

THE SPECTRUM OF GAMMA-RAYS ~~ABOVE 200 MeV~~

FROM THE GALACTIC PLANE ABOVE 200 MeV .

A Thesis Submitted

By

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ABSTRACT

Gamma-ray astronomy is one of the most powerful methods available for probing the universe since gamma-rays pass undeflected through space, retaining their initial direction and momenta. It is possible to infer from the shape of the observed gamma-ray spectrum the production mechanisms causing the emission. This in turn gives a further insight into the structure and evolution of the Galaxy.

The possible mechanisms for gamma-ray production are discussed with special attention being given to the spectral shape.

The detector described here consists of a spark chamber, to give the gamma-ray's arrival direction, and a lead glass calorimeter to give its energy. The calorimeter was sensitive in the range 200 MeV to 10 GeV. The detector was flown from Longreach, Australia (8.8 GV cut-off rigidity) on November 18, 1973. The data were analysed and scrutinised for point sources. However, none of any statistical significance were observed and upper limits were placed on known hard X-ray sources. The Galactic plane was also scanned for evidence of line emission of gamma-rays. This was observed and the spectrum was measured. The results favour a π^0 decay production mechanism for the Galactic line emission.

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CHAPTER I

INTRODUCTION

1.1 Introduction

Gamma-ray astronomy is now accepted as being a powerful method for the unravelling of the physical processes occurring in the universe. Morrison (1958) was among the first to realise this and in his paper he suggested that objects such as the sun, crab nebula and the M87 galaxy might produce large fluxes of gamma-rays. As a probe, electro-magnetic radiation has the important advantage of retaining its source information and initial momentum. In contrast, charged corpuscular radiation undergoes extensive deflection in the interstellar magnetic fields and its distribution is thus reduced to an isotropy at the earth, giving little source information. Other constituents of cosmic radiation are neutral particles such as neutrons, neutral mesons, and neutrinos. However, the first two of these suffer from short lifetimes and the latter from a very small interaction cross-section which makes their detection difficult.

Some of the interesting problems which gamma-ray observations could elucidate because of their high penetrability and their simple relationship to nuclear reactions and high energy electrons and protons were given by Fazio (1967):

- (a) The origin of cosmic rays
- (b) The density of cosmic radiation in the Galaxy and in inter-galactic space
- (c) The density and composition of galactic and inter-galactic space

- (d) The presence of anti-matter in the universe and in particular the hypothesis of the continuous creation of matter
- (e) The strength of galactic and interstellar magnetic fields

The detection of gamma-rays is not, in general, feasible from the ground since the gamma radiation (interaction length 40 gm/cm^2) is absorbed by the atmosphere and the expected primary fluxes are very low compared with cosmic radiation. Experiments must be performed on high-altitude balloons or on satellites with long observation times. However, despite these difficulties, the importance justifies the effort required.

Since Morrison's optimistic prediction of large gamma fluxes, the negative results of sophisticated experiments caused the fluxes to be revised steadily downwards. The first encouraging exception to this negative trend was the detection of a high flux of gamma-rays from the plane of the galactic disc. This was observed by Clark et al. (1968) with the OSO-3 satellite. This enhancement of flux was in agreement with a prediction made by Pollack and Fazio (1963) when they considered the distribution of neutral hydrogen in the galaxy as measured by Oort (1959), using radio techniques. The distribution was such that in a uniform cosmic-ray intensity, the resulting gamma-ray flux would appear anisotropic at the earth, the intensity being greatest along the galactic disc. Attention will be paid to this source in later chapters but at this stage gamma-ray astronomy will be considered in general terms.

1.2 Gamma-Ray Production

The physical processes bringing about cosmic gamma-ray production have been reviewed by many authors, for example, Ginzburg and Syrovatskii (1965), Fazio (1967), Stecker (1971 and 1975). The following sections will be concerned only with those mechanisms capable of producing gamma-rays of energies greater than 100 MeV, paying attention to the spectral form of each.

Any gamma-ray production mechanism may be expressed in terms of its source strength $S(E_\gamma, \underline{r})$ which is defined as the number of photons produced at the source, per unit volume, per unit time, per unit solid angle in the energy range E_γ and $E_\gamma + dE_\gamma$ where $\underline{r}$ is the vector from the detector to the source element. This source strength may be expressed as:

$$S(E_\gamma, \underline{r}) = q(E_\gamma, \underline{r}) n(\underline{r}) \quad (\text{cm}^3 \text{sec.str.GeV})^{-1}$$

for a mechanism involving the reaction between an incident particle (or photon) and a target particle (or photon); $n(\underline{r})$ is the density of target particles and $q(E_\gamma, \underline{r})$ is the rate of production of gamma-rays per target particle, $q(E_\gamma, \underline{r})$ 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 $\sigma(E_\gamma, E_i)$ is the cross-section for creation of a gamma-ray in the interval E_γ to $E_\gamma + dE_\gamma$ by an incident particle of energy E_i and $I_i(E_i, \underline{r}) dE_i$ is the intensity of incident particles in the interval E_i and $E_i + dE_i$.

For an extended source (linear dimensions comparable to the distance R between the point of observation and the source), Ginzburg and Syrovatskii give the differential intensity of gamma-rays as :

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

where $N(L)$ is the number of gaseous atoms per unit area along the line of sight. The integral spectrum is given by:

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

In the case of discrete sources they give the flux, $F_{\gamma}(E_{\gamma})$ as:

$$\begin{aligned}
 F_{\gamma}(E_{\gamma}) &= \int_{\Omega} I_{\gamma}(E_{\gamma}) d\Omega \\
 &\approx \frac{N_v}{R^2} \int_{E_{\gamma}}^{\infty} \sigma(E_{\gamma}, E) I(E) dE \quad (\text{cm}^2 \text{sec. GeV})^{-1}
 \end{aligned}$$

where the first integration is evaluated over the solid angle Ω subtended by the source and

$$N_v = R^2 \int_{\Omega} N(L) d\Omega \approx n(\underline{r}) dV$$

is the total number of gaseous atoms in the source.

1.2.1 Gamma-Rays From π^0 Meson Decay

A cosmic ray of high enough energy can produce various secondary particles of short lifetime upon collision with interstellar or inter-galactic gas nuclei. Of these secondaries the most important for production of gamma-radiation is the π^0 meson which decays almost 100% of the time into two gamma-rays. When this decay occurs, (rest frame lifetime of 10^{-16} sec) because of conservation of momentum, the two gammas are produced with an energy of 67.5 MeV (half the pion rest mass) in the rest frame of the pion. However, in the terrestrial observer's frame these gamma-rays have unequal energies which are determined by the relativistic Lorentz transformation.

So the gamma energies are given by:

$$E_{\gamma 1,2} = E_{\pi}(1 \pm \beta_{\pi} \cos \theta)$$

where θ is the angle between the gamma-ray and the axis of the transformation in the pion rest system, E_{π} is the rest energy of the pion and β_{π} refers to its velocity. Thus the spread in gamma energy is from $(1 - \beta_{\pi})E_{\pi}$ to $(1 + \beta_{\pi})E_{\pi}$ giving the distribution symmetry about 67.5 MeV on a log-log plot.

Production of neutral pions in space can occur in the following ways:

1.2.1.1 Nucleon-Nucleon Collisions

Cosmic ray particles traversing inter-stellar or inter-galactic space will collide with the ambient nuclei. Most of these collisions will be proton-proton interactions as protons comprise 90% of cosmic rays and hydrogen about 90% of the cool inter-stellar gas.

Pollock and Fazio (1963) have given the important interactions as follows:

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

$$p + p \longrightarrow p + n + \pi^+ + c(\pi^+ + \pi^-) + d\pi^0$$

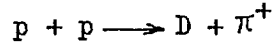
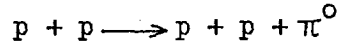
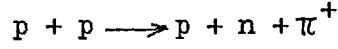
$$p + p \longrightarrow n + n + 2\pi^+ + f(\pi^+ + \pi^-) + g\pi^0$$

$$p + p \longrightarrow D + \pi^+ + h(\pi^+ + \pi^-) + i\pi^0$$

where p indicates a proton, n a neutron and D a deuteron and a, b, c, d, f, g, h, i positive constants. They also give the threshold kinetic energy $T_{\min}$ needed for the production of x mesons as:

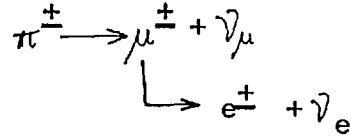
$$T_{\min} = x(280 + 10x) \text{ MeV}$$

i.e., $T_{\min} = 290 \text{ MeV}$ for a single meson. In the energy range 290 MeV to 1 GeV, only single pion production is important giving:



where the first reaction dominates.

The charged mesons decay into electrons or positrons in 10^{-6} sec,



These electrons subsequently lose energy in electromagnetic interactions until they eventually leak out of the galaxy or annihilate with their antiparticles to produce two low energy gamma-rays, (~ 0.5 MeV Stecker (1969)).

The rate of production of gamma-rays per target proton can be represented as:

$$q(E_\gamma, \underline{r}) dE_\gamma = dE_\gamma \int_{E_{th}}^{\infty} I_p(E_p, \underline{r}) \xi(E_p) dE_p \int_{E_{\pi_{min}}}^{\infty} \sigma(E_\pi, E_p) f_\gamma(E_\gamma, E_\pi) dE_\pi$$

where $I_p(E_p, \underline{r})$ is the proton differential spectrum, $\sigma(E_\pi, E_p) dE_\pi$ is the cross-section for the production of a π^0 meson with energy E_π in the interval dE_π , $\xi(E_p)$ is the multiplicity of pion production, $f_\gamma(E_\gamma, E_\pi)$ is the gamma-ray distribution function from π^0 decay given by Stecker (1971) to be represented by the Green's function:

$$f_\gamma(E_\gamma, E_\pi) = \begin{cases} (E_\pi^2 - m_\pi^2)^{-\frac{1}{2}} & \text{for } \frac{1}{2}E_\pi(1 - \beta_\pi) \leq E_\gamma \leq \frac{1}{2}E_\pi(1 + \beta_\pi) \\ 0 & \text{otherwise} \end{cases}$$

Stecker (1975) has evaluated the resulting gamma-ray source function also including the contribution to the total gamma-ray flux from the $p - \alpha$, $\alpha - p$, $\alpha - \alpha$ interactions. The resulting integral production spectrum is illustrated in figure 1.1.

An asymptotic form of the gamma-ray spectrum can be derived (following the argument of Stecker (1971)) for gamma-ray

energies above a few GeV produced by cosmic rays having a power law spectrum of the form $E_p^{-\Gamma}$. Fazio (1967) showed that at these energies the pion production cross-section was constant (~ 27 mbarns). The pion multiplicity rises as a power of the primary energy ($\propto E^a$). Also, assuming that the average pion energy rises as E_p^b gives:

$$q(E_\gamma, \underline{x}) dE_\gamma = 8\pi dE_\gamma K_p \sigma_o \int_{E_{th}}^{\infty} dE_p E_p^{a-\Gamma} \int_{E_\gamma}^{\infty} dE_\pi \frac{\delta(E_\pi - X_o E_p^b)}{E_\pi}$$

K_p, X_o, a, b, Γ being constants,

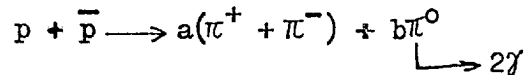
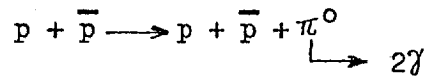
$$\begin{aligned} &= 8\pi K_p \sigma_o \int_{(E_\gamma/X_o)^{1/b}}^{\infty} dE_p \frac{E_p^{-(\Gamma+b-a)}}{X_o} \\ &= \frac{8\pi K_p \sigma_o X_o^{(g/b-1)}}{g} E_\gamma^{-g/b} \end{aligned}$$

where $g = ((\Gamma + b) - (a + 1))$

thus the gamma-ray spectrum is also a power law but one which is different and in general steeper than the primary spectrum. For example, in the case $\Gamma = 2.5$ and $a = \frac{1}{4}$, $b = \frac{3}{4}$ (Fermi model for meson production), the gamma index $g/b = 2.67$. The primary cosmic ray and gamma-ray spectra have the same index in the important case where a constant and large fraction of the primary energy of the cosmic ray is carried off by the single secondary which decays to produce a π^0 meson. This corresponds to the case $a = 0$, $b = 1$ and therefore $g/b = \Gamma$.

1.2.1.2 Matter-Antimatter Annihilation

Protons and antiprotons may react in one of two inelastic collisions, either a strong, pion producing interaction, or, direct annihilation,



Stecker (1971) has dealt at length with this production mechanism considering rest gas interaction with rest gas to provide the primary source since the annihilation cross-section is greatest at low c.m.s. velocities. The annihilation cross-section can be approximately fitted by:

$$\sigma = \frac{\sigma_0}{\beta} = \frac{4.8 \times 10^{-26} \text{ cm}^2}{\beta} \quad \text{Stecker (1971)}$$

Consequently this mechanism will be most significant for low c.m.s. velocity systems. Rest gas is defined as a gas of particles in which no particle has an energy > 286 MeV which precludes the first reaction quoted at the beginning of this section.

Stecker has taken coulomb interactions between the antiparticles into account, when calculating the spectrum and the modified cross-section σ_A , giving the approximate production rate as:

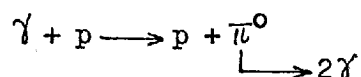
$$S_A(E_\gamma, \underline{r}) = n_p(\underline{r})n_{\bar{p}}(\underline{r})c\sigma_A \quad \xi_\gamma \left(\frac{2mc^2}{kT} \right)^{\frac{1}{2}} f(E_\gamma, \underline{r})$$

where n_p and $n_{\bar{p}}$ are the densities of matter and antimatter in gaseous form at 10^6 °K, σ_A is the cross-section and ξ_γ the gamma-ray multiplicity.

$$I_{\text{RG-RG}}(E_\gamma > 100 \text{ MeV}) = 4.1 \times 10^{-14} \int n_p(\underline{r})n_{\bar{p}}(\underline{r})d\underline{r} \quad (\text{cm}^2 \text{sec, str.})^{-1}$$

1.2.1.3 Photo-Pion Production

A process which may be important in producing gamma-rays of energies in the 10^{19} eV range is that of photomeson production i.e., reactions of the type:



This involves the collision of an ultra-high energy cosmic ray proton with a starlight photon. For the production of a neutral pi-meson 140 MeV is required in the centre of mass system. Therefore, the energy of the proton must exceed 10^{17} eV for its collision with a starlight photon (typically 1 eV) to produce a pion.

1.2.2 Gamma-Rays From Electro-Magnetic Interactions

1.2.2.1 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 $\sim 1\%$ of the cosmic radiation.

Stecker (1975 and 1971) gives an approximate expression for the bremsstrahlung cross-section as:

$$\sigma_b(E_\gamma, E_e) dE_\gamma = \frac{m dE_\gamma}{X_0 E_\gamma}$$

where m is the average mass of the target atoms in grams and X_0 is the average radiation length for the gas ($X_0 = 65 \text{ gm/cm}^2$ for the inter-stellar and inter-galactic gas). The intensity of gamma-rays due to bremsstrahlung is thus given by:

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

therefore,

$$\begin{aligned} I_\gamma(E_\gamma) &= N(L) \frac{m}{X_0 E_\gamma} \int_{E_\gamma}^{\infty} I_e(E_e, \underline{r}) dE_e \\ &= \frac{M(L)}{X_0 E_\gamma} \int_{E_\gamma}^{\infty} I_e(E_e, \underline{r}) dE_e \end{aligned}$$

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

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

then,

$$I_\gamma(E_\gamma) = \frac{M(L)}{X_0} \frac{K_e}{(\Gamma_e - 1)} E_\gamma^{-\Gamma_e}$$

and

$$I_\gamma(>E_\gamma) = \frac{M(L)}{X_0} \frac{K_e}{(\Gamma_e - 1)^2} E_\gamma^{-(\Gamma_e - 1)}$$

Thus, for the observed value of $\Gamma_e = -2.6$ the differential gamma spectral index is -2.6 and the integral index -1.6 .

1.2.2.2 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. If the cosmic ray electron has an energy $E = \gamma mc^2$ and the photon an initial energy ϵ , then on average, the photon would emerge from the interaction with energy (in the observer's frame) ϵ' such that:

$$\epsilon' \approx \gamma^2 \epsilon \quad (\gamma \epsilon \ll mc^2)$$

For the astrophysical conditions of primary concern here, the condition $\gamma \epsilon \ll mc^2$ ($\epsilon \sim 1$ eV) holds and the cross section for the scattering reduces to the Thompson cross-section:

$$\sigma_T = \frac{8\pi}{3} \left(\frac{e^2}{mc^2} \right)^2 = 6.65 \times 10^{-25} \text{ cm}^2$$

If, as in the previous section, we assume the shape of the electron differential spectrum to be:

$$I_e(E) = K E^{-\Gamma}$$

then since

$$I_\gamma(E_\gamma) = \int_0^L dr \int_{E_i} I_e(E_e, \underline{r}) dE_e \int_0^\infty d\varepsilon n_{ph}(\varepsilon, \underline{r}) \sigma(E_\gamma, \varepsilon, E_e)$$

we have,

$$I_\gamma(E_\gamma) = \frac{1}{2} \varphi_{ph} L \sigma_T (m_e c^2)^{1-\Gamma} (\bar{\varepsilon})^{(\Gamma-3)/2} K E_\gamma^{-(\Gamma+1)/2}$$

where L is the path length to the source, φ_{ph} is the energy density of target photons and $\bar{\varepsilon}$ is the average photon energy.

Thus it can be seen:

$$I_\gamma(E_\gamma) \propto E_\gamma^{-(\Gamma+1)/2}$$

and

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

So, given the same electron spectrum, the inverse Compton exponent is half that for the bremsstrahlung spectrum.

1.2.2.3 Synchrotron Radiation

Synchrotron radiation or magnetic bremsstrahlung, is the radiation emitted by a relativistic particle spiralling in a magnetic field. Schwinger (1949) gives the rate of synchrotron energy loss for an electron energy $\gamma m_e c^2$ as:

$$\left(\frac{dE}{dt} \right)_{\text{syn}} = - \frac{4}{3} \sigma_T c \gamma^2 \varphi_H$$

where φ_H is the magnetic energy density ($= H^2/8\pi$). This rate can be compared with the corresponding rate for Compton interactions:

$$\left(\frac{dE}{dt} \right)_C = - \frac{4}{3} \sigma_T c \gamma^2 \varphi_{ph}$$

where $\sigma_T c \varphi_{ph}/\varepsilon$ is the collision rate between the electron and photon field and $\gamma^2 \varepsilon$ is the energy lost per collision.

Photons emitted by synchrotron radiation have a characteristic frequency:

$$\omega_{\text{syn}} = \frac{3}{2} \gamma^2 \left(\frac{e H_{\perp}}{mc} \right)$$

and an energy:

$$E_{\gamma, \text{syn}} = \frac{3}{2} \gamma^2 \left(\frac{\hbar}{mc} \right) e H_{\perp}$$

Because this is the same type of energy dependence as that for Compton radiation, a power law cosmic ray electron spectrum of the form $KE^{-\Gamma}$ will again generate a synchrotron spectrum of the form:

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

It can be seen by comparing the energy loss equations that:

$$\frac{(dE/dt)_{\text{syn}}}{(dE/dt)_c} = \frac{\gamma_H}{\gamma_{\text{ph}}}$$

assuming an electron of energy $\gamma_c mc^2$ will radiate a Compton photon at the same mean energy as an electron of energy $\gamma_s mc^2$ will radiate a synchrotron photon
i.e.,

$$\frac{(dE/dt)_{\text{syn}}}{(dE/dt)_c} = \frac{H_{\perp}^2}{8\pi E_{\text{ph}}} \frac{1}{\gamma_c} \approx 10^{10}$$

where $H_{\perp} \sim 1$ microgauss and $E_{\text{ph}} \sim 1$ eV. Thus it can be seen that synchrotron radiation may be neglected as a gamma-production mechanism compared to the Compton effect.

However, by observing Compton gamma-rays and synchrotron radiation (in the radio region) a powerful tool is afforded for the checking of the electron spectral index or the perpendicular field components of sources.

1.3 Gamma-Ray Absorption

The intensity of gamma-rays produced in the Galaxy and in the universe is depleted by various processes of astrophysical importance. These processes fall into two main categories:

- (1) The absorption in matter
- (2) The absorption through interactions with radiation

The latter will be shown to be of greater importance because of the existence of the universal 2.7°K thermal radiation field.

1.3.1 Absorption in Matter

The interactions of importance are Compton scattering of the photon on a cosmic ray electron resulting in a transfer of energy to the electron, and pair production which may occur when a gamma-ray passes the coulomb field of a nucleus.

It is useful to define an absorption length k such that

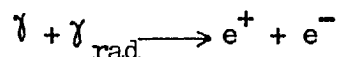
$$I = I_0 e^{-L/k}$$

where I_0 and I are the initial and final gamma-ray intensities, and L the effective path length in the medium. For Compton scattering $k \gtrsim 1.5 \times 10^{23} \text{cm}$ for the Galaxy (which is 5 galactic radii) and $k \gtrsim 1.5 \times 10^{29} \text{cm}$ for the metagalaxy which is 30 times the photometric radius of the universe. Thus it can be seen that Compton scattering is negligible as an absorption process.

In the pair production process $k \gtrsim 3 \times 10^{23} \text{cm}$ for the galaxy and $k \gtrsim 3 \times 10^{28} \text{cm}$ for the metagalaxy. Thus absorption is again negligible. The cross-sections for these processes are given by Stecker (1971) and plotted in figure 1.2.

1.3.2 Absorption Through Interactions With Radiation

The following types of radiation are available for gamma-ray absorption: starlight photons, universal microwave radiation, radio photons:



This process can only take place if the total energy of the gamma-rays in the centre of mass system of the interaction is greater than or equal to $2m_e c^2$. The threshold energy for pair production is easily estimated since when a gamma-ray of energy E_γ collides with a photon of energy E_{rad} at an angle θ , the available energy E^* in the c.m.s. is given by:

$$E^{*2} = 2E_{\text{rad}} E_\gamma (1 - \cos\theta)$$

giving the threshold energy (head on collision, $\cos\theta = -1$)

$$E_\gamma = \frac{(m_e c^2)^2}{E_{\text{rad}}} = \frac{(0.51 \times 10^6)^2}{E_{\text{rad}}} \text{ eV}$$

Gould and Schreder (1967 a,b) evaluated the absorption probability as a function of gamma-ray energy and their results are shown in figure 1.3. The curve representing the microwave absorption has been corrected by Stecker (1971) since when Gould and Schreder originally calculated it, the universal radiation was believed to be at 3°K instead of the present accepted value of 2.7°K .

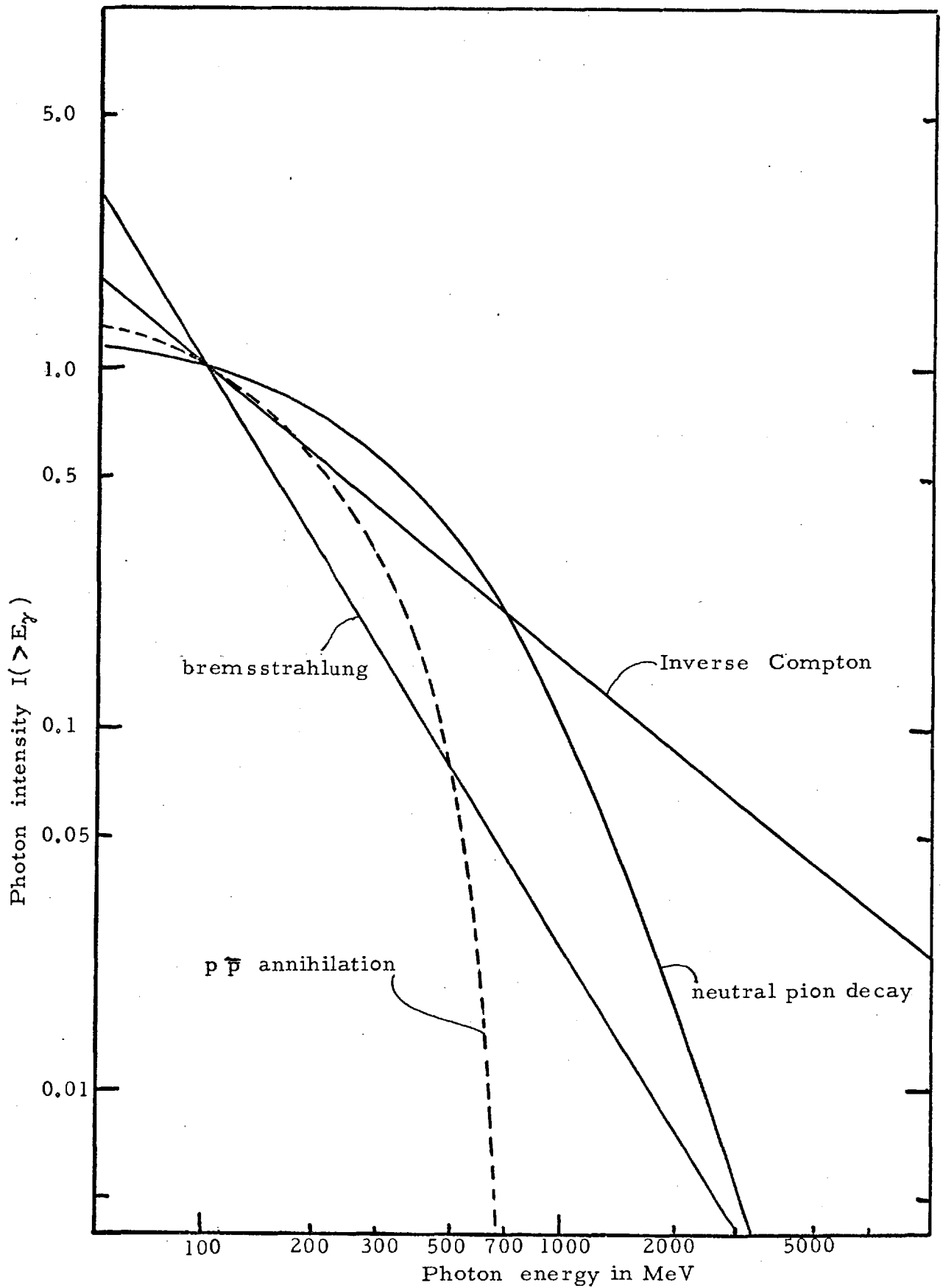


Figure 1.1

Gamma-ray spectra from inverse Compton, bremsstrahlung, neutral pion decay, and $p \bar{p}$ annihilation production mechanisms. All the curves are normalized to 1 at 100 MeV for comparison.

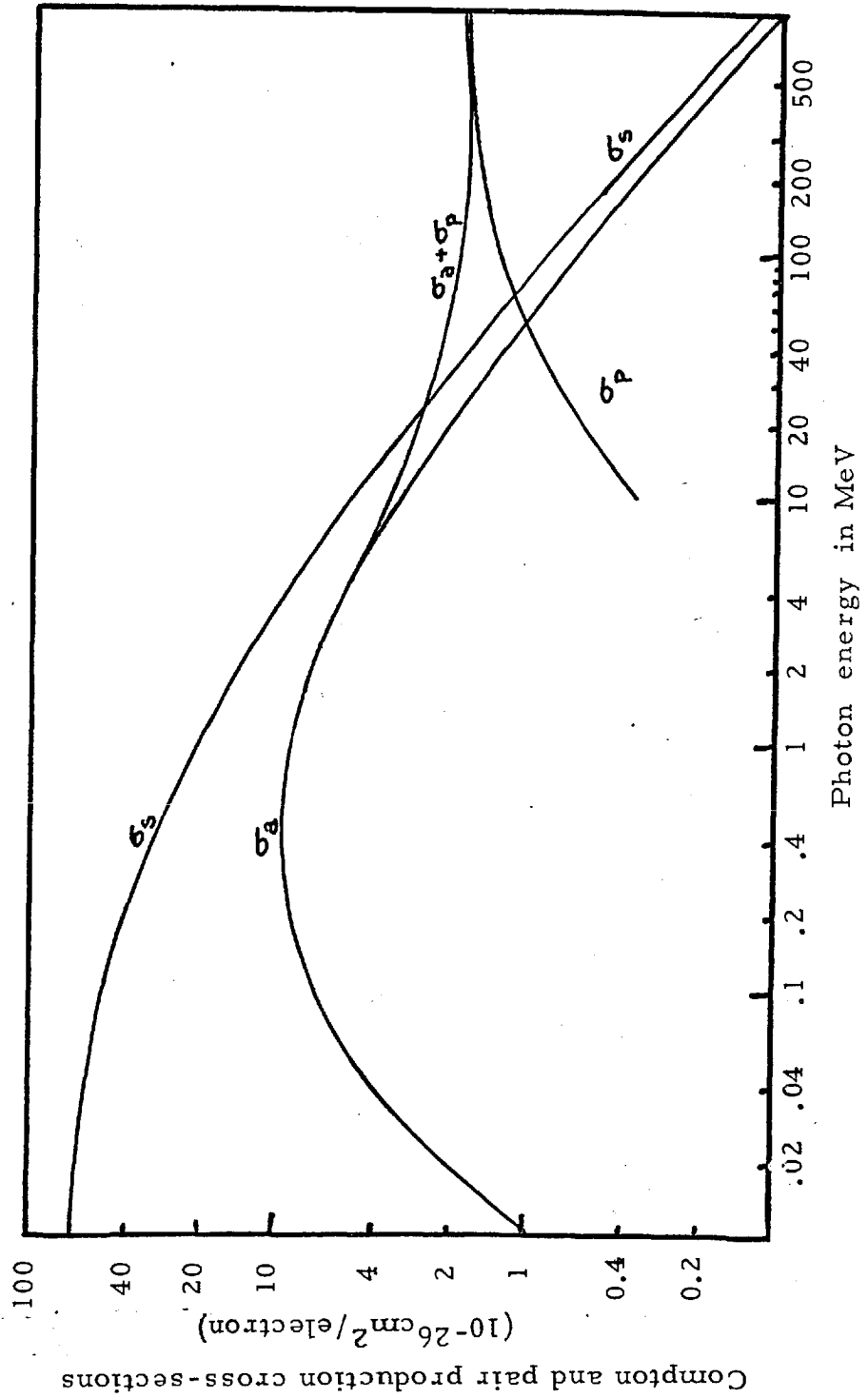


Figure 1.2
Compton scattering (σ_s), Compton absorption (σ_a),
pair production (σ_p) and total ($\sigma_a + \sigma_p$) cross-sections
as a function of gamma-ray energy for absorption of
gamma-rays in hydrogen gas.

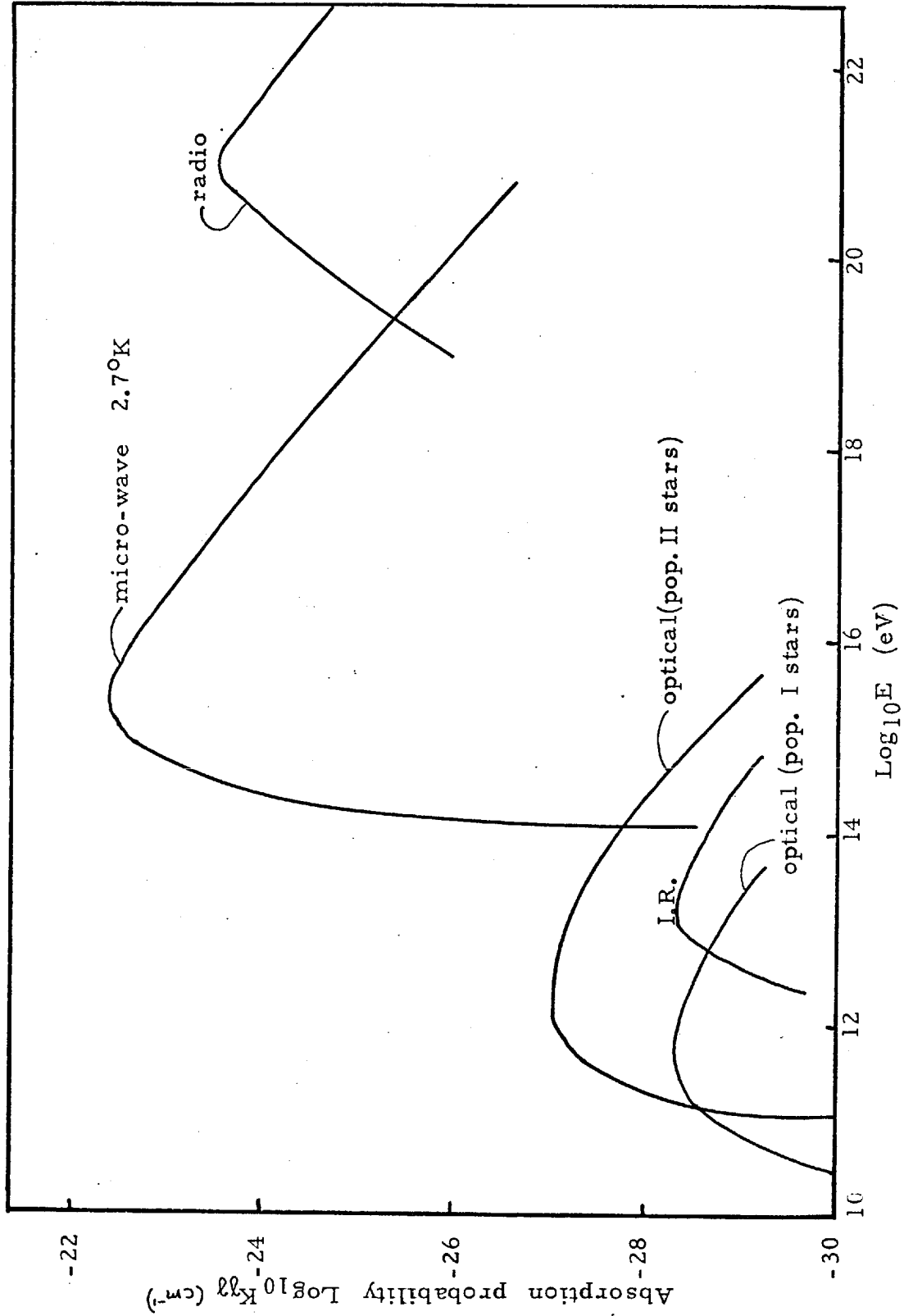


Figure 1.3

The absorption probability $K_{\gamma\gamma} \text{ cm}^{-1}$ by the $\gamma + \gamma \rightarrow e^+ + e^-$ process for gamma-rays traversing the universal photon field.

