

A SEARCH FOR HIGH ENERGY GAMMA-RAY EMISSION
FROM THE GALACTIC DISC

by

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A Thesis Submitted for the Degree of Doctor of Philosophy
of the University of London

July, 1972

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ABSTRACT

The detection, by the OSO-3 satellite, of energetic gamma-rays from the plane of the galactic disc was the first positive measurement of a primary extra-terrestrial gamma-ray source. A series of equatorial balloon flights carried out by Sood in 1967 and 1968 from Kampala, Uganda, although unsuccessful in its original intention to detect energetic π^0 -decay gamma-rays emitted from active solar regions, was successful in detecting the galactic line source.

Two further balloon flights have been carried out from Lusaka, Zambia in another attempt to confirm the existence of this source. In order to provide some experimental continuity and grounds for comparison and combination of results, the detectors employed were essentially the same wide-angle scintillator-Cerenkov coincidence telescopes used by Sood. The detectors were successfully flown to a residual atmospheric depth of 5 gm/cm^2 in January and February 1971, although the period of data collection was restricted by the high winds encountered during ascent and at altitude. From these two flights alone, a null result for the galactic source was recorded. The corresponding upper limit at the 95% confidence level was $3.9 \times 10^{-4} \text{ photons/cm}^2 \text{ rad sec}$ for a uniform line source of gamma-rays of energy $>30 \text{ MeV}$. When combined with the results of Sood at Kampala, the best-fit value for a uniform line source of $>30 \text{ MeV}$ was $(3.5 \pm 1.2) \times 10^{-4} \text{ photons/cm}^2 \text{ rad sec}$. This probably constitutes a positive measurement and the relatively large error is partly due to the previously measured extra enhancement from the galactic centre region making the assumption of a uniform

line source in the field of view somewhat invalid.

Comparison is made between these results and those of other investigators, and the various possible theoretical mechanisms for the production of these gamma-rays are reviewed in the light of the results. It seems probable that the decay of π^0 -mesons produced in cosmic ray-interstellar gas interactions is the production mechanism, provided that fairly modest increases in the cosmic ray and gas densities can be accepted.

During the course of one of the equatorial balloon flights on October 31st 1968, a short-lived but significant increase in the charged particle flux at altitude was recorded. The event was subsequently found to be coincident in time with the negative 'bay' in the initial phase of the intense magnetic storm of that day. Various possible explanations are considered and a detailed study is carried out on the theory that energetic protons (of ~ 500 MeV) dumped from the Inner Radiation Belt were responsible. Estimates are made to show that if this interpretation were correct, that such events would constitute a major loss mechanism for energetic trapped protons. There is unfortunately no direct evidence that the necessary conditions existed, at the time of the event, for such a dumping by any of the present theories of trapped particle perturbation.

Acknowledgements

I am indebted to Professor H. Elliot under whose guidance and supervision this work was carried out.

Dr. R. K. Sood was responsible for the initiation and original development of the gamma-ray project, and I thank him sincerely for his valued advice and friendship during my association with him. I should like to express my appreciation of the help rendered by other members of the Cosmic Ray Group at various times.

The University of Zambia provided the base facilities at Lusaka, and I wish to thank the staff of the Physics Department there for their hospitality and their assistance during the balloon flights.

I am grateful to the Science Research Council for their financial support of the project, and the award of a Research Studentship during part of this work.

I thank Miss Susan Baker for her excellent typing of this thesis.

Finally I should like to thank my wife and my parents for their constant encouragement and patience during the course of this work.

CONTENTS

	<u>Page</u>
<u>CHAPTER I An Introduction to Gamma-ray Astronomy</u>	7
1.1. General Introduction	7
1.2. Gamma-ray Production	9
1.2.1. Decay of π^0 -mesons	12
1.2.2. Bremsstrahlung	16
1.2.3. Inverse Compton scattering	17
1.3. Gamma-ray Absorption	18
1.3.1. Compton scattering	19
1.3.2. Pair production in collisions with charged particles	20
1.3.3. Pair production in photon-photon collisions	21
1.4. Gamma-ray Detection	23
1.4.1. General requirements and methods	23
1.4.2. Experimental detectors for the 10 MeV - ~ 10 GeV energy region	26
1.4.3. Detectors for photons in the $>10^{11}$ eV energy region	29
<u>CHAPTER II The Gamma-ray Detector</u>	34
2.1. General Description	34
2.2. Geometrical Properties	35
2.3. Physical Properties	35
2.3.1. The scintillator elements	35
2.3.2. The Cerenkov elements	38
2.3.3. The response to gamma-rays	39
2.4. The Electronics	46
2.4.1. Event identification	46
2.4.2. Subsidiary data	47

	<u>Page</u>
2.4.3. Transmission	48
2.4.4. Power converters and batteries	49
2.4.5. Gain setting and stability	49
 <u>CHAPTER III The Balloon Flights</u>	 60
3.1. Location of Launch Site	60
3.2. Flight Equipment	60
3.3. Ground Receiving Station	61
3.4. Flight Details	61
3.4.1. Flight 1 - January 24th, 1971	62
3.4.2. Flight 2 - February 1st, 1971	62
3.5. Preliminary Data Analysis and Results	62
3.5.1. Data analysis equipment	63
3.5.2. Charged particle data	64
3.5.3. Gamma-ray data	65
 <u>CHAPTER IV The Galactic Gamma-ray Source</u>	 75
4.1. Analysis of the Data for Possible Galactic Gamma-rays	75
4.2. Comparison with the Measurements at Kampala	76
4.3. Other Galactic Gamma-ray Measurements	79
4.3.1. The galactic centre region	79
4.3.2. Longitudes excluding the galactic centre region	 83
4.4. Measurements in the X-ray Energy Region	85
4.5. Possible Theoretical Explanations of the Gamma-ray Intensity	 87
4.5.1. π^0 -meson decay	87
4.5.2. Unresolved discrete sources	92
4.5.3. Inverse Compton scattering	94
4.6. Significance of the Present Results and Discussion	100

	<u>Page</u>
<u>CHAPTER V A Short-lived Increase in the Charged Particle Flux Observed During an Equatorial Balloon Flight ..</u>	117
5.1. Description of the Event	117
5.2. Solar-geophysical Conditions at the Time of the Event ..	118
5.2.1. Solar events	118
5.2.2. Cosmic rays	119
5.2.3. Geomagnetic events	119
5.3. Possible Explanations of the Balloon Event	121
5.3.1. Solar particles	121
5.3.2. Reduction of the geomagnetic threshold ..	122
5.3.3. Dumping of particles from the Inner Radiation Belt into the atmosphere	123
<u>CHAPTER VI Energetic Protons in the Inner Radiation Belt ..</u>	133
6.1. Charged Particle Motion in the Magnetosphere	133
6.1.1. Adiabatic theory of trajectories	133
6.1.2. The B - L coordinate system	136
6.2. Behaviour of Trapped Protons of Energy $\gtrsim 500$ MeV	138
6.2.1. Spatial distribution	138
6.2.2. Characteristic time constants	140
6.2.3. Total population	142
6.3. Origin and Loss of Energetic Trapped Protons	145
6.3.1. The CRAND theory	145
6.3.2. Other possible theories	146
6.3.3. Adiabatic loss processes	148
6.4. Non-adiabatic Effects on Inner Zone Trapped Protons ..	152
6.4.1. Diffusion and acceleration	152
6.4.2. Experimental observations of significant events	156
6.4.3. Conclusions	159
<u>References</u>	168

I An Introduction to Gamma-ray Astronomy

1.1. General Introduction

The present interest in gamma-ray astronomy can be traced back to the paper of Morrison (1). His suggestion that certain astronomical objects might be copious producers of energetic gamma rays led to a general realisation that the investigation of gamma radiation could be a most powerful probe into the physical processes of the Universe.

As a probe, electromagnetic radiation has as its paramount advantage, the fact that it travels in straight lines from its source to the earth. This advantage is not shared with charged corpuscular radiation which undergoes deflections in the ambient magnetic fields of the source region and in space. The charged particle distribution is reduced to isotropy at the earth and the amount of useful information that can be obtained from them is correspondingly reduced. Other neutral particles, such as neutrons, neutral mesons and neutrinos, suffer either from short lifetimes or small interaction cross-sections which makes their detection extremely difficult.

Energetic gamma radiation is particularly important as an astronomical probe because of its generally high penetrability through galactic and intergalactic matter. Some of the fundamental problems into which gamma rays can provide insight are summarised by Fazio (2) and Lust (3) as:

- (a) the origin of cosmic rays,
- (b) the density of cosmic radiation and the density and compo-

- sition of matter in interstellar and intergalactic space,
- (c) the presence of antimatter in the universe, and particularly the hypothesis of the continuous creation of matter,
 - (d) the strength of Galactic and metagalactic magnetic fields, and the density of energetic electrons, by comparison of gamma radiation with synchrotron radiation in the radio region,
 - (e) nuclear reactions in stellar atmospheres, surroundings of stars, interstellar space, the halo and extragalactic nebulae.

Morrison (4) pointed out, with hindsight, that the cosmic electromagnetic spectrum exhibits a monotonic decline in intensity per unit frequency, as a function of frequency, so that it might be more profitable experimentally to investigate the lowest photon energy beyond the visible that can be transmitted through a given galactic region. This is confirmed by the fact that X-rays achieved an early preeminence in astronomy, over gamma rays, following the discovery of cosmic X-rays in 1962 and by the subsequent intense activity in that field.

Indeed, since Morrison's original paper, the history of gamma-ray astronomy is of the initially optimistic estimates of intensities from likely sources, being steadily revised downwards in the face of consistently negative results from increasingly sophisticated detection apparatus. Disappointing though these results have seemed, they are not without significance in that they place more rigorous constraints

on theoretical speculations and consequently have already contributed to our knowledge of the Universe.

There has, however, been one encouraging exception to the negative trend - the detection of a surprisingly high flux of gamma-rays from the plane of the galactic disc. Initially detected at gamma-ray energies of >100 MeV by the MIT experiment of Clark et al. (5), on board the OSO-3 satellite, it has since been supported by the results of other groups. In view of the fact that this is the only region where results have consistently challenged intensity estimates in a positive sense, it obviously merits further investigation theoretically and experimentally.

Special attention will be devoted to this gamma-ray source in later chapters, but at this stage gamma-ray astronomy will be considered in general terms.

1.2. Gamma-ray Production

Any mechanism for the production of gamma-rays can be expressed in terms of its source strength $S(E_\gamma, \underline{r})$, which is defined as the number of quanta with energy between E_γ and $E_\gamma + dE_\gamma$, which are produced at the source per unit volume, per unit time, and per unit solid angle, where $\underline{r}$ is the vector from the detector to the source volume element.

Most gamma-ray production mechanisms involve the reaction between an incident particle (or photon) of energy E and a target particle (or photon). Fazio (2) gives that S can be expressed as

$$S(E_\gamma, \underline{r}) = q(E_\gamma, \underline{r}) n(\underline{r})$$

where $n(\underline{r})$ is the number density of target particle and $q(E_\gamma, \underline{r})$ is the rate of production of gamma-rays per target particle.

Typical units for $S(E_\gamma, \underline{r})$ are $(\text{cm}^3 \text{sec sr GeV})^{-1}$. $q(E_\gamma, \underline{r})$ is given by

$$q(E_\gamma, \underline{r}) dE_\gamma = dE_\gamma \int_E \sigma(E_\gamma, E_i) I_i(E_i, \underline{r}) dE_i$$

where $I_i(E_i, \underline{r}) dE_i$ is the intensity of incident particles in the energy interval between E_i and $E_i + dE_i$, typically in units of $(\text{cm}^2 \text{sec sr GeV})^{-1}$. $\sigma(E_\gamma, E_i) dE_\gamma$ is the cross-section for the creation of a gamma quanta in the energy range E_γ to $E_\gamma + dE_\gamma$ by an incident particle of energy E_i .

For an extended source (diameter comparable to distance or alternatively $\int S dr$ does not vary over the solid angle of the viewing detector), we define the gamma-ray intensity, $I_\gamma(E_\gamma)$, equal to the number of quanta per unit area, unit time, unit solid angle and unit energy, by

$$\begin{aligned} I_\gamma(E_\gamma) &= \int_0^L S(E_\gamma, \underline{r}) dr \\ &= \int_0^L n(\underline{r}) dr \int_E \sigma(E_\gamma, E_i) I_i(E_i, \underline{r}) dE_i \\ &= N(L) \int_E \sigma(E_\gamma, E_i) I_i(E_i, \underline{r}) dE_i \quad (\text{Ginzburg}) \end{aligned}$$

Here L is the effective length of the source, along the line of sight

and $N(L) = \int_0^L n(\underline{r}) dr$ is the number of target particles per unit area along the line of sight.

$I_\gamma(E_\gamma)$ represents the differential spectrum, so the integral spectrum is given by

$$I_\gamma(>E_\gamma) = \int_{E_\gamma}^{\infty} I_\gamma(E_\gamma) dE_\gamma$$

For discrete sources (diameter much smaller than distance, R , or alternatively solid angle subtended at the detector much smaller than the detector solid angle), it is more convenient to define the flux, $F_\gamma(E_\gamma)$ which is equal to the number of quanta which arrive from the source per unit area, unit time and unit energy.

$$F_\gamma(E_\gamma) = \int_{\Omega} I_\gamma(E_\gamma) d\Omega \quad (\text{cm}^2 \text{sec}^{-1})$$

$$\approx \frac{N_V}{R^2} \int_E \sigma(E_\gamma, E_i) I_i(E_i, \underline{r}) dE_i \quad (\text{Ginzburg and Syrovatskii (6)})$$

The first integration is carried out over the solid angle subtended by

the source, $N_V = R^2 \int_{\Omega} N(L) d\Omega \approx \int n(\underline{r}) dV$ is the total number of

target particles in the source. By analogy with $I_\gamma(>E_\gamma)$ we can define the integral gamma-ray flux

$$F_{\gamma}(> E_{\gamma}) = \int_{E_{\gamma}}^{\infty} F_{\gamma}(E_{\gamma}) dE_{\gamma}$$

In discussing the various processes which produce gamma-rays in space, account will only be taken of those which are likely to yield significant intensity of gamma quanta of energy >20 MeV. This energy threshold is chosen because at these energies, pair production dominates over other mechanisms for gamma-ray detection and thus comparison of experimental results in later sections becomes most meaningful.

1.2.1. Decay of π^0 -mesons

π^0 -mesons, produced in high energy interactions, decay with a lifetime of 10^{-16} seconds into 2 gamma quanta. In the centre of mass system the energy of each quantum is $E_0 \approx 70$ MeV. In the laboratory system, the energy of the quanta is in the range

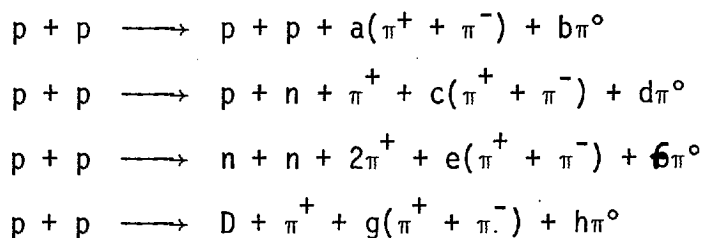
$$E_0 \left(\frac{1 - \beta}{1 + \beta} \right)^{\frac{1}{2}} \leq E \leq E_0 \left(\frac{1 + \beta}{1 - \beta} \right)^{\frac{1}{2}}$$

where βc is the velocity of the π^0 -meson. (Garmire and Kraushaar (7))
The resultant differential gamma-ray spectrum tends to peak at ~ 70 MeV.

Production of π^0 -mesons in space can occur in the following ways.

(a) Nucleon-nucleon collisions Cosmic ray particles traversing interstellar and intergalactic space will collide with ambient nuclei. Most of these collisions will be proton-proton interactions as protons comprise about 85% of cosmic rays, and hydrogen about 90% of the interstellar gas.

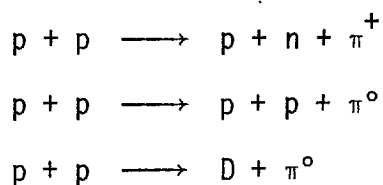
Pollack and Fazio (8) have given the important reactions as



Here a, b, c, d, e, f, g, h, are positive integers depending on the energy of the incident proton. They give the threshold kinetic energy, T_{MIN} , needed for the production of q mesons as

$$T_{\text{MIN}} \approx q(280 + 10q) \text{ MeV}$$

i.e. $T_{\text{MIN}} \approx 290 \text{ MeV}$ for single meson production. In the region $290 \text{ MeV} - 1 \text{ GeV}$ only single meson production is important, so we have



where the first of these reactions dominates. There is a large suppression of π^0 and π^- production relative to π^+ production in the proton energy region $< 2 \text{ GeV}$.

Fazio (2) gives the rate of production of gamma rays per target proton as

$$q(E_\gamma, \underline{r}) dE_\gamma = dE_\gamma \int_E I_p(E_p, \underline{r}) dE \int_{E_{\pi\text{MIN}}}^\infty \sigma(E_\pi, E_p) f_\gamma(E_\gamma, E_\pi) dE_\pi$$

Here $I_p(E_p, \underline{r})$ is the proton differential spectrum, $\sigma(E_\pi, E_p)dE_\pi$ is the cross section for the production of a π^0 -meson of energy E_π in the interval dE_π , and its magnitude is inclusive of the multiplicity function. $f_\gamma(E_\gamma, E_\pi)$ is the gamma ray distribution function from π^0 decay.

If a proton differential spectrum of the form

$$I_p(E_p, \underline{r}) = K_p E_p^{-k_p}$$

is assumed, it is shown by Fazio, that in the high energy limit $E_\pi \gg m_\pi c^2$, that

$$q(E_\gamma, \underline{r}) \sim K_\gamma E_\gamma^{-4/3(k_p - 1/2)}$$

therefore $I_\gamma(E_\gamma) \propto E_\gamma^{-4/3(k_p - 1/2)}$

and $I_\gamma(>E_\gamma) \propto E_\gamma^{-4/3(k_p - 5/4)}$

In the high energy limit with $k_p = 2.6$ then $I_\gamma(E_\gamma) \propto E_\gamma^{-2.8}$ at $E_\gamma > 1$ GeV. At $E_\gamma < 1$ GeV, $I_\gamma(E_\gamma)$ reaches a maximum at ~ 70 MeV and falls rapidly below this.

Account must also be taken of the collisions of cosmic ray α -particles with interstellar hydrogen, and cosmic ray protons with interstellar alphas. The assumption of a relative α -particle intensity of 15% in cosmic rays, and an α -particle density of 10% in the interstellar gas gives a contribution of about 35% to the gamma ray source strength. (Lust (3))

(b) Proton-antiproton annihilation Among the products of proton-antiproton interaction are π^0 -mesons from the annihilation process

$$p + \bar{p} \longrightarrow a(\pi^+ + \pi^-) + b\pi^0$$

The annihilation cross-section is approximately fitted by

$$\sigma = \sigma_0/\beta = 50 \times 10^{-27}/\beta \text{ cm}^2$$

where βc is the relative velocity of the two particles.

Being proportional to $1/\beta$, annihilation occurs mainly at low energies. The resulting differential gamma-ray spectrum is sharply peaked at ~ 70 MeV and falls fairly steeply above and below this. (Frye and Smith (9)) The shape of the integral spectrum is such that there are effectively no annihilation gamma-rays of energy $\gtrsim 850$ MeV.

The mean lifetime of an antiproton in a gas of proton number density n_p is given by Lust as

$$\tau = (n_p \sigma_0 c)^{-1}$$

and the total source strength as

$$S = \frac{n_p n_{\bar{p}} \sigma_0 c}{4\pi} \cdot m_\gamma$$

where m_γ is the mean gamma-ray multiplicity (given as 3.5 by Fazio (2)) and $n_{\bar{p}}$ the antiproton number density.

The gamma-ray spectrum (Lust and Pinkau (10)) has a shape quite distinct from that of the proton-proton inelastic collision spectrum.

(c) Proton-photon interaction The production of π^0 -mesons by the col-

lision of gamma-rays ($E_\gamma > 140$ MeV) with protons is a well known phenomenon whose cross-section has been measured. In space this process can be effective when a proton of sufficiently high energy collides with a "thermal" photon. For the production of a π^0 -meson, 140 MeV is required in the centre of mass system. Therefore the energy of the protons must exceed 10^{17} eV if the thermal photons have an energy of about 2 eV (typical for a starlight photon).

Hayakawa et al. (11) have derived the cross-section by this process.

1.2.2. Bremsstrahlung

The probability that a charged particle of energy E in passing near another charged particle, will emit a photon of energy E_γ is inversely proportional to the ^{Square of the} mass of the incident particle. This means that bremsstrahlung due to relativistic protons may be neglected in comparison with that due to relativistic electrons, even though electrons comprise only ~1% of the cosmic radiation.

Ginzburg and Syrovatskii (6) give as the approximate expression for the bremsstrahlung differential cross-section

$$\sigma(E_\gamma, E_e) dE_\gamma = m/X_0 \cdot dE_\gamma/E_\gamma$$

where X_0 is the radiation length in a gas of atoms of mass m .

The intensity of bremsstrahlung gamma-rays is thus

$$I_\gamma(E_\gamma) = \int_0^L n(\underline{r}) d\underline{r} \int_{E_\gamma}^{\infty} \sigma(E_\gamma, E_e) I_e(E_e, \underline{r}) dE_e$$

$$\begin{aligned} \text{therefore } I_Y(E_Y) &= N(L) \frac{m}{X_0} \frac{1}{E_Y} \int_{E_Y}^{\infty} I_e(E_e, \underline{r}) dE_e \\ &= \frac{M(L)}{X_0} \frac{1}{E_Y} \int_{E_Y}^{\infty} I_e(E_e, \underline{r}) dE_e \end{aligned}$$

Here $M(L)$ is the mass of gas per unit area along the integration path, and $I(E_e, \underline{r})$ is the relativistic electron spectrum. If its form is assumed to be

$$I(E_e, \underline{r}) = K_e E_e^{-k_e}$$

then for the relativistic case

$$I_Y(E_Y) = \frac{M(L)}{X_0} \frac{K_e}{(k_e - 1)} E_Y^{-k_e}$$

$$\text{and } I_Y(>E_Y) = \frac{M(L)}{X_0} \frac{K_e}{(k_e - 1)^2} E_Y^{-k_e+1}$$

Thus if $I(E_e, \underline{r}) \propto E_e^{-2.6}$ as has been observed, then $I_Y(E_Y) \propto E_Y^{-2.6}$ and $I_Y(>E_Y) \propto E_Y^{-1.6}$.

1.2.3. Inverse Compton scattering

In this process, collision between a high energy electron and a thermal photon results in a large transfer of energy to the photon. For the intensity of Inverse Compton gamma-rays, Ginzburg and Syrovatskii have

$$I_Y(E_Y) = \int_0^L dr \int_{E_Y}^{\infty} I_e(E_e, \underline{r}) dE_e \int_0^{\infty} d\epsilon n_{ph}(\epsilon, \underline{r}) \sigma(E_Y, \epsilon, E_e)$$

where $n_{ph}(\epsilon, \underline{r}) d\epsilon$ is the density of thermal photons in the interval $d\epsilon$ at $\underline{r}$, while $\sigma(E_\gamma, \epsilon, E_e) dE_\gamma$ is the cross-section for the production of a gamma-ray with energy in the interval dE_γ , when a photon of energy ϵ is scattered by an electron of total energy E_e .

For a differential electron spectrum of the form

$$I_e(E_e, \underline{r}) = K_e E_e^{-k_e}$$

Fazio gives

$$I(E_\gamma) = \frac{1}{2} \cdot L p_{ph} \sigma_T \cdot (m_e c^2)^{1-k_e} \cdot (\bar{\epsilon})^{(k_e-3)/2} \cdot f(k_e) \cdot K_e E_\gamma^{-(k_e+1)/2}$$

where L is the path length of the source,

p_{ph} is the thermal photon density,

$\bar{\epsilon}$ is the average thermal photon energy,

σ_T is the Thomson cross-section,

and $f(k_e) \approx 1$ for k in the range 1 to 2.

From above

$$I_\gamma(>E_\gamma) \propto E_\gamma^{-(k_e-1)/2}$$

Thus for $k_e = 2.6$, as in the previous section, $I_\gamma(E_\gamma) \propto E_\gamma^{-1.8}$ and

$$I_\gamma(>E_\gamma) \propto E_\gamma^{-0.8}.$$

1.3. Gamma-ray Absorption

Gamma-rays of the energy with which we are concerned ($E_\gamma > 20$ MeV), can for the most part, pass practically unaffected through interstellar and intergalactic space. There are, however, certain processes which under specific conditions can lead to the absorption of gamma-rays in

space.

In general, gamma-ray absorption can be represented in the form

$$I = I_0 e^{-L/\lambda}$$

where I_0 and I are the initial and final gamma-ray intensities, λ is the absorption length in the medium traversed and L the effective path length in the medium. The most important absorption mechanisms are given in the following sections, which follow the treatment of Lust (3).

1.3.1. Compton scattering

For gamma-rays of energy < 100 MeV, the Compton scattering by electrons should be considered.

The cross-section decreases with increasing energy and is always less than or equal to the Thomson cross-section, so the Compton absorption length can not be less than,

$$\lambda_c = \frac{1}{n_e \sigma_T}$$

where n_e is the electron number density in the region of space under consideration.

(a) The galaxy Here $n_e < 10 \text{ cm}^{-3}$ for all but a few local regions, so that with

$$\sigma_T = 6.6 \times 10^{-25} \text{ cm}^2$$

then $\lambda_c > 1.5 \times 10^{23} \text{ cm}$

This is of the order of five galactic radii so absorption can be taken as negligible.

(b) The metagalaxy The electron density in the metagalaxy is not well known, but even if it is as large as 10^{-5} cm^{-3} , then

$$\lambda > 1.5 \times 10^{29} \text{ cm}$$

which is about 30 times the photometric radius of the universe, given by Ginzburg and Syrovatskii (6) as $5 \times 10^{27} \text{ cm}$. So once again absorption is negligible.

1.3.2. Pair Production in Collisions with Charged Particles

Pair production may occur when a gamma-ray ($E_\gamma > 2m_e c^2$) passes the Coulomb field of a nucleus. The absorption length for this process is given by

$$\lambda_{pp} = \frac{X_0}{n_H m_p}$$

where X_0 is the radiation length in the medium (taken as 52 gm/cm^2 for interstellar matter), n_H is the number density of interstellar hydrogen and m_p the proton mass.

(a) The galaxy Even if n_H is taken as 100 cm^{-3} which it is only in a few clouds in our galaxy, then

$$\lambda_{pp} > 3 \times 10^{23} \text{ cm}$$

which is about ten galactic radii, and absorption is insignificant.

(b) The metagalaxy If n_H is taken as 10^{-3} cm^{-3} , then

$$\lambda_{pp} > 3 \times 10^{28} \text{ cm}$$

which is about six universal radii; once again negligible absorption.

1.3.3. Pair production in photon-photon collisions

For the collision of gamma-ray of energy E_γ , with a thermal photon of energy ϵ to produce an electron-positron pair, an energy of $2m_e c^2$ must be available in the centre of mass system.

This criterion is satisfied when

$$E_\gamma \epsilon > m_e^2 c^4$$

The absorption length for the process one finds as

$$\lambda > \frac{\epsilon}{\rho_{E_\epsilon} \pi r_e^2}$$

where ρ_{E_ϵ} is the energy density of the thermal photons.

The sources of thermal photons in the galaxy and metagalaxy are starlight, the universal microwave radiation and radio frequency photons.

(a) Starlight photons For starlight photons, with an average energy of ~ 2 eV, the threshold for pair production is about 10^{11} eV. Nikishov (12) has calculated the absorption lengths for gamma-rays in the 10^{11} - 10^{14} eV energy region, in the galaxy and metagalaxy.

(i) The galaxy Even if the photon energy density is assumed as high as 1.0 eV cm^{-3} , the minimum absorption length (at $\sim 10^{12}$ eV) is approximately 10^{25} cm which is about 300 galactic radii.

(ii) The metagalaxy Estimates here depend on the value taken for the photon energy density. Nikishov uses 0.1 eV cm^{-3} which produces an absorption length of about 1.5×10^{26} cm at 10^{12} eV, which is considerably less than the radius of the universe. This

is probably an overestimate of the absorption because the starlight photon density is probably about $10^{-3} \text{ eV cm}^{-3}$, when once again the absorption is not too serious. This is the energy region for which the atmospheric Cerenkov method of gamma-ray detection is used (see section 1.4.3.).

(b) Universal microwave radiation It was pointed out by Jelley (13), and Gould and Schreder (14), that the absorption of photons in the $10^{14} - 10^{18} \text{ eV}$ region by the universal microwave radiation was much more serious. This radiation was originally discovered by Penzias and Wilson (15) and has been measured by Stokes, Partridge and Wilkinson (16) as having a Black Body temperature of 2.7°K , corresponding to an average photon energy of $6 \times 10^{-4} \text{ eV}$ and an energy density $\sim 0.25 \text{ eV cm}^{-3}$. The high photon density means that the metagalaxy is virtually opaque to gamma-rays in this energy region. The absorption length is such that even the galactic centre cannot be seen clearly at these energies.

This is the energy region covered by the Extensive Air Shower arrays of the Bolivian Air Shower Joint Experiment (see section 1.4.3.) and tends to cast doubt upon the usefulness of its results on gamma-rays.

(c) Radio photons Goldreich and Morrison (17) have computed the absorption length for pair production by $10^{18} - 10^{20} \text{ eV}$ photons on radio photons. The minimum value for photons $> 10^{20} \text{ eV}$ of $2 \times 10^{26} \text{ cm}$ is much less than the radius of the universe so that absorption is significant.

The absorption of gamma-rays in space is summarised in Fig. 1.1,

taken from Jelley (18). The curve for the microwave radiation has been corrected to the now accepted temperature of 2.7°K, whereas Jelley's original calculations used the Penzias and Wilson original value of 3.5°K.

Jelley (18) has also estimated the possible absorption of energetic photons in the very high density photon fields of objects such as quasars and point X-ray sources. His calculations showed considerable absorption of gamma radiation above 10^{11} eV in the core of quasars. Absorption at lower energies is very model dependent.

1.4. Gamma-ray Detection

Gamma-rays can only be detected through the charged particles they produce. The only efficient process for charged particle production, above a few MeV, is electron-positron pair creation.

1.4.1. General requirements and methods

The general requirements for an efficient gamma-ray detector may be given as:-

- (i) high photon conversion efficiency
- (ii) unambiguous recognition of the electron-positron pair and rejection of spurious background events
- (iii) high angular resolution to enable investigation of discrete sources
- (iv) good energy resolution
- (v) high time resolution - this has become increasingly important since the possibility of gamma-ray pulsars

has arisen

- (vi) low energy threshold for gamma-rays
- (vii) relative simplicity and low cost.

Unfortunately the very property of matter which makes an efficient gamma-ray-to-pair-converter is also the property which makes large the probability of multiple scattering, which produces loss of angular resolution. While the probability for this scattering decreases with increasing energy, and the pair production probability does not, the flux of gamma-rays is in all cases a decreasing function of energy. Selection of the amount of converter is usually a compromise with the acceptable angular resolution of the instrument. Three types of instrument have primarily been used to detect the pair of charged particles: nuclear emulsions, scintillation-Cerenkov counter systems and spark chambers.

The nuclear emulsion has many advantages as a gamma-ray detector, such as high conversion efficiency, unambiguous pair recognition, high angular resolution, good energy resolution from pair opening angle and multiple scattering measurements, and low gamma-ray threshold energy. It does, however, have the major disadvantages of no time resolution and continuous sensitivity. Thus an inconvenient number of background pairs accumulate in the emulsion during ascent and descent of the stack, and extrapolation to zero atmospheric depth is awkward as each depth observation requires a separate flight. Also, the stacks have to be recovered and the data retrieval by scanning of the emulsions by microscope is long and tedious.

A scintillator-Cerenkov telescope following a high-Z gamma-ray-to-pair-converter (such as a thin lead sheet) has been used by many experimenters. A further scintillator above the lead sheet, set in anticoincidence, is used for charged particle rejection. These telescopes have advantages in that their sensitive area can be large and their detection efficiency high. Also the Cerenkov counter is directional and insensitive to low energy particles, which gives the detector a certain degree of immunity to background radiation. Energy measurements can also be made, to a fair resolution, by making the Cerenkov counter of a dense material such as lead glass and using it as a total energy spectrometer. Scintillator-Cerenkov systems also have good time resolution and can be relatively simple and cheap. They do, however, have what is now regarded as a serious disadvantage, a poor angular resolution (typically 15° - 30° half-angle) which limits their sensitivity in the study of possible point sources. They are also suspect in that their gamma-ray recognition is not necessarily entirely unambiguous.

The spark chamber has been regarded recently as offering the most advantages as a gamma-ray detector. They offer angular resolution as good as $\sim 1^\circ$ and absolute pair recognition provided it can be resolved in the chamber. The gamma-ray-to-pair-converter can be replaced by using the plates of the chamber themselves as converters. Energy measurements can be made from multiple scattering measurements or by using a lead glass Cerenkov counter as before. Spark chambers can also have large sensitive areas and large total solid angles. Trig-

gering can be achieved by using a scintillator-Cerenkov system to select a certain type of interaction.

1.4.2. Experimental detectors for the 10 MeV - $\sim$ 10 GeV energy region

Several methods have been tried to overcome the continuous sensitivity of nuclear emulsions and separate gamma-rays at altitude from those of the ascent and descent phase of the flight.

Klarmann (19) flew two emulsion stacks from the same balloon. One of the stacks was cut down immediately upon reaching altitude whereas the other was left at altitude for eight hours before being cut down. Subtraction of the number of pairs recorded in the first stack from those in the second yielded the true altitude flux. In the emulsion experiments of Bracessi et al. (20) and Anand et al. (21) the emulsion stack was flown upside down during ascent and descent and turned through 180° at altitude, thus keeping the contamination to that due to upward moving albedo.

Cline (22) flew a scintillator-Cerenkov system, from a balloon, with a mercury gamma-ray-to-pair-converter and a mercury absorber which could be inserted in flight to measure the attenuation of the beam, in order to identify the measured flux as photons. Gamma-ray collimation and charged particle rejection were accomplished by using a heavy lead collimator between two anticoincidence scintillator shields. There was a CsI(Tl) scintillator, beneath the mercury, which acted as a pair detector, in coincidence with a perspex element.

The detector described by Fazio and Hafner (23) and flown by Duthie et al. (24) contained as its principle element a Cerenkov counter.

designed to yield simultaneous data on charged particles and gamma-rays in different cones of sensitivity, by using the inherent narrow cone of emission of Cerenkov light.

The gamma-ray experiment on board the Explorer-11 satellite (Kraushaar et al. (25)) was the first satellite-born gamma-ray detector. It employed an active converter composed of alternate layers of NaI(Tl) and CsI(Tl) scintillators - the pulse height from which helped to determine which events were true gamma-ray events.

The scintillator-Cerenkov type of instrument reached its most sophisticated development with the MIT experiment on board the OSO-3 satellite, described by Kraushaar et al. This experiment was responsible for the first positive detection of high energy cosmic gamma-rays (Clark et al. (5)). This was a complex detector with CsI-plastic scintillator active converter sandwich, a perspex element and crude energy calorimeter comprised of NaI and tungsten in a multi-layer sandwich.

The introduction of spark chambers in conjunction with scintillator-Cerenkov systems greatly increased the sensitivity of gamma-ray detectors. The main variation in spark chamber detectors is in the method used to record the location of the spark.

The spark chamber employed by Cobb et al. (26) and also by Duthie et al. (27) had a pair of photographic chambers, separated by a lead sheet (which acted as the pair producer) and by one of the telescope scintillator elements. A resulting angular resolution of 4° at 100 MeV was claimed.

In the photographic spark chamber developed by Frye and Smith (9) and also used with minor modifications by Frye and Wang (28) and (29), the lead converter was replaced by the stainless steel plates of the chamber itself. This resulted in improved angular resolution (an overall 3° at 100 MeV) and energy measurements by study of the multiple scattering of the electrons.

In their search for point sources of gamma-rays at >1 GeV, Ogelman et al. (30) employed a pair of sonic spark chambers beneath a lead converter, and a lead scintillator sandwich was used for energy measurements. The angular resolution was 2° for $E_\gamma > 1$ GeV.

The photographic spark chamber of Fazio et al. (31) also used the plates of the chamber as an extended gamma-ray converter but there was a vidicon readout which rendered payload recovery non-essential. A lead glass Cerenkov total absorption spectrometer was incorporated, for the first time, for energy measurements. The angular resolution at 100 MeV was 3° , including steering errors.

The spark chamber flown by the NASA group (Fichtel et al. (32) and (33)) took the form of a series of wire grid modules separated by thin pair producing plates. This system had a digitized magnetic core readout. Energy estimation was once again by investigation of the Coulomb multiple scattering of the electron pair.

The spark chambers described so far, are basically limited in their sensitivity, in that in order to provide a reasonable conversion efficiency with a finite number of spark gaps, the material between the gaps must be an appreciable fraction of a conversion length. Thus the

uncertainty in the true direction of arrival of the initial gamma-ray is compounded by multiple scattering of the electrons in the producing and successive layers. As the sensitivity is proportional to the angular resolution, the detector flown by May and Waddington (34) and Valdez and Waddington (35), was of particular interest. Here photographic nuclear emulsions were used as the converter material, above two thin plate spark chambers, scintillator telescope elements and a gas Cerenkov detector which was insensitive to particles with energy $< 40 m_e c^2$. The angular resolution of this detector at 100 MeV was $\sim 1^\circ$.

Another significant development has been the gas Cerenkov detectors which are soon to be flown. The detector of Helmken and Hoffman (36) for gamma-rays in the 10 - 100 MeV region spreads the amount of converter material over a much greater area, thus decreasing the absolute efficiency but improving the angular resolution and area-time product for a point source. Thus there is an increase in sensitivity. Fig. 1.2 gives the minimum detectable gamma-ray flux levels at 100 MeV over the years (Fazio (37)).

The sensitivity that is likely to be achieved in the next few years makes it clear that even the most pessimistic of flux predictions will come into the detection range and many important astrophysical theories will be put to the test.

1.4.3. Detectors for photons in the $> 10^{11}$ eV energy region

Gamma-ray photons with energy $> 10^{11}$ eV can be detected by the cascade of shower particles they produce upon interaction with the

atmosphere. There are two experimental ways of detecting the showers and hence the gamma-rays.

(a) Atmospheric Cerenkov light The electrons in these air showers, which have velocities βc , such that $\beta > 1/n$ (where n is the refractive index of the air), will emit Cerenkov radiation in a narrow cone around the shower axis. The light which is primarily in the blue and ultra-violet region of the visible spectrum, occurs as a burst lasting about 10^{-8} seconds and covers a ground area of about 10^8 cm^2 . Given a dark site and a moonless, cloudless night this radiation can be detected by ground-based detectors in which the light is focussed by special mirrors on to photomultiplier tubes. A review of this technique is given by Jelley (38).

Because of the narrow width of the Cerenkov light cone, an angular resolution of about $1^\circ - 2^\circ$ can be obtained. There is, however, a uniform distribution of Cerenkov light over the sky due to charged particle induced showers. Gamma-rays from a particular source can only be detected by looking for an increase from that particular direction in the sky.

Cudakov et al. (39) and Fruin et al. (40) have pioneered the search for gamma-rays of $>5 \times 10^{12} \text{ eV}$ from likely sources using this technique. Recently the technique has also been applied to investigations of pulsars. (Charman et al. (41), Fazio et al. (42), Fazio et al. (43).)

No definite sources have yet been detected and a considerable increase in sensitivity would be desirable. This might be achieved

if a way could be found of separating gamma-ray and nucleon induced showers.

(b) Scintillation counter arrays The thin 'disc' of charged particles in the gamma-ray generated shower can be detected for energies $>10^{14}$ eV by coincidence pulses from a large ground level scintillation counter array. The arrival direction is found by noting the firing sequence of the counters. Gamma-ray showers can be distinguished from charged particle showers by any anisotropy from a possible source direction and in principle by assuming that gamma-ray showers are predominantly electromagnetic interactions, lacking mesons and nucleons in the cone.

Two groups have set up experiments to try and exploit this circumstance. They are the Bolivian Air Shower Joint Experiment (BASJE) (Kamata et al. (44)) on Mt. Chacaltaya and the Polish group at Lodz (Gawin et al. (45)).

A more recent paper by Catz et al. (46), however, investigating the muon-poor showers detected at Lodz and Verrieres, produced evidence which questions the hypothesis that these showers are due to primary photons. They found the angular distribution of the muon-poor showers flatter than that of normal showers. Thus they attributed the form of the shower to a primary charged particle producing a very high energy intermediate particle on its initial interaction, and the intermediate particle transferring its energy to the electromagnetic component in a secondary interaction. This theory is consistent with the postulated heavy absorption of photons in the $10^{14} - 10^{20}$ eV range by the universal black-body radiation.

