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SAS-2 Observations of the Diffuse Gamma Radiation in the Galactic Latitude Interval $10° < |b| \leq 90°$

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ABSTRACT

An analysis of all of the second Small Astronomy Satellite (SAS-2) γ-ray data for galactic latitudes with $|b| > 10°$ has shown that the intensity varies with galactic latitude, being larger near 10° than 90°. For energies above 100 MeV the γ-ray data are consistent with a latitude distribution of the form $I(b) = C_1 + C_2/\sin b$, with the second term being dominant. This result suggests that the radiation above 100 MeV is coming largely from local regions of the galactic disk. Between 35 and 100 MeV, a similar equation is also a good representation of the data, but here the two terms are comparable. These results indicate that the diffuse radiation above 35 MeV consists of two parts, one with a relatively hard galactic component and the other an isotropic, steep spectral component which extrapolates back well to the low energy (< 10 MeV) diffuse radiation. The steepness of the diffuse isotropic component places significant constraints on possible theoretical models of this radiation.

Subject headings: gamma rays: diffuse--cosmology

I. INTRODUCTION

For some time there have been indications that there is a general diffuse γ-radiation. There have also been numerous theories suggesting that such a radiation should exist. These theories 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. These latter theories would,in general, suggest a variation of intensity with galactic latitude. The experimental situation at low γ-ray energies has been confused by a relatively large number of measured values or upper limits which have often been inconsistent or contradictory. Those results are summarized later in this letter. At high energies (> 35 MeV), the preliminary results from SAS-2 (Fichtel et al. 1973) confirmed the existence of a diffuse flux first suggested by the OSO-3 γ-ray experiment data (Kraushaar et al. 1972). The entire SAS-2 celestial γ-ray data set has now been analyzed in accordance with procedures outlined by Fichtel et al. (1975). The analysis used the detailed sensitivity, angular response function, γ-ray arrival direction determination, energy measurements and energy resolution function determined in the extensive calibration outlined in that paper, as well as extensive (> 80%) rescans of the γ-ray event films to search for possible inefficiencies,and selected measurements of the earth albedo during the satellite's history to check for possible changes in detector performance. A summary of results for absolute galactic latitude greater than 10° will be presented here, followed by a discussion of their significance.

II. RESULTS

The regions of the sky covered by the SAS-2 γ-ray observations include a full strip between the plane and the north pole in the vicinity of b = 0°, and also for b $\approx$ 240°, well away from the intense central region of the galactic plane (see Fichtel et al. 1975 for the exact regions viewed.). Measurements of the γ-rays from the south polar region unfortunately do not exist, but observations were made as far south as b $\simeq$ -60°. The data have been summarized for the energy ranges 35 to 100 MeV and E > 100 MeV for both the region near the center and elsewhere. They are presented in Fig. 1. No distinction was made between the central region and the rest of the sky for $|b| > 60°$. The data included in the central region are those for which ℓ is generally within 60° of ℓ = 0°.

The most striking feature of all four graphs of Figure 1 is that the intensity is not constant as a function of latitude, but generally rises toward the galactic plane. The angular accuracy of the detector is such that a 100 MeV γ-ray will have an average uncertainty in b of 2.7°, with the uncertainty being smaller above 100 MeV and larger below 100 MeV. The intensity in the interval -10° > b > 10° is quite high due to the radiation from the galactic disk and is not shown in the figure. Notice also that the intensity for negative latitudes is generally the same within uncertainties as that for positive latitudes in all four figures, except that there is a tendency for the intensity to be higher in the central region of the galaxy for $10° < b < 30°$ than elsewhere for both energy ranges, and possibly with very marginal significance in the $30° < b < 60°$ region. The excess in the $10° < b < 30°$ region in the central region has been noted earlier (Fichtel et al. 1975) to be possibly from the relatively dense region of Gould's Belt in that direction. However, the most significant point which will be pursued here is the general variation with latitude which is reflected on all four graphs for positive and negative latitudes.

