strip between the plane and the north pole exists in the vicinity of  $l = 0^\circ$  and also for  $l \approx 240^\circ$ , or in the general anticenter region well away from the intense central region of the galactic plane.

In the analysis to be presented here, the galaxy has been divided into eight parts, which are shown in Figure 1. Region A encompasses the inner galaxy, regions B and F allow study of directions tangent to the solar circle, and regions C through E display the anticenter. Each of regions A through E includes all latitudes with  $|b| < 60^\circ$  and all longitudes for which SAS-2  $\gamma$ -ray observations exist with the exception of the regions in which the strong contributions from the Vela pulsar PSR 0833-45 (Thompson et al. 1975 and Thompson et al. 1977a), Cygnus X-3 (Lamb et al. 1977b), the Crab pulsar PSR 0531+21 (Kniffen et al. 1974 and Thompson et al. 1977) and the  $\gamma$ -ray source at  $l=195^\circ$ ,  $b=+5^\circ$  (Thompson et al. 1977b) exist. Regions for which  $b > 60^\circ$  and  $b < -60^\circ$

(G and H respectively) have also been included in our analysis. The choice of the analysis regions was determined to a significant degree by the availability of  $\gamma$ -ray observations and the photon statistics.

For purposes of orientation, the  $E > 100$  MeV and the  $35 \text{ MeV} < E < 100$  MeV  $\gamma$ -ray intensities are plotted as a function of galactic latitude for regions A through F in Figures 2 and 3. (See the caption to Figure 2 regarding the reason for the latitude interval boundaries not being integers.) Notice first that there is a significant variation with latitude.

Note also in Figure 2 that near  $l=0^\circ$ , there is an excess on the positive latitude side of the plane in the  $60^\circ < l < 100^\circ$  and the  $100^\circ < l < 150^\circ$  intervals and on the negative side in the  $210^\circ < l < 250^\circ$  interval. This effect is similar to the "hat brim" effect seen in the galactic matter distribution, and is presumably a reflection of large-scale galactic structure.

In order that they may be compared to the  $\gamma$ -ray data, the column densities of atomic hydrogen,  $N_{\text{HI}}$ , and the  $150 \text{ MHz}$  brightness temperature,  $I_{150}$ , have been averaged over longitude within narrow latitude intervals for each of the regions in which  $\gamma$ -ray data exist. For direct comparison to the  $\gamma$ -ray data, these intensity measurements have been "defocused" to take into account the lesser angular resolution of the  $\gamma$ -ray observations. The knowledge of the molecular hydrogen in the local region is not sufficient to make a similar comparison, and it will be discussed later.

The correlations between the atomic hydrogen column density and both the low energy and high energy  $\gamma$ -ray emission are shown in Figures

4 and 5 for  $|b| > 12.8^\circ$ . In these figures, points near the origin, having small column densities, correspond to high latitude  $\gamma$ -ray observations, since the shortest paths out of the galactic disk are at high latitudes. For the same reason, these points represent predominantly local matter. The low-latitude data correspond to high column densities, and include radiation from the more distant regions in the survey.

The local  $\gamma$ -ray matter correlation is described rather well by a linear relationship of the form:

$$I_\gamma = AN_{\text{HI}} + B \quad (1)$$

where  $N_{\text{HI}}$  is the column density of atomic hydrogen in units of atoms/cm<sup>2</sup>, and  $I_\gamma$  is the  $\gamma$ -ray intensity in units of photons cm<sup>-2</sup>ster<sup>-1</sup>s<sup>-1</sup>. The straight line shown on each sub-figure of Figures 4 and 5 is the least squares fit to the combined observations from all the sky intervals with  $|b| \geq 12.8^\circ$ . Each fit has  $\chi^2/\nu = 0.8$  where  $\nu$  is the number of degrees of freedom. In view of the thickness of the matter disk, the latitude of  $12.8^\circ$  corresponds to a distance of about 500 pc to the point of one scale height from the plane. Within the uncertainties of the measurements all of the regions are seen to be consistent with this single curve. The values of "A" and "B" in equation (1) are:  $3.0 \times 10^{-26}$  photons cm<sup>-2</sup>ster<sup>-1</sup>s<sup>-1</sup>(atoms/cm<sup>2</sup>)<sup>-1</sup> and  $1.0 \times 10^{-5}$  photons cm<sup>-2</sup>ster<sup>-1</sup>s<sup>-1</sup> for  $E > 100$  MeV and  $4.3 \times 10^{-26}$  photons cm<sup>-2</sup>ster<sup>-1</sup>s<sup>-1</sup>(atoms/cm<sup>2</sup>)<sup>-1</sup> and  $4.9 \times 10^{-5}$  photons cm<sup>-2</sup>ster<sup>-1</sup>s<sup>-1</sup> for  $35 \text{ MeV} < E < 100 \text{ MeV}$ . The uncertainties in these numbers are illustrated in Figures 4 and 5 since the coupling of the errors precludes giving a single

meaningful one-parameter error estimate. Clearly the first term represents a source which is proportional to the matter density and the second term represents an isotropic component. The 35 MeV  $< E < 100$  MeV interval has a relatively larger "B" term, implying a steep energy spectrum for the isotropic component, at least on a coarse scale.

The low latitude intensities, involving integrals over more distant points, show significant deviations from the linear relationship. In all regions for which data exist free of substantial clearly established point source contributions except A (See Figure 1), the low latitude points fall below the previously determined line, as seen in Figures 6 and 7. In these regions, the  $\gamma$ -ray intensity from the low latitudes corresponds to a substantial contribution from regions lying at distances from the galactic center greater than that of the Sun. By contrast, in region A the  $\gamma$ -ray intensity within a few degrees of  $b=0^\circ$  lies above an extrapolation of the same straight line.

For comparison to the continuum radiation, the 150 MHz survey of Landecker and Wielebinski (1970) was used. The 150 MHz radiation has characteristics which are very similar to those of the  $\gamma$ -ray emission. Figure 8 shows the 150 MHz observations plotted as a function of the 21 cm column density. For  $|b| \geq 12.8^\circ$  the relationship between the brightness temperature and the matter density may be well represented ( $\chi^2/\nu = 1.2$ ) by  $T_{150} = (1.55 \times 10^{-19}) N_{\text{HI}} + 165$ . The uncertainties in these numbers are given in the figure. Since the temperature  $T_{150}$

is directly proportional to intensity, this expression is identical in form to that of equation (1). For regions away from the galactic center, the low-latitude 150 MHz data points fall below the line, in the same manner as the  $\gamma$ -radiation illustrated in Figure 6.

The correlation between the 150 MHz continuum radiation and the 35-100 MeV  $\gamma$ -ray data is shown in Figure 9. This figure shows a good linear correlation between the  $\gamma$ -ray and 150 MHz intensities ( $\chi^2/\nu=1.0$ ) with no evidence of a significant deviation from linearity or a non-zero intercept. The least squares fit straight line and its error are shown in the figure. The  $E > 100$  MeV  $\gamma$ -ray intensities show a similar correlation. In addition, on a large scale the  $\gamma$ -radiation, the 21 cm column density, and the 150 MHz brightness temperature are all reasonably consistent with a function of the form  $C_1+C_2/\sin |b|$  for  $|b| > 10^\circ$ , as noted previously for the  $\gamma$ -rays (Fichtel et al. 1977) and for the 21 cm column density (e.g. Heiles, 1976). This relationship is in fact to be expected for any form of diffuse radiation originating in the disk of the galaxy, simply from the geometry of a thin disk.

Finally, the energy distribution of the diffuse radiation was examined as a function of latitude and longitude. These data are shown in Figure 10. For this comparison it was necessary to multiply the high energy ( $> 100$  MeV)  $\gamma$ -ray intensities by an appropriate resolution function (thereby in effect defocusing the high energy data) so that they would be directly comparable to the 35-100 MeV  $\gamma$ -ray measurements, for which there is a poorer angular resolution. A least squares analysis of these data shows that a linear correlation is consistent with the

data, as shown in Figure 10, ( $\chi^2/\nu=0.8$ ). The straight line, in fact, fits the data within uncertainties over the entire latitude and longitude range included in the data set. There is no evidence for a variation in  $\gamma$ -ray energy spectrum with direction, although within present uncertainties the possibility of more than one major source with a somewhat different energy spectrum cannot be eliminated. Finally, the intercept not being at (0,0) is another indication of the different spectral shape of the isotropic component.

Because of the limited energy resolution of the detector the energy spectrum cannot be determined in fine detail. Further, the previously determined constants, "A" and "B" for equation (1) cannot be used directly in determining the constants of an assumed spectral shape, but must be used together with the energy resolution function (Fichtel et al., 1975) and an assumed spectrum. If power law spectra are assumed, for the "isotropic" component a differential index of  $2.85^{+0.50}_{-0.35}$  and intensities above 35 MeV and 100 MeV of  $(6.3 \pm 1.4) \times 10^{-5}$  and  $(0.9 \pm 0.4) \times 10^{-5}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{ster}^{-1}$  respectively are obtained. For the galactic component, a differential spectral index of  $1.7 \pm 0.3$  and intensities above 35 and 100 MeV of  $(6.9 \pm 1.7) \times 10^{-26} N_{\text{HI}}$  and  $(3.3 \pm 0.8) \times 10^{-26} N_{\text{HI}}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{ster}^{-1}$  respectively are obtained. These correspond to intensities of  $(1.6 \pm 0.4) \times 10^{-5}$  and  $(0.8 \pm 0.2) \times 10^{-5}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{ster}^{-1}$  for galactic latitudes near the pole and  $(8.3 \pm 2.1) \times 10^{-5}$  and  $(4.0 \pm 1.0) \times 10^{-5}$  photons  $\text{cm}^{-2} \text{s}^{-1} \text{ster}^{-1}$  for a typical region with a galactic latitude of about  $15^\circ$ . If a combination of a

a nuclear interaction ("π<sup>0</sup>") and power law spectrum (of the Compton or bremsstrahlung type spectral index) is assumed, almost identical results are obtained primarily because a relatively large power law component must be assumed. The two deduced spectra are shown individually together with their sum in Figure 11. These two spectra are very similar (agreeing within the indicated uncertainties) to those determined earlier assuming  $C_1 + C_2/\sin|b|$  dependence for the γ-rays (Fichtel et al. 1977).

Finally, there is the matter of calculating the degree of isotropy of the "isotropic" component. To accomplish this goal, the galactic disk component has to be subtracted first in a manner which is as unbiased as possible. The material already presented has shown that the atomic hydrogen column density, the synchrotron radiation, and the γ-radiation are all linearly correlated with each other for  $|b| > 12.8^\circ$  on the coarse scale being considered here. In the next section, it will be seen that because of the nature of the distribution of the two components involved in each of the interactions believed to be relevant, theoretical considerations also indicate that the major components of the local galactic γ-radiation should be proportional to either the matter column density (high energy, nuclear interactions, and bremsstrahlung) or the cosmic ray electron column density (Compton radiation) which is approximately represented by the continuum radiation. Since the matter column density has no known component beyond the galactic disk whereas the continuum radiation may very well have, the previously determined linear correlation between the HI column density and the γ-ray intensity was used to determine the multiplying factor for the column density.

The galactic disk  $\gamma$ -ray component determined in this manner was then subtracted from the total to find the  $\gamma$ -ray component not associated with the galactic disk in the various regions of the sky being considered. This approach does attribute a small center-to-anticenter dependence to the galactic disk  $\gamma$ -ray component, incidentally.