CHAPTER II

THE GAMMA-RAY TELESCOPE

2.1 Introduction and Design Considerations

The present detector supercedes the two smaller, simpler detectors flown in 1971 from Lusaka by members of the Cosmic Ray Group at Imperial College (Bennett 1972) and was flown in order to elucidate the unresolved problems of gamma-ray production mechanisms and the possibilities of point sources of gamma-radiation. Owing to the small fluxes of primary gamma-radiation above 200 MeV expected from the galactic disc, $5 \times 10^{-4}(\text{cm}^2 \text{rad. sec})^{-1}$, the following considerations were taken into account when designing the present detector:

- (a) good angular resolution
- (b) high energy resolution
- (c) a large sensitive area and opening angle in order to scan a large area of the sky per unit time
- (d) a high unambiguous gamma-detection efficiency combined with a small dead time
- (e) efficient rejection of charged particle and noise events
- (f) a mechanically strong construction to withstand the extremes of temperature and pressure experienced during the balloon flight and the rigours of launch which could bring large accelerations into play
- (g) a light weight to achieve a maximum altitude, commensurate with the balloon available and the weight involved in satisfying the above requirements.

The above requirements may be related by an equation giving the minimum flux I_m observable above an average flux of ϕ at a given signal to noise ratio S_m :

$$I_m \cdot \epsilon \cdot A \cdot T = S_m (\phi_o + \phi_{B.w.f}) AT)^{\frac{1}{2}}$$

i.e.,

$$N_s = S_m (N_T)^{\frac{1}{2}}$$

where N_s is the number of source counts and N_T the total number of counts, assuming Gaussian statistics. ϕ_o is the source intensity and ϕ_B the background intensity. This may be rewritten as:

$$I_m = S_m \sqrt{\frac{\phi_{w.f}}{\epsilon \cdot AT}}$$

where ϵ is the overall detector efficiency, w is the solid angle viewed around the source, f is the dead time correction, A is the sensitive area of the detector and T is the exposure time of the source. The gamma-ray telescope constructed to optimize all these requirements is shown schematically in figure 2.1.

The telescope had cylindrical symmetry about its axis. The scintillator A was an anti-coincidence shield to reject charged particles. An incident gamma-ray photon passed through A and was converted into an electron-positron pair in the $1/2$ radiation length lead converter. The pair travelled through scintillators B and C and into the Cerenkov element D. The gamma-ray signature of ABCD triggered the electronics of the system which flashed the high voltage across the spark gaps. Sparks formed preferentially down the ionised tracks defining the secondary electrons' path, from which could be inferred the arrival direction of the incident photon. The photon's energy was measured in the Cerenkov element D by a pulse height analysis of the light emitted by the cascade shower produced by the passage of the secondary electrons. The energy threshold

was set at 200 MeV. The detector was flown from Longreach, Queensland, Australia on November 18, 1973. The spark chamber and pulse height data together with various housekeeping data were telemetered back to the ground station and recorded in real time on an Ampex instrumentation tape recorder.

2.2 The Coincidence Telescope

2.2.1 Scintillator Elements

The scintillator elements B and C were 38 cms diameter discs of NELO2A plastic scintillator $\frac{1}{4}$ " and $\frac{1}{2}$ " thick respectively. They were each viewed by a single 2" photomultiplier tube (EMI type 6097A) through a perspex light pipe. The whole assembly was coated by layers of aluminium foil covered with black adhesive tape to prevent light reaching the photomultiplier from outside the body of the scintillator.

The light pipes were constructed from strips of highly polished CQ perspex twisted and bent to match the edge of the scintillator to the photomultiplier window. For B, the light pipe consisted of six $\frac{1}{4}$ " x $1\frac{1}{2}$ " x 15" strips and four $\frac{1}{2}$ " x $1\frac{1}{2}$ " x 15" strips for C. In designing these light pipes for maximum transmission of scintillation light the following points must be borne in mind:

- (a) the thickness of the pipe should be the same as that of the scintillator
- (b) the total area of the ends of the light pipes must be equal to the area of the photomultiplier used
- (c) the radius of curvature R of the bent pipes must satisfy

$$R > 8r$$

where r is the thickness of the strip

- (d) the pipe surfaces must be highly reflective to keep light losses down to a minimum. Figure 2.2 gives an impression of the finished scintillator element

The photomultiplier tubes were optically coupled to the light pipes through a block of perspex whose cross-section changed slowly from square to circular, to match the square end of the light pipe to the circular tube window. Coupling was achieved using Tensol 104 cement which formed a strong but flexible bond which could allow for the different temperature expansion coefficients of the perspex and the photo-tube window.

NE102A was chosen because of its high photon output for a charged particle traversing it and also because of its fast recovery time. The scintillation light peaks at about 424 nanometers which was at approximately the same position as the maximum response of the photo-tube used to view it.

The energy dE transferred in excitation and ionization along an element of path dL to a homogeneous medium containing N atoms cm^{-3} each of atomic number Z by a relativistic particle of rest mass M , charge ze , velocity $v (= \beta c)$ and energy E , was given by Birks (1964) as:

$$\frac{dE}{dL} = \frac{4\pi e^4 Z^2}{m_e \beta^2 c^2} \cdot N \cdot Z \left[\ln(2m_e \beta^2 c^2 / I) - \ln(1 - \beta^2) - \beta^2 \right]$$

where I is an empirical constant for a given medium corresponding to the mean ionization and excitation potential. Crispin and Hayman (1964) have evaluated the energy loss for a minimum ionizing singly charged particle in NE102A and give a value $\sim 1.8 \text{ MeV/gm/cm}^2$. Barnaby and Barton (1961) have given a phosphor efficiency of approximately 1 photon per 140 eV liberated in NE102A. Thus for $\frac{1}{4}$ " and $\frac{1}{2}$ " discs of NE102A photon yields of

approximately 9000 and 18000 respectively could be expected. The number of photoelectrons arriving at the photocathode of the tube was difficult to estimate due to the complex shape of the light pipe used. However, by consideration of the mu-meson peak in the half inch scintillator, it was estimated that at least 66 photoelectrons were produced for a mu-meson traversing any part of the scintillator.

The output from the photo-tube viewing the $\frac{1}{2}$ " scintillator element C was fed through a charge amplifier into a pulse height analyser. The pulse was stored in a delay line for 250 nanoseconds until a 'decision' was made, by adding the outputs of the scintillation telescope, as to whether the pulse was from a gamma-ray or charged particle. If it was a gamma-ray (signature $\overline{ABCD}$) the pulse was used to set a coil ringing, the number of oscillations of the coil being an accurate measure of the pulse magnitude. These oscillations were counted up to a maximum of 200 and the number stored in a 9 bit Johnson Logic Store.

2.2.2 The Lead-Glass Element

The third element of the three-fold coincidence system was a lead glass Cerenkov detector, seven radiation lengths deep (24.5 cms). A Cerenkov element is a very useful detector of high energy particles. When a particle travels through a medium of refractive index n with a velocity v , which is greater than the velocity of light in that medium, Cerenkov light is emitted in a cone at an angle θ to the direction of motion, according to the following relationship:

$$\cos\theta = \frac{1}{\beta n} \quad \text{where } \beta = v/c$$

The critical velocity after which light is emitted is $v = c/n$ when $\theta = 0$, θ then increases as v increases to a maximum value of $\theta = \cos^{-1}(1/n)$ ($\sim 52^\circ$ in this case) as $\beta \rightarrow 1$. The number of photons emitted per unit path length L was given by Litt (1973):

$$\frac{dN}{dL} = 2\pi\alpha \cdot Z^2 \int_{\lambda_2}^{\lambda_1} (1 - (1/\beta^2 n^2)) \frac{d\lambda}{\lambda^2}$$

where α is the fine structure constant and Ze is the charge of the particle traversing the medium ($Z = 1$ in this case). λ_1 and λ_2 are the limits of wavelength imposed on the system by the transmission properties of the elements making up the Cerenkov system. It can be seen from this equation that,

$$\frac{d^2N}{dLd\lambda} \sim \frac{1}{\lambda^2}$$

i.e., that the emitted light intensity peaked towards the blue end of the visible spectrum. This is illustrated in Figure 2.5a which gives the number of photons/cm/200A. Thus in designing the Cerenkov system its transparency towards the short wavelengths should be as high as possible bearing in mind that the photomultipliers used (EMI 9530A) were only sensitive in the spectral range 300 to 650 nanometers. This is shown in figure 2.3a for four samples of Schott lead glass. These samples were also tested in the 5 GeV electron test beam at the Daresbury Nuclear Physics Laboratory, Warrington (Sood 1974) to determine their energy resolutions. These were obtained by analysing the output of the photomultiplier (9530A) used for the test and are shown plotted in figure 2.3b. As a result of these two plots RS360 was chosen, a radiation shielding glass whose physical properties are listed in table 2.1.

Schott RS360

Density	3.6 gm cm^{-3}
Refractive index	1.62
Radiation length	3.5 cms

Table 2.1

The material used for the light pipe must also have high transmission down to short wavelengths. Four types of perspex were tested in this respect, common perspex, Rohm perspex, CQ (clinical) perspex and plexiglass. The percentage transmission per centimetre is shown in figure 2.4 for these materials; clinical perspex was chosen.

It can now be seen that the wavelength limits in the above equation should be set between 340 and 650 nanometers, by consideration of properties of the elements of the system. If it were assumed that the refractive index was constant over this range and that for a typical mu-meson $\beta \approx 1$, we can obtain:

$$\frac{dN}{dL} = 375 \text{ photons/cm}$$

Thus for a lead glass element seven radiation lengths deep a yield of ~ 9250 photons is obtained for the passage of one singly charged particle. The number of photo-electrons produced at the photo-tube's cathode is not easily calculated owing to the difficulty in calculating the light collection of the system L_c . However, if we introduce a system light detection efficiency $E(\lambda)$ and a light collection efficiency L_c (assuming independence of λ), we have:

$$\frac{dN_{pe}}{dL} = 2\pi \cdot \kappa \cdot L_c \int_{\lambda_2}^{\lambda_1} \frac{E(\lambda) d\lambda}{\lambda^2}$$

where $E(\lambda)$ was found by compounding the photo-tube's quantum efficiency with the transmission efficiencies of the light pipe and lead glass, $E(\lambda)$ is shown in figure 2.5a.

This equation gives the number of photoelectrons for the seven radiation lengths of RS360 as:

$$N_{pe} = L_c \times 1040 \text{ photoelectrons.}$$

The shape of the light pipe and lead glass was determined to make L_c as large as possible; factors affecting the light collection efficiency are given below:

- (a) the large opening angle of the detector
- (b) the large half opening angle of the Cerenkov light cone, typically $\sim 38^\circ$
- (c) the reflectivity of the walls of the light pipe and lead glass (the top surface of which was blackened and therefore light absorbing)
- (d) the arrangement of the photo-multiplier tubes
- (e) the angles of the faces relative to each other
- (f) the differing refractive indexes of the materials used.

The resultant shape is shown in figure 2.1 and by consideration of the mu-meson calibration peak, a value of 5% was estimated for L_c , giving approximately 50 photoelectrons for the passage of each singly charged particle. The performance of the Cerenkov element will be dealt with in section 3.6.

The lead glass and its CQ perspex light pipe were optically coupled using silicon fluid (MS 200/500,000) and viewed by six 5" photomultiplier tubes (EMI type 9530A) clamped

into shallow wells on the conical surfaces of the light pipe. Optical coupling was again achieved using silicone fluid. The curved surfaces of the lead glass were highly polished and covered with aluminium foil and black tape, the top was roughened and blackened to absorb light from upward moving showers. The light pipe was vacuum coated with aluminium and covered by black tape. The gains of the photomultiplier tubes were equalised, the outputs summed and fed into a pulse height analyser, after charge amplification, as in the $\frac{1}{2}$ " scintillator element C.

A photo-diode was attached to the top of the lead glass element to provide on-board calibration of the pulse height channel. This diode was designed to flash for each solar sensor event (section 2.5.5) and comparison of its pulse height output in flight with that on a calibration run could give an indication of any change in the photo-tube gains.

The threshold level of the pulse height analyser's discriminator was set to be 200 MeV so that particles below this energy were automatically rejected.

2.2.3 The Anticoincidence Shield

The shield A was made from sections of NE102A plastic scintillator, the top was a 30" diameter disc $\frac{3}{8}$ " thick and the cylindrical part was made up of 4 sections 20" deep and $\frac{1}{4}$ " thick. The top scintillator was viewed directly by two 2" photomultipliers (EMI type 6097A) and each side section was viewed through a perspex light pipe by a 1" photomultiplier (EMI type 9524A). As with the elements B and C, the sections of the shield were covered with aluminium foil and black tape to cut out the ambient light.

Ground level cosmic rays (mostly muons) were used to estimate how efficiently the shield A rejected charged particle events from the gamma-ray channel (coincidence logic ABCD for a charged particle). The efficiency achieved exceeded 99.9% for the predominantly downward moving ground level flux.

2.3 The Lead Converter

The converter was made of a half radiation length disc of lead 38 cms in diameter, placed directly above scintillator B. The probability of pair production in a medium varies as the square of the medium's atomic number so lead with an atomic number of 82 provides a relatively cheap, efficient and easily available gamma radiation ^{converter} ~~absorber~~. Figure 2.6 shows the interaction probability of an incident photon by the Compton effect and pair production as a function of energy (Rossi 1952). The probability of pair production increases with thickness of the absorber. However, so does the scattering of the secondary pair. If a high degree of scattering were allowed, there would be a significant loss in the accuracy with which the photon's arrival direction could be determined. Thus a compromise of half a radiation length was arrived at. This will be dealt with in greater detail in section 3.2.1.

2.4 The Spark Chamber

The spark chamber used in this detector was built by IRD in Newcastle, and comprised four spark gaps, arranged in pairs, as shown in figure 2.1. The chamber was filled with a mixture of helium and neon gases, (31% He, 69% Ne) this mixture having a lower breakdown potential than pure helium and also a

quicker recovery time. Each spark gap consists of two planes of wires, mutually orthogonal, forming a grid. The wires (copper-beryllium, 0.1 mm diameter) are spaced at 0.6 mm intervals and soldered to a bus bar at one end, the orthogonal pair of planes were 1 cm apart and the corresponding gaps in the top and bottom pairs were 30 cm apart. One bus bar of each gap was connected to the high voltage supply and the other to ground so the current path was from the high bus bar down one of the plane's wires, across the ionised track, formed by the charged particle, to ground down one of the orthogonal, grounded plane's wires. The position of the spark in the gap was found by a magnetostrictive technique first suggested by Perez-Mendez and Pfab (1965). The magnetostrictive wires were made of Permendur alloy and lay in the grooves at the edge of the spark planes in close physical contact to the plane's wires but electrically insulated from them by a thin PTFE sleeving and an additional strip of melenex on the 'high' plane. Close physical contact between the magnetostrictive wire (MSW) and the plane wires was essential to produce a high amplitude pulse in the MSW. A head amplifier was magnetically coupled to each end of the wire to sense the magnetostrictive signals travelling along the wire. The MSW were annealed and magnetised along the section in contact with the planes but not under the pick-up coils of the head amplifiers. The biasing field here was provided by placing the pick-up coil between two small cylindrical magnets. The arrangement for sensing the spark position is shown in figure 2.7. The typical outputs from the complimentary head amplifiers are also shown.

As the magnetostrictive pulse travelled at a velocity of 5.185 m/sec down the MSW to the head amplifiers, the timing

of the arrival of the pulses after the spark chamber triggering gave an accurate estimate (see section 3.1.2) of the spark's co-ordinates. The amplified outputs from the head amplifiers, sixteen in all, were fed separately into eight pairs of gating circuits where the pulses were shaped and their mid-points found by zero crossing circuits. The timing of the magnetostrictive pulses was performed by gating on a 2.15 MHz clock, 4 μ s after the spark chamber was fired (to minimise spark interference) and gating it off again by the arrival of the pulse. The 2.15 MHz clock was derived from a 4.3 MHz free running oscillator, after dividing its frequency by two. This reduced the random phase error in the first clock pulse. One gating circuit in each pair could also detect a second pulse, providing this occurred more than 2 clock pulses after the first (giving the time t_3). The number of clock pulses before gating off the clock was counted and stored in twenty four, nine bit Johnson logic stores, giving three numbers per MSW, twenty four in all. The clock was allowed to run for a maximum of 192 pulses before being automatically gated off in the absence of a magnetostrictive pulse, 192 clock pulses being sufficient time for a magnetostrictive pulse to travel from the extreme edge of the chamber to the sensing coil. A 192 number would thus correspond to the gap not firing or the magnetostrictive pulse amplitude being below the threshold level set on the gating circuits. For single track events, t_3 was 192. Each MSW had a length characterised by the average time taken for a pulse to travel from one head amplifier to the other, t_{av} , this being the most probable value of $t_1 + t_2$ (~ 196 clock pulses) in the single track case and $t_1 + t_3$ in the double track

case ($t_3 \neq 192$). The spark co-ordinates were calculated as follows.

2.4.1 Single Track Events

In this case $t_3 = 192$

$$X_i = \frac{(t_{1i} + (t_{avi} - t_{2i})) \times Sc - OR_i}{2}$$

where X_i was the spark co-ordinate in cms (i^{th} plane), t_{1i} and t_{2i} were delays in cycles as defined in figure 2.7, Sc converted from cycles to cms, OR_i was the origin adjustment parameter for the i^{th} plane in the spark chamber co-ordinate system.

2.4.2 Two Track Events

In this case $t_3 \neq 192$ and $t_1 + t_2 < t_{av} - 4$

$$X_{iI} = \frac{1}{2}(t_{1i} + (t_{avi} - t_{3i})) \times Sc - OR_i \quad \text{Prong I}$$

$$X_{iII} = (t_{1i} + (t_{3i} - t_{2i})) \times Sc - OR_i \quad \text{Prong II}$$

For an event to be classed as a two track co-ordinate, the following criteria had to be satisfied:

- (a) $t_3 \neq 192$
- (b) $t_1 + t_2$ must be more than 4 numbers less than t_{av}
- (c) $t_1 + t_3$ must be not more than 4 numbers less and not more than a realistic limit set empirically for the plane.

These criteria distinguished between genuine two track events and noise or shower events. Also, in general, shower events forming multiple sparks were not detected very efficiently because the greater the number of sparks, the lower the amplitude of the magnetostrictive pulses. These events could be

distinguished against by the setting of the gating circuit's thresholds. However, multiple spark (> 2) events were still detected as evidenced by the $\frac{1}{2}$ " scintillator pulse height distribution. Such events comprised $\sim 5\%$ of the flight data.

2.5 Payload Orientation and Tracking

In order to infer the arrival direction of the incident gamma-ray in the celestial or galactic sphere from the spark chamber directional information, it was necessary to know the following three pieces of information:

- (a) the latitude and longitude of the detector
- (b) the orientation of the payload (spark chamber axes) with respect to the terrestrial co-ordinate system
- (c) the arrival time of the gamma-ray.

2.5.1 Tracking Of The Payload

Transmitted data from the detector was received using a steerable twin Yagi aerial. The polar diagram of such an array is highly peaked in the forward direction with a gain of ~ 18 db. An identical aerial was used to determine the bearing of the payload from the receiving station. In this aerial the outputs of the two elements were combined, after introducing a π phase change in the output of one, to give a null reading when the array pointed directly at the distant detector. With the aerial at its null position, its bearing was taken with a magnetic compass to an accuracy of about a degree. This bearing was taken at frequent intervals of time. The line of sight distance to the payload was

determined using an onboard transponder. This device received a square wave modulated signal on the 108 MHz waveband which was retransmitted on the data channel (136 MHz). The delay between the transmitted and received square waves was measured on an oscilloscope. This time was converted into a distance to give the range. The position of the payload could then be established in geodetic co-ordinates using the range, bearing and altitude data. By plotting the flight history thus obtained, the position of the detector was found to an accuracy of about $\frac{1}{4}^{\circ}$.

2.5.2 Altitude Measurement

The altitude of the payload was measured by two 'Olland cycle' devices on board the detector. Each gave a measurement of the atmospheric pressure, outside the detector's pressure dome, on a coarse (200 - 1000 millibars) and fine (2 - 200 millibars) scale to an accuracy of ± 0.2 mb at 3 mb residual pressure. The devices also had a temperature measurement scale of $+30^{\circ}$ to -60° C. The information from these two devices was used to modulate two subcarrier frequencies, one at 1.3 KHz and the other at 2.3 KHz. This information was transmitted continuously. These devices were powered by their own 5V batteries and were sited on the detector's frame outside the pressure dome.

2.5.3 The Magnetometer

The magnetometer used was a three axis flux gate, the mode of operation of which has been discussed in detail by Sanderson (1972). The elements were manufactured by Smith's Industries. The output of each element ranged from 0 volts in a field of -50,000 gamma (-0.5 gauss) to 5 volts in a field of

+50,000 gamma and was digitised so that 10^5 gamma = 2000 digits, giving a sensitivity of 50 gamma per number. The elements were set orthogonal to within a tenth of a degree and mounted on a boom one metre long in order to remove the effects of stray fields produced by the detector. The boom length was arrived at in the following manner: the magnetometer was set up on a rigid support and the reading noted, the detector was then pushed towards it until the position was found at which the magnetometer readings changed by one digit. The magnetometer was then placed on the boom outside the detector's range of influence. The orientation of the payload for each event was obtained by instantaneously sampling the magnetic field with the magnetometer and the information obtained was stored in three eleven bit Johnson stores, ready for transmission. In the ideal situation of the payload always hanging vertically below the balloon, only the X and Y field components would be needed to determine the payload orientation relative to the earth's magnetic field. In practice however, the payload was rotating and swinging slightly and, in fact, had a permanent tilt of 0.6° which had to be corrected for.

2.5.4 Event Timing

The data received from the payload was recorded at 30 ips on an Ampex instrumentation tape recorder. As this experiment was not designed to look for fast time varying phenomena, it was deemed sufficiently accurate to interpolate time along a magnetic tape record, knowing the starting and finishing time of each tape reel (approximately 30 minutes in duration) and the relationship between time and the instrument's revolution counter.

2.5.5 The Solar Sensor

This was a cylindrical drum of diameter 10.5 inches and height 17 inches, with three slits machined along its length, viewed by three photo-transistors. As the payload rotated, the sun passed across these slits and, providing a gamma event was not being processed, triggered one of the photo-transistors. This occurrence was designed to trigger the light diode on the Cerenkov element, the magnetometer and the spark chamber circuits (these would give all 192 as this would not be a true gamma event). However, in flight, due to an electronics malfunction, the light diode did not function and the 'pseudo' event was read out on the next true gamma event. So the pseudo event became a normal gamma event with one photo-transistor fired. However, as the detector was rotating very slowly (~ 10 degrees/minute) compared to the event rate of 2 - 3 events per second, a negligible error in the determination of the solar angle was incurred. The sun itself being 0.5 degrees wide. The solar sensor could be used to check the magnetometer since both the solar sensor and the magnetometer could give the bearing of the detector relative to true north, given the sun's position and the magnetic declination.

2.6 Electronics and On Board Data Handling

2.6.1 Power Supplies

The power for the payload was provided from three power packs of 1.25 volt Nickel Cadmium rechargable batteries. The packs were arranged to provide two 12.5 volt and one 25 volt supplies, providing 1.0, 10.0 and 17.5 watts respectively. The 25 volt pack provided power for the low tension supplies to the

electronics which required various supply voltages. These differing voltages were supplied by low tension converters containing monolithic voltage regulators which provided stability in the output voltage to $\pm \frac{1}{4}\%$ for temperature variations of $\pm 20^{\circ}\text{C}$ and variations in the 25 volt input voltage of ± 3 volts. The efficiency of these converters being typically 80%. One of the 12.5 volt packs supplied the spark chamber power requirements through two high tension converters and the other supplied the high tension converter for the photo-multiplier tubes of the elements A, B, C and D.

2.6.2 Data Handling and Transmission

The gamma-ray event word contained 276 bits of information. This may be broken down as follows:

Spark Chamber	24 channels each of 9 bits	216 bits
Scintillator C	1 channel of 9 bits	9 bits
Lead Glass D	1 channel of 9 bits	9 bits
Magnetometer	3 channels each of 11 bits	33 bits
Solar Sensor	3 channels each of 1 bit	3 bits

This came to a total of 270 bits, leaving four bits at the beginning and two bits at the end of the word redundant. However, these extra six bits served a useful purpose as padding for the event word, preventing useful information being lost, due to poor transmission or transcription. These 'redundant' bits could be replaced in the computer, if necessary, to make up the proper length and internal structure of the word.

The information from the channels itemised above was stored in Johnson random logic stores until the whole word was

compiled. Then the stores were clocked out sequentially into the data encoder. In this encoder the 'one' and 'zero' states received from the stores were encoded into bursts of a 124 KHz oscillator so that a one corresponded to 30 pulses (250 micro-sec burst) and a zero to 15 pulses (125 micro-sec burst). This stream of wave trains was used to modulate a 136 MHz FM transmitter. The event word was read out in 175 milliseconds which was the instrumental dead time during which the coincidence logic was suppressed.

Other information transmitted was the two Olland signals, the transponder, the four-fold coincidence (charged particle) rate (a 2 millisecc burst of a 10 KHz oscillator per coincidence). The radiated power from the transmitter was 2 watts which was more than sufficient to give a flight range of 600 km before the detector inevitably dropped below the horizon. The transmitter fed a crossed turnstile aerial.

2.7 Environmental Stability

The whole detector was enclosed in a pressure dome of 1/16" thick aluminium, maintaining the instrument at ground level atmospheric pressure. This removed the possibility of coronal discharge occurring in the rarefied upper atmosphere, also this put less stress on the spark chamber which contained the He-Ne mixture at atmospheric pressure. The whole payload was enclosed in an expanded polystyrene box to provide thermal insulation at high altitude. The outside of the box was partially (75%) blackened to absorb radiated heat from the sun, in an attempt

to maintain the detector at about 15°C. The lowest temperature experienced in flight was 5°C.

The individual elements of the detector were rigorously tested against temperature variations and the whole detector was tested in a refrigerated trailer down to 0°C. No change in performance was detected.

2.8 Contamination Of The Gamma Event Channel By Spurious Events

Due to the expected low flux of primary gamma-rays at altitude, it was vital to exclude or recognise non-gamma events which trigger the coincidence system. Below, possible spurious events are categorised and their importance determined.

2.8.1 Chance Coincidences

According to Janossy (1948) the chance coincidence rate R is given as:

$$R = n \times R_1 \times R_2 \times \dots \times R_n \times t^{n-1}$$

where n is the number of coincidence elements.

Here we have:

$$R = 3 \times R_b \times R_c \times R_d \times t^2 \quad \text{sec}^{-1}$$

Where $R_{b,c,d}$ are the individual counting rates of the elements B, C, D due to their photomultipliers (mainly due to thermal noise) and t was the resolving time of the coincidence circuits. Typical values are 80 nanoseconds resolving time and 500 counts/second for each channel which gives a value for R of 2.4×10^{-6} or one chance coincidence in 4×10^5 seconds.

Another possible chance coincidence would be a noise pulse in B in coincidence with a charged particle moving upwards

through D and C but being absorbed in C or the spark chamber walls. However this mechanism could not be expected to provide more than 0.01% of events even at the Pfozter maximum.

The spark chamber has a memory for ionised tracks of one microsecond when the clearing field applied to the planes is 100 volts. In order for the chance coincidence to give meaningful spark chamber co-ordinates, the chance coincidence must be within this microsecond dead time after a cosmic-ray interaction. However, the anti-coincidence electronics was set so that the veto remained operative for one microsecond after the anti-coincidence had been triggered. Thus the probability of a chance coincidence must be multiplied by the probability of two cosmic rays traversing the detector in a microsecond which is 10^{-6} . Thus the probability of such an event is negligible and contamination of the gamma-ray channel from chance coincidences can be ignored.

2.8.2 Neutron Induced Events

In these events a neutron passes undetected through the anticoincidence shield and produces a proton in the lead converter which triggers elements B, C, and D. This type of event could masquerade as a gamma event if more than 200 MeV is deposited in the lead glass.

The rate of occurrence of these events was investigated by considering the atmospheric neutron flux reported by Eyles et al. (1972) of $4.1 \times 10^{-3} \text{ cm}^{-2} \text{ sec}^{-1} \text{ str}$ (for neutron energies between 50 MeV and 350 MeV). This gives about 36 neutrons per minute incident on the present detector at altitude with energies greater than 200 MeV. Hadley and York (1950) indicate that the

probability of a 90 MeV neutron interacting in $\frac{1}{2}$ r.l. of lead producing a proton of energy greater than 20 MeV was 0.15%.

The probability of producing a proton with an energy greater than 200 MeV (needed to trigger the lead glass) is much less than this but even using this figure it can be estimated that less than 3 neutron induced events per hour could be expected which corresponds to less than 0.01% of the total count rate. Thus these events may be disregarded from the gamma channel contamination.

2.8.3 Upward Moving Particles

A cosmic ray proton could form an upward moving shower in the lead glass. However only showers of this type in which the upward moving particles are stopped in the lead converter or spark chamber walls could masquerade as gamma-rays, otherwise the anti-coincidence shield would be triggered. Sood (1969) has investigated the likelihood of shower event contamination in the gamma channel for a similar arrangement of scintillator elements and arrived at a figure of $\frac{1}{2}\%$. In the present detector the $\frac{1}{2}$ " scintillator gives an indication of how many particles traverse the system and this with the spark chamber's response to showers combine to give an efficient shower rejection system.

A slow single electron could also trigger the system as described above and would be indistinguishable from a gamma-ray in the spark chamber (as not all genuine gamma-rays produce two distinguishable tracks in the spark chamber). However the $\frac{1}{2}$ " scintillator can register single particle events which could then be rejected. Thus the contamination due to upward moving charged particles can be efficiently ($\ll \frac{1}{2}\%$) removed.

A cosmic ray proton could also produce a low energy gamma-ray as a secondary after a nuclear interaction in the lead glass, which could then travel up the telescope. The gamma-ray could trigger the scintillators (the lead glass already being triggered by the proton) and be absorbed completely in the lead converter. However, this type of event is easily recognised since the output from the spark chamber would be 192 in each channel (no sparks since no ionised track) and a large amount of energy would be deposited in the lead glass. Such events accounted for about 2% of the events at altitude but were easily rejected, using the spark chamber producing no resultant contamination.