In order to obtain a general picture of the variation with latitude of the diffuse radiation, all the data for γ-ray energies above 100 MeV and for $35 < E < 100$ MeV have been combined to give the intensity as a function of $|b|$ as shown in Figure 2. The simplest assumption is that the radiation is the sum of a galactic component and an isotropic component. The latter would, of course, be a constant as a function of latitude, whereas the former would vary approximately as (constant)/ $\sin|b|$ at least for $|b| > 10°$ for any model of the galaxy for which the thickness of the disk for the γ-ray emission was small compared to galactic dimensions. Hence, for the results plotted in Figure 2 a function of the form

$$I(b) = C_1 + C_2/\sin|b| \qquad (1)$$

was compared to the data using a least squares fit. This procedure was also followed with the galactic center region excluding the possible

Gould's Belt contribution. In each case, the constants were determined with and without the $10° < |b| < 20°$ data point. The results are given in table 1. The fits for $|b| > 10°$ and $|b| > 20°$ were so close that only one ($|b| > 10°$) was shown in the figure. A least squares fit with only the $C_2/\sin b$ term was also tried with the results shown in figure 2 and table 1. Although slightly poorer, the agreement for the energy range above 100 MeV is still reasonable (χ^2 probabilities of 5% to 10% compared to about 50% for the least squares fit for equation [1]); whereas the curve is clearly not an acceptable result for $35 < E < 100$ MeV. The clear conclusion to be drawn is that above 100 MeV the "$C_2/\sin b$" term, or galactic component, strongly dominates and in the $35 < E < 100$ MeV region, both terms are important with the "C_1", or isotropic term, appearing slightly larger.

Since there appear to be two components comprising the diffuse radiation with different energy spectra, it is worthwhile trying to estimate these spectra. The statistics and energy resolution do not permit an attempt to determine the spectra in detail, but it is reasonable to assume that both components are power laws over the range of the measurements and then to determine the intensity and power of the spectrum. If this procedure is followed, the results for the least squares fits for the isotropic ("ISO") and "$C_2/\sin b$" or galactic ("GAL") terms are:

$$\frac{dJ}{dE}_{ISO} = 0.7\times10^{-7}\ (E/100)^{-3.4} \qquad (2)$$

$$\frac{dJ}{dE}_{GAL} = 1.1\times10^{-7}\ (E/100)^{-1.6}/\sin b \qquad (3)$$

with E in MeV.

If only the anticenter data are included, the similar results are:

$$\left.\frac{dJ}{dE}\right|_{ISO} = 1.0\times10^{-7}\ (E/100)^{-3.2} \qquad (4)$$

$$\left.\frac{dJ}{dE}\right|_{GAL} = 0.8\times10^{-7}\ (E/100)^{-1.5}/\sin b \qquad (5)$$

The energy spectrum determined for the total diffuse radiation is shown in figure 3 and is representative of an effective value of galactic latitude of 55°. (The spectrum incidentally is consistent with that of Fichtel et al. 1973). Also shown in the figure are the lines representing equations 4 and 5 (for b = 55°). The uncertainties for these two curves depend on the accuracy with which the assumed spectra match the true spectra, as well as statistics, so no specific error limits are shown in the figure for these two curves.