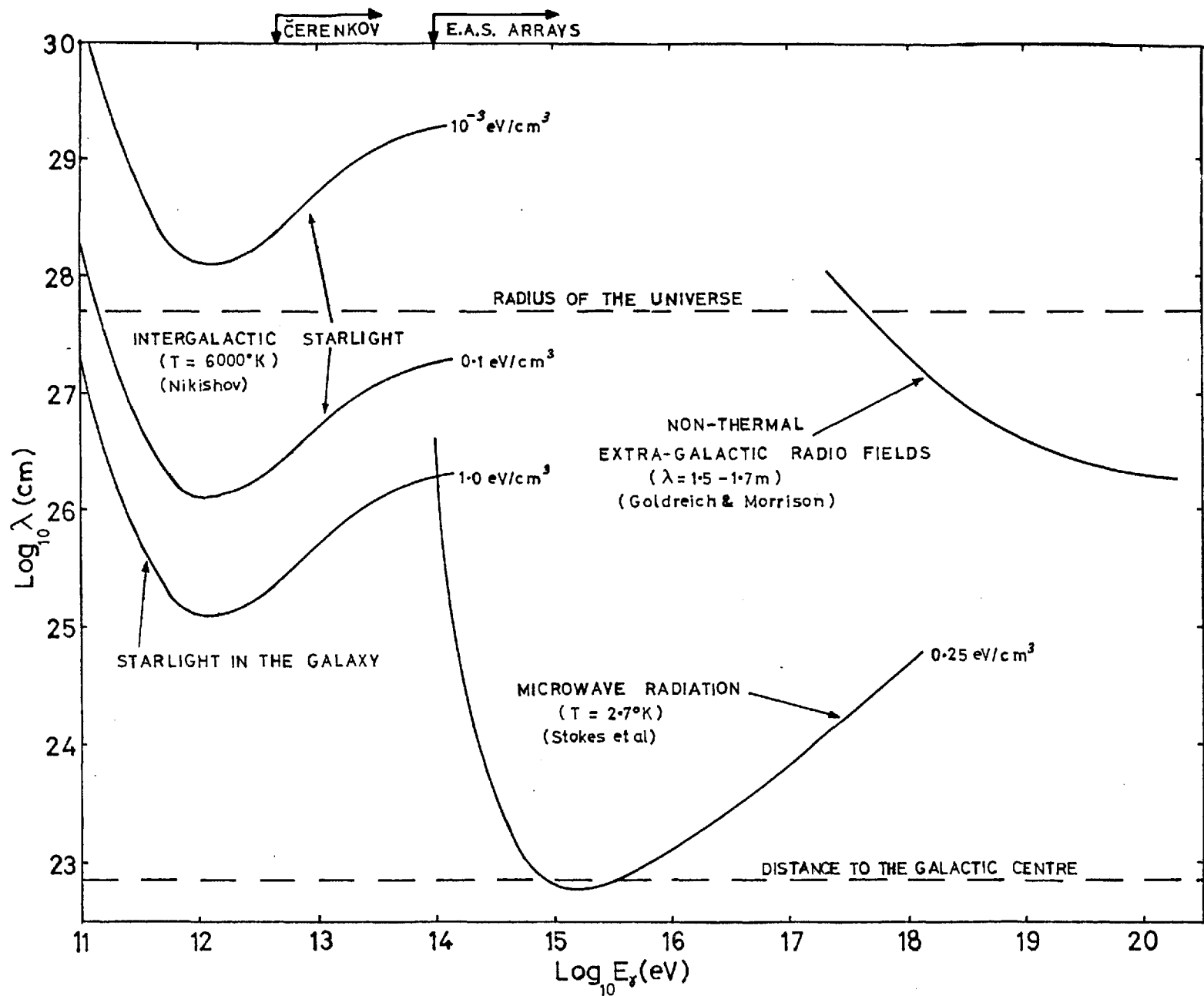


Fig. 1.1 The absorption of gamma-rays in space.

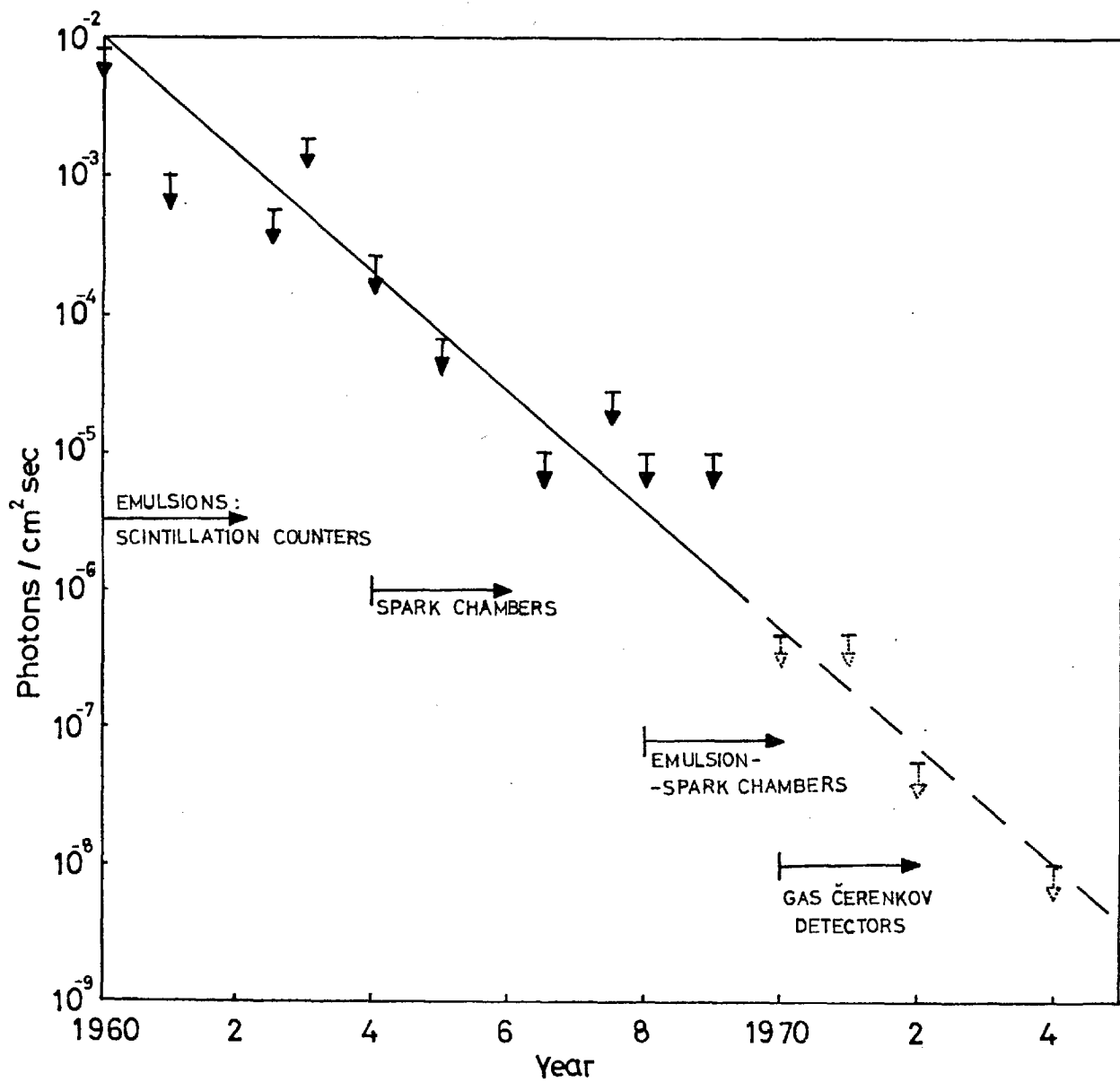


Fig. 1.2 The minimum detectable gamma-ray flux at >100 MeV, as measured over the years.

II The Gamma-ray Detector

The detector used in this experiment was originally designed to search for possible energetic π^0 -decay gamma-rays emitted from active regions of the sun (Sood (47)). While the results from that experiment were inconclusive, due to unfavourable solar activity, the detector was successful in detecting gamma-rays from the galactic disc (Sood (48)).

The known effectiveness, reliability, and relative simplicity and cheapness, of the detector, were factors in the decision to continue the investigation of the galactic disc source with two further balloon flights employing similar detectors.

2.1. General Description

The detector is illustrated in Fig. 2.1 and its basic mode of operation was as follows. Any energetic gamma-ray entering the top of the detector had a certain probability of being converted into an electron-positron pair in the lead disc, which was half a radiation length thick (2.9 gm cm^{-2}). The electron pair (or one of the electrons) was then detected by a three-fold coincidence in the cosmic ray telescope formed by the two perspex Cerenkov elements B and C (14.0 cm diameter, 2.54 cm thick) and the scintillator element D. The scintillator element A was set in anticoincidence and rejected charged particles which traversed the detector.

2.2. Geometric Properties

In its final configuration the detector had a geometrical factor of $15.2 \text{ cm}^2 \text{ sr}$ for an isotropic flux. The geometrical half angle was 20° and the maximum sensitive area 153.2 cm^2 . The angular response for a point source, passing radially across the polar diagram of the detector, is shown in Fig. 2.2 - which indicates an angular resolution of 17° FWHM. The angular response to a line source is shown in Fig. 2.3.

2.3. Physical Properties

2.3.1. The scintillator elements

(a) The sensitivity of a detector for gamma-ray astronomy depends upon its ability to discriminate against all non-gamma events. In consequence the anticoincidence element has to detect charged particles with near 100% efficiency. The plastic scintillator NE 102A was used in this anticoincidence element, as it combined a high light output for a charged particle traversing it, fast recovery time, and good light transmission properties with relative cheapness.

The element A was made of 0.635 cm thick NE 102A, the top disc being 16.5 cm in diameter. The cylindrical part of the element was also of 0.635 cm NE 102A, being joined to the disc by NE 580 optical cement, and extended well down past the lead disc and Cerenkov element B. This was to eliminate the possibility of energetic particles entering the lead at an oblique or obtuse angle, missing the top scintillator disc, and pro-

ducing secondaries in such a direction that the event masqueraded as a gamma-ray. The whole assembly was coupled to a perspex light guide using NE 580 optical cement - the light pipe being optically coupled to an EMI 9524A photomultiplier by Tensol 104 flexible acrylic cement. This cement has been found perfectly adequate for tropical balloon flights (Sood (47)). The scintillator and light pipe were wrapped in aluminium foil.

For a particle of rest mass $M(> m_e)$, charge ze , velocity $v (= \beta c)$ and energy E , the energy dE transferred as excitation and ionisation along an element of path dl , to a homogeneous medium containing N atoms cm^{-3} , each of atomic number Z is given by Birks (49) as

$$\frac{dE}{dl} = \frac{4\pi e^4 z^2}{m_e v^2} NZ \left(\frac{1}{2} \ln \frac{m_e v^2}{I} - \ln(1 - \beta^2) - \beta^2 \right)$$

where I is an empirical constant for a given medium, corresponding to the mean ionisation and excitation potential. For NE 102A, Crispen and Hayman (50) have given the energy loss for a minimum ionising particle of unit charge as $\sim 1.8 \text{ MeV/gm cm}^{-2}$.

Barnaby and Barton (51) have given a phosphor efficiency of approximately 1 photon per 140 eV energy liberated for NE 102A. For the thickness of scintillator used, and the energy loss figure given above, the total useful photon yield from a minimum ionising particle of unit charge was ~ 8500 photons. Estimation of the actual number of photons incident on the photocathode was difficult, but following the treatment of Barnaby and Barton for a scintillator connected to a photo-

multiplier tube by a tapered light guide, the fraction of light collected, F , is given by

$$F \approx 0.5 S/A$$

where S = area of photocathode, and A = area of element to which the light guide is attached. From this a figure of ~ 1000 photons incident on the photocathode was obtained for this detector element, A .

The peak wavelength of the scintillation output was close to the maximum of the response curve of the S-11 photocathodes of the tubes used.

The detection efficiency of element A was tested by operating it between the Cerenkov elements in a three-fold coincidence arrangement to count cosmic ray μ -mesons, and then comparing the counting rate to that of just the two Cerenkov elements in coincidence. The efficiency was found to be better than 99.5%.

(b) The scintillator element D (14.0 cm diameter, 0.32 cm thick), was originally introduced into the detector to enable the gamma-ray channel to be characterised by a three-fold coincidence - $\bar{A}BCD$. As given in section 2.3.3., the chance coincidence rate is $n r_1 r_2 \dots r_n \tau^{n-1}$, for n counters, where τ is the resolving time.

In this detector, the reduction of the chance rate by the introduction of element D was typically by a factor of $>10^4$.

Element D was coupled to a 1" photomultiplier (EMI 9524A), via a perspex light guide in the same way as element A . The useful photon yield from a minimum ionising particle was ~ 4000 photons, and the number of photons incident on the photocathode estimated at ~ 1200 photons.

2.3.2. The Cerenkov elements

A charged particle traversing a medium of refractive index n will cause the emission of electromagnetic radiation if its velocity $v(=\beta c) > c/n$ where c is the velocity of light in vacuo.

The radiation is emitted in a well defined cone, in the forward direction, about the track of the particle. The half-angle of the cone is given by

$$\cos \theta = \frac{1}{\beta n}$$

Thus as β tends to 1, θ tends to maximum value of $\cos^{-1}(1/n)$.

The detection of this radiation, known as Cerenkov radiation after its discoverer, has become one of the most important means of detecting energetic particles, as it combined directionality with discrimination against low energy particles.

The number of Cerenkov photons produced per unit path length is given by Jelley (52) as

$$\frac{dN_p}{dl} = \frac{2\pi z^2}{137} \left(1 - \frac{1}{\beta^2 n^2} \right) \int_{\lambda} \frac{d\lambda}{\lambda^2}$$

where z is the charge of the incident particle and λ is the wavelength of the emitted radiation.

For the detection of Cerenkov photons in the optical region using a photomultiplier tube of quantum efficiency $Q(\lambda)$, the number of photoelectrons per unit path length produced at the photocathode is given by

$$\frac{dN_e}{dI} = \frac{2\pi z^2}{137} \epsilon \left(1 - \frac{1}{\beta^2 n^2} \right) \int_{\lambda} \frac{Q(\lambda)}{\lambda^2} d\lambda$$

where ϵ is the optical efficiency of light collection.

For the photomultiplier tubes used, EMI type 9618A (S-11 photocathode), the quantity $Q(\lambda)/\lambda^2$ is plotted against λ in Fig. 2.4.

Graphical integration yielded

$$\frac{dN_e}{dI} \approx 100 \epsilon \left(1 - \frac{1}{\beta^2 n^2} \right) \text{ photoelectrons/cm}$$

for singly charged particles.

For efficient light collection the perspex Cerenkov elements (14.0 cm diameter, 2.54 cm thick) were optically coupled directly to the faces of the 5" photomultipliers (EMI type 9168A), using the flexible acrylic cement tensol 104. The calculated photoelectron yield per cm for an electron in one of the perspex ($n=1.495$) elements is shown in Fig. 2.5. ϵ was assumed to be ~ 1 .

The total yield for a vertically moving highly relativistic electron was ~ 140 photoelectrons. The threshold energy for Cerenkov emission in perspex is 180 KeV for electrons and 330 MeV for protons. The maximum angle of Cerenkov emission is $\sim 48^\circ$.

The perspex elements were blackened on their top surfaces using matt black paint, to absorb the Cerenkov light emitted by particles moving upward through the detector. The response of the detector was measured, using sea level μ -mesons, to be unidirectional at the 98% level of confidence.

The response of the detector to non-relativistic particles was investigated by Sood and was found to be $\leq 0.01\%$. This was consistent with the results of Anderson (53).

2.3.3. The response to gamma-rays

(a) Energy response and conversion efficiency Some fraction of photons incident on the detector interact in the lead converter to produce electrons. At gamma-ray energies the only important interaction processes were Compton scattering and pair production. The low energy threshold for gamma-ray detection was determined by the minimum energy required for an electron to traverse the detector and register a coincidence. Energy loss and scattering calculations showed that an electron would require an energy of at least 20 MeV to be detected.

(i) Compton scattering The differential probability that a photon of energy E traversing a thickness dx gm cm^{-2} will produce an electron of energy between E'' and $E'' + dE''$ ($E'' \gg m_e c^2$) was obtained from Rossi (54) as

$$\Phi_{\text{COM}}(E, E'') dE'' = C \frac{m_e c^2}{E} \left(1 + \left(\frac{E - E''}{E} \right)^2 \right) - \frac{dE''}{(E - E'')}$$

where $C = \pi N Z / A = 0.15 Z / A$.

The total probability for a Compton interaction is then

$$\mu(E) = \int_{\frac{E - m_e c^2}{2}}^0 \Phi_{\text{COM}}(E, E'') dE''$$

This was integrated to give

$$\mu(E) = C \frac{m_e c^2}{E} \left[\ln \left(\frac{E - E''}{E} \right) + \frac{1}{2} \left(\frac{E - E''}{E} \right) \right]_{E - \frac{m_e c^2}{2}}^0 \text{ cm}^2 \text{ gm}^{-1}$$

If the electron must have a certain minimum energy $E''_{\min}$, the probability becomes

$$\mu(E, E''_{\min}) = C \frac{m_e c^2}{E} \left[\ln \left(\frac{E - E''}{E} \right) + \frac{1}{2} \left(\frac{E - E''}{E} \right) \right]_{E - \frac{m_e c^2}{2}}^{E''_{\min}} \text{ cm}^2 \text{ gm}^{-1}$$

The probability $P(E, E''_{\min})$ of the production of an electron of energy $E''_{\min}$ in the half-radiation length (2.9 gm cm^{-2}) of lead used as the converter is this detector, was calculated from $P(E, E''_{\min}) = 1 - \exp(-\mu(E, E''_{\min}) \times 2.9)$ for various $E''_{\min}$, as a function of E and is shown in Fig. 2.6.

As can be seen, for a minimum electron energy of 20 MeV, the probability is $\sim 1\%$ for all gamma-ray energies. This would seem to show that Compton scattering was not an important process for this detector.

(ii) Pair production Whilst the Compton interaction cross-section decreases with increasing energy, the pair production cross-section increases and should be the dominant process for gamma-ray energies $> 20 \text{ MeV}$.

The conversion efficiency is proportional to the thickness of

the converter, but Coulomb multiple scattering is also proportional to that thickness, and the trajectories of the electrons are primarily determined by the scattering. For a 100 MeV gamma-ray, Stearns (55) calculated that for equipartition of energy, the r.m.s. angle between the trajectory of a secondary electron and that of the incident photon is $\sim 1.5^\circ$, and for a 50 MeV gamma-ray $\sim 2.5^\circ$. The r.m.s. scattering angle in one quarter of the radiation length of lead is $\sim 12^\circ$ for a 50 MeV electron and $\sim 23^\circ$ for a 25 MeV electron (Overås (56)). One quarter of a radiation length was taken as the average thickness of lead converter traversed by the pair produced electrons (Kohn et al. (57)). If scattering was taken into consideration, the effective threshold for gamma-ray detection was about 30 MeV, and for the higher level discriminator the threshold was estimated at 50 MeV.

The differential probability $\phi_{\text{PAIR}}(E, E')$ where E' represents the energy of the positron or electron is given in Rossi, for lead. The total interaction probability in the half-radiation length used in the detector was obtained by graphically integrating the differential probability and using the exponential relationship as in the previous section. The results are shown in Fig. 2.7. The top curve represents the total conversion efficiency and the lower curve represents the conversion efficiency when a minimum energy of 30 MeV is required for either the electron or the positron.

The efficiencies $\epsilon(E)$ calculated are for gamma-rays of specific energies whereas the detector was an integral energy detector. By assuming a specific form for the gamma-ray spectrum to be observed,

$I_Y(E)$, the effective integral efficiency was calculated from

$$\epsilon_{\text{eff}}(>E) = \frac{\int_E^{\infty} \epsilon(E) I_Y(E) dE}{\int_E^{\infty} I_Y(E) dE} = \frac{\int_E^{\infty} \epsilon(E) I_Y(E) dE}{I_Y(>E)}$$

The majority of gamma-rays counted were of course atmospheric secondaries with a spectrum indicative of their π^0 -decay origin. It is probable that the gammas from the galactic line source also have a π^0 -decay origin, so that such a spectrum may be legitimately folded with $\epsilon(E)$ to obtain the effective integral efficiency. The atmospheric gamma-ray spectrum at balloon altitudes has been measured by several experimenters. The results of Svensson (58) at high latitude are representative and typical. The atmospheric spectrum calculated by Perola and Scarsi (59) for a high latitude site (<0.5 GV) is in quite good agreement with the spectrum of Svensson, (as shown in Fig. 2.8). This being the case, a differential and an integral gamma-ray spectrum were derived from the results of Perola and Scarsi for a site with a vertical cut-off rigidity corresponding to that of Lusaka (11.3 GV). The resulting spectra were used in the expression above to obtain an estimate of the effective integral efficiency. For gamma-rays of >30 MeV the value calculated was 30%. For a threshold of 50 MeV the efficiency was found to be the same within 1%. The expression for $\epsilon_{\text{eff}}(>E)$ was found to be not too sensitive to the form of $I_Y(E)$. When a differential spectrum with an E^{-2} dependence was substituted, a value of 28% was obtained for gamma-rays of >30 MeV. This difference would

not be significant at the statistical accuracy of this experiment.

The value of 30% is used in all subsequent calculations.

(b) Spurious events in the gamma-ray channel Certain events may occur which register in the gamma-ray channel but are not due to high energy gamma-rays materialising in the converter. As all these events combine to lower the sensitivity of the detector, some estimate of the importance of various types of spurious events was made.

(i) Anticoincidence inefficiency The efficiency of anticoincidence scintillator A was tested, as previously mentioned, by counting sea level μ -mesons. The efficiency was estimated at >99.5%, which at altitude produces a contribution to the gamma-ray channel of $\lesssim 5\%$.

(ii) Upward Albedo It was possible for a charged particle moving upwards through the telescope elements to stop in the lead converter and masquerade as a gamma-ray. But due to the blackening of the top surface of the Cerenkov elements, the relative response of the telescope elements to upward moving particles was <2%. So this possible contribution to the gamma channel was negligible.

(iii) Chance coincidence The chance coincidence rate in a system of counters was given by Janossy (60) as

$$R = n r_1 r_2 \dots r_n \tau^{n-1}$$

where $r_1, r_2 \dots r_n$ are the counting rates of the n counters and τ the resolving time of the coincidence system. In this system, the accidental rate in the important gamma-ray channel, characterised by $\bar{A}B_1CD$ was thus

$$R = r_{B_1} r_C r_D \tau^2$$

with $\tau \approx 100$ n sec and typically at ground level, r_{B_1} (Cerenkov) $< 400/\text{min}$, r_D (scintillator) $\leq 20,000/\text{min}$ and r_C (Cerenkov) $< 400/\text{min}$, the accidental coincidence rate was $< 10^{-8}$ cts/min, which was completely negligible. Even a factor of 10 increase in all the single rates would still have produced an insignificant contribution to the gamma-ray channel.

Another possible contribution to the accidental rate was due to a coincidence between a noise pulse from discriminator B_1 and a particle traversing elements C and D. Using even the high particle fluxes of the Pfozter maximum, this contribution was calculated to be $< 4 \times 10^{-3}$ cts/min, once again negligible.

(iv) Neutron interactions An atmospheric energetic neutron might interact in the lead to produce a relativistic particle which could trigger the remainder of the telescope elements.

For this detector, the n-N interaction only becomes important at neutron energies of $\gtrsim 500$ MeV. The total cross-section increases rapidly with energy to become almost geometric at $\gtrsim 5$ GeV. To calculate an upper limit to the neutron contribution the assumption of a geometric cross-section was made.

The atmospheric neutron spectrum is not well known at > 500 MeV, but using the calculated spectrum of Newkirk (61) extrapolated to higher energies, together with the measurements of Apparao et al. (62) of atmospheric neutrons of > 50 MeV at 16.9 GV and Eyles (163) of > 150 MeV

at 15.0 GV, the upper limit contribution to the gamma-ray channel at altitude was estimated to be 1%.

(v) Gamma-ray horizon brightness Kraushaar et al. (25) suggested that the horizon brightness in gamma-rays at balloon altitudes might contribute substantially to the background in the gamma channel. Sood showed that this detector had a relative response of <1% for gamma-rays incident at $\sim 90^\circ$ to its vertical axis.

2.4. The Electronics

In order to obtain meaningful results, the main requirement for balloon payload electronics is stability against the extreme temperature and pressure changes that will be encountered, and against long-time drifts. Lower power consumptions is important because in these light-weight detectors, batteries are a significant fraction of the total weight. Integrated circuits were widely used because of their simplicity and reliability. The block diagram of the detector electronics is shown in Fig. 2.9.

2.4.1. Event identification

The signal from each photomultiplier was amplified and fed into a fast discriminator with a 150 nsec output pulse.

The output from Cerenkov element B passed into two amplifiers B_1 and B_2 , with a gain setting of B_2 such that its discriminator was only fired by a large pulse from the Cerenkov. This should correspond to the passage of an electron-positron pair through the perspex, which is

the case for the higher energy gamma-rays.

The coincidence and anticoincidence gates after the discriminators recognised the following types of events;

- | | |
|-------------------------------|--|
| AB_1CD | - relativistic charged particles |
| $\bar{A}B_1CD$ | - low energy gamma-rays and background |
| $\bar{A}B_1CD + \bar{A}B_2CD$ | - mainly high energy gamma-rays |

No other type of event was possible with the logic system used.

The coincidence resolving time was ≈ 100 nsec. The output of each coincidence triggered a 10 msec univibrator. The square output pulse of this univibrator was then used to gate an oscillator - the frequency of the oscillation being determined by the combination of the outputs from the univibrators. The fixed frequencies chosen for the various types of events were 1.7 kHz for the charged particles, 1.3 kHz for the low energy gammas and background and 2.3 kHz for the high energy gammas. The peak repetition frequency of this system was about 65 events/sec which was calculated to miss very much less than 1% of events, even at the Pfozter maximum.

2.4.2. Subsidiary data

The pressure was measured using an Olland cycle device, described by Linney (63). It measured pressure in two ranges 200 - 1000 mb and 0 - 200 mb with an accuracy of 0.2 mb at 4 mb on the latter range. It also measured the temperature inside the payload within the range $+30^\circ\text{C}$ to -60°C . The device modulated a 750 Hz oscillator, its information

was delivered in morse code form every 30 seconds.

Additional temperature measurement was obtained from two thermistor controlled oscillators, the thermistors being in different parts of the detector box. These low frequency variable oscillators had previously been calibrated against temperature.

The single rates of discriminators A, B₁, C and D were scaled down to less than 300 Hz in order to be monitored during the flight, when they would be used as a check on detector performance. The four tube rates and the two thermistor controlled oscillators were fed into a ± 6 counter, controlled by external clock, such that each channel was fed into the telemetry for about 50 seconds at a time.

2.4.3. Transmission

The gating system was such that the background single rate or temperature information was transmitted continuously except when it was inhibited by the particle channel. The output of the gating system was fed into a mixer which then modulated a 136 MHz FM transmitter. These transmitters were liable to drift in frequency by ~ 0.02 MHz/ $^{\circ}$ C, but the power output was fairly constant ~ 150 mWatts from -25° C to $+25^{\circ}$ C.

The transmitter was matched to hybrid ground plane-turnstile antenna.

In conjunction with receiving system used, the effective telemetry range was 300 - 400 miles.

2.4.4. Power converters and batteries

The low tension voltage lines for the electronics and transmitter were provided from a ringing choke converter, driven by 12 volt Ni-Cd battery, with an efficiency of about 65%. The temperature coefficient of the output was $<0.03\%/^{\circ}\text{C}$ and was stable to 2% for input voltage changes of ± 3 volts.

An E.H.T. converter for the photomultipliers supplied 1200 v from a 12 v input, with a temperature coefficient of $<0.02\%/^{\circ}\text{C}$ and a stability of 1% for a supply voltage change of ± 3.5 volts.

The H.T. and E.H.T. converters were supplied from the same battery stack, but were decoupled from each other. The total power consumption was about 1.5 Watts. The batteries used were a stack of 2000 DK Deac Ni-Cd cells, which had the advantage of being rechargeable and having a good temperature coefficient.

The Olland cycle was powered by a separate unstabilised 5 v line provided by a Deac 500 DKZ battery stack.

2.4.5. Gain setting and stability

The voltages of the photomultipliers were set by counting μ -mesons at sea level, the gains being set well on the coincidence plateaus. This insured that the detector was quite insensitive to temperature changes which would change the individual tube gains. The gain in the external circuit was determined by the amplifier and matched discriminator, which together had a temperature coefficient of $0.05\%/^{\circ}\text{C}$. The overall temperature coefficient of the detector was estimated at

<0.1%/°C over the range +25°C to -20°C. The rest of the circuitry basically did not contribute to the temperature coefficient, being mainly digital. All E.H.T. points on the detector were corona-proofed by potting in the silicone rubber compound Silastomer 961. The corona proofing was tested down to <2 mb residual pressure in the laboratory. Electrical pick-up was minimised by decoupling or screening appropriate points in the electronics.

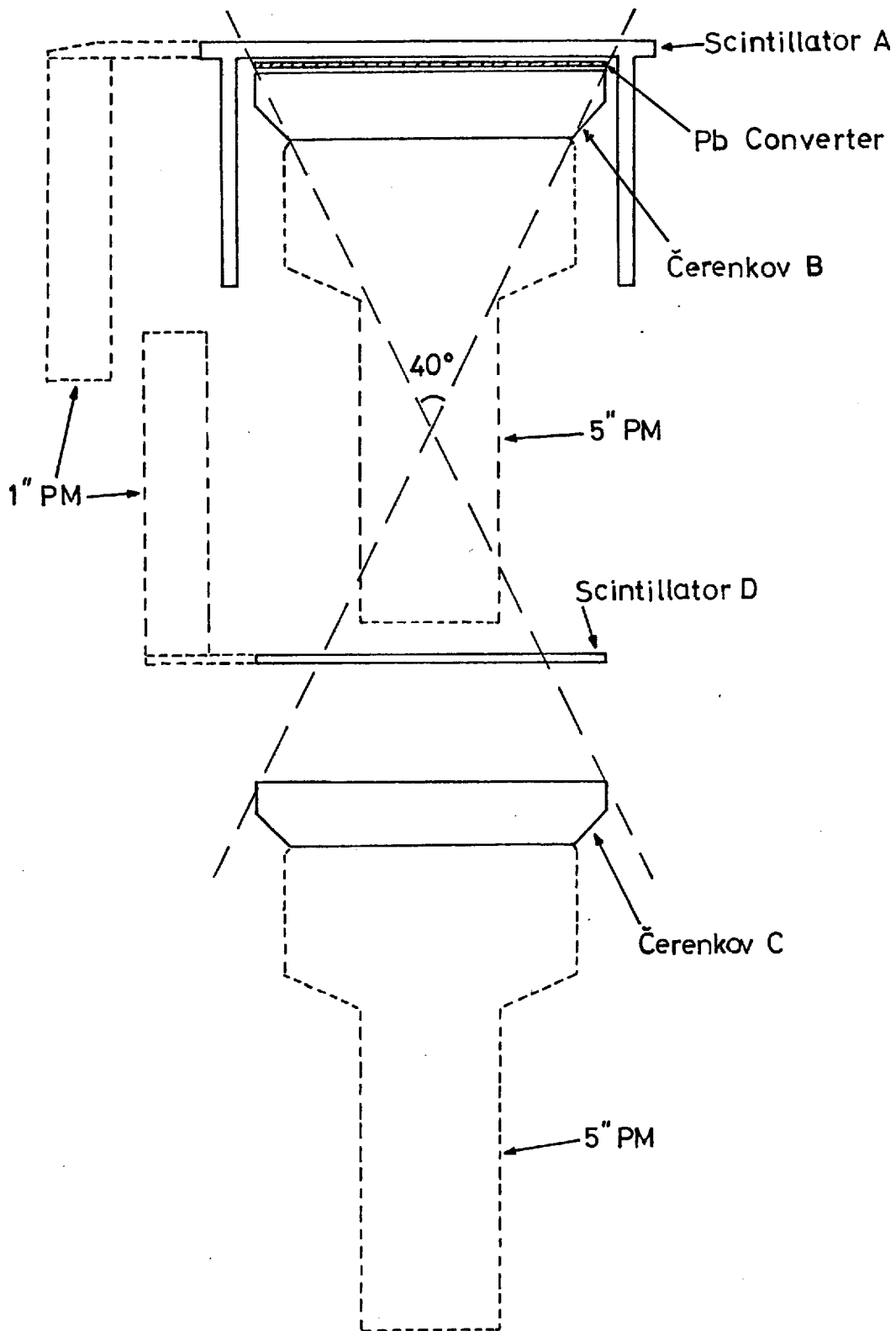


Fig. 2.1 Schematic diagram of the detector used for the present gamma-ray measurements.

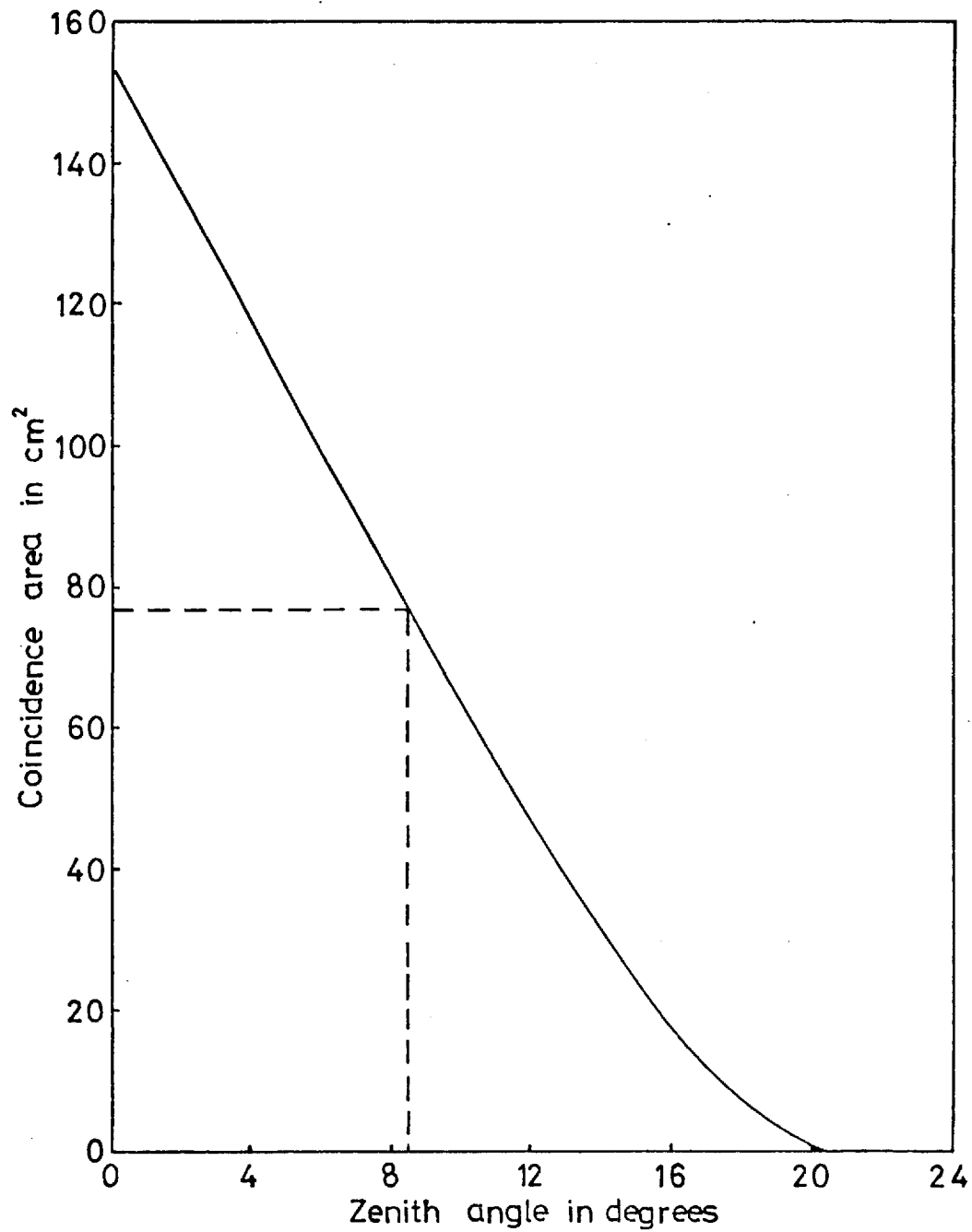


Fig. 2.2 Angular response of the detector to a point source.

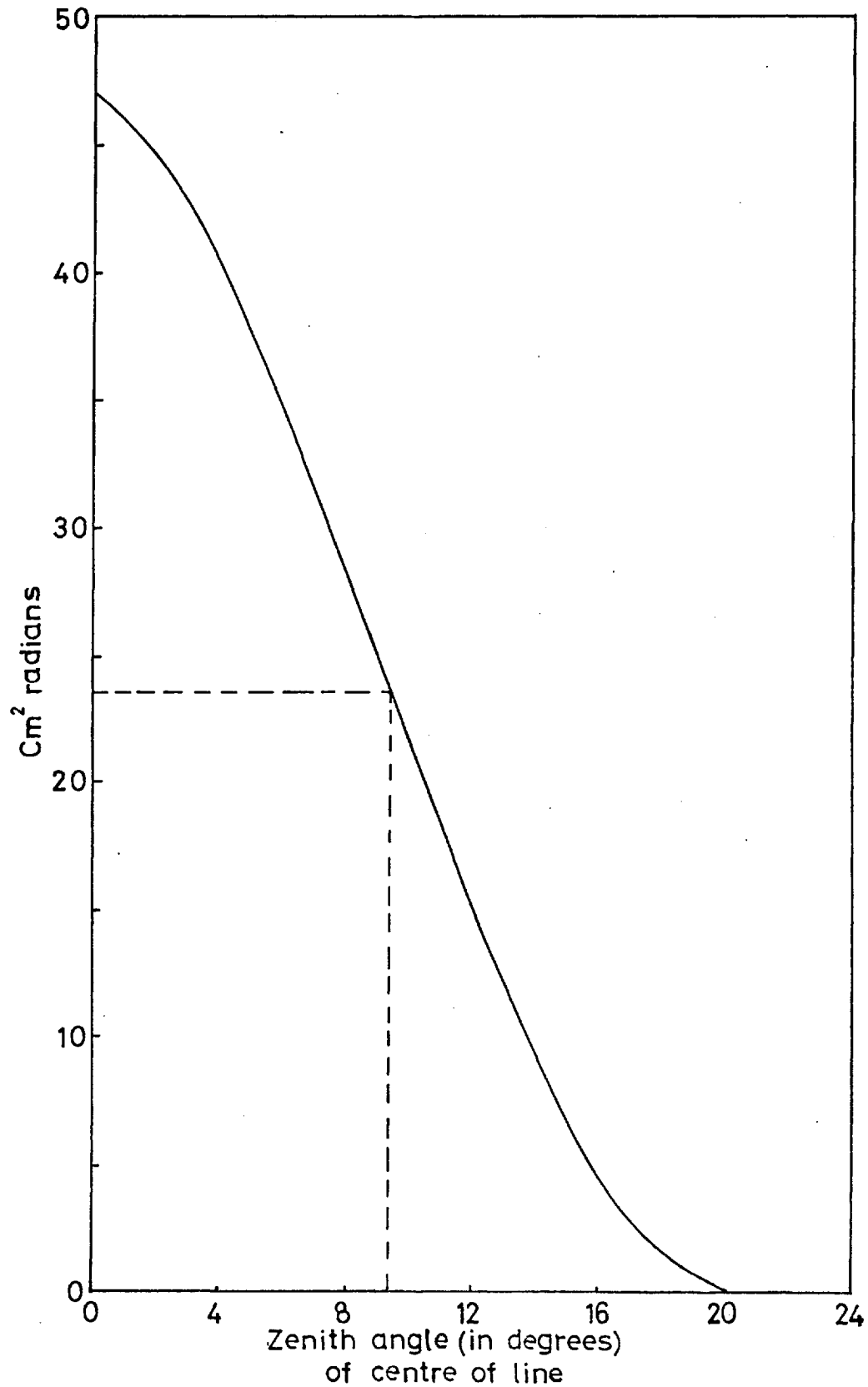


Fig. 2.3 Angular response of the detector to a line source.