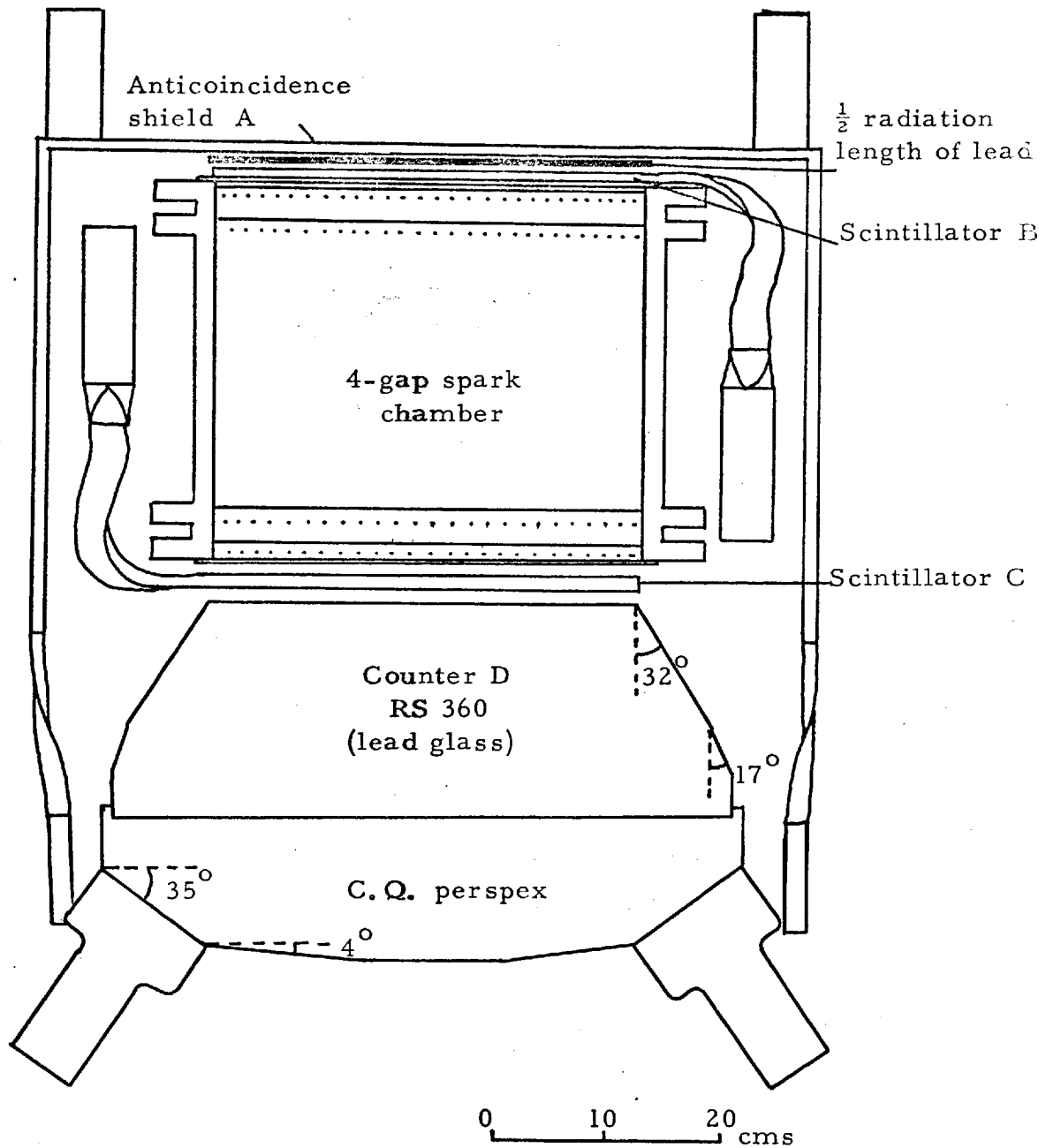


figure 2.1

The Detector

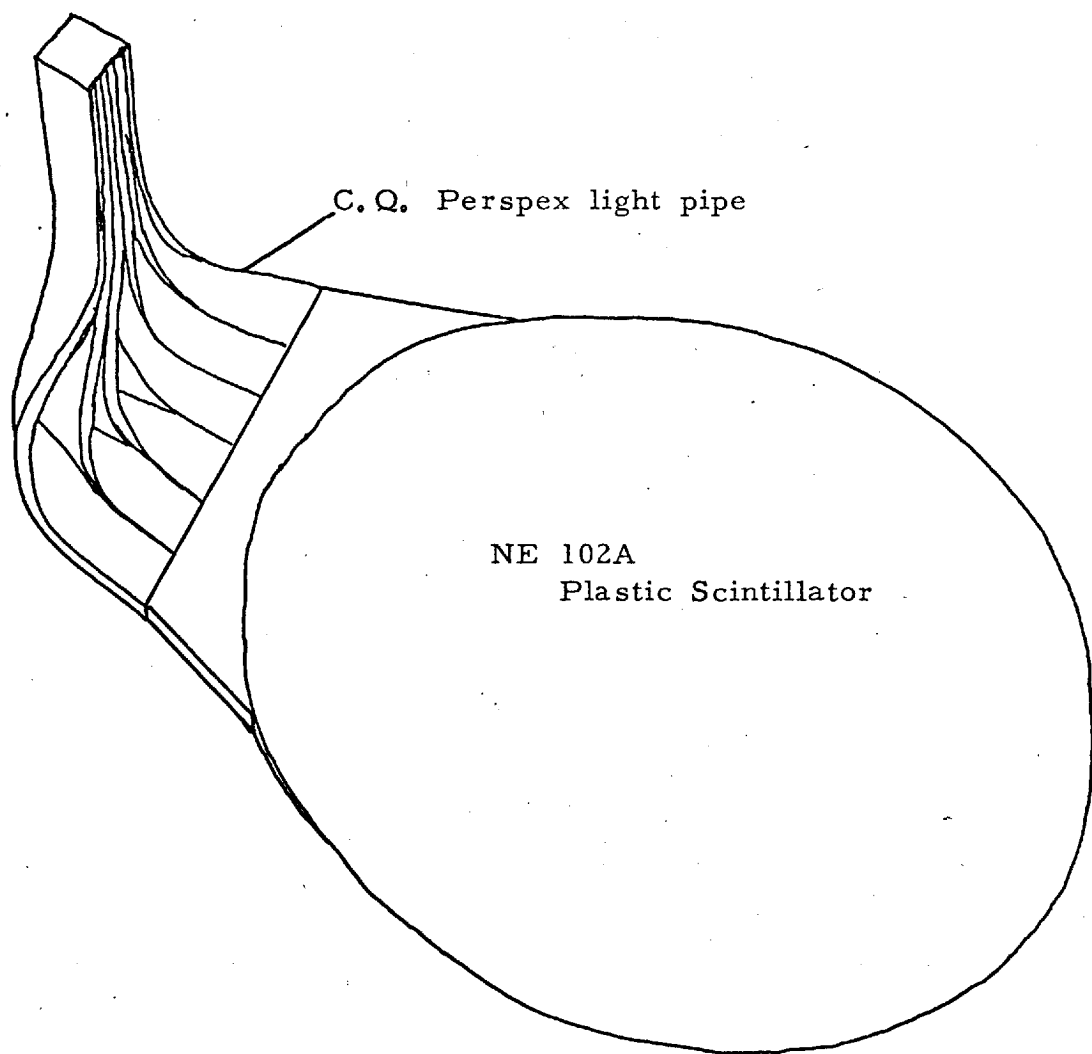


Figure 2.2
The $\frac{1}{4}$ " scintillator and its light pipe

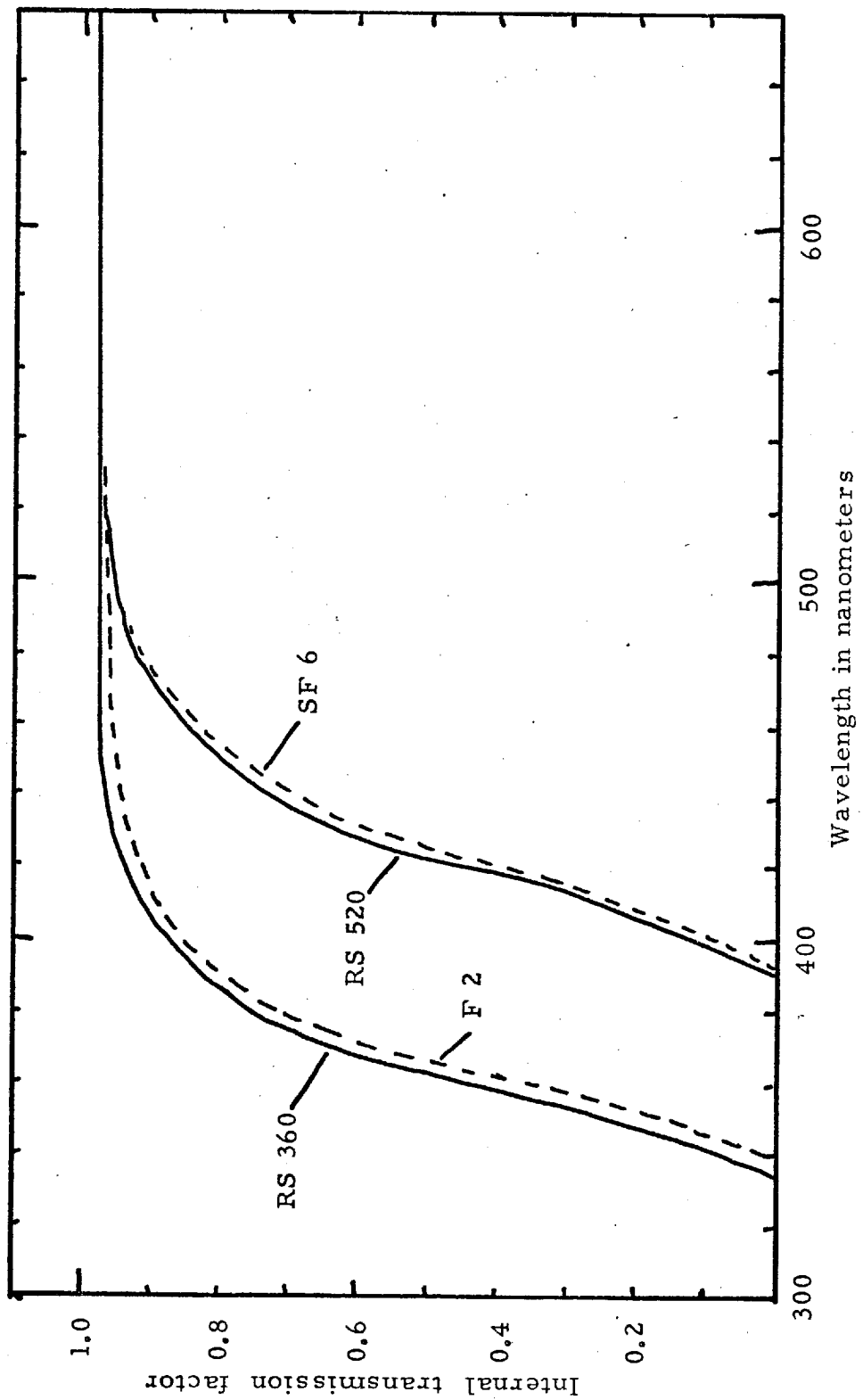


Figure 2.3a
The internal transmission factors for various
lead glasses (10cm thickness)

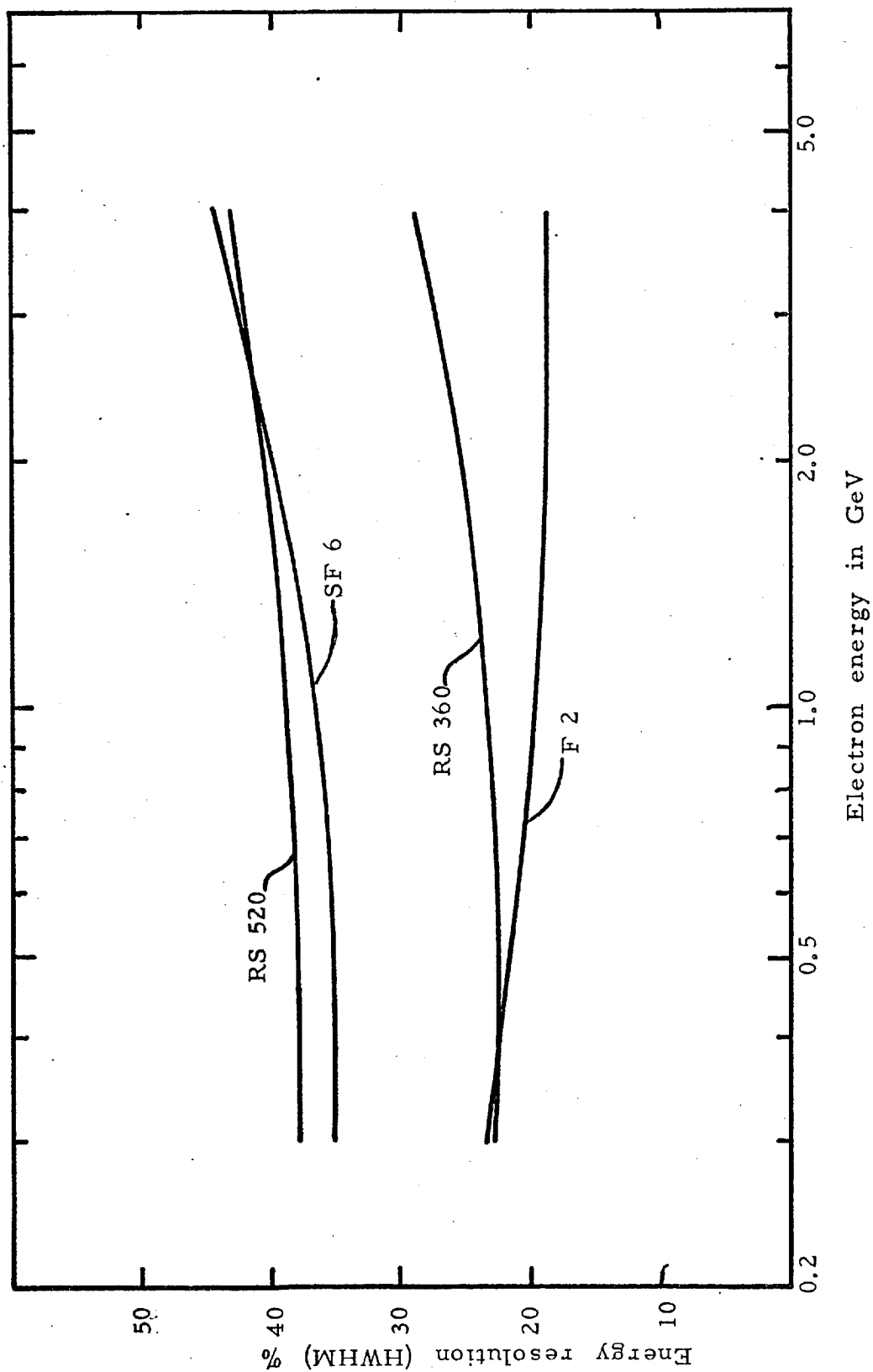


Figure 2.3b
The measured energy resolution of
various lead glasses for electrons

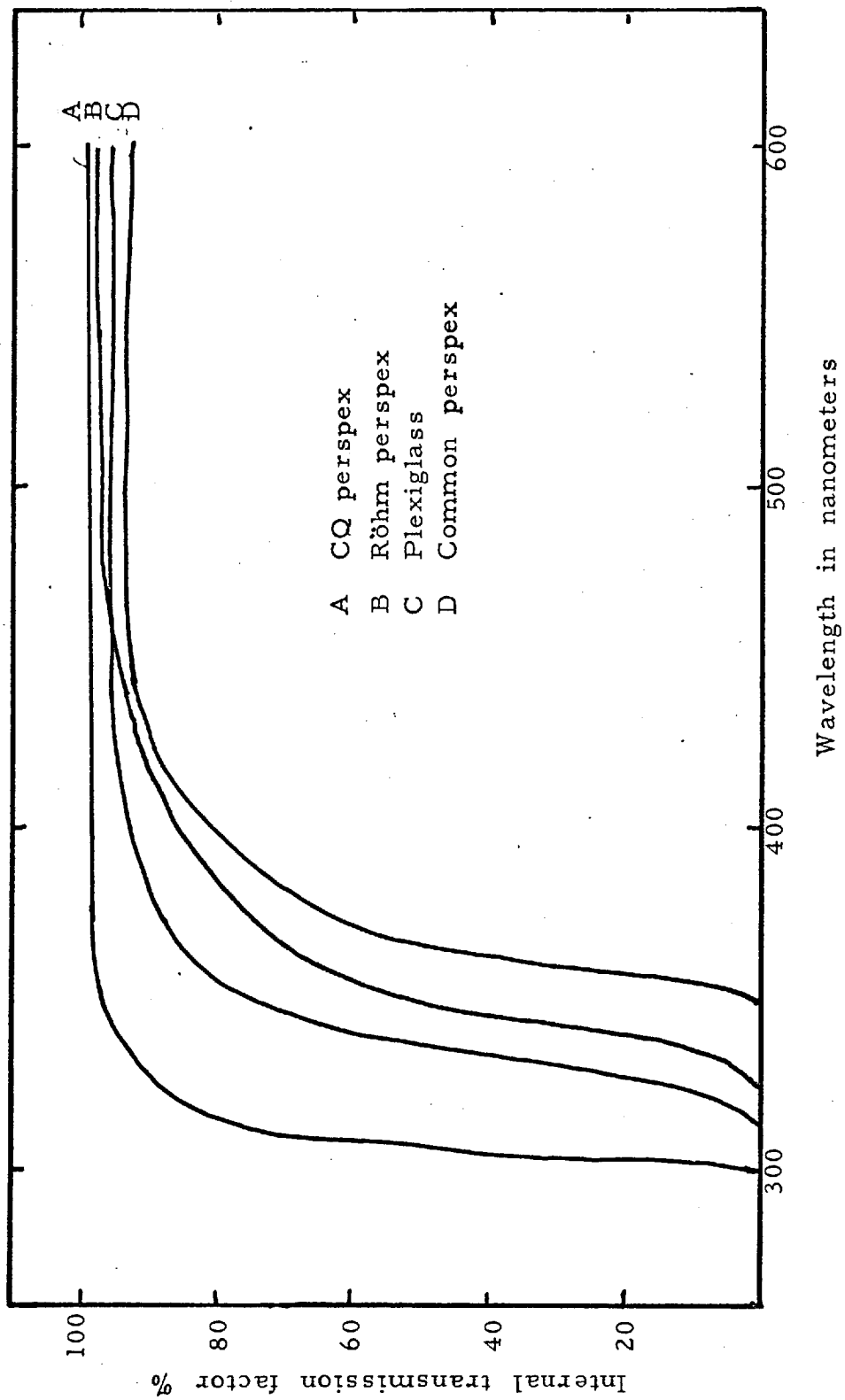


Figure 2.4

Internal transmission factors of various samples of perspex

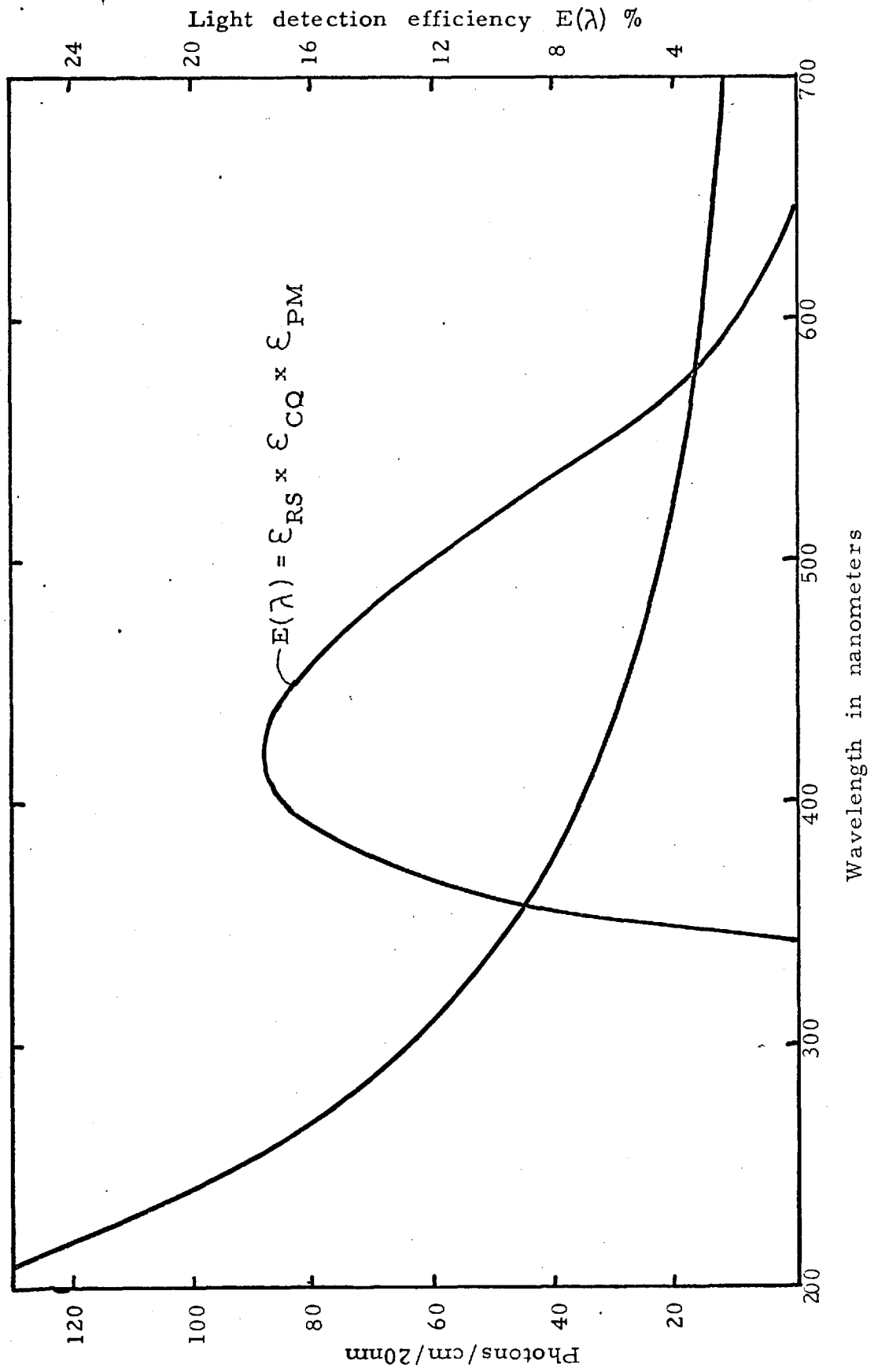


Figure 2, 5a
The system light detection efficiency and photon
yield for a singly charged particle

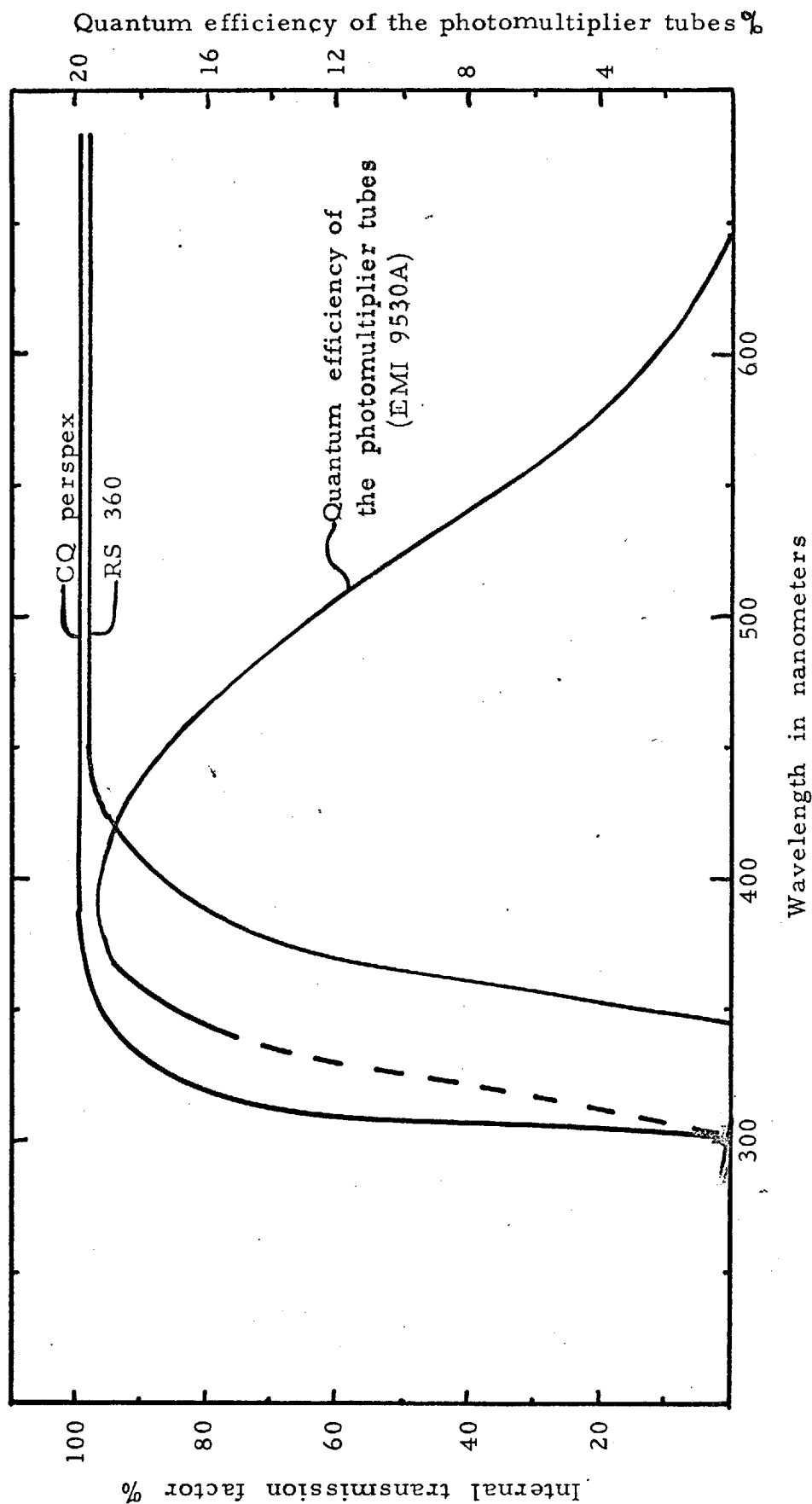


Figure 2.5b
Transmission factors of CQ perspex and RS360 together
with the quantum efficiency of the photo-tubes used

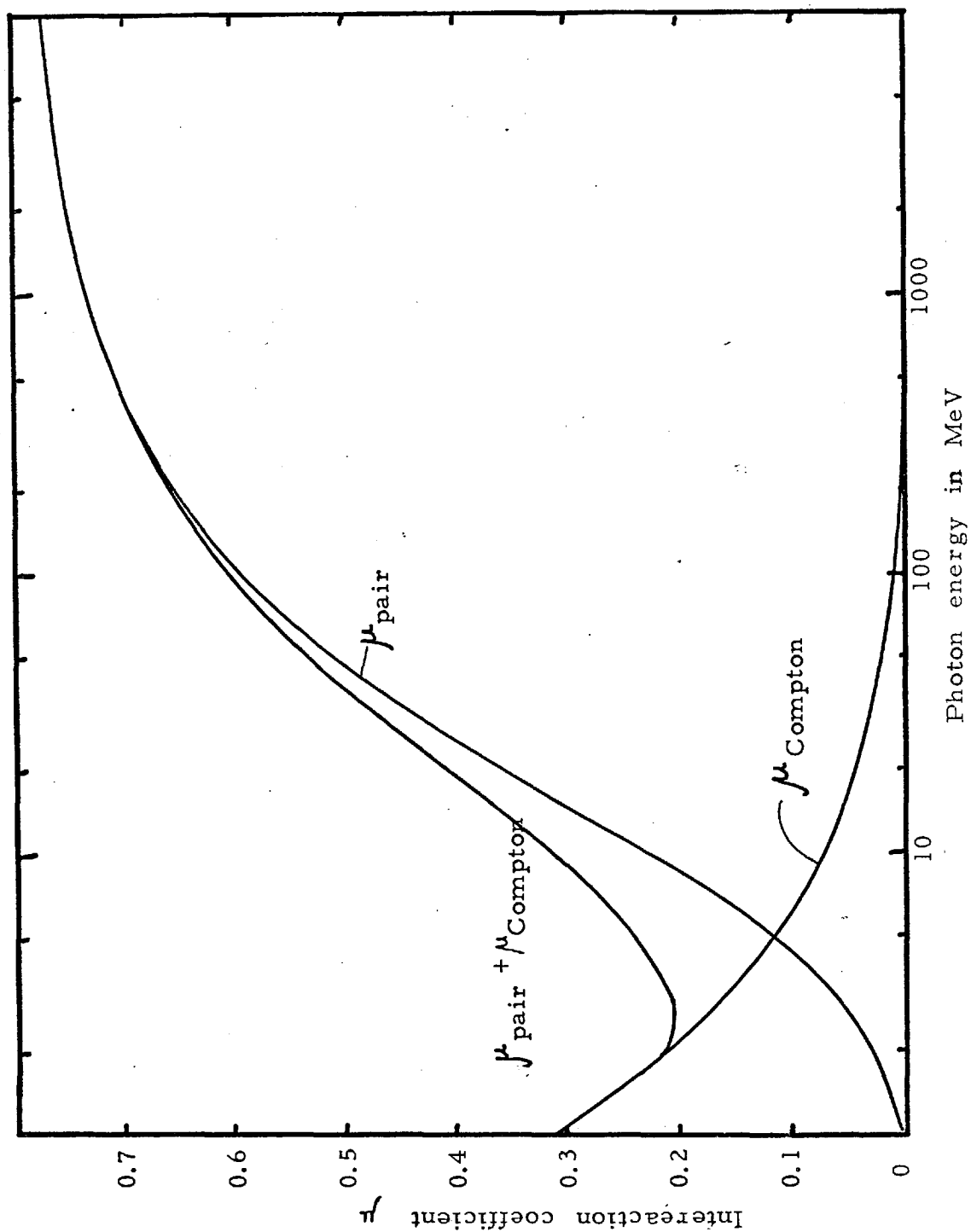


Figure 2.6
The total probability per radiation length for lead for Compton scattering, for pair production, and for either effect.

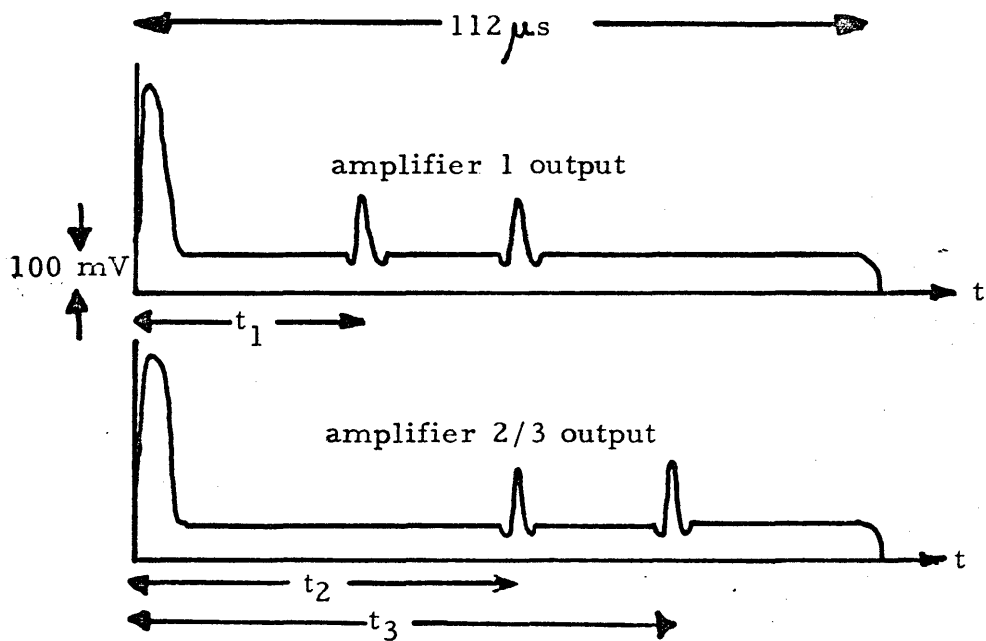
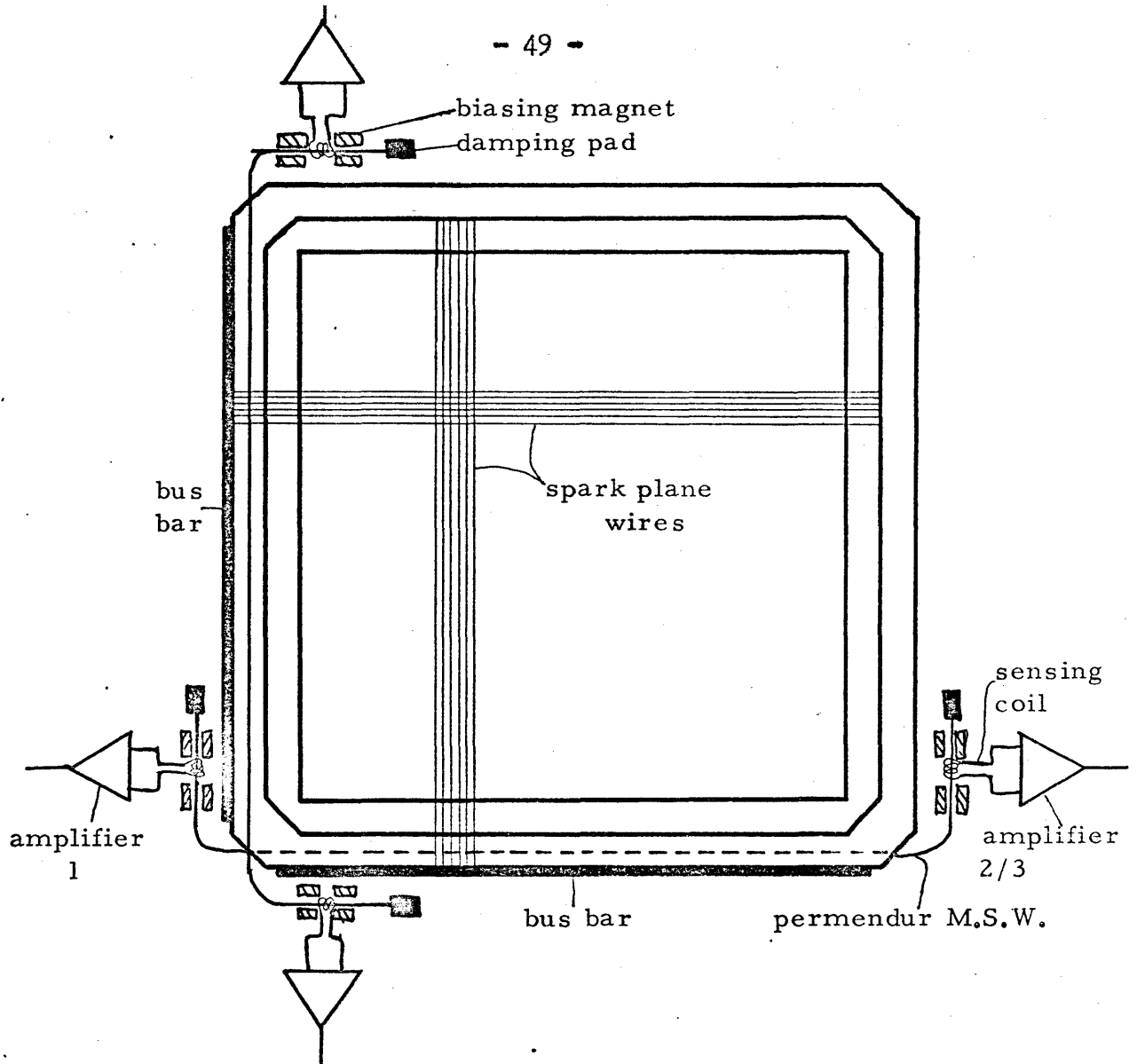


Figure 2.7

- (a) Schematic diagram of a spark plane
- (b) Typical output from the complimentary amplifiers

CHAPTER III

DETECTOR CALIBRATION

Chapter II has outlined the design requirements of the gamma-ray detector together with a brief description of how the detector works. This chapter will be concerned with showing how well the detector satisfied these design requirements by deriving various parameters of the detector. The results brought together in this chapter are data from ground level mu-meson runs, gamma-ray accelerator runs and analysis of the actual flight data. The accelerator data were collected using the tagged gamma-ray beam facility at DESY, Hamburg, a detailed description of this beam facility has been published by Christ et al. (1974).

3.1 The Spark Chamber

3.1.1 Absolute Sparking Efficiency

The main inefficiencies in the spark chamber were caused by failure to detect the magnetostrictive pulses or production of meaningless numbers in one or more planes. The information from a plane (three numbers, see figure 2.7) was deemed meaningless if any of the following occurred:

- (a) a 192 number in the first or second channel of the plane
- (b) if the sum of the complimentary channels (first and second in a single track event, first and third for two tracks) was greater than a realistic upper limit or less than a lower limit both set

empirically

- (c) if a number greater than 192 appears anywhere in the plane's data.

The events were classified in types according to their spark patterns as shown in table 3.1.

Z ↑ 	4	*	*	*	*	0	*	*	0	0		* denotes a satisfactory signal from the plane
	3	*	*	0	*	*	0	0	*	*		
	2	*	0	*	*	*	0	*	0	*	any	
	1	*	*	*	0	*	*	0	*	0	other	
	type	1	2	3	4	5	6	7	8	9	10	

Table 3.1

If the efficiency of the plane in detecting a spark, when one was present, was η then the probability of obtaining 4, 3 or 2 sparks (4, 3, 2 satisfactory signals from the planes) was as follows:

$$\begin{array}{ll}
 4 \text{ sparks} & \eta^4 \\
 3 \text{ sparks} & 4\eta^3(1-\eta) \quad 4\eta^3(1-\eta) \\
 2 \text{ sparks} & 4\eta^2(1-\eta)^2 \quad 4\eta^2(1-\eta)^2
 \end{array}$$

Thus, by comparing the frequency of 4, 3, 2 spark events (type 1 : type (2,3,4,5) : type (6,7,8,9)) a value for η was obtained. This gives the absolute spark chamber efficiency as:

$$\epsilon = \eta^4 - 4\eta^3 + 4\eta^2$$

The variation of the spark chamber efficiency with zenith angle was found for ground level muons and compared with that for gamma-rays in flight. This is shown in figure 3.1. As can be seen from this diagram, the plots are virtually the same shape with a constant efficiency out to a zenith angle of 32.5° after

which the fall off in efficiency was very marked. This rapid fall off was due to the increased length of the ionized track within the spark gap. This effectively reduced the electric field available to produce the spark down the ionized track, to below the threshold value (6.4 kV) necessary to complete the breakdown of the gas, forming a spark. Thus, effectively, the plane had not 'seen' the passage of the secondary electron.

The change in efficiency between the mu-meson line and the flight data was due to the relative 'ages' of the gas in the spark chamber. As the flight progressed, the efficiency fell off as shown in figure 3.2. This was also due to the aging of the spark chamber gas towards the end of the flight. In general, the gas in the spark chamber could be expected to last about 14 days during calibration runs of the chamber. However, for the flight, the chamber was filled and sealed ready for launch but the launch was delayed by ten days because of unfavourable conditions and consequently the gas was not as fresh as it might otherwise have been; leading to the fall of efficiency during the flight, and the difference between the mu-meson and flight data plots against zenith angle.