III. DISCUSSION

A wide variety of theories have been proposed to explain the diffuse radiation. Whereas it is well beyond the scope of this letter to summarize and discuss them, some basic points can be made. First, the theories generally fall into two classes, galactic and extragalactic. For the galactic emission the source possibilities include (a) cosmic ray nucleon, matter interactions--principally π° decay, (b) cosmic ray electron, matter interactions (bremsstrahlung), (c) Compton radiation from the starlight and blackbody fields, (d) synchrotron radiation, and (e) point sources. Several papers have been written on this subject including those of Schlickeiser and Thielheim (1976), Worrall and Strong (1976), and Stecker (1977), and it is generally agreed that only the first three of these mechanisms are important. Based on the local source functions (e.g. Fichtel et al. 1976), unless there is a major halo component, only the first two of these mechanisms are important. If the cosmic rays are assumed to have a scale height somewhat larger than the matter (specifically twice the scale height was assumed although this parameter is not sensitive), but less than the arm width scale, the total galactic cosmic ray--matter interaction , from Kniffen et al. (1977), is estimated to contribute the amount shown in figure 3. This result is similar to that of Stecker (1977) and Schlickeiser and Thielheim (1976) for just these components. It is seen that the extrapolations of the theoretical prediction and the experimental data to higher energies agree to within a factor of about 1.5, which is reasonable considering the uncertainties. At low energies the agreement for the galactic component is poor, and, if subsequent work with smaller uncertainties should confirm this difference, an additional low energy galactic component would be suggested.

For the disk models of the galaxy, including those for which the cosmic ray scale height exceeds the matter scale height but does not exceed 1 kpc, the Compton radiation from electrons interacting with both the blackbody radiation and starlight is quite small. For example, for a scale height of 500 pc it is only about 6% of the cosmic ray--matter interaction total. However, if as has sometimes been suggested the cosmic rays filled a halo with a diameter of about 15 kpc then not only would the Compton radiation be important, but the radiation from the center directions would substantially exceed that from the anticenter. At $|b| = 30°$, for energies above 100 MeV, for example, the center direction would have a blackbody γ-radiation of about 1.5×10^{-5} photons/(cm^2ster s) compared to slightly less than 0.3×10^{-5} in the anticenter direction. Approximately 1.0×10^{-5} is predicted for the local cosmic ray--matter interactions. Although there is an excess in the observed over the predicted flux above 100 MeV at $|b| = 30°$, there seems to be no evidence for an enhancement towards the center relative to other regions although more refined data will be needed before this question is finally answered.

Regarding the very steep isotropic component, there are a large number of extragalactic theories. Many of them, such as most galaxy models, the primordial black holes hypothesis (Page and Hawking 1976), primordial cosmic ray interaction theories (Stecker 1971), intergalactic cosmic ray electron, blackbody Compton radiation models for which the observed intensity may also be a serious problem (e.g. Felten 1973; Brecher and Morrison 1969), and a model involving secondary processes following pair production by cosmic ray protons on the microwave background (Strong et al. 1974) predict spectra significantly flatter than the spectrum implied by the γ-ray data summarized here. Extragalactic theories which do agree with such a steep spectrum include the baryon-symmetric big bang theory (Harrison 1967; Omnes 1969; Gamow 1948; Stecker et al. 1971), which also predicts the apparent hump around a few MeV, and source models for which the high energy electron spectrum is very steep.

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Table 1

(A) Values of "C_1" and "C_2" for equation (1)

	C_1*	C_2*
(1) Full Sky		
(a) $\|b\| > 10°$ & $E > 100$ MeV	0.42×10^{-5}	1.22×10^{-5}
(b) $\|b\| > 20°$ & $E > 100$ MeV	0.25×10^{-5}	1.32×10^{-5}
(c) $\|b\| > 10°$ & $35 < E < 100$ MeV	0.43×10^{-4}	0.34×10^{-4}
(d) $\|b\| > 20°$ & $35 < E < 100$ MeV	0.47×10^{-4}	0.31×10^{-4}
(2) Galactic Center Region Excluded		
(a) $\|b\| > 10°$ & $E > 100$ MeV	0.52×10^{-5}	1.05×10^{-5}
(b) $\|b\| > 20°$ & $E > 100$ MeV	0.44×10^{-5}	1.11×10^{-5}
(c) $\|b\| > 10°$ & $35 < E < 100$ MeV	0.47×10^{-4}	0.25×10^{-4}
(d) $\|b\| > 20°$ & $35 < E < 100$ MeV	0.51×10^{-4}	0.22×10^{-4}

