REVIEW OF OBSERVATIONAL RESULTS ON γ-RAY BACKGROUND*

(Invited Discourse)

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Abstract. Recent observations in the X- and γ-ray region of the electromagnetic spectrum have given strong evidence for the existence of an extragalactic intensity with a slowly steepening power law spectrum in the region 10^3 to 10^8 eV. Further data from the OSO-III high energy γ-ray detector are in agreement with earlier published reports, and suggest that the γ-rays from high galactic latitudes have a softer spectrum than those from the galactic plane.

The previous paper by Dr. Oda of the University of Tokyo has reviewed the status of measurements of the diffuse radiation in the region below 100 keV. We shall be concerned here with the region of the electromagnetic spectrum above that energy.

Measurements of the diffuse radiation are difficult in this energy region. γ-rays are produced in collimators, in nearby pieces of apparatus, and in the earth's atmosphere by the ever-present charged particle cosmic radiation. In the region of a few MeV, in fact, Peterson (1967, 1969) has shown that the albedo from the earth is just equal to the apparent diffuse radiation. At higher energies, as will be discussed presently, the albedo is enormously greater than the diffuse radiation. Because γ-ray production in matter is such an important phenomena, the use of shutters, inactive collimators and background evaluation by viewing the earth – all important and useful devices in the lower energy region – are quite impossible in the energy region under discussion.

Figure 1, taken in part from a similar figure prepared by Gorenstein *et al.* (1969), summarizes representative measurements of the diffuse γ-radiation. Up to 1 MeV, at least, all measurements above 20 keV fall with reasonable consistency on a straight line of slope -2, indicating a photon number spectrum of the form $\mathrm{d}E/E^2$. In the region 1–10 MeV, there are only measurements of Vette *et al.* (1970) indicated by 'Peterson *et al.* (1969-ERS)' on Figure 1. As with the measurement of Metzger *et al.* (1964) the observations were carried out far from the earth where albedo effects are small. The apparent deviation from a power law, if real, has possible cosmological indications as discussed by Stecker (1970).

* Supported in part by the National Aeronautics and Space Administration under contract NAS5-3205, grant NsG-386 (MIT), grant NSG-426 (CIT), and NGR 50-002-044 (University of Wisconsin).

L. Gratton (ed.), Non-Solar X- and Gamma-Ray Astronomy, 269–279. *All Rights Reserved*

https://doi.org/10.1017/S007418090000440X Published online by Cambridge University Press