3.1.2 Spatial And Angular Resolution Of The Spark Chamber

As has already been mentioned, the spark chamber co-ordinates were determined by gating on and off a 2.15 MHz clock (4.3 MHz crystal controlled clock, divided by 2) and converting these times into distances (the magnetostrictive pulse travels at a velocity of 5.185 m/sec along the MSW). The frequency of

the clock pulses was limited to a maximum of 2.3 MHz by the switching speed of the integrated circuits in the stores, the choice of which was in turn limited by power considerations on board the gondola. The magnetostrictive pulse was timed to each end of the wire and the co-ordinate was determined, as shown in section 2.4, by combining the outputs of the complementary sensors. By this method it was possible to locate the position of each spark to ± 0.5 digits (± 1 digit for 2 track) or ± 1.25 mm in each co-ordinate that is ± 1.5 mm for each spark. The shift of spark position for non-vertical tracks (jitter) was another possible source of error but this was shown by Alkofer (1969) to be less than the error due to digitisation.

Another source of error was the width of the magnetostrictive pulse which was mainly due to the width of the pick-up coil of the head amplifier. A compromise was sought here because the amplitude of the pulse is considerably increased by having many turns on this pick-up coil but this inevitably led to an increased pulse width which can be typically 2 digits. However, in this instance, the effect was considerably reduced and was not serious, due to the use of zero crossing detection circuits in the gating electronics which accurately located the centre of the peak. By this method of estimating the co-ordinate and making the conservative assumption that there was no gain in angular resolution by making a least squares fit to 4 sparks as against drawing a line through only two, we obtain a value for the angular resolution of the spark chamber of $\pm \frac{3 \text{ mm}}{300 \text{ mm}} = \pm 0.6^\circ$

where the distance between corresponding planes in the top and bottom pairs was 300 mm.

3.1.3 Line Fitting Criterion

In estimating the direction of the secondary electron(s) in the spark chamber a least squares fit was performed on 3 and 4 spark events (types 1 - 5). These events could then be accepted or rejected by the deviation of the spark co-ordinates from this best fit line. A tolerance $\pm S$ was set on this deviation with events having co-ordinates outside this tolerance rejected, in the case of 3 spark events, or reclassified as 3 spark events in the case of 4 spark events when only one co-ordinate was outside this limit. Figure 3.3a shows a plot of S against percentage of events accepted for single high energy charged particles (cosmic ray mesons). It can be seen from this graph that 68% of events (3 & 4 spark events) were accepted when the line fitting tolerance S on each co-ordinate was set at ± 0.8 mm. This effect was shown to be independent of angle of incidence and energy by performing this analysis in different zenith and energy ranges. The values for gamma-rays during flight was similar although as can be seen from figure 3.3b, the plot continues to rise slightly as S is increased. This was probably due to two track events in which the two tracks have not shown up in all the planes but some planes have sensed one prong and other planes the other prong so that the event has been treated as a single track event and a best fit line, which in fact closely approaches the bisector of the two prongs, has been drawn. This effective drop in the double spark sensing efficiency was due to the aging of spark chamber gas and consequent drop in MS pulse amplitudes. In

flight S was set at .4 and .5 cm in the upper and lower planes respectively. This corresponds to 90% of the events which were line fitted being accepted, taking the drop of two spark efficiency into account.

3.2 The Lead Converter

3.2.1 Conversion Efficiency

The absolute conversion efficiency was measured at DESY. For this test the readout electronics was disabled and the $\overline{ABCD}$ coincidence rate noted and compared with the incoming flux. The dead time of the coincidence channel was then 1 millisecond so this did not limit the response of the system to the incoming gamma-rays. The result is shown in figure 3.4a where the solid line represents the theoretically predicted conversion efficiency. This conversion efficiency ε was calculated from:

$$\varepsilon = 1 - \exp(-\mu t/X_0)$$

where μ was given by Rossi as shown in figure 2.6 for one radiation length ($t = X_0$). In this case $t = \frac{1}{2}X_0$ for a half radiation length converter. The effect of the sides of the anti-coincidence shield on the conversion efficiency was also investigated at DESY and it was found to reduce the efficiency by 2% when they were active. The detector was tilted relative to the beam direction and displaced parallel to it. The efficiency obtained again agreed very well with the theoretical value, as shown in figure 3.4b, c. As the detector was tilted the thickness of the lead converter increased as $\sec \theta$ for a zenith angle θ and the theoretical line in figure 3.4b has been corrected

for this. In both these figures the theoretical curves have been corrected for the observed dependence of the flux on radial distance and energy as discussed below.

The variation of ~~flux~~^{efficiency} across the lead converter was calculated in the following way. The converter was split up into bins of zenith, azimuth (relative to the radius vector) and radial distance (annuli). The area solid angle factors for each of these bins was also calculated by numerical integration. Thus it was possible to calculate the flux by categorising events into these bins and dividing by the relative factor. No significant variation with azimuth was found for ground level mu-mesons or flight gamma-rays. However there was a variation with annulus (radial distance) and zenith as are shown in figure 3.5a, b for flight gamma-rays. Also shown in figure 3.5a is the zenith dependence for muons together with the expected variation of intensity as a $\cos^{2.1}\theta$ (Moroney and Parry (1954)).

Examination of figure 3.5a indicates that the mu-meson data exhibit the $\cos^{2.1}\theta$ dependence expected and that the flight gamma-rays had a $\sec \theta$ dependence after correction for the converter thickness change with zenith. When the data obtained from DESY was examined, no variation with zenith from the theoretical line was found, as evidenced by figures 3.4a, b. This suggested that the $\sec \theta$ dependence for gamma-rays at altitude was not due to an instrumental effect but was real as would be expected since at a zenith angle θ the apparent depth of the atmosphere increases as $\sec \theta$.

The flux depended on the area solid angle factor which in turn depended upon the effective length of the telescope

The telescope length was the distance between the converter (for gamma-rays, the $\frac{1}{4}$ " scintillator for mu-mesons) and the point in the lead glass to which the secondary electrons (or muons) must penetrate to produce a pulse height output large enough to trigger the system. This point depended upon, shower growth statistics for the electrons, but only on path length for the muons which did not form electromagnetic showers in the lead glass. The correct zenith dependence gave confidence that the correct telescope lengths had been used in calculating the area solid angle factors. This is extremely important in the calculation of the exposure factors for the flight data used to calculate source intensities. This is described later in section 4.2.2.3. These results give values to the opening angle of 36.7° for gamma-rays of energy less than 1.4 GeV and 35.8° for energies greater than this and also for mu-mesons.

Figure 3.5b shows the dependence of the conversion efficiency on energy and radial distance across the lead converter. This figure shows the drop in efficiency with radial distance which was due to the increased number of slow electrons which were scattered into the anti-coincidence shield as the radial distance increased. These plots are for events with a zenith angle less than 22° .

3.2.2 Scattering In The Lead Converter

In general, the electron and positron emerged from the converter at different inclinations to the direction of the parent photon. This was due to scattering of the secondary products by the nuclei in the lead sheet, due to a transfer of momentum between the photon and the neighbouring nucleus during

pair production. This effect has been described in detail by Olsen (1963) where he related the most probable opening angle of the pair θ to the photon energy E_γ by:

$$\theta = \frac{1.6}{E_\gamma (\text{MeV})} \quad \text{radians}$$

for equipartition of energy between the secondary pair. It can be seen that for a 200 MeV photon θ was $\sim \frac{1}{2}$ deg. which gives an error in the bisector of $\sim \frac{1}{4}$ deg. which was small compared with the angular resolution of the spark chamber derived in section 3.1.2. However this relationship does not take multiple coulomb scattering, after materialisation, or non-equipartition of energy into account. These effects combine to produce a greater uncertainty in the photon arrival direction than would be estimated from the above relation.

3.2.3 Multiple Coulomb Scattering

Olsen (1963) gave a condition for multiple coulomb scattering to be important, this was if $a^2 \gg 1$, where

$$a^2 = \frac{1}{3} \langle \theta_s^2 \rangle \left(\frac{E_\gamma}{4} \right)^2 L$$

where $\langle \theta_s^2 \rangle$ was the mean square angle of deflection, L was

the thickness of material to the point of origin of the pair.

Rossi (1952) gave an expression for $\langle \theta_s^2 \rangle$ which when substituted into the above equation gave:

$$a^2 = 0.21 \left(\frac{Z(Z+1)}{A} \right) \ln \left(\frac{196}{(ZA)^{1/6}} \right) L$$

L is now measured in gm/cm^2 . For lead, $Z = 82$, $A = 217.2$ so we have:

$$a^2 = 24.91 L$$

which was much greater than 1. Olsen (1963) then gave the expression for the measured opening angle after scattering as:

$$\theta = 2a \left[1 + \frac{(\ln 2a^2 + 1.29)}{4a^2} \right] / E_{\gamma \text{ MeV}}$$

This method was used by Claverie et al. (1971) to estimate the energy E_{γ} from the measured value of θ after scattering through their detector. They obtained excellent agreement when comparing their results for the atmospheric gamma-ray spectrum with the experimental results of Carlson et al. (1950) and the theoretical predictions of Hayakawa (1964).

The curves of figure 3.6a show how the scattering angles for $\frac{1}{4}$ r.l. and $\frac{1}{2}$ r.l. of lead vary with energy indicating that the degree of scattering of the secondary electrons depended on the depth at which the pair materialised. Bennett (1973) investigated the distribution of scattering angles for 100 MeV electrons produced at various depths in $\frac{1}{2}$ r.l. of lead and derived the effective distribution of scattering angles. This curve was compared with the $\frac{1}{4}$ r.l. scatterer in figure 3.6b. It can be seen that they peak at approximately the same angle although the long tail in the derived curve reduced its relative amplitude on normalisation. However, Bennett concluded that it was a reasonable approximation to assume that on average all electrons formed in the lead were scattered by a quarter of a radiation length.

Thus for equipartition of energy the opening angle for electron and positron was $\sim 7^\circ$ for a 200 MeV photon.

3.2.4 Partition Of Energy Between The Electron And Positron

This model was improved on when partition of energy between the electron and positron was taken into account as

given by Rossi and Greisen (1941). Their results were presented in the form of normalised curves; the relevant ones for this detector are shown in figure 3.7. The ordinate is $E\phi_{\text{pair}}(E, E')$ and the abscissa v the fraction of the photon energy carried by the electron (or positron). If $E\phi_{\text{pair}}(E, E')$ was the differential probability per r.l. of the electron carrying an energy E' from a photon of energy E it may be deduced from the curve of Rossi and Greisen the average energies of the low and high energy members of the pair

$$\bar{E}_{\text{low}} = \frac{\int_0^{\frac{E}{2} - mc^2} E\phi_{\text{pair}}(E, E') E' dE'}{\int_0^{\frac{E}{2} - mc^2} E\phi_{\text{pair}}(E, E') dE'}$$

and since $v = \frac{E' + m_e c^2}{E}$ the fraction of the photon energy

carried by the low energy electron

$$\bar{v}_{\text{low}} = \frac{\int_0^{1/2} E^2 \phi_{\text{pair}}(v) v dv}{\int_0^{1/2} E^2 \phi_{\text{pair}}(v) dv}$$

This integration was performed numerically for curves of several energies. The results are shown in table 3.2. It can be seen that on average 25% of the photon's energy is carried by the low energy partner at 200 MeV this figure reducing to 23% at 5 GeV. It can be seen from this table that one of the pair was scattered very little compared to its low energy partner, to which the loss in angular information was mainly due.

In some cases the low energy partner would have been scattered to such an extent that it would not cross the spark chamber leading to a single electron event, or may have been scattered into the anticoincidence shield. (See section 3.2.1)

photon energy MeV	average energy of low energy electron MeV	scattering angle for $\frac{1}{4}$ r.l. Pb degrees		average error in photon direction estimation degrees
		low energy	high energy	
200	50	7.35	2.36	5.13
300	72	5.0	1.57	3.48
500	120	3.0	1.0	2.1
1000	235	1.5	0.5	1.05
3000	700	0.5	0.2	0.35
5000	1160	0.3	0.1	0.2

Table 3.2

In the case of the single electron event, the photon energy could be underestimated by as much as 25% but probably less since an electron with an appreciable energy would stand a good chance of triggering the anticoincidence shield if its trajectory was so steep as to miss the $\frac{1}{2}$ " scintillator and consequently the lead glass. However a low energy secondary could be absorbed by the spark chamber walls or lead converter and this would lead to only a slight underestimation. It will be seen in section 3.5 that for the DESY calibration data less than 6% of the events were single track. So it can be seen that the measurement of the photon energy can be considered to be better than 94% accurate (within the energy resolution, section 3.6). Thus, when the low energy electron is lost the remaining high energy electron describes the parent photon's arrival direction to high precision and also its energy to an accuracy comparable to the energy resolution of the system.

In the case of the low energy electron triggering the anti-coincidence shield, this would lead to the loss of the event

together with the inaccuracies in photon direction estimation brought about by scattering in the lead converter. This would lead, on average, at low energies, to an angular resolution better than that predicted on the basis of scattering in the lead. This is however not the case as is shown in section 3.4.

3.3 Payload Orientation

The accuracy to which the orientation of the payload and hence the gamma-ray's point of origin could be determined, depended upon the following:

- (1) the accuracy of the magnetometer, alignment, digitisation and calibration
- (2) the agreement between the magnetometer's bearing and that obtained by the solar sensor
- (3) the accuracy of the earth's field model, used to check the field values obtained by the magnetometer and to calculate the magnetic declination, given the altitude and position of the detector.

The digitisation of the magnetometer has already been discussed in section 2.5.3. It follows from this that the upper limit to the accuracy of the measurement, due to digitisation, of the horizontal field component of 30,000 γ was $\pm 0.2^\circ$ corresponding to a change of ± 1 digit in each of the X and Y axes.

The magnetometer axes were mechanically aligned to an accuracy of $\pm 0.1^\circ$. The magnetometer calibration was found not to be linear and had to be fitted by a polynomial. Also, it was found to vary with temperature and as the temperature of the magnetometer electronics was only known to $\pm 5K^\circ$ this introduced

a further error of ± 1 digit or $\pm 0.2^\circ$.

The orientation of the payload was also determined by the solar sensor which was mounted independently of the magnetometer on the spark chamber base plate. The width of the solar sensor slits limited the accuracy of solar measurement to $\pm 0.5^\circ$ and the alignment between the solar sensor and the magnetometer was accurate to $\pm 0.2^\circ$. After correcting the magnetometer for its non-linear calibration and the permanent tilt of the detector (0.6°) the bearing calculated by it and the solar sensor were compared and found to be in agreement to $-0.41 \pm 0.43^\circ$ over the whole flight.

When the corrected magnetometer field values were compared with those of the International Geographical Reference Field (IGRF) (Malin 1969) values, the following points were noted:

- (a) The dip angle measured by the magnetometer differed from the IGRF value by about 1.4° .
- (b) The Air Ministry value of the declination along the balloon's flight path exceeded the IGRF value by $0.15^\circ \pm 0.02^\circ$.
- (c) The values for the total field measured by the magnetometer and computed from the IGRF model agreed to within $\pm 50\%$ at the beginning and end of the flight but differed by as much as $\pm 800\%$ in the middle. This may have been caused by local topological variations from the more general IGRF model. However, since the orientation of the payload was derived from the magnetic declination, the other discrepancies were not significant and 0.15° was added to the IGRF declination to bring

it into agreement with the Air Ministry value.

Combining the errors, the total error in the payload orientation was:

$$\pm (0.2^2 + 0.1^2 + 0.2^2 + 0.02^2)^{\frac{1}{2}} = \pm 0.3^\circ$$

which is considerably less than the error produced due to the spatial resolution of the spark chamber. By the comparison of magnetometer and solar sensor bearings an error on the magnetometer of $\pm 0.02^\circ$ to $\pm 0.84^\circ$ is obtained which agrees very favourably with the theoretical prediction of $\pm 0.3^\circ$.

3.4 The Angular Resolution

The total angular resolution can be calculated by considering the contributions due to the spark chamber, multiple coulomb scattering in the lead, and the payload orientation. The resulting theoretical resolution is shown as the solid line in figure 3.8 together with the experimentally measured values from the DESY calibration run. The angular resolution was defined as the cone angle containing 68% of the events when a parallel beam of gamma-rays was incident. Christ et al. (1974) have given the average beam spread at DESY to be $\pm 0.2^\circ$ and this small angle was subtracted from the experimental measurements. The measurements were made at four angles of incidence 3.7° , 7.7° , 27.7° and 1.4° , these directions being computed by taking the average direction of all the high energy tracks through the spark chamber. It was found that the measured angle of incidence for each position was independent of energy within experimental errors and therefore it was concluded that there was no bias induced by scattering or by absorption of the slow electron for example, which could shift the apparent position of a point source of gamma-rays.

It can be seen from figure 3.8 that the angular resolution was virtually independent of angle of incidence as would be expected from section 3.1.1 since the spark chamber efficiency was flat out to a zenith angle of 32° . Also, it can be seen that the experimental points are a good fit to the theoretical curve. This indicates that the low energy partner was in general reaching the lead glass, a point borne out by figure 3.9b showing the $\frac{1}{2}$ " scintillator output for the DESY data. Here it can be seen that the majority of the events were from two particles.

3.5 Scintillator Element C

The $\frac{1}{2}$ " scintillator element was designed to indicate the number of electrons passing from the spark chamber into the lead glass. By knowing this number, it was possible to categorise events still further, e.g., a single electron could indicate a primary gamma-ray converting into two electrons, one of which was low energy and was absorbed in the lead or spark chamber walls or a single back-scattered electron from a nuclear interaction in the lead glass which stopped in the lead converter. Multiple electrons could signify a high energy primary forming a shower of secondary electrons in the lead or a shower from a nuclear lead glass interaction, although this is not as likely as the diverging shower would have more chance of one of its number triggering shield A. Also a high energy primary shower would be compact but an upward-moving shower could be low energy and therefore dispersed. Thus the scintillator was used to discriminate against single slow electron events, probably upward-moving, which would contaminate the gamma-ray channel. In fact

quite a marked improvement was seen in the signal to noise ratio across the galactic disc when this was done. However no similar increase was noted when scintillator C was used to reject shower type events. Figure 3.9a shows the pulse height distributions in three energy intervals for the flight data and figure 3.9b the distributions for the DESY gamma data. The $\frac{1}{2}$ " scintillator was calibrated on both ground level cosmic-ray secondaries (muons and fast electrons) and the tagged gamma beam. From the muon data a map of the scintillator was built up to show variations in pulse height across it for single particles and an empirical correction was made to unify the pulse height across the scintillator to that obtained for axial particles. The effect of this is shown in figure 3.10a, 3.10b, (a) being before correction and (b) after correction. It can be seen that the peak has become narrower after applying this correction, although it is still broader than it should be because of the presence of fast electrons with a different Lorentz factor producing a slightly higher pulse height. The same narrowing effect occurred for gamma-data from the tagged beam. It was possible, in this data, to pick out multiple electron peaks especially at high energy and by summing these energies and fitting peaks to the experimental curve it was possible to find the positions of the pulse heights corresponding to multiple electron interactions. This data was used to discriminate against noise events in the flight data.

3.6 The Energy Calorimeter

3.6.1 Uniformity Of Light Collection

The energy calorimeter was designed, as discussed in section 2.2.2, to produce a high number of photo-electrons for

the transit of a singly charged particle. Another requirement of the system's optics was to produce a uniform pulse height across the whole face of the lead glass, independent of arrival direction, for isoenergetic electrons. This ideal depends upon the uniformity of the light collection efficiency of the system. This uniformity was investigated by analysing a large amount of mu-meson data (minimum ionizing particles which pass right through the calorimeter). The number of photons produced by a mu-meson depends only on its path length in the lead glass, however, after path length correction, the pulse heights obtained were found to have highly significant variations with azimuth, zenith and radial distance from the centre of the lead glass. This was due to the non-uniformity of the light collection efficiency.

Using the results of this data analysis it was possible to construct an empirical map of the lead glass face to correct the pulse heights at various trajectories to those of axial events. Figures 3.12 a and b show the mu-meson peak before and after correction for differing trajectories. It can be noted that the width of the peak has been reduced by the correction. This empirical correction was also applied to the gamma data obtained at DESY, figure 3.13 a, b, illustrate its effect. It will be seen that the points for different positions in the beam have been brought on to a common line and the width of the pulse height peaks (indicated by the horizontal bars) has also been reduced. Thus the correction arrived at from the mu data applies equally well to gamma-ray data in spite of the lateral spread of the showers produced in the lead glass by the secondary electrons from a gamma-event. Messel and Crawford (1970) give the lateral spread of the shower as one r.l. after seven radiation lengths,

for a 200 MeV electron shower. Thus the shower is totally contained in the lead glass element up to zenith angles approaching 30 degrees, which was outside the range examined at DESY. However as has been seen from section 3.1.1, the spark chamber efficiency fell off rapidly after 32 degrees thus discriminating against high zenith events. This in turn reduced the error in energy measurement, produced by loss of part of the shower, to insignificance compared with the volume of lower zenith data.

3.6.2 Energy Measurement On Gamma-Rays

As mentioned in the previous section, the data obtained from the tagged gamma beam at DESY was corrected for the variation in light collection efficiency. This corrected data was then used to estimate the error in measuring the energy of a gamma-ray using the calorimeter. The data is shown in figure 3.13b where the vertical bars represent an estimate of the reproduceability of the DESY gamma energy (Christ et al. 1974). The horizontal bars include the estimated contribution to the observed pulse height distribution from the spread in the DESY beam energies. This means that the systematic error in measuring the gamma energy is in fact less than the full width of these bars by this amount. The experimental points were combined in a weighted least squares fit to produce the line shown in figure 3.14, the horizontal bars on this plot representing the RMS deviations of the experimental points (not shown) from the best fit line. The error in fitting this line thus represents the calibration error of the calorimeter. The energy resolution can now be compounded from the calibration error and the error in making the energy measurement (due to shower development statistics). This resolution is shown in figure 3.15. The energy resolution is defined by saying

that the probability is 68% that the true energy of a gamma-ray differs from the measured value by less than the resolution.

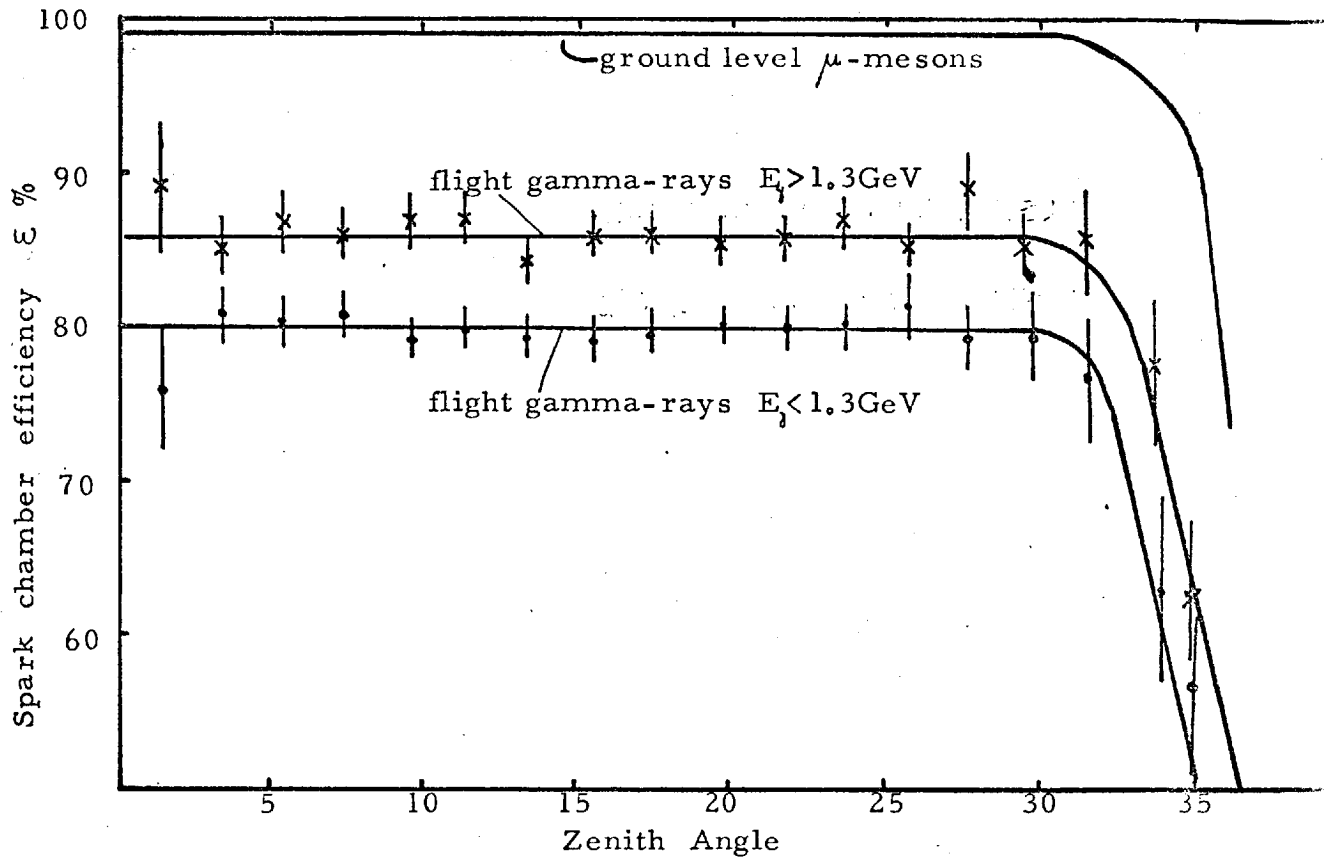


Figure 3.1

The spark chamber efficiency as a function of zenith angle

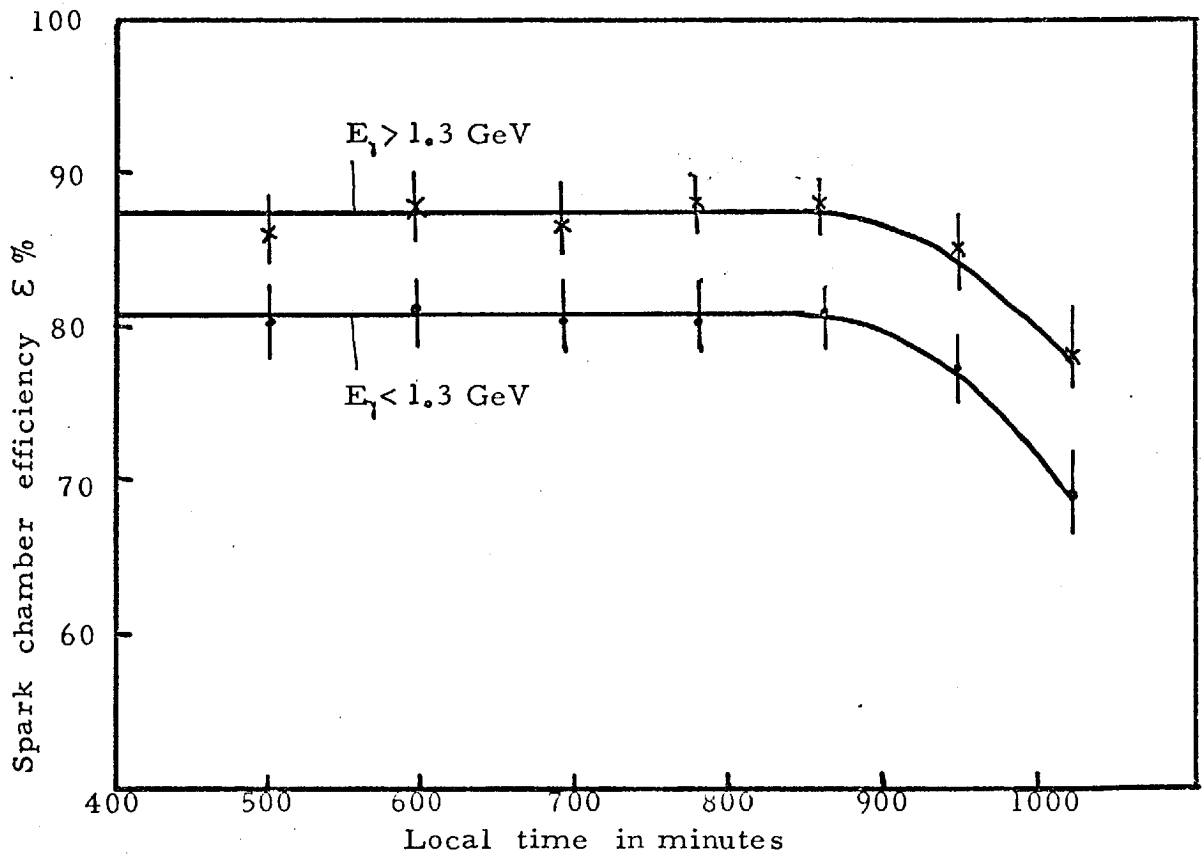


Figure 3.2

The variation in spark chamber efficiency throughout the flight

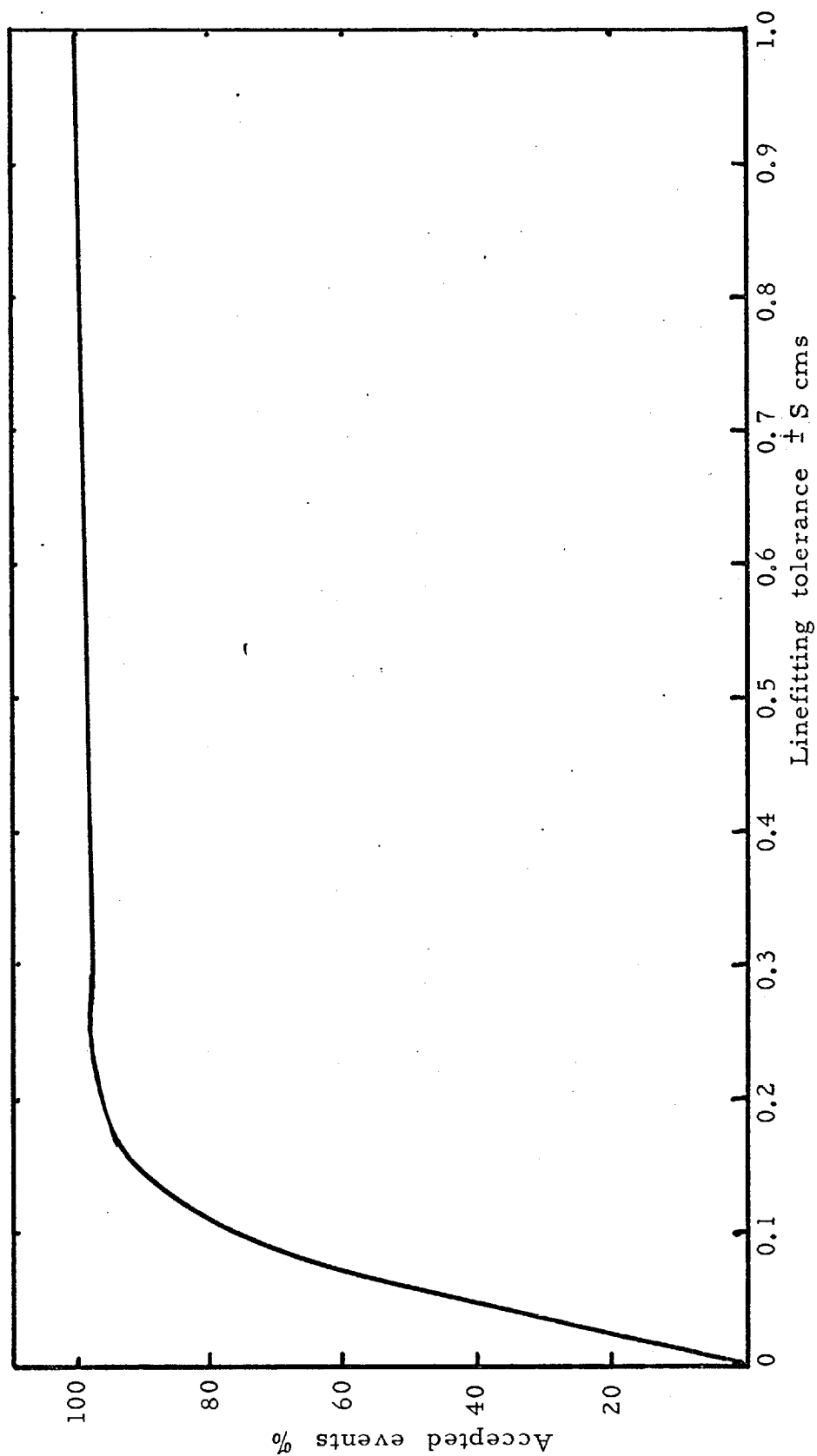
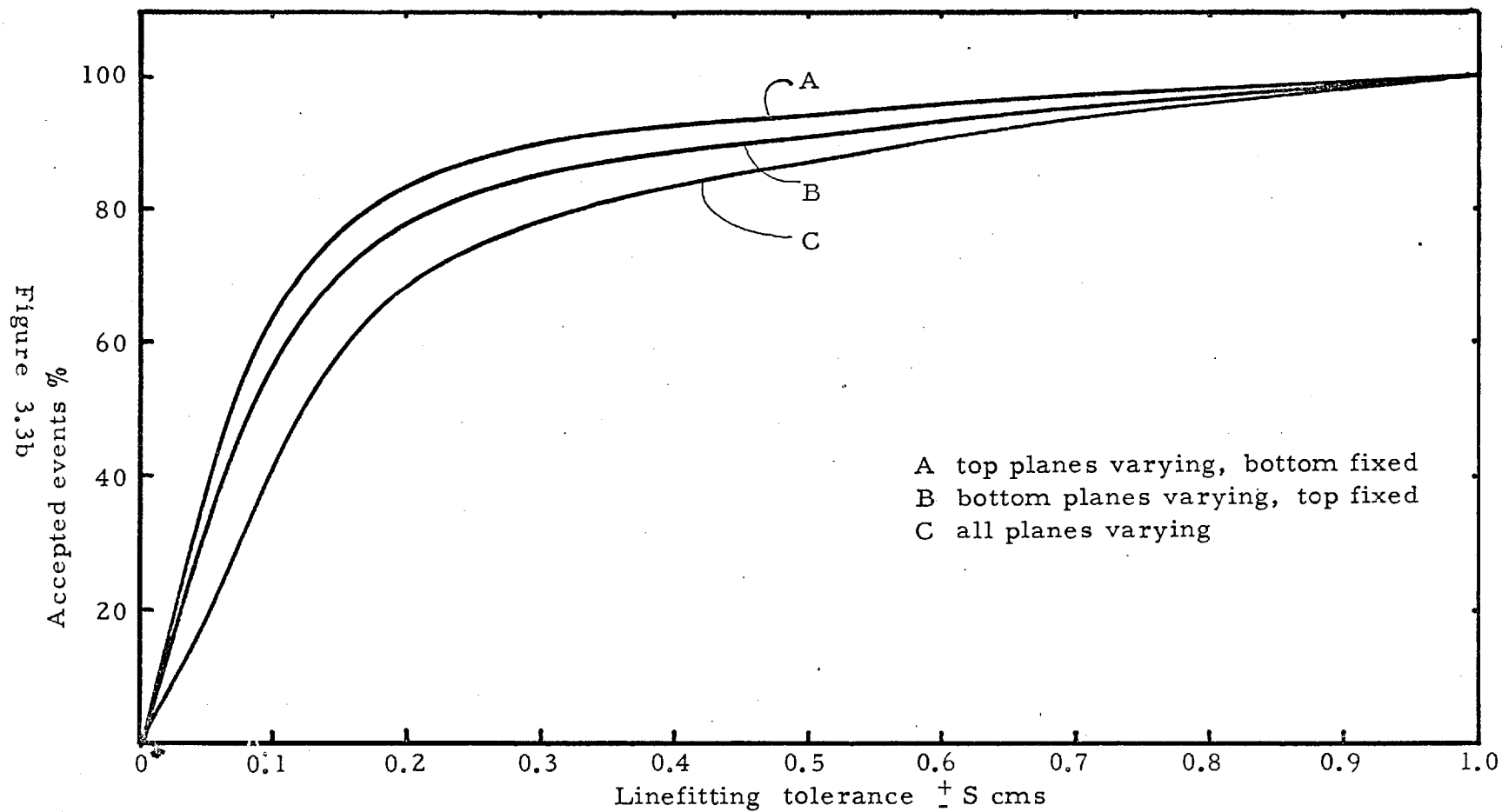