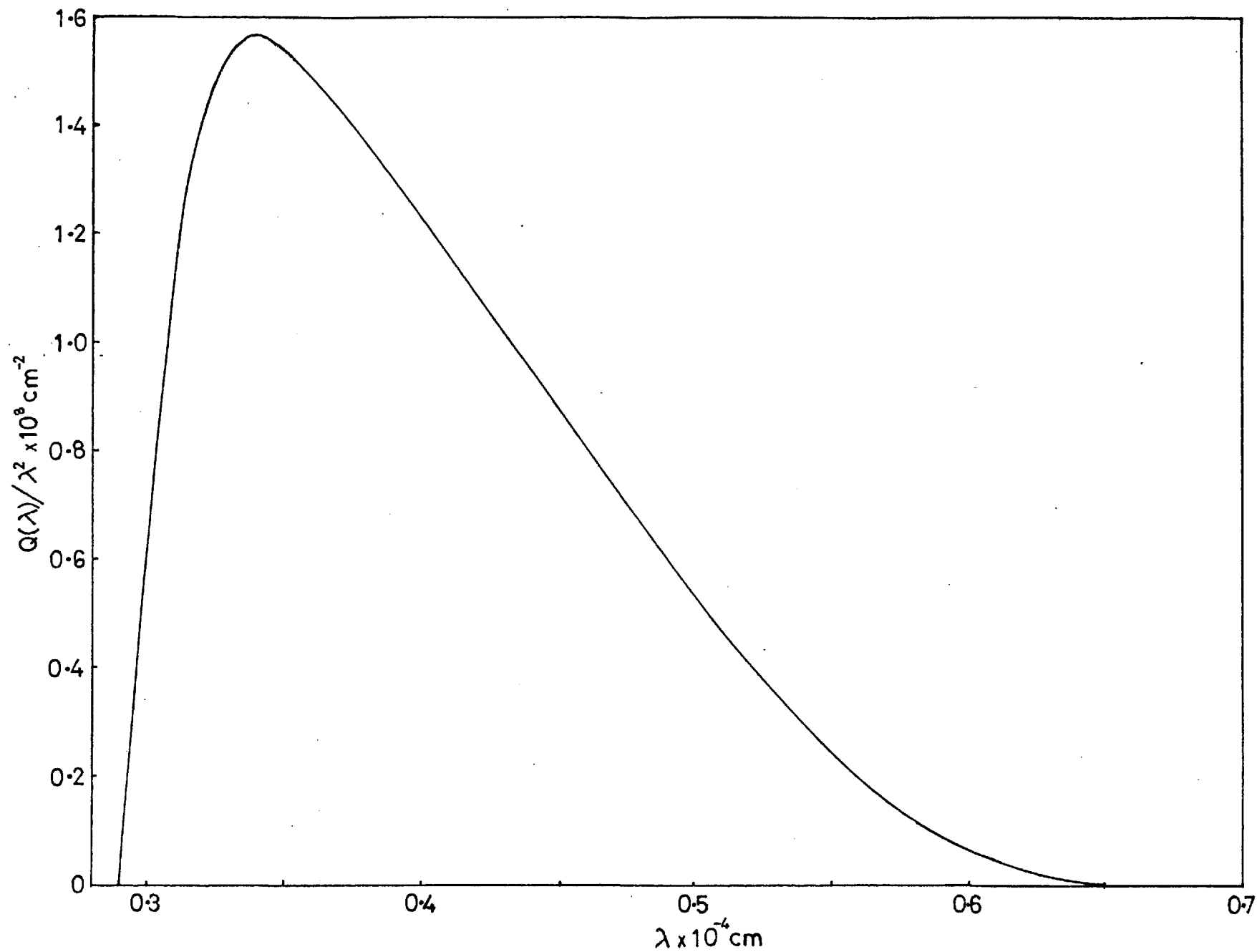


Fig. 2.4 The quantity $Q(\lambda)/\lambda^2$ for a photomultiplier photocathode type S-11.

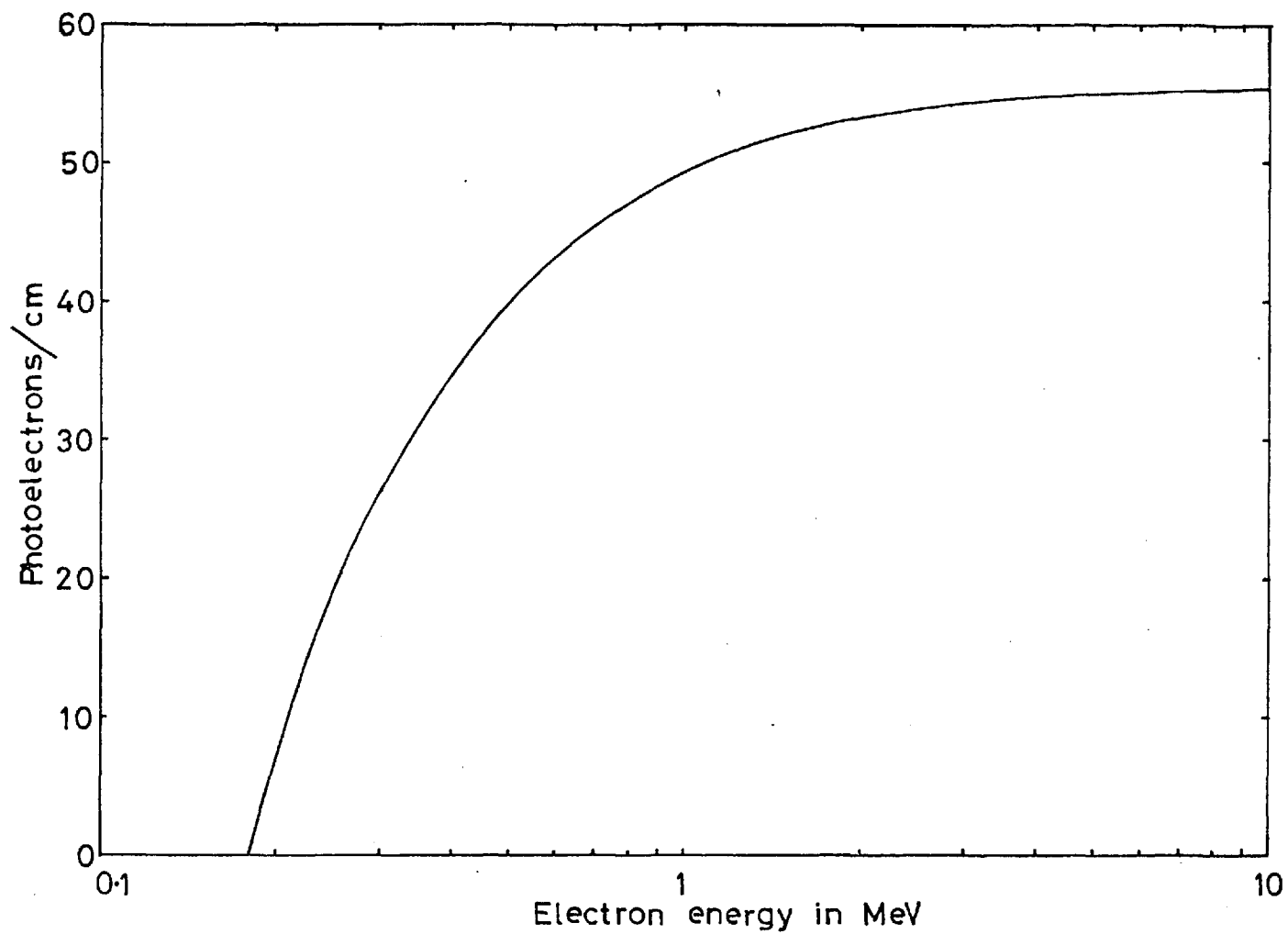


Fig. 2.5 Theoretical photoelectron yield per cm for an electron in one of the perspex elements.

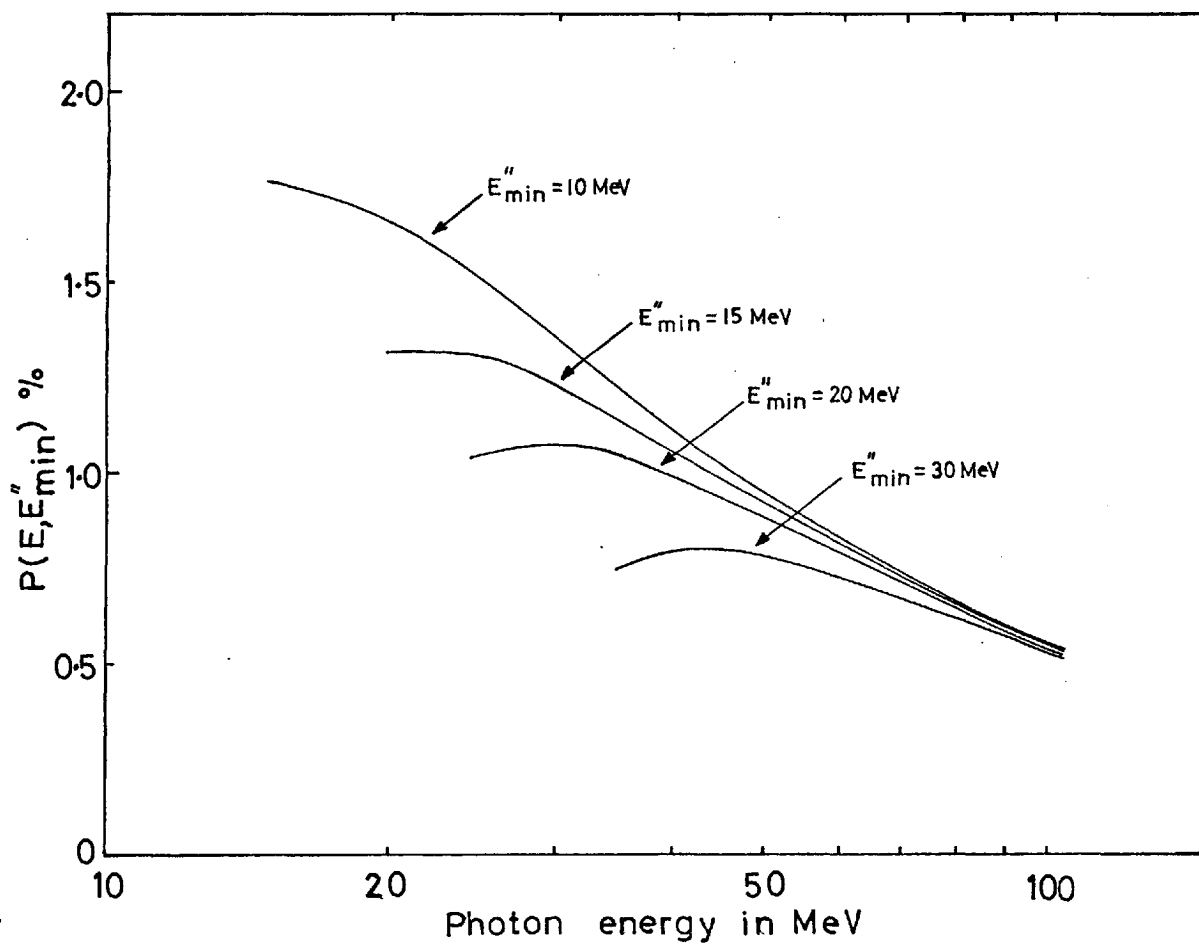


Fig. 2.6 Probability of the production by Compton Scattering of an electron of energy $>E''_{\min}$ in one half radiation length of lead.

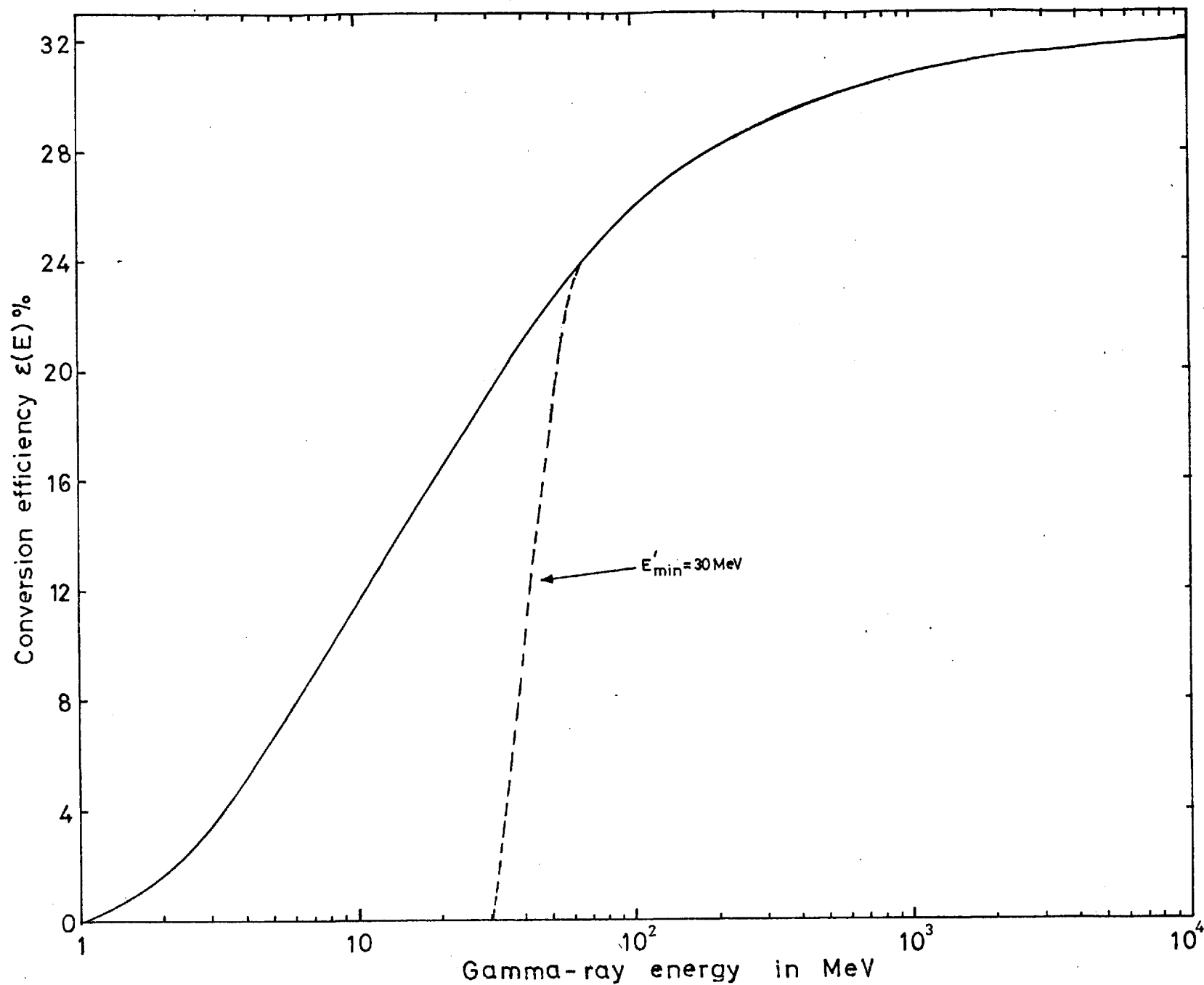


Fig. 2.7 Total probability of interaction by Pair Production in one half radiation length of lead.

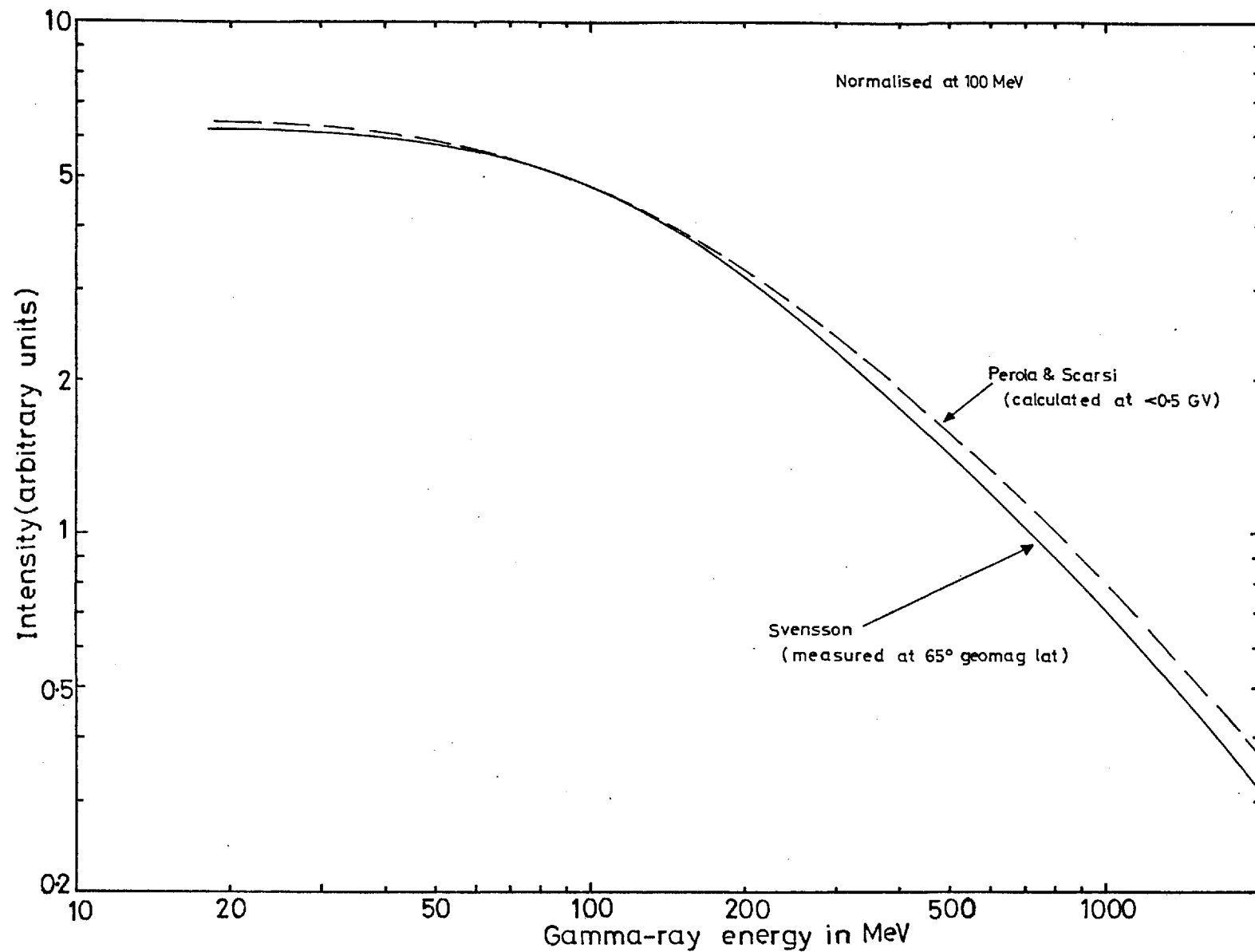


Fig. 2.8 The integral atmospheric gamma-ray spectrum at balloon altitudes as measured by Svensson and calculated by Perola and Scarsi; both for high latitudes.

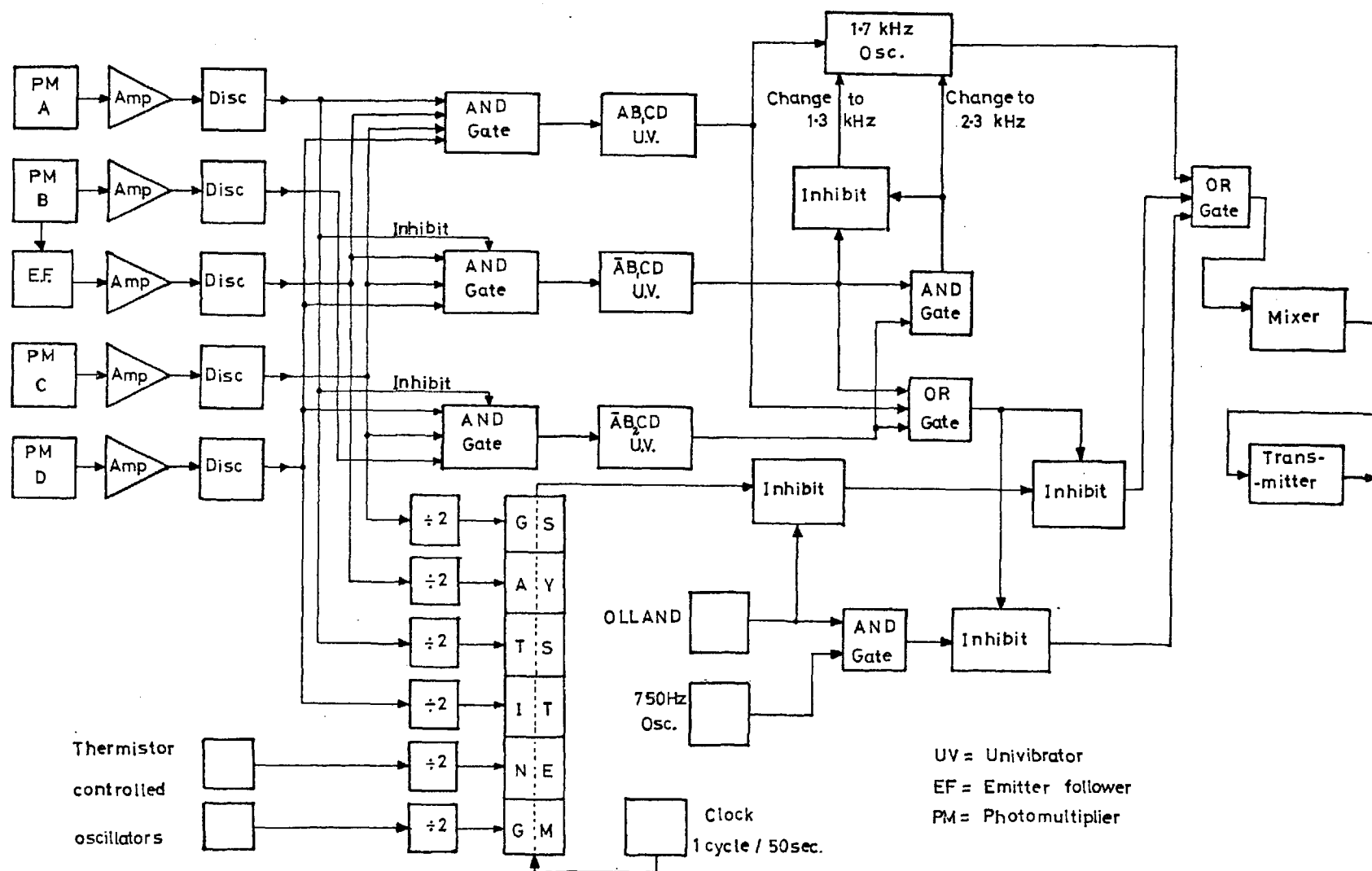


Fig. 2.9 Block diagram of the detector electronics.

III The Balloon Flights

3.1. Location of Launch Site

Lusaka, Zambia (28°E , $15\frac{1}{2}^{\circ}\text{S}$) was chosen as the launch site as being the most convenient place which satisfied requirements. The measurements of Clark et al. (5) showed a gamma flux coincident with the galactic equator. The distribution in longitude showed an extra enhancement in the region of the galactic center. A flight from Lusaka would scan a section of the galactic equator centred at a galactic longitude of 16° , whereas the flights from Kampala were centred at $\sim 30^{\circ}$. Thus any excess gamma-rays due to the galactic component should be more apparent. It was hoped that this expected increase in the galactic plane anisotropy would more than compensate for the increase in the atmospheric secondary gamma-rays, which would result in moving from Kampala, where the vertical cut-off rigidity was 15.0 GV, to Lusaka where it was 11.3 GV (Shea and Smart (64)).

3.2. Flight Equipment

Each detector was enclosed in an insulating box made of $1\frac{1}{2}$ " thick expanded polystyrene, with 60% blackening on the outside, to try and maintain an even temperature well above 0°C inside the box. The box also had a cover of thin polythene to reduce convective cooling during ascent. The total weight of each flight package, including cut-down device, parachute and suspension ropes was 12 kg.

The balloons used were 250,000 cu ft, 0.5 ml Stratofilm balloons
(manu-

factured by Winzen Research Co., U.S.A.) and were selected because of their known superior performance in the very low temperatures ($\sim -80^{\circ}\text{C}$) which are encountered in the tropopause at low latitudes.

3.3. Ground Receiving Station

The block diagram of the station is shown in Fig. 3.1a. The transmitted signals were received by a 2-array, 8 element Yagi aerial with a 30° half beam-width, and then fed into a transistorized low-noise preamplifier, covering the 135 - 138 MHz frequency band. The output of the preamplifier was fed into a VHF receiver (Eddystone 990 R), the audio output of which was recorded on magnetic tape on a Tandberg 64 XX tape recorder. The signal being recorded was monitored on an oscilloscope and could be optimized by rotating the receiving aerial, which was mounted on a motor.

The direction in which the balloon was moving was also followed by another aerial-receiver system in which the two arrays were out of phase. Thus there would be a signal null when this aerial was pointing at the balloon

3.4. Flight Details

The ascent rate of the balloons was about 1000 ft/min, so that altitude was reached in just under two hours. This meant that both launches had to be made at about 6.30 a.m. Zambian time, so that altitude was reached before the galactic disc came into the field of view of the detectors.

Data collection time was unfortunately restricted by the high

velocity winds encountered by the balloon during ascent and at altitude. On both flights, data collection time was reduced to about four hours at altitude, after which time the balloon had drifted over the telemetry horizon.

3.4.1. Flight 1 - January 24th, 1971

Launched at 6.40 a.m. L.T. this flight reached a maximum altitude of 4.8 mb at 8.38 a.m. L.T.. This altitude was maintained for only about 45 minutes and after this the balloon started to descend slowly - and when the signal was lost at about 12.40 L.T. it was at 9.2 mb. The descent was presumably caused by some defect in the balloon. The altitude-time profile is shown in Fig. 3.2. The temperature-time profile for this flight is shown in Fig. 3.3.

3.4.2. Flight 2 - January 1st, 1971

Launched at 6.21 a.m. L.T., this flight reached an altitude of 4.5 mb at 8.12 L.T.. This altitude was maintained until the signal was lost, also at about 12.40 p.m. L.T.. The altitude-time profile is shown in Fig. 3.2 and the temperature-time profile in Fig. 3.3.

The temperature minimum at the end of each flight were caused when the payload went into the shadow of the balloon at local noon. In spite of this the temperature changes during the flights would not be enough to have any significant effects on the detectors.

3.5. Preliminary Data Analysis and Results

The same procedure was followed for both flights.

3.5.1. Data analysis equipment

The data analysis equipment is shown in Fig. 3.1b.

The output of the tape recorder was fed, via amplifiers, simultaneously into three band-pass filters, centre frequencies 1.3, 1.7 and 2.3 KHz ($\pm 7\frac{1}{2}\%$ bandwidth). The filtered output was put through a Schmitt trigger discriminator, which eliminated low level noise, and then into an integrator which produced a pulse corresponding to the envelope of the filtered output. The integrator time constant was such that at least 6 pulses were needed to produce an output square pulse. As at least 12 pulses should be present in a data pulse, this system was effective in discriminating against noise. The outputs from the integrators were squared and fed directly into scalars.

The nature of the Olland cycle output, with pulse length being dependent on speed of rotation of the Olland drum, made an electronic readout impossible. The amplified audio output had to be listened to and the morse signal decoded. Noise due to dirt and scratches on the Olland drum was partly overcome by putting a long time constant on the Olland contact on the balloon payload.

The low frequency single rates and thermistor controlled oscillators were separated from the other information by passing the amplified signal through a low pass filter, which strongly attenuated frequencies higher than 300 Hz. The filtered output was displayed on a digital frequency meter.

3.5.2. Charged particle data

The charged particle count rate was averaged over 5 minute intervals, during the ascent phase in both flights. The count rate - altitude profile for flight 1 is shown in Fig. 3.4. It exhibits the expected broad maximum at the Pfotzer maximum around 170 mb.

The rate was linearly extrapolated to zero atmospheric depth, over the range 0 - 30 mb; using a weighted least-square fit to the data.

Using the isotropic geometrical factor of $15.2 \text{ cm}^2 \text{ sr}$, the average value, obtained from the two flights, for the charged particle flux incident on the top of the atmosphere was $266 \pm 12 \text{ particles/m}^2 \text{ sr sec}$. It should be possible to compare this result directly with that of Sood (47), who flew an essentially identical detector from Kampala (vertical cut-off rigidity 15.0 GV). His value, for the flux incident on the top of the atmosphere, was $200 \pm 10 \text{ particles/m}^2 \text{ sr sec}$ of which $\sim 40 \text{ particles/m}^2 \text{ sec sr}$ was estimated to be due to reentrant albedo (electrons $> 20 \text{ MeV}$ and protons $> 500 \text{ MeV}$). According to Webber (65) splash albedo within 30° of the equator is not confined to narrow trapping regions with conjugate points in the two hemispheres, as is the case for high latitudes, but can be returned to the atmosphere anywhere within these equatorial latitudes. If this is the case, then the albedo flux at Kampala and Lusaka should be approximately the same. Thus the integral primary charged particle flux at Lusaka (11.3 GV) is estimated at

$$226 \pm 10 \text{ particles/m}^2 \text{ sr sec}$$

If the integral primary rigidity spectrum at >10 GV can be represented by

$$I(>R) = KR^{-1.5}$$

then taking the primary flux at Kampala as 160 ± 8 particles/m² sr sec, the primary flux at Lusaka should be

$$\begin{aligned} & (160 \pm 8) \times (15.0/11.3)^{1.5} \\ & = 245 \pm 12 \text{ particles/m}^2 \text{ sr sec.} \end{aligned}$$

The average Mt. Washington neutron monitor hourly rate at the time of the Kampala flight was 2309, whereas the average for the Lusaka flights was 2213. For a decrease of this magnitude at this epoch of the last solar cycle, Webber (66) estimated a decrease of ~9% in the integral primary flux at 11.3 GV. When this is taken into account the two results are in excellent agreement.

The counting rate of the altitude phase of each flight was averaged over 10 minute intervals and corrected to a depth of 4.5 mb using the linear part of the depth curve.

The corrected altitude count rate for flights 1 and 2 are shown plotted against local time in Fig. 3.5. There are no statistically significant fluctuations in either flight.

3.5.3. Gamma-ray data

Once again the count rate was averaged over 5 minute intervals

during the ascent phase. The count rate - altitude profile for flight 1 is shown, also in Fig. 3.4, and exhibits a similar depth dependence on the charged particle data.

The altitude count rates were corrected to a pressure of 4.5 mb using the linear part (0 - 30 mb) of the depth curve. The count rates, averaged over 30 minute intervals are shown plotted against local time for flights 1 and 2 in Fig. 3.6.

There are two integral gamma-ray channels. In the one, identified by $\bar{AB}_1CD$, are all the events which satisfied the $\bar{AB}_1CD$ coincidence. In the other, identified by $\bar{AB}_2CD$, are those events in which the pulse height in the Cerenkov element B was sufficient to trigger both the $\bar{AB}_1CD$ and $\bar{AB}_2CD$ coincidence.

As is shown in the figures, there were not statistically significant fluctuations in either flight.

The local time average count rates for the two flights together are shown in Fig. 3.7. The mean rates for the two channels were 2.15 ± 0.07 cts/min and 1.03 ± 0.05 cts/min respectively. These values may be compared to these of Sood (47) obtained at Kampala, using the calculations on atmospheric gamma-rays of Perola and Scarsi (59). From Perola and Scarsi the ratio

$$\frac{I_{\gamma}(>30 \text{ MeV}) \text{ at } 11.3 \text{ GV}}{I_{\gamma}(>30 \text{ MeV}) \text{ at } 15.0 \text{ GV}} = 1.45$$

At Kampala, the average count rate at 4.5 mb for regions with no contribution from the galactic disc, when corrected to the geometrical factor

of the detector at Lusaka, was 1.47 cts/min. The predicted average count rate at Lusaka is then

$$1.47 \times 1.45 = 2.13 \text{ cts/min at } E_{\gamma} > 30 \text{ MeV}$$

This is in excellent agreement with the measured value and indicates that the detectors were functioning satisfactorily.

The statistics of the extrapolation to the top of the atmosphere were insufficient to draw any positive conclusions about the existence of a primary diffuse gamma-ray flux. The extrapolated intensities were

$$(0.9 \pm 2.1) \times 10^{-3} \text{ photons/cm}^2 \text{ sr sec for } E_{\gamma} > 30 \text{ MeV}$$

and $(-0.4 \pm 1.3) \times 10^{-3} \text{ photons/cm}^2 \text{ sr sec for } E_{\gamma} > 50 \text{ MeV}$

These are obviously consistent with zero, and not inconsistent with the latest upper limit of

$$3 \times 10^{-5} \text{ photons/cm}^2 \text{ sr sec for } E_{\gamma} > 100 \text{ MeV}$$

obtained from the OSO-3 measurements of Clark et al..

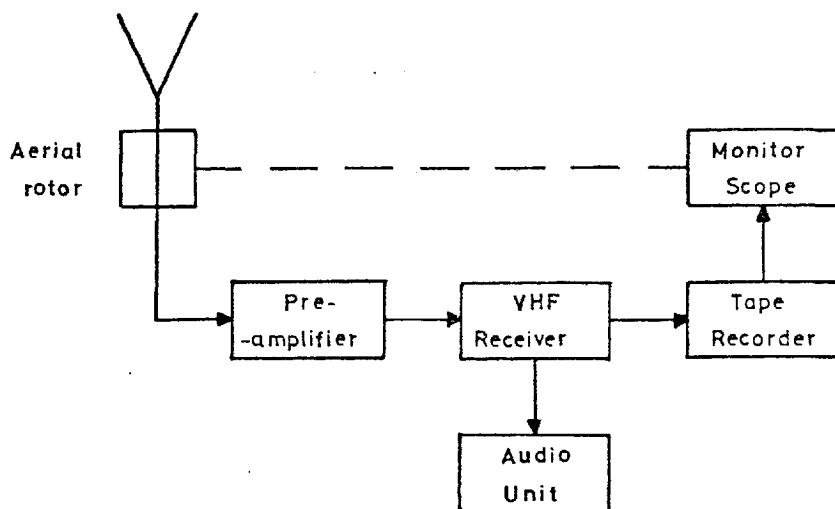


Fig. 3.1a Block diagram of ground receiving station.

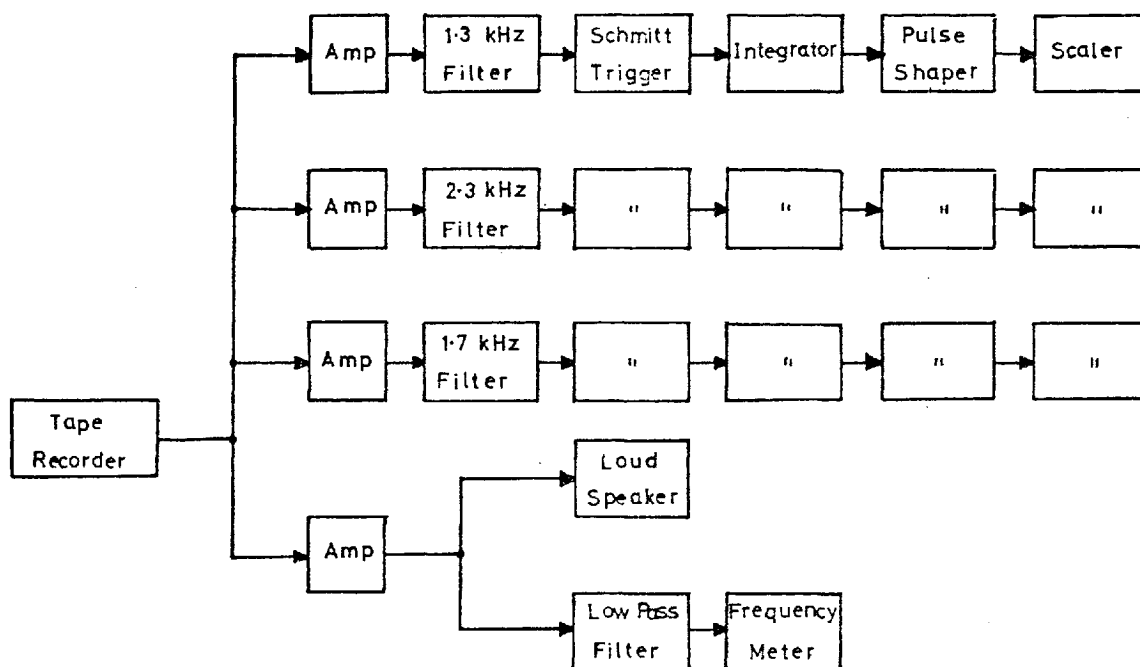


Fig. 3.1b Block diagram of data analysis equipment.

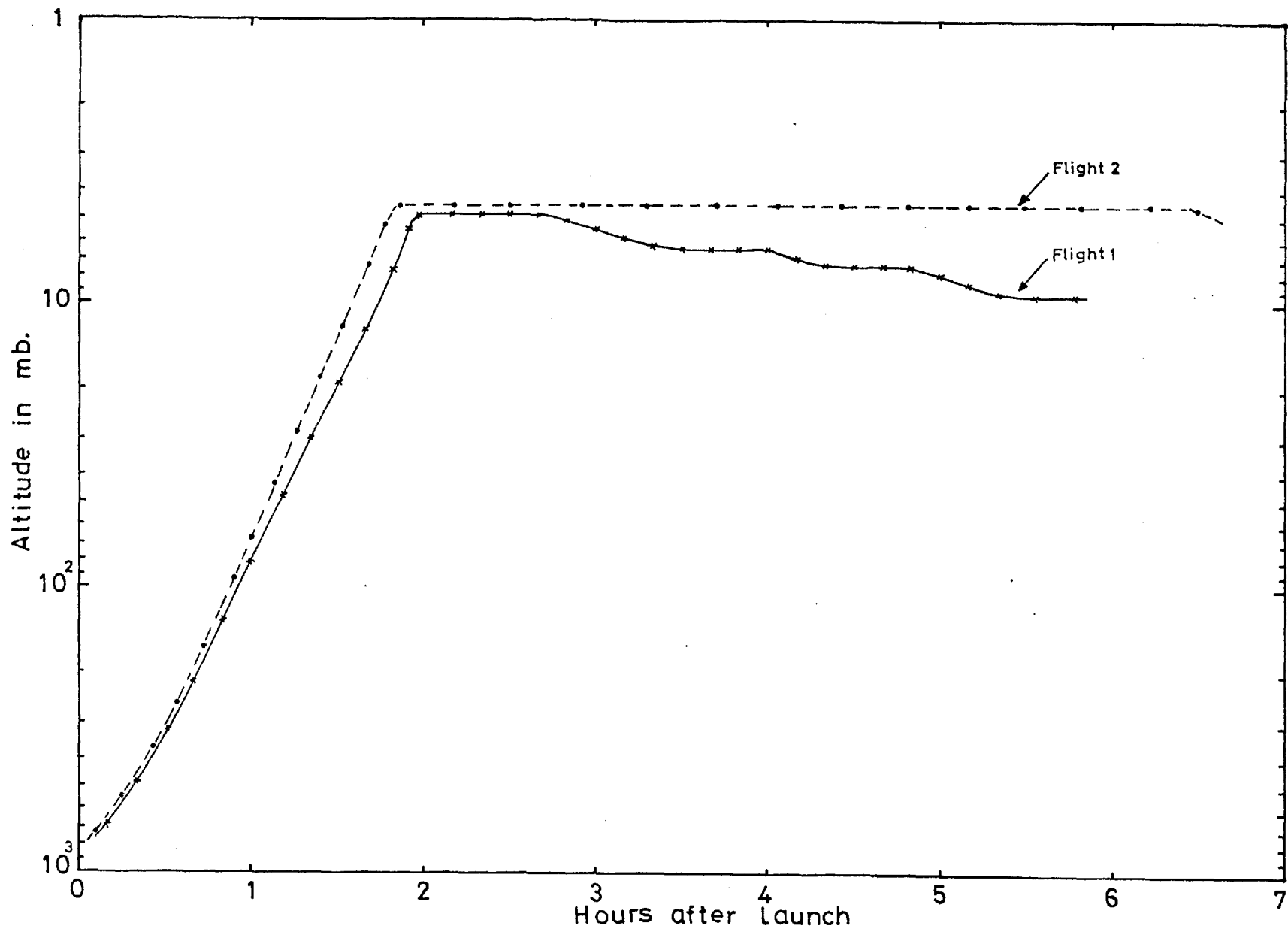


Fig. 3.2 Altitude-time profiles for the two balloon flights.

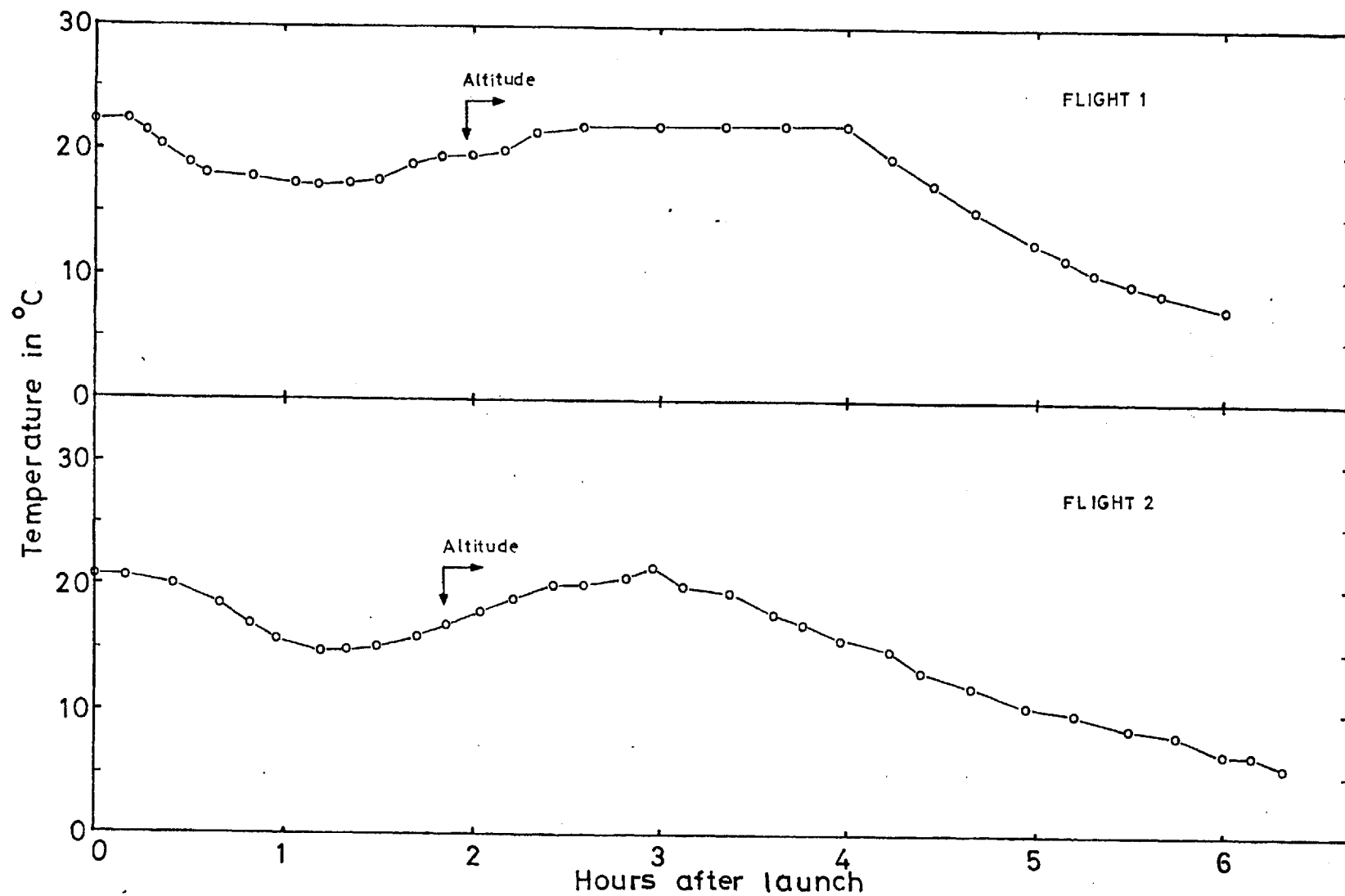


Fig. 3.3 Temperature-time profiles for the two balloon flights.