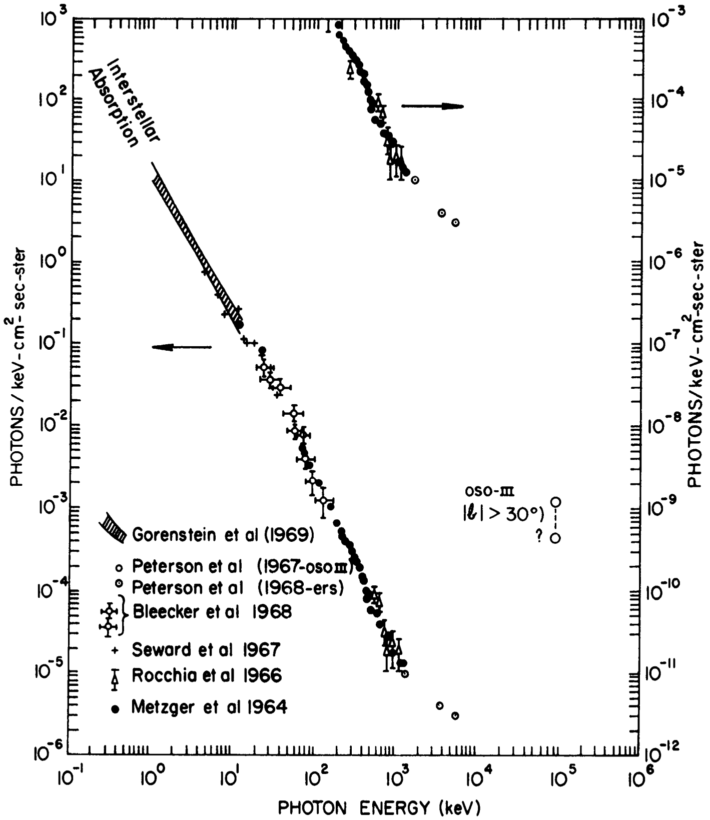

Fig. 1. Representative measurements of the apparently diffuse cosmic X- and γ-ray spectrum. Interstellar absorption is an important effect below 1 keV and the meaning of measurements in this range is unclear at present.

The highest energy measurement labeled 'OSO-III' at 100 MeV refers to the published results of Clark *et al.* (1968). Since that initial report, more observations have been reduced and while the earlier conclusions are unchanged, the statistical evidence is now appreciably improved.

Figure 2 shows the detected rate of γ-rays referred to a satellite-centered coordinate system with polar axis at the instantaneous zenith. The data have been separated into two parts; one in which the satellite was within 20° of the geomagnetic equator, the other in which the satellite was more than 20° from the geomagnetic equator. The horizon of the earth is brighter when the satellite is far from the equator because the earth's magnetic field permits a larger portion of the galactic cosmic ray flux to enter there. The counting rate for angles more than 40° above the horizon is statistically the same for both parts of the data. This is to be expected, of course, if these γ-rays are of celestial not terrestial origin.

The next several figures describe in various ways the anisotropic character of the detected high energy γ-radiation. Each point on the upper map of Figure 3 corre-

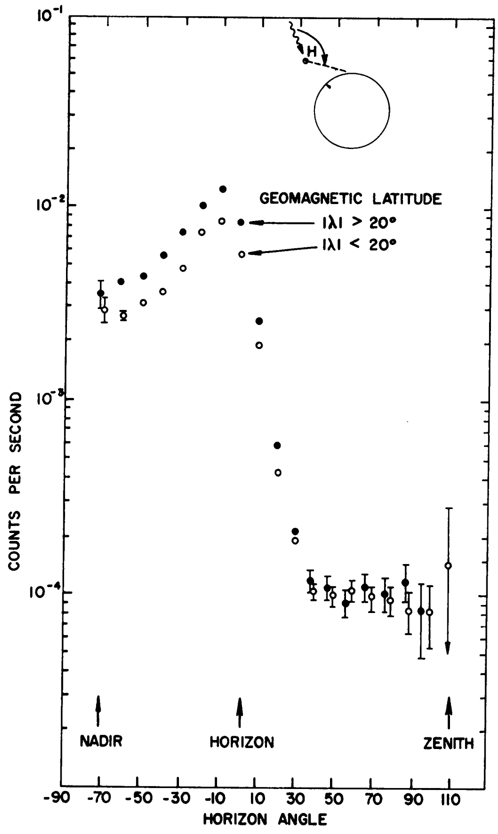

Fig. 2. Distribution of high energy γ-rays relative to the earth.

sponds to the arrival direction in galactic coordinates of a γ-ray. In itself this map has little significance because the exposure of the instrument to various parts of the sky was not uniform. Correspondingly, each point on the lower map of Figure 3 corresponds to a certain time that the instrument spent viewing in the indicated direction. In other words, the density of points in a given region on the upper map divided by the density of points in the same region on the lower map is proportional to the directional gamma ray intensity. Once the data are available in the form described by Figure 3, variation of the intensity with galactic latitude, galactic longitude, etc. can be investigated conveniently.