Figure 3.3a

Variation in accepted events with change in the line-fitting tolerance S for ground level mu-mesons



Variation in accepted events with change in the line-fitting tolerance S for flight gamma-rays

Figure 3.3b

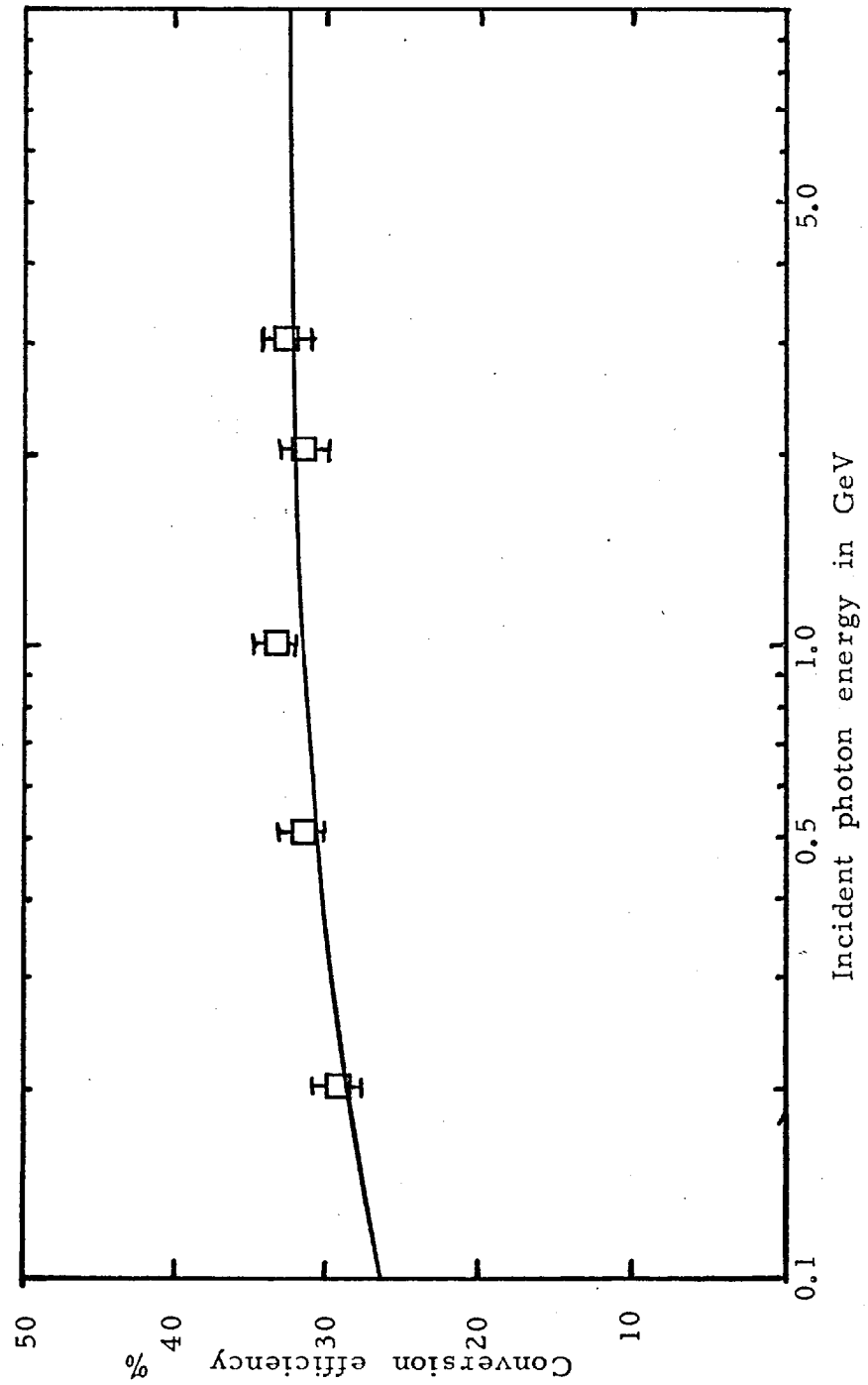


Figure 3.4a

Variation in conversion efficiency with incident photon energy

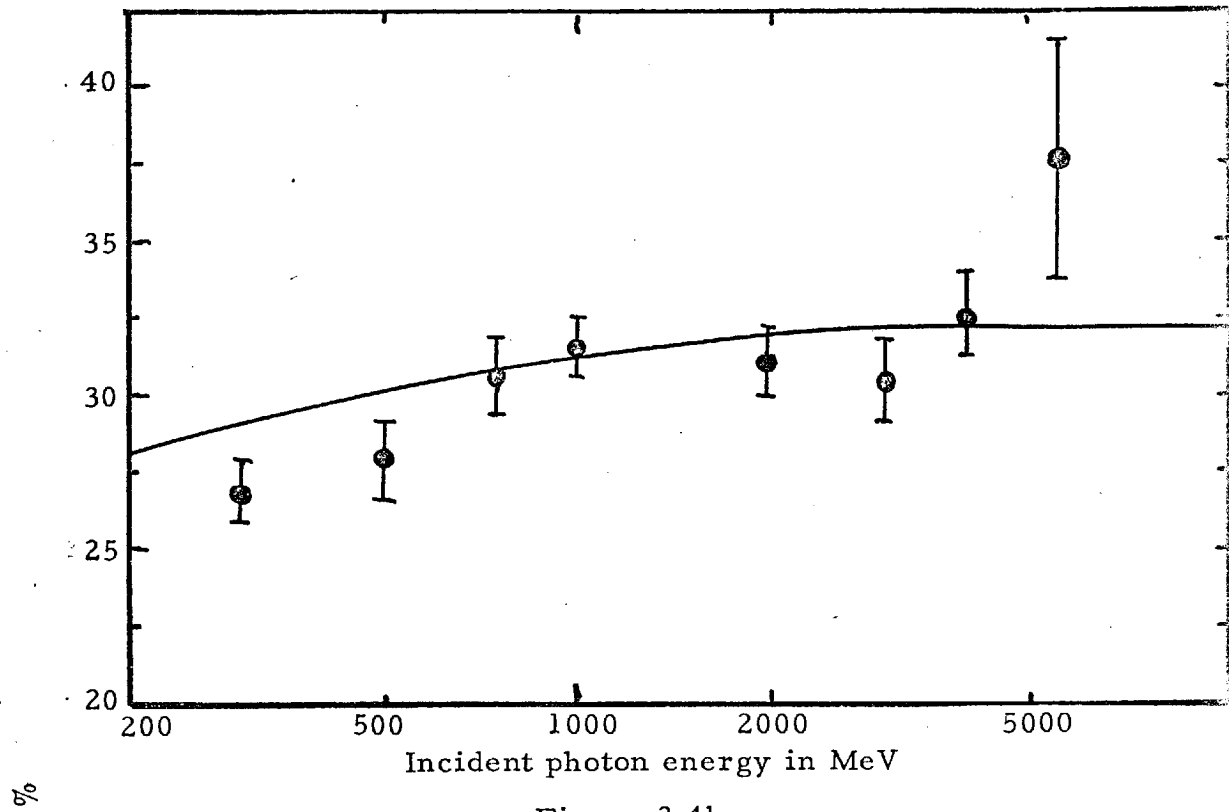


Figure 3.4b

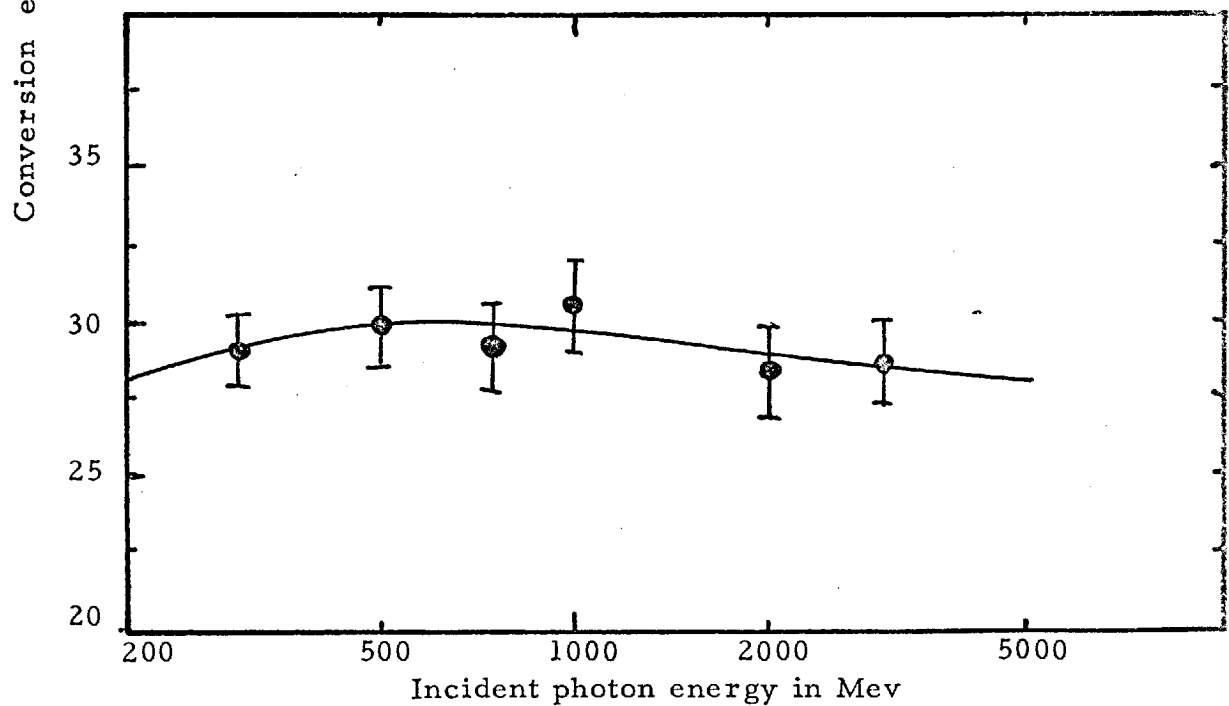


Figure 3.4c

The variation in conversion efficiency with energy;
(b) for a beam inclination of 34° , 15.7 cms from the detector axis.
(c) for a beam inclination of 0° , 13 cms from the detector axis.

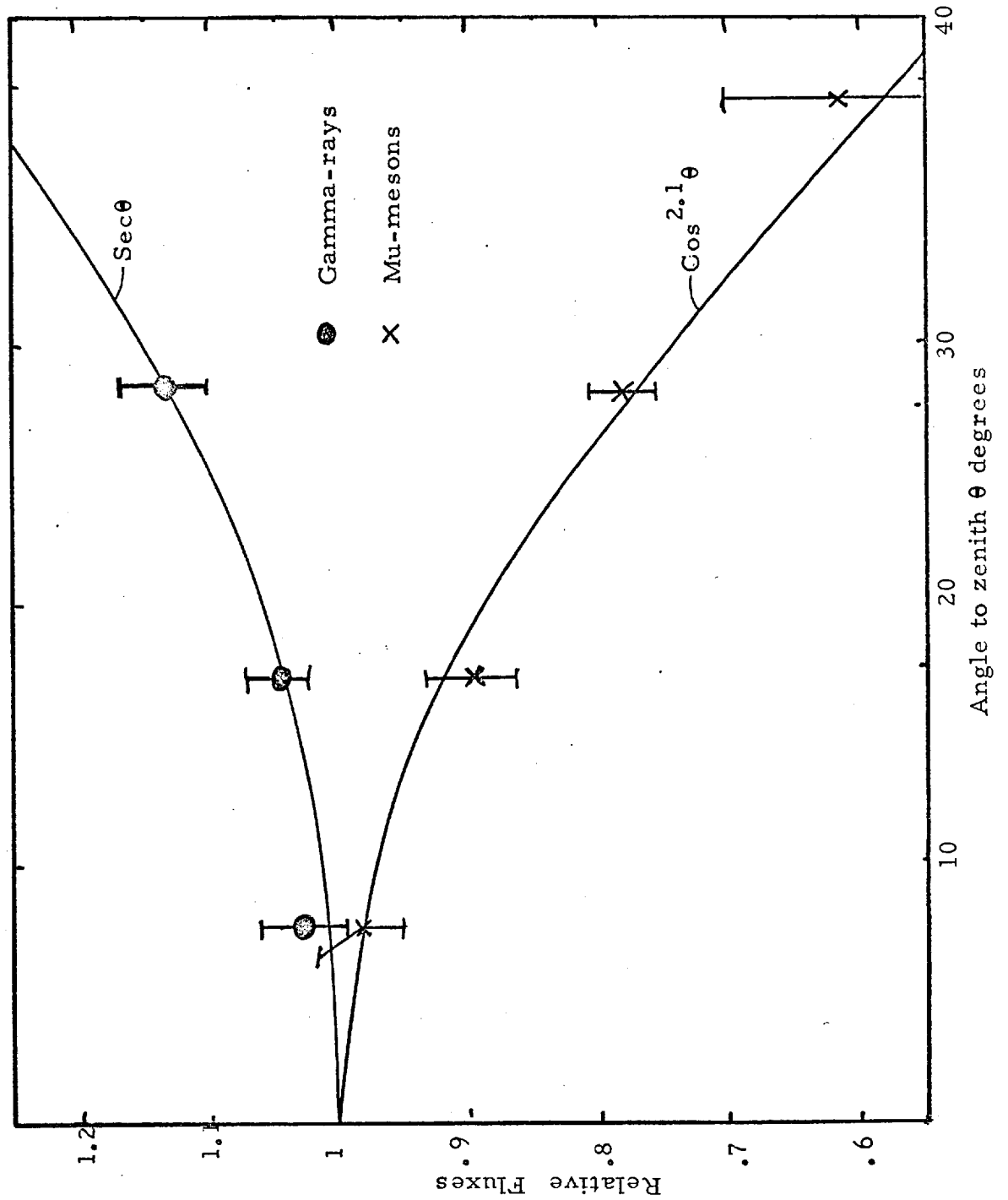


Figure 3.5a
Variation of flux with zenith angle for mu-mesons and flight gamma-rays. Also shown are the expected zenith dependences, $\sec \theta$ for gamma-rays, $\cos^{2.1} \theta$ for muons.

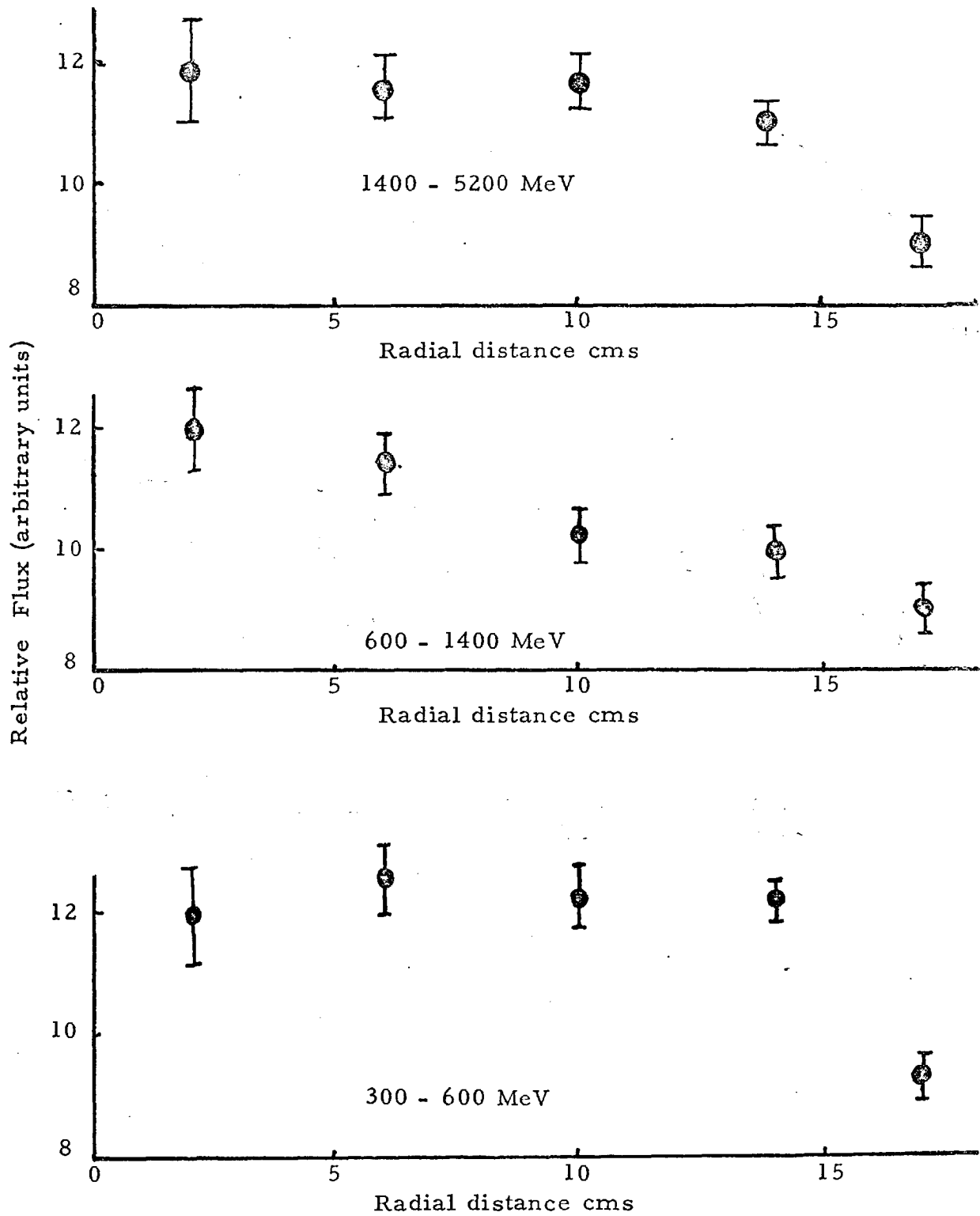


Figure 3.5b
Variation in flux with radial distance from the axis of
the detector.

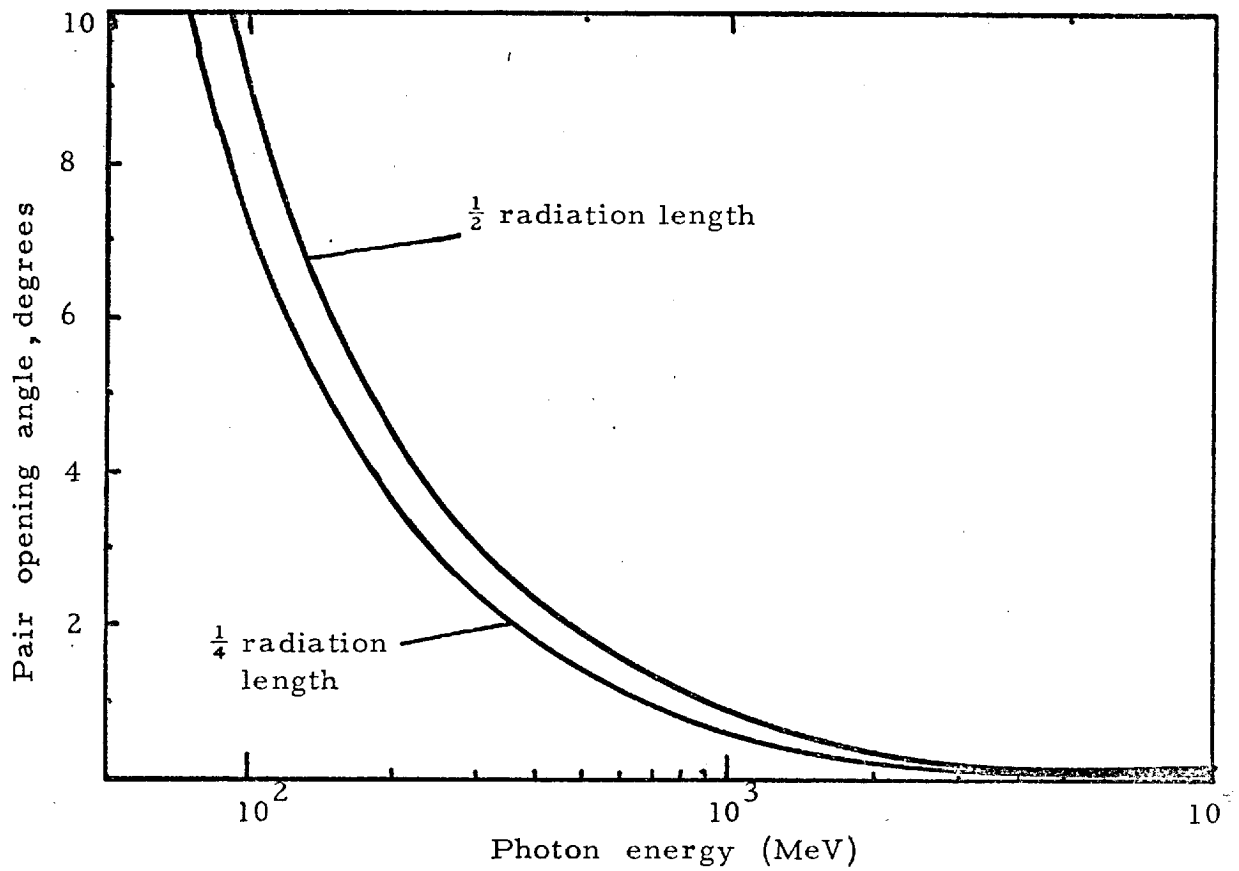


Figure 3.6a

Variation in the opening angle of the pair with parent photon energy

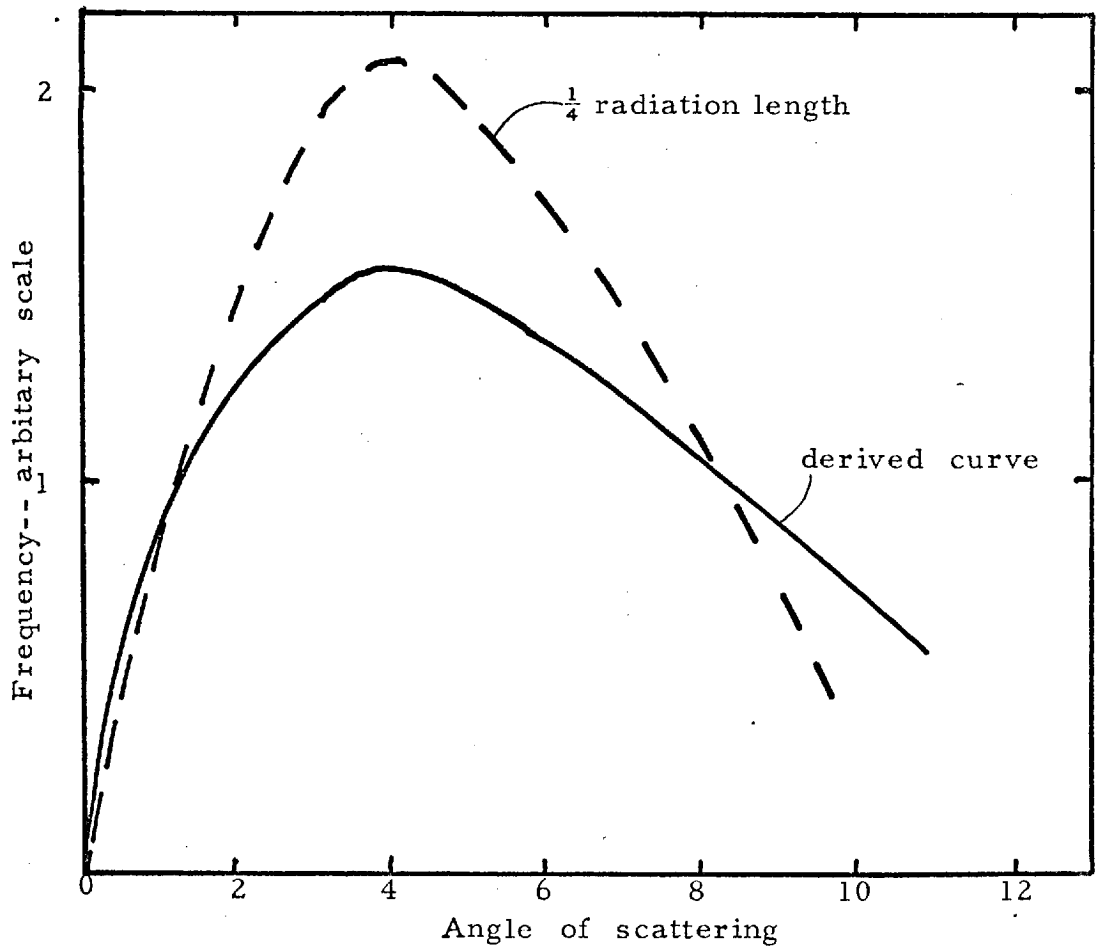


Figure 3.6b

The distribution of scattering angles for 100MeV electrons created $\frac{1}{2}$ way through the converter and at all depths in the $\frac{1}{4}$ r.l. converter

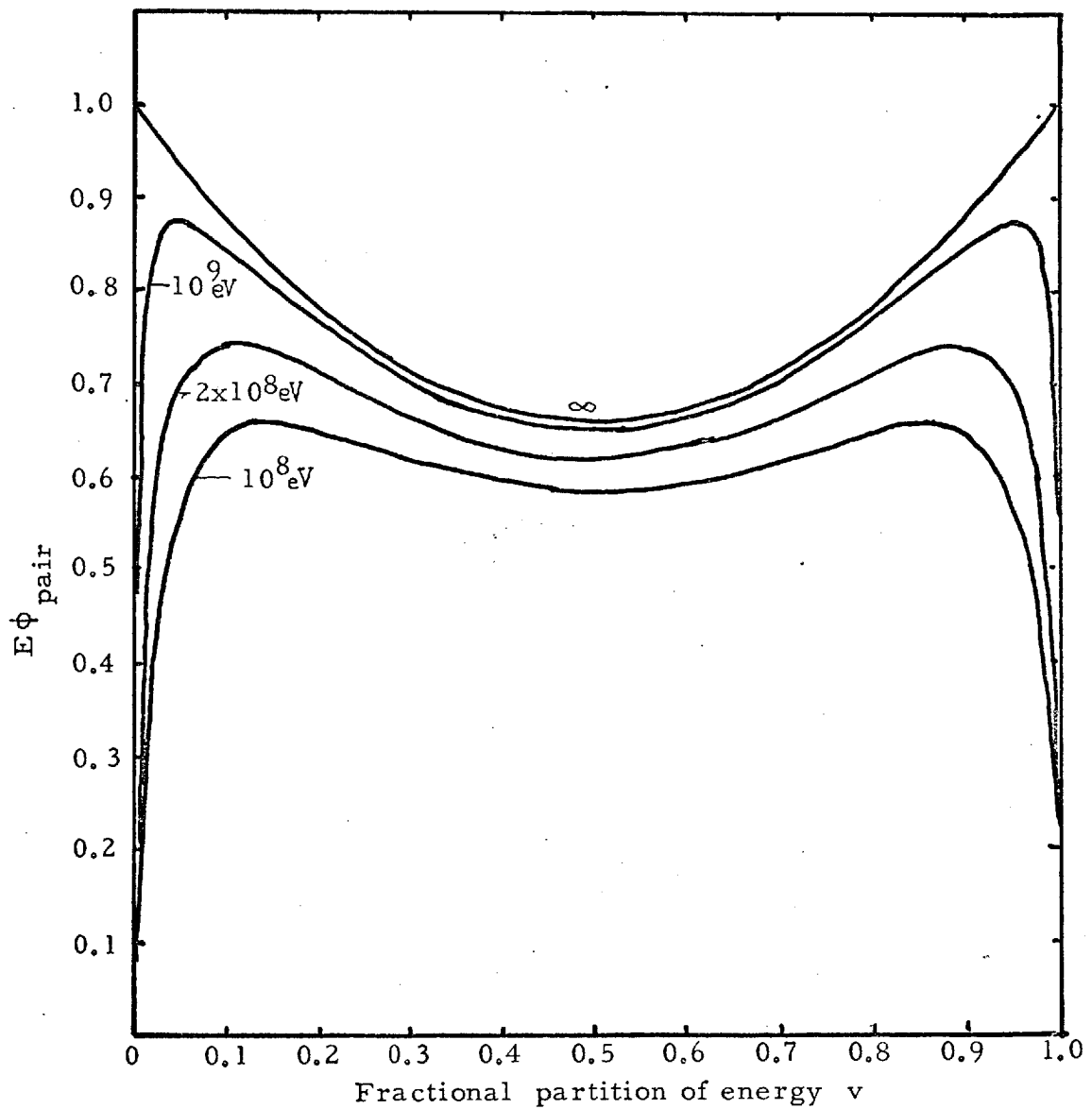


Figure 3.7

Differential probability of pair production per radiation length of lead for photons of various energies. The numbers attached to the curves indicate the energy E of the primary photon. Abscissa $v = (E' + m_e c^2)/E$;
 Ordinate $E\phi_{\text{pair}}(E, E')$

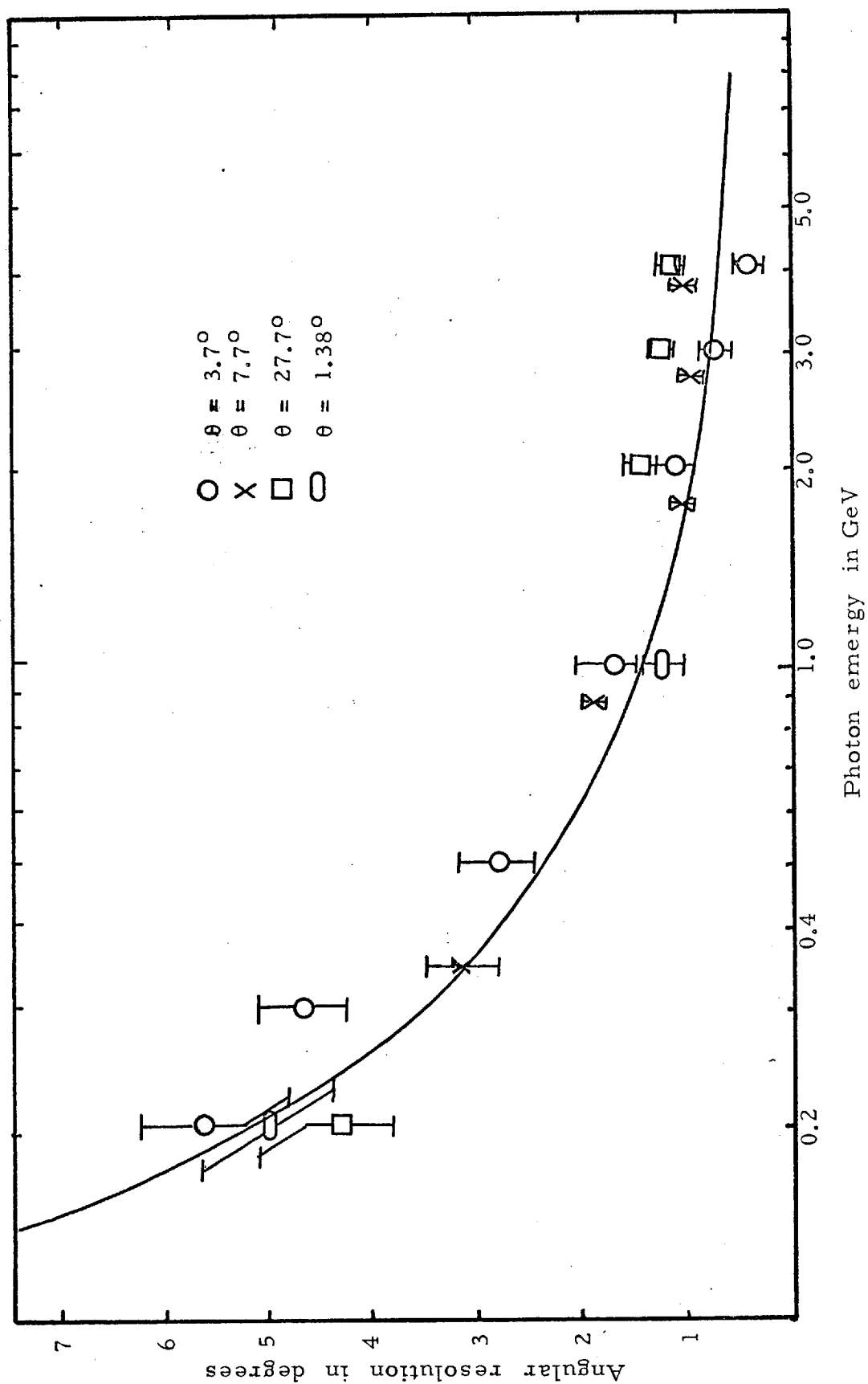


Figure 3.8

The measured angular resolution of the detector as a function of energy and angle of incidence compared with the theoretical curve (solid line)

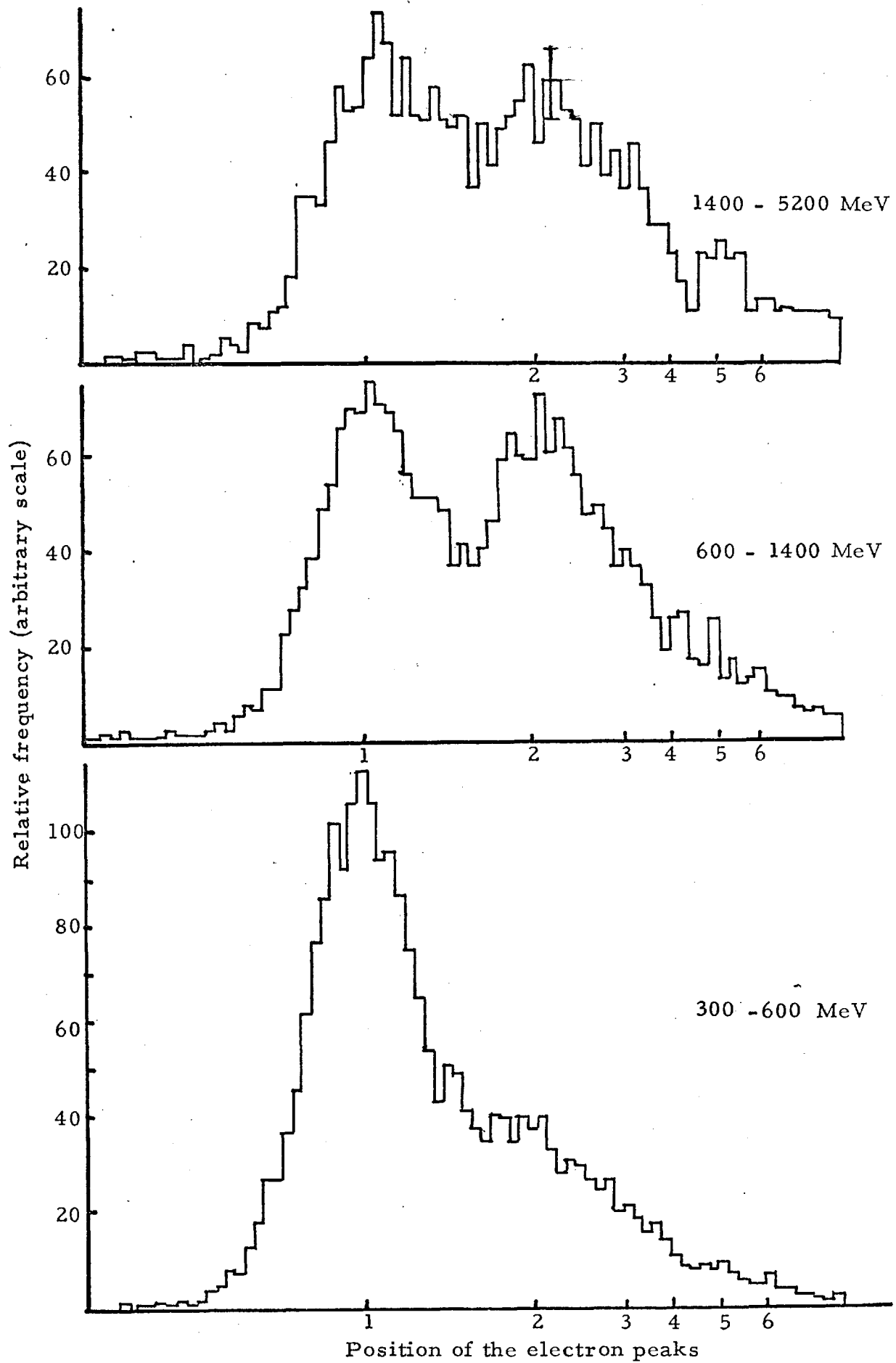


Figure 3.9a
Half inch scintillator distributions for three energy intervals
for flight gamma- rays.