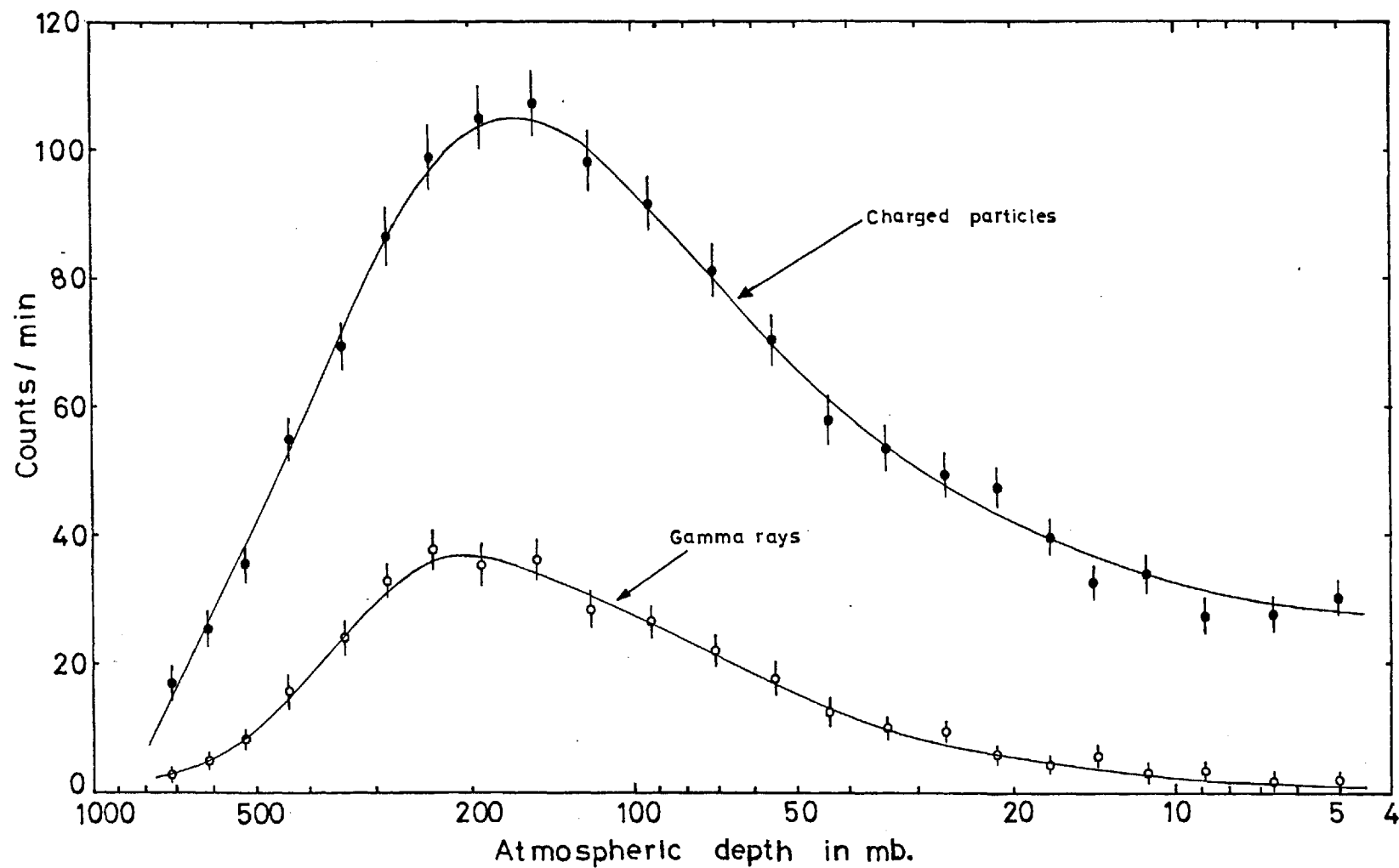


Fig. 3.4 Altitude profiles of the relativistic charged particle and gamma-ray count rates for Flight 1.

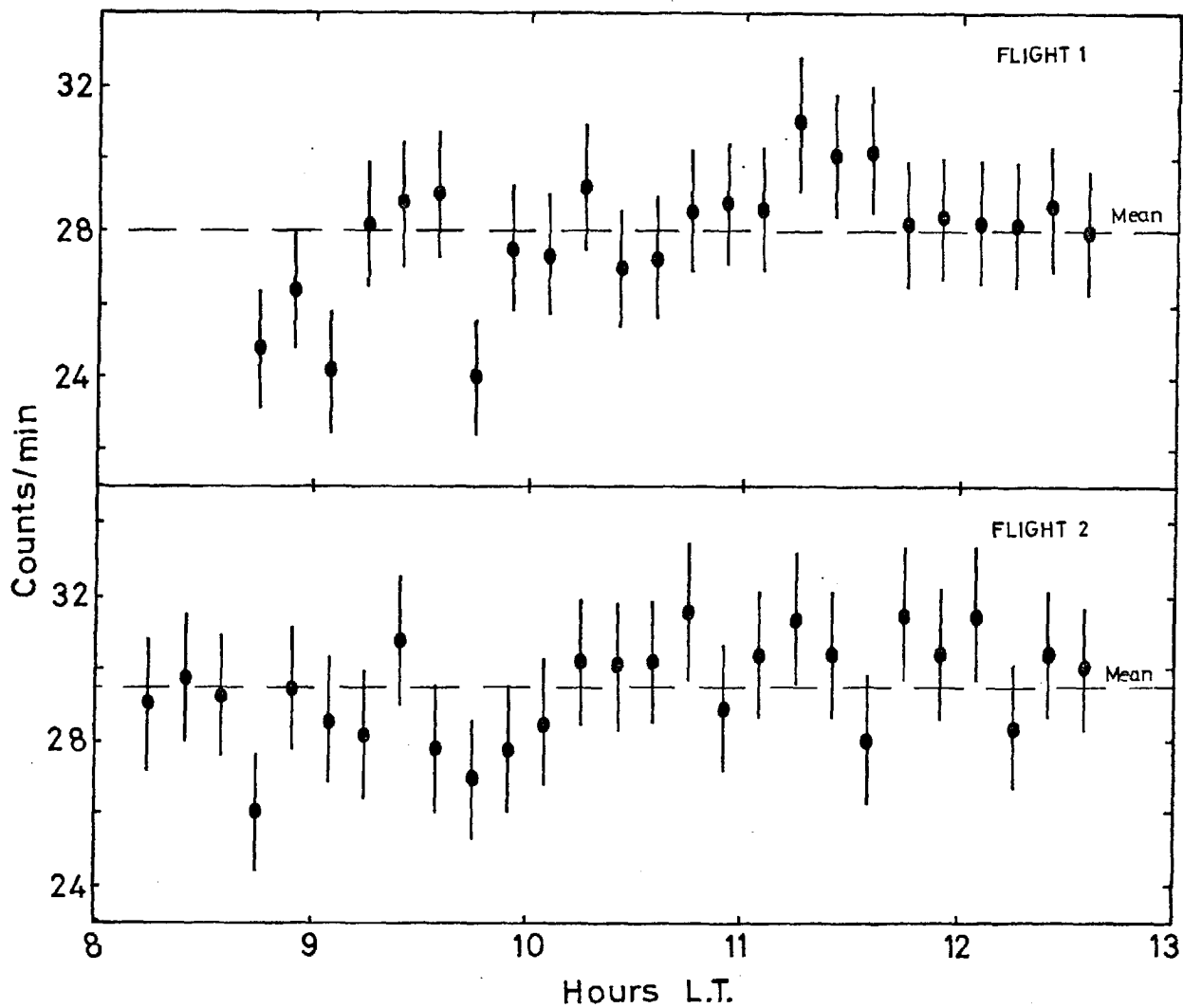


Fig. 3.5 Count rates at altitude of the charged particle channel; averaged over 10 minute intervals and corrected to 4.5 mb atmospheric pressure.

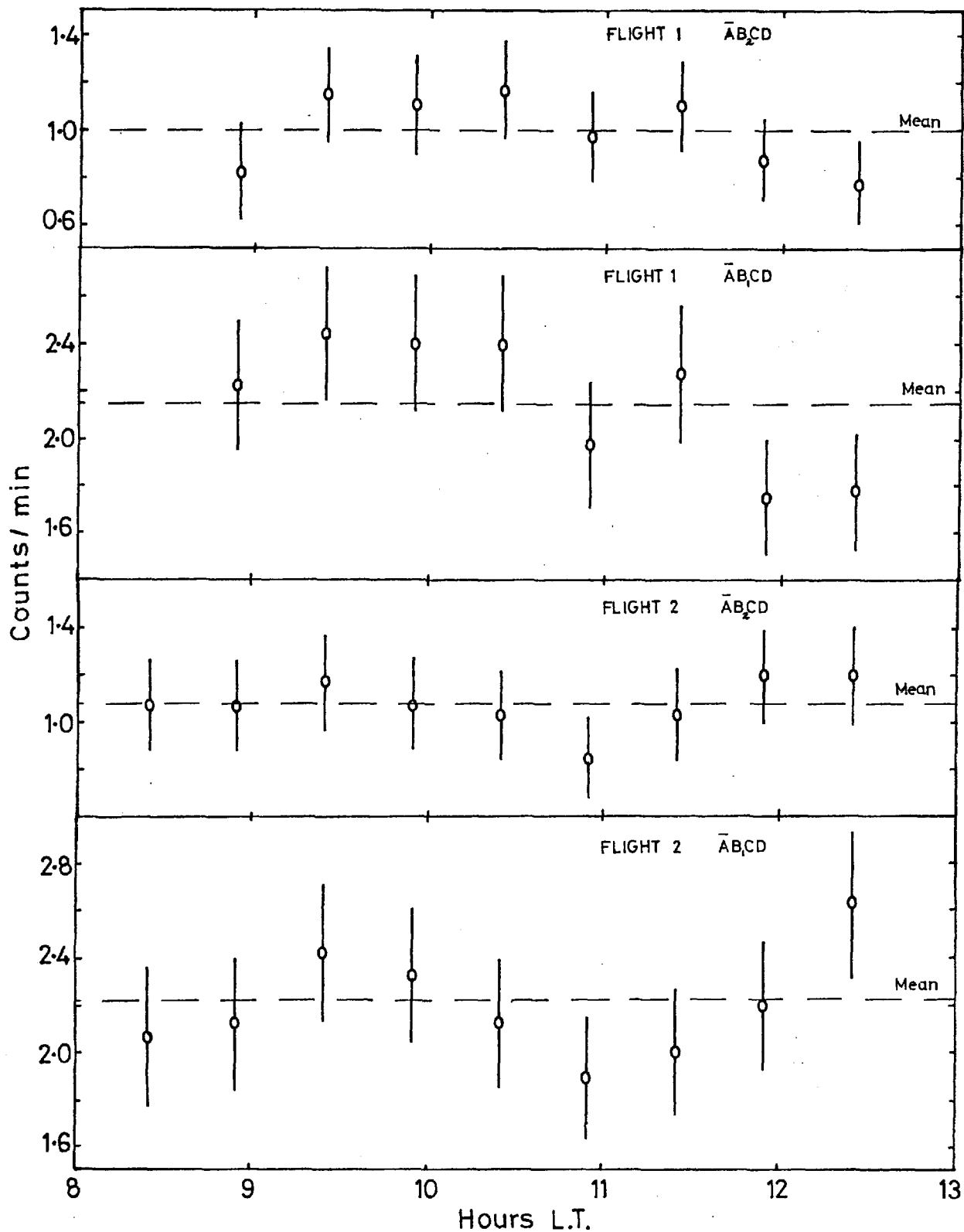


Fig. 3.6 Count rates at altitude of the two integral gamma-ray channels; averaged over 30 minute intervals in local time and corrected to 4.5 mb atmospheric pressure.

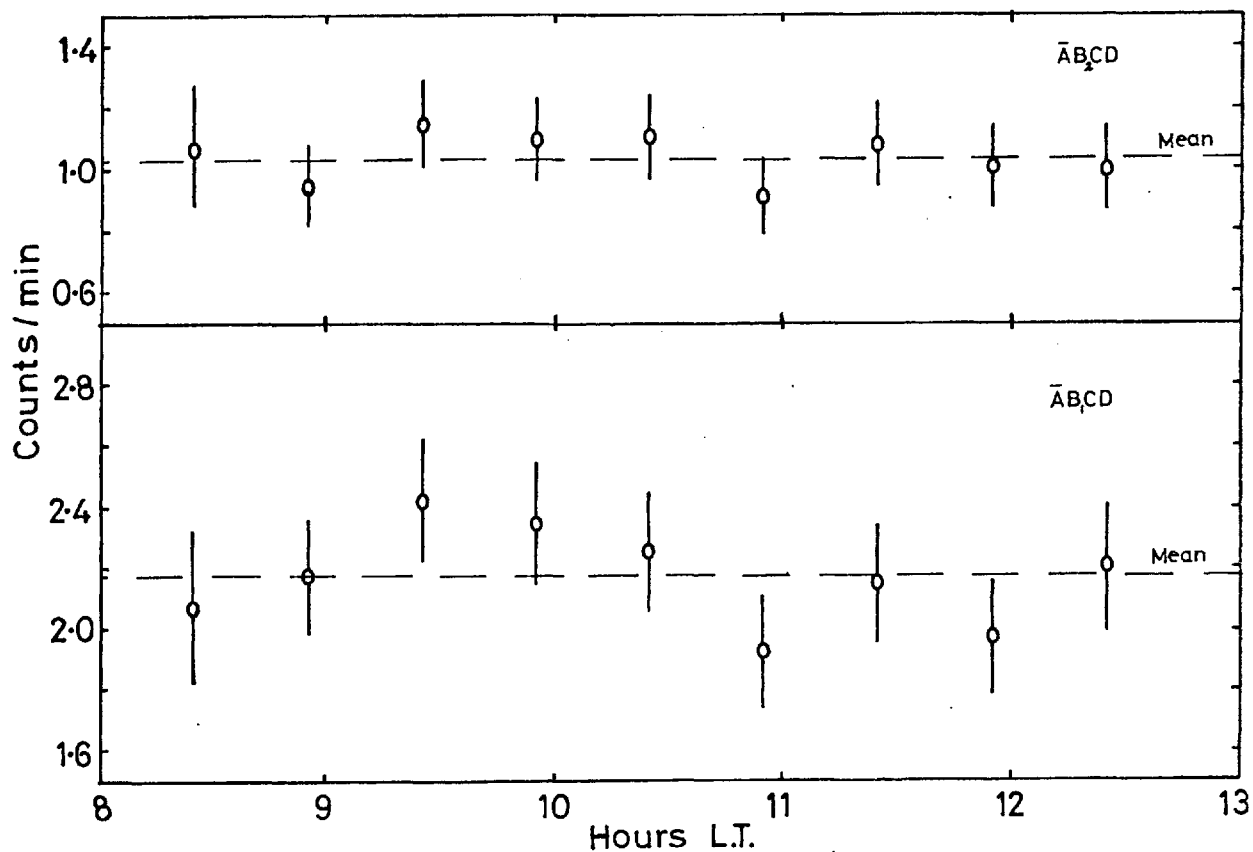


Fig. 3.7 Count rates at altitude of the two integral gamma-ray channels; averaged over 30 minute intervals and summed in local time over the two flights.

IV The Galactic Gamma-ray Source

4.1. Analysis of the Data for Possible Galactic Gamma-rays

If there was any enhancement in the gamma-ray count rate due to emission from the plane of the galactic disc, it should have been more apparent if the results from the two flights were summed and averaged in sidereal time instead of local time. The position of the galactic plane is of course constant in sidereal time. The translation into sidereal time was made, taking into account the drift in position of the balloon. The resulting sidereal time average count rates are shown in Fig. 4.1. There was ~~no~~ statistically significant increase from the direction of the galactic plane.

The region of the sky scanned during the flights is shown in Fig. 4.2. The section of the galactic plane viewed was centred at a galactic longitude $l^{II} \approx 16^\circ$. The sidereal time averages are also shown plotted in galactic coordinates in Fig. 4.1.

An upper limit, at the 95% confidence level, to the average gamma-ray integral line intensity of this region of the galactic disc was calculated from

$$I(>E) = \frac{1.96 (\bar{n} \sum_i T_i)^{\frac{1}{2}}}{P_{\epsilon_{\text{eff}}}(>E) \sum_i \int F_i(t) dt}$$

Here, $\bar{n}$ is the average count rate over i flights, which was found to be 2.15 cts/min and 1.03 cts/min for the two integral gamma-ray channels over the two flights.

T_i is the total time of observation of the galactic disc during the i th flight; which was calculated to be 204 minutes for each flight.

$\epsilon_{\text{eff}}(>E)$ is the effective integral efficiency, estimated in section 2.3.3. as 30%.

$F_i(t)$ is the cm^2 rad factor subtended by the detector to the galactic disc at time t . $\int F_i(t) dt$, in cm^2 rad sec, was obtained by graphical integration of the curves in Fig. 4.3 and was found to be $2.66 \times 10^5 \text{ cm}^2 \text{ rad sec}$ for each flight.

P is the transmission factor for primary gamma-rays through the air and other absorbing material above the converter in the detector. For these detectors, at 4.5 mb, P was calculated to be approximately constant at energies above 10 MeV and equal to 0.93.

The upper limits from the two flights were hence calculated to be

$$3.9 \times 10^{-4} \text{ photons/cm}^2 \text{ rad sec for } E > 30 \text{ MeV}$$

and $2.7 \times 10^{-4} \text{ photons/cm}^2 \text{ rad sec for } E > 50 \text{ MeV}$

4.2. Comparison with the Measurements at Kampala

The present work and the measurements at Kampala by Sood (48) employed essentially identical detectors; except that at Kampala their geometrical factor was $22 \text{ cm}^2 \text{ sr}$ and their geometrical half-angle was $\sim 25^\circ$. The two investigations also surveyed a common sector of the galactic plane, at $6^\circ \lesssim l^{\text{II}} \lesssim 36^\circ$, which was a major fraction of the total region scanned by each. With these common factors, the results may be validly compared and combined.

The results of Sood and of the present work are shown in Fig. 4.4a as a function of galactic latitude. The Lusaka results have been normalised to the results from Kampala; firstly by correcting for the change in geometrical factor and secondly by correcting for the decrease in the atmospheric background gamma-rays (due to the increase in cut-off rigidity) by using the reciprocal of the Perola and Scarsi ratio used in section 3.5.3.. The resulting total normalisation factor was in fact 1.0. Both sets of measurements are corrected to 4.5 mb. Only the data from the >30 MeV channel were available from Kampala. Weighted means were taken for appropriate points of the two data sets and the combined results are plotted in Fig. 4.4b.

For the Kampala data and the combined data the same analysis procedure was used. Firstly the weighted mean of all the measurements of each set were taken. A χ^2 -test was then performed to see if the data points were consistent with a normal distribution about this mean. For the Kampala data alone χ^2 was found to be 34.7, whereas $\chi^2_{.95}(\nu=13) = 22.4$. For the combined data χ^2 was found to be ~~12.8~~^{39.7}, whereas $\chi^2_{.95}(\nu=14) = 23.7$. Thus in both cases the hypothesis that the results could be normal distribution can be clearly rejected.

The weighted mean of the data points at $|b^{II}| > 21^\circ$ was taken as a measure of the true atmospheric background component (no disc contribution) at this latitude. A χ^2 -test was then performed to see if these data points were consistent with a normal distribution about their mean. For the Kampala data alone χ^2 was found to be 12.8, whereas $\chi^2_{.95}(\nu=7) = 14.1$. For the combined data χ^2 was found to be 13.5, whereas

$\chi^2_{.95}(\nu=8) = 15.5$. Thus a normal distribution is a good fit to these points. On the assumption that the measurements at $|b^{II}| < 21^\circ$ were the result of a uniform line source along the galactic plane superimposed on this normal atmospheric background, a best-fit line intensity to these points was obtained by the method of least squares. For the Kampala data alone the best-fit line intensity was calculated to be

$$(4.4 \pm 1.4) \times 10^{-4} \text{ photons/cm}^2 \text{ rad sec at } >30 \text{ MeV.}$$

For the combined data the best-fit was

$$(3.5 \pm 1.2) \times 10^{-4} \text{ photons/cm}^2 \text{ rad sec at } >30 \text{ MeV.}$$

Whilst the two results are not in disagreement, the significance of the second result is obviously lower than the first. A χ^2 -test for the goodness of fit of these line intensities to the data points also mirrored this. For the Kampala data χ^2 was calculated to be 6.20, and for the combined data, 9.21. For $\nu=4$, $\chi^2_{.95}$ is 9.49. One possible explanation for this discrepancy may be that the assumption of a uniform line source in the field of view is not entirely accurate. OSO-3 reported an extra enhancement from a broad region around the galactic centre. This region came into the field of view of the present detectors before the galactic plane came directly overhead. This may explain why the maximum of the distributions in Figs. 4.4a and 4.4b are apparently shifted off the galactic plane. As the survey by the Lusaka flights was centred nearer this galactic central region it is perhaps not surprising that the assumption of a uniform line source is not such a good

fit to the data for the combined results.

4.3. Other Galactic Gamma-ray Measurements

The first evidence for the existence of a primary gamma-ray flux from the galactic disc came from the experiment of Clark et al. (45) on board the OSO-3 satellite. As the angular resolution of their detector was about $\pm 15^\circ$, the angular distribution in galactic latitude of gamma-rays of energy > 100 MeV was consistent with a line source along the galactic plane, with strongest emission from the galactic centre region. The distribution in galactic longitude, however, was broader than the distribution expected from a point source at the galactic centre. The average line intensity in regions more than 60° from the galactic centre was about one quarter of the line intensity near the centre. The gamma-ray distribution in galactic latitude and longitude as measured by OSO-3 are shown in Fig. 4.5. Because of the apparent extra enhancement of the gamma-ray intensity in the central region it is convenient to discuss the experimental results for the central region separately from longitudes excluding this region.

4.3.1. The galactic centre region

For a galactic interval $|b^{II}| < 15^\circ$ and longitude region $|l^{II}| < 30^\circ$, the average line intensity for $E_\gamma > 100$ MeV, from the OSO-3 was originally given as $(4.1 \pm 0.7) \times 10^{-4}$ photons/cm² rad sec. Discrepancies between the gamma-ray albedo intensity measured by OSO-3 and that measured by various balloon borne experiments, led to a recalibration of the OSO-3 detector and a subsequent downward revision of their

quoted intensities. The revised intensity for the same region as above was $(1.2^{+0.4}_{-0.5}) \times 10^{-4}$ photons/cm² rad sec (Clark et al. (67)).

The strongest evidence in support of these measurements has come from the GSFC balloon-borne spark chamber of Kniffen and Fichtel (68). In the latitude interval $|b^{II}| < 6^\circ$, and the longitude region $-39^\circ < l^{II} < 24^\circ$ they obtained an average line intensity for $E_\gamma > 100$ MeV of $(2.0 \pm 0.7) \times 10^{-4}$ photons/cm² rad sec. The longitude regions scanned by the two experiments were sufficiently close for the results to invite direct comparison and there is agreement, within the experimental errors. The statistical evidence in the GSFC data for the detection of a positive intensity was stronger than it appears from their result. The observed number of gamma-rays lay 4.3σ above the number expected from the atmospheric background alone. The GSFC result was in itself consistent with their earlier results using a similar but smaller detector (Fichtel et al. (33)). For the longitude region $-10^\circ < l^{II} < 25^\circ$ they obtained some evidence for a galactic plane emission, but it had less statistical significance than their subsequent results. For the interval $|b^{II}| < 3^\circ$ their intensity was $(2.2 \pm 1.1) \times 10^{-4}$ photons/cm² rad sec and for $|b^{II}| < 15^\circ$ it was $(2.4 \pm 2.4) \times 10^{-4}$ photons/cm² rad sec, both for $E_\gamma > 100$ MeV.

Comparison of the above positive results with the measurements of Sood (48) at the lower energy threshold depends upon the form chosen for the gamma-ray spectrum. If a flat π° -decay type integral spectrum is chosen, then both the Sood and the combined result of the previous section (if it represents a true measurement) appear rather high if the

OSO-3 result is considered as the true intensity at >100 MeV. If the intensity measured by GSFC is nearer the true one, the Sood and combined results are in much better agreement. However, if an integral spectral dependence of $E^{-0.8}$ representative of an Inverse Compton origin, or of $E^{-1.05}$ as favoured by Frye's discrete source hypothesis (see later), then the GSFC measurement predicts a much higher intensity at >30 MeV than that measured by Sood, whereas the OSO-3 measurement produces good agreement. With regard to the spectral shape, both Clark and Fichtel and Kniffen have some evidence to indicate that the galactic gamma-rays have a rather flat integral spectrum which would seem to indicate that a significant fraction of them are produced in π^0 -decay.

All these results, at first sight, seem in serious disagreement with the results of Frye et al. (69) and (70). In the first paper their data obtained from a balloon borne spark chamber revealed no evidence for a galactic gamma-ray line intensity at >50 MeV, in approximately the same region of longitude covered by GSFC and OSO-3. For the latitude interval $|b^{II}| < 2.3^\circ$ their upper limit was 3×10^{-5} photons/cm² rad sec and for $|b^{II}| < 15^\circ$ it was 7×10^{-5} photons/cm² rad sec, well below the intensities predicted from the previous results. No explanation of this large discrepancy was offered at that time. However in his second paper, which contained the results from two other flights with a similar detector, in which a similar portion of the galactic disc was observed, a possible explanation was advanced. The discovery of two point sources of gamma-rays was announced, the flux from each being about $(1.5 \pm 0.5) \times 10^{-5}$ photons/cm² sec for

$E_\gamma > 100$ MeV. The two sources, named $G_\gamma 2+3$ and $G_\gamma 341+1$ by Frye, were both close to the galactic plane and within the longitude region covered by GSFC and OSO-3. They were also found to be coincidental, within the uncertainties, with the hard X-ray sources GX 1+4 and GX 340-2 detected by Lewin et al. (71 and 72). Also, the measured gamma-ray flux of $G_\gamma 2+3$ could be obtained by extrapolating downwards from the measured flux for the source GX 1+4 in the X-ray region (Busselli et al. (73), Haymes et al. (74)), using a spectral index -2.05 which was in good agreement with the value obtained in the X-ray region.

Frye analysed his data for the regions scanned by GSFC and OSO-3 and found that if the effects of the two sources were not removed, that for the GSFC region a line intensity of $(2.4 \pm 1.5) \times 10^{-5}$ photons/cm² rad sec or an upper limit of 5.3×10^{-5} photons/cm² rad sec was obtained. The removal of the discrete sources left an upper limit of 3×10^{-5} photons/cm² rad sec, well below the positive intensity measured by GSFC at approximately the same time, but in good agreement with the value originally predicted by Pollack and Fazio (8) for this region on basis of π^0 -decay alone. The difference could not be explained by a sudden increase in intensity of one or several point sources, because the angular resolution of the GSFC detector was sufficient to resolve several point sources over a line a radian long. Thus no explanation for the discrepancy in results could be found.

For the OSO-3 region, with the limits $|b^{II}| < 15^\circ$, the Frye detector had least sensitivity, and an upper limit of 5.4×10^{-5} photons/cm² rad sec was derived, which is more than a factor of 2 below the revised

OSO-3 measurement. The angular resolution of the OSO-3 detector was poor, so Frye suggested that the OSO-3 measured intensity could have been caused by one or several gamma-ray point sources in the region being at a much higher intensity at the time of the OSO-3 observations, which were finished before Frye's flights took place. Flaring in hard X-rays has been observed, on a shorter time scale, in Cen XR-2, so the explanation is not implausible.

4.3.2. Longitudes excluding the galactic centre region

The results for regions excluding the galactic centre seem roughly confined to two sections, the galactic anticentre direction and the Cygnus region.

The revised OSO-3 measurement for the anticentre ($l^{II} \sim 180^\circ$) direction was given by Clark et al. (67) as $(3^{+1.0}_{-1.2}) \times 10^{-5}$ photons/cm² rad sec for $E_\gamma > 100$ MeV, which also is in quite good agreement with the calculations of Pollack and Fazio (8). An earlier survey by Kniffen et al. (75) of the longitude region $142.5 < l^{II} < 194^\circ$, yielded no evidence of a positive intensity. Their 95% confidence upper limits were

$$\begin{aligned} &2.3 \times 10^{-4} \text{ photons/cm}^2 \text{ rad sec for } |b^{II}| < 3^\circ \\ \text{and} \quad &5.4 \times 10^{-4} \text{ photons/cm}^2 \text{ rad sec for } |b^{II}| < 15^\circ \end{aligned}$$

both for $E_\gamma > 100$ MeV. Clearly these results do not challenge the revised OSO-3 intensity. The data from the balloon borne spark chamber of Niel et al. (76) also produced a negative result for the section $130^\circ < l^{II} < 183^\circ$ with $|b^{II}| < 9^\circ$.

In another paper, Frye and Wang (77) also reported no evidence of

emission from the anticentre direction, $165^\circ < l^{\text{II}} < 195^\circ$ and $|b^{\text{II}}| < 3^\circ$. For the same latitude range they did however produce evidence, significant at the 2σ level, for galactic plane emission in the Cygnus region, $55^\circ < l^{\text{II}} < 85^\circ$. The sonic spark chamber of Hutchinson et al. (78) on board the OSO-5 satellite, covered approximately the same section, $45^\circ < l^{\text{II}} < 75^\circ$ and recorded a gamma-ray intensity at >40 MeV of $(4.9 \pm 2.1) \times 10^{-4}$ photons/cm² rad sec. The results from the Minnesota group, (Valdez and Waddington (35) and Valdez et al. (79)), for a similar section $60^\circ < l^{\text{II}} < 90^\circ$, with $-3^\circ < b^{\text{II}} < 5^\circ$, also showed a positive intensity significant at the 2σ level. For $E_\gamma > 100$ MeV they obtained $(3 \pm 1.5) \times 10^{-4}$ photons/cm² rad sec. Although individually, the statistical weight of these observations is not completely convincing, (particularly the Minnesota result where the analysis procedure is somewhat uncertain), together they do seem to indicate some definite intensity from the galactic plane in this region. With this in mind, it is surprising that the revised OSO-3 measurement for this region, although not directly quoted, can be estimated as only $6 - 7 \times 10^{-5}$ photons/cm² rad sec at >100 MeV. It is difficult to reconcile this apparent difference unless there is experimental error, or a variable discrete source, similar to those proposed by Frye, is postulated for this region and is superimposed upon a quiescent disc intensity of a much lower value. There may already be some possible evidence for a fluctuating source in the Cygnus region. Duthie et al. (27) found a flux of $(1.5 \pm 0.8) \times 10^{-4}$ photons/cm² ~~rad~~ sec, for $E_\gamma > 100$ MeV, from the direction of Cyg XR-1. Later however, Frye and Wang (28) could only estab-

lish an upper limit of 9×10^{-6} photons/cm² ~~rad~~ sec for the same location.

The results from the anticentre direction are all self-consistent and the positive value obtained from the OSO-3 data is not in serious disagreement with the original intensity estimates of Pollack and Fazio (8) for this direction.

The regions of the sky for which the results of the other experimental groups are valid are shown in Fig. 4.2, along with the positions of the gamma-ray and known X-ray sources.

4.4. Measurements in the X-ray Energy Region

The results of the investigation of the galactic plane in the X-ray energy region are of importance in that any mechanism proposed to explain the measured gamma-ray intensity must have certain consequences in the X-ray region.

A scan of the galactic plane in the Vela-Carina-Centaurus region ($220^\circ < l^{\text{II}} < 320^\circ$) by a rocket-borne X-ray detector of the University of Leicester (Cooke et al. (80)) revealed an excess flux in the energy range 1.4 - 18 KeV. The anisotropy measured was $\sim 10\%$, the excess intensity rising from 0.3 photons/cm² rad sec near $l^{\text{II}} \approx 260^\circ$, to 0.5 photons/cm² rad sec in the Centaurus region, near $l^{\text{II}} \approx 300^\circ$. The region contained no resolvable discrete sources. The differential number spectrum of the results was best represented with an energy dependence $\propto E^{-1.1}$.

The sky survey by the X-ray experiment on the OSO-3 satellite

(Schwartz (81)) revealed a finite galactic excess intensity only in the lowest energy channel, 7.7 - 12.5 KeV. The other four channels, which covered an energy range up to 110 KeV produced only upper limits to the galactic intensity. The discrete source removal procedure used by Schwartz meant that the measurements applied only to the galactic longitude regions $130^\circ < l^{II} < 160^\circ$ and $220^\circ < l^{II} < 240^\circ$. The intensity measured in the lowest energy channel was in agreement with the Leicester result.

A balloon borne experiment of Bleeker and Deerenberg (82), investigated the galactic plane in the energy range 20 - 80 KeV. In order to remove possible contributions from discrete sources, the data in the latitude range $|b^{II}| < 10^\circ$ were limited to the longitude region, $130^\circ < l^{II} < 160^\circ$. Their results also indicated no finite galactic intensity and their upper limits were in excellent agreement with those of Schwartz.

These X-ray measurements are shown as the differential photon number spectrum in Fig. 4.6, along with the upper limit points in the 1 - 6 MeV range determined from the ERS-18 satellite measurement (Vette et al. (83 and 84)) and plotted by Schwartz on the assumption that the entire excess of the ERS-18 count rate over the rate predicted by a power law extrapolation of the Ranger-3 0.07 - 1 MeV data (Metzger et al. (85)) on the diffuse X-ray background, resulted from a uniform galactic line source. The present thinking on this 1 - 6 MeV intensity is however that it is most likely of extragalactic origin. This is because the electron-bremsstrahlung model of Rees and Silk (86), which

sought to explain all the galactic gamma-rays greater than 1 MeV, would require an electron intensity and spectral form quite contrary to experimental results, if the 1 - 6 MeV flux were to be incorporated with the other galactic photon measurements. The thickness of the bar on the Leicester results indicates the quoted variation in their measured excess intensity. All the X-ray measurements are for regions of the galactic plane well away from the galactic centre. To try and obtain a complete picture of the galactic line source, gamma-ray results for comparable regions are plotted in the same figure. These are differential intensities derived from the revised average intensity measured by Clark for regions away from the galactic centre. The conversion of the measured integral intensities into differential intensities is dependent upon the form chosen for the photon differential number spectrum. For the OSO-3 measurement two alternative intensities were derived, the higher one assuming an $E^{-1.8}$ energy dependence corresponding to an Inverse Compton origin, and the lower one assuming a π^0 -decay origin. The spectrum shown is the Inverse Compton one derived by Ipavich and Lenck (102), and normalised to the OSO-3 intensity. It is discussed in more detail in section 4.5.3..

4.5. Possible Theoretical Explanation of the Gamma-ray Intensity

4.5.1. π^0 -meson decay

High energy gamma-ray production from the π^0 -mesons produced in the collisions of cosmic ray protons with nuclei of the interstellar gas, has been considered by several authors. The spectrum of the

galactic line source of gamma-rays was shown by Clark et al. (87), to be roughly matched to that of the horizon-albedo gamma-rays from the earth. As that spectrum arises mainly from the decay of mesons produced by cosmic ray interactions with the earth's atmosphere, this is evidence that at least a significant fraction of the galactic gamma-rays have a similar production mechanism. The results of Kniffen and Fitchel also indicated a rather flat integral spectrum consistent with π^0 -decay gammas.

Indeed, on the assumption that the cosmic ray intensity was the same throughout the galaxy and equal to that measured at the earth at sunspot minimum, predictions had already been made which included the galactic disc anisotropy, well before the first flux measurement. The absolute predicted intensity, however, was a factor of up to 10 times less than the original measured intensity of Clark et al.. For this mechanism still to remain viable, the accepted values of some of the physical quantities involved obviously needed drastic revision and the interstellar gas density seemed to be the least well known.

The accepted average value of ~ 0.5 nucleons/cm³ was based on 21 cm line measurements and was inadequate to explain the measured flux. Clark et al. (87) also showed that the observed gamma-rays had a much stronger dependence upon galactic longitude than the averaged columnar density of hydrogen atoms. The hydrogen density contours are nearly flat at all longitudes and do not display the broad maximum in the galactic centre region exhibited by the gamma-ray measurements (Fig. 4.7 from Clark et al. (87)).

In the earlier calculations of gamma-ray intensities, the H_2/H ratio had usually been taken at 0.1, though Gould and Saltpeter (88) and Gould, Gold and Saltpeter (89) studied the formation and dissociation of interstellar molecular hydrogen and concluded that the ratio H_2/H could vary from 0.1 to 10. Thus in order to explain the original OSO-3 measurements, Stecker (90) proposed that a true gas density of 5 nucleons/cm³ would not only produce the required gamma-ray flux but would be more consistent with other astronomical evidence. The majority of the interstellar hydrogen would be molecular, in which form it would be undetectable by 21 cm measurements. Stecker did, however, observe that the value of 5 nucleons/cm³ was close to the upper limit allowed by gas dynamics and also, such a large value would have significant repercussions on the primary electrons and heavy nuclei in cosmic rays. Ramaty and Lingenfelter (91) showed the observed electron spectrum, with its $(e^+/e^+ + e^-)$ ratio of 0.2, could be explained in a two component model. All the positrons and some of the electrons would be produced in cosmic ray nucleon interactions in 3 - 6 gm/cm² of interstellar matter, and the remaining large majority of the electrons would be directly accelerated. A large increase in the interstellar gas density would result in a very much reduced trapping time for the cosmic rays, or a severe loss mechanism for the electrons in order to maintain compatibility with the electron measurement.

Similarly the light and medium nuclei observed at the earth are thought to be the result of the spallation of heavier nuclei in 3 gm/cm² of interstellar matter (von Rosenvinge and Webber (92)). Thus postu-

lating this large increase in gas density would bring about a large decrease in the lifetime of these heavy nuclei. This would impose a further demand upon the supply mechanism for these heavy cosmic rays, which are believed to be produced in galactic supernovae.

The subsequent downward revision of the intensity measured by Clark et al., obviated the need for quite such a large increase in gas density. Even allowing for an increased gas density the extra gamma-ray enhancement from the galactic centre region was more than predicted by the theory of Pollack and Fazio (8). Thus Stecher and Stecker (93) discussed the galactic line source as a two component model with an increased gas density in the disc producing a component at all longitudes, and an extra 'source' superimposed in the galactic centre region. The gas density required was now only ~ 2 nucleons/cm³. They observed that the molecular hydrogen needed to make up this density could not be present in any significant quantity, in the interstellar medium because of its photodestruction in the interstellar radiation field (Stecher and Williams (94)). In dark clouds, however, the rate of H₂ formation was expected to exceed the photodestruction rate and nearly all the hydrogen would be molecular form. Other evidence was produced to show that a mean nucleon density of 1 - 2 nucleons/cm³ was feasible. They suggested that a scan in longitude of the galactic disc with gamma-ray detectors of better sensitivity and resolution might detect gamma-ray 'hot-spots' which would reflect the true distribution of interstellar gas. Stecher and Stecker also suggested that one way of explaining the galactic centre region excess was to postulate an increase in the cosmic

ray intensity towards the galactic centre, by an additional factor of ~ 2 . There is evidence for the concentration of cosmic rays towards the galactic centre in the non-thermal radio noise distribution in galactic longitude. The radio noise and high energy gamma-ray intensities (Clark et al. (87)) are distributed rather similarly in galactic longitude, as shown in Fig. 4.7.