Figure 4 shows the variation with galactic latitude, data from all galactic longitudes having been summed. We see a pronounced intensity peak at the galactic equator, and a definite non-zero intensity at all galactic latitudes. The shape of the pronounced rise near $b=0$ essentially reproduces the response of the instrument to a line source. The 'line' could be several degrees wide, of course. The data are sufficient to allow division into six regions of galactic longitude, as shown in Figure 5. The most pronounced peak at the galactic equator occurs near the galactic center, although significant peaks towards the equator but of lesser intensity are apparent elsewhere.

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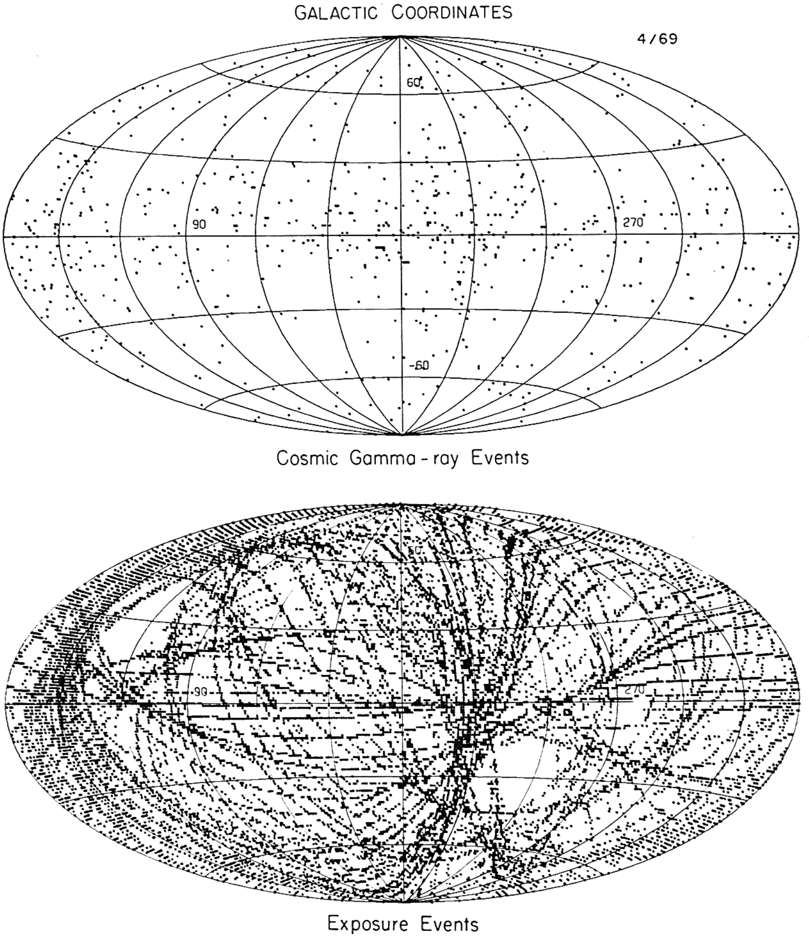

Fig. 3. Distribution of detected γ-rays in galactic coordinates (upper map). Each point on the lower map is proportional to a fixed amount of time that the instrument viewed in the indicated direction.

Figure 6 shows the galactic longitude distribution for all those γ-rays that arrived within 15° of the galactic equator. The strongest emission, as was evident from Figure 5, is from regions near the galactic center. The distribution in l, however, is much broader than the distribution to be expected from a point source at the galactic center.

One of the frequently discussed mechanisms for high energy γ-ray production is the collision of cosmic ray protons with nuclei of the interstellar gas. If the cosmic ray proton flux is the same everywhere in the galactic disc, the γ-ray intensity should be proportional to the columnar hydrogen density. In Figure 7 is shown the columnar hydrogen density averaged over the 5°, 10°, and 15° closest to the galactic equator plotted *versus* l. The dependence on l is surprisingly weak. This is because when one averages over several degrees in galactic latitude, much of the gas included is, in fact, relatively local. We conclude on these grounds alone that our data are not consistent