The ratio of the average residual (and larger portion) of the 35-100 MeV  $\gamma$ -ray intensity in the directions ( $300^\circ < \ell < 60^\circ$ ,  $20^\circ < |b| < 40^\circ$ ) to that from ( $100^\circ < \ell < 250^\circ$ ,  $20^\circ < |b| < 40^\circ$ ) was then determined. The ratio was found to be  $1.10 \pm 0.19^*$  with a cor-  


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 \*For the reader who may be interested, the similar ratio for the total  $\gamma$ -ray intensity before subtracting the galactic component is  $1.24 \pm 0.15$   


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 responding 98% confidence upper limit of 1.48. Hence, there is no evidence for a residual center-to-anticenter anisotropy. The ratio between the average  $\gamma$ -ray intensity from regions with  $|b| > 60^\circ$  to that from  $20^\circ < |b| < 40^\circ$  is found to be  $0.87 \pm 0.09$ . This result naturally argues against a thin oblate spheroid. Both of these ratios will be discussed in terms of constraints on specific models in section III.

### III. DISCUSSION

From the material presented in the previous section it is apparent, both on the basis of the latitude and the energy distributions, that the  $\gamma$ -radiation consists of two components, one galactic based on its latitude and longitude distribution and its correlation with the matter distribution, and the other apparently isotropic, at least on a coarse scale, with a relatively steep spectrum. These two components will now be treated separately.

## a) The Local Galactic Component

Based on its angular distribution and intensity, the  $\gamma$ -ray emission from the galactic plane has generally been assumed to result primarily from cosmic ray interactions with matter, with a much smaller contribution from localized sources. The latter are discussed later in this subsection. Calculations related to other production mechanisms in the local galactic region including Compton radiation from cosmic ray electrons interacting with starlight, infrared photons, and the blackbody radiation show that these may also make a contribution, but that synchrotron radiation is quite negligible (e.g. Schlickeiser and Thielheim, 1976; Worrall and Strong, 1977; Fichtel et al., 1976; Piccinotti and Bignami, 1976; and Stecker, 1977). It seems reasonable to test the assumption that the latitude dependent portion of the high-latitude  $\gamma$ -ray emission also has its origin principally in cosmic ray matter interactions in view of the similar energy spectrum, its correlation with the 21 cm emission, and its smooth connection to the radiation from the galactic plane. This hypothesis, which will now be pursued, will be seen to have some difficulties with the observed intensity and possibly the energy spectrum. Explanations for the differences will be suggested.

Along a line of sight in the direction  $(\ell, b)$  for the range of parameters being considered here, the  $\gamma$ -ray intensity produced by interactions between cosmic rays and matter can be shown (Fichtel et al. 1976) to be given by the expression:

$$\begin{aligned}
 I(E_\gamma, \ell, b) = & \frac{1}{4\pi} \int dr [S_{\gamma_n}(E_\gamma, r=0)g_n(r, \ell, b)f_m(r, \ell, b) \\
 & + S_{\gamma_{e_p}}(E_\gamma, r=0)g_e(r, \ell, b)f_m(r, \ell, b) \\
 & + S_{\gamma_{e_s}}(E_\gamma, r=0)g_n(r, \ell, b)f_m^2(r, \ell, b)] \quad (2)
 \end{aligned}$$

where  $f_m$  is the ratio of the total interstellar gas density at a distance  $r$  from the sun in the direction  $(\ell, b)$  to that at  $r=0$ ,  $S_{\gamma_n}$  represents the  $\gamma$ -rays produced per second per  $\text{cm}^3$  in interactions of nucleonic cosmic rays (with the intensity and spectral distribution in the solar vicinity) with the interstellar gas, and  $S_{\gamma_{e_p}}$  and  $S_{\gamma_{e_s}}$  are similar functions for primary and secondary cosmic ray electrons, respectively.  $g_m$  and  $g_e$  express the spatial variation with galactic position of the ratio of the primary cosmic-ray nucleon and electron components respectively to their interstellar value in the solar vicinity.

It is seen readily from equation (2) that, if the cosmic ray primary electron component is proportional to the cosmic ray nucleon component, as is commonly assumed, and if the secondary electron component is small compared to the primary electron component locally as the positron data suggest, the  $\gamma$ -ray intensity is simply proportional to the integral over the product of the ratios of the cosmic ray intensity and matter density to their local values.

Hence equation (2) may then be rewritten in the approximate form

$$I(E_{\gamma}, \ell, b) = \frac{1}{4\pi} \int dr S_{\gamma_{cr}}(E_{\gamma}, r=0) g_{cr}(r, \ell, b) f_m(r, \ell, b) \quad (3)$$

where the subscript cr refers to the combination of the cosmic ray electrons and protons.

With regard to the matter, as has already been noted, a reasonably accurate estimate of the atomic hydrogen column density in any direction can be obtained from the 21 cm measurements; however, the current status

of the knowledge of the other major component, namely the molecular hydrogen, is much less clear. A detailed picture of the molecular hydrogen density or even the column density does not exist. From the Copernicus data on the local interstellar gas densities, Savage et al. (1977) estimate the fraction of the gas in molecular form to be at least 0.25 and possibly as high as 0.5. Although not directly applicable to the local region, the large-scale survey of Gordon and Burton (1976) indicates that the fraction of gas in molecular form may be about 0.5 for an average distance of 10 kpc from the galactic center. Thus a reasonable range for the average ratio of the molecular hydrogen density to the atomic hydrogen density in the local region of the galaxy appears to be 0.3 to 1.0. There is the additional consideration that molecular hydrogen is generally believed to be preferentially concentrated in clouds; however, if, as will be discussed later it is true that the cosmic ray density is uniform on a scale of the average cloud-to-cloud dimension, this difference in distribution between the atomic and molecular hydrogen is not of concern here. Other tracers of the total matter, such as interstellar reddening and galaxy counts, are generally correlated with the HI column density in a linear manner for the local region (Heiles, 1976), although there are some small scale differences.

A consideration in relation to the bremsstrahlung radiation is the percentage of helium nuclei and heavier nuclei in the interstellar medium, because of the  $Z(Z+1)$  dependence of this radiation. Fichtel et al. (1976) assumed the helium-to-hydrogen ratio to be 0.10 and the

heavy-to-hydrogen ratio to be 0.01 leading to contributions relative to hydrogen of 0.30 and 0.25 respectively. There seems to be no basis for changing these estimates, although there is substantial uncertainty in them. If the interstellar medium were particularly rich in heavy nuclei, the bremsstrahlung could be somewhat larger, but in fact a heavy-to-hydrogen ratio of 0.01 appears to be on the high side of current estimates.

Turning now to the  $\gamma$ -ray source functions,  $S_{\gamma}^{cr}$  in equation (3) consists of the sum of  $S_{\gamma}$  and  $S_{\gamma_n}$ , where  $S_{\gamma_e}$  in turn is the sum of  $S_{\gamma_{e_p}}$ , the primary electron contribution, and a small correction for the secondary electron term. For  $S_{\gamma_n}$  ( $E > 100$  MeV) there is the recent value of  $13.0 \times 10^{-26}$  photons ( $E > 100$  MeV)  $\text{cm}^{-3} \text{s}^{-1}$  from the work by Fichtel et al. (1977b) and Kniffen, Fichtel, and Thompson (1977) based on the earlier calculations of Stecker (1973), but using more recent values for the parameters. For  $S_{\gamma_e}$  ( $E > 100$  MeV) the same authors give  $3.5 \times 10^{-26}$  photons  $\text{cm}^{-3} \text{s}^{-1}$ . These numbers are based on there being 1.04 protons and electrons, or "atoms", per  $\text{cm}^3$  in either atomic or molecular form, a helium-to-hydrogen ratio of 0.1, and a heavy-nuclei-to-hydrogen ratio of 0.01. Using the same procedures, values of  $3.3 \times 10^{-26}$  photons  $\text{cm}^{-3} \text{s}^{-1}$  for  $S_{\gamma_n}$  ( $35 \text{ MeV} < E < 100 \text{ MeV}$ ) and  $5.9 \times 10^{-26}$  photons  $\text{cm}^{-3} \text{s}^{-1}$  for  $S_{\gamma_e}$  ( $35 \text{ MeV} < E < 100 \text{ MeV}$ ) are obtained. More recently Savage et al. (1977) have estimated the number of "atoms"  $\text{cm}^{-3}$  to be 1.15 or possibly slightly larger, and hence  $S_{\gamma_n}$  ( $E > 100$  MeV) and  $S_{\gamma_e}$  ( $E > 100$  MeV) would become  $14.4 \times 10^{-26}$  and  $3.9 \times 10^{-26}$  photons  $\text{cm}^{-3} \text{s}^{-1}$  respectively, and

$S_{\gamma_n}$  ( $35 \text{ MeV} < E < 100 \text{ MeV}$ ) and  $S_{\gamma_e}$  ( $35 \text{ MeV} < E < 100 \text{ MeV}$ ) become  
 $3.6 \times 10^{-26} \text{ photons cm}^{-3} \text{ s}^{-1}$  and  $6.5 \times 10^{-26} \text{ photons cm}^{-3} \text{ s}^{-1}$ , respectively.

Hence,  $S_{\gamma_{cr}}$  ( $E > 100 \text{ MeV}$ ) becomes  $18.3 \times 10^{-26} \text{ photons cm}^{-3} \text{ s}^{-1}$  and

$S_{\gamma_{cr}}$  ( $35 \text{ MeV} < E < 100 \text{ MeV}$ ) becomes  $10.1 \times 10^{-26} \text{ photons cm}^{-3} \text{ s}^{-1}$ . If it

is assumed that there might be as much as a factor of three more

molecular hydrogen, i.e. that the molecular-to-atomic hydrogen ratio

is 1.0 rather than 0.3, then  $S_{\gamma_{cr}}$  ( $E > 100 \text{ MeV}$ ) and  $S_{\gamma_{cr}}$  ( $35 \text{ MeV} < E$

$< 100 \text{ MeV}$ ) might be as large as  $27.5 \times 10^{-26} \text{ photons cm}^{-3} \text{ s}^{-1}$  and

$15.2 \times 10^{-26} \text{ photons cm}^{-3} \text{ s}^{-1}$  respectively.

In addition to the uncertainty in  $S_{\gamma_{cr}}$  due to the uncertainty in the molecular hydrogen density, there is an uncertainty in the electron bremsstrahlung contribution (which results primarily from electrons in the 10 to a few hundred MeV range), which in turn is determined largely by the lack of knowledge of the electron cosmic ray spectrum in the appropriate energy range. From an analysis of these uncertainties, Shukla and Cesarsky (1977) conclude that an upper limit to the electron source function is about 50% larger than the source function used here. Such a picture would be consistent with the closed galaxy model (Rasmussen and Peters, 1976). On the other hand, Webber (1977) has argued on the basis of radio data that the interstellar electron spectrum (in the energy range above 1 GeV) is actually lower than the standard demodulated spectrum (Cummings, 1973). The  $\gamma$ -ray spectrum observed here and that observed in the galactic plane (Fichtel et al. 1975; and Bennett et al. 1977) are consistent with a larger electron contribution or some other similar power law spectral component. If the possibility of a 50% larger electron intensity is

considered,  $S_{\gamma_{cr}} (E > 100 \text{ MeV})$  and  $S_{\gamma_c} (35 \text{ MeV} < E < 100 \text{ MeV})$  would have values of  $30.4 \times 10^{-26} \text{ photons cm}^{-3} \text{ s}^{-1}$  and  $20.1 \times 10^{-26} \text{ photons cm}^{-3} \text{ s}^{-1}$  respectively. Hence, from these considerations, the range of values for  $S_{\gamma_{cr}} (E > 100 \text{ MeV})$  and  $S_{\gamma_c} (35 \text{ MeV} < E < 100 \text{ MeV})$  are  $(1.8 \text{ to } 3.0) \times 10^{-25} \text{ photon cm}^{-3} \text{ s}^{-1}$  and  $(1.0 \text{ to } 2.0) \times 10^{-25} \text{ photon cm}^{-3} \text{ s}^{-1}$  respectively.