Hayakawa and Tanaka (95) pointed out that although the gamma-ray longitude distribution was not strongly correlated with the columnar hydrogen density distribution, there was a much better correlation with the column square density of hydrogen atoms, i.e. $\langle n_H^2 L \rangle$ (Fig. 4.8a). This would indicate that the density of gamma-ray sources was proportional to the square density of the interstellar gas. The same relationships had been suggested to hold also for X-ray sources, as star formation rate is proportional to the square density of gas and most X-ray sources are associated with stars younger than 10^9 years. The authors went on to suggest that the same argument may hold for gamma-ray sources and assumed that most of them are associated with supernova remnants. These remnants are identified with galactic non-thermal radio sources. The authors compared the radio intensity of these sources with the gamma-ray intensity of Clark et al. in each galactic longitude range (Fig. 4.8b) and as can be seen the correlation is fairly good if several strong sources such as CasA and TauA are discarded. They suggested that this correlation shows that galactic gamma-rays are produced mainly by π^0 -meson decays in supernova remnants. Electrons would also be produced by the decay of charged π -mesons but

they have also calculated that if strong magnetic fields are concentrated in an expanding shell rather than distributed uniformly in the whole remnant, then the interstellar intensity of electrons with energies around and below 100 MeV expected from the necessary gamma production rate, would not be inconsistent with the observed intensity of positrons.

4.5.2. Unresolved discrete sources

Clark et al. (87) have also shown that their gamma-ray intensity is similar in galactic longitude distribution to the cumulative flux from X-ray sources within 15° of the galactic plane (Fig. 4.7). This was also pointed out by Ogelman (96). Assuming an average differential spectral index of -2.1, Ogelman obtained agreement with the measured galactic gamma-ray intensity flux by extrapolating the fluxes of known galactic X-ray sources in the disc to gamma-ray energies. Although there is not spectral coverage of all galactic X-ray sources, it is worth noting that the chosen index was a reasonable fit in the hard and soft X-ray region for Tau XR-1, Cyg XR-1 and the Sagittarius X-ray complex, which with a few other sources comprise about 70% of the galactic X-ray flux. By unfolding the galactic longitude distribution of X-rays with the angular response of the OSO-3 detector, and summing over $\pm 15^\circ$ of galactic latitude, Ogelman obtained a very good fit to the galactic gamma-ray longitude distribution. His results are shown in Fig. 4.9, where they are plotted against Clark's original results. The subsequent downward revision of Clark's intensities should not be taken as too serious a blow to Ogelman's theory, because

as Clark himself pointed out, in extrapolation over three decades gamma-ray energies, an uncertainty of 20% in the index results in a dynamic range of 16 to 1 within which agreement may be claimed. Thus a slight steepening of the chosen power law spectrum would produce the source intensities. The inherent large uncertainties do however tend to make a meaningful extrapolation rather doubtful. The original extrapolated gamma-ray fluxes from individual strong X-ray sources were just slightly above their experimentally measured limits of 10^{-4} to 10^{-5} photons/cm² sec at >100 MeV. So the later reduction in the required intensities is more in line with the experimental results.

It should be pointed out that there is even a peak at the position of the Crab Nebula (Tau XR-1) in the data of Clark et al., and it may be that this represents a real observation of the Crab as a gamma-ray source. The discovery of two point sources of gamma-rays in the galactic centre region by Frye et al. (70) has obviously lent weight to the discrete source theory, particularly for this central region. It is worth noting that the power law dependence of $E^{-2.05}$ chosen by Frye to fit his results was in excellent agreement with the value of $E^{-2.1}$ selected by Ogelman. One of the drawbacks of the discrete source theory is its choice of a power law spectrum to represent X-ray and gamma-ray spectra. Many X-ray sources have the exponential spectrum indicative of free-free emission and although many of the larger ones do have the power law energy dependence, the production mechanism needed for this is not well understood. These sources represents a unique class of astronomical object. The known variability of some X-ray

sources could account for the negative results from some of the other gamma-ray detection experiments that have scanned the galactic disc in the past.

4.5.3. Inverse Compton scattering

The strong galactic gamma-ray intensity measured by OSO-3 could not be explained by the Inverse Compton scattering of cosmic ray electrons with the stellar photons or the 2.7°K universal blackbody radiation.

However, following the discovery of an unexpectedly high flux of radiation in the 0.4 - 1.3 mm band (Shivanandan et al. (97)), efforts were made, to explain the gamma-ray intensity by Inverse Compton scattering on this infra-red radiation. The Shivanandan measurements, which were later confirmed by the same group (Houck and Harwit (98)), extended from the galactic disc to the halo region of the galaxy and showed isotropy of the radiation. Muehlner and Weiss (99), using increased spectral resolution in the same wavelength range found that their results were consistent with a 2.7°K background on which a strong absorption feature at 11^{-1} - 12^{-1} cm was superimposed. The infra-red radiation was interpreted as blackbody radiation with a characteristic temperature of 8.3°K, and a corresponding energy density of 13 eV/cm^3 . An isotropic flux at 100μ was also reported (Houck and Harwit (100)), (although it has been questioned by McNut and Feldman (101)). It represented an energy density of 2.6 eV/cm^3 . In comparison with these two measurements, the universal blackbody microwave radiation, contains only 0.25 eV/cm^3 ,

of which 0.17 eV/cm^3 would fall in the $0.4 - 1.3 \text{ mm}$ band.

Ipavich and Lenchek (102) fitted a greybody curve with a characteristic temperature of 16°K and a dilution factor of 6, to the measurements at the two wavelengths and the Rayleigh-Jeans side of the 2.7°K microwave spectrum. Such a greybody flux would represent the enormous energy density of 53 eV/cm^3 .

The strongest argument against the greybody continuum hypothesis was given by Bortolot et al. (103), who by their study of optical absorption lines in interstellar molecules placed upper limits, at various wavelengths; which were well below the greybody curve. However, it is possible for the infra red to be concentrated in sharp lines which avoid the wavelengths examined by the molecular absorption technique. Fig. 4.10 shows the data on the cosmic microwave and infra red radiation as collected by Ipavich and Lenchek. The Princeton data are from Roll and Wilkinson (104), and Boynton et al. (105). If universal in extent, the infra red background would produce a diffuse cosmic gamma-ray intensity by Inverse Compton scattering, much in excess of the upper limits already measured.

Doubt is also cast upon the infra red radiation being universal by evidence of the existence of cosmic rays protons with extremely high energy, $>10^{19} \text{ eV}$ (Andrews et al. (106), Linsley (107), and Scarsi and Linsley (108)). Cosmic rays at energies $>10^{17} \text{ eV}$ are thought to be of metagalactic origin. The 2.7°K universal radiation field already implies a cut-off of the primary cosmic ray spectrum at an energy $\sim 3 \times 10^{19} \text{ eV}$ due to photo-meson production, (Zatsepin and Kuz'min (109))

and Greisen (110)). The presence of a universal infra red radiation with a temperature of 16°K would indicate a cut-off at a much lower energy, about 5×10^{18} eV. O'Connell and Verma (111) considered the infra red as a blackbody radiation of 8.3°K but this would still mean a cut-off at about 10^{19} eV, inconsistent with the high energy proton results. These results need not necessarily be incompatible with the existence of a universal black or greybody radiation, but only with the assumption that the ultrahigh energy cosmic rays are universal. Stecker (112) for example, proposed that they are produced in the local supercluster of galaxies, which includes the large Virgo cluster of galaxies, the intense Virgo A radio source and the exploding galaxy M82.

Using the radiation energy density of 13 eV/cm^3 , Shen (113) and Cowsik and Pal (114) were the first to derive a 100 MeV gamma-ray flux approximately equal to the original OSO-3 measurement.

The derivation of the absolute value of the linear intensity of the X- and gamma-rays should depend, for one, upon the half width; z_0 , of the disc occupied by the electrons. Analysis of 400 Mhz non-thermal continuum radiation has indicated that the synchrotron radiation from cosmic ray electrons (of energies up to a few GeV) comes from a disc of half-width, $z_0 \sim 400 \text{ pc}$, so confinement regions of the order of 1 kpc may be considered reasonable. Any Inverse Compton theory must also inevitably make predictions about the galactic photon emission in the X-ray energy region which invite comparison with the experimental results.

Shen's model contradicted the 1.4 - 18 KeV galactic X-rays seen

by Cooke et al. (80). It predicted that the electrons needed to produce photons of this energy would occupy a disc with $z_0 \sim 5$ kpc and have a spectrum which was a continuation of the power law spectrum of 10 - 200 GeV electrons. With this electron spectrum the predicted intensity in this X-ray region would be four times greater than measured and the differential spectral index equal to -1.7, compared to the observed value of -1.1. In addition the X-rays were observed to come from an emission region $\leq 6^\circ$ wide, normal to the plane, which is inconsistent with $z_0 \sim 5$ kpc.

Like Shen, Cowsik and Pal assumed that the infra red radiation pervaded the whole galaxy. Their theory was criticised by Ipavich and Lenchek (102) on the grounds that they failed to take into account the thickness of the electron confinement disc and assumed that the gamma-rays were isotropic over the solid angle of the detector when in fact they were quite anisotropic. Also, in their second paper (Cowsik and Pal (115)), it was not valid to compare the solid angle intensity, from the direction of the galactic centre, with the diffuse X-rays. However, using the high energy (1.5 - 300 GeV) spectrum of cosmic ray electrons given by Anand et al. (116),

$$I_e(E) = 905 E^{-2.62} \text{ electrons/cm}^2 \text{ sec sr MeV},$$

Cowsik and Pal (115) obtained a photon differential spectrum $E^{-1.81}$, down to energies ≈ 30 KeV. Also for electron energies < 1.5 GeV, they used the spectrum derived by Anand et al. (117) from an analysis of the observed radio spectrum,

$$I_e(E) = 4.06 \times 10^{-2} E^{-1.2} \text{ electrons/cm}^2 \text{ sec sr MeV},$$

which produced a photon spectrum $\propto E^{-1.1}$ for energies < 30 KeV. This was in excellent agreement with the Leicester result of $E^{-1.1}$ in the range 1.4 - 18 KeV. Ipavich and Lenchek made careful calculations using an electron confinement disc of half-width 750 pc and an infra red energy density of 13 eV/cm³. With the high energy electron spectrum of Anand et al. (116) and a demodulated version of the measured cosmic electron, at lower energies, they obtained good agreement with the original OSO-3 and Leicester intensities (their calculated spectrum was $\propto E^{-1.2}$ in the same X-ray region).

An important prediction of the Inverse Compton theory, as stated by Cowsik and Pal, was that the galactic anisotropy, which was only $\sim 10\%$ in the X-ray region of the Leicester results, would increase in going to higher energies (say ~ 200 KeV). The hard X-ray results of Bleeker et al. and Schwartz et al. have not, however, borne this out, there being only upper limits to the galactic flux in the 20 - 110 KeV region. This would seem to be a major blow to the Inverse Compton theory.

The downward revision of the OSO-3 gamma-ray intensities, followed by the announcement of Houck (118) that an instrument recalibration had resulted in a figure of 6.5 eV/cm³ for the energy density of their infra red flux, led Ipavich and Lenchek to recalculate their intensities. With a disc of half-width $z_0 = 500$ pc they once again obtained good agreement with the OSO-3 100 MeV results. Their predictions for the intensity > 100 MeV were

9.5×10^{-5} photons/cm² rad sec from the galactic centre region

4.5×10^{-5} photons/cm² rad sec from the anticentre

and a minimum intensity of

1.5×10^{-5} photons/cm² sr sec from the galactic poles.

The linear differential gamma-ray spectrum due to Inverse Compton as derived by them and normalised to the revised OSO-3 100 MeV measurement is also shown in Fig. 4.6. Within experimental errors the hard X-ray measurements are now more or less consistent with the gamma-ray X-ray results, particularly if these are still a little high as the Frye measurements indicate. The measuring intensities in the soft X-ray region are a factor of 4 above the predicted values, and there is no obvious explanation for this discrepancy unless there is another component in this energy region, from an additional source mechanism. It would be possible to make the soft X-ray and gamma-ray results compatible by normalising the spectra to the soft X-ray results and assuming, that the electron spectrum steepens at high energies in order to obtain the required gamma-ray intensity. This contrivance would once again cause the hard X-ray result to be inconsistent. In general then it seems that the experimental data in the three energy regions is incompatible with a model that explains the galactic soft X-ray, hard X-ray and gamma-ray emission in terms of Compton scattering of the infra red photons with galactic electrons. Bleeker et al. pointed out that the X-ray emissions were consistent with a thermal origin and that some

other mechanism must be sought to explain the gamma-rays.

Even if the Inverse Compton hypothesis is rejected for galactic longitudes away from the galactic centre region, it might still be worthwhile to consider the process as responsible for the extra enhancement of the gamma-ray intensity in the central region. Both the π^0 -decay and original Compton theories predicted intensities that were inadequate. Whilst one possible explanation is that the cosmic ray intensity in this region is higher, as previously mentioned, Stecher and Stecker suggested that there was no need to postulate the existence of such an increase. They theorised that there might be an additional gamma-ray source in the central region produced by the Compton interactions of cosmic ray electrons with the intense infra red field located at the galactic centre and detected in the $80 \mu - 120 \mu$ band by Hoffman and Frederick (119). They calculated an intensity in the range $2 - 7 \times 10^{-5}$ photons/cm² rad sec at $E_\gamma > 100$ MeV. Ipavich and Lenchek however, maintained that the solid angle ($2^\circ \times 6.5^\circ$) subtended by the source was too small to cause a significant enhancement of the gamma-ray flux at our position in the galaxy unless the absolute intensity of the source came in for revision. This infra red source is represented in Fig. 4.10 where the point is plotted as the intensity resulting from averaging the reported flux density over the whole sky.

4.6. Significance of Present Results and Discussion

It seems convenient, once more, to consider the galactic centre region separately from other longitude regions.

As regards the latter it appears that the experimental results are now more or less consistent with the original calculations of Pollack and Fazio (8) based on the decay of π^0 -mesons produced in cosmic ray-interstellar gas interactions. Any inadequacy of this model can be overcome by postulating a modest increase in the cosmic ray density or the interstellar hydrogen density, because as pointed out by Stecher and Stecker (93) this quantity is flexible due to amounts of undetectable molecular hydrogen that may be present in dark clouds. The shape of the π^0 -decay spectrum means that it cannot explain the galactic photon intensity in the soft X-ray region, for which some alternative mechanism must be found. This natural π^0 -decay explanation makes it unnecessary to postulate the existence of an infra red flux which is galactic in extent, when there is already evidence against it. More detailed gamma-ray spectral measurements should resolve any further arguments on this theory, as they would on the discrete source hypothesis. The predicted extrapolated intensities at gamma-ray energies for point sources are becoming increasingly within the sensitivities of modern gamma-ray detectors.

There is some evidence, which although not completely convincing, that does indicate that there is an extra intensity in the Cygnus region of the galactic plane. If this is due to a discrete source, perhaps variable in intensity, it should have been identified by some of the high resolution observations of the region.

For the galactic centre region, (say $|l^{II}| \lesssim 40^\circ$), most of the measurements show a gamma-ray enhancement greater than expected by a factor of at least 2. An increase in the cosmic ray density would be

the most convenient way to explain this, but would not be consistent with the measurements of Frye et al. (44). Calculations based on the original work of Pollack and Fazio and on the anticentre measurements show that at least 50% of the gamma-ray intensity measured in the central region by OSO-1 should have a π^0 -decay origin. As can be seen in Fig. 4.2, the section of the galactic disc scanned in the present experiment was covered, at least in part, by all three of the groups which have investigated the galactic plane in the central region, so the present results may validly be compared with all of them. The present balloon flights took place 14 months after the gathering of the most recent of the other data.

Frye et al. (70) suggested that the contributions from the two gamma-ray point sources are the most significant in the central region. The region scanned by the present experiment (angular resolution 19° FWHM for a line source) included one of the two point sources, $G_{\gamma 2+3}$, although the zenith angle of the source was never less than $\sim 10^\circ$, so the exposure was limited. The data were however, examined for possible emission and the 95% confidence upper limits obtained were

$$2.7 \times 10^{-4} \text{ photons/cm}^2 \text{ sec, } >30 \text{ MeV}$$

and $1.9 \times 10^{-4} \text{ photons/cm}^2 \text{ sec, } >50 \text{ MeV.}$

If the Frye flux for $G_{\gamma 2+3}$ of $(1.5 \pm 0.5) \times 10^{-5} \text{ photons/cm}^2 \text{ sec}$ at $>100 \text{ MeV}$ is to be believed, then the above upper limits are obviously not in conflict, as an extrapolation to the lower energies with the proposed integral number dependence of $E^{-1.05}$ would yield fluxes of

5.3×10^{-5} photons/cm² sec
and 3.1×10^{-5} photons/cm² sec respectively.

In his attempt to explain the OSO-3 galactic centre results Frye suggested that one or more discrete sources may have been at the $\sim 1 \times 10^{-4}$ photons/cm² sec level, (at >100 MeV) at the time of the observation. If G_{2+3} had been that level during the present flights it would have been detectable.

The Frye results are in particularly serious conflict with the GSFC data, which were gathered at approximately the same time, and Frye contended that the GSFC measured intensity could not have been due to many unresolved discrete sources or one large variable source. The former would need to be too numerous and the latter should have been detectable. Indeed the upper limits at the lower energies from the present experiment can only be reconciled with the GSFC result at >100 MeV if at least 80% of their measured intensity is of π^0 -decay origin. The upper limit from the present work at >50 MeV is in good agreement with the conservative upper limit at >50 MeV obtained by Fichtel et al. (120) from the complete analysis of their data from three balloon flights. Whilst they measured a positive intensity at >100 MeV their results showed no gamma-ray excess in the 50 - 100 MeV region. Their result was

$$\frac{I(50 - 100 \text{ MeV})}{I(>100 \text{ MeV})} < 0.50,$$

which is also consistent with the large majority of the gamma-ray inten-

sity from the galactic centre region being of π^0 -decay origin. This is demonstrated in Fig. 4.11 where the various integral gamma measurements of the galactic centre region are shown. All the spectra are normalised to the intensities at 100 MeV and the composite shape is derived for an 80% : 20% proportion of the π^0 -decay and $E^{-0.8}$ (Inverse Compton) contribution. Such a large π^0 -decay contribution can be consistent with the OSO-3 measurement if approximately the whole of that measurement is of π^0 -decay origin. Whatever the π^0 -decay contribution is in the central region it should remain constant in time if it arises from cosmic ray-interstellar hydrogen interactions. If this is the case it is difficult to understand how the results of Frye et al. (70) and of the GSFC group can be made compatible.

For the OSO-3 region, the Frye results indicated an upper limit at >100 MeV for the line source which even when the contribution of the two point sources is retained, tends to contradict the idea that even 50% of the OSO-3 intensity is due to π^0 -decay. Their present upper limits at the lower energies are not in agreement with a totally electromagnetic origin for the ^{GSFC}~~OSO-3~~ gamma-rays unless they are from variable sources. Confirmation of the sources discovered by Frye et al. would obviously be of help, as they represent a unique class of astronomical object of which very little is understood.

Further surveys of the galactic centre region with precise spectral and angular resolution would help to resolve the theories and discrepancies just described. The critical region is the 10 - 50 MeV range where the π^0 -decay gamma-ray integral spectrum is particularly

flat. The difficulty is to maintain a good angular resolution at these energies where Coulomb scattering is so significant. In this range the new gas Cerenkov detectors seem to offer the most promising solution to the problem and their results are awaited with interest.

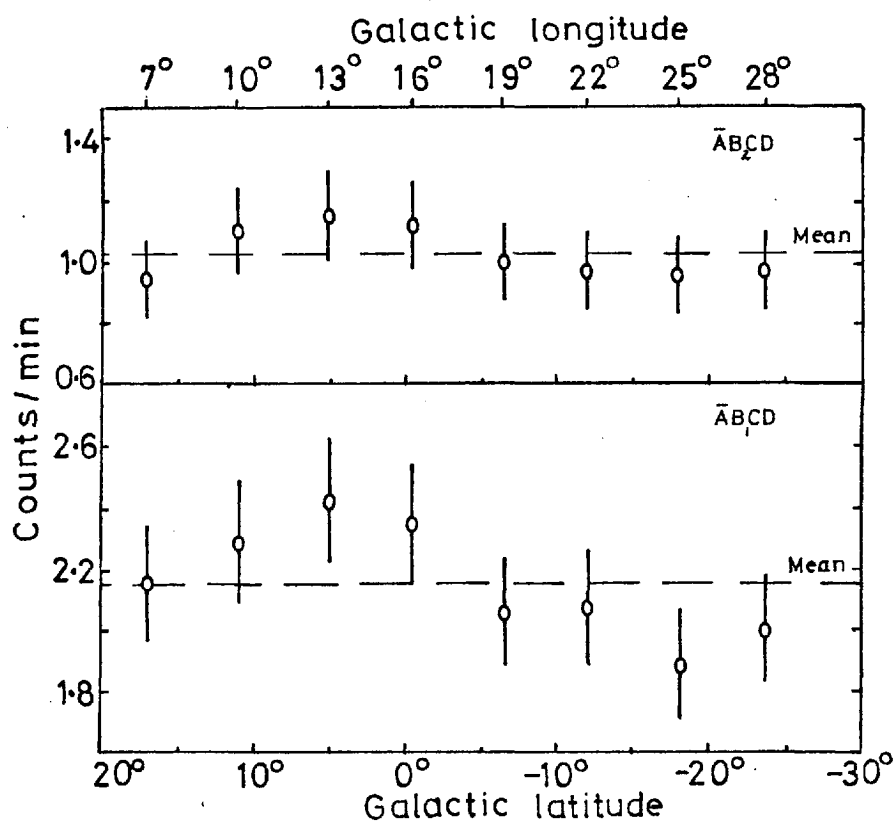
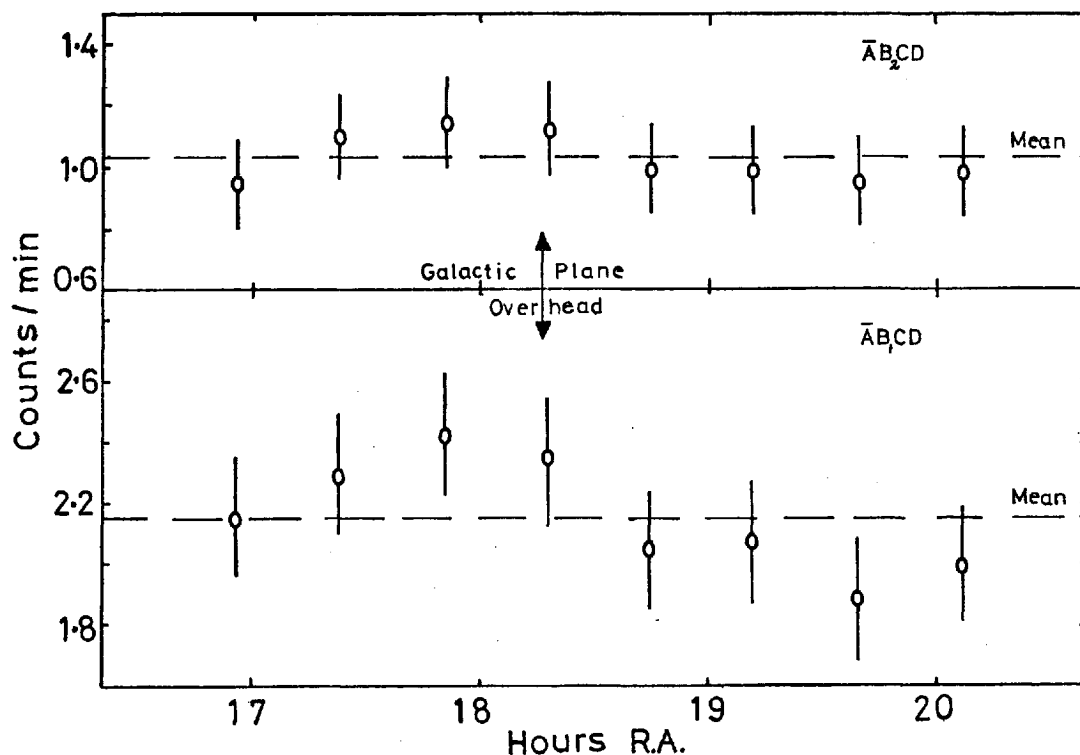


Fig. 4.1 Count rates at altitude of the two integral gamma-ray channels; averaged over 30 minute intervals and summed in sideareal time over the two flights, and plotted in sideareal and galactic coordinates.

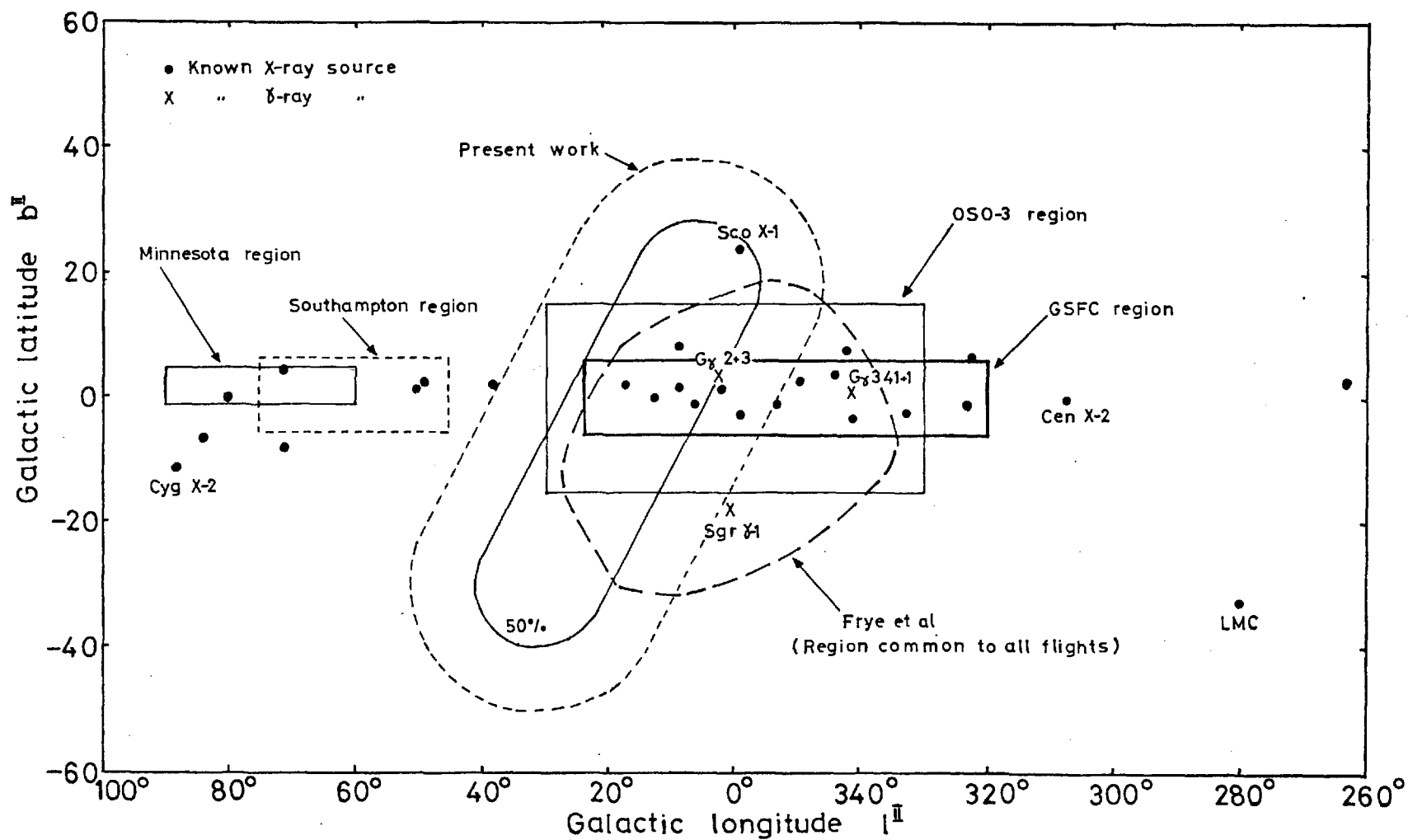


Fig. 4.2 Galactic map showing the regions scanned by the present and other gamma-ray investigations.

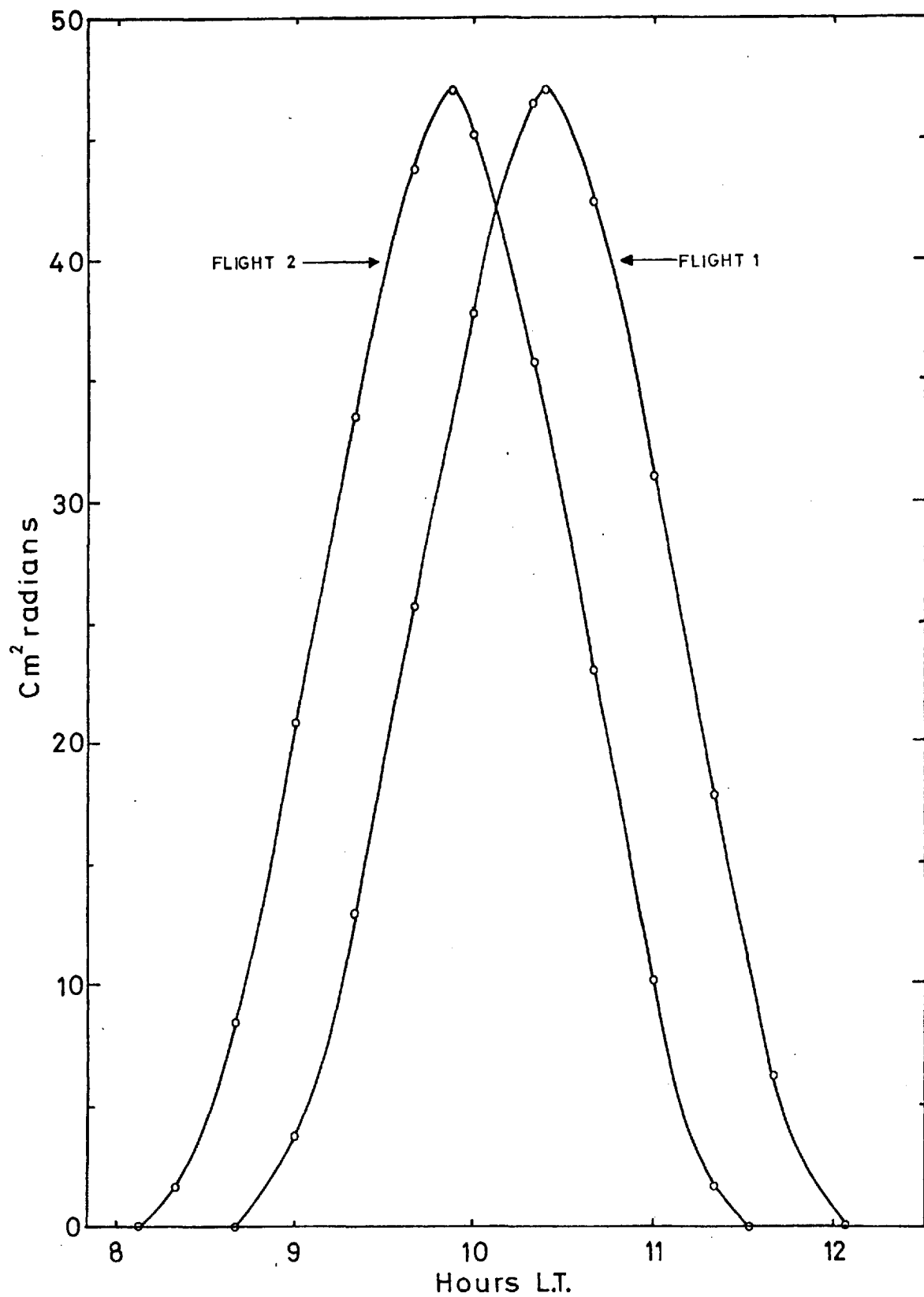


Fig. 4.3 Cm² rad factor presented to the galactic disc as a function of time.

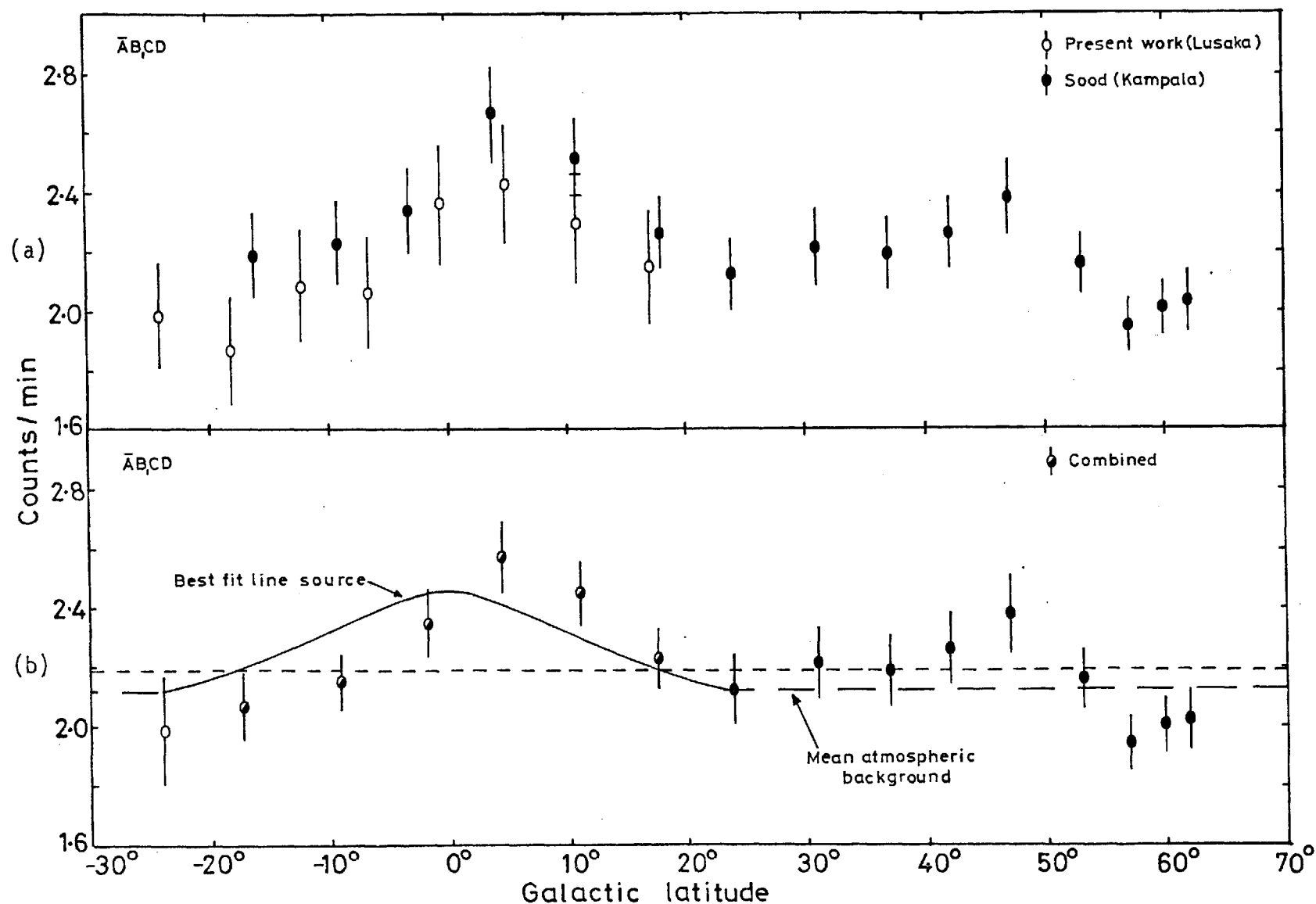


Fig. 4.4 (a) Comparable gamma-ray measurements of Sood and of the present work.
 (b) Combined gamma-ray measurements from Sood and the present work.

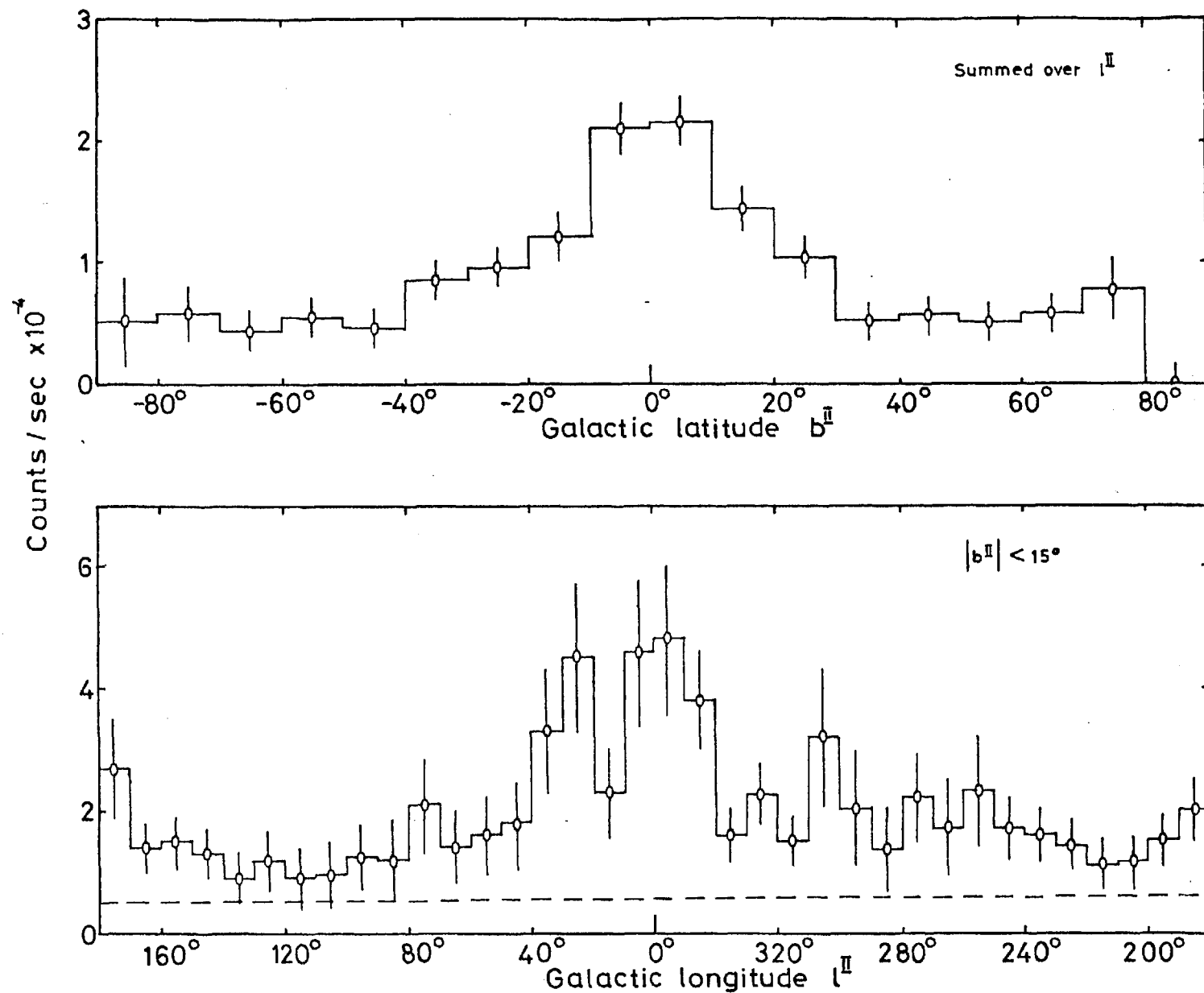


Fig. 4.5 Dependence of the gamma-ray intensity, as measured by OSO-3, on galactic latitude and longitude. The dotted line represents the average count rate at high galactic latitudes.

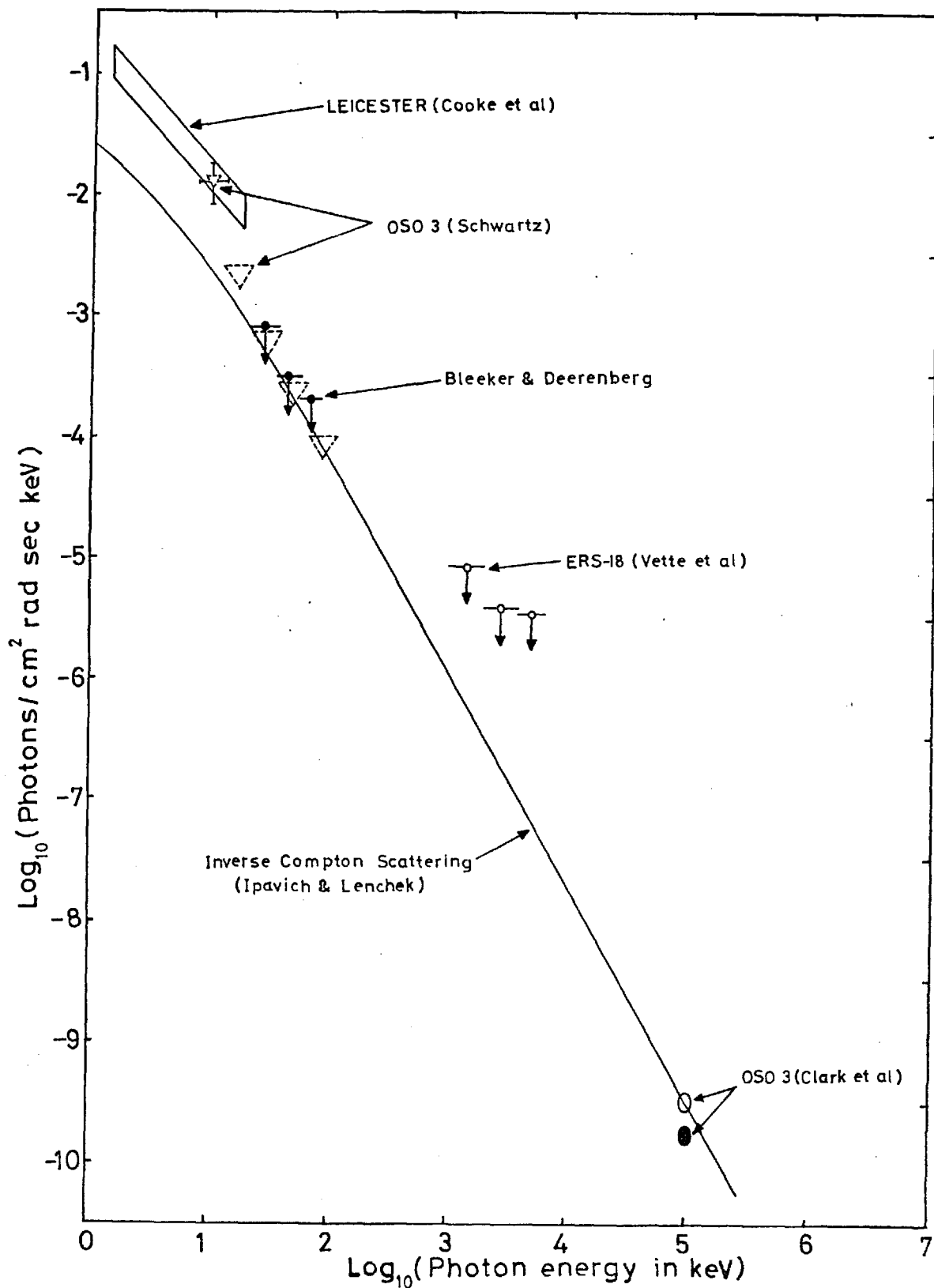


Fig. 4.6 Equivalent line component spectrum of galactic photons.