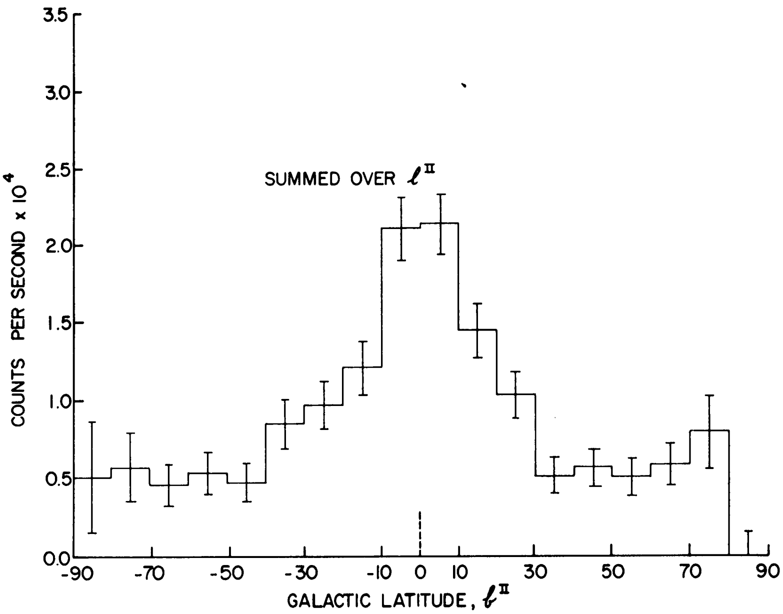

Fig. 4. Dependence of γ-ray intensity on galactic latitude. Here the data have been summed over all galactic latitudes.

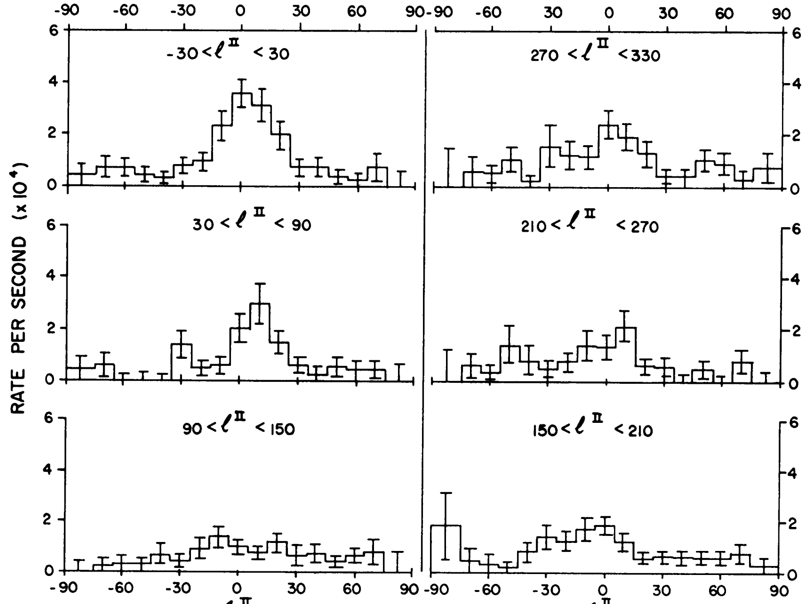

Fig. 5. Galactic latitude distribution for six regions of galactic longitude.