(B) Values "C_2" for least squares fit to $C_2/\sin b$

(1) Full Sky	
(a) $\|b\| > 10°$ & $E > 100$ MeV	1.39×10^{-5}
(b) $\|b\| > 20°$ & $E > 100$ MeV	1.47×10^{-5}
(c) $\|b\| > 10°$ & $35 < E < 100$ MeV	0.53×10^{-4}
(d) $\|b\| > 20°$ & $35 < E < 100$ MeV	0.60×10^{-4}
(2) Galactic Center Region Excluded	
(a) $\|b\| > 20°$ & $E > 100$ MeV	1.28×10^{-3}
(b) $\|b\| > 20°$ & $E > 100$ MeV	1.38×10^{-5}
(c) $\|b\| > 10°$ & $35 < E < 100$ MeV	0.40×10^{-4}
(d) $\|b\| > 20°$ & $35 < E < 100$ MeV	0.54×10^{-4}

*photons/(cm^{2}ster-s)

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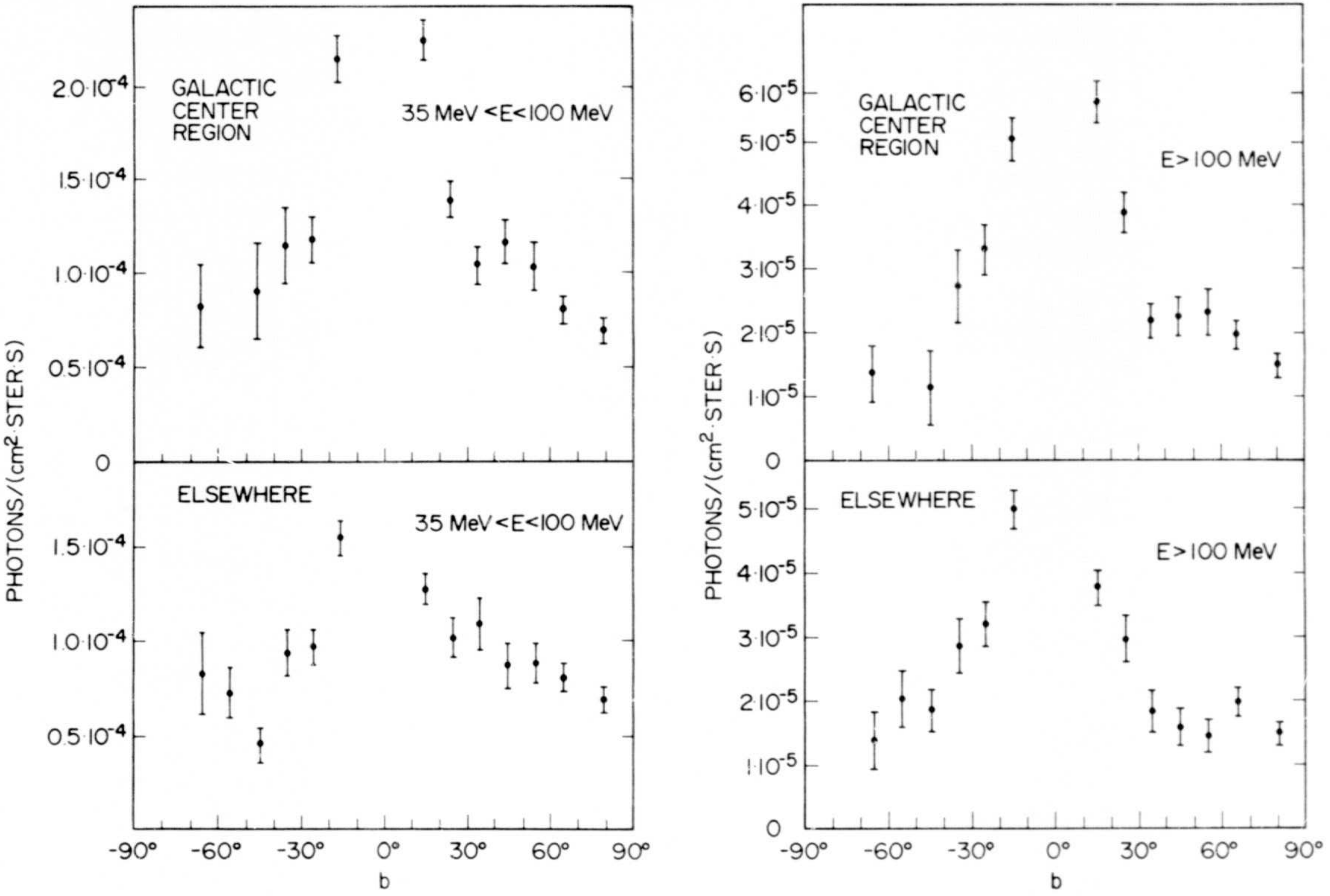
FIGURE CAPTIONS