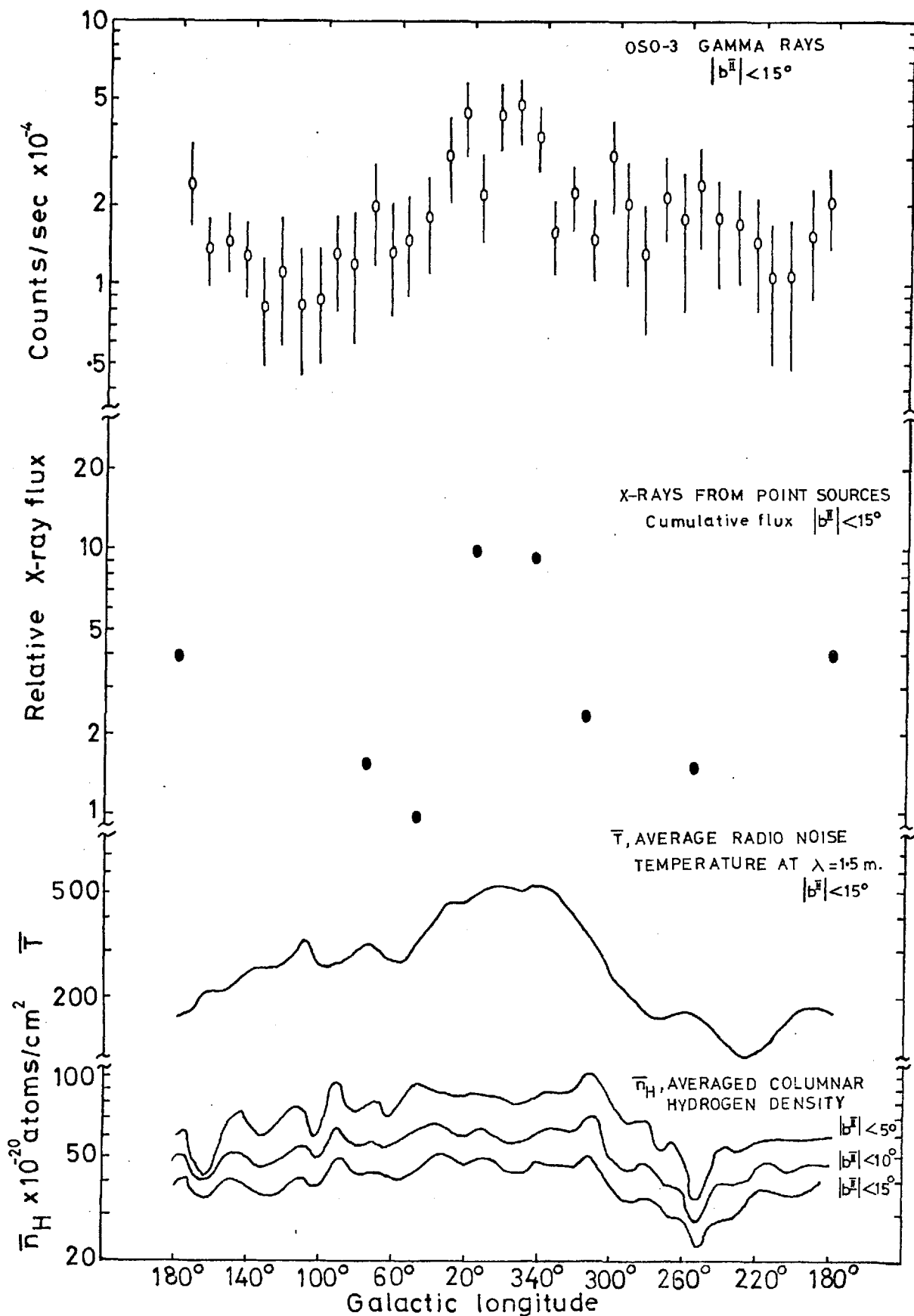


Fig. 4.7 Galactic longitude dependence of gamma-rays, cumulative X-ray flux, 1.5 m non-thermal radio noise and columnar hydrogen density.

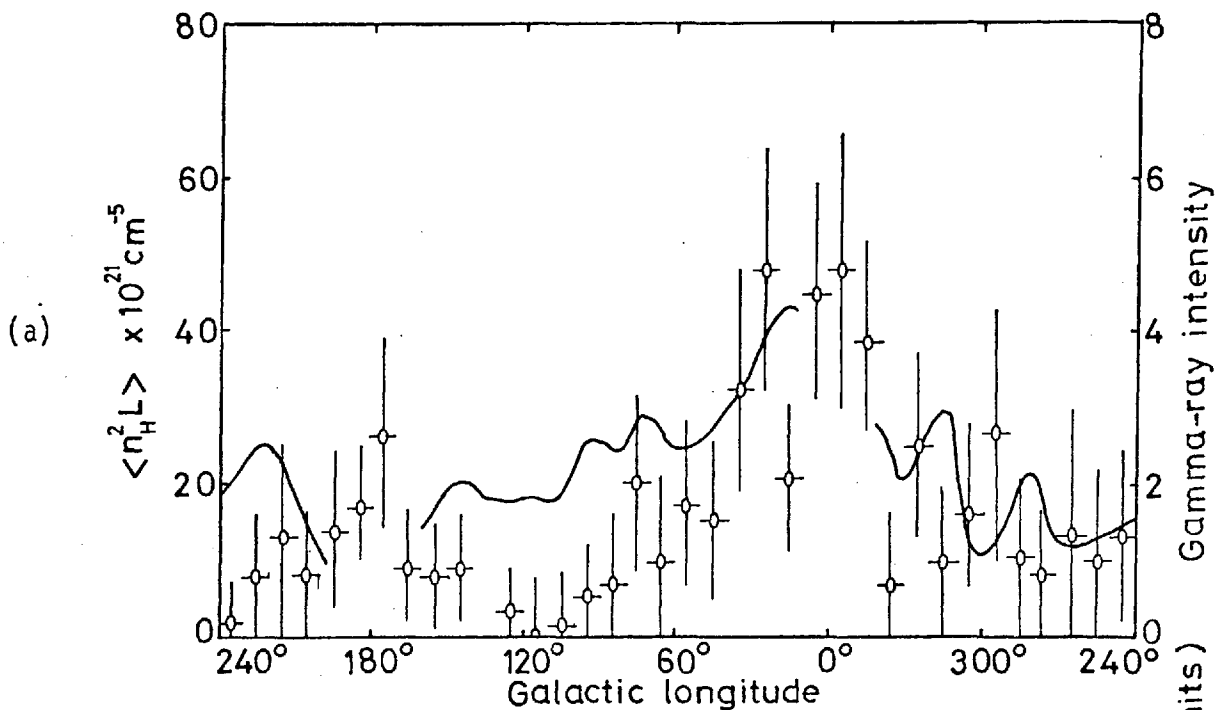


Fig. 4.8 (a) Galactic longitude dependence of the gamma-ray intensity and the column square density of hydrogen atoms.

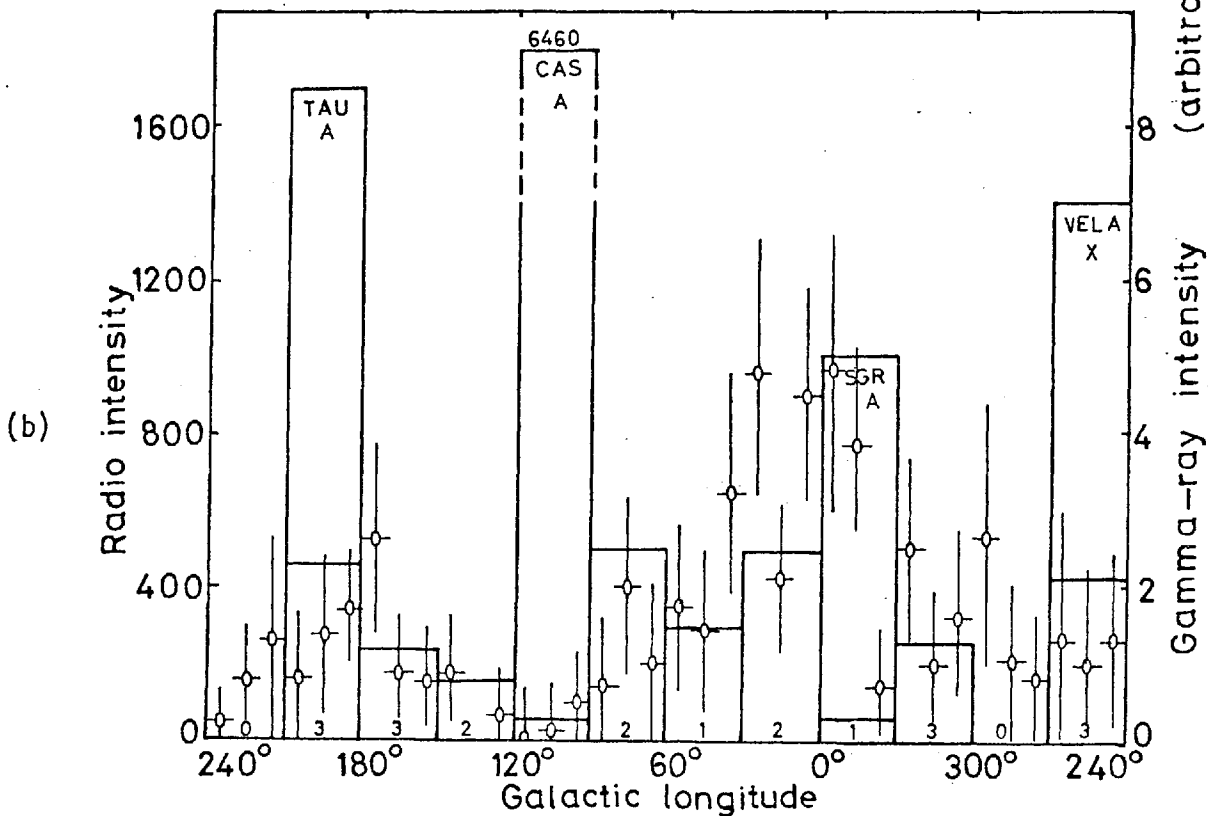


Fig. 4.8 (b) Correlation between the gamma-ray intensity and the radio intensity of supernova remnants. The numbers of remnants adopted are indicated. The four strongest sources are indicated separately.

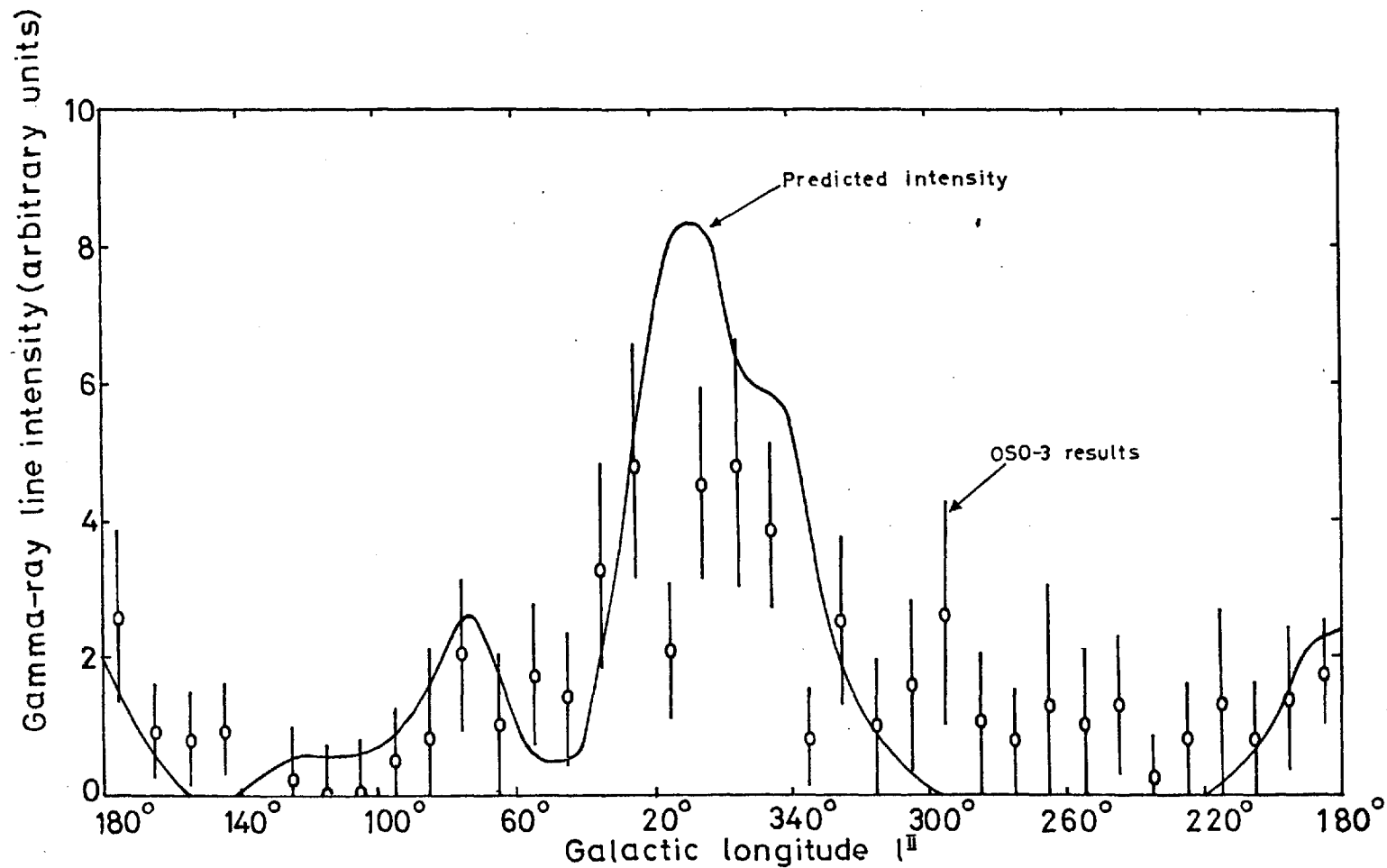


Fig. 4.9 Distribution in galactic longitude of gamma-rays; as experimentally measured by OSO-3 and predicted by Ogelmann from unresolved discrete sources.

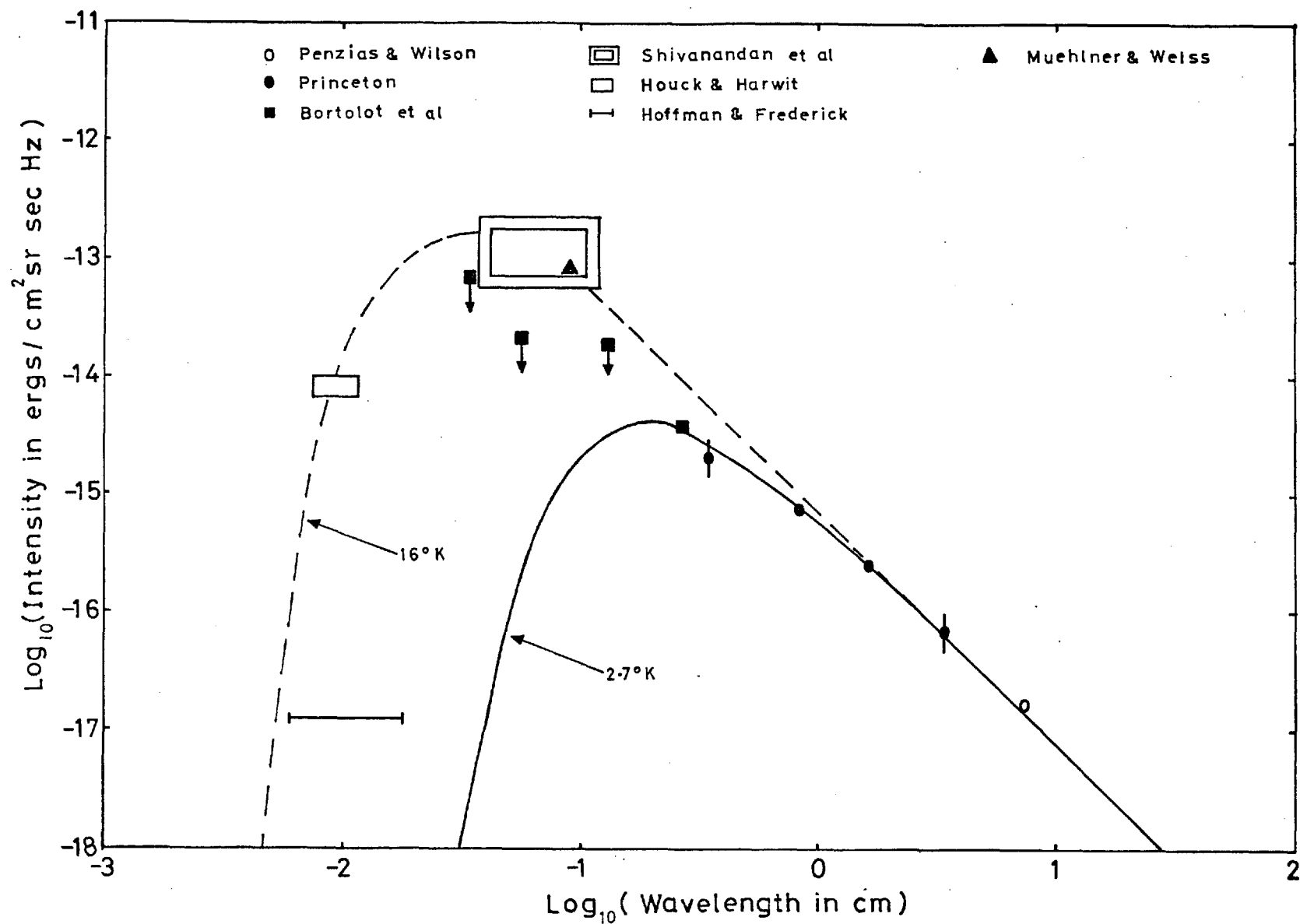


Fig. 4.10 Cosmic microwave and infra-red radiation.

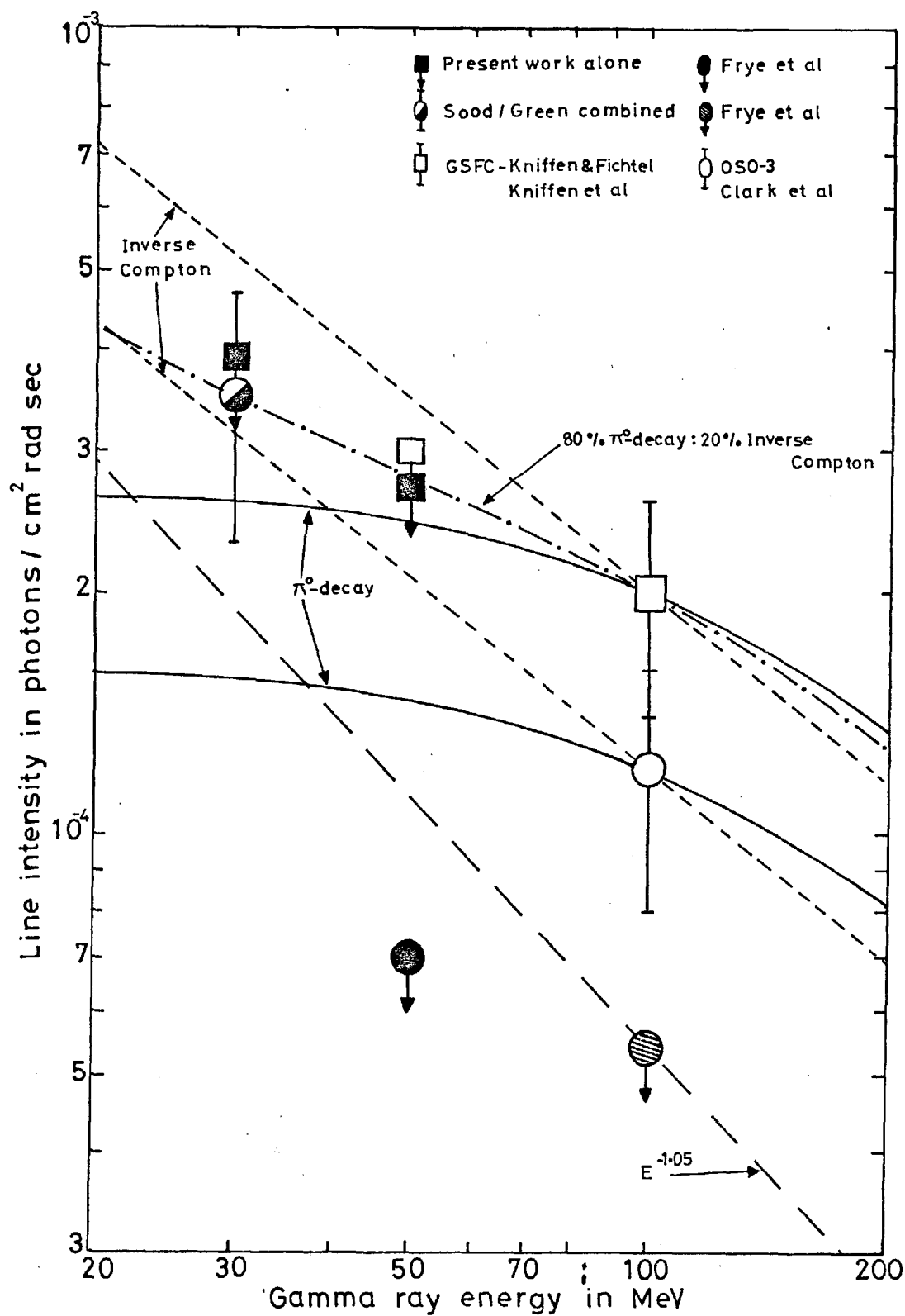


Fig. 4.11 Integral gamma-ray measurements in the galactic centre region.

V A Short-Lived Increase in the Charged Particle Flux
Observed During an Equatorial Balloon Flight

5.1. Description of the Event

The event to be described was observed during the course of a balloon flight at the equator, from Kampala, Uganda, and was part of the programme to search for possible π^0 -decay gamma-rays emitted from active regions of the sun. As previously mentioned, the detector used for the present gamma-ray astronomy experiment was originally designed for this programme, and the detectors flown in 1968 were essentially identical to the description in Chapter II, except that their isotropic geometrical factor was 22 cm² sr and their geometrical half-angle 24°.

The flights were made on the basis of observed and predicted solar activity, and the conditions on 31st October 1968 were such that a flight was carried out which reached floating altitude of 4.5 gm/cm² at 0630 U.T.. The detector remained within telemetry range until 1530 U.T. by which time it had descended to an atmospheric depth of 6.3 gm/cm².

At ~1030 U.T., when the detector was at 5 gm/cm², the 4-fold coincidence channel (AB₁CD), which recorded the charged particles, registered a significant increase in count rate which lasted until ~1300 U.T.. The charged particle count rate at altitude was normalised to 4.5 gm/cm² atmospheric depth and averaged in 30 and 10 minute intervals, and is shown in Fig. 5.1.

There was no reason to suspect a malfunction of the detector.

The count rate in the gamma-ray channels remained at a level corresponding to the normal atmospheric background throughout the flight. The single rates of all the photomultiplier tubes, which were monitored continuously throughout the flight, provided a check on the performance of the detector. These single rates and the count rate in the gamma-ray channel ($\overline{AB}_1CD$), for the duration of the event, are shown in Fig. 5.2. They show no significant fluctuations and it is believed that the event was produced by a real increase in the charged particle flux. The design of the detector was such that a proton required a minimum energy of about 500 MeV and an electron a minimum energy of about 20 MeV to register a 4-fold ($\overline{AB}_1CD$) coincidence.

5.2. Solar-Geophysical Conditions at the Time of the Event

Subsequently it was found this particle increase was coincident with the bay-like depression in the initial phase of the magnetic storm, which had begun with a sudden commencement at 0859 U.T.. This storm was just part of the intense solar and magnetic activity which took place in the period 27th October - 4th November, 1968.

5.2.1. Solar events

The McMath plage region 9740 was responsible for most of the major solar activity during this period. It came round the east limb on October 21st, crossed the central meridian on October 28th, and disappeared over the west limb on November 4th. During this transit it was responsible for 69 optical flares (12 of importance 2 or greater), of which 40 had associated radio bursts. The most significant flare was

of 3B importance and began at 2340 U.T. on October 30th and lasted for about 2 hours.

The period was heavily populated with low energy solar particle events. There were two small low energy enhancements on October 29th and October 30th, followed early on October 31st by a larger and more energetic event associated with the importance 3B flare already mentioned. The event persisted for several days, slowly decaying away until the sharp onset of another event on November 4th.

5.2.2. Cosmic rays

Neutron monitors recorded a large Forbush decrease which began at about 0000 U.T. on October 29th. The decrease reached a maximum value of $\sim 10\%$ - 12% , at high latitude stations, and $\sim 6\%$ at low latitudes, in the early hours of October 30th. The balloon event occurred during the recovery phase following the decrease.

5.2.3. Geomagnetic events

The planetary magnetic 3-hour range indices K_p , and the hourly values of equatorial Dst (Sugiura and Cain (121)) for the period October 27th - November 4th are shown in Fig. 5.3. They indicate the highly disturbed character of this period.

The first storm in the period began with a double ssc at 0640 U.T. and 0909 U.T. on October 29th. The relatively weak main phase followed the second ssc after about 12 hours of si activity. The storm had the major characteristics of a western limb flare and was not thought to be due to the 9740 plage region.

The storm which began with a large ssc at 0859 U.T. on October 31st was part of the most intense period of magnetic disturbance since the major storm of May 25th - 26th 1967. Collections of H component magnetic records for the October 31st storm are shown in Fig. 5.4 from six low latitude stations, and in Fig. 5.5 from ten high latitude stations. The ssc was followed at about 1000 U.T. by a single polar substorm which lasted until about 1200 U.T.. During this substorm a large negative "bay" was evident in the low latitude records. The bay was asymmetric, being most intense in the late morning - early afternoon sector. The single substorm was followed by intense si activity which lasted until about 1340 U.T., when a series of polar substorms occurred. A large main phase developed at low latitudes during the substorm activity. This main phase was also quite asymmetric, being most severe in the evening sector. Honolulu which was in the early morning sector during the growth period of the storm recorded only a moderate disturbance.

The balloon event was recorded at Makerere, Kampala, which was also in the late morning - early afternoon sector during the initial phase of the storm. The event was coincident in time with the "bay" observed in the low latitude records. The H component magnetic records for the low latitude stations Hermanus and Nairobi, and the middle latitude station Hartland, are shown along with the time history of the balloon event in Fig. 5.6. All these stations were in the "noon" sector during the event. There is a very evident similarity between the time profiles of the bay and the event. An examination of the magnetograms

available for all the major magnetic storms from October 31st 1968 until the present, revealed that the occurrence of such a large bay ($\sim 150 \gamma$) in the initial phase of a storm was quite exceptional. None of the storms examined had such a characteristic. Thus if the balloon event was directly related to the bay then it is probable that such events are rare.

The other significant storm during the October 27th - November 4th period began with a distinct ssc at 0917 U.T. on November 1st. The main phase was weaker than in the October 31st storm.

5.3. Possible Explanations of the Balloon Event

5.3.1. Solar particles

Although it was the largest and most energetic of the period, the solar event which began around 0300 U.T. on October 31st and was in progress at the time of flight, was still predominantly a low energy event. Solar protons of up to 60 MeV were observed by the IMP F satellite outside the magnetosphere, and of up to 90 MeV by ESRO-2 over the polar regions.

The geomagnetic vertical cut-off rigidity at Kampala is 15 GV and the possibility that the balloon event could have been due to an influx of solar protons of energy greater than this geomagnetic threshold, is ruled out by the absence of any ground level neutron event.

The 10-minute, pressure corrected, data from various neutron monitors (supplied by J. F. Steljes) for the period of flight, are shown in comparison with the balloon event in Fig. 5.7. No enhancement is

evident at any station, whatever its cut-off rigidity.

As there is also no known mechanism whereby the geomagnetic threshold at the equator could be reduced to a few hundred MeV during the initial phase of the magnetic storm, it seems unlikely that the particle increase could be ascribed to solar particles.

5.3.2. Reduction of the geomagnetic threshold

A reduction in the geomagnetic threshold to below the quiet time value of 15 GV would automatically produce an increased cosmic ray flux. Such increases, associated with intense magnetic activity, have already been recorded on at least three occasions.

The most recent and best documented occurred during the large magnetic storm of May 25th - 26th 1967. The data from a large number of neutron monitor stations were collected by Wada (122). A Forbush decrease happened during the initial phase of the storm, and just after the abrupt decrease in intensity, most of the stations detected an increase. Analysis revealed that the increases, which lasted for ~24 hours, were larger for mountain and low latitude stations, and were consistent with a decrease in cut-off rigidities through the addition of a uniform field antiparallel to the dipole axis of the earth (Kondo (123)).

The balloon event observed at Kampala cannot, however, be ascribed to this process. If the form of the integral primary rigidity spectrum is taken as $I(>R) = KR^{-1.5}$ at high rigidities, then in order to produce the measured increase of ~30%, the geomagnetic threshold would have to fall to a value R_s , given by

$$\frac{130}{100} = \left(\frac{R_s}{15} \right)^{-1.5}$$

i.e. $R_s \approx 12.6 \text{ GV}$

This would require a perturbation of the geomagnetic field, far in excess of the short-lived decrease in H ($\sim 150 \gamma$ at equatorial latitudes) which was observed during the "bay" which occurred simultaneously with the event.

Furthermore this explanation would mean that there should have been an observable increase in the sea level neutron monitor rates, as in the 1967 event. Fig. 5.7 has shown that no such increase was in evidence. In addition, this mechanism would predict that there should have been a much bigger increase in the particle flux at the time of the main phase of the storm, when the horizontal component reached a minimum value well below that recorded at the time of the balloon event. In fact, the particle flux had returned to the normal background level by that time.

5.3.3. Dumping of particles from the inner radiation belt into the atmosphere

It seems likely that the inner radiation belt was the source of the protons and/or electrons required to produce the event.

It seems unlikely that electrons contributed significantly, if at all, to the observed event because of the very probable low flux values of electrons $> 20 \text{ MeV}$ in the trapping region. Early measurements of very energetic electrons in the inner belt were sparse. From his scintillator-

Cerenkov gamma-ray telescope on the Explorer-11 satellite during April - August 1961, Garmire (125) estimated that whilst in the inner belt, electrons of energy >10 MeV contributed $<10\%$ the charged particle count rate, the remainder being due to protons of energy >350 MeV. Although not fully investigated the spectrum of naturally injected trapped electrons is thought to be falling steeply at these energies. Thus 10% may be taken as a generous upper limit for the flux of electrons of >20 MeV with respect to the flux of protons of >500 MeV. Later estimates of the magnitude of the observed event will show that such electron flux levels are inadequate to explain the event.

The Starfish nuclear explosion of July 9th 1962 injected large quantities of relativistic electrons into the inner belt. The differential number spectrum of fission electrons was measured by Carter et al. (164) and was found to be well represented by

$$N(E) = 3.88 e^{-(0.575E + 0.055E^2)}$$

for $1 \lesssim E \lesssim 7$ MeV, where E is the electron energy in MeV and $N(E)$ is in units of electrons per fission per MeV. Assuming a smooth extrapolation to zero energy and to energies >7 MeV, an integrated fission spectrum $F(>E)$ was obtained. Here

$$F(>E) = \frac{\int_E^\infty N(E) dE}{\int_0^\infty N(E) dE}$$

and represents the fraction of the total spectrum above a fixed energy E . It was found that

$$F(>20 \text{ MeV}) \approx 10^{-15}$$

The total number of electrons injected into the inner belt by Starfish has been estimated to be $\sim 10^{26}$, giving $\sim 10^{11}$ as an upper limit for the number above 20 MeV. Even without taking into account the decay of the excess trapped flux due to interactions with the residual atmosphere from July 1962 to October 1968, it is obvious that Starfish addition to the natural trapped fluxes at >20 MeV was very small, and could not have increased the population enough for it to be responsible for the balloon event.

The inner belt proton spectrum extends to energies sufficiently high (~ 2 GeV) to allow penetration to balloon altitudes but not high enough to produce a ground level event. The relative integral response curves for neutron monitors at sea level and at 680 gm/cm^2 are shown in Fig. 5.8. From these curves it is evident that protons of energy <2 GeV contribute $<2\%$ and $<5\%$ respectively to the neutron monitor rates at the two altitudes. Averaged over the duration of the event, the observed excess charged particle intensity above the normal cosmic ray intensity, corresponded to about $5 \times 10^{-3} / \text{cm}^2 \text{ sr sec}$ for a period of about 10^4 sec. The intensity of trapped protons with energy >500 MeV in the inner radiation belt is a strong function of position; so an estimate of the relative magnitude of this event with respect to the total population of such protons is a fairly difficult procedure that will be attempted in a later section after a general introduction to radiation belt characteristics. It is worthwhile to mention, however, that the inner edge of the belt comes to within several hundred kilometres of the balloon and is at an even lower altitude in South Atlantic anomaly. Thus a relatively small perturbation of the trapped particle trajectories may be sufficient to cause appreciable atmospheric dumping.

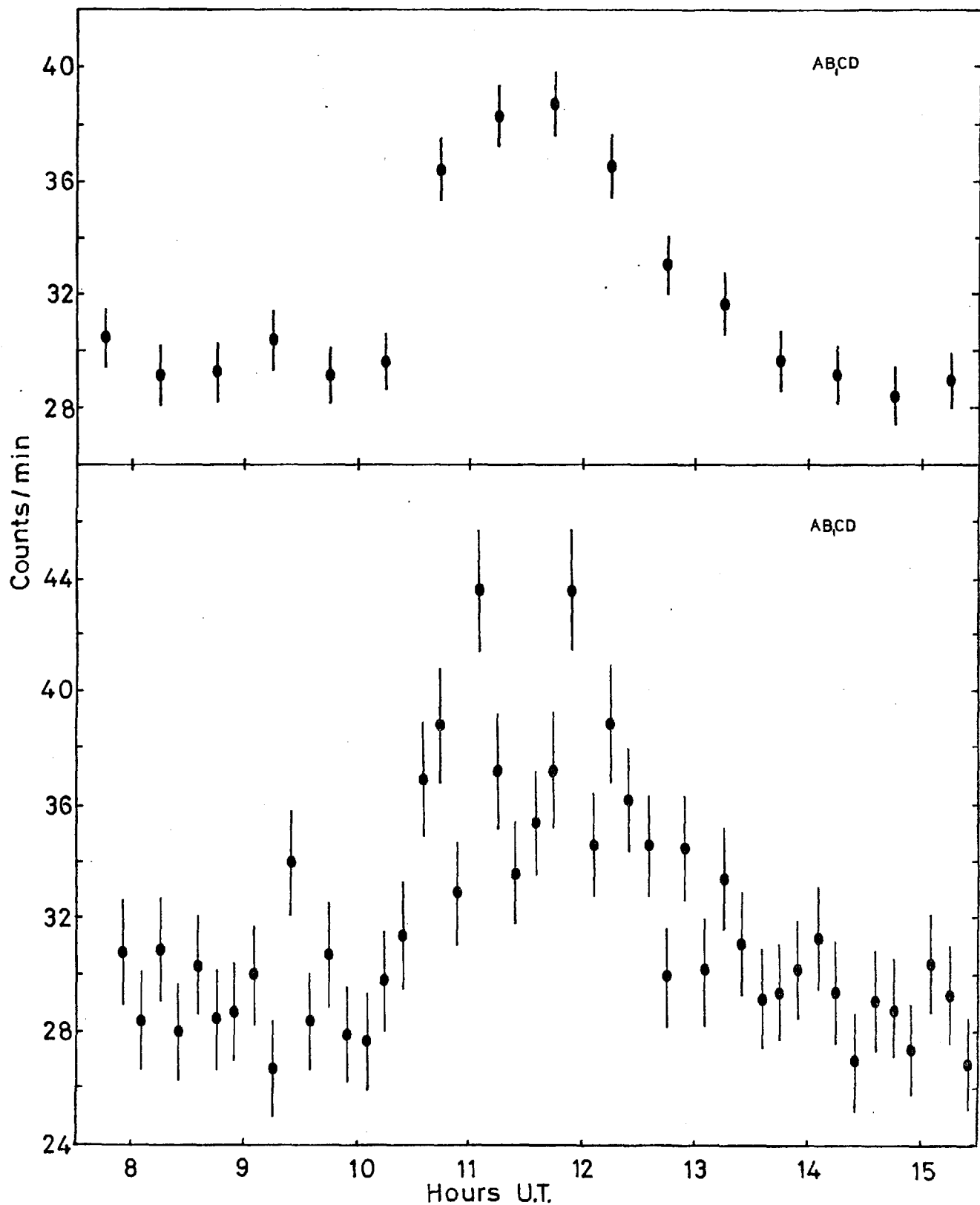


Fig. 5.1 The charged particle increase observed during the balloon flight of Oct. 31st 1968. Data are normalised to 4.5 gm/cm^2 and analysed in 30 and 10 minute intervals.

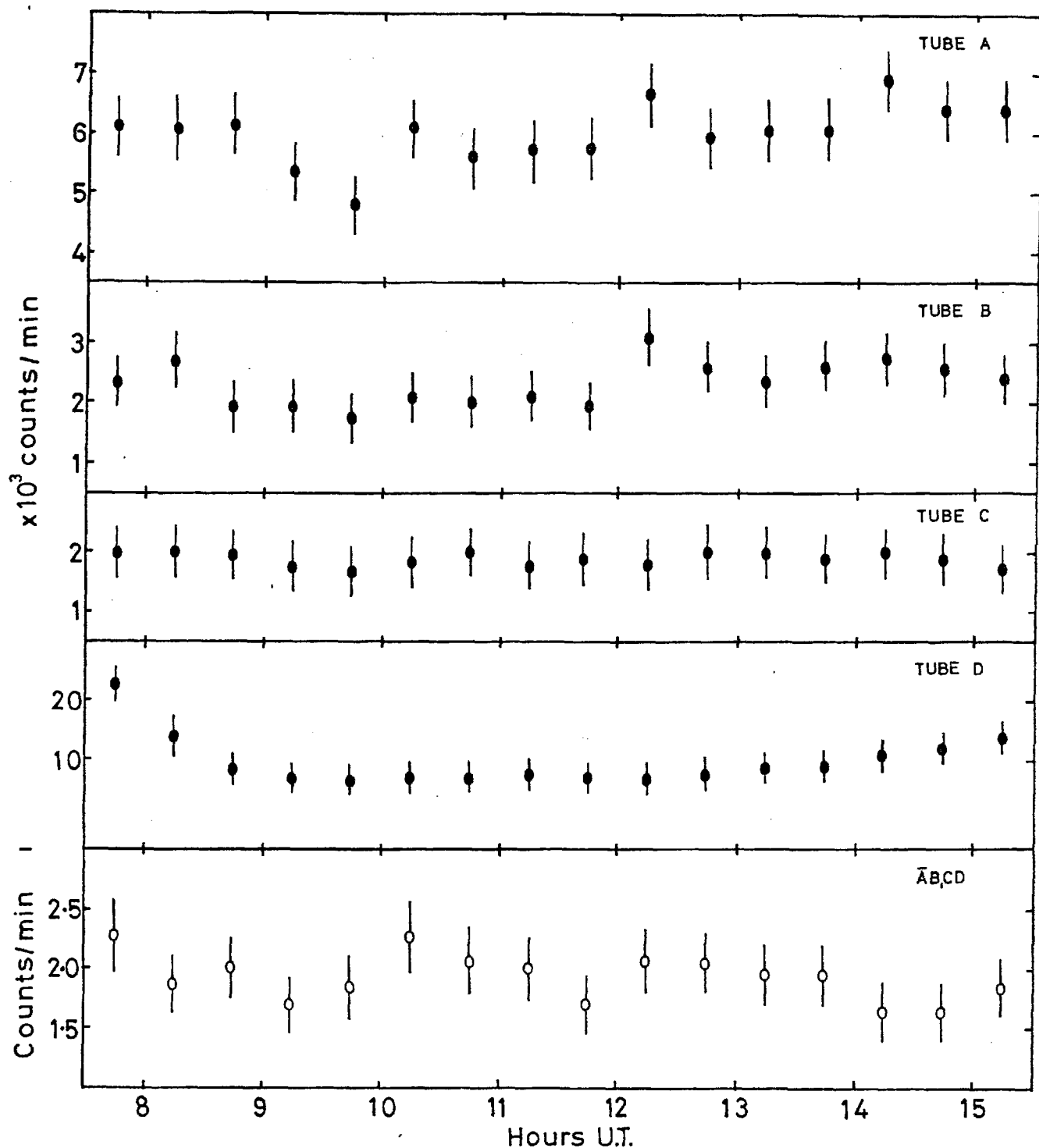


Fig. 5.2 Altitude count rates of the four photomultipliers and the gamma-ray channel ($\overline{AB}, CD$) for the duration of the flight of Oct. 31st 1968.