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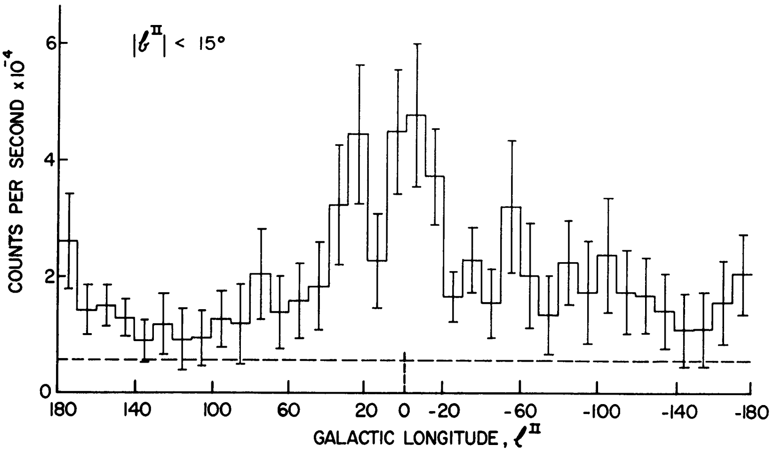

Fig. 6. Dependence of γ-ray intensity near the galactic disc on galactic longitude. The dotted line shows the average rate at high galactic latitudes.

with the nuclear collision production mechanism unless there are large amounts of molecular or cool gas undetected in the 21 cm surveys and concentrated in the galactic plane near the galactic center. In addition, as was pointed out in our initial paper announcing the OSO-III results, the observed intensity is more than 10 times that expected from the nuclear collision mechanism.

It is possible, of course, that cosmic rays are themselves concentrated towards the galactic center. The non-thermal radio noise distribution in galactic longitude, as indicated in Figure 7, may in fact be taken to indicate that this is likely. The radio noise and high energy γ-ray intensities are distributed rather similarly in galactic longitude.

The cumulative flux from discrete X-ray sources located within 15° of the galactic plane has a distribution in galactic longitude similar to that of the high energy γ-rays. This has also been pointed out by Ogelman (1969), who in addition has suggested that when a power law spectrum of index 2 is assumed, the extrapolated X-ray intensity falls near the measured γ-ray intensity. It is interesting to point out that when extrapolating over 3 decades, an uncertainty of 20% in the index results in a dynamic range of 16 to 1 within which 'agreement' may be claimed. Further, many X-ray sources have energy spectra indicative of free-free not power law emission so that the appropriateness of a power law extrapolation is doubtful.

Table I summarizes the predictions of some of the frequently discussed high energy galactic γ-ray production mechanisms relative to our measured intensity near the galactic center. The galactic center region is unique in many respects and it is likely that at least a partial understanding of γ-ray emission can be more easily realized in regions 60° or more away from the center. Here an appreciable fraction of the measured intensity in the galactic plane is, in fact, the apparent isotropic intensity discussed further in the following paragraphs. We estimate the average line intensity in regions more than 60° from the center to be about $\frac{1}{4}$ of the line intensity near the center.