If the cosmic ray density in the local region is essentially constant near the plane (The justification for this assumption will be discussed in the next paragraph.) where the great majority of the cosmic ray matter interactions occur, then  $g_{cr}$  of equation (3) becomes 1.0 and equation (3) becomes:

$$I_{\ell}(E_{\ell}, \ell, b) = \frac{S_{\gamma_{cr}}}{4\pi} \int f_m dr \quad (4)$$

Assuming that in the local region the ratio of molecular hydrogen to the total matter is invariant on a broad scale averaged over a column as discussed before, equation (4) becomes

$$I_{\ell}(E_{\ell}, \ell, b) = \frac{S_{\gamma_{cr}}}{4\pi} \frac{N_{HI}(\ell, b)}{\rho_a} \quad (5)$$

where  $N_{HI}(\ell, b) = \int n_{HI}(r, \ell, b) dr$  is the column density of atomic hydrogen which can be determined from 21 cm radio observations and  $\rho_a$  is the local atomic hydrogen density.  $\rho_a$  is taken to be  $0.86 \text{ atoms cm}^{-3}$  to be consistent with the value used in determining  $S_{\gamma_{cr}}$ . Then

$$I_{\gamma_{cr}}(E > 100 \text{ MeV}, \ell, b) = (1.7 \text{ to } 2.8) \times 10^{-26} N_{HI}(\ell, b) \quad (6)$$

$$I_{\gamma_{cr}}(35 \text{ MeV} < E < 100 \text{ MeV}, \ell, b) = (0.9 \text{ to } 1.9) \times 10^{-26} N_{HI}(\ell, b) \quad (7)$$

There are several considerations supporting the point of view that the cosmic ray distribution is relatively uniform in the vicinity ( $\leq 0.5$  kpc) of the solar system. First, the observed cosmic ray anisotropy is extremely small. Further, whereas the cosmic rays are expected to be correlated with matter on the scale of galactic arms within the plane because the cosmic rays and magnetic fields on a broad scale can only be held by the gravitational attraction of the matter (Parker, 1966 and 1969), the cosmic rays are expected to be uniform on a cloud-to-cloud scale within the plane, although varying with height above the plane (Kniffen, Fichtel, and Thompson, 1977). The concept of local uniform cosmic ray density is also supported by the analysis of Freier, Gilman, and Waddington (1977) who show that the level of the  $\gamma$ -ray emission can only be explained if the cosmic rays are uniform locally since the predicted  $\gamma$ -ray emission would be much too large for the cosmic rays to be proportional to the matter on the scale of clouds. Further, since the magnetic fields are expected to bulge significantly between the clouds, the scale height of the cosmic rays is expected to be large compared to that of the matter (e.g. Parker, 1966; Bignami et al. 1975; Kniffen et al. 1977). This concept is supported by the large scale height ( $\sim 0.75$  kpc) observed for the radio continuum radiation (e.g. Baldwin, 1976). If it is assumed that the electron density and magnetic field energy density both have the same distribution on the average and that it is gaussian, then since

the synchrotron radiation is proportional to the product of the two, the scale height of each individually is  $\sqrt{2} \times 0.75$  kpc.

This scale height becomes important in the consideration of the Compton radiation. Following the work of Fichtel et al. (1977), the calculations on which the work was based, and assuming a gaussian electron distribution perpendicular to the plane with a scale height of  $\sqrt{2} \times 0.75$  kpc, the Compton radiation resulting from cosmic ray electrons interacting with the blackbody radiation is given by the following equations:

$$I_{C_{bb}}(E > 100 \text{ MeV}) = 0.074 \times 10^{-5} [\sin|b|]^{-1} \text{ photons cm}^{-2} \text{ ster}^{-1} \text{ s}^{-1} \quad (8)$$

$$I_{C_{bb}}(35 \text{ MeV} < E < 100 \text{ MeV}) = 0.117 \times 10^{-5} [\sin|b|]^{-1} \text{ photons cm}^{-2} \text{ ster}^{-1} \text{ s}^{-1} \quad (9)$$

The combined contribution from the infrared radiation and starlight is much more difficult to estimate not only because the average photon density in the plane is not very well known, but also its variation with height above the plane is poorly known. The effective scale height appears to be much smaller ( $\sim 0.2$  kpc based on the paper of Lambrecht, 1965) than that estimated for the electrons, so that even though the combined source function in the plane is slightly larger (Fichtel et al. 1976 and Piccinotti and Bignami, 1976), the net contribution is apparently smaller and is estimated to be:

$$I_{C_{s,ir}}(E > 100 \text{ MeV}) = 0.025 \times 10^{-5} (\sin|b|)^{-1} \text{ photons cm}^{-2} \text{ ster}^{-1} \text{ s}^{-1} \quad (10)$$

$$I_{C_{s,ir}}(35 \text{ MeV} < E < 100 \text{ MeV}) = 0.039 \times 10^{-5} (\sin|b|)^{-1} \text{ photons cm}^{-2} \text{ster}^{-1} \text{s}^{-1} \quad (11)$$

Hence, on this basis the combined estimate for Compton radiation is:

$$I_C(E > 100 \text{ MeV}) = 0.10 \times 10^{-5} (\sin|b|)^{-1} \text{ photons cm}^{-2} \text{ster}^{-1} \text{s}^{-1} \quad (12)$$

$$I(35 \text{ MeV} < E < 100 \text{ MeV}) = 0.16 \times 10^{-5} (\sin|b|)^{-1} \text{ photons cm}^{-2} \text{ster}^{-1} \text{s}^{-1} \quad (13)$$

The uncertainty in these last two numbers is quite large, in part due to the substantial uncertainty in the electron spectrum in the relevant range for the blackbody Compton radiation, namely one to several hundred GeV (e.g. Hartman, Müller, and Prince, 1977), partially due to the lack of knowledge of the electron density distribution perpendicular to the plane, and in part due to the uncertainty in the starlight and infrared photon distributions. A factor of two uncertainty is tentatively assigned to these estimates.

It is perhaps worth mentioning that the starlight and infrared contributions above the plane may be relatively more important in the central region of the galaxy, and this possibility should be kept in mind when examining low latitudes in the central galactic region. The Compton component will be mentioned again in the next section where the "isotropic" component is discussed.

The discussion of the predictions of the intensities is summarized in Table I and compared to the observed intensities using typical  $N_{HI}$  values for a given latitude. In both energy bands, the ranges of values allowed by the observations overlaps the upper end of the range

of values suggested by the theoretical considerations given here. The distribution between the two energy ranges as well as the intensity does, however, suggest that there is a relatively important and perhaps larger Compton or bremsstrahlung type spectrum contribution since the cosmic ray nucleon, matter interaction contribution is relatively better known and has a spectrum which by itself is inconsistent with the observed spectrum. It is important to note that a similar situation for both the absolute intensity of the ( $35 \text{ MeV} < E < 100 \text{ MeV}$ ) radiation and its ratio to the ( $E > 100 \text{ MeV}$ ) radiation had been found previously for the galactic plane radiation (Fichtel et al., 1975 and Bennett et al., 1977). Therefore, this situation is not peculiar to the high latitude galactic radiation, but is a general feature of the galactic emission at all latitudes.

In considering the possible origin of this larger than predicted galactic radiation (primarily in the lower energy region) three possibilities seem most likely. These are a large bremsstrahlung contribution, a larger Compton component, and a significant point source contribution. The latter is a possibility which is difficult to verify or deny with the limited angular resolution of current experiments. It does, however, seem a bit ad hoc to postulate a class of low-luminosity  $\gamma$ -ray sources with relatively steep spectra to explain these observations. The SAS-2 results show no evidence of high-latitude  $\gamma$ -ray sources, with a typical  $2\sigma$  upper limit of about  $2 \times 10^{-6}$  photons ( $E > 100 \text{ MeV}$ )  $\text{cm}^{-2} \text{s}^{-1}$ , and COS-B has also reported no source with a latitude greater than  $|b| = 7^\circ$  (Hermsen et al. 1977).

Regarding the possibility of a larger bremsstrahlung contribution, it would be possible to have a larger electron intensity in the lower energy (35 MeV to several hundred MeV) region relevant to the  $\gamma$ -rays being discussed here without demanding a larger intensity in the higher energy region which is relevant for synchrotron radiation. It should be realized, however, that the required bremsstrahlung spectrum implies an electron intensity which is about three to five times that assumed by Fichtel et al. (1976) based on the work of Daugherty et al. (1975) in the lower energy region, if it is to be the explanation in itself. It is about three if the molecular-to-atomic hydrogen mass ratio of 1.0 is assumed and the larger number if the molecular-to-atomic hydrogen mass ratio is assumed to be one-third.

If the Compton component is to be the primary contributor, from the earlier discussion it is reasonable to assume that the excess is due to a larger than expected cosmic ray electron, blackbody interaction and not electron, starlight and infrared interactions since the latter is the smaller component and is already defined within relatively narrow limits. It is true that the electron spectrum is relatively poorly known above about 50 GeV, but there are some reasons for believing that the current best estimate used here cannot be exceeded by much. First, the most recent spectral measurement (referenced earlier) of many which have been made lies a bit below this estimate. Secondly, theoretical considerations on galactic trapping and escape are very uncertain, but, if there is an energy-dependent escape mode it more likely would lead to relatively fewer high energy electrons at greater distances above the plane. There is little

experimental evidence to argue against a very thick electron disk of lower electron density (thereby avoiding a major conflict with the radio synchrotron data) which would increase the volume for the electrons and hence the Compton radiation.

The apparent correlation between the cosmic rays and the matter distribution in the spiral arms mentioned earlier might be thought to argue against a scale height much larger than the arm dimensions ( $\sim 1$  kpc). It should, however, be kept in mind that this correlation is observed in the inner galaxy, and, in the less defined outer part of the galaxy where the cosmic rays may also not be tied to the plane as strongly, the scale height for electrons might be larger.

In view of these considerations, it is worth examining the non-thermal radio emission in more detail. As noted earlier, it is generally associated with the galactic disk, but has a scale height of about 0.75 kpc rather than the much smaller ones for galactic atomic and molecular hydrogen, .12 and .05 kpc, respectively. The scale height for the continuum radiation is consistent with the concept of the cosmic rays and magnetic fields being tied to the plane by the material in the more dense regions of the clouds. Clearly the correlation between the Compton radiation and the continuum emission would be expected to be quite good even though the scale height of the former would be expected to be slightly larger as discussed before.

The physical connection between the continuum radiation and column density of matter at high latitudes is not direct, although, as shown in Figure 8, observationally there is a strong correlation between the

two. The effect may be largely one of geometry, in which roughly disk-like distributions of matter and high energy electrons show a correlation because they both have approximately  $(\sin b)^{-1}$  latitude dependences even though they occupy different regimes in height above the plane. This argument may also explain the continuum radiation's correlation with the disk component of the  $\gamma$ -radiation (Figure 9), if it is accepted that locally the cosmic rays are uniform over the region the matter occupies.

The fact that the best least squares line passes nearly through the (0,0) point in Figure 9 is probably fortuitous because both the  $35 \text{ MeV} < E < 100 \text{ MeV}$   $\gamma$ -ray emission and the continuum radio emission have major "isotropic" components which are likely to be of different origin, as will be discussed in section IIIc.

Figure 9 gives a comparison between the intermediate energy  $\gamma$ -ray emission and the continuum emission, which shows that on a coarse scale the correlation is in fact generally quite good. The approximately linear relationship is to be expected for the reasons outlined in the previous paragraph, and the consideration that, although the  $\gamma$ -ray bremsstrahlung radiation comes primarily from electrons in a range which barely overlaps in energy, generally falling below that of the synchrotron radiation, which in turn falls below that of the Compton blackbody radiation, the electron spectrum probably does not vary much at least in the local region of the galaxy.