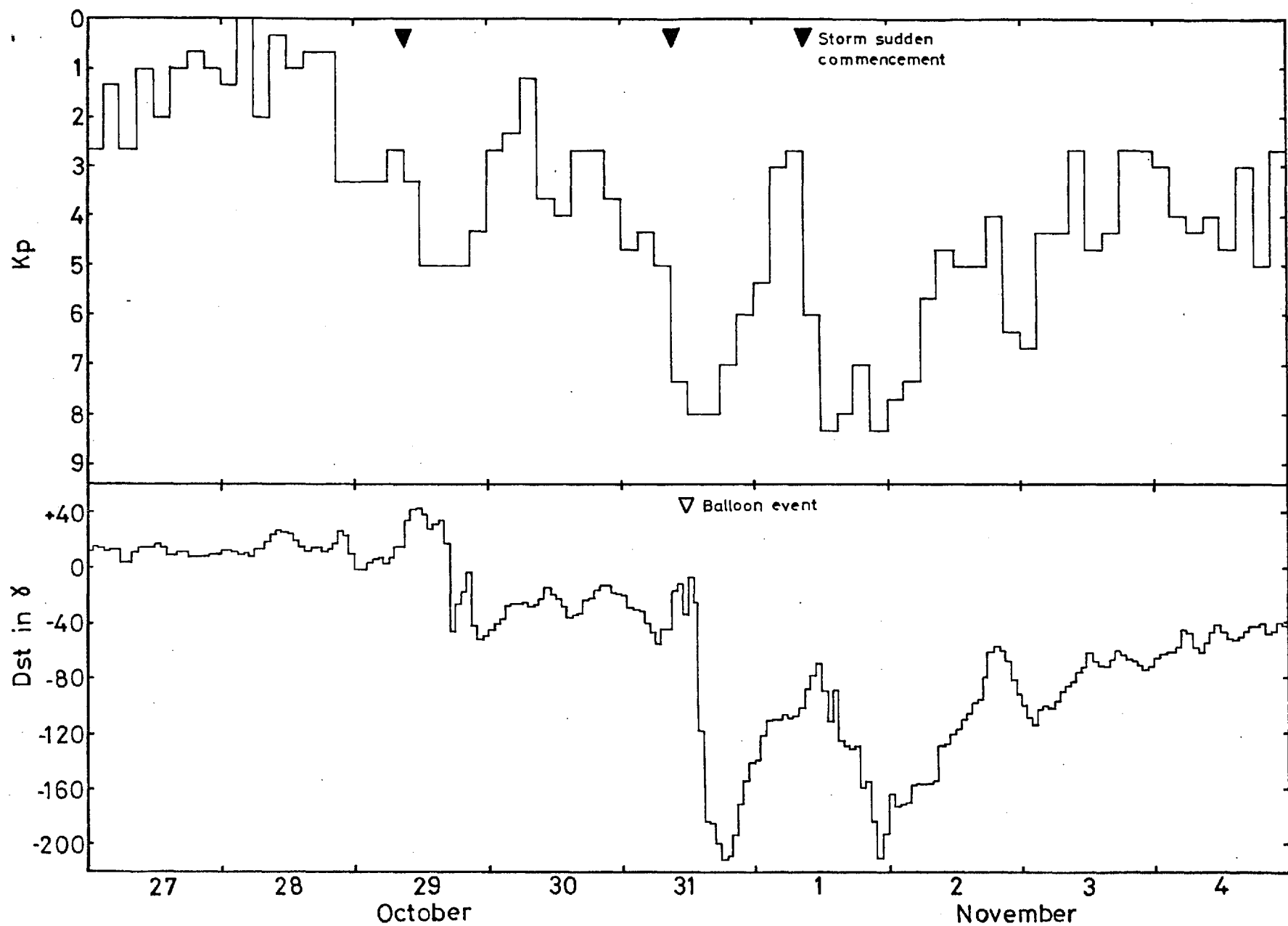


Fig. 5.3 Planetary magnetic 3-hour range indices, Kp, and the hourly values of equatorial Dst, for the period 27th Oct. - 4th Nov. 1968.

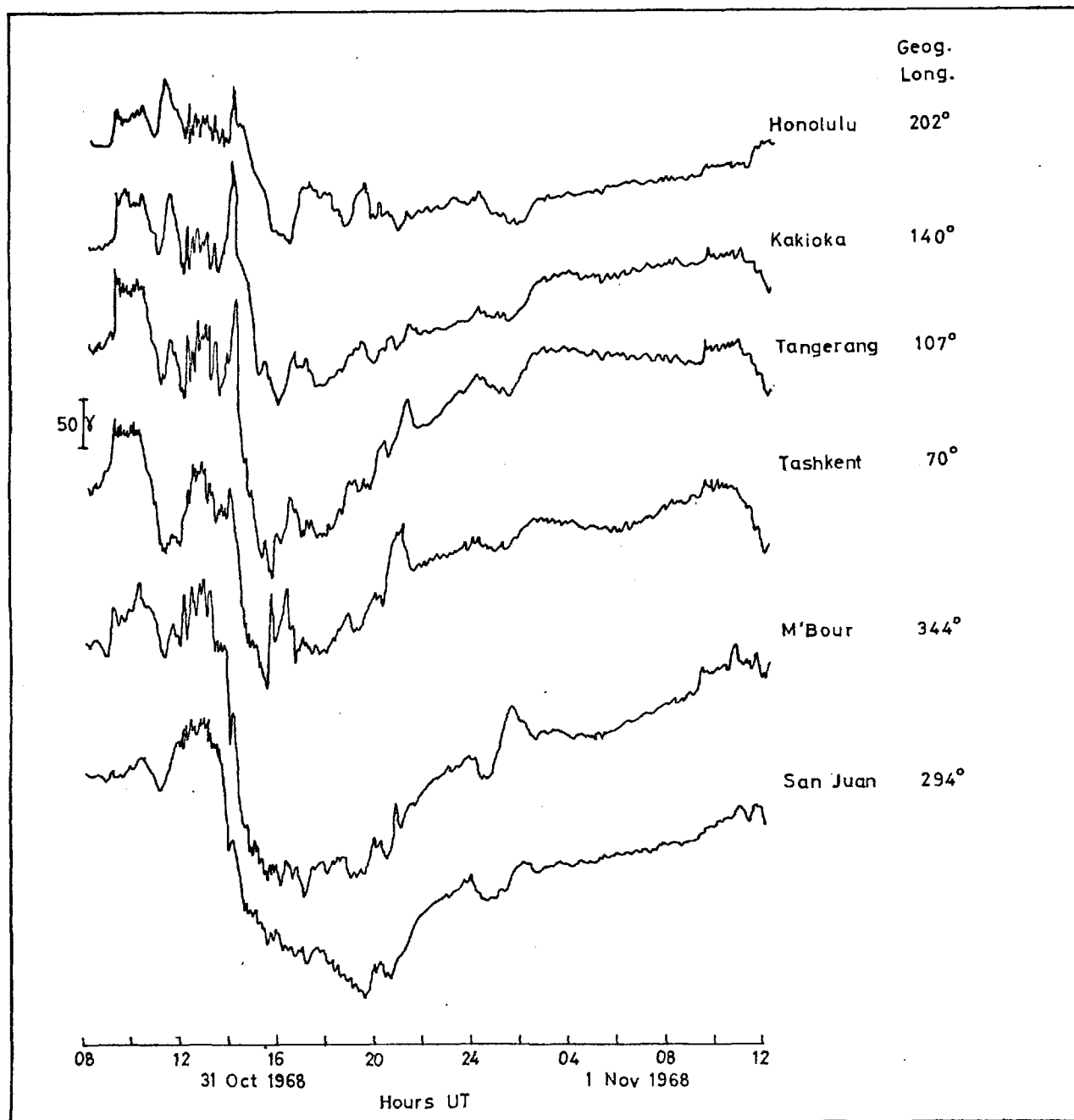


Fig. 5.4 H component magnetic records from six low latitude stations for the Oct. 31st storm.

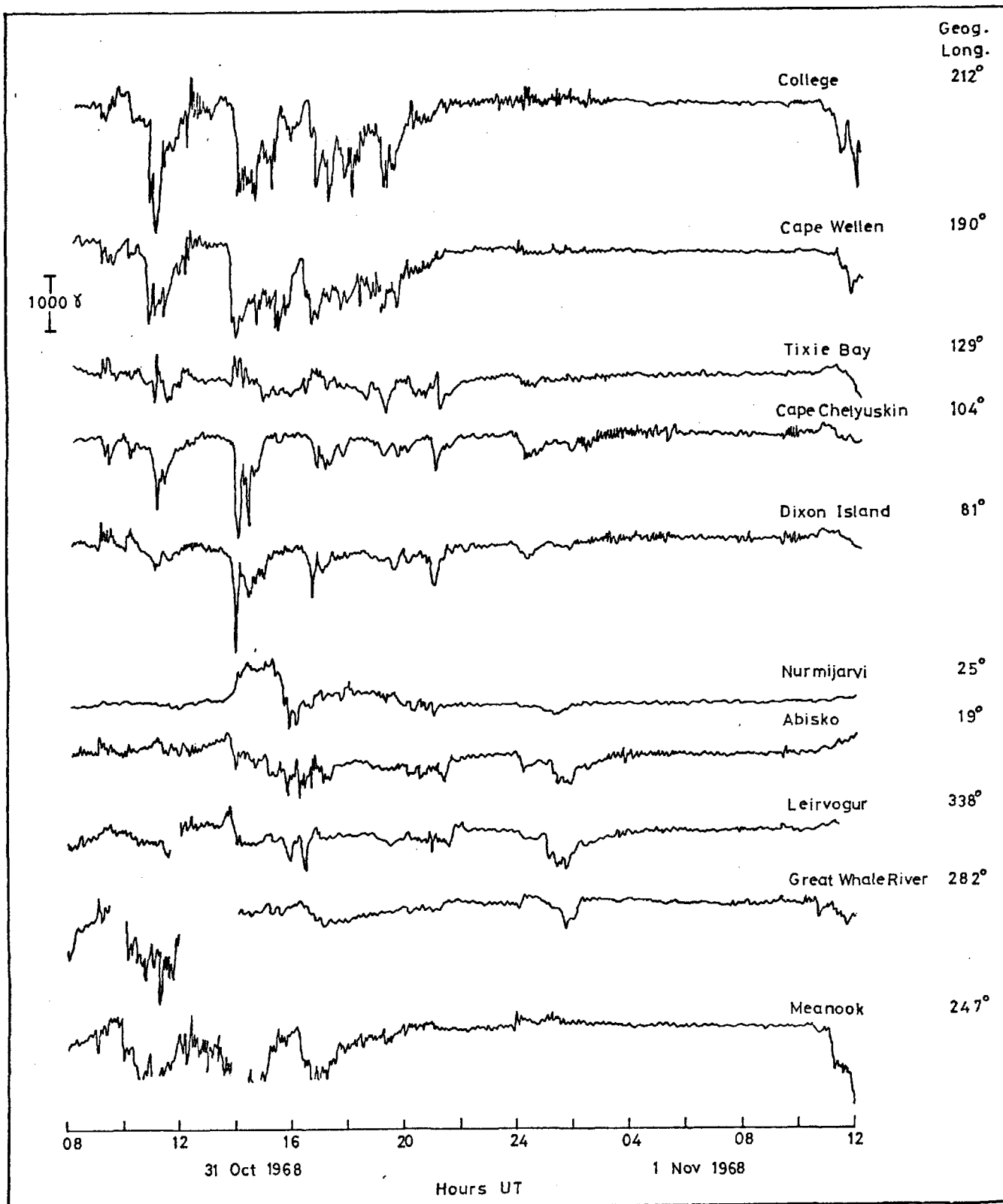


Fig. 5.5 H component magnetic records from ten high latitude stations for the Oct. 31st storm.

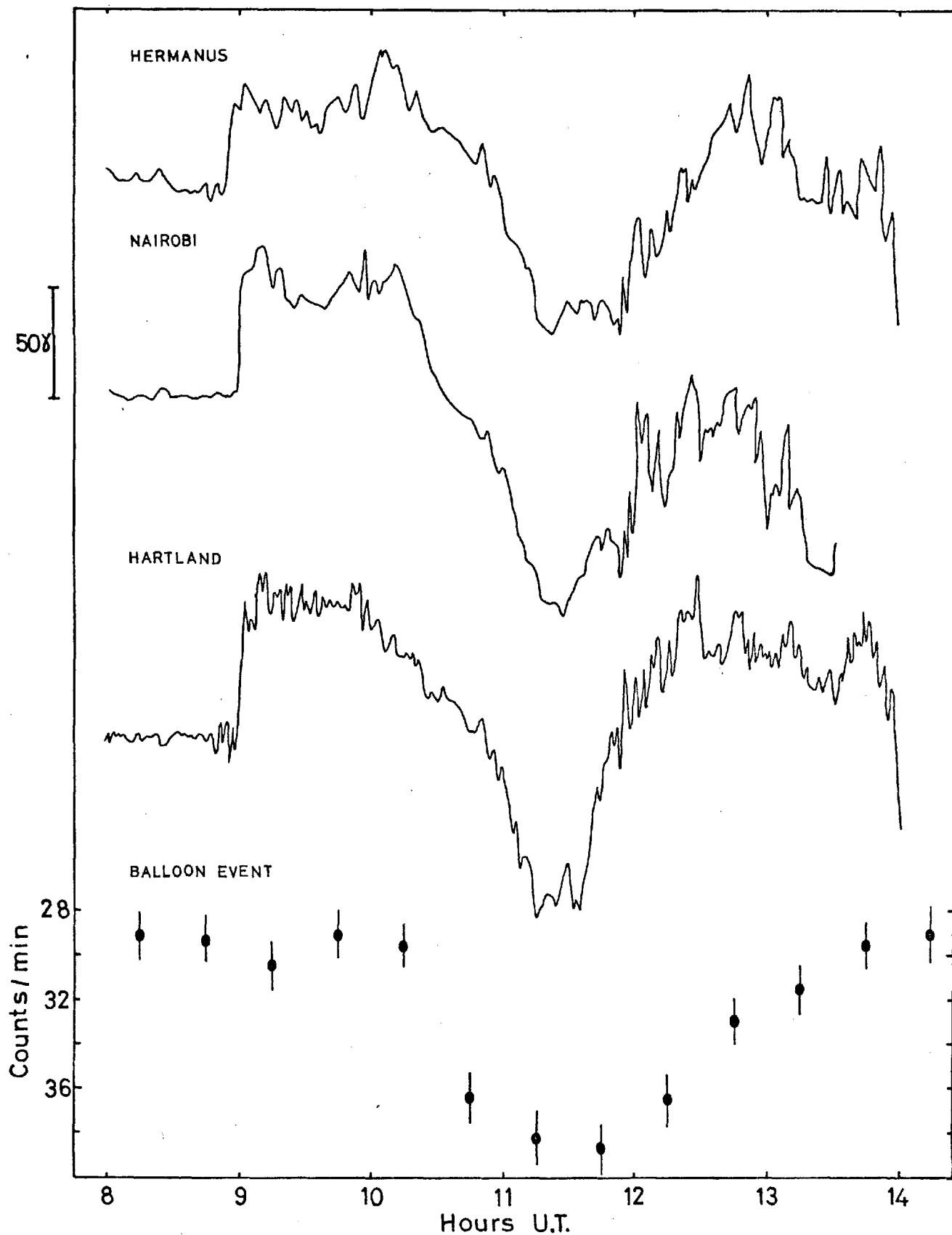


Fig. 5.6 H component magnetic records at the time of the balloon event for three stations in approximately the same local time sector as

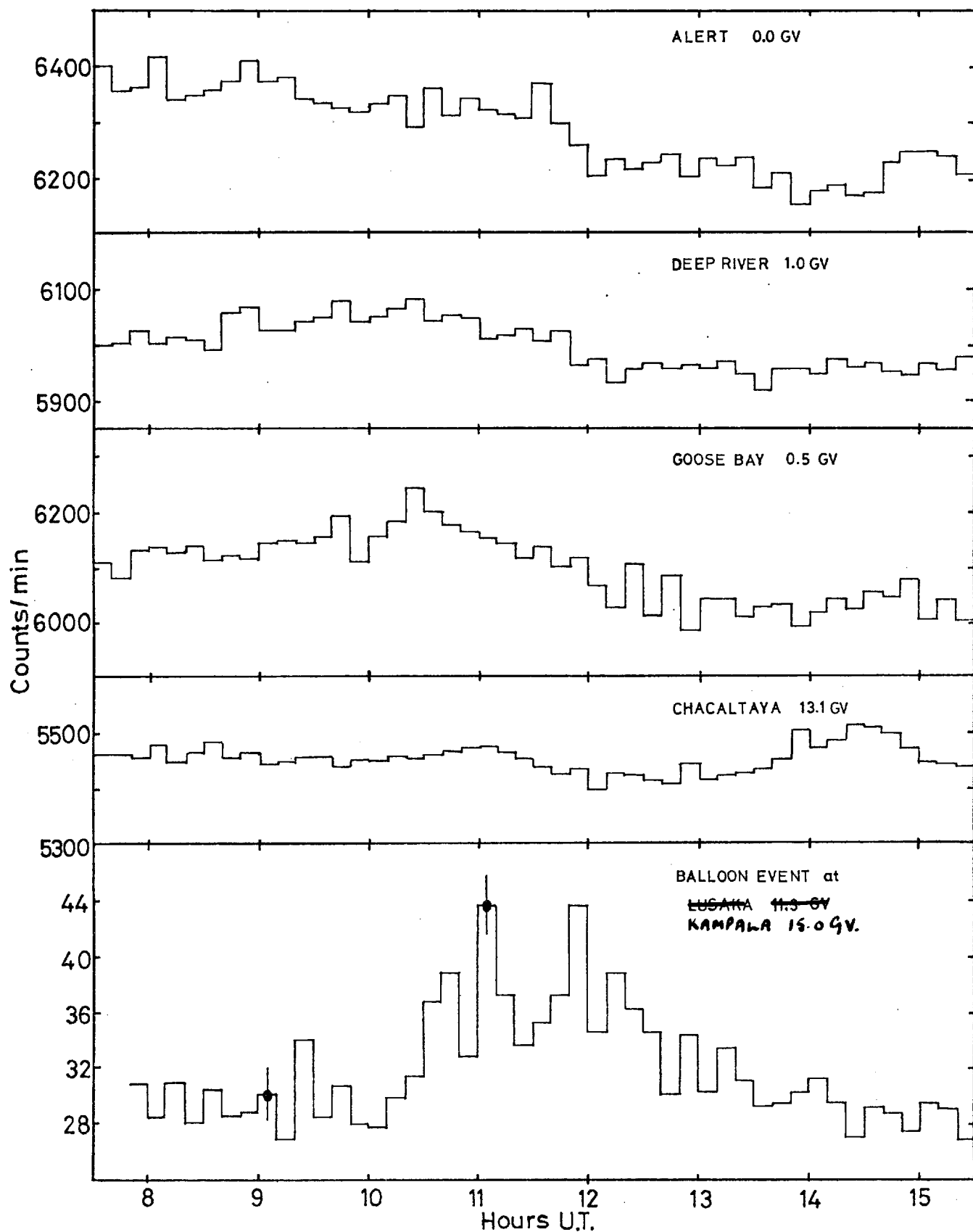


Fig. 5.7 Ten minute pressure corrected data from various neutron monitor stations for the time of the balloon event.

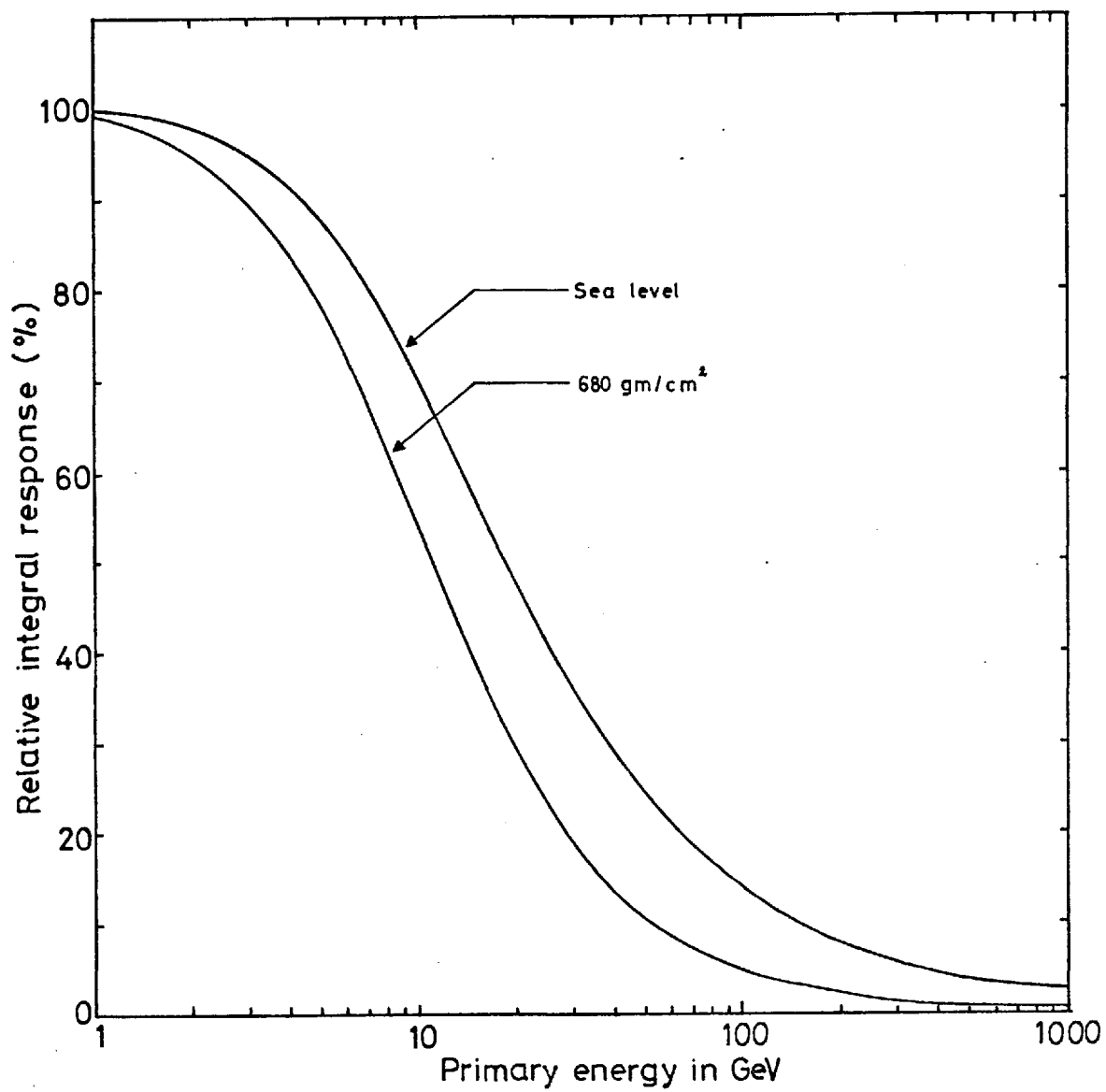


Fig. 5.8 Relative integral response for neutron monitors at sea level and at 680 gm/cm².

VI Energetic Protons in the Inner Radiation Belt

6.1. Charged Particle Motion in the Magnetosphere

6.1.1. Adiabatic theory of trajectories

The motion of a charged particle in the earth's magnetic field is complicated, but fortunately can be simplified by use of the Alfven guiding centre approximation and the so-called adiabatic invariants.

If a particle of charge q has a velocity $\underline{v}$ with components $v_{||}$, parallel to the magnetic field $\underline{B}$, and $v_{\perp}$, perpendicular to $\underline{B}$, then in the absence of an electric field the motion is generally a spiral about a line of force in a helix-like path of radius of gyration

$$a = \frac{mv_{\perp}}{qB} = \frac{mv \sin \alpha}{qB} \quad (1)$$

Here m is the relativistic mass and α is the pitch angle defined by

$$\tan \alpha = v_{\perp}/v_{||}$$

Provided that the magnetic field varies slowly in time and space the motion may be regarded as a circling motion about a guiding centre which tends to follow a line of force.

The gyration about the line of force generates a current loop.

The magnetic moment μ of this loop is the current times the area enclosed

$$\begin{aligned} \text{i.e.} \quad \mu &= IA \\ &= \left(\frac{qv_{\perp}}{2\pi a} \right) \pi a^2 \end{aligned}$$

and thus from (1)

$$\begin{aligned}\mu &= \frac{1}{2} \frac{mv_{\perp}^2}{B} \\ &= \frac{E_{\perp}}{B}\end{aligned}$$

If the variation of B is slow enough so that the motion is periodic, then μ is the first adiabatic invariant. The conditions for adiabatic invariance of μ are that changes of magnetic field are small over one radius of gyration a and during one gyroperiod t_g . The gyroperiod is the characteristic time period of the first invariant and is defined by

$$t_g = \frac{2\pi m}{qB}$$

The requirements are

$$\left| \frac{\nabla B}{B} \right| \ll \frac{1}{a}$$

and
$$\frac{dB}{dt} \ll \frac{B}{t_g}$$

We can write

$$\mu = \frac{E_{\perp}}{B} = \text{constant} = \frac{E \sin^2 \alpha}{B}$$

Then since a static magnetic field does no work on a particle, the energy remains constant. Thus

$$\frac{\sin^2 \alpha}{B} = \text{constant}$$

From this equation we can see that as the particle spirals along the

field line into a region of higher B , α must increase until bouncing or reflection occurs when α reaches $\pi/2$. On a line of force B has a minimum at the geomagnetic equator and the particle has bounce or mirror points at points of equal field strength in the Northern and Southern hemispheres. If α_0 and B_0 are the pitch angle and field strength at some arbitrary reference point (usually the geomagnetic equator), then the particle will mirror where the field strength is

$$B_m = \frac{B_0}{\sin^2 \alpha_0}$$

The bouncing motion leads to the second adiabatic invariant, known as the longitudinal invariant, defined by

$$J = 2 \int_{M_S}^{M_N} mv_{\parallel} ds$$

The integration is over the path length between the two mirror points. Because of the constancy of μ , this can be written

$$J = 2mv \int_{M_S}^{M_N} \left(1 - \frac{B}{B_m}\right)^{\frac{1}{2}} ds$$

The reduced longitudinal invariant $I (= J/2mv)$ is often more convenient. The second characteristic period of trapped particle motion is associated with the longitudinal invariant, and is the bounce period defined by

$$t_b = 2 \int_{M_S}^{M_N} \frac{ds}{v_{\parallel}}$$

Alfven also shows that a particle subject to a small force $\underline{f}$ will drift at right angles to both $\underline{f}$ and $\underline{B}$. Thus if $\underline{f}$ lies in the plane through the centre of the earth containing the earth's axis, the drift will be azimuthal and will represent a drift in longitude. For energetic particles in the earth's magnetic field this drift has two components both caused by non-uniformity of the field. These are the curvature of the field lines and the gradient of the field strength normal to $\underline{B}$. The third natural period of trapped particle motion is the longitudinal drift period t_d , the time for the particle to complete one orbit of the earth. The drift of guiding centres is westward for protons and eastward for electrons.

The final adiabatic invariant is associated with this drift period and is called the flux invariant Φ , where

$$\Phi = \int \underline{B} \cdot d\underline{A}$$

The integral is taken over the surface of a magnetic shell on which the guiding centre of the particle remains on its longitudinal drift. Because of the drift, the mirror points form circles in the northern and southern hemispheres and Φ is the magnetic flux through these circles.

6.1.2. The B - L coordinate system

Early attempts to map the intensity distribution of trapped particles were hampered by the very large spatial gradients. At low altitudes in the inner zone, a change in geocentric distance of $\sim 3\%$ results in an intensity change of over a factor of 10. The fact that the earth's field deviates more than 3% from any possible dipole repre-

sentation and that there are even more significant local anomalies at low altitudes, meant that attempts to use dipole based coordinate system produced disordered results.

To overcome these difficulties McIlwain (124) introduced a 'natural' magnetic system of coordinates for trapped particles, which had the advantage of reducing the 3-dimensional problem to a 2-dimensional one. This system has become the most widely used in the representation of trapped particle distributions.

If the adiabatic invariants are conserved for a given set of trapped particles, the directional intensity perpendicular to the lines of force will be the same at all points characterized by the same values of B and I. These points form rings in both hemispheres and a particle will remain on a 'magnetic shell' formed by those lines of force which are connected by a line of constant B and I. The McIlwain system defined a parameter, L, which labels the magnetic shells. Because each locus of constant B or I is a line on a magnetic shell, the parameter could be a function, F(B,I) which was also constant along lines of force. McIlwain defined

$$\frac{L^3 B}{M_e} = F \left(\frac{IB}{M_e} \right)$$

where I and B are calculated for the point in question with the use of a representation of the real field while F is calculated with a dipole field.

It should be noted that this mapping of a point from the real field into a point in the dipole field is unique, strictly speaking,

only for particle orbits which mirror at the point in question. However, because the field distortion is not too severe, all the orbits passing through a given point in the real field hopefully should map into the same point in the dipole field. McIlwain's calculations show that the variation of L along most lines of force was $<1\%$.

L is usually given in earth radii and gives the equatorial distance of the shell it defines.

6.2. Behaviour of Trapped Protons of Energy $\gtrsim 500$ MeV

Although it is possible that a process responsible for dumping trapped protons of $\gtrsim 500$ MeV also affected protons of lower energies, specific mention must be made of the characteristics of those of $\gtrsim 500$ MeV. The population of such energetic protons in the inner radiation zone has been shown in the past to be particularly stable.

6.2.1. Spatial distribution

Measurements in the inner zone of such highly energetic protons have been few. The most comprehensive were by Garmire (125), who with the gamma-ray detector on the Explorer 11 satellite also measured trapped protons of energy >350 MeV up to about 1.2 earth radii and between $\pm 25^\circ$ geomagnetic latitude. The average proton energy measured by the detector near the geomagnetic equator was estimated at ~ 600 MeV.

The normalised equatorial pitch angle distribution of these protons as measured by Garmire is shown in Fig. 6.1. The solid line is a theoretical derivation and is a good fit to the data. In a dipole field the equatorial pitch angle, α_e , is related to the mirror point latitude,

λ_m , by

$$\sin^2 \alpha_e = \frac{\cos^6 \lambda_m}{(4 - 3 \cos^2 \lambda_m)^{\frac{1}{2}}}$$

Using this, the theoretical pitch angle distribution was converted to a mirror point latitude distribution. This is also illustrated in Fig. 6.1. From this it can be seen that the HWHM of the mirror point latitude distribution is about $4\frac{1}{2}^\circ$, and that apparently all the protons mirror within 12° of the geomagnetic equator. For protons of energy >500 MeV, the distribution will tend to be even more sharply peaked around the geomagnetic equator.

It was suggested by Singer (126) that the absence of protons above a certain energy on a given magnetic shell was due to the breakdown of trapping conditions because of the violation of the first invariant. This happens when the gyradius becomes comparable to the scale length of the inhomogeneities of the magnetic field. For the maximum momentum of a trapped particle on a given field line he obtained

$$P_{\max} = P_0 L^{-2}$$

The value of P_0 has been obtained empirically from trapped particle measurements. The results of Fan et al. (127) were interpreted by Lenckek and Singer (128) as corresponding to a value $P_0 = 1800$ MeV/c. The data from Explorer 11 (Garmire) were more consistent with a value of 2000 MeV/c. Imhof and Smith (129) also found that their data for proton in various integral channels from >34 MeV to >148 MeV was also fitted by $P_0 = 2000$ MeV/c. The variation in maximum trapped proton

energy with L , derived using $P_{\max} = P_0 L^{-2}$ with $P_0 = 2000 \text{ MeV/c}$, is plotted in Fig. 6.2, along with the results of Garmire and Imhof and Smith.

Dragt (130) and Wentzel (131) considered the breakdown of trapping conditions in the resonance between the gyrofrequency of a particle and a low frequency hydromagnetic wave propagating along the field line. The two authors reach somewhat different conclusions in spite of the use of similar models. The maximum trapped proton energy as a function of L as determined by Dragt for a maximum h.m. wave frequency, $\nu_{\max}$, of 3 hz and 1.5 hz are shown in Fig. 6.2. $\nu_{\max}$ is dependent upon the local ion cyclotron frequency.

From the figure it can be seen that the Singer theory predicts that for protons of $>500 \text{ MeV}$, the maximum L value is ~ 1.36 , whilst the Dragt theory predicts a maximum L value of ~ 1.76 . The experimental evidence appears to support the adiabatic invariant breakdown, so it would appear reasonable to conclude that trapped protons of energy $>500 \text{ MeV}$ do not extend to more than $L \approx 1.36$.

6.2.2. Characteristic time constants

As already described, there is a characteristic time constant associated with each invariant of adiabatic motion. Any perturbation which results in a departure from adiabatic motion due to the violation of an adiabatic invariant, must take place in a time short compared to the corresponding time constant. Typical time constants for trapped 500 MeV protons are calculated in the following sections.

(a) The gyroperiod is defined as

$$\begin{aligned} t_g &= \frac{2\pi m}{qB} \\ &= \frac{2\pi m_0}{e} \frac{\gamma}{B} \end{aligned}$$

In the equatorial plane, the magnetic field at a distance L earth radii is given by M_e/L^3 where M_e is the magnetic field at ground level at the equator. So for a 500 MeV proton ($\gamma = 1.533$) at 1.2 earth radii on the equator, the gyroperiod is ~ 5.6 m sec. The corresponding gyroradius, a , is ~ 200 km.

(b) The bounce period, t_b , has been calculated by Hamlin et al. (132), who found that good approximations were obtained from some simple formulae. Their approximations gave

$$\begin{aligned} t_b &\approx \frac{4LR_E}{v} (1.30 - 0.56 \sin \alpha_e) \\ &= 3.3 \times 10^9 (L/v) (1 - 0.43 \sin \alpha_e) \text{ sec} \\ &= 0.11 (L/\beta) (1 - 0.43 \sin \alpha_e) \text{ sec} \end{aligned}$$

The equatorial pitch angle distribution of 500 MeV protons is sharply peaked around 90° , with a minimum at $>60^\circ$: so even for $\alpha_e = 60^\circ$, a 500 MeV proton at 1.2 earth radii has $t_b = 0.11$ sec.

(c) The drift period was also calculated by Hamlin et al. Their expression was

$$t_d \approx \frac{3.9 \times 10^9}{EL(1 + 0.29 \sin \alpha_e)} \text{ sec}$$

where E is the kinetic energy of the particle in eV. For a 500 MeV proton as above, $t_d \approx 5.2$ sec.

6.2.3. Total population

A rough estimate of the total population of trapped protons of >500 MeV can be made, to appraise the significance of the intensity measured at the balloon.

The variation of the proton integral intensity with distance in the equatorial plane is controlled by two factors; the atmospheric density at low L , and the breakdown of the first adiabatic invariant at higher L . If $\phi(E)$ is the differential directional source spectrum and $\bar{\rho}_e(L)$ is the average effective atmospheric electron density at L , then the integral directional intensity at L is given by

$$j(>500, L, \alpha_e) = K \frac{1}{\bar{\rho}_e(L)} \int_{500}^{E_c} \phi(E) dE \quad \text{protons/cm}^2 \text{ sr sec}$$

where K is a constant at low L and high energies. The cut-off energy E_c is a function of L and was obtained from the graph in Fig. 6.2. Using $\phi(E)$ and $\bar{\rho}_e(L)$ as given by Lenchek and Singer (128) a radial profile of $j(>500, L, \alpha_e)$ in the equatorial plane was obtained. Although no direct measurements at >500 MeV have been made, Garmire measured the radial profile at >350 MeV at $1.10 \leq L \leq 1.18$. With the integral spectrum derived from the Lenchek and Singer differential spectrum (as used by Garmire himself), the Garmire measurements were reduced to measurements at >500 MeV. The calculated radial profile of $j(>500, L, \alpha_e)$ for the whole trapping region was then normalised to these values.

The omnidirectional intensity, $J(>500, L)$, was obtained from the directional intensity by

$$J(>500, L) = 4\pi \int_{\alpha_{e\min}}^{\pi/2} j(>500, L, \alpha_e) \sin \alpha_e d\alpha_e \quad \text{protons/cm}^2 \text{ sec}$$

If $j(>500, L, \alpha_e)$ can be expressed as $j(>500, L) f(\alpha_e)$, where $f(\alpha_e)$ is the normalised equatorial pitch angle distribution, then

$$\begin{aligned} J(>500, L) &= j(>500, L) 4\pi \int_{\alpha_{e\min}}^{\pi/2} f(\alpha_e) \sin \alpha_e d\alpha_e \quad \text{protons/cm}^2 \text{ sec} \\ &= j(>500, L) I(\alpha_e) \end{aligned}$$

The normalised equatorial pitch angle distribution for protons of >350 MeV as measured by Garmire (Fig. 6.1), was taken as applicable at the higher energies and the integral $I(\alpha_e)$ was evaluated graphically.

If t_b is the bounce period (approximately constant at 0.1 sec over the range of interest), then the total number of protons/cm² at L is given by

$$t_b J(>500, L)$$

Thus the total number of protons in the trapping region is

$$t_b \int J(>500, L) dA_e$$

where dA_e is the area element in the equatorial plane. If it is assumed that there is azimuthal symmetry and that the longitudinal drift does

not effect the number of particles passing through unit area, then dA_e is given by $2\pi R_E^2 L dL$, where R_E is the radius of the earth. Therefore the total number of protons, $N_T(>500 \text{ MeV})$, in the inner radiation zone is given by

$$N_T(>500) = 2\pi R_E^2 I(\alpha_e) t_b \int_{L_{\min}}^{L_{\max}} j(>500, L) L dL$$

The quantities $j(>500, L) L$ are shown in Fig. 6.3. The integral was evaluated graphically and the final result was

$$N_T(>500) \approx 98 R_E^2$$

This figure can be compared with the number of excess protons measured during the balloon event. The intensity was $5 \times 10^{-3}/\text{cm}^2 \text{ sr sec}$ for a period of about 10^4 secs. Thus if the precipitation was isotropic and uniform over the whole trapping region ($\pm 12^\circ$ geomagnetic latitude), then the total number of protons, N_M , measured during the event was

$$N_M(>500) \approx 86 R_E^2$$

Whilst the calculation of the trapped proton population most probably cannot be trusted to much better than a factor of ten, and the assumption of a precipitation uniform over the whole available area is probably unjustified, it is evident that if trapped protons were responsible for the event, then the event was of major significance with respect to the total population.

6.3. Origin and Loss of Energetic Trapped Protons

6.3.1. The CRAND theory

Shortly after the initial observations of trapped particle fluxes, it was proposed that they were not electrons from the solar plasma but energetic protons produced by the decay of cosmic ray albedo neutrons - CRAND. (Singer (133), Hess (134), Lenchek and Singer (128) and (135).) A fraction of the upward moving albedo neutrons produced by the interaction of cosmic rays with atmospheric nuclei would decay close enough to the earth for the decay protons to be trapped in the geomagnetic field. In conjunction with the adiabatic loss processes to be described later, the equilibrium spectra predicted by the CRAND theory were in fair agreement with the early measured spectra in the range from about 30 MeV to 300 MeV, for altitudes of $L \leq 1.6$ near the equator. The agreement was not so good at higher L and higher B .

The calculated fluxes at low altitudes can, however, only be said to agree with experiment if allowances are made for deficiencies as large as a factor of 6.5 (Haerendel (136)), a factor of 20 (Hess and Killeen (137)), or a factor of 50 (Dragt et al. (138)). Discrepancies might be reduced by considering the uncertainties in both the measured and calculated fluxes. The latter are particularly sensitive to the models chosen for the atmosphere and magnetic field. They are also based on an albedo neutron flux extrapolated from <20 MeV, there being no reliable measurements at higher energies. The absolute fluxes agreed better at higher altitudes but this was probably fortuitous and may be due to the

existence of additional loss mechanisms not included in the calculations. The discrepancies are also less near the equator than at low altitude on the same field line, so it was suggested (Freden et al. (139)) that CRAND was still the dominant source but that the trapped protons were scattered down the lines of force by non-atmospheric processes.