Fig. 1: Intensity distribution of the γ-radiation as a function of galactic latitudes for energies of 35 MeV to 100 MeV and greater than 100 MeV, both for the galactic center region, as defined in the text, and elsewhere (No distinction is made for $|b| > 60^\circ$).

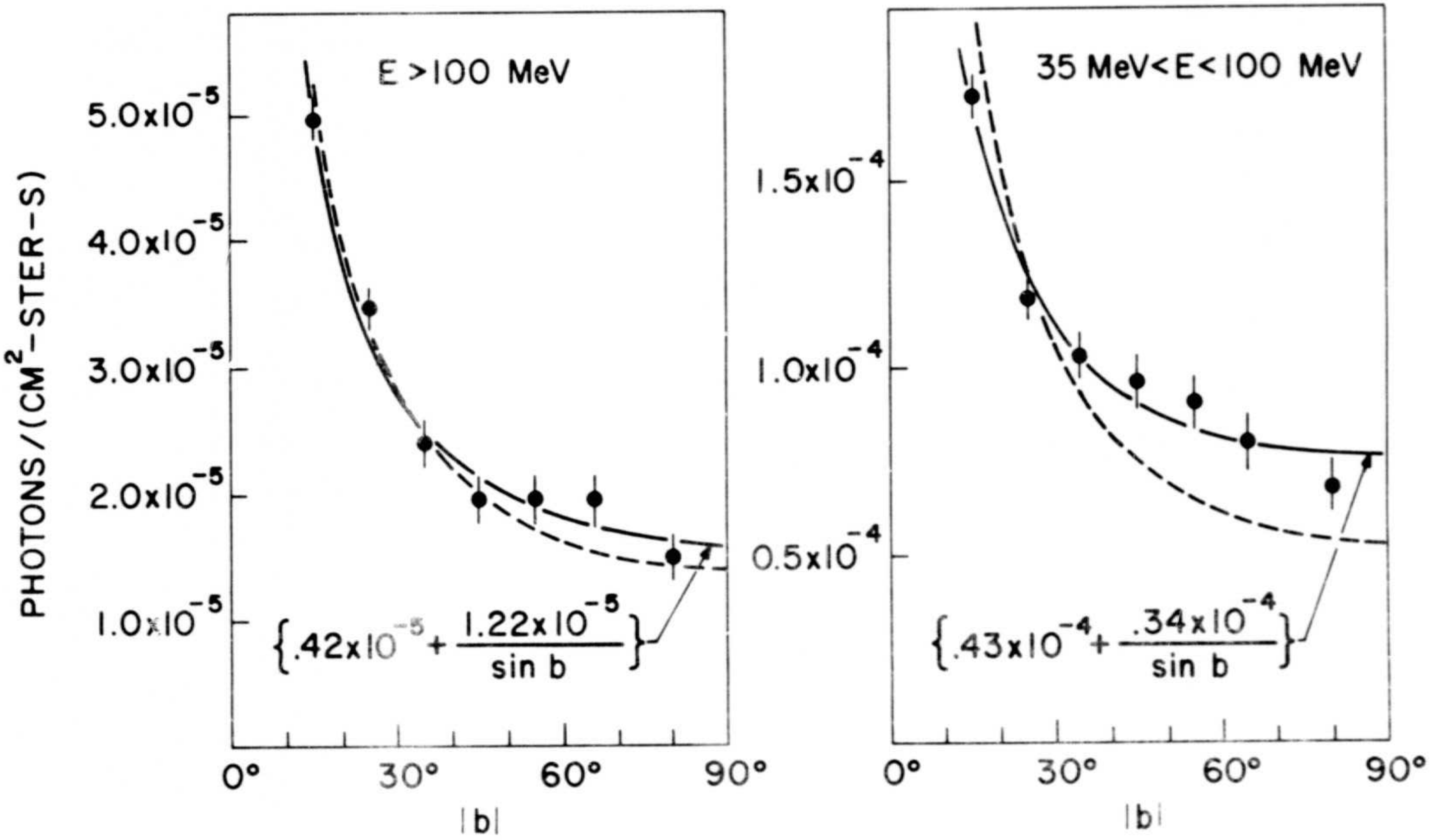
Fig. 2: Intensity distribution of the γ-radiation as a function of the absolute galactic latitude for all the data.