### b) More Distant Galactic Plane Regions

Previous studies of the high energy  $\gamma$ -rays coming from the galactic plane have suggested that either both the cosmic ray intensity and the molecular-to-atomic hydrogen ratio increase toward the central part of the galaxy or one of the two increases dramatically (e.g. Bignami and Fichtel, 1974; Paul et al. 1974; Schlickeiser and Thielheim, 1974; Bignami et al. 1975; Paul et al. 1975; Stecker et al. 1975; Stecker, 1976; Puget et al. 1976; Paul et al. 1976). The concept that both increase is the more likely assuming the galactic dynamic balance described by Parker (1966 and 1969) and applied to the galactic  $\gamma$ -rays by Bignami and Fichtel (1974) is essentially correct. It has also been noted that the intensity of the high energy  $\gamma$ -radiation from the plane in the region away from the center ( $270^\circ < \ell < 90^\circ$ ) suggests the cosmic ray intensity is less than the local value (Dodds, Strong, and Wolfendale, 1975). With the data presented in Section II, it is now possible to look at these considerations and especially the latter in more detail. It should be kept in mind, however that unresolved point sources may be making a contribution.

For small latitudes, marked deviations from a linear relationship between the  $\gamma$ -ray emission and the 21 cm column density were observed in Figures 6 and 7 for those regions where data exist. In all the longitude intervals except  $300^\circ < \ell < 60^\circ$ , the  $\gamma$ -ray intensity falls below the line derived from the high latitude regions. In each of these intervals, the low latitude data include a substantial contribution from regions which lie beyond the solar circle. These more distant regions are generally in the lower density outer galaxy. The observed

depression of the  $\gamma$ -ray intensity below the line observed for these regions is then consistent with the concept that the cosmic ray density is coupled to the total matter density on a large scale, and is hence lower in these regions.

On the other hand, in the region encompassing the galactic center, the  $\gamma$ -ray intensity actually lies above the line deduced for the local region for low galactic latitudes. Again, this is consistent with the concept of cosmic-ray and matter coupling.

In addition, studies of the 2.6 mm CO line (e.g. Scoville and Solomon, 1975; Burton et al. 1975) indicate that the molecular hydrogen in the galactic plane does not follow the same distribution as the atomic hydrogen. Although some caution must be used in using the CO data to deduce  $H_2$  densities, it seems probable that the  $H_2$  densities are relatively larger toward the galactic center than the HI densities and relatively smaller toward the outer parts of the Galaxy. Thus, the molecular-to-atomic hydrogen ratio would be smaller in the outer Galaxy contrary to the assumption of a constant ratio for the local region leading to a decrease in the  $\gamma$ -ray emission. Conversely the inverse would be true for the  $360^\circ < \ell < 60^\circ$  region.

Thus, it seems most reasonable to explain the observed deviation in terms of a combination of a decrease in the molecular-to-atomic hydrogen ratio and in the cosmic ray density in the outer Galaxy and a combination of increases in both the quantities in the inner Galaxy, rather than variation in either quantity alone. For example, being more quantitative, to explain the result on the basis of molecular hydrogen alone would require nearly all the molecular hydrogen to vanish.

within about 0.5 kpc of the solar system. Since regions B and F are generally tangential to the solar circle, such a rapid decline in molecular hydrogen would imply that the solar system is in a very unique position in the Galaxy, a conclusion which is physically unappealing at best. Second, the decline in molecular hydrogen would not account for the similar deviation seen in Figure 8 comparing the 150 MHz and  $N_{\text{HI}}$  data.

The results here then support the concept of the variation of the cosmic ray density in association with the matter density on the scale of arms and large features, and, as seen in the previous section, argue against cosmic ray density variations on a cloud-to-cloud scale. (The cosmic ray density is, of course, also believed to vary with height above the plane in the manner described previously.) The results here do suggest a larger local matter density than assumed earlier. This result would imply a relatively lower cosmic ray density in other parts of the Galaxy than used by Kniffen, Fichtel, and Thompson (1977), since the cosmic ray density is normalized to the local matter density. However, the increased source function approximately compensates, and the general agreement remains. A major contribution from unresolved point sources could, of course, affect this discussion. A substantial  $\gamma$ -ray intensity from point sources in the inner galaxy would probably weaken the argument for a cosmic ray density increase there; however, the conclusion of a low cosmic ray flux in the outer galaxy would seem to remain or be strengthened.

### c. The Isotropic Component

Although there is clearly a substantial apparently isotropic  $\gamma$ -ray excess beyond the galactic disk component which was discussed in the last section, it should be kept in mind that, with the SAS-2 resolution of about  $4.5^\circ$  in the 35-100 MeV range and the limited statistics, isotropy has only been established on a rather coarse scale. However,

the degree of isotropy which has been established, and the steep energy spectrum, which also distinguishes it from the galactic disk radiation, will be seen to place strong constraints on models for the origin of this component. In the next few paragraphs, the galactic and extragalactic hypotheses for the origin of this isotropic component will be examined.

Galactic theories for the origin of the isotropic  $\gamma$ -radiation are generally built around a galactic halo which has the shape of a sphere or thick oblate spheroid and is populated with cosmic rays held by weak magnetic fields. The source of the  $\gamma$ -rays in the halo is Compton radiation from cosmic ray electrons interacting with the blackbody radiation and to varying degrees, depending on the model, with escaping starlight and infrared radiation. The matter and stellar distributions appear to preclude bremsstrahlung or point source models, and the synchrotron intensity is just too low to contribute significantly to the isotropic flux.

Theoretical models involving a galactic halo have generally postulated a halo with dimensions of the order of the galaxy and hence a radius, at least in the plane, of about 15 kpc. The implications of a much larger halo will be considered later. Since the sun is about 10 kpc from the galactic center, if such a halo exists and is responsible for the  $\gamma$ -rays, a very marked anisotropy would be seen, with the  $\gamma$ -ray intensity from the general direction of the galactic axis being much larger than that from the same latitudes in the anticenter direction. In fact, no such anisotropy is seen; specifically the ratio of the average

intensity in the ( $300^\circ < l < 60^\circ$ ,  $20^\circ < |b| < 40^\circ$ ) region to that in the ( $100^\circ < l < 250^\circ$ ,  $20^\circ < |b| < 40^\circ$ ) region was found in Section II to be  $1.10 \pm 0.19$  compared to a calculated value for the same ratio of 2.85 for a model with a uniform cosmic ray sphere with a 15 kpc radius. The result for a thick oblate spheroid is similar.

It is also of interest to consider the possibility of a halo of larger dimensions. If the region is assumed to be spherical and have a uniform cosmic ray density, the upper limit ( $2\sigma$ ) set for the anisotropy demands that the radius be at least 45 kpcs. Finally, it is also possible to set constraints on the oblateness of such a region which might be in the shape of an oblate spheroid. The ratio between the absolute value of the polar axis vector and the radius of the circle in the plane is found to be  $0.80 \pm 0.15$  based on the intensity for  $|b| > 60^\circ$  compared to that for  $20^\circ < |b| < 40^\circ$  given in Section II. This result argues against a major deviation from a spherical shape, under the assumptions which have been used here.

It might be suggested that within the framework of a galactic oblate spheroidal or spherical halo, a Compton component might have a different and particularly weaker dependence on galactic longitude. However, the analysis in Section IIIb and related general arguments would actually suggest the opposite, if anything, since the cosmic ray intensity most likely decreases in the outer regions of the Galaxy and increases toward the center. Thus, the Compton disk radiation would be expected to show a stronger, not weaker, longitude dependence than the conservative (but probably less realistic) assumption of uniformity.

This conclusion is probably significantly amplified when diffusion is taken into account, for three reasons: 1) an outwardly decreasing electron density would result from the diffusion, 2) the diffusion and escape parameters would most likely be position and energy dependent in such a way as to enhance the anisotropy, and 3) the older electrons, which have had the greater energy loss at high energies tending to steepen the energy spectrum and preferentially suppressing the higher energy electrons which produce the relevant Compton  $\gamma$ -rays are more likely to be in the outer regions.

Next, the possibility of a much larger halo can be explored. Based on the results given in section II, the electron halo would have to have a radius of the order of 45 kpc or more for Compton radiation from cosmic ray electrons interacting with the black body radiation to explain the isotropic component. This again a conservative limit because, as above, it is more likely that the electron density especially in the relevant energy range would be larger toward the center; hence, if this possibility is being considered, a substantially larger radius would be a better choice for a tentative model. With a dimension of this size, one is then in effect considering an intergalactic model since, if other galaxies are similar, the halos would be beginning to overlap. Further since the required density decreases only as the inverse of the radius, but the number of electrons to fill the volume increases as the cube of the radius, the increase in the required number of electrons would be proportional to  $r^2$ . In turn, this demands a major increase in source strength or electron age which implies

greater energy loss and hence a still larger source. The difficulties of the intergalactic theories (principally intensity) are then rapidly approached.

The differential electron spectrum would have to be quite steep, with the spectral index being  $5 \pm 1$  for a power law, because of the relationship  $m_\gamma = (m_e + 1)/2$  between the  $\gamma$ -ray and electron spectral indices for the Compton radiation. If the escape time from the halo is large compared to  $10^7$  years for most of the electrons in the halo, as it probably is since this is a typical estimate for the lifetime of cosmic rays in the disk, the spectrum for the electrons with energies relevant to  $10^2$  MeV  $\gamma$ -rays, that is near  $10^5$  MeV, will be substantially steeper than that observed in the Galaxy, due to Compton energy loss by the electrons. In the case of equilibrium and no escape, the spectral index would be only one power greater or about 3.8 (e.g. Owens and Jokipii, 1977) however, diffusion considerations, which lead to the younger electrons being nearer the disk, combined with the likelihood of an energy dependent escape mechanism, make an index in the range calculated above, i.e. 4 to 6, seem reasonable. The difficulties discussed earlier, however, suggest that it is not worth pursuing specific large halo models since only a rather ad hoc model could simultaneously satisfy the intensity and isotropy constraints.

Among the extragalactic theories, primordial black hole emission (Page and Hawking, 1976) universal primordial cosmic ray interactions (Stecker, 1971), interactions of cosmic rays leaking from galaxies (e.g. Felten, 1973), and emission from normal galaxies (e.g. Strong,

Wolfendale, and Worrall, 1976) all face the combined problems of the steep energy spectrum and the intensity level. Specifically, if it is assumed that normal galaxies are represented by our own, the galactic  $\gamma$ -ray emission above 100 MeV would be inadequate by from over one to two orders of magnitude and cosmic rays escaping from the galaxies interacting with intergalactic blackbody radiation by an even much larger factor. Galactic evolutionary consideration may make normal galaxies a somewhat more likely candidate (Licht et al., 1977); however, somewhat more interesting possibilities appear to be radiation from exceptional galaxies, such as radio galaxies, Seyferts, and QSO's (however, if the radiation originates with electron interactions, the electron spectrum must be quite steep), or the  $\gamma$ -ray emission (Stecker et al. 1971, and Stecker 1977) from the matter-antimatter interactions in the baryon symmetric big bang (Harrison 1969, and Omnes 1969).

The  $\gamma$ -ray spectrum predicted from the latter theory is shown in comparison with the data in Figure 11. It must be remembered that, whereas the calculation of the  $\gamma$ -ray spectrum is straightforward in the baryon-symmetric big bang theory, there is substantial question as to whether the required separation into regions of matter and antimatter which ultimately become superclusters can occur (e.g. Steigman, 1974). In spite of this serious reservation, the very steep energy spectrum, which results primarily from the energy shifted  $\pi^0$  spectrum from  $p\bar{p}$  annihilation integrated over cosmological times, predicted by this theory is a strong point in its favor, or at least in favor of some cosmological model involving low energy  $\pi^0$  decay.

The question of radiation from exceptional galaxies is a rather speculative one because very little data exist. Until further evidence is available, it must remain as a possible explanation; however, the combination of the intensity and the energy spectrum remains a matter of concern for such theories. Some specific considerations are discussed by Worrall (1977) and the reader is referred to this thesis for further amplification of this problem.