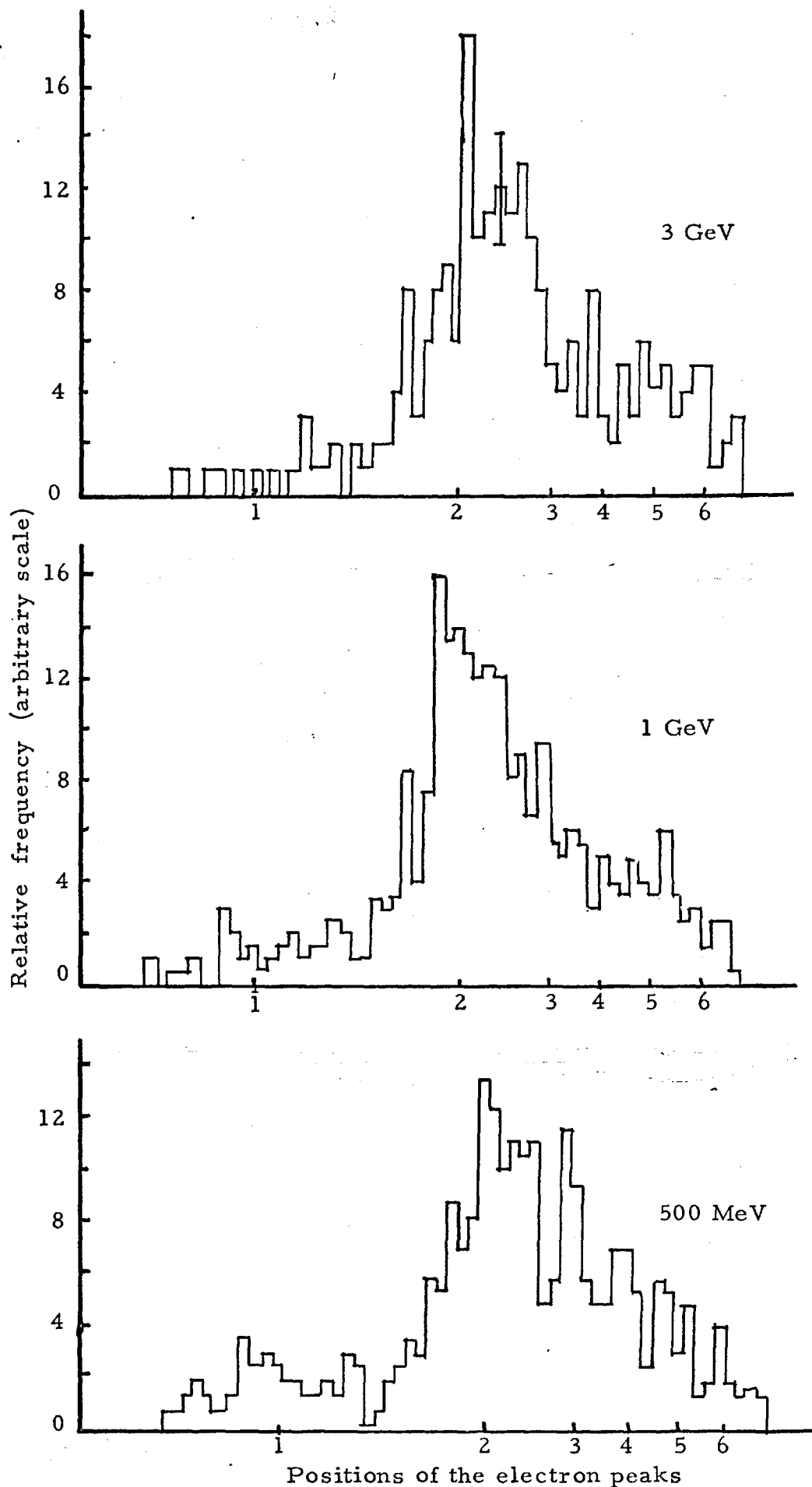


Figure 3.9b
Half inch scintillator distributions for three energies
for DESY gamma-rays.

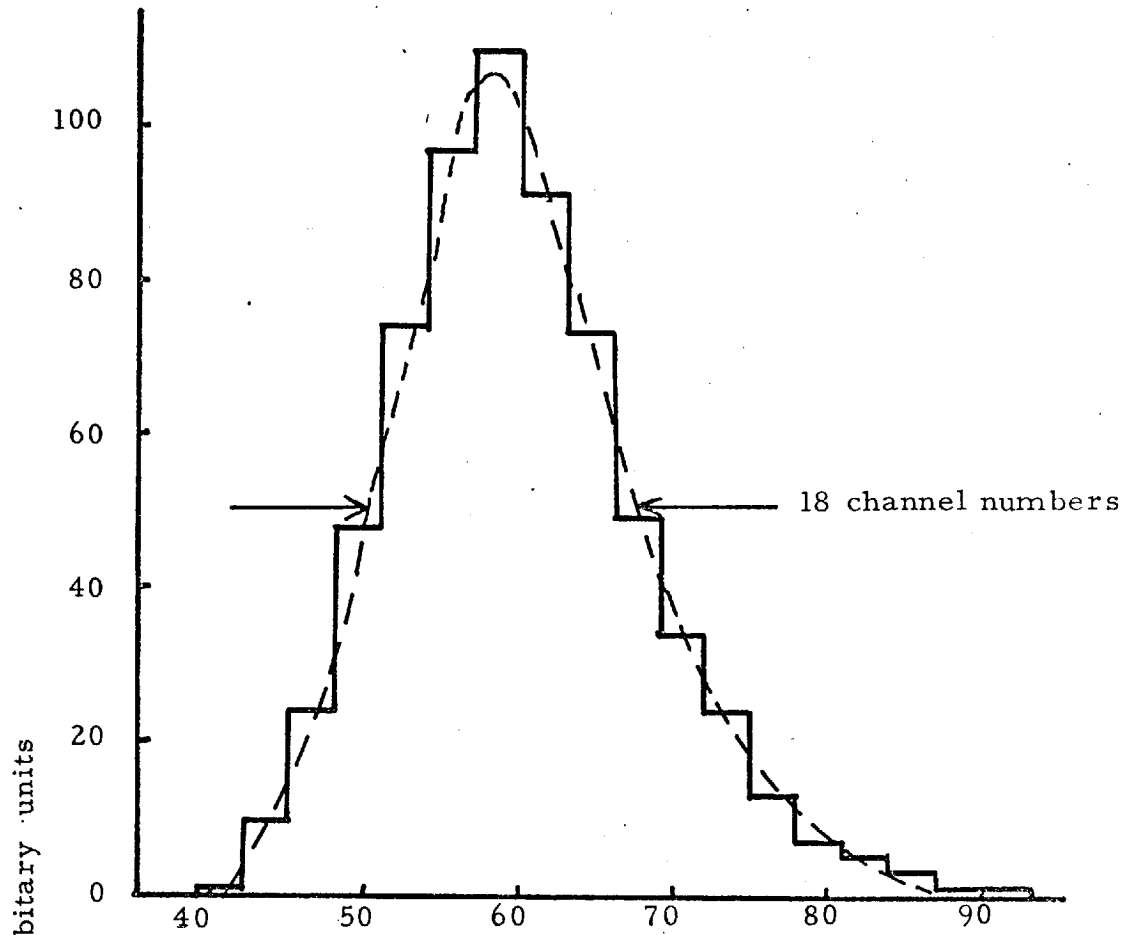


Figure 3.10a

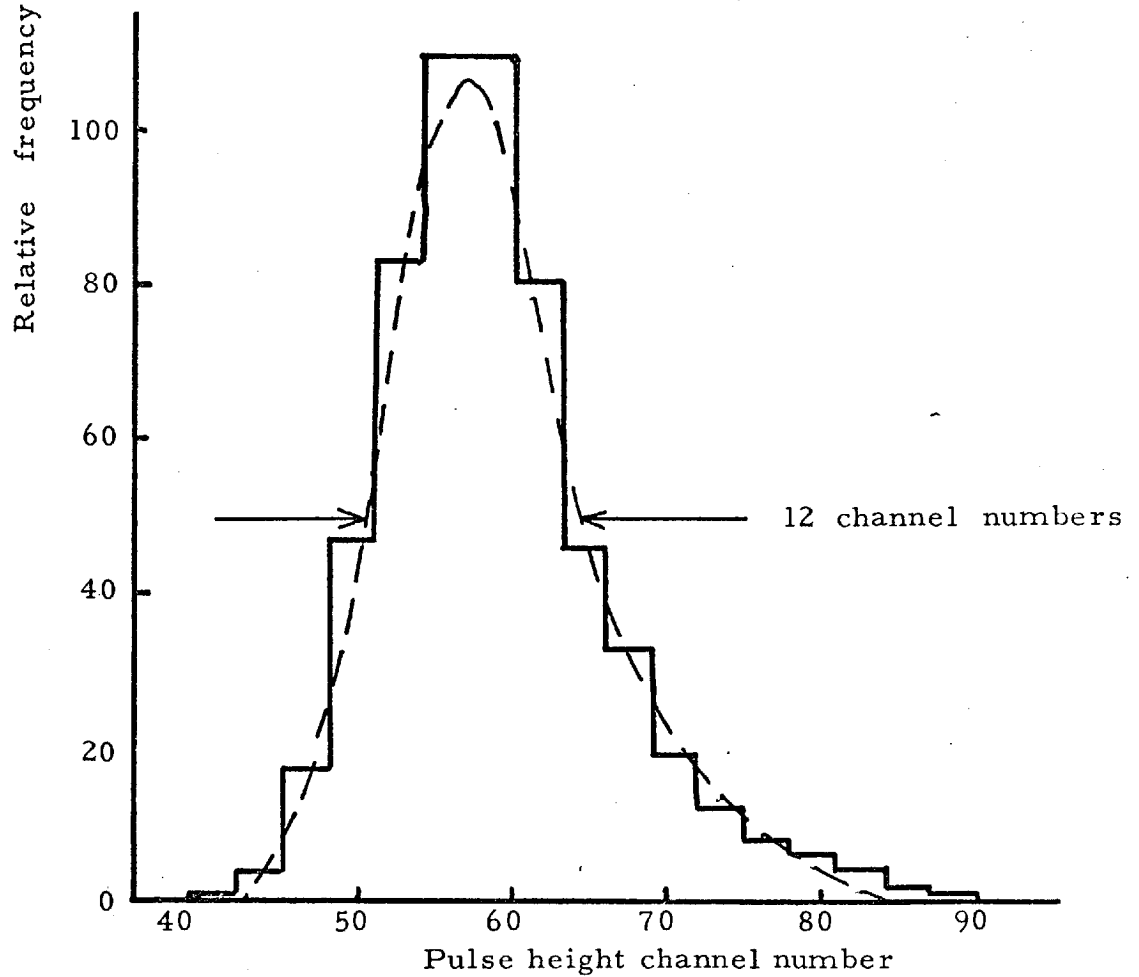


Figure 3.10b

The $\frac{1}{2}$ " scintillator pulse height distributions for ν -mesons (a) before and (b) after correction for particle trajectories.

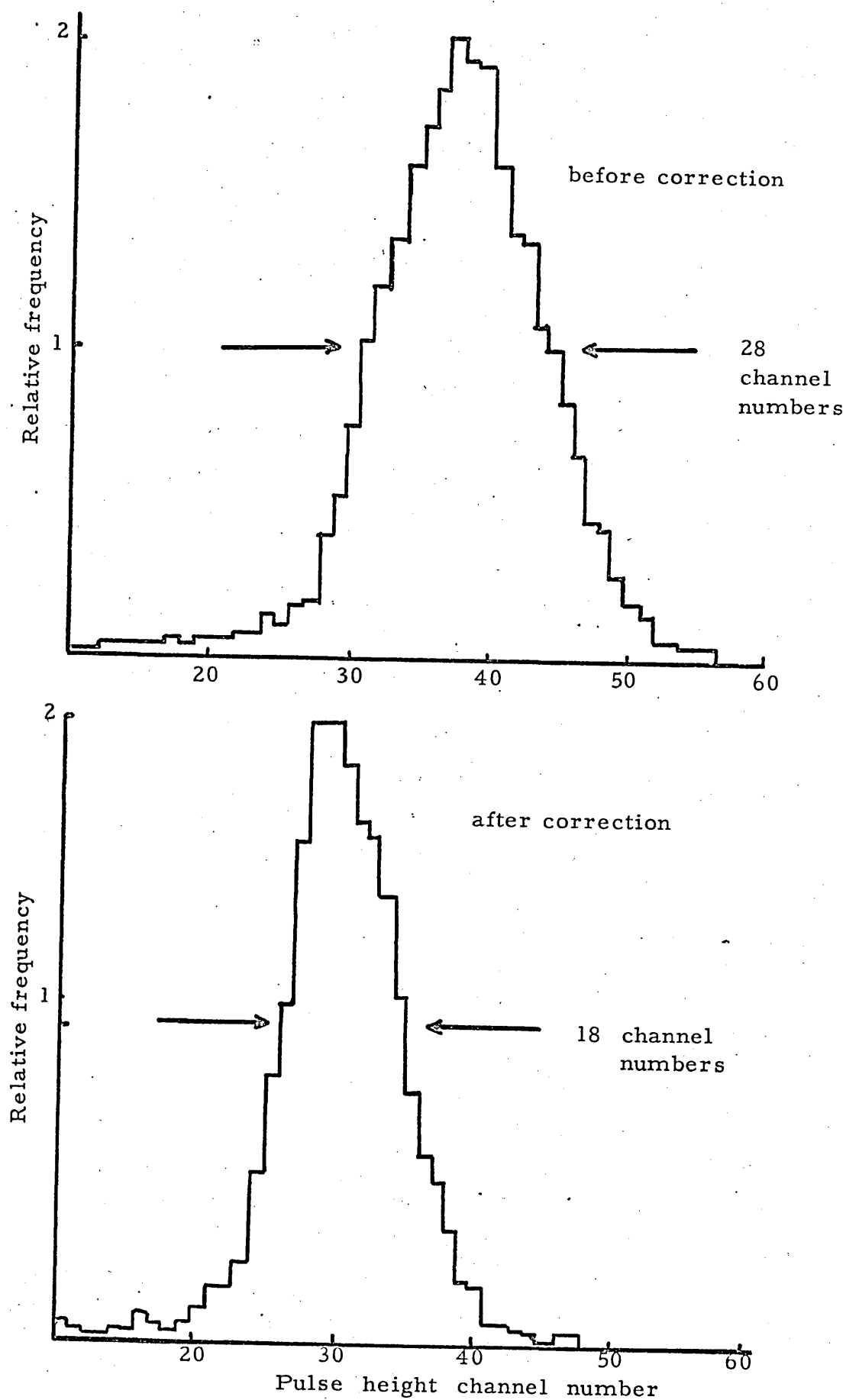


Figure 3,12

Mu-meson peak in the Cerenkov element (a) before
(b) after correction for the photon collection efficiency

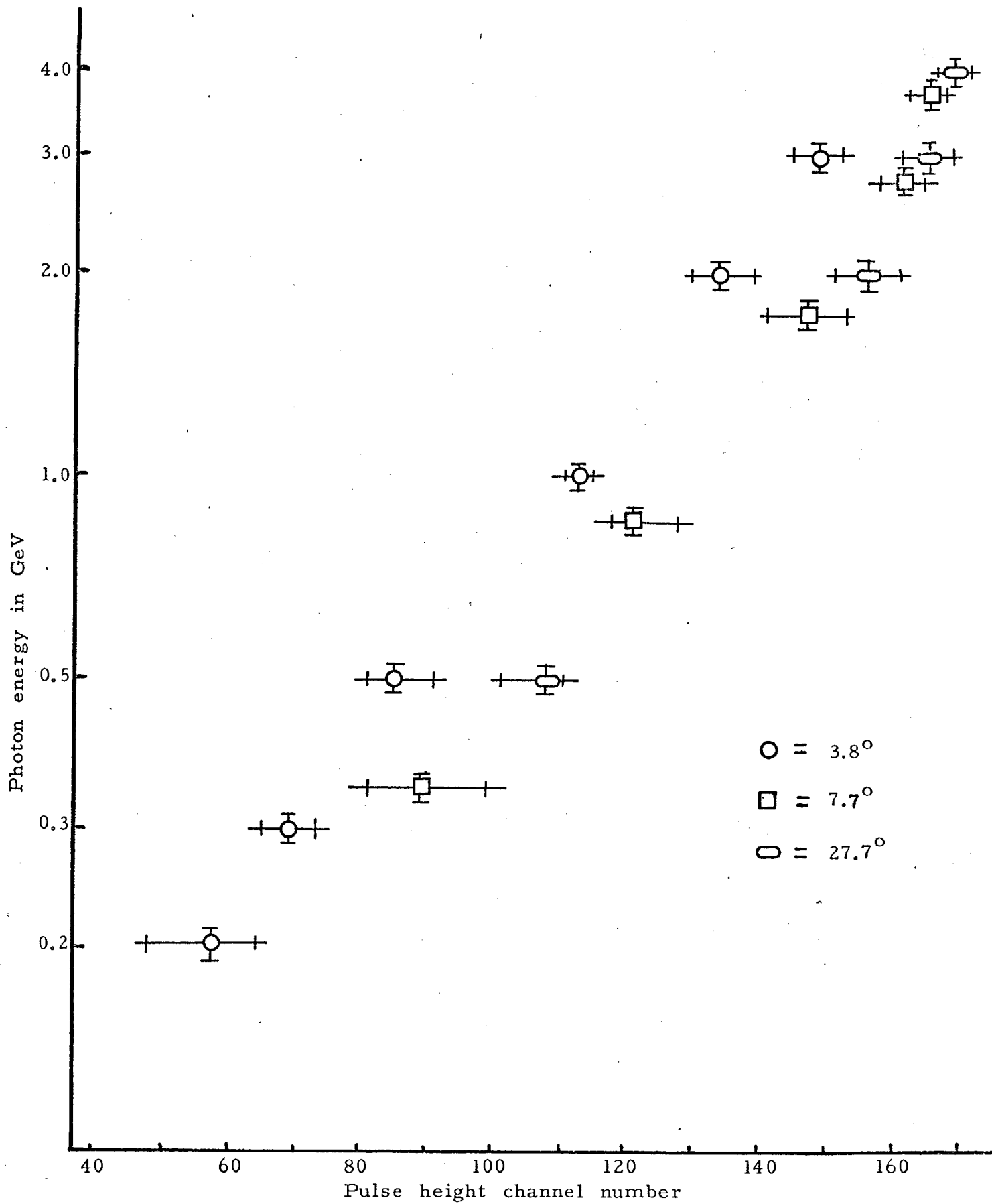


Figure 3.13a

Gamma energy calibration of the Cerenkov element before correction for the photon collection efficiency as a function of angle of incidence

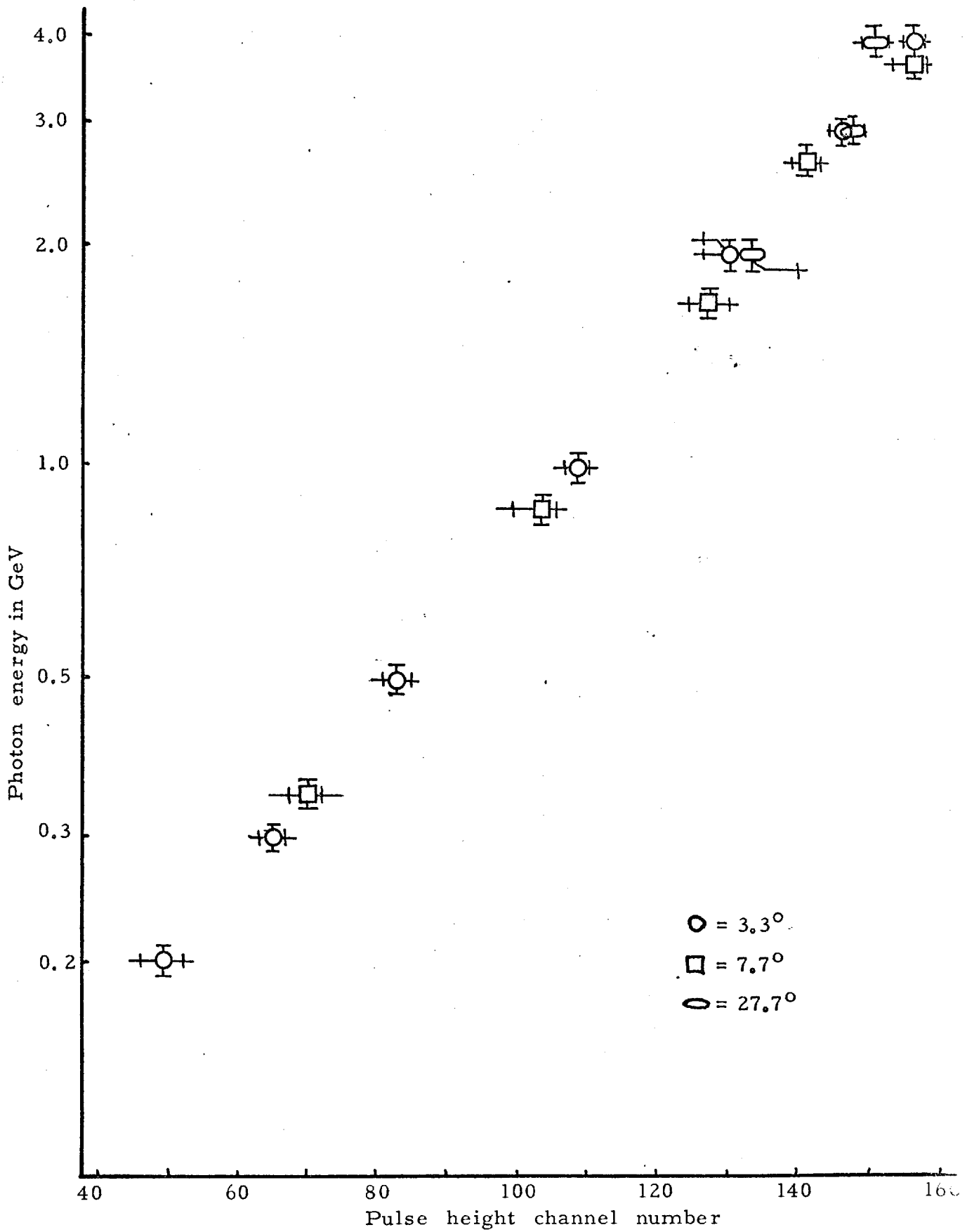


Figure 3.13b

Gamma energy calibration of the Cerenkov element after correction for the photon collection efficiency as a function of angle of incidence

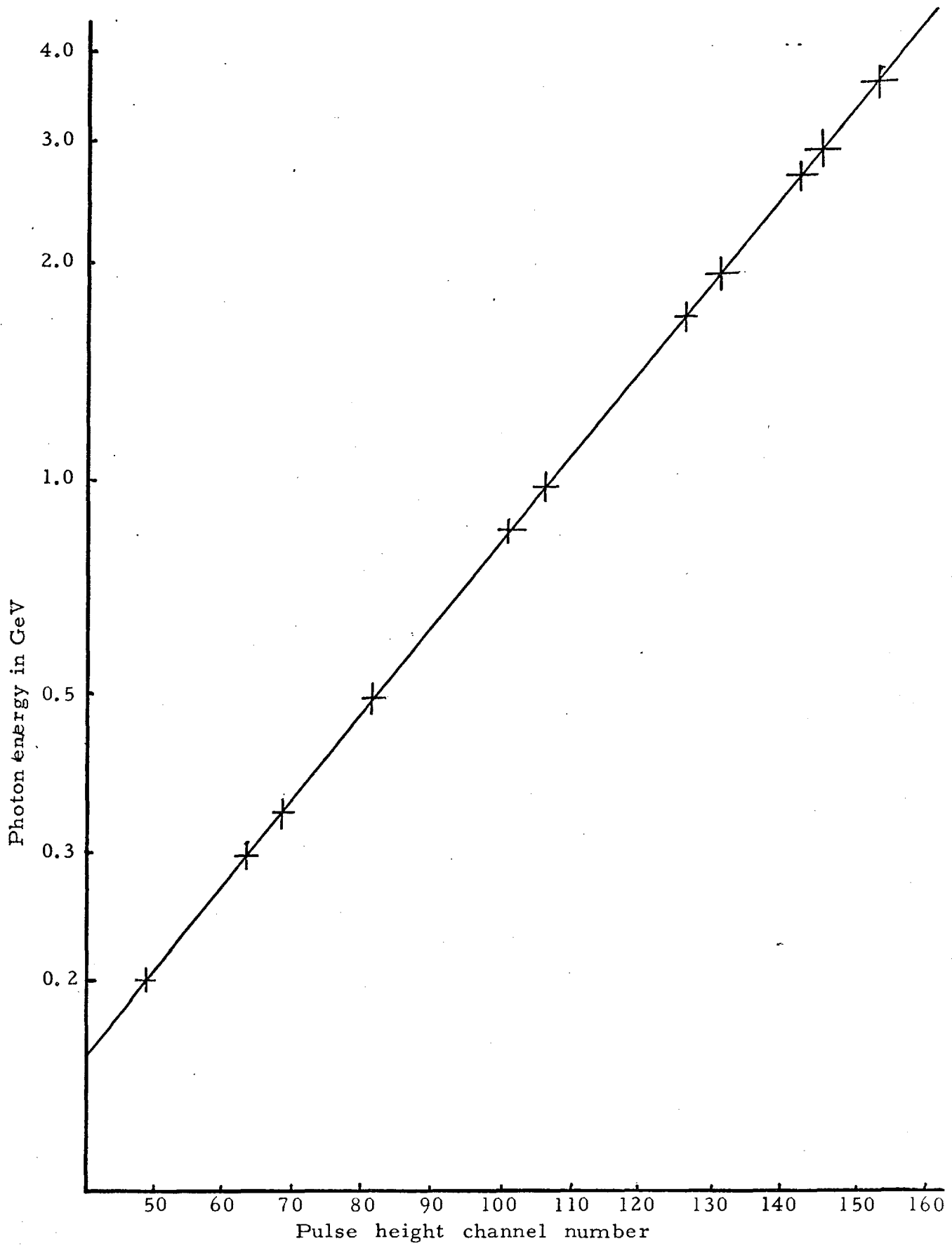


Figure 3.14

Gamma energy calibration of the Cerenkov element
This is a least squares fit to more data points than are shown on the
previous figures

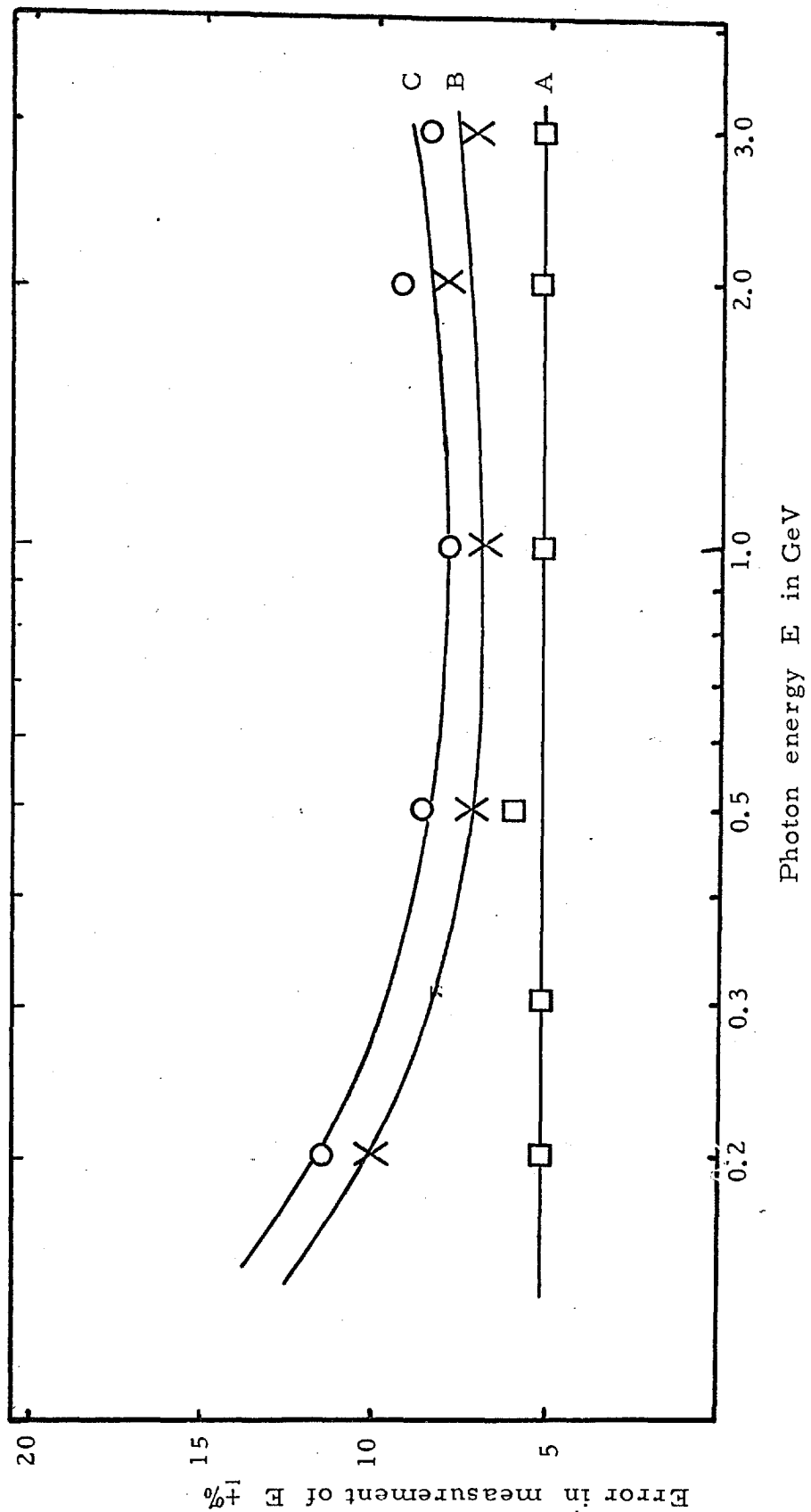


Figure 3.15

The energy resolution as a function of E

- A calibration error ($\pm\%$) mainly due to the DESY beam calibration
- B contribution ($\pm\%$) from the resolution of the Cerenkov element
- C total error in energy measurement ($\pm\%$)

CHAPTER IV

GROUND EQUIPMENT AND DATA ANALYSIS

4.1 Introduction

The main aerial array consisted of two twin 7-element Yagi aeriels with gains of ~ 18 db and a single 3-element Yagi. One of the twin Yagi arrays was the main receiving aerial and the other had its elements connected together after a π phase difference had been introduced. This latter arrangement gave a null reading for maximum signal strength on the main receiving aerial. Thus, this array could be used for tracking the balloon and steering the whole aerial system in zenith and azimuth. The single Yagi was used to transmit the transponder signal on the 108 MHz band. As mentioned in section 2.5.1 this signal was received by the payload, mixed with the event data and house-keeping data and retransmitted on the data channel at 136 MHz. The input to this aerial and the filtered signal received from the transponder (both square waves) were continuously monitored on an oscilloscope and the time delay between the two signals was measured to give the range. The raw data from the main receiving aerial was pre-amplified, monitored on a defence electronics GPR 20 F.M. receiver and recorded on two tracks of a 7-track Ampex instrumentation tape recorder at 30 i.p.s. The raw data was also filtered to extract the event information at the subcarrier frequency of 124 KHz which was also recorded on a single track on the Ampex. The Olland signals were monitored continuously during the flight and decoded to provide temperature and pressure information. The temperature and pressure profiles are shown plotted against local time in figure 4.1 a, b.