Fig. 3: The energy spectra of the diffuse radiation including both the data reported here and results at lower energies. The two components deduced in the text for the high energy region together with their extrapolations are also shown. The light dashed lines are extrapolations of the SAS-2 observations.



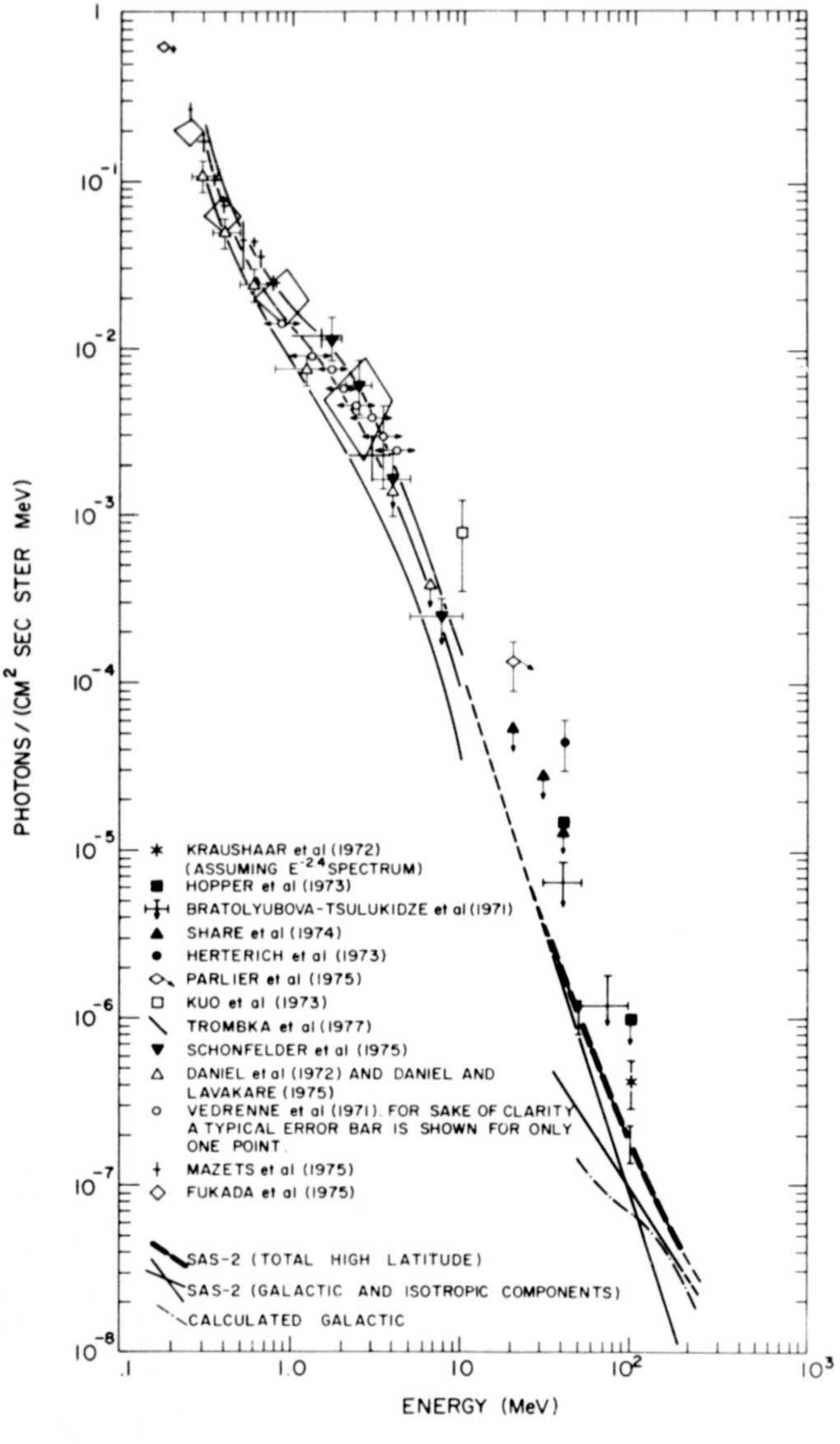
GALACTIC CENTER REGION
35 MeV <E< 100 MeV
ELSEWHERE
35 MeV <E< 100 MeV
2.0·10⁻⁴
1.5·10⁻⁴
1.0·10⁻⁴
0.5·10⁻⁴
0
PHOTONS/(cm² · STER · S)
GALACTIC CENTER REGION
E > 100 MeV
ELSEWHERE
E > 100 MeV
6·10⁻⁵
5·10⁻⁵
4·10⁻⁵
3·10⁻⁵
2·10⁻⁵
1·10⁻⁵
0
PHOTONS/(cm² · STER · S)
-90°
-60°
-30°
0°
30°
60°
90°
b

Fig. 1



PHOTONS/(CM^2-STER-S)
E >100 MeV
5.0x10^{-5}
4.0x10^{-5}
3.0x10^{-5}
2.0x10^{-5}
1.0x10^{-5}
$\left\{.42\times10^{-5}+\frac{1.22\times10^{-5}}{\sin b}\right\}$
0°
30°
60°
90°
|b|
35 MeV<E<100 MeV
1.5x10^{-4}
1.0x10^{-4}
0.5x10^{-4}
$\left\{.43\times10^{-4}+\frac{.34\times10^{-4}}{\sin b}\right\}$
0°
30°
60°
90°
|b|

Fig. 2


PHOTONS / (CM^2 SEC STER MeV)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
.1
1.0
10
10^2
10^3
ENERGY (MeV)
KRAUSHAAR et al (1972) (ASSUMING E$^{-2.4}$ SPECTRUM)
HOPPER et al (1973)
BRATOLYUBOVA-TSULUKIDZE et al (1971)
SHARE et al (1974)
HERTERICH et al (1973)
PARLIER et al (1975)
KUO et al (1973)
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MAZETS et al (1975)
FUKADA et al (1975)
SAS-2 (TOTAL HIGH LATITUDE)
SAS-2 (GALACTIC AND ISOTROPIC COMPONENTS)
CALCULATED GALACTIC

Fig. 3