As CRAND is essentially a local time-independent source (varying only $\sim 12\%$ from its mean value over a solar cycle), the very low L-shell region was suggested by Imhof and Reagan (140) as being the best region to test the validity of the CRAND theory. At sufficiently low altitudes, the atmospheric effects are such that only protons with short lifetimes exist, so that any protons observed there would not have had time to be transported from elsewhere and must have been produced by the conjectured local source mechanism in conjunction with the atmospheric scattering process. The low L-shell region was suggested as being preferable to the low altitude region on higher L-shells, where pitch angle diffusion might continually add protons to the population. The experimental measurements of Imhof and Reagan on trapped protons of >64 MeV at $1.10 \leq L \leq 1.20$, confirmed the results of the other authors (also at low altitudes but on higher L-shells) when they found CRAND inadequate to explain the measured fluxes by a factor of ~ 20 .

The CRAND theory is also totally insufficient to explain the fluxes of protons of <30 MeV throughout the inner radiation belt.

6.3.2. Other possible sources

(a) The detection of a large flux of low energy protons in the inner belt by Naugle and Kniffen (141) led Lenchek (142) to postulate

an additional source due to solar proton albedo neutron decay (SPAND). Dragt et al. and Hess and Killeen, however, calculated that the SPAND contribution to the inner belt energetic proton was much less than that of CRAND. The geometry of SPAND, with a latitude cut-off of 60° , forbade any trapping below $L = 1.6$ and allowed no particles mirroring on the equator below $L = 3.5$.

(b) Lingenfelter et al. (143) investigated the solar neutron flux and calculated that it should exceed the cosmic ray albedo neutron flux for $L > 2$ and $E > 30$ MeV. Following this, Claflin and White (144) calculated that correspondingly the solar neutron decay (SND) contribution to the trapped proton population should exceed the CRAND contribution at $L > 2$ and $E > 30$ MeV.

(c) Either of these two sources could only become important in the low L-shell regions which directly concern this present work if there was some inward diffusion mechanism. If a particle diffused inwards in the earth's field with conservation of the first adiabatic invariant then it would be accelerated. An early suggestion by Kellogg (145) was that the radiation belts arose from injection of solar plasma at large distances, followed by an inward diffusion process. However, as pointed out by Dragt (146), the solar plasma is rich in alpha-particles whereas although some low energy alpha-particles have been detected in the radiation belts (Krimigis and Van Allen (147)), there appear to be none at higher energies (Fenton (148)). As radial diffusion is a non-adiabatic process it will be discussed in more detail later.

6.3.3. Adiabatic loss processes

Energetic protons are mainly lost from the radiation belts by Coulomb collisions with the constituents of the exosphere. Nuclear interactions are important ~~only~~ above ~ 300 MeV. Charge exchange with neutral hydrogen is significant only below ~ 1 MeV, and ~~elastic scattering~~ ~~ing~~ can be ignored.

Over most of the volume in which the trapped protons exist, the exosphere is composed of partly ionised hydrogen. At about 1.3 - 1.4 earth radii however, there is a transition region, below which the effective electron density increases sharply as the oxygen and nitrogen become predominant over the hydrogen. Thus the time variations of particles trapped on very low L-shells or with mirror points below the transition level are thought to be controlled by the variations in the atmospheric density. The most significant of these is the 11-year variation over the solar cycle, caused by the atmospheric heating due to the emission of extreme ultra-violet radiation by the sun.

The critical quantity for the trapped proton is its lifetime against atmospheric losses, and is a measure of the characteristic time with which the trapped flux would decay if the source were suddenly switched off. This quantity, T_p , is proportional to the energy of the proton and inversely proportional to the effective electron density averaged over the drift orbit. The latter is critically dependent upon the orbit and hence upon the models chosen for the magnetic field and the atmosphere. The usual approximation is to average the electron density over the drift orbit of the guiding centre, but for very energy-

tic protons where the gyroradius is large with respect to the atmospheric scale height, the density must also be averaged over the cyclotron orbit. The average density is mainly determined by the density at the minimum mirror altitude.

Exhaustive calculations of proton time variations were made by Dragt (146), which incorporated all atmospheric loss mechanisms. On orbits where the atmospheric loss time, T_p , was short with respect to the solar cycle period, T_s , he calculated that the intensities of both high and low energy protons would follow nearly exactly inversely the variation in the atmospheric density over the solar cycle. For $T_p \gg T_s$ he predicted very little variation even at low energies, the absolute flux being determined by the electron density averaged over the solar cycle for the orbit. For intermediate values of T_p the predicted intensity variations were complex and depended upon the energy of the protons, hence there would be spectral changes over the solar cycle as originally suggested by Blanchard and Hess (149). Dragt used the Harris and Priester (150) model of the atmosphere, where the influence of the solar cycle was incorporated by the inclusion of a function of the solar radio noise at 2800 MHz. This radio noise is closely correlated with the solar extreme ultra-violet radiation; both phenomena are related to the electron number density in the solar corona.

Macy et al. (151) calculated the time variation of 55 MeV trapped protons over the period 1961 - 1969 using the atmospheric density changes over that period as measured by the 2800 MHz solar radio noise. Taking a time independent source term they found excellent agreement

between their calculations and the experimental observations of 55 MeV protons on $L = 1.4$ at points with altitudes between 275 and 440 Km. From this they concluded that the atmospheric density controlled the intensity variation of all trapped protons which were at low altitude during some part of their orbits.

Other experimenters have not always been so successful in looking for predicted solar cycle variations and this has been regarded as another measure of the inadequacy of the CRAND source.

The atmosphere is also known to respond to geomagnetic disturbances. this response has been represented by an additional term in the generalised "total heating parameter", $S(t)$, (cf. $\bar{S}$ - Harris and Priester) which is used for specifying the atmospheric density. The geomagnetic term basically uses the 3-hour planetary index of magnetic activity, K_p . There is an observed time lag in the response of the atmosphere, and the improved version of the empirical geomagnetic term (Lew (152)) estimated that the lag was dependent upon the intensity of the disturbance and for unusually large storms could be as short as 0.1 day.

The measurements of the Echo-2 satellite revealed that there was a very significant short-term fluctuation in the atmospheric density associated with the intense magnetic activity of 31st October - 4th November 1968. The Echo-2 data are shown in Fig. 6.4 and 6.5, and indicate a maximum increase by a factor of ~ 4 , at 1060 Km. Dragt gave the expression for the atmospheric loss time as

$$T_p \approx 6 \times 10^{11} (\overline{\rho_e})^{-1} \tau(E) \text{ sec,}$$

where $\overline{\rho_e}$ is the effective average electron density and $\tau(E)$ is the "lifetime function" which is proportional to the energy. For a proton of 500 MeV, $\tau(E)$ was given as ~ 1000 sec/cm³. For such a proton at a typical L-value of 1.3, (even with the absolute minimum equatorial pitch angle of $\sim 60^\circ$) $\overline{\rho_e}$ was estimated from the calculations of Dragt and Cornwall et al. (153) as only $\sim 10^6$ atomic electrons/cm³. Substitution in the relationship above gives, for 500 MeV protons,

$$T_p \approx 6 \times 10^8 \text{ sec} \approx 20 \text{ years.}$$

With such a long lifetime it is difficult to see how a transient increase of a factor of ~ 4 in the atmospheric density could effect the trapped protons enough to cause the observed balloon event. At $L = 1.3$, the equatorial pitch angle would have to be $< 38^\circ$ for the mirror altitude to be < 100 Km, whereas the minimum angle is normally $\gtrsim 60^\circ$. The density change is insufficient to produce the catastrophic change in pitch angle required. A density change of much greater magnitude and short duration may have taken place, but the sampling interval of the Echo-2 data is insufficiently short to resolve such a possibility. It is difficult, however, to imagine that such a change occurred at the time of the balloon event, if it was dependent upon the geomagnetic activity as described above. Just prior to and during the balloon event the activity level was not exceptional by general standards and would be attained or exceeded on many occasions. If the significance of the event on the trapped proton population has not been grossly overestimated, then the idea of such events being fairly common occurrences is not in keeping with the

measured long-term stability of the population.

As it seems improbable that adiabatic processes can explain the balloon event, then non-adiabatic mechanisms must be considered.

6.4. Non-adiabatic Effects on Inner Zone Trapped Protons

One non-adiabatic effect has already been discussed in section 6.2.1.. The breakdown of the first invariant causes the loss of energetic protons beyond a certain L-value but cannot be responsible for the balloon event.

6.4.1. Diffusion and acceleration

The only mechanism that can apparently cause significant inward movements of trapped particles is a radial diffusion following violation of the third invariant. The term "diffusion" is used because the process is usually incorporated in the Fokker-Planck transport equation as a diffusion term.

Kellogg (145) was the first to suggest that particles could be transported through the geomagnetic field by a process that violated the third adiabatic invariant but conserved the first and second. He suggested that electric fields, induced by magnetic field fluctuations, in conjunction with irregularities in the geomagnetic field would produce a movement of trapped particles inwards or outwards. The irregularities in the earth's field would mean that the longitudinal drift velocity would vary with longitude. Thus provided that the field fluctuations took place in a time shorter than the drift period (the condition for violation of the third invariant), the particles would either gain or

very energetic protons, but the amplitude was $\sim 1 \gamma$ which is clearly inadequate if Kellogg's mechanism is applied.

The present magnetic storm displayed such micropulsations with a period ~ 3 secs and maximum amplitude $< 0.4 \gamma$, which occurred in two short groups just after 1600 U.T.. Unfortunately there are no balloon data available for this time. The pulsations were recorded at mid-latitude at Chambon-la-Forêt and at equatorial latitude at Addis Ababa (Selzer and Roquet (154)). Both these stations are in approximately the same local time sector as Kampala. The rapid-run magnetogram from M'bour is shown in Fig. 6.6. M'bour was in the mid-morning sector at the time of the balloon event; about $3\frac{1}{4}$ hours earlier in local time than Kampala. High frequency oscillations are apparent in the record, particularly around 1045 U.T. which was coincident with the growth of the bay and the balloon event. The period of these oscillations is ~ 9 secs but the amplitude is still only $\sim 0.2 \gamma$. The sensitivity of the La Cour type magnetometer at M'bour was such that it was not suitable for the recording of pulsations of a much shorter period than this. The M'bour record did not show the oscillations after 1600 U.T. recorded at Addis Ababa and Chambon-la Forêt. The former is about $3\frac{3}{4}$ hours later and the latter about $1\frac{1}{4}$ hours later in local time than M'bour.

Walt (155) has done an extensive review of radial diffusion in the radiation belts. Various workers have shown the diffusion coefficients to be strongly L dependent, with an approximately L^{10} dependence for magnetically induced diffusion. The process is less effective at low L shells because the geomagnetic fluctuations are less significant with

respect to the static magnetic field. By similar reasoning the process is most efficient, on a given L-shell, at the equator where the unperturbed field is a minimum. It is a factor of 10 less effective at mirror latitudes.

Electric potential field variations have also been suggested as a probably dominant contributor to diffusion. The work of Birmingham (156) for $L > 2$ showed that even moderate electric field fluctuations would produce a diffusion (with an L^6 dependence) several powers of ten larger than magnetic fluctuations could produce. Despite this, an extrapolation of his results to low L still indicates a time scale of greater than 100 days for even a 1% change in L . Clearly neither magnetic nor electric field induced radial diffusion can, on the simple theory, explain the impulsive balloon event.

Radial diffusion was applied, with a fair degree of success, by Farley et al. (157) in an analysis of the equilibrium distribution of 20 - 170 MeV trapped protons on the geomagnetic equator at $1.15 \leq L \leq 1.7$. With a local CRAND source and atmospheric losses, plus an additional radial diffusion term with a coefficient of $5 \times 10^{-9} L^9/\text{day}$, they obtained good agreement between experimental and theoretical intensity contours. The diffusion term effectively distributes the high energy protons produced by CRAND and accelerates low energy protons from higher L-shells in sufficient quantities to make up for the deficiency of CRAND in the <30 MeV range. It has however been pointed out by Haerendel (158) that care should be taken, even for protons, when applying diffusion to equilibrium conditions because the loss term is critical. A

balance between diffusive transport (which may be expected to vary with geomagnetic activity) and independent collisional loss alone, seems a doubtful basis for stable behaviour.

It appears that the violation of the third adiabatic invariant normally results in a continuous acceleration as a consequence of inward radial diffusion. The resulting perturbations of the inner belt protons caused by any one magnetic storm are generally very small and undetectable, particularly at low L and high energies. On a few occasions, however, during particularly violent storms the perturbations have been large and impulsive. The rapidity that characterized these events excludes simple diffusion as a means of transport and leaves direct electric field drift as a more likely explanation. As with diffusion the inward motion is associated with acceleration.

6.4.2. Experimental observations of significant events

During the large magnetic storm of September 22nd - 23rd 1963, the scintillation counter experiment on the Relay 1 satellite recorded sharp, almost discontinuous changes in the intensities of trapped protons of >34 MeV, over quite a broad region of space (McIlwain (159)). The most important changes took place in a matter of hours. The intensity decreased by over a factor of 10 in the region $L > 2.50$ and $B > 0.05$, but changed by $<10\%$ in the region $1.80 < L < 2.10$. The data revealed that the L dependence of the change depended strongly on the B value, there being little change on any line of force at the equator.

The magnetic record from the Fredricksburg observatory ($L \approx 2.7$)

showed low frequency fluctuations that McIlwain suggested might be directly related to the fluctuations occurring in the region of space where the motions of the trapped protons were perturbed. The rapid-run record revealed important components in the power spectrum of the fluctuations over the whole observable range ($\sim 0.1 - 0.0001$ Hz).

During the period of observation of the satellite five other magnetic storms with fluctuations of approximately the same period, but of only about one third of the amplitude, failed to cause any detectable variation, transient or permanent, in the proton intensities. This led McIlwain to surmise that either there was some threshold effect involved or that the low frequency fluctuations were not a good indicator of the magnitude of the fluctuations in the frequency range which actually perturbed the proton. McIlwain was confident that violation of the third invariant could account for his observations.

The effects of this storm were also observed by the Telstar 2 satellite (Gabbe and Brown (160)). They measured depletions of the 49 - 145 MeV trapped proton intensity at $L > 2.2$ which were in good qualitative agreement with McIlwain's result in regions where the data overlapped in space. They confirmed McIlwain's findings that the changes on a given L-shell were much more pronounced at high B. As the simple radial diffusion process is supposedly more efficient on the equator, this is another indication that some other process was at least in part responsible for the event. The reaction of the 18 - 27 MeV flux distribution, as recorded by Telstar, was similar to the 49 - 145 MeV reaction only less pronounced.

The April 18th 1965 storm also produced a non-adiabatic effect on 40 - 110 MeV trapped protons (McIlwain (161)). A decrease in intensity was observed at $L > 2.4$, although it was not as significant as in the September 23rd 1963 storm. This storm was also notable for the adiabatic redistribution of the protons at $L < 2.4$, in phase with the D_{ST} variation of the storm.

The effect of the trapped protons of September 23rd 1963 storm was so significant that the population did not recover completely to its prestorm intensity for nearly a year. The satellite 1963-38C observed this recovery on its measurements of trapped protons from 1.2 MeV to 100 MeV in the region $1.2 \leq L \leq 3.0$, from September 1963 through December 1968 (Bostrom et al. (162)). Following the recovery, the only other major perturbation in the highest energy channel (25 MeV - 100 MeV) during the period of observation was caused by the major storm of May 25th - 26th 1967. The data coverage from this satellite is not extensive but it is evident that there was a sharp decrease by a factor of ~ 3.5 at $L = 2.20$. On L shells < 1.80 this highest energy channel was apparently not effected by the storm. The recovery time at $L = 2.20$ was once again more than a year.

The response of the lower energy channels to this storm was much more complicated, with increases being noted on some L-shells and decreases in others, but in no case was there any effect at $L < 1.50$. There were also some fluctuations in the intensities measured by the lower energy channels, at the higher L-shells, on the occasions of other lesser storms.

The October 31st 1968 storm, during which the balloon event was recorded, is near the end of the data coverage of this satellite and it is difficult to see clearly the quantitative effects of that storm in their data. It does appear however that there were fluctuations in the proton intensity, but they were mostly at low energies and at $L > 1.50$.

6.4.3. Conclusions

Violation of the third adiabatic invariant results in a radial diffusion; the time scale of which for significant changes in L on low L shells is too long for it to ordinarily produce large impulsive flux changes during one magnetic storm.

The several large perturbations in the inner belt protons that have been observed during large magnetic storms have however had most of the characteristics of a violation of the third invariant. There is doubt, however, whether on the simple theory, the fluctuations in the geomagnetic field as recorded at ground level were sufficient to cause the changes. The flux changes were observed to be dependent both upon proton energy and positron. The energy dependence can be understood by the need for the geomagnetic fluctuations to have significant components in a period less than the proton drift period, which is itself energy dependent. The general decrease of the magnitude of the changes with decreasing L can be understood in terms of the decrease in the significance of the geomagnetic fluctuations with respect to the static magnetic field.

Thus to explain the October 31st 1968 balloon event in terms of

the dumping of 500 MeV trapped protons from regions close to the equator at $L \approx 1.35$ is doubly difficult. Certainly the magnetic records for the period showed no evidence of fluctuations sufficient to cause the dumping, by the simple theory alone. It may well be that ground level magnetic records do not adequately represent the conditions in the trapping region, and that these particular storms have peculiar characteristics which enable them to cause the changes in distribution by a process as yet unknown.

It is regrettable that no long term studies of the very high energy protons in the inner radiation belt have been attempted. If there are redistributions or depletions of the inner belt effecting these high energies in particular, then geiger and scintillation counter surveys at a much lower energy threshold are insensitive ways of detecting them. Even on the geomagnetic equator at $L = 1.3$ (the maximum of their spatial distribution) protons of >500 MeV would contribute only a few percent to the count rate of an integral detector with a threshold of 30 MeV. No high energy data were available for the period of the event.

If trapped protons were responsible for the event, it would have far reaching consequences on the theories of their origin. If such events are only associated with very exceptional magnetic storms then they are undoubtedly rare. Despite this, the magnitude of the depletion of these very energetic protons would mean that repopulation by the CRAND source could not take place sufficiently rapidly to be consistent with the accepted long term stability of the population. If the interpretation of the event as an important phenomenon is correct then there is

an obvious need for further investigations, particularly in the theoretical field.

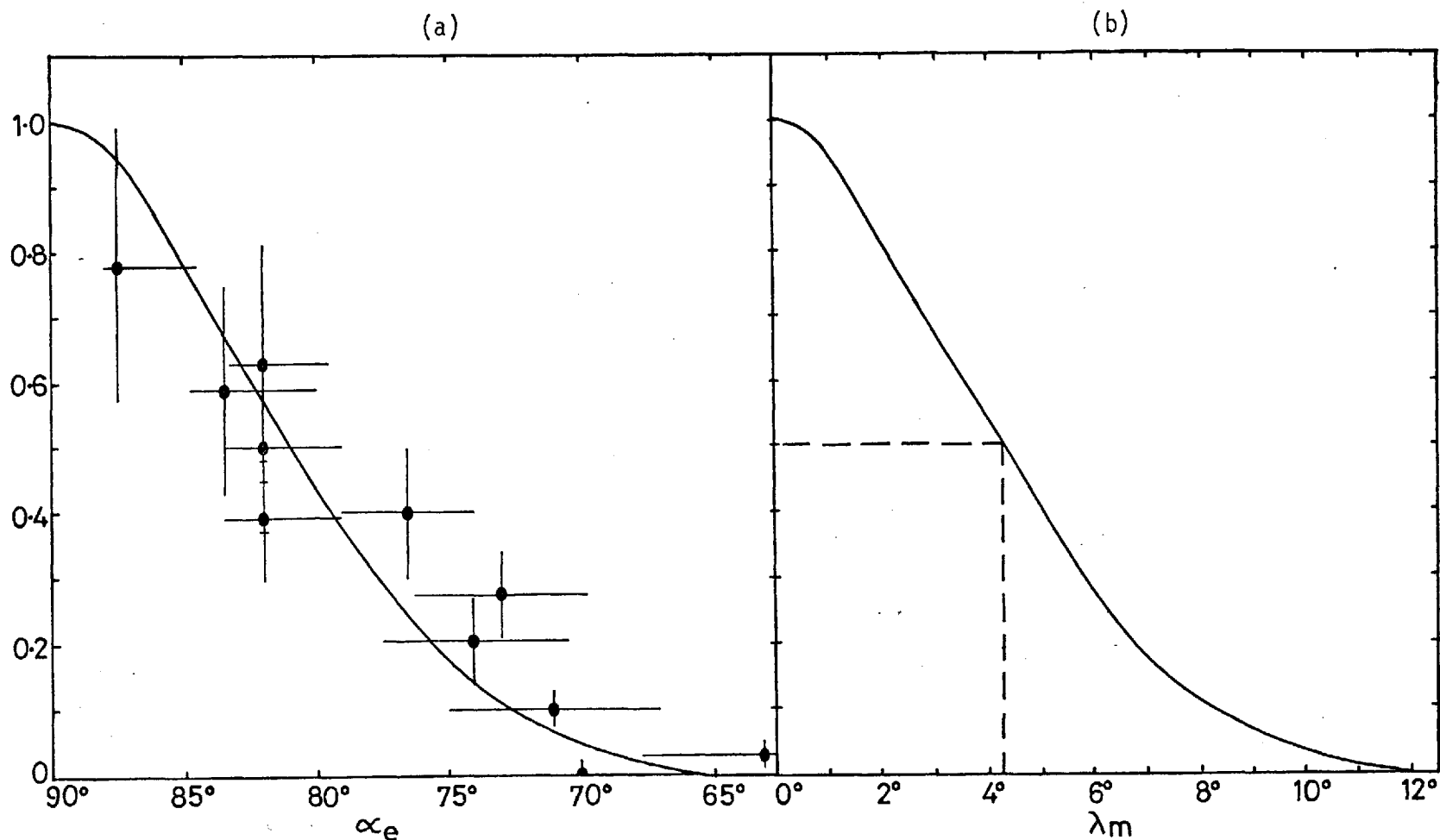


Fig. 6.1 (a) Normalised equatorial pitch angle distribution for trapped protons with $E_p > 350$ MeV at $L = 1.185$.

(b) Normalised mirror point latitude distribution for trapped protons with $E_p > 350$ MeV.

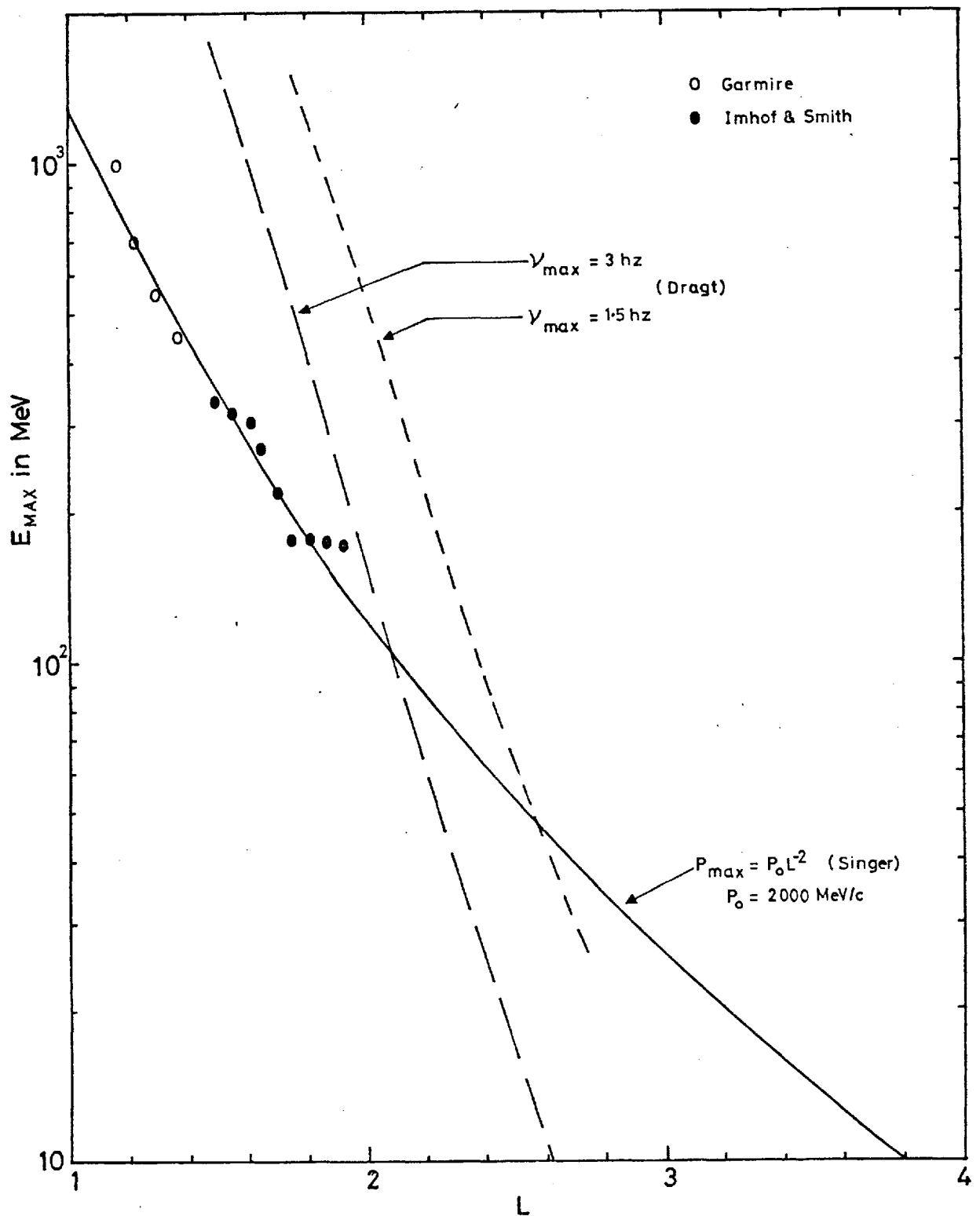


Fig. 6.2 Variation of maximum trapped proton energy with L value.

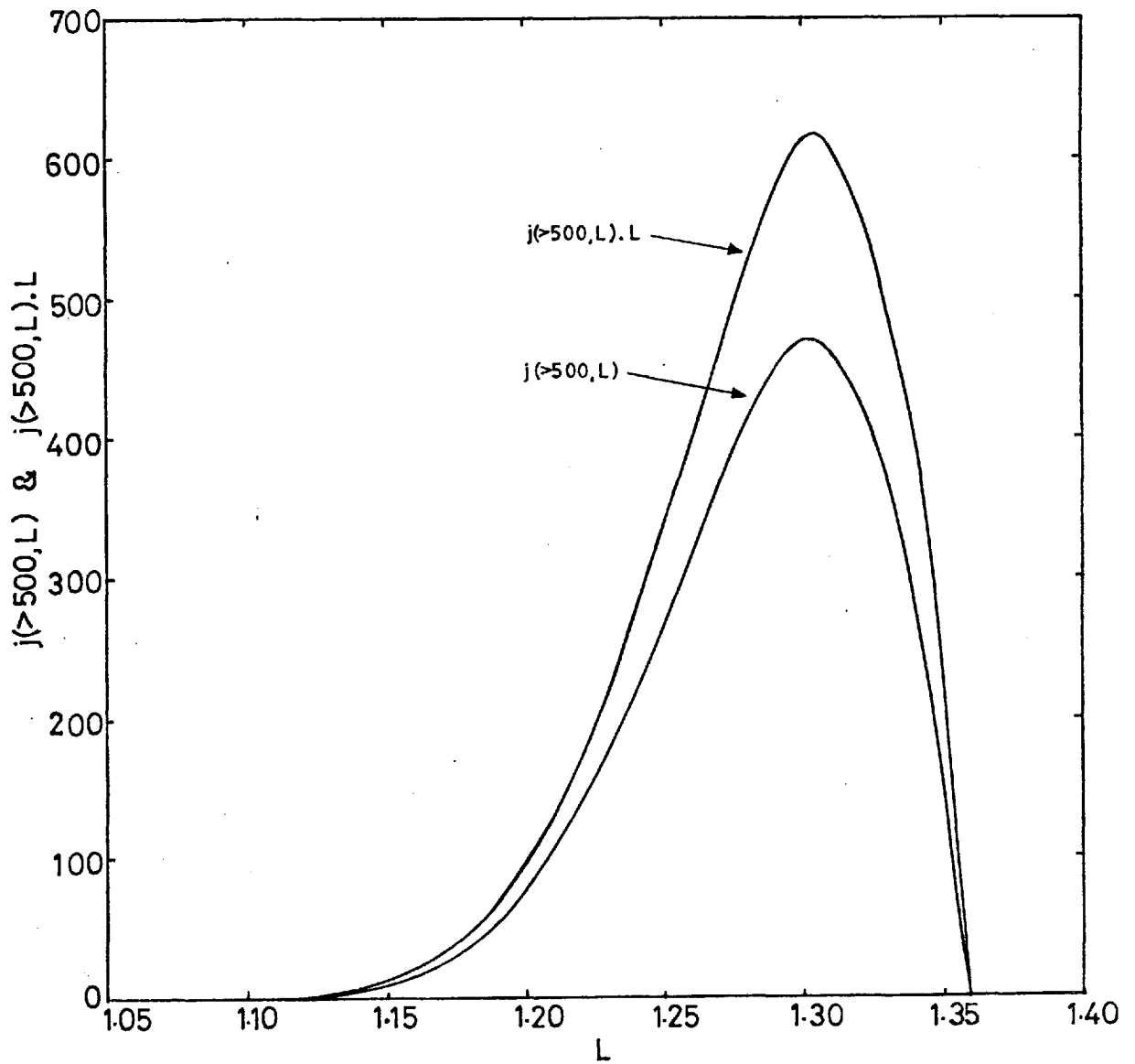


Fig. 6.3. The quantities $j(>500,L)$ and $j(>500,L).L$ as a function of L .

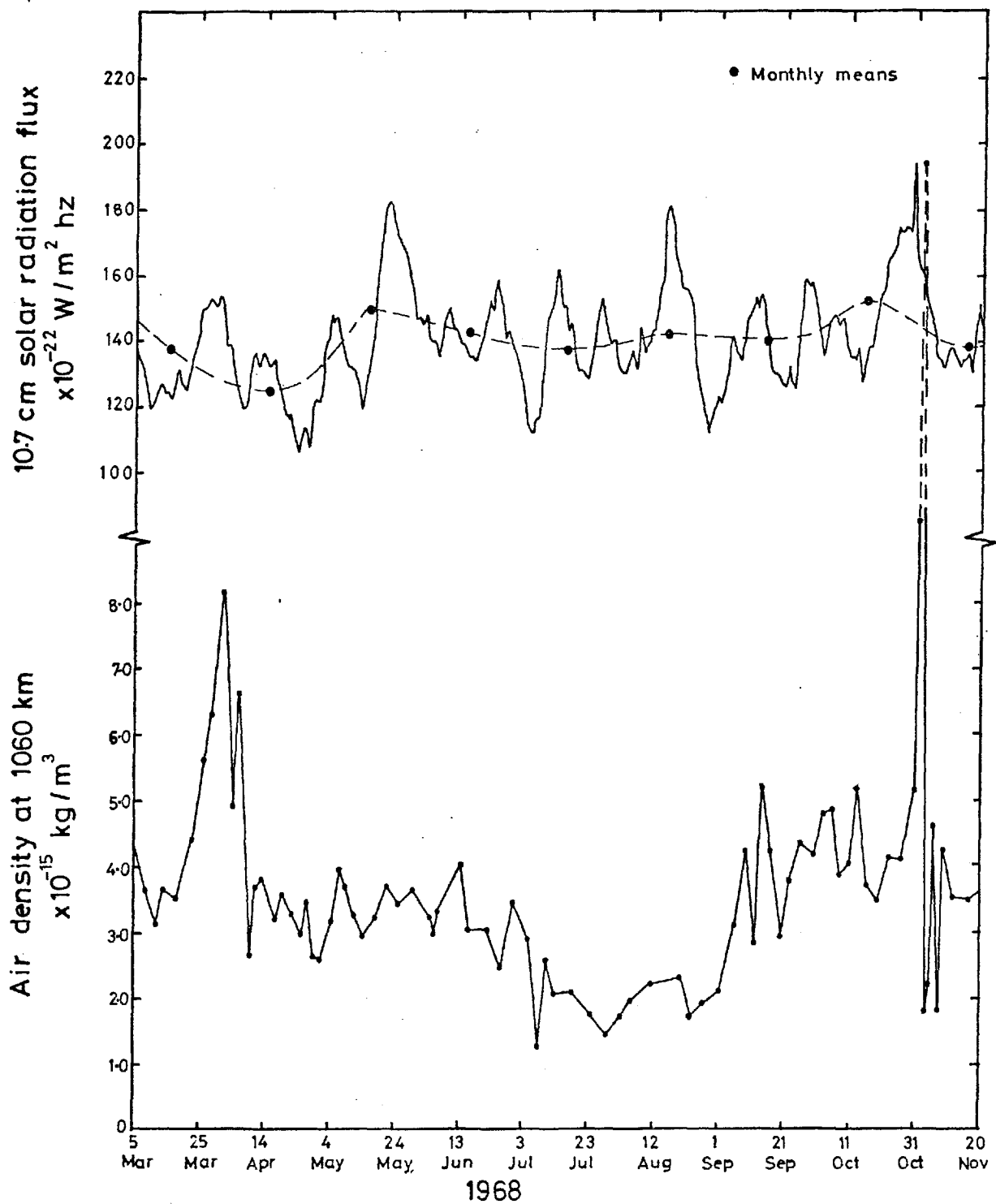


Fig. 6.4 The 10.7 cm solar radio flux and the values of air density reduced to a height of 1060 km (as measured by the Echo-2 satellite).

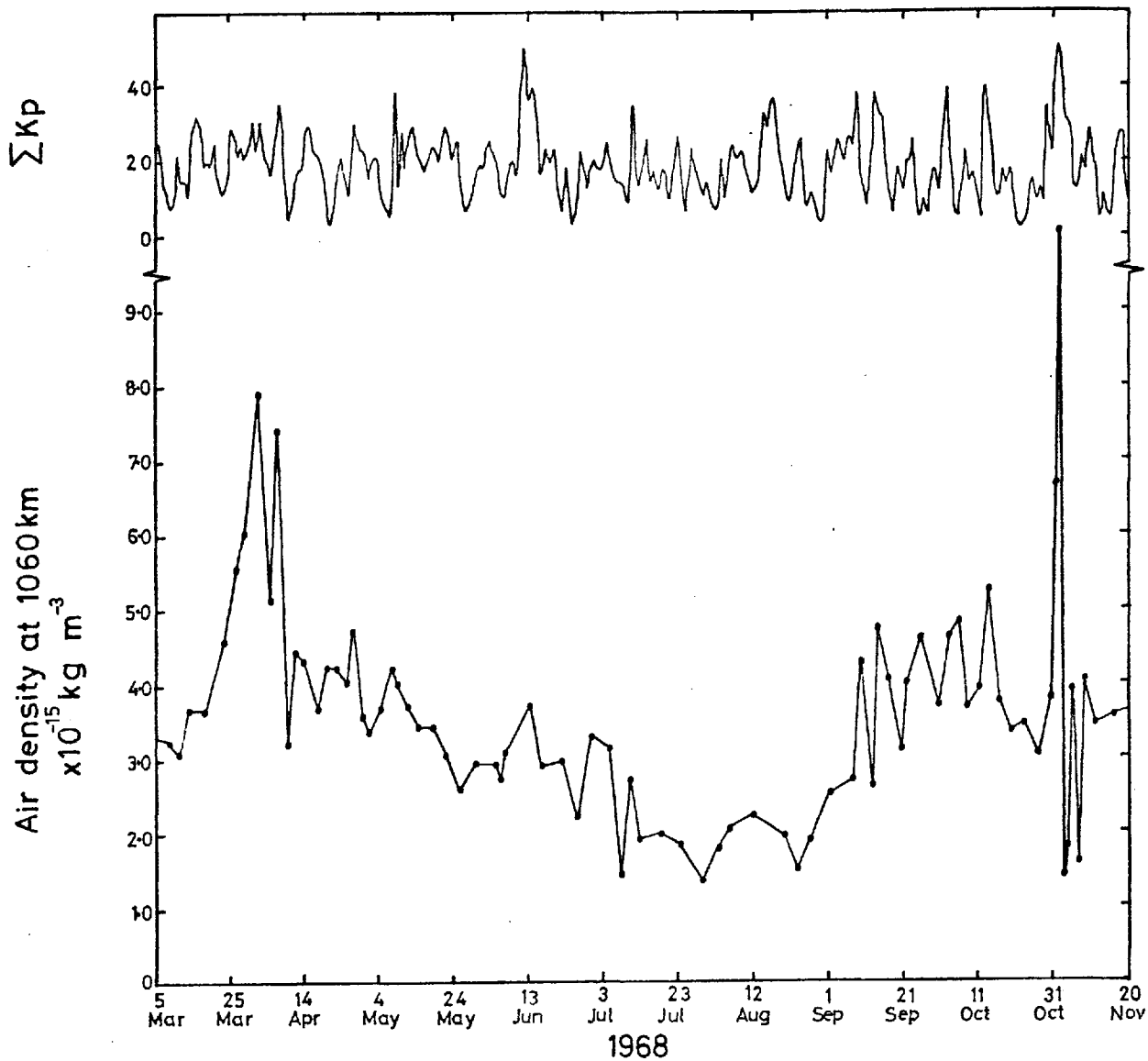


Fig. 6.5 The daily sums of Kp and the values of air density obtained from Echo-2 after adjustment to a height of 1060 km and a 10.7 cm radiation flux of $140 \times 10^{-22} \text{ W/m}^2 \text{ Hz}$.

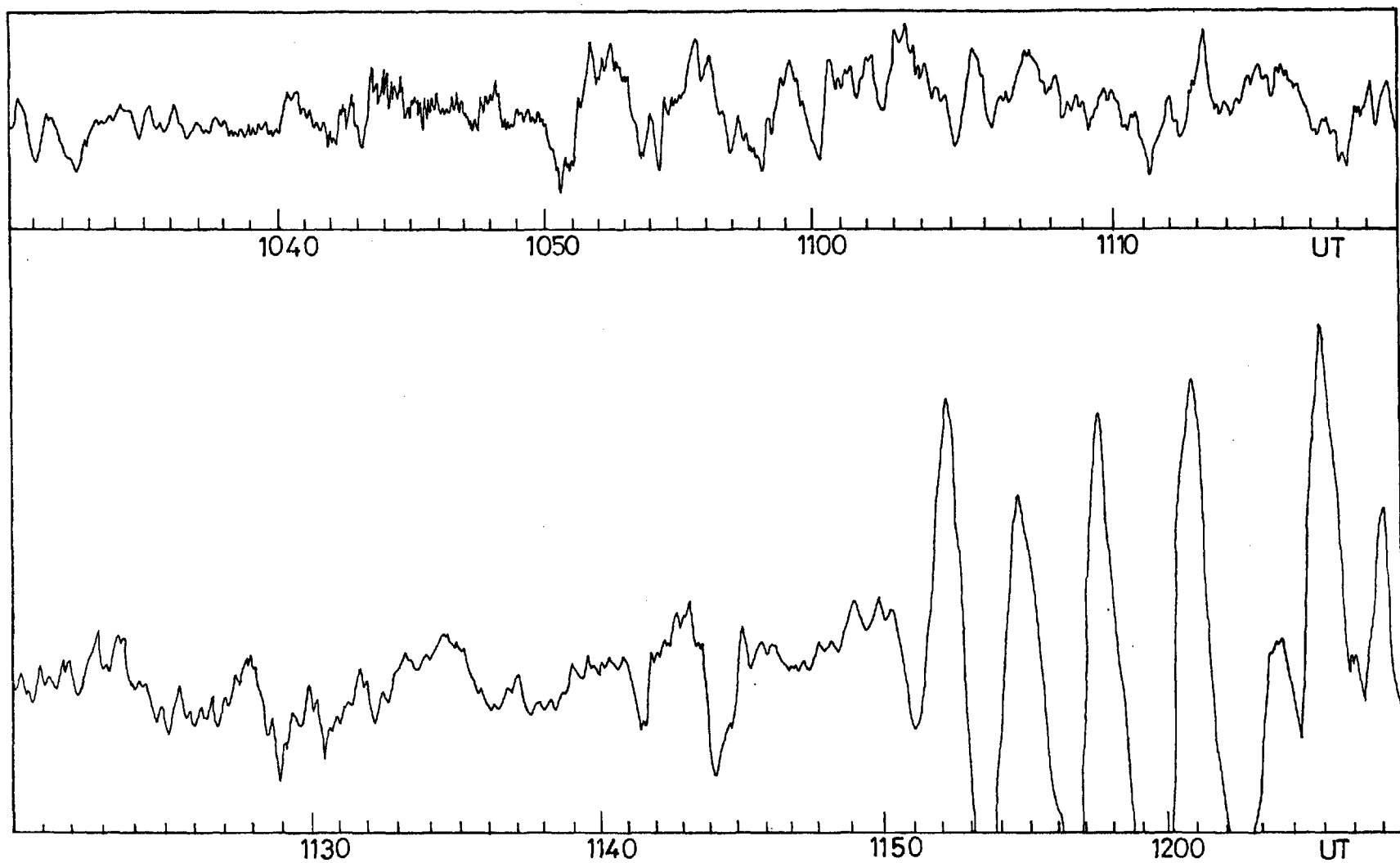


Fig. 6.6 H component record of the rapid-run magnetogram from M'bour at the time of the balloon event.

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