4.2 Data Analysis

4.2.1 Preliminary Analysis

A preliminary analysis of the gamma-ray data was performed to obtain the gamma-ray rate recorded during the flight. This was achieved as follows: the leading edge of each data word (276 bits long - 175 ms) was used to trigger a monostable multivibrator to provide a pulse just longer than the data word. These pulses were counted on a scalar and the count-rate plotted for 10 minute averages through the flight. This profile is seen in figure 4.2 after correction was made for instrumental dead time. It can be seen that there are no unexpected surges in the count rate which might point to a malfunction in the coincidence telescope (e.g., a leaking pressure dome giving rise to coronal discharge producing noise which was picked up by the photomultipliers' circuits). The cosmic ray channel (4-fold coincidence) was also looked at in this respect but was found to be irrecoverable due to intermodulation distortion from other data channels.

4.2.2 Main Computer Analysis

Before the data could be used by the computer it had to be taken off the tape recorder's tape record and punched on to paper tape. The 'facit' punch used could not operate at the real time data rate so the tape recorder was slowed down by a factor of 32 to drive the punch via pulse shaper and interface at ~50 characters a second.

The preliminary reduction of the data was performed on an Interdata 70 computer. In this analysis the paper tapes were converted into a more useful format by decoding the Johnson

numbers and the resulting output was written on to magnetic tape for further analysis. A record was kept during the Interdata analysis of the events written to tape and those rejected.

The summary recorded:

- (1) the number of events analysed
- (2) the number accepted and written to tape
- (3) the number of 'saved' short events
- (4) the number of 'very short' events (less than 275 bits long)
- (5) the number of rejected events which also included correct length events with impossible numbers resulting from the Johnson decoding
- (6) the number of solar sensor events

Subsequent analysis of events was done on a CDC 6400 computer. The main programmes written for the reduction of flight data are outlined below.

4.2.2.1 The Calibration Programme

This programme was used for test runs as well as actual flight data. It had several options built into it to perform several types of data reduction. Some of these are outlined below:

- (A) Produced histograms of various functions; the sum of the primary delays used to set the empirical and characteristic average limits (section 2.4); the distribution of spark co-ordinates across the planes to indicate correct functioning of the plane and 'dead' places on the MSW; pulse height distribution from the lead glass and $\frac{1}{2}$ " scintillator which can be used to detect spark interference in

these channels on meson runs; zenith dependence of the data; the deviation of spark co-ordinates from the least square fitted line (S parameters, section 3.1.3).

- (B) Produces a map of the distribution of events over any part of the detector.
- (C) Evaluates the value of S (permitted deviation from the best fit line fitted to 3 and 4 sparks) and produces a table giving the number of events accepted and rejected for values of S set in the top 2, bottom 2 and all 4 planes. Such an output could produce a plot like figure 3.3 a, b.
- (D) Produces a flux map of the converter by splitting it into zenith, azimuth and radial bins given the area solid angle factors for these bins.
- (E) Produces a pulse height map of the lead glass element, again split up into zenith, azimuth and radial bins. From this map, produced from mu-meson data, the empirical corrections for particle incidence were built up.
- (F) Produces a pulse height map for the $\frac{1}{2}$ " scintillator split up into squares.
- (G) Used with the DESY calibration data to deduce the angular resolution of the detector. This version transformed the calculated direction cosines of the photon (relative to the vertical axis of the detector) to the corresponding cosines relative to the gamma-ray beam direction. A distribution of arrival directions was produced about the true

beam direction. The angular resolution was defined by the half angle of the cone which contains 68% of the events.

- (H) Outputs the solar sensor events to magnetic tape.
- (I) Converts the data into a form (on magnetic tape) suitable for further analysis by the 'flight' programme.

Each version of the calibration programme can be used over any given time interval, scintillator or energy range, producing a summary on completion which categorised the accepted and rejected events.

4.2.2.2 The Flight Programme

This programme took its input data from the output of the calibration programme (version I) in the form of event number, direction cosines of the event (CX, CY, CZ), pulse height and magnetometer data. The main function of this programme was to transform the event into the geomagnetic, geodetic, celestial or galactic frames of reference. During this analysis the earth's magnetic field values measured by the magnetometer were compared with those calculated from the I.G.R.F. model. If the total measured field differed from the I.G.R.F. value by more than 500 gamma (5×10^{-4} gauss) that event's magnetometer readings were ignored and those of the previous event used (up to a maximum of ten events). This process introduced a negligible error into the photon's position of origin due to the slow rotation of the detector compared with the high counting rate. The I.G.R.F. model was also used to calculate the magnetic

declination ψ at the payload's present position. The angle between the X spark axis and the horizontal field vector δ was determined from the measured field values and the orientation of the spark chamber relative to the magnetometer,

The first transformation was into geomagnetic co-ordinates:

$$\begin{pmatrix} CX1 \\ CY1 \\ CZ1 \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta & 0 \\ -\sin\delta & \cos\delta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} CX \\ CY \\ CZ \end{pmatrix}$$

By taking the balloon's geographic position into account and calculating the magnetic declination ψ from the I.G.R.F. transformation into geodetic co-ordinates was performed by:

$$\begin{pmatrix} CX2 \\ CY2 \\ CZ2 \end{pmatrix} = \begin{pmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} CX1 \\ CY1 \\ CZ1 \end{pmatrix}$$

To transform into siderial co-ordinates the latitude and longitude of the payload together with the local time of the event were needed:

λ = the colatitude of the payload

σ = the angle to the true equinox

T_l = the local time of the event

T_d = the time difference between local time zone and G.M.T.

$T_u = T_l - T_d$ = the universal time of the event

T_σ = the time in minutes from the true equinox

T_σ was calculated from the relationship:

$$T_\sigma = T_u + (N \times 24 + T_u/60) \times 9.8296/60 \text{ minutes}$$

where N was the whole number of days from the true equinox, 9.8296 was the number of seconds difference between a solar and

siderial hour,

$$\sigma = \frac{T_G \times 15 + \text{LONGITUDE in degrees}}{60}$$

Thus the direction cosines of the track in siderial co-ordinates was given by:

$$\begin{pmatrix} CX3 \\ CY3 \\ CZ3 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\sigma & \sin\sigma \\ 0 & -\sin\sigma & \cos\sigma \end{pmatrix} \begin{pmatrix} \cos\lambda & 0 & -\sin\lambda \\ 0 & 1 & 0 \\ \sin\lambda & 0 & \cos\lambda \end{pmatrix} \begin{pmatrix} CX2 \\ CY2 \\ CZ2 \end{pmatrix}$$

The transformation into the galactic frame was performed by a two fold rotation in which α_N and δ_N defined the position of the galactic north pole on the celestial sphere and a further rotation through γ degrees about the X axis which pointed the new Z axis towards $l''=0$, $b''=0$, the galactic centre.

According to the I.A.U. system of galactic co-ordinates (1959):

$$\alpha_N = 192.5^\circ$$

$$\delta_N = 27.4^\circ$$

$$\gamma = 57.5^\circ$$

thus

$$\begin{pmatrix} CX4 \\ CY4 \\ CZ4 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & \sin\gamma \\ 0 & -\sin\gamma & \cos\gamma \end{pmatrix} \begin{pmatrix} \sin\delta_N & 0 & \cos\delta_N \\ 0 & 1 & 0 \\ -\cos\delta_N & 0 & \sin\delta_N \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha_N & \sin\alpha_N \\ 0 & -\sin\alpha_N & \cos\alpha_N \end{pmatrix} \begin{pmatrix} CX3 \\ CY3 \\ CZ3 \end{pmatrix}$$

Upon completion of the transformation the event was placed in a bin in the co-ordinate system in use, e.g., galactic, according to its right ascension and polar declination. The galactic sphere was split up into bins 2° wide in longitude and such a width in latitude as to subtend a solid angle equal to that subtended by a $2^\circ \times 2^\circ$ bin at the galactic equator. The event was then output to

tape again in the format, event number, bin co-ordinates and pulse height information from the lead glass and $\frac{1}{2}$ " scintillator. A skymap showing the distribution of events across the galactic sphere was also produced.

4.2.2.3 The Exposure Programme

This programme calculated the area-time factors for the bins described in the previous section. As the flight progressed the vertical axis (pointing direction) of the detector traced a path across the sky, as described by its motion in latitude and longitude. The pointing direction was transformed into the celestial or galactic frame of reference (as described in the previous section) which gave the track of the payload across the celestial or galactic sphere.

Taking the mid-point as being representative of each bin, the area of the detector presented to it was calculated for successive $2\frac{1}{2}$ minute intervals (dT) according to:

$$A(l'', b'') = L^2 \times \cos\theta \times dT \times (A2 - A3)$$

where

$$A2 = \frac{\pi \tan^2 \alpha}{4} - \left(\frac{\tan \theta}{2} \times (\tan^2 \alpha - \tan^2 \theta)^{\frac{1}{2}} \right)$$

$$A3 = \frac{\tan^2 \alpha}{2} \times \sin^{-1} \left(\frac{\tan \theta}{\tan \alpha} \right)$$

where α = half opening angle of the detector

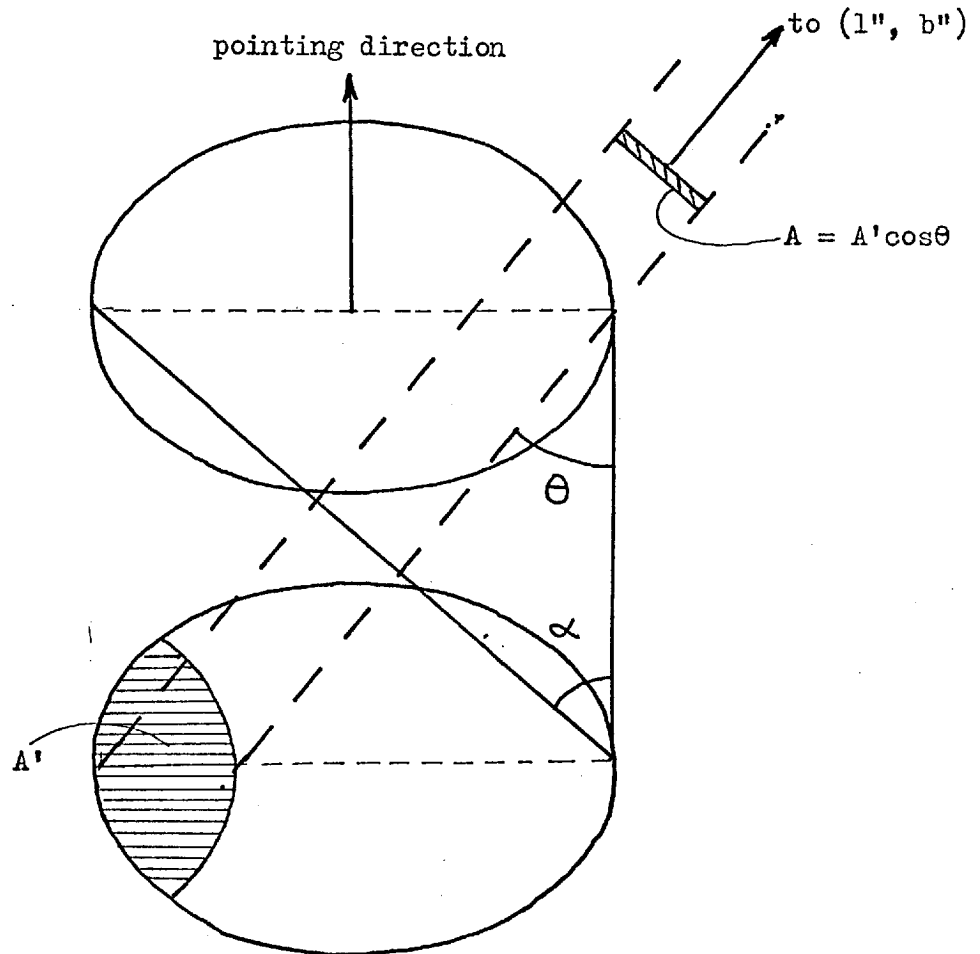
$$= \frac{\text{scintillator diameter}}{\text{effective telescope length (L)}}$$

θ = the angle between the detector pointing direction and the point (l'', b'')

and for $\theta \leq \alpha$ $\Delta A > 0$, and for $\theta > \alpha$ $\Delta A = 0$ (i.e. the point (l'', b'') was invisible to the telescope).

The following diagram illustrates this point where the exposure to (l",b") was:

$$A(l'',b'') = A \times dT$$



Thus the exposure for each bin was evaluated for the whole flight and written on to a magnetic tape for subsequent use. The results can be illustrated in terms of the exposure contours of figure 4.3. For the flight the exposure values were corrected for the various efficiencies described in chapter 3, so that when the number of counts per bin was divided by the relevant exposure factor the actual flux would result in units of counts/ $2^\circ \times 2^\circ$ bin/cm²/min.

4.2.2.4 The Magnetometer And Solar Sensor Correlation

As previously mentioned in section 2.5.3, the detector did not hang vertically below the balloon. Consequently, the Z axis of the magnetometer did not point vertically upwards and the X and Y axes were not in the horizontal plane. This latter effect would introduce an error in measuring the bearing between the spark X axis and magnetic north and consequently an error in estimating the photon's point of origin. This must be corrected for. The tilt was estimated by scrutinising the magnetometer data plotted as a function of time, for evidence of the tilt and the value calculated for it was 0.6° down at $\pm 12^\circ$ to the direction of the positive X axis. After correction for this and for the non-linear calibration of the magnetometer had been made, the accuracy of the magnetometer was determined by analysis of the solar sensor events.

The solar sensor events output by the calibration programme contained the event number, the magnetometer data and the identity of the fired photo-transistor. The event number provided access to the time of the event and the position of the detector at that time, so by adding the sun's declination, δ , at that time, the sun's bearing angle β (angle between true north and the fired slit) could be calculated from:

$$\beta = \tan^{-1} \left(\frac{\sin(\text{lat})\cos(\text{long}) - \tan(\delta)\cos(\text{lat})}{\sin(\text{long})} \right)$$

where lat and long refer to latitude and longitude.

The magnetometer gave the bearing between magnetic north and its X axis, the orientation between it and the slit being known. The I.G.R.F. model provided the magnetic declination to give the bearing to true north once more. These values agreed to $+0.02^\circ$, -0.84° throughout the flight.

4.3 The Atmospheric Background

4.3.1 Dead Time Correction

The coincidence telescope and associated electronics were disabled while the gamma-ray event information was read out of the stores and transmitted. This produced an instrumental dead time of 175 milliseconds after each event during which another gamma-event would not be registered. This would produce an under-estimate in the counting rate of the detector if not corrected for. Correction was made as follows, where C is the observed counting rate and R is the true rate at which gamma-rays are hitting the detector on average:

$$R = \frac{C}{1 - 0.175C}$$

where R and C are in counts per second.

At altitude, the ratio R/C was 1.6 on average. Thus it can be seen that the under-estimate would be considerable if the dead time correction were ignored.

4.3.2 Depth Curves

The counting rates for accepted gamma-rays was evaluated for the ascent phase of the flight and these are shown plotted in figure 4.4 at different energy intervals at a mean zenith angle of 17° . It can be seen that they all rise to the Pfotzer maximum at around 100 gm/cm^2 and then fall off with decreasing residual pressure with comparable slopes. The shape of these curves are in very good agreement with the results of a Monte-Carlo calculation performed by Thompson (1974).

4.3.3 Atmospheric Gamma-Rays

The flight lasted for 610 minutes at altitude. The energy range of the detector was confined between 300 MeV and 5.2 GeV to remove the effects of a high energy pile up in the P.H.A. (which could be real) and the non-ideal action of the discriminator in the P.H.A. which although nominally set at 200 MeV did not produce a sharp cut-off at this energy. The $\frac{1}{2}$ " scintillator was also used to discriminate against possible 'noise' events (section 3.5). As can be seen from the plot of local time against altitude, figure 4.1b, the payload descended during the flight so that the atmospheric gamma-ray intensity was not constant. However since at the top of the atmosphere the gamma-ray intensity varies almost linearly with the residual pressure, a spectrum could be obtained by normalising the intensity at various atmospheric depths to unit atmospheric pressure. This was done, to a maximum residual pressure of 6 gm/cm², by dividing the flux observed at depth t by t gm/cm². The spectrum of secondary gamma-rays at t gm/cm² was calculated according to:

$$I(E,t)dE = \frac{N_t \times g(E) \times f}{\xi(E) \times A\Omega(E) \times T_t}$$

and the spectrum at unit atmospheric depth

$$I(E,1)dE = \frac{f \times g(E)}{\xi(E) \times A\Omega(E)} \times \sum_{n=1}^n \frac{N_t / (t \times T_t)}{n}$$

where n is the number of depth intervals used, f is the dead time correction (see previous section), $g(E)$ is the correction arising due to the finite energy resolution of the detector, $A\Omega(E)$ is the area solid angle factor of the detector, T_t is the time at depth t gm/cm², N_t is the number of events at depth t gm/cm², $\xi(E)$ is the total detection efficiency at energy E .

The correction $g(E)$ arises from the finite energy resolution of the detector (figure 3.15). Consequently at an energy boundary some of the photons of lower energy than the boundary would register high and some of higher energy register low. However, because of the form of the energy spectrum (monotonically decreasing) more photons will register high than low. This leads to an over-estimate of the count rate in each energy interval or, alternatively, a shift in the energy scale towards lower energies. This effect was estimated for each energy interval by consideration of the energy resolution and the expected shape of the secondary spectrum near the energy boundary. The over-estimates so calculated were 7% in the 300 - 600 MeV range and 6% at higher energies.

The effective solid angle $\Omega(E)$ of the telescope also varies with energy because of the secondary electrons being scattered in the lead converter (section 3.2.1). However this effect was much reduced since the spark chamber efficiency fell off rapidly after a zenith angle of 32.5° (figure 3.1).

The intensity was also corrected with respect to the genuine events lost through scintillator discrimination. This fraction was found by comparing the scintillator pulse height distributions for the flight and the DESY gamma-rays as shown in figure 3.9 a, b.

The resulting experimentally measured fluxes are shown in figure 4.5 together with a theoretical curve derived from Perola and Scarsi (1966) for a cut-off rigidity of 8.8 GV. The curve of Perola and Scarsi refers to conditions at solar minimum. At the time of the present flight, the next solar minimum had nearly been reached but the difference produced a change in cosmic ray flux of 6% at 100 MeV. However, this

was not a significant effect in this analysis since the effect on the gamma-ray intensity was considerably less than this at 450 MeV (the first data point) where the error bar on the flux measurement was $\pm 7\%$.

It can be seen from this figure that the agreement with the theoretical curve is excellent which is a good indication that all the efficiency and dead time factors have been correctly evaluated. However, it can also be seen that the data point at 450 MeV is a factor of 1.2 above the line. This curve of Perola and Scarsi is derived from the neutral pion decay in the atmosphere and as such has the characteristic peak at 68 MeV. This curve does not take bremsstrahlung from the electrons in the atmosphere into account. Beuermann (1971) shows that this is an important process in the atmosphere and the dashed line on figure 4.5 indicates the spectral shape which may be expected as a result of this process together with pion decay.

4.3.4 Comparison With Other Experimental Results

Most experimental measurements of the atmospheric spectrum for gamma-rays have been taken at lower cut-off rigidities, Palestine (4.5 GV) being a popular site. An attempt has been made to compare the present results with those of other experimenters at different cut-off rigidities. The flux measurements shown are normalised to unit atmospheric pressure for this comparison. This was done by dividing the flux measured at an atmospheric depth of t by $t \text{ gm/cm}^2$. Further, the theoretical curves of Perola and Scarsi have been used to normalise the results to 4.5 GV rigidity for solar minimum conditions.

It can be seen from figure 4.6 that the total cosmic ray intensity changes considerably ($\sim 30\%$) between solar minimum (1966) and maximum (1968) and this must be corrected for. One method of doing this, and the one employed here, is to consider the solar modulation causing a shift in rigidity and then transposing from the resultant rigidity of the measurement to 4.5 GV.

The comparison of the results is shown in figure 4.7. Fazio et al. (1968) and Fichtel et al. (1969) both launched from Palestine (4.5 GV), Anand et al. (1968) from Hyderabad, India (16 GV), Bennett et al. (1972) from Lusaka, Zambia (11.6 GV), and the present results from Longreach, Australia (8.8 GV). Also shown is the theoretical curve derived from Beuermann (1971) which has been corrected to solar minimum conditions from the value which he presented for solar maximum.

It can be seen from figure 4.7 that the sets of results show a good agreement in spectral shape although not in the absolute magnitude. This is probably caused by the normalisation to unit pressure, 4.5 GV cut-off and solar minimum conditions. Also Frye et al. (1971) reported that the secondary gamma-ray intensity (at 100 MeV), measured at Parkes, New South Wales (4.5 GV cut-off) was 1.45 times that measured at Longreach when the corresponding ratio of total cosmic-ray intensity over this rigidity range was 2.2. Also, the predicted ratio of gamma-ray fluxes from Perola and Scarsi was 2.5. Thus it can be seen that normalisation of fluxes between different rigidities and solar conditions using the model of Perola and Scarsi and the cosmic ray flux ratios is suspect and no significance is given to the different absolute fluxes between experiments. However, the excellent agreement between the present experimental results and

the theoretical prediction derived from Perola and Scarsi at 8.8 GV cut-off rigidity, shown in figure 4.5, indicates that the detector was correctly calibrated and was functioning properly in flight.

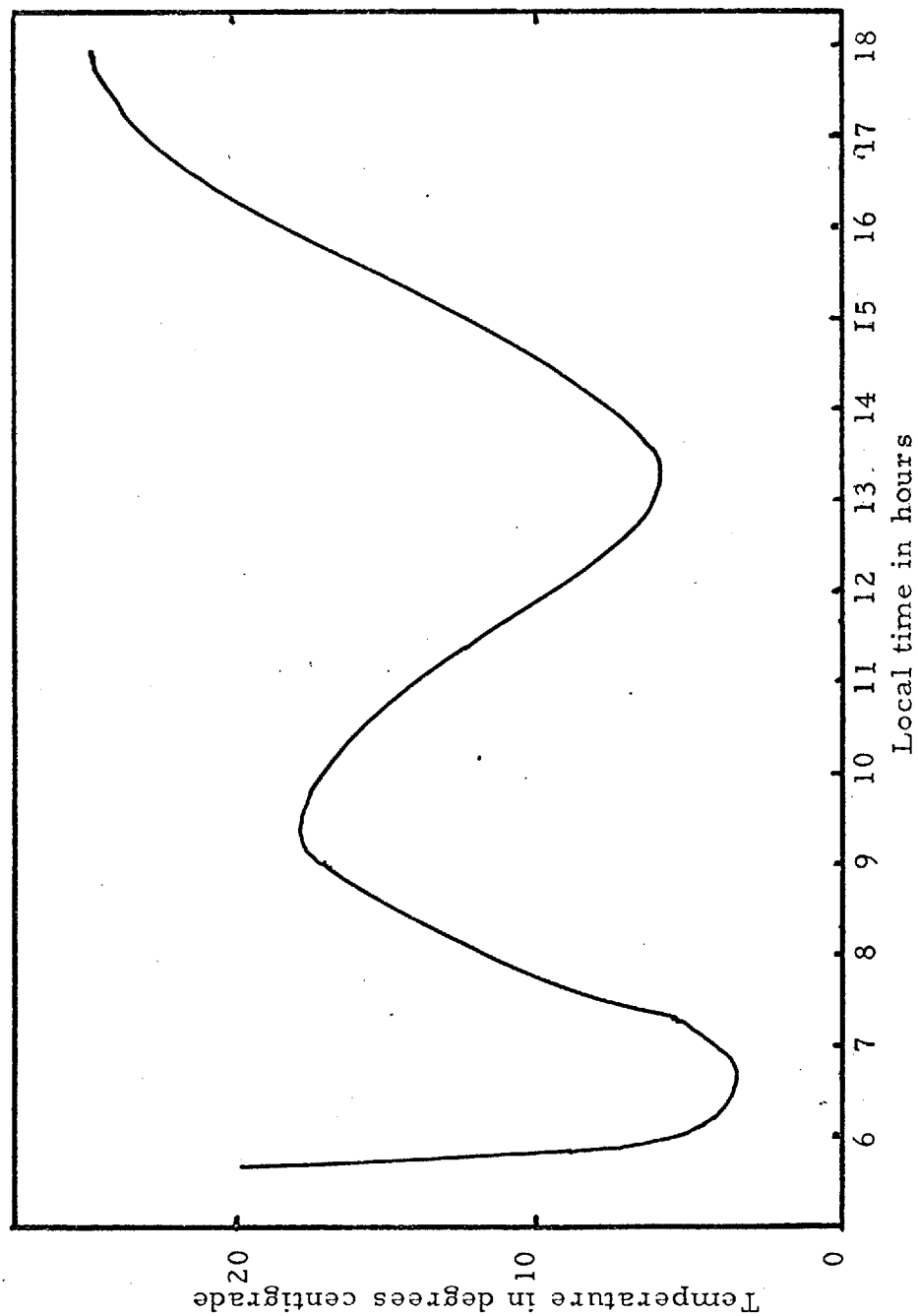


Figure 4.1a
Plot of payload temperature against local time

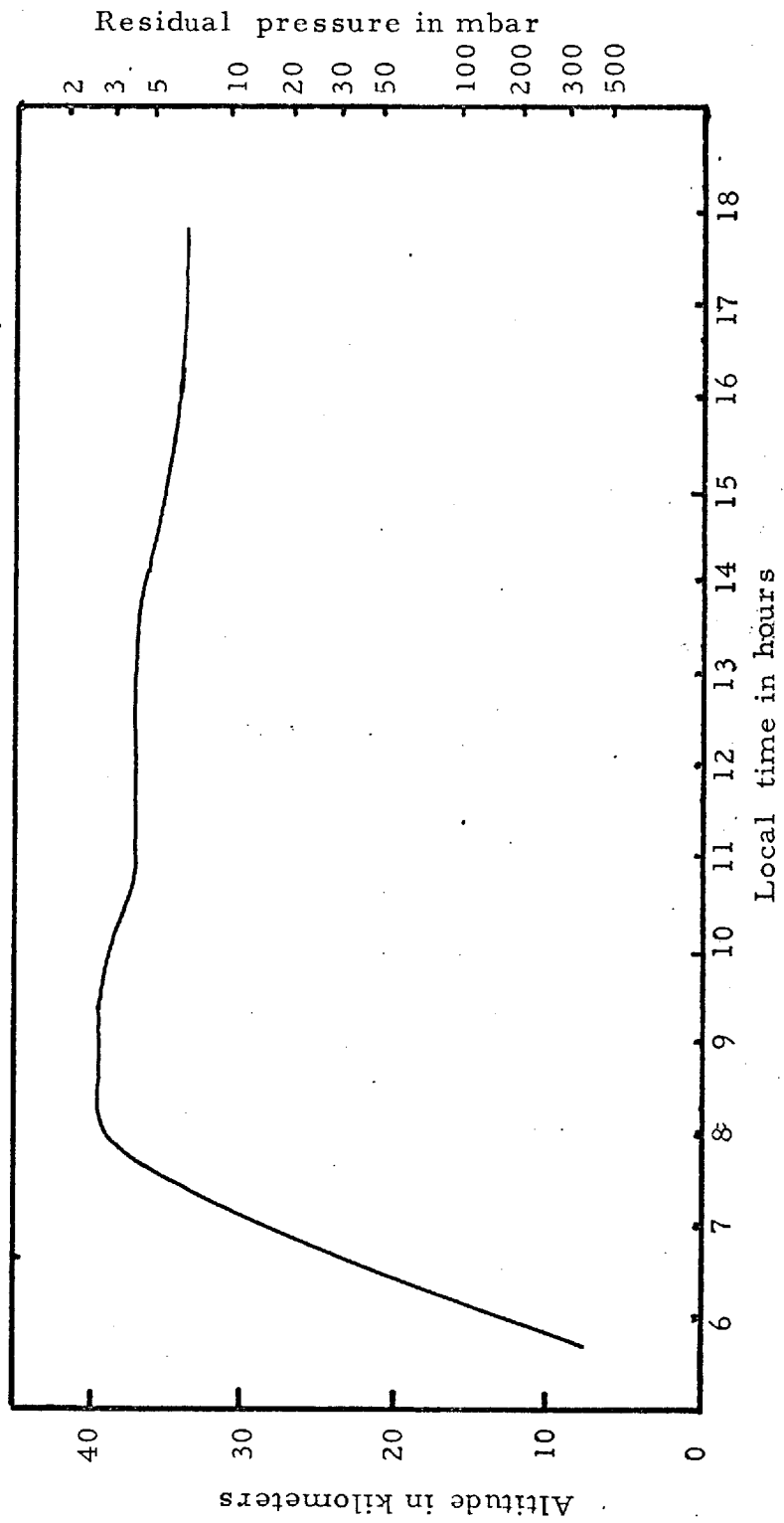


Figure 4.1b
Variation in altitude against local time

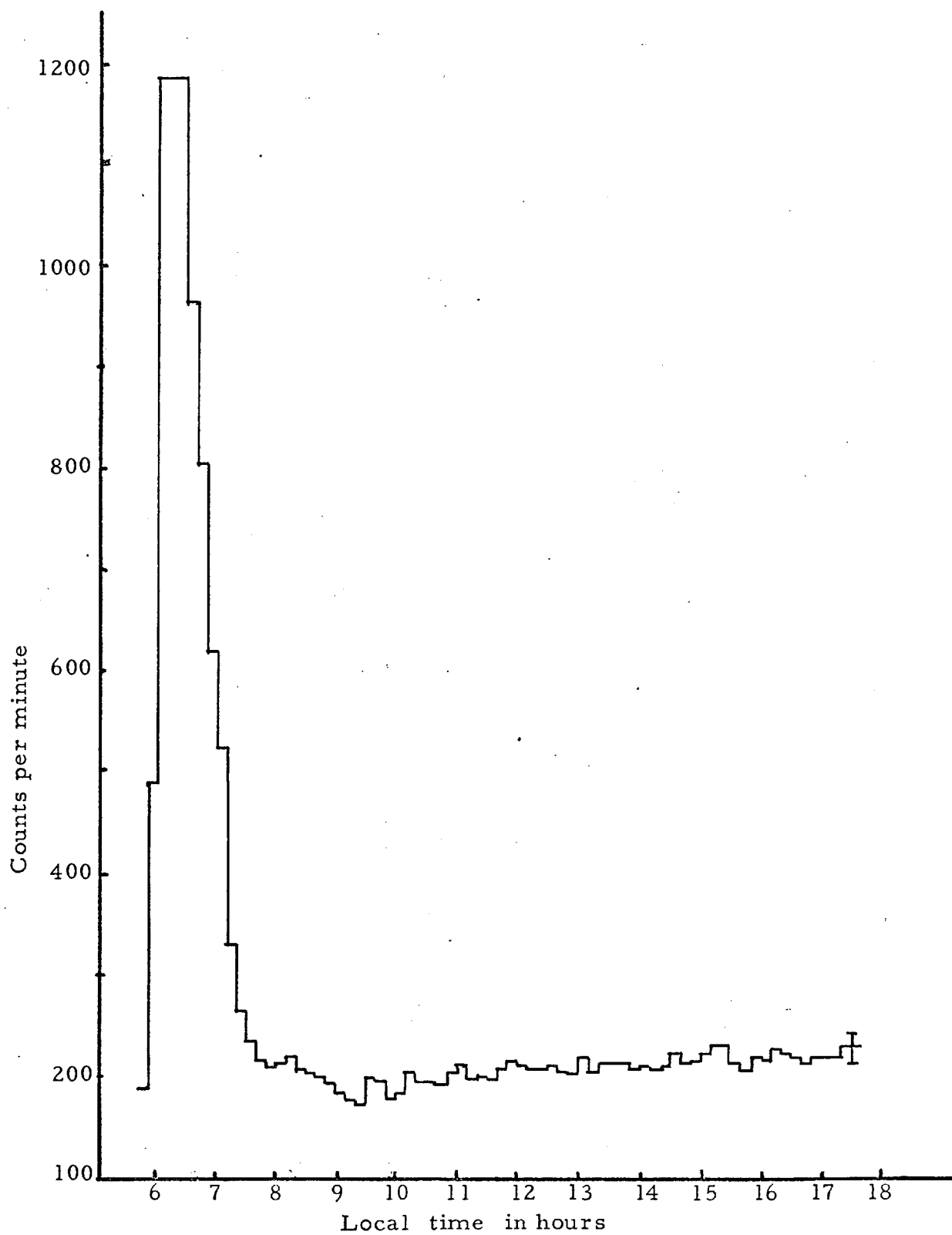


Figure 4.2
The raw gamma-ray counting rate, corrected for dead time,
as a function of local time.

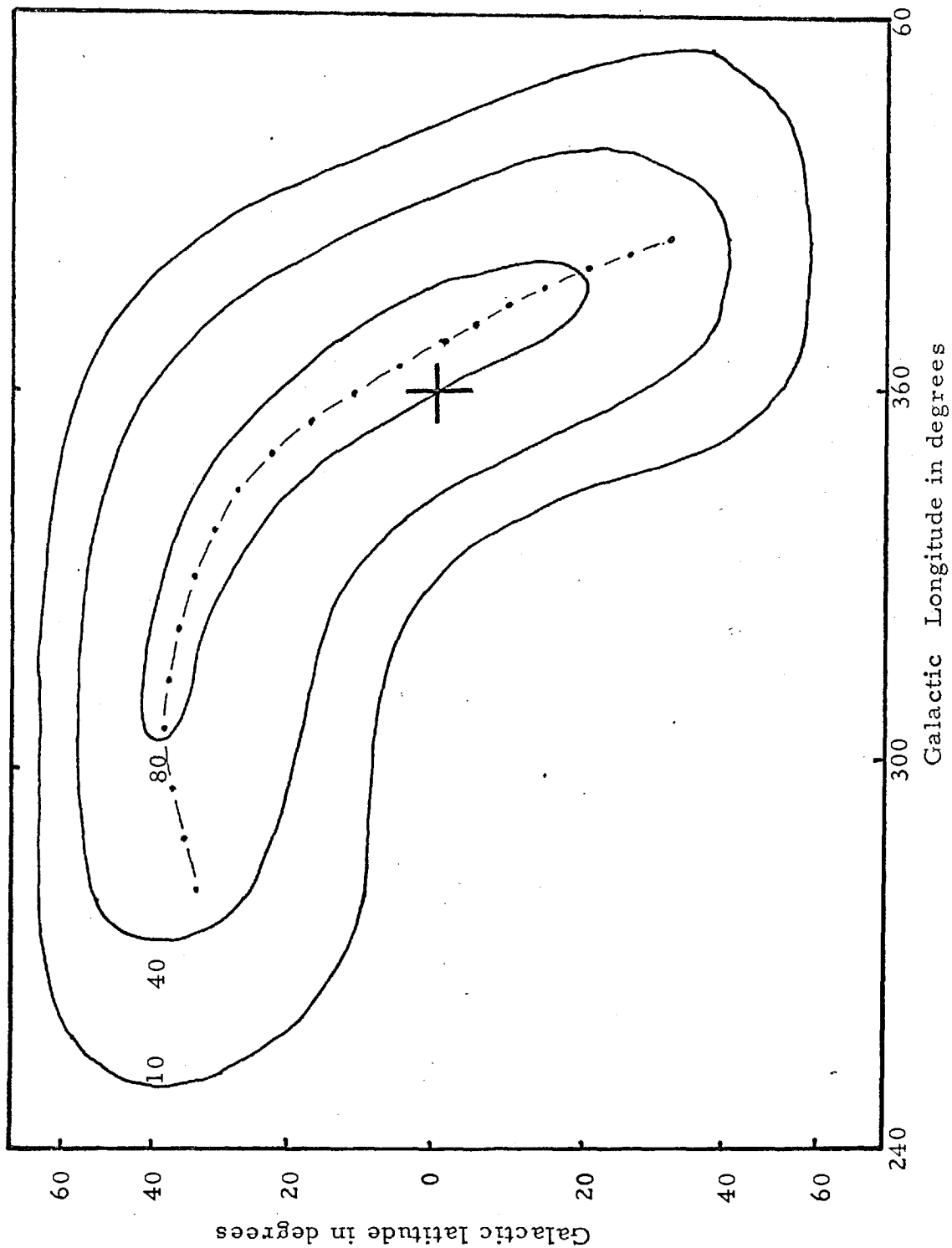


Figure 4.3
The smoothed exposure contours for the flight, the dashed line indicates the the payload trajectory.