In summary, it seems fair to say that there is no single explanation for the diffuse radiation which is without difficulties or reservations. The status of the experimental data does not seem to justify consideration of a combination of several origins in detail for the isotropic component, but it is conceivable that both Compton radiation from a region of diffusion of cosmic rays from the thick disk discussed in sections III-A and III-B and extragalactic radiation of some form may be combining to give the observed "isotropic" radiation.

#### IV. SUMMARY

An examination of the intensity, energy spectrum, and spatial distribution of the diffuse  $\gamma$ -radiation observed by SAS-2 in the energy range above 35 MeV has shown that it consists of two components. One component is generally correlated with galactic latitude, the atomic hydrogen column density, and the continuum radio emission. It has an energy spectrum similar to that in the plane, and joins smoothly to the intense radiation from the plane, which has been examined in some detail previously. It is therefore presumed to be of galactic origin. The other component is apparently isotropic, at least on a coarse scale, and

has a quite steep energy spectrum. The features of the galactic component of the  $\gamma$ -radiation and conclusions which can be inferred from the data are now summarized first:

- There is a strong linear correlation between both the 35 MeV  $< E < 100$  MeV and the  $> 100$  MeV  $\gamma$ -ray intensity and the radio continuum radiation as measured at 150 MHz.
- For  $|b| > 12.8^\circ$ , there is a good linear correlation between the  $\gamma$ -ray intensity in the same two energy ranges and the deduced atomic hydrogen column density. The constant residual  $\gamma$ -ray intensity at the extrapolation to zero column density implies an "isotropic"  $\gamma$ -ray component, whose properties are summarized below.
- For  $|b| < 12.8^\circ$  and  $60^\circ < \ell < 300^\circ$ , there remains a correlation between the  $\gamma$ -ray intensity and the atomic hydrogen column density deduced from the 21 cm emission, but there is less  $\gamma$ -radiation than would be expected from the linear extrapolation based on data for  $|b| > 12.8^\circ$ . The magnitude of the decrease implies that most likely both the cosmic ray density and the molecular-to-atomic hydrogen ratio decrease relative to the local region for galactic radii larger than that for the solar system, although the possibility that only one of these two components decreases dramatically cannot be excluded.
- For  $300^\circ < \ell < 60^\circ$ , the  $\gamma$ -ray intensity from the galactic plane actually is well above that suggested by a linear extrapolation based on data for  $|b| > 12.8^\circ$ . This result implies that either

the cosmic ray density and the molecular-to-atomic hydrogen ratio both increase in the principal features in the inner galaxy or one of the two increases dramatically. Previous studies of the galactic plane along suggest that the most plausible assumption is that both quantities increase.

- The energy spectra of the  $\gamma$ -rays from the galactic plane and from the high latitudes are the same within uncertainties. This similarity and the smooth connection in intensity suggest a similar origin.
- There is a larger intensity in the 35 MeV to 100 MeV range relative to that above 100 MeV than expected from most current estimates of the cosmic ray electron spectrum. If this 35 MeV to 100 MeV excess emission is interpreted as being due largely to cosmic ray electron bremsstrahlung, a significant ( $\sim 3$  times) enhancement in the low energy (35 MeV to several hundred MeV) cosmic ray electron spectrum over previously assumed spectra is implied. If the excess is attributed largely to Compton radiation, the electron intensity above 50 GeV must be substantially above that given by current measurements at the earth. No enhancement is necessary for the 1 to 30 GeV range, so there is not necessarily a conflict with the radio continuum observations. A much larger low rigidity solar modulation would, however, be implied for the cosmic ray electrons.

The "isotropic" component was found to have the following properties and implications:

- It appears to exist for all seven regions of the sky examined.
- The intensity above 35 MeV is  $(6.3 \pm 1.4) \times 10^{-5}$  photons  $\text{cm}^{-2}$   $\text{ster}^{-1} \text{s}^{-1}$ .
- The energy spectrum is quite steep, having a  $2.85 \pm \begin{matrix} 0.50 \\ 0.35 \end{matrix}$  differential power law index for a best fit straight line between 35 MeV and  $\sim 150$  MeV.
- When extrapolated to 10 MeV, this deduced power law joins smoothly to the diffuse "isotropic" intensity measured at low energies (0.1 to 10 MeV).
- Relatively few theoretical models are consistent with the combination of the observed spectral shape intensity and lack of strong anisotropy, and those are not entirely free of other difficulties.
- The origin of this "isotropic"  $\gamma$ -ray emission must, however, be considered a major open question with further high sensitivity measurements of the intensity, uniformity, and energy spectrum being very important.

Table I

## Comparison of Predicted\* and Observed Gamma Ray Intensities

A. Polar Region ( $N_{\text{HI}}$ (typical) = $2.4 \times 10^{20}$ atoms/cm <sup>2</sup> )		
Energy Range	(35-100 MeV)	(>100 MeV)
Cosmic Ray Nucleon, Matter Interactions	(0.08-0.12) $\times 10^{-5}$	(0.32-0.48) $\times 10^{-5}$
Cosmic Ray Electron, Matter Interaction	(0.14-0.33) $\times 10^{-5}$	(0.08-0.20) $\times 10^{-5}$
All Compton Interactions	(0.08-0.32) $\times 10^{-5}$	(0.05-0.20) $\times 10^{-5}$
Total Predicted	(0.30-0.77) $\times 10^{-5}$	(0.45-0.88) $\times 10^{-5}$
Observed <sup>+</sup>	(0.83 $\pm$ 0.21) $\times 10^{-5}$	(0.76 $\pm$ 0.19) $\times 10^{-5}$
B. $ b  \approx 15^\circ$ ( $N_{\text{HI}}$ (typical) = $11 \times 10^{20}$ atoms/cm <sup>2</sup> )		
Energy Range	(35-100 MeV)	(>100 MeV)
Cosmic Ray Nucleon, Matter Interaction	(0.37-0.55) $\times 10^{-5}$	(1.47-2.20) $\times 10^{-5}$
Cosmic Ray Electron, Matter Interaction	(0.64-1.51) $\times 10^{-5}$	(0.20-0.80) $\times 10^{-5}$
All Compton Interactions	(0.31-1.24) $\times 10^{-5}$	(2.0-3.9) $\times 10^{-5}$
Total Predicted	(1.3-3.3) $\times 10^{-5}$	(2.0-3.9) $\times 10^{-5}$
Observed <sup>+</sup>	(4.0 $\pm$ 0.8) $\times 10^{-5}$	(3.6 $\pm$ 0.7) $\times 10^{-5}$

\*A range of predicted values is given, rather than a specific value, as discussed in the text.

<sup>+</sup>The errors quoted for the observed intensities reflect systematic uncertainties and the estimated uncertainty in separating the two components, which for example, do not effect ratios of total  $\gamma$ -ray intensities in the same measured energy intervals.

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## FIGURE CAPTIONS

- Figure 1 Diagram of the sky in galactic coordinates showing the portion of the sky viewed by SAS-2 (shaded) and the regions used in the present analysis, which are bounded by dark lines and designated by letters.
- Figure 2 Distribution of  $\gamma$ -ray ( $E \geq 100$  MeV) intensities as a function of galactic latitude for the indicated longitude intervals. Points for  $|b| > 61.0^\circ$  represent data summed over all longitudes and are indicated by open circles. Latitude division boundaries are not necessarily integers because the regions represent sums of smaller areas formed from dividing the sky into equal solid-angle regions formed by fixed longitude intervals and 72 latitude intervals. The intensities shown are based on assuming a typical spectrum; however, since the actual values are somewhat affected by the energy spectral shape because of the finite energy resolution, the reader is referred to the later parts of this paper for improved estimates of the intensity and energy spectrum based on a two-component analysis and specific energy spectra.
- Figure 3 Distribution of  $\gamma$ -ray ( $35 \text{ MeV} < E < 100 \text{ MeV}$ ) intensities as a function of galactic latitude for the indicated longitude intervals. Points for  $|b| > 61.0^\circ$  represent data summed over all longitudes and are indicated by open circles. See also the comments in the caption for Fig. 2

Figure 4 Distribution of  $\gamma$ -ray ( $E_{\gamma} \geq 100$  MeV) intensity as a function of atomic hydrogen column density deduced from 21 cm radio data for  $|b| > 12.8^{\circ}$  for the indicated longitude and latitude intervals. Error bars shown on the  $\gamma$ -ray intensities are statistical. An uncertainty of approximately 10% should be attached to the 21 cm column densities. The solid line is the best fit to all the data points shown. Upper right: acceptable ( $1\sigma$  above the minimum  $\chi^2$ ) values of the fitted parameters in the equation  $I_{\gamma} = A \cdot N_{\text{HI}} + B$ .

Figure 5 Distribution of  $\gamma$ -ray ( $35 \text{ MeV} < E_{\gamma} < 100 \text{ MeV}$ ) intensity as a function of atomic hydrogen column density deduced from 21 cm radio data for  $|b| > 12.8^{\circ}$  for the indicated longitude and latitude intervals. Error bars shown on the  $\gamma$ -ray intensities are statistical. An uncertainty of approximately 10% should be attached to the 21 cm column densities. The solid line is the best fit to all the data points except the point at (1.8, 1.1) in the region  $250^{\circ} < l < 300^{\circ}$  (this anomalous point is incompatible with any linear fit to the rest of the data). Upper right: acceptable ( $1\sigma$  above the minimum  $\chi^2$ ) values of the fitted parameters in the equation  $I_{\gamma} = A N_{\text{HI}} + B$ .

Figure 6 Distribution of  $\gamma$ -ray ( $E_{\gamma} > 100$  MeV) intensity as a function of atomic hydrogen column density deduced from 21 cm radio data for  $|b| < 60^{\circ}$  for the indicated longitude intervals. The longitude intervals not shown did not have meaningful data

for the present purpose because of known point source contributions. The solid line is the one derived from the high-latitude data shown in Fig. 4.

Figure 7 Distribution of  $\gamma$ -ray ( $35 \text{ MeV} < E_{\gamma} < 100 \text{ MeV}$ ) intensity as a function of atomic hydrogen column density deduced from 21 cm radio data for  $|b| < 60^{\circ}$  for the indicated longitude intervals. The longitude intervals not shown did not have meaningful data for the present purpose because of known point source contributions. The solid line is the one derived from the high-latitude data shown in figure 5.

Figure 8 150 MHz brightness temperature as a function of atomic hydrogen column density for  $|b| < 60^{\circ}$  and the indicated longitude ranges. The estimated uncertainties are approximately 10% for the 21 cm column densities and 15% for the 150 MHz brightness temperatures. The solid line is the best fit to all the data with  $|b| > 12.8^{\circ}$ , averaged over the same regions used for the  $\gamma$ -ray studies. Inset: acceptable ( $1\sigma$  above the minimum  $\chi^2$ ) values for the fitted parameters in the equation  $I_{150} = A N_{\text{HI}} + B$ , using only data with  $|b| > 12.8^{\circ}$ .

Figure 9 Gamma-ray intensity ( $35 \text{ MeV} < E < 100 \text{ MeV}$ ) as a function of 150 MHz brightness temperature. Only typical error bars are shown because of the high data density of the figure. The estimated uncertainty in the 150 MHz brightness temperatures is approximately 15%. Straight line is the best fit to all

the data points. Inset: acceptable ( $1\sigma$  above the minimum  $\chi^2$ ) values of the fitted parameters in the equation  $I_\gamma = A I_{150} + B$ .

Figure 10 (35 MeV < E < 100 MeV)  $\gamma$ -ray intensity as a function of (E > 100 MeV)  $\gamma$ -ray intensity. Only typical uncertainty limits are shown because of the high data density of the figure. The high energy  $\gamma$ -ray data have been "defocused" for comparison to the 35-100 MeV data, as described in the text. The straight line is the best fit to all the data points. Inset: acceptable ( $1\sigma$  above the minimum  $\chi^2$ ) values for the fitted parameters in the equation  $I_{35-100} = A I_{>100} + B$ .