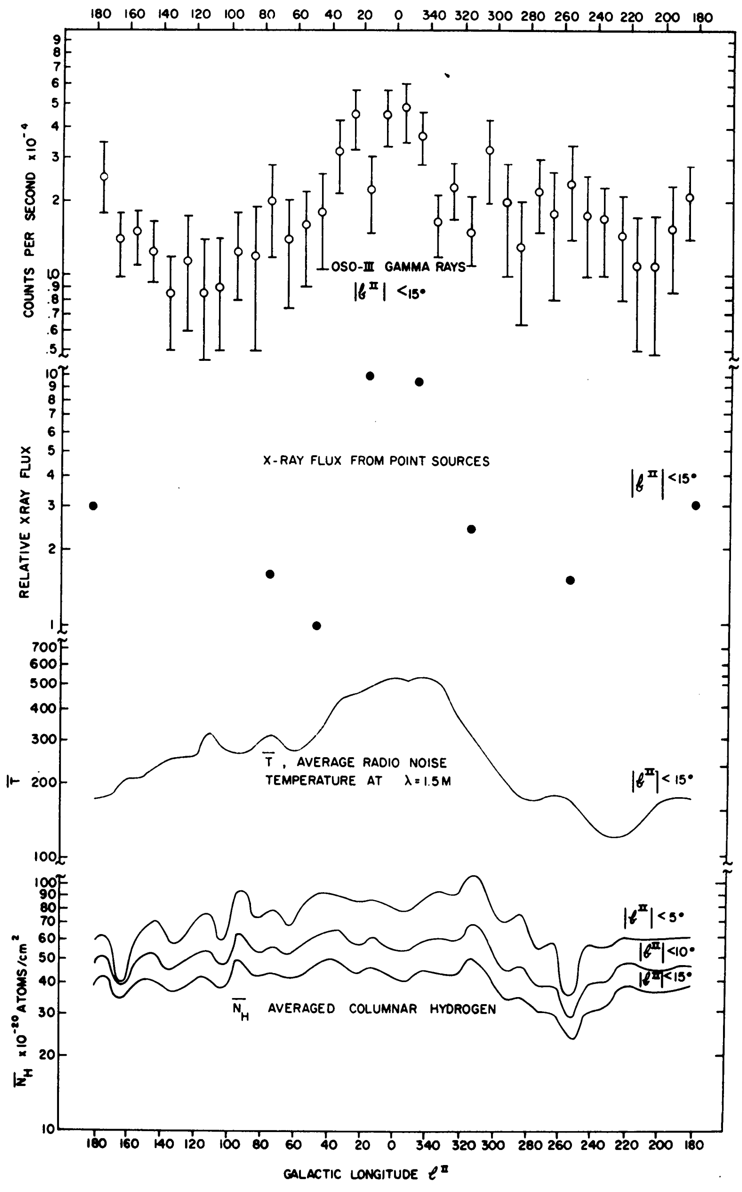

Fig. 7. Galactic longitude dependence of γ-rays, cumulative X-ray flux, 1.5 meter non-thermal radio noise and columnar hydrogen density.

Because the longitude distribution of N_H (see Figure 7) is so nearly flat, the predicted line intensity from π° production or bremsstrahlung near the galactic center is about the same as elsewhere in the galactic plane. While this factor of 4 decreases the apparent discrepancy between predictions and observations appreciably, we do not wish to minimize the significance of the remaining difference. Indeed, we now have

TABLE I

γ-rays from galactic center region observed intensity $\approx 3 \times 10^{-4}$ cm^{-2}sec^{-1}rad^{-1}

Mechanism	Responsible momentum	Predicted / Observed
π^0 production by nominal[a] CR protons on known gas	$P_p > 2$ GeV/c	0.07
Bremsstrahlung by nominal[a] CR electrons on known gas	$P_e > 0.1$ GeV/c	0.01
Inverse Compton by nominal CR electrons on known stellar photons	$P_e > 5$ GeV/c	0.02
Inverse Compton by nominal CR electrons on enhanced Becklin and Neugebauer (1968) Galactic Center stellar photons	$P_e > 5$ GeV/c	0.04
Inverse Compton by nominal CR electrons on Shivandan *et al.* (1968) infra-red 8 K photons. Cowsik and Pal (1969), Shen (1969)	$P_e > 50$ GeV/c	~ 1
Extrapolated (3 decades) discrete X-ray sources Ogelman (1969)		~ 1

[a] By nominal cosmic ray protons and electrons we mean the measured intensity near the earth at solar minimum.

a clearer discrepancy with expectation because the complex galactic center region is removed from consideration.