Figure 11 Gamma-ray spectrum for the "isotropic" component of this work, together with other data and the theoretical spectral shape predicted by the baryon symmetric big bang theory discussed in the text.

Present addresses for authors:

Dr. C. E. Fichtel  
Code 662  
NASA/Goddard Space Flight Center  
Greenbelt, MD 20771

Dr. G. A. Simpson  
Code 662  
NASA/Goddard Space Flight Center  
Greenbelt, MD 20771

Dr. D. J. Thompson  
Code 662  
NASA/Goddard Space Flight Center  
Greenbelt, MD 20771



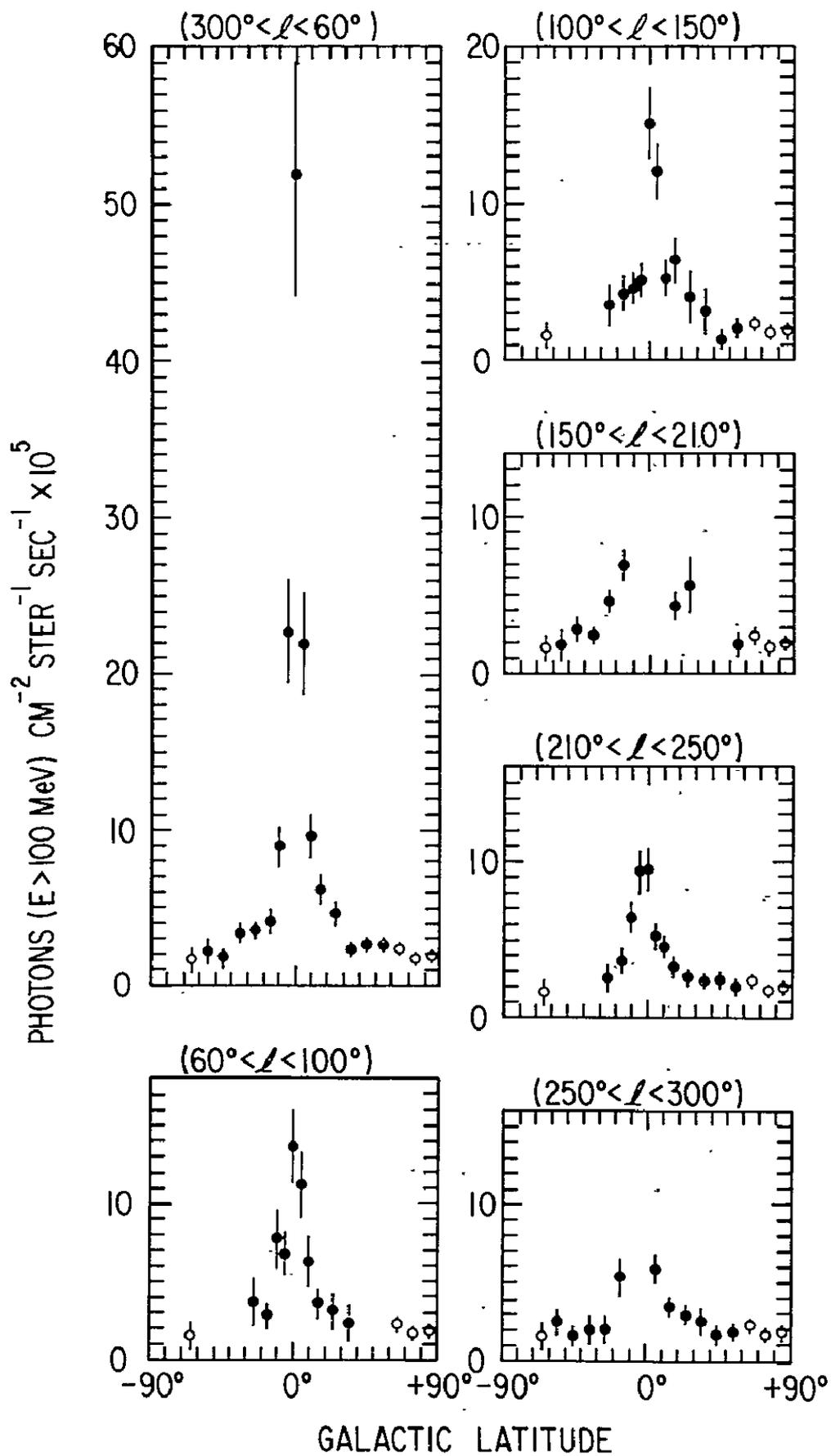


Fig. 2

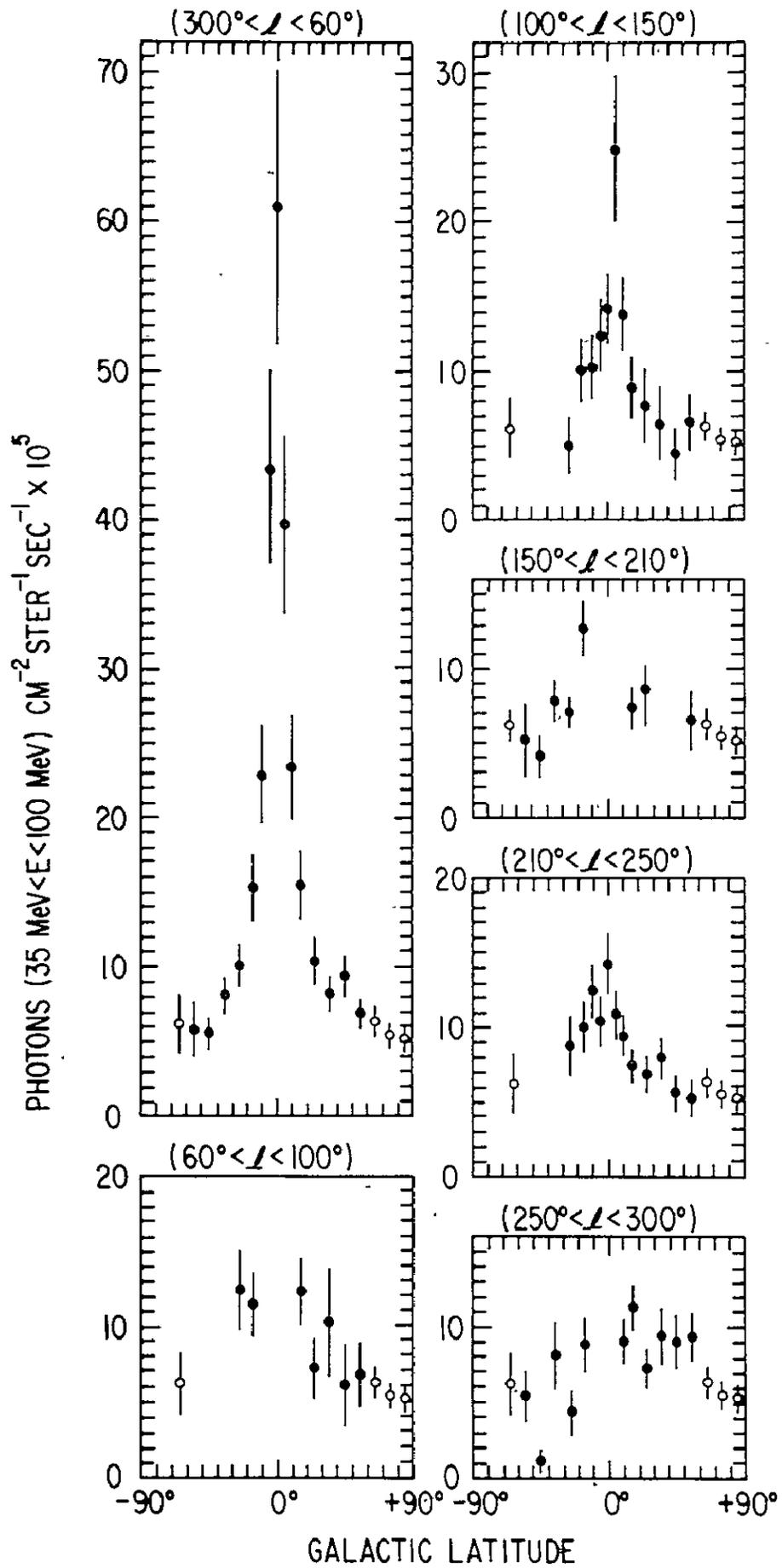
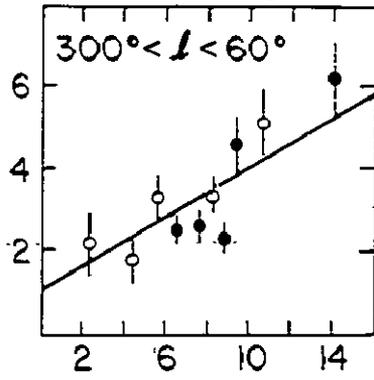
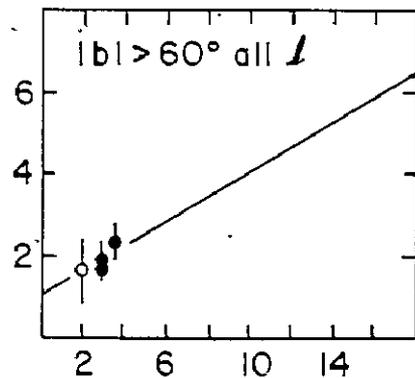
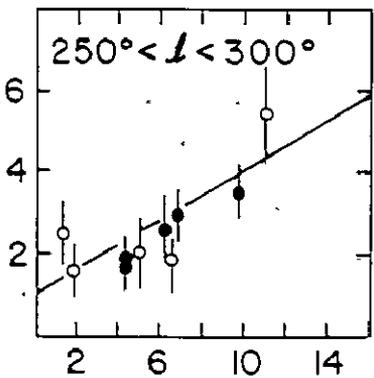
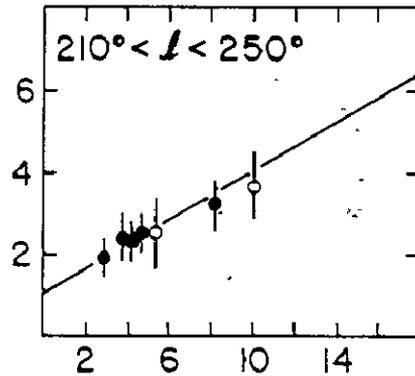
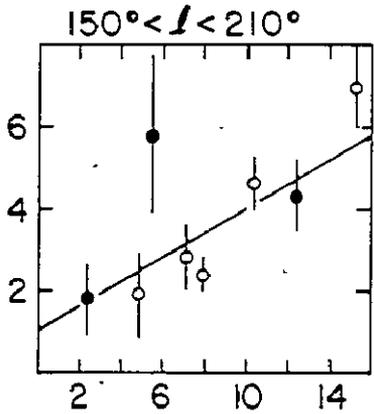
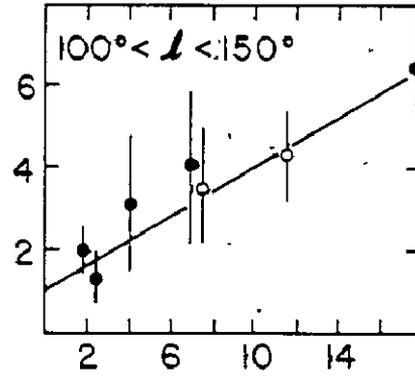
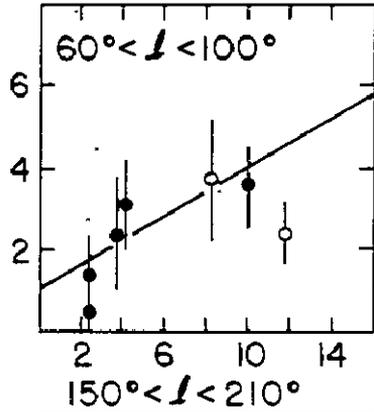
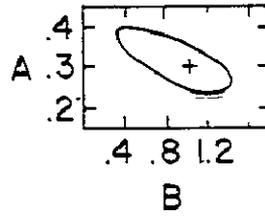


Fig. 3

GAMMA RAYS ( $E > 100 \text{ MeV}$ )  $\text{CM}^{-2} \text{S}^{-1} \text{STER}^{-1} \times 10^5$



•  $b > 0$   
○  $b < 0$



21 CM COLUMN DENSITY  $\text{ATOMS} \cdot \text{CM}^{-2} \times 10^{20}$

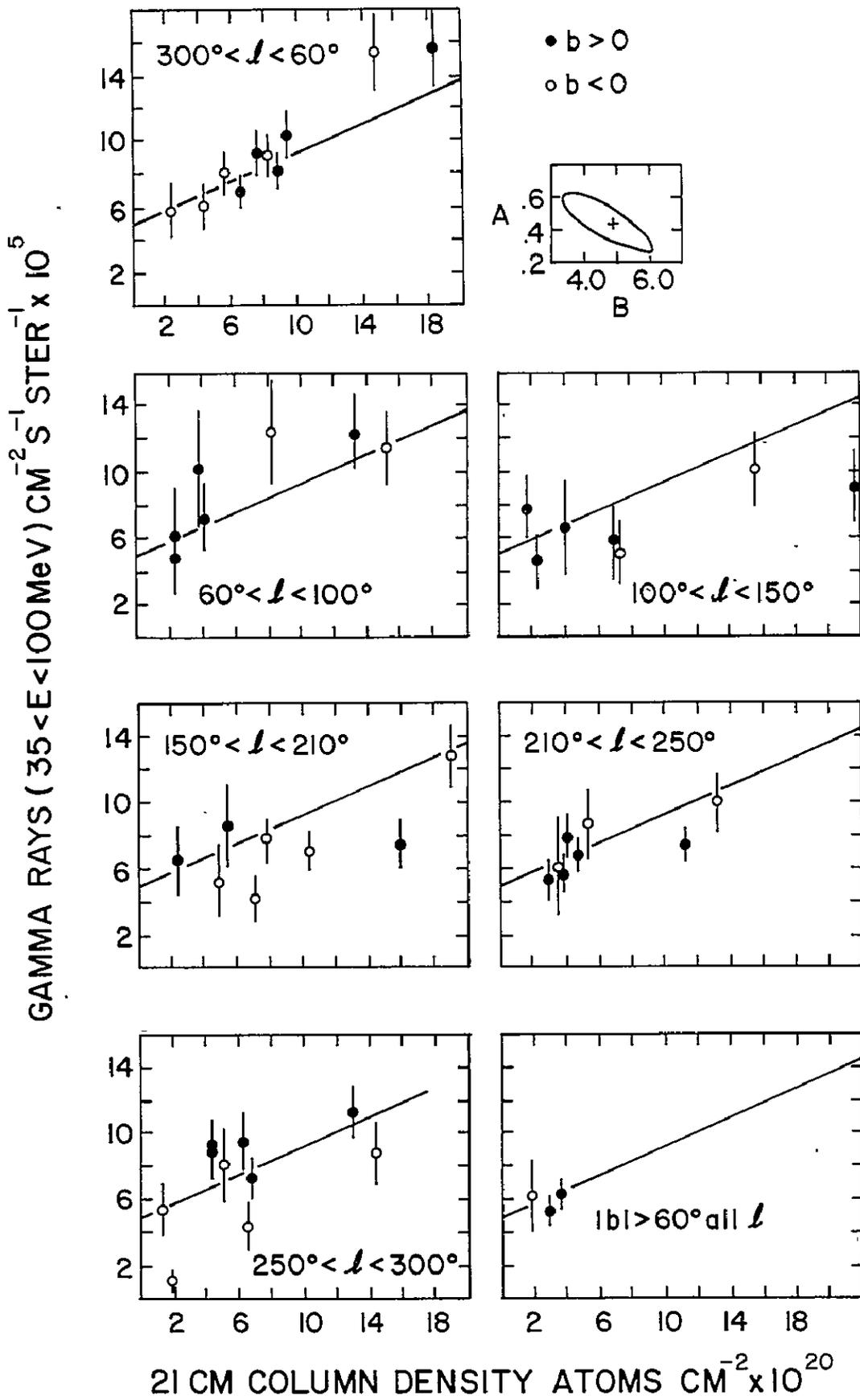