The existence of γ-rays of galactic origin can hardly be questioned in view of the highly directional properties of the measured intensity. No such convincing evidence exists to prove the reality of the measured high galactic latitude and presumably

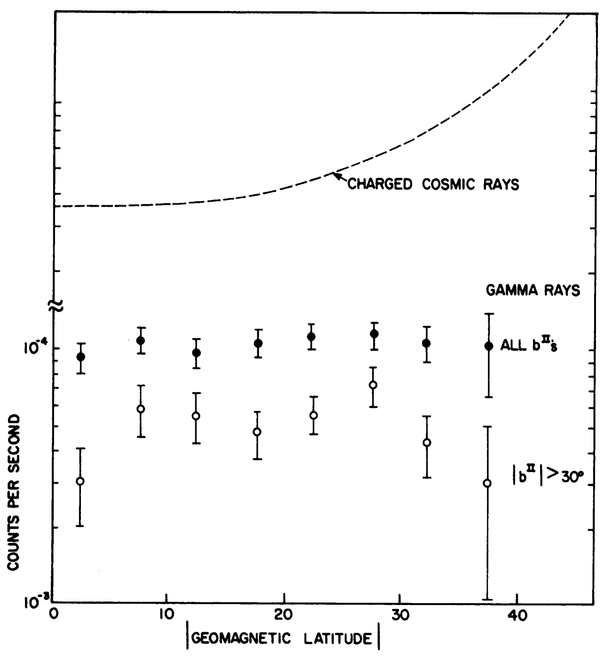

Fig. 8. Variation of γ-ray intensity with geomagnetic latitude of the satellite.

https://doi.org/10.1017/S007418090000440X Published online by Cambridge University Press

isotropic component. All conceivable forms of background are related to the charged cosmic ray flux incident on the orbiting instrument or on the atmosphere beneath it. Since the orbit of OSO-III traverses a range of geomagnetic latitudes between $+40°$ and $-40°$, and since the charged cosmic ray flux varies significantly over this range, any background should vary also with geomagnetic latitude. We have therefore examined our data for this type of dependence and the results are shown in Figure 8. Certainly neither the total γ-ray intensity nor the γ-ray intensity from high galactic latitudes have any obvious tendency to increase with geomagnetic latitude. In order to investigate the question quantitatively, we have computed, for the high galactic latitude component, the ratio of measured intensity for $|\lambda| > 20°$ to that for $|\lambda| < 20°$. We have

$$R = \frac{I(|\lambda| > 20°)}{I(|\lambda| < 20°)} = 1.14 \pm 0.18$$

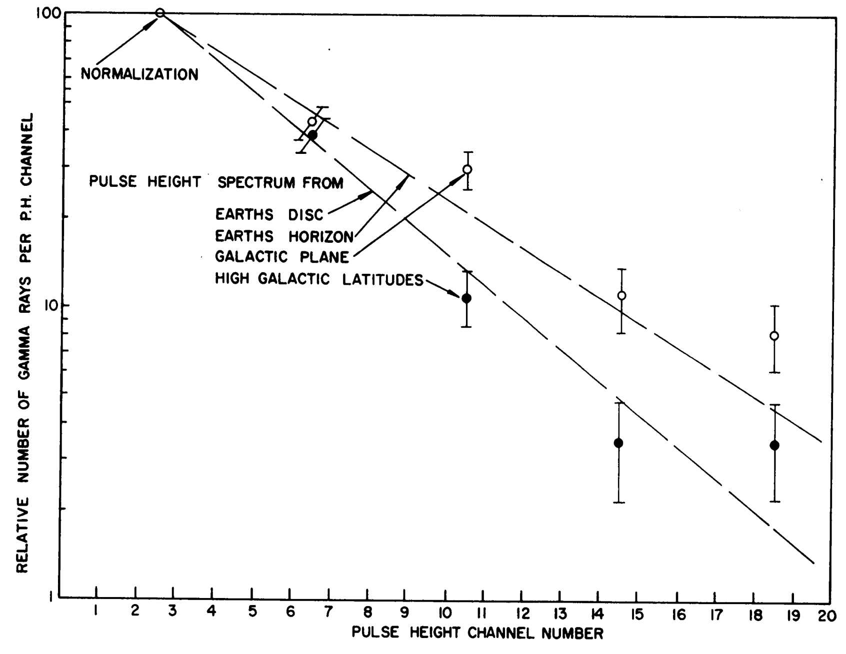

Fig. 9. Pulse height distribution of γ-rays from the earth's disc, from the earth's horizon, from the galactic plane and from high galactic latitudes.