Fig. 5

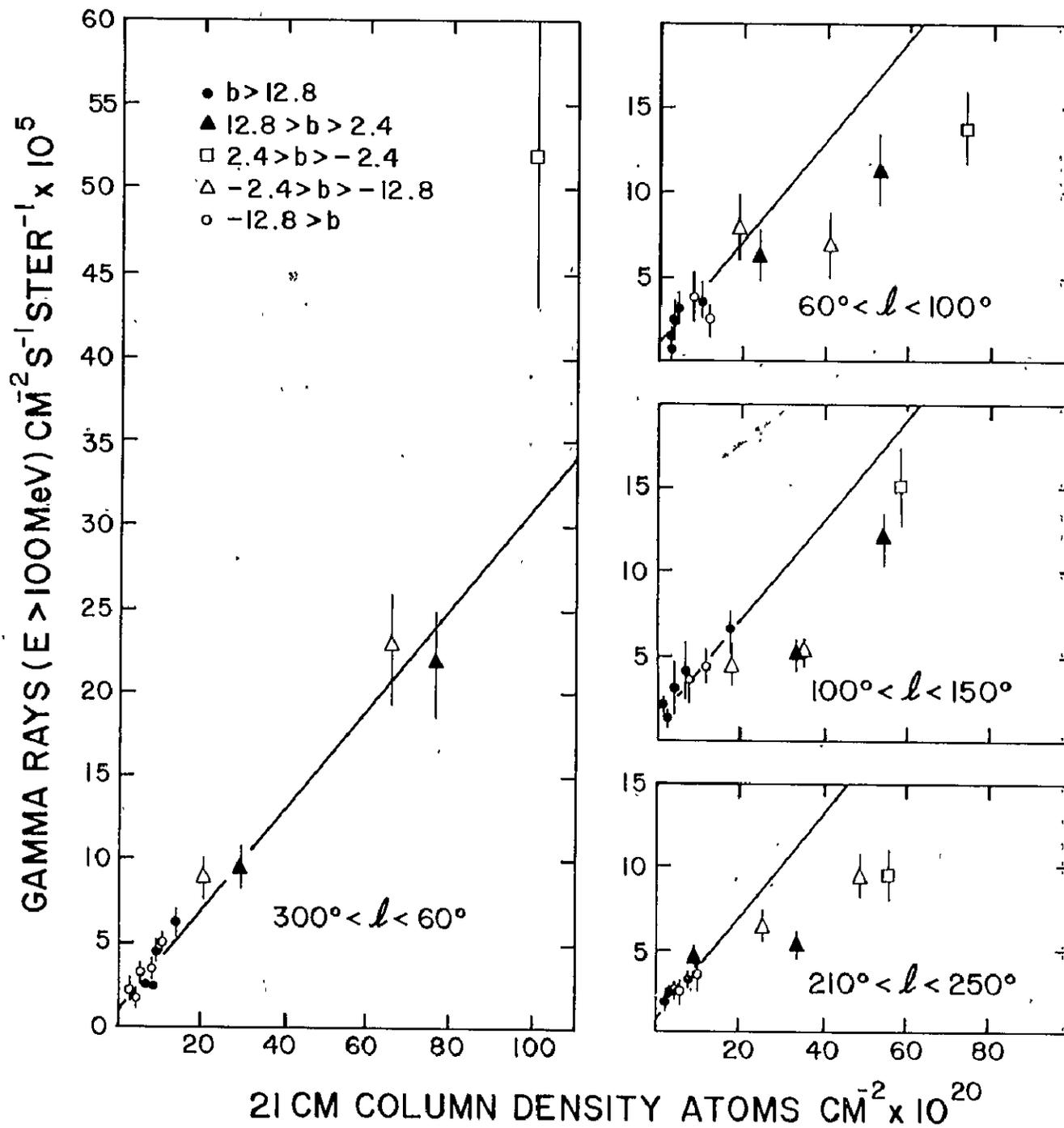


Fig. 6

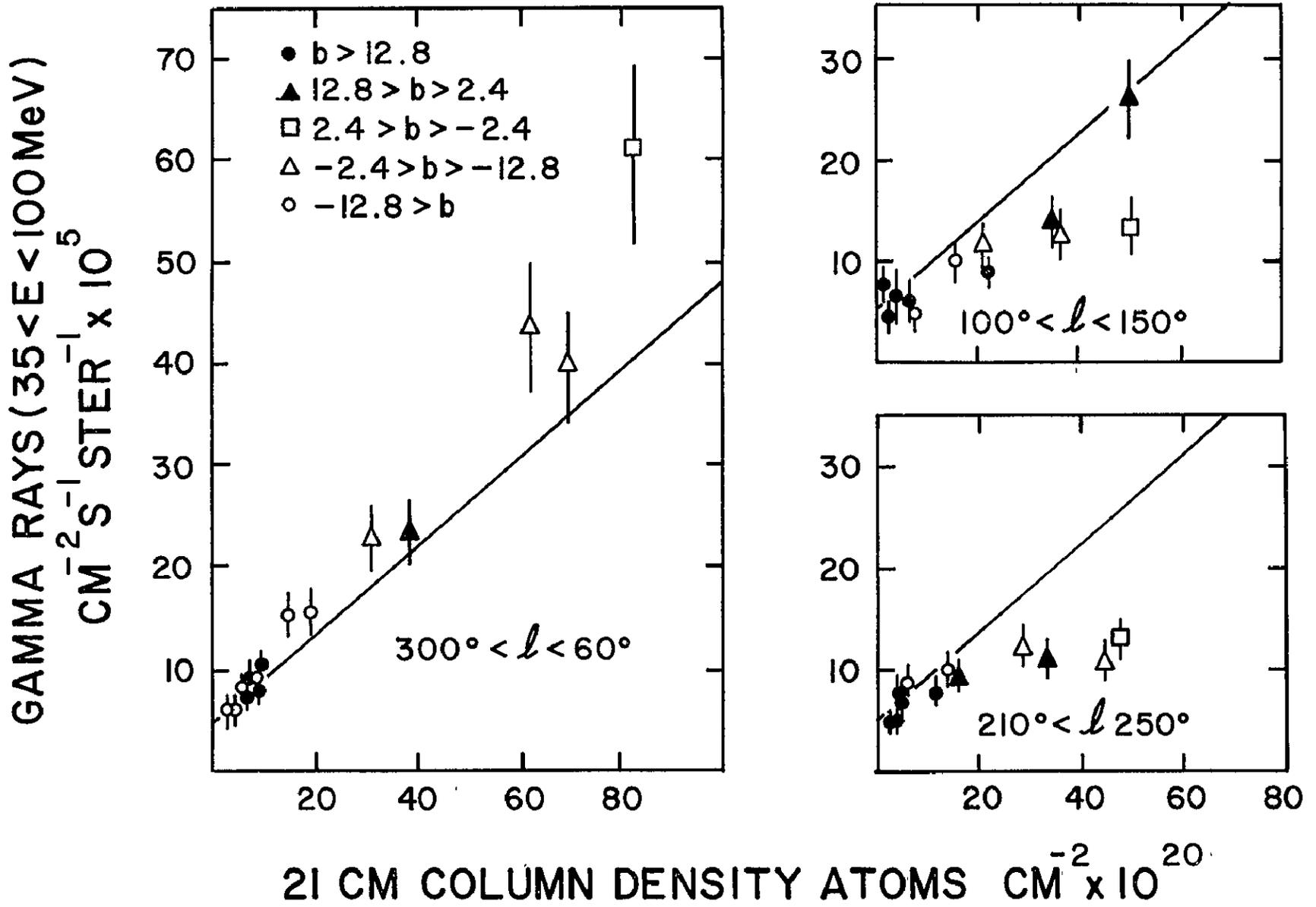


Fig. 7

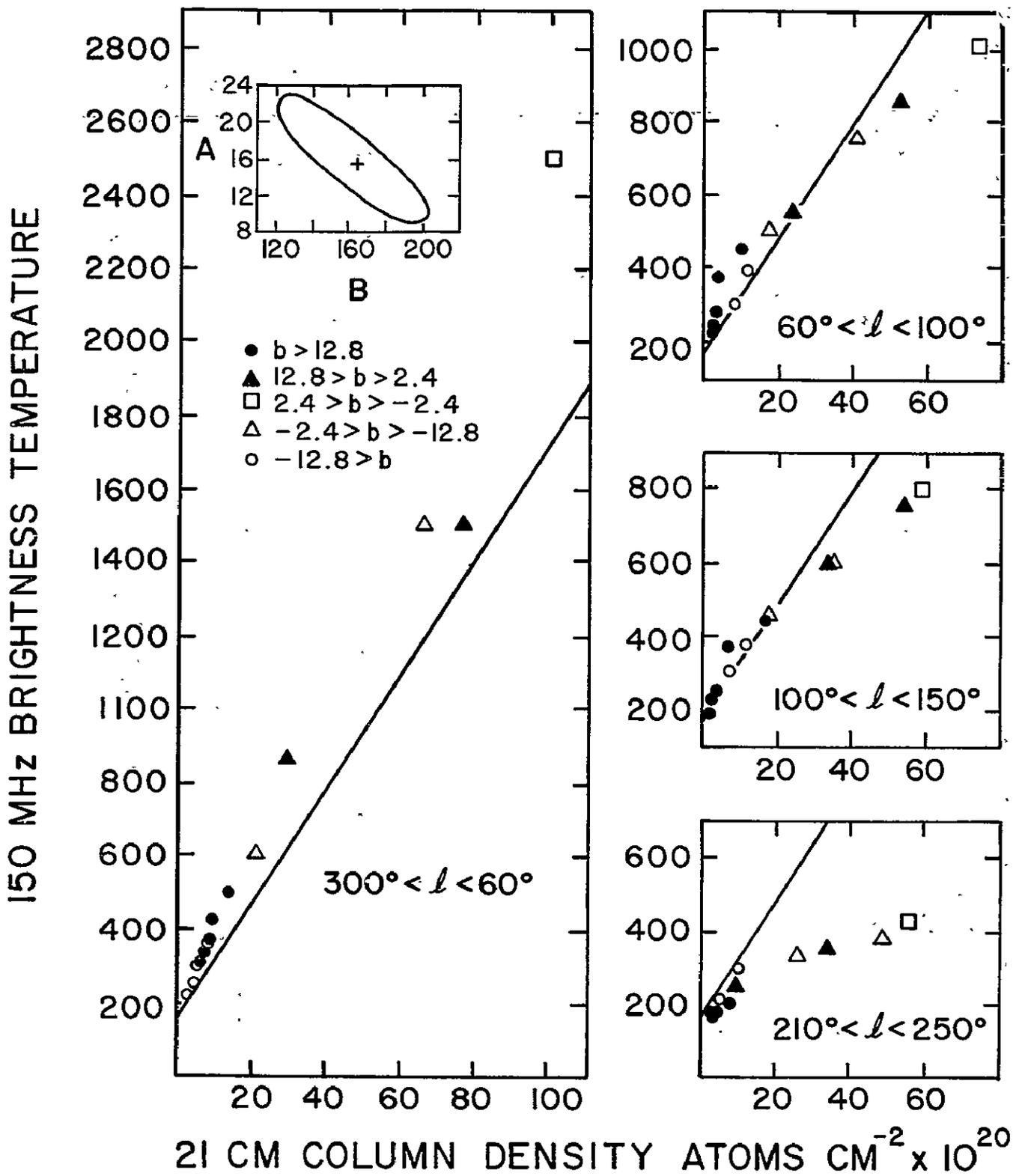


Fig.8

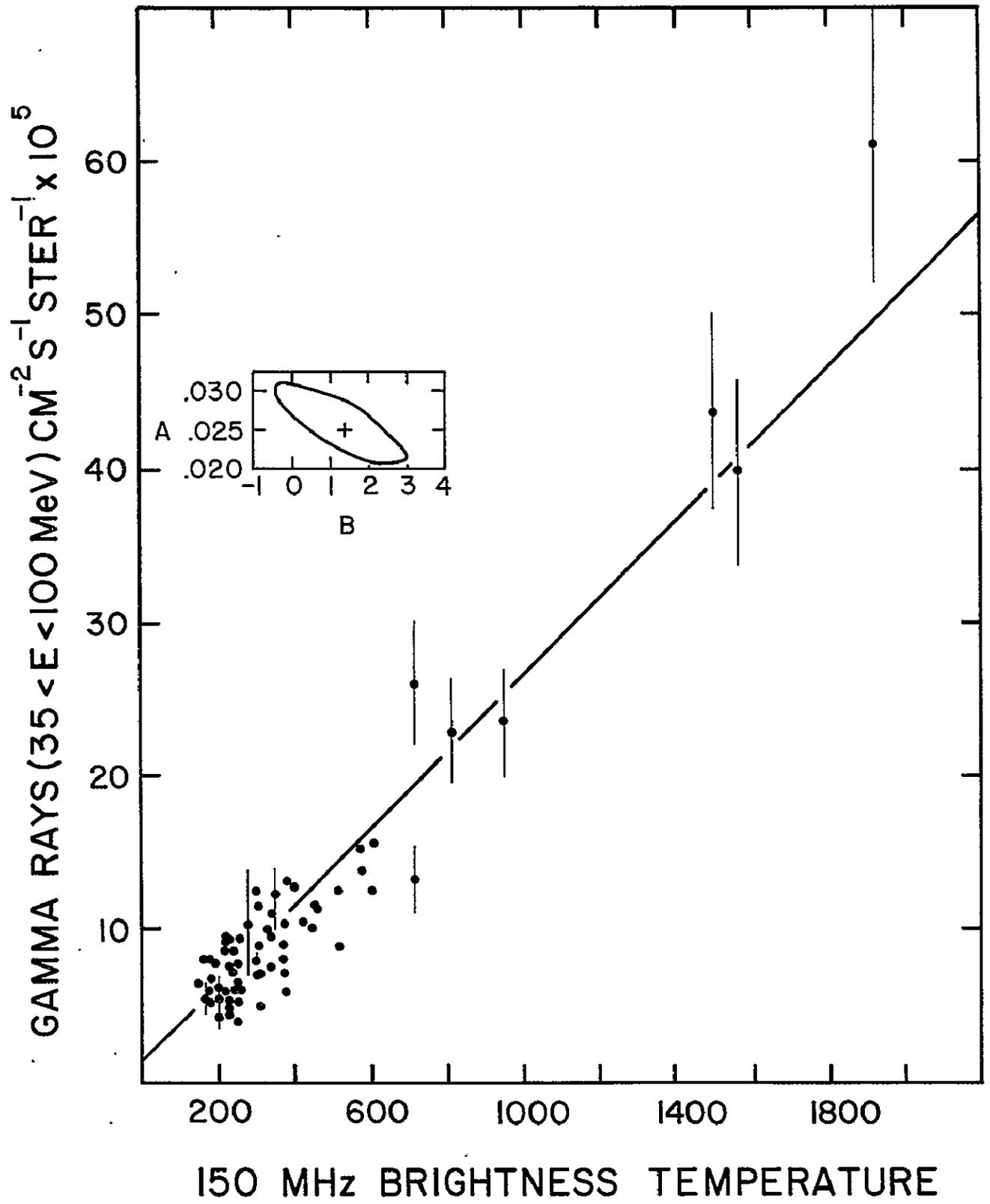


Fig.9



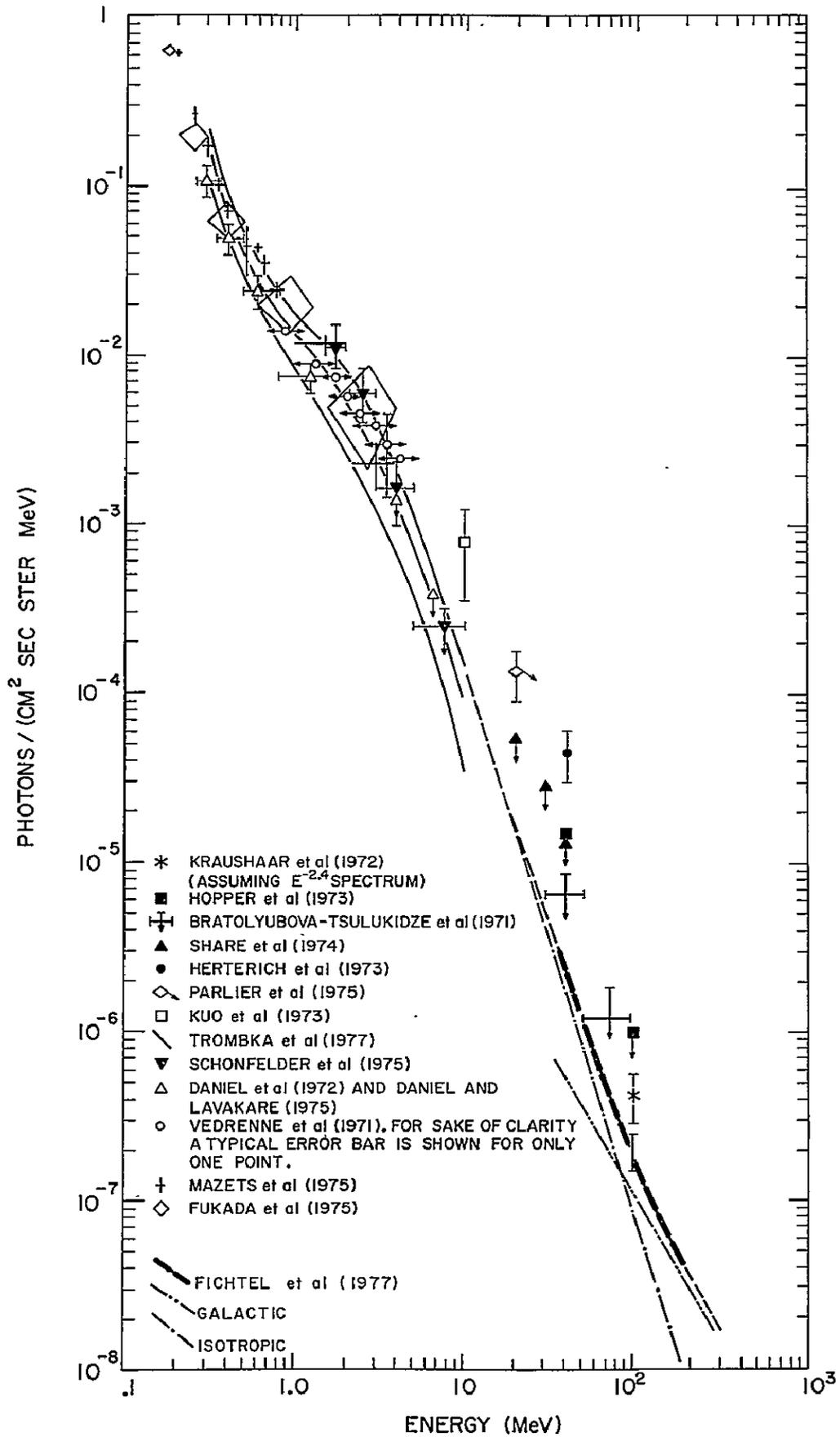


Fig.11