The corresponding ratio for charged cosmic rays is 1.8, so the independence is established to about a 3.5σ level.

The instrument is equipped with a rather poor resolution γ-ray energy calorimeter. The results of the approximate energy measurements are still being studied but such preliminary results as are available are shown in Figure 9. The upper and lower dashed curves show pulse height distributions for γ-rays from the horizon of the earth and from the earth's disc, respectively. As is to be expected from simple kinematic arguments, γ-rays from the horizon, having followed the direction of the primary cosmic rays, have higher average energies. γ-rays from high galactic latitudes have a pulse height distribution similar to those from the earth's disc, while γ-rays from the galactic plane have a pulse height distribution similar to those from the horizon. We conclude that γ-rays from the galactic plane are on the average more energetic than those from high galactic latitudes. This qualitative statement is in agreement with the hypothesis that γ-rays from the galactic plane have a π°-decay (nuclear interaction) origin while those from high galactic latitudes have an electromagnetic origin. Our results cannot be taken to prove this, of course.

The values of the high energy γ-ray intensity are unchanged since our initial report. Fichtel *et al.* (1970) have recently flown their balloon-borne spark chamber instrument upside down so as to measure the upward moving γ-ray albedo intensity from the earth's disc. Their value for this intensity is about $\frac{1}{3}$ as large as ours. We feel it unlikely that our efficiency-solid angle calibration could be off by a factor as large as three, but the possibility has been recognized in preparing Figure 1. We and the GSFC group are currently planning a recalibration of both instruments in the same tagged γ-ray beam at the California Institute of Technology electron synchrotron.

In recent months a number of groups have provided supporting evidence, though at a marginal statistical level, for a narrow line of high energy γ-ray emission from the galactic plane. These measurements are summarized in Table II. In addition, as reported in these Proceedings, Hutchinson *et al.* (1970) have detected a somewhat enhanced emission from the galactic plane with their spark chamber aboard OGO-5.

TABLE II

Recent reports of high energy γ-ray detection via balloon-borne instruments

Cornell:	Delvaille, Albats, Greisen and Ogelman (1968) Spark Chamber; $E > 1$ GeV, $-1° < b^{II} < 1°$; $l^{II} \approx$ AC to Cygnus $I = (6 \pm 3) \times 10^{-4}$ $(\mathrm{cm}^2\text{-sec-sr})^{-1}$
Minnesota:	Valdez and Waddington (1969) Emulsion-Spark Chamber, $E > 100$ MeV. $b^{II} \approx 0$, $l^{II} \approx 65°$ 2σ
GSFC:	Fichtel *et al.* (1970) Spark Chamber; $E > 50$ MeV, $-3° < b^{II} < 3°$, $l^{II} \sim -10°$ to $25°$ $J = (2.2 \pm 1.1) \times 10^{-4}$ $(\mathrm{cm}^2\text{-sec-rad})^{-1}$
Case-Western Reserve:	Frye and Wang (preprint) Spark Chamber; $E > 100$ MeV, $-3° < b^{II} < 3°$, $l^{II} \approx 55°$ to $85°$ $J = (4 \pm 2) \times 10^{-5}$ $(\mathrm{cm}^2\text{-sec-rad})^{-1}$
Imperial College:	Sood (preprint) Čerenkov Counters, $E > 50$ MeV, $b^{II} \approx 0$, $l^{II} \approx 30°$ $J = (1.5 \pm .5) \times 10^{-4}$ $(\mathrm{cm}^2\text{-sec-rad})^{-1}$ (estimated)

Acknowledgements

We acknowledge with gratitude the important contributions to the design and construction of our instrument by the Lincoln Laboratory of MIT and the able help with computational matters provided by Mrs. T. Thorsos.

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