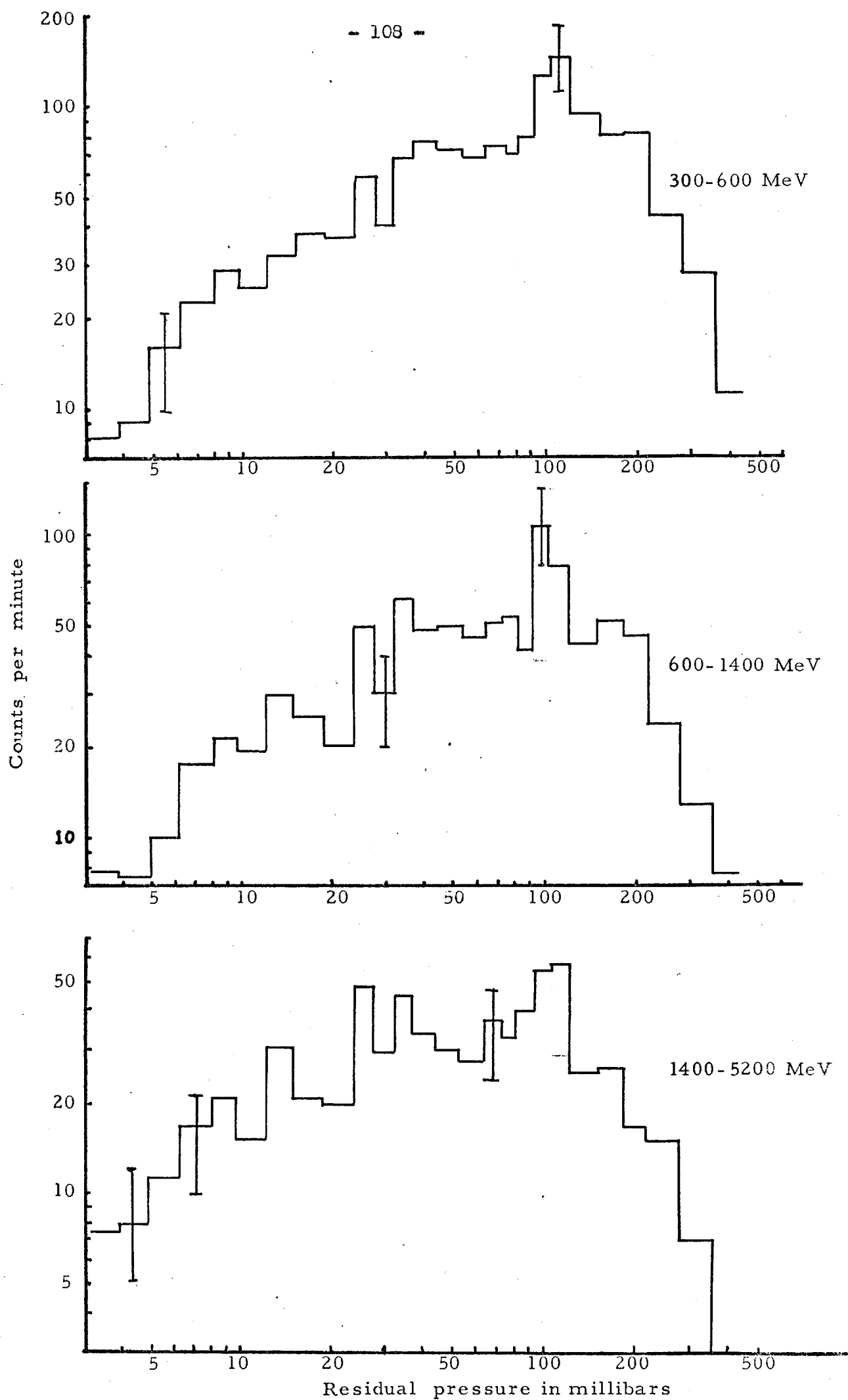


Figure 4.4
Variation in the gamma-ray counting rate for the ascent

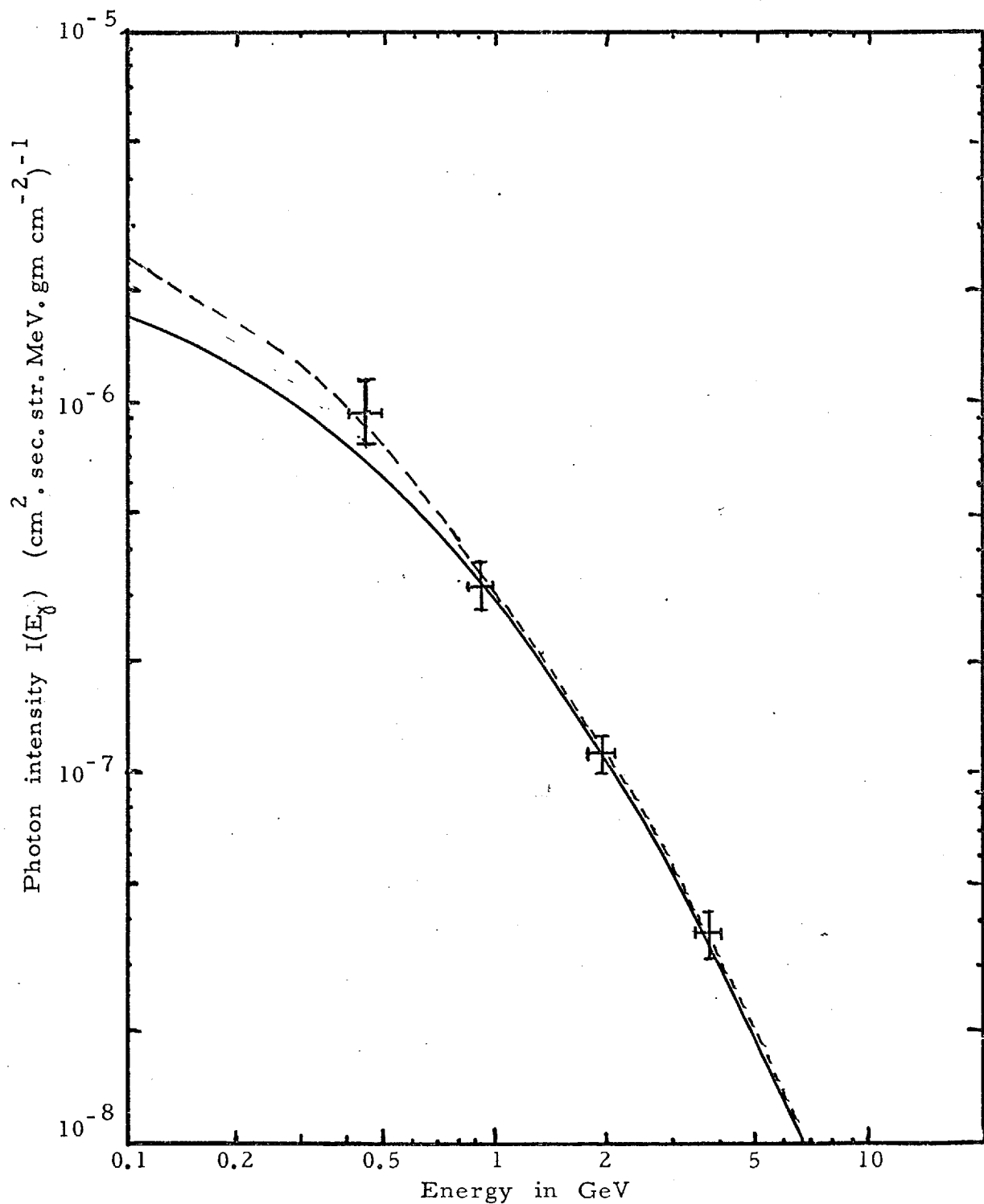


Figure 4.5

Experimental measurement of the atmospheric spectrum at 8.8 GV cut-off rigidity and solar minimum conditions. The solid line is the spectrum predicted by Perola and Scarsi for neutral pion decay, the dashed line corrects this by taking electron bremsstrahlung into account.

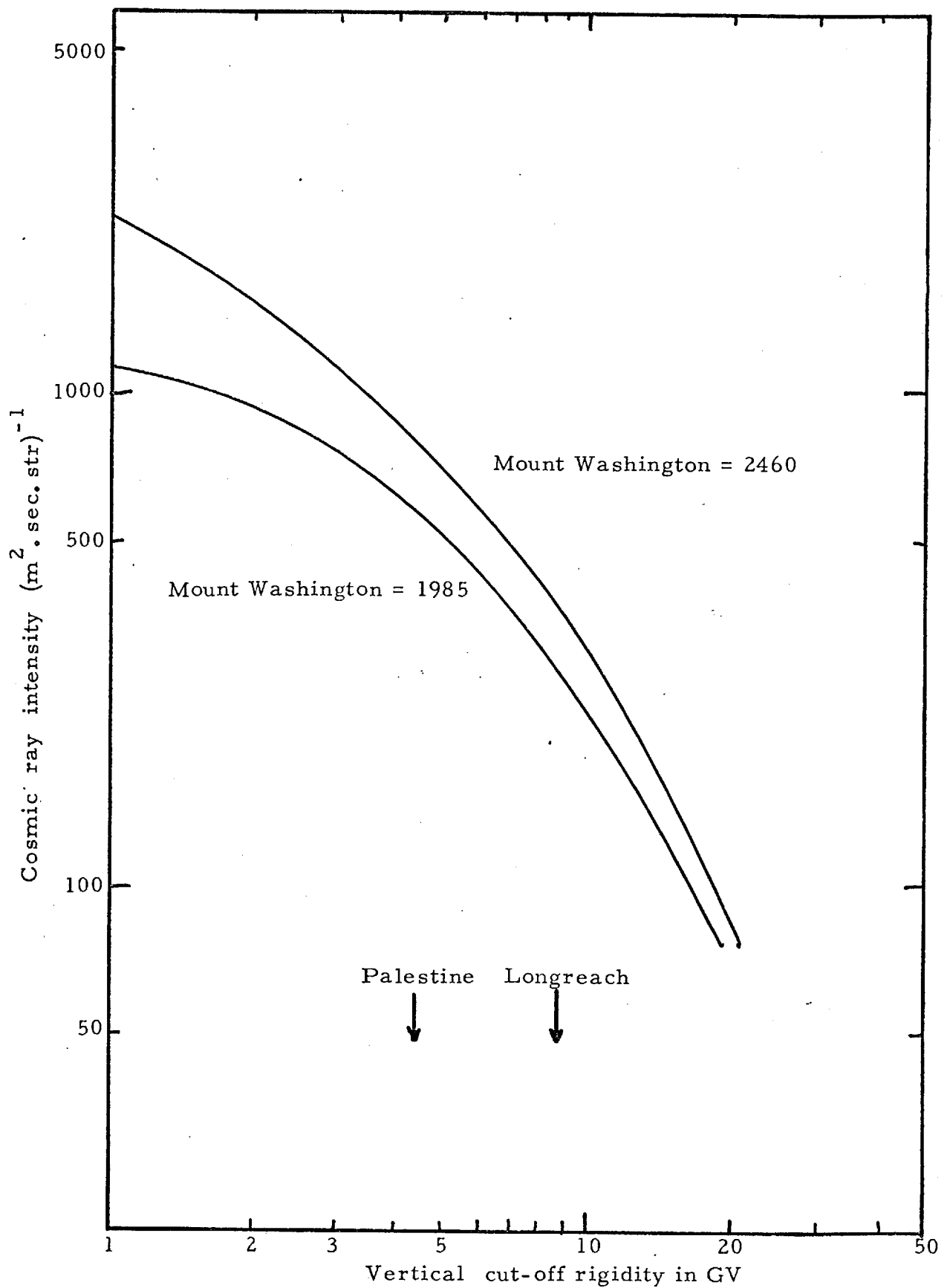


Figure 4.6

The integral rigidity spectrum of the total primary cosmic radiation at sun spot minimum and sunspot maximum. (after Webber, 1967)

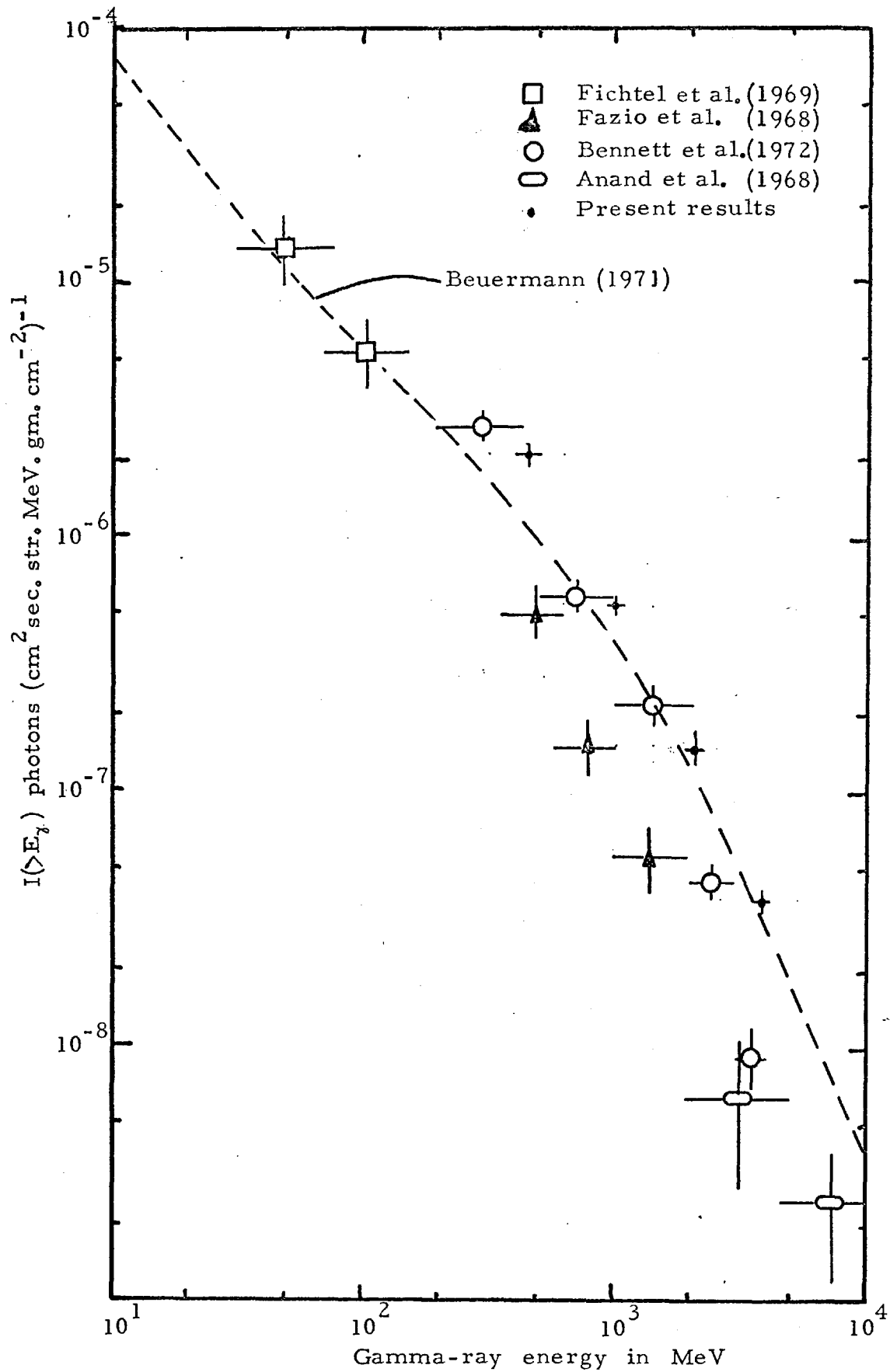


Figure 4.7
Comparison of the measured atmospheric spectrum of several experiments normalised to 4.5GV, 1 gm/cm³ and solar minimum conditions.

CHAPTER V

GAMMA-RAY SOURCES

5.1 Point Sources

5.1.1 Sensitivity to Point Sources

The relationship between the minimum source intensity I_m , observable above a background flux is given by:

$$I_m = S \cdot \left(\frac{\phi \cdot w \cdot f}{\epsilon \cdot AT} \right)^{\frac{1}{2}}$$

assuming Gaussian statistics, where the terms have the same meaning as in section 2.1. It can be seen from this relationship that the detector's efficiency, angular resolution, dead time and the exposure, limit the source intensity for a given signal to noise ratio. The first three of these quantities have already been discussed in Chapter III and the exposure to a point source will now be considered.

I_m will be a minimum when the exposure is at a maximum which corresponds to an on-axis transit of a point source. Figure 5.1 shows the sensitive area of the detector exposed to the point source as it tracks across the field of view of the detector. The figure shows the curves for an on-axis transit, and 10° , 20° , 25° off-axis transits. It can be seen from this figure that for maximum sensitivity the area profile is approximately triangular. The exposure is then $A \times T/2$ where A is the area of the detector and T is the time taken for the source to cross the detector's field of view. For this detector, with an opening angle of $\sim 36^\circ$, T was typically 5 hours. Figure 5.2 shows the minimum source intensities observable by the detector along its track across the celestial sphere. This line was calculated from the above expression

where Gaussian statistics could be assumed (low energies) and following the method of Hearn (1969) for high energies where the number of counts in the angular resolution cone was small.

In practice the sensitivity of the detector was less than this ideal value. This was due to the various efficiencies contributing to ϵ varying with time and zenith as discussed in Chapter III. Consequently the exposure values were calculated numerically by the computer as described in section 4.2.2.3. The efficiencies could be fed into this programme to modify the exposure values obtained for the $2^\circ \times 2^\circ$ bins considered, thus the quantity ϵAT was evaluated for each bin. Figure 5.3 shows smoothed exposure contours together with the positions of possible point sources.

5.1.2 The Search For Point Sources

A skymap of counts divided by exposure was produced for the flight data, split up into bins giving the same solid angles as a $2^\circ \times 2^\circ$ bin at the Galactic equator. This map was scrutinised together with the corresponding maps of counts and exposure to the bins, to look for any evidence of clustering of events which might indicate a point source. The positions of known hard X-ray sources were examined rather than scanning the whole map in an arbitrary way. This latter process could give rise to statistical fluctuations in the background masquerading as point sources. In fact, it has been calculated that the probability of finding a 3 standard deviation fluctuation in the background flux, somewhere on the skymap of this flight, by arbitrarily choosing the position of bins combined into the resolution cone, was 54%. This has been looked into by O'Mongain (1973).

The survey was undertaken in three energy intervals:
300 - 600 MeV, 600 - 1400 MeV, 1400 - 5200 MeV.

During this analysis adjacent bins were added together around the possible source position to include an angle equal to the angular resolution of the detector. The number of counts in this angular bin was compared with the number expected from the background, calculated from the flux in the region of sky nearby. Table 5.1 displays the observed and expected number of counts from the possible source regions examined. It can be seen that no significant excess was seen and 95% confidence level upper limits have been placed, using the method of Hearn (1969) which was especially useful at high energy due to the low counting rates observed.

5.2 Gamma-Ray Emission From The Galactic Plane

Pollack and Fazio (1963) and Hayakawa (1964) were among the first to predict, from the measured distribution of neutral hydrogen in the Galaxy, that in the presence of an isotropic cosmic ray flux, the primary gamma-ray flux observed at the earth would be anisotropic. This would appear as an enhancement towards the direction of the Galactic centre forming a line source in the Galactic plane. Several experiments have observed this line source and this enhancement was looked for in the data from this flight. The data reduction is outlined below.

5.2.2 Data Reduction

The flight programme produced a Galactic skymap containing the extrapolated gamma-ray arrival directions in

$2^\circ \times 2^\circ$ bins (normalised to the Galactic equator). The exposure programme produced a similarly normalised exposure skymap. For the purposes of this analysis only bins having an exposure greater than 10% of the maximum exposure were used.

The bins were combined into strips 2° wide in Galactic latitude and the number of counts and the total exposure of the strips were determined. From this the average flux per strip was evaluated. These strips were then summed together, beginning at the Galactic equator, to produce strips with a width approximately equal to the average angular resolution in the energy range being used (300 - 600, 600 - 1400, 1400 - 5200 MeV). At high Galactic latitudes the strips were wider to include more counts, thus improving the statistics of the measurements. The resulting average flux per strip for the three energy intervals is plotted in figure 5.4. The dashed line indicates the average background flux which was arrived at by averaging the fluxes from the strips, excluding the central strip in each interval. A pronounced signal above the background can be seen in the 600 - 1400 MeV range. The non-uniformity of the background flux can also be seen from these plots, showing a decrease towards negative latitudes corresponding to the end of the flight.

5.2.3 Background Uniformity

The background flux observed by the detector arises mainly from interactions between cosmic ray particles and the atmosphere. The flux arising in this way increases almost linearly with residual atmospheric pressure at the top of the atmosphere. During the flight, the payload descended slowly from 3.3 mbars to 6 mbars residual pressure which produced an increase in the background as the flight progressed. Another

effect produced in the upper atmosphere was the increase in gamma intensity with increasing zenith angle. This was due to the greater effective depth through which the detector was scanning and this produces a $\sec\theta$ dependence in the observed gamma-ray intensity, where θ was the zenith angle.

Also, the earth's magnetic field has two major effects on the intensity distribution of the incoming cosmic rays and consequently on the gamma-rays, a latitude effect and an east-west effect.

(a) The Latitude Effect

The effective cut-off rigidity in the vertical direction increases steadily with decreasing geomagnetic latitude. Thus, as one proceeds from the poles to the equator, particles of greater and greater rigidity are removed by the earth's magnetic field and the total flux of primary cosmic rays, incident upon the top of the atmosphere, decreases. Consequently, the intensities of the various secondary components observed in the upper atmosphere will also decrease with decreasing latitude. Thus it can be seen that as the detector drifts in geomagnetic latitude, the atmospheric flux of gamma-rays (from π^0 decay and electron bremsstrahlung) will also change. The latitude drift during this flight is shown in figure 5.5, together with the corresponding change in cut-off rigidity.

(b) The East-West Effect

For a given point of observation and for a given zenith angle, the cut-off rigidity is a function of azimuth. This has a maximum in the eastern direction and a minimum to the west for positively charged particles (vice versa for negative particles). Thus, primary particles of a given sign will

reach the top of the atmosphere with an asymmetric intensity distribution relative to the magnetic North-South plane, positive particles arriving in greater abundance from the western part of the sky, negative from the east. For this flight the east-west effect could be seen very clearly by stopping the transformations performed by the 'flight' and 'exposure' computer programmes after the arrival directions had been transformed into geomagnetic co-ordinates. The variation thus observed compared very favourably with that predicted by Byerley (private communication).

When these effects were taken into account and corrected for, the intensity variations across the Galactic plane were as shown in figure 5.6. It can be seen that the increase in flux due to altitude variation at the end of the flight was compensated by the decrease produced by the geomagnetic effects. The plots in figure 5.6 have been scaled relative to the previous ones of figure 5.4 to preserve the total flux after correction. Again, a marked signal can be seen in the middle-energy range corresponding to 66 excess counts (3.85 standard deviations) above the background. An enhancement was also seen in the low energy interval but this is only of marginal significance (1 standard deviation) and is treated as an upper limit.

Another feature of figure 5.6 is an apparent enhancement at $b'' = -25^\circ$ in the two lower energy intervals. This enhancement arises due to a clustering of events in the region $b'' = -25^\circ$, $l'' = 350^\circ$. However, this clustering of events could not be correlated with any known X-ray source and as it occurred very near to the edge of the exposure map, no significance was attached to it. If these events were left

out of the analysis, only a smooth increase towards $b'' = 0$ would be noted.

The plot in the high energy range appears to track the exposure distribution, an effect not observed in the other intervals. This was suggestive of a constant contamination by noise events in the high energy channel throughout the flight, rather than an incorrect exposure. The magnitude of this effect for each latitude strip was dependent upon the time for which the detector scanned at that latitude.

It was also noted in the flight analysis that at high energies there was a bias towards low zenith events. This suggests that the contamination was most likely due to proton interactions in the lead glass element producing upward-moving secondary products. Unfortunately, it was not possible to remove this contamination as no significant improvement occurred when the scintillator was set at different thresholds, suggesting that the contamination was not purely from single particles as it seemed to be at lower energies. This problem will have to be looked into for subsequent generation detectors in order to distinguish unambiguously between upward and downward-moving particles.

5.2.4 Galactic Line Source Intensity

The differential source intensity was calculated from the following expression:

$$I(E) = \frac{N \cdot n \cdot f \cdot g(E) \cdot 57.3 \cdot C}{AT \cdot \epsilon(E) \cdot A \cdot E_n \cdot 2} \text{ photons (cm}^2\text{sec.rad.100 MeV)}^{-1}$$

where N is the excess number of counts observed above the average background in a $2n^\circ$ wide strip, having the exposure factor AT ($\text{cm}^2\text{sec.per cm}^2$ of the detector). $\epsilon(E)$ is the total efficiency

of the detector compounded from the conversion efficiency and the spark chamber efficiency. f is the dead time correction, $g(E)$ is the spillage factor, already discussed. C is the correction for the atmospheric absorption at 4 gm/cm^2 . A is the detector area and E_n the width of the energy interval in 100 MeV's.

Table 5.2 summarises the results from the line emission and figure 5.7 shows the measured differential intensity spectrum together with the theoretical spectra for π^0 meson decay and inverse Compton interactions. Both these theoretical curves are normalised to $2 \times 10^{-4} \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ rad}^{-1} > 50 \text{ MeV}$ for comparison with the SAS-2 results. The thick horizontal error bars represent the energy resolution and the thin bars, the energy interval over which the measurement was made. It can be seen that the π^0 decay mechanism is favoured, with the point at 950 MeV being 1.17 standard deviations from the π^0 curve, while it is 1.8 deviations from the inverse Compton line. The theoretical π^0 curve was taken from Stecker (1971). In this paper Stecker acknowledges a possible error of 35% in the absolute intensities (which is not of concern here, due to normalisation) and a possible error of 6% in the average spectral index at energies greater than a few GeV, (giving the average index as 2.9). As shown in section 1.2.2.2, the index of the inverse Compton line is $-(\Gamma + 1)/2$ where Γ is the spectral index of the electron spectrum. The value used for Γ was 2.62 giving an index of 1.81 for the inverse Compton line. Anand et al. (1969) give an error in the electron index of ± 0.05 which corresponds to an error of half this amount in the gamma spectrum. Thus a π^0 decay mechanism is more consistent with the experimental data.

5.2.5 The Longitude Sum

The experimental data was also summed in Galactic longitude in the latitude band $|b''| < 10^\circ$. The variation in intensity is shown in figure 5.8. Again, it can be seen that an enhancement was present in the 600 - 1400 MeV range, as a broad peak in the interval $335 < l'' < 25^\circ$. This also corresponds to 65 excess counts above the average background. This distribution is a similar shape to that observed by SAS-2 (Kniffen et al. 1973) which shows a broad peak in the interval $330^\circ < l'' < 30^\circ$.

Source	Energy	Cone Width degrees	Observed counts	Expected counts	95% Confidence Upper flux $\cdot 10^{-6} \text{ } (\text{cm}^2 \text{sec})^{-1}$
SCO XR2 (GX342-3)	> 300	6	23.7	27.4	9.48
	> 600	4	9.7	16.9	6.68
	>1400	4	1.1	8.6	1.57
The Sun	> 300	6	37.8	30.9	8.60
	> 600	4	24.2	22.3	4.75
	>1400	4	15.6	14.0	2.30
Galactic centre	> 300	6	62.7	42.7	9.28
	> 600	4	26.2	19.7	6.30
	>1400	4	12.0	8.5	2.51
G12+3	> 300	6	41.7	44.8	4.53
	> 600	4	16.2	20.8	3.28
	>1400	4	7.5	8.9	1.40
SGR XR1 (GX3+1)	> 300	6	50.8	45.1	5.61
	> 600	4	20.9	21.2	3.95
	>1400	4	10.2	9.1	1.95
SGR A	> 300	6	41.7	43.6	5.37
	> 600	4	16.6	20.1	3.68
	>1400	4	6.8	8.6	1.36
OPH XR1 (GX6+6)	> 300	6	43.2	44.3	5.78
	> 600	4	20.8	20.3	4.5
	>1400	4	7.4	8.7	1.55

TABLE 5.1

Source	Energy	Cone Width degrees	Observed counts	Expected counts	95% Confidence Upper flux $\cdot 10^{-6} \gamma (\text{cm}^2 \text{sec})^{-1}$
SER XR1 (GX16+6)	> 300	6	34.0	37.35	7.14
	> 600	4	13.6	16.8	3.68
	> 1400	4	7.2	7.2	1.90
SER XR2 (GX17+2)	> 300	6	42.6	38.2	8.65
	> 600	4	21.2	16.8	6.20
	> 1400	4	9.8	7.2	2.70
SGR XR2 (GX13+1)	> 300	6	44.5	43.8	7.50
	> 600	4	27.2	19.8	6.50
	> 1400	4	8.8	8.5	1.95

TABLE 5.1 contd

TABLE 5.2

Photon Energy Range MeV	Observed counts	Expected counts	Line Source Flux $\times 10^{-5}$ $\text{d}(\text{cm}^2 \text{secrad} 100 \text{MeV})^{-1}$	Width Of Strip
300 - 600	381	363	1.9^*	$ b'' < 6^\circ$
600 - 1400	285	219	0.8 ± 0.26	$ b'' < 4^\circ$
1400 - 5200	176	188	0.08^*	$ b'' < 4^\circ$

* indicates a 95% confidence upper limit

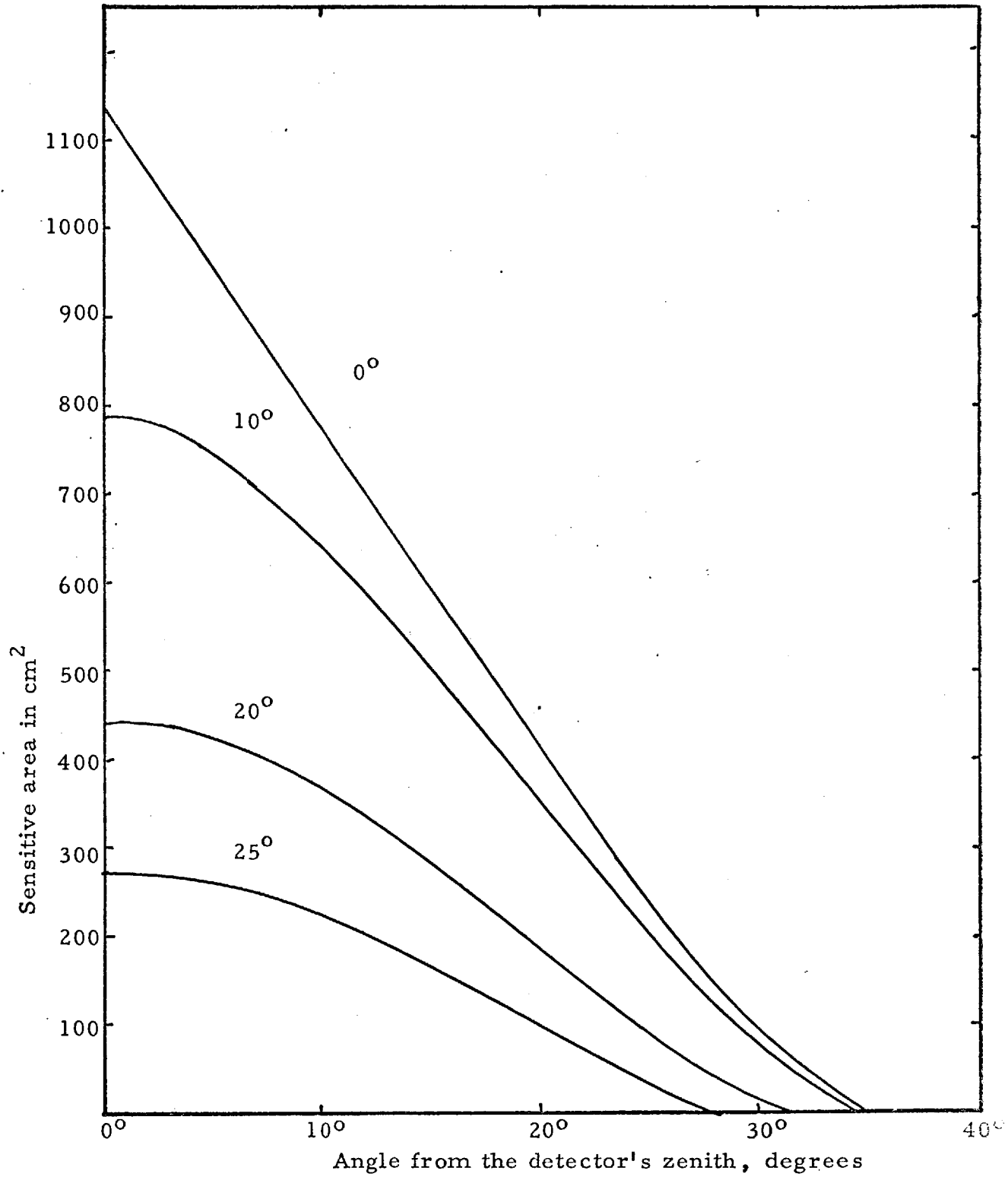


Figure 5.1

The variation in sensitive area as a point source passes over the detector's field of view. The curves for several off-axis transits as well as an on-axis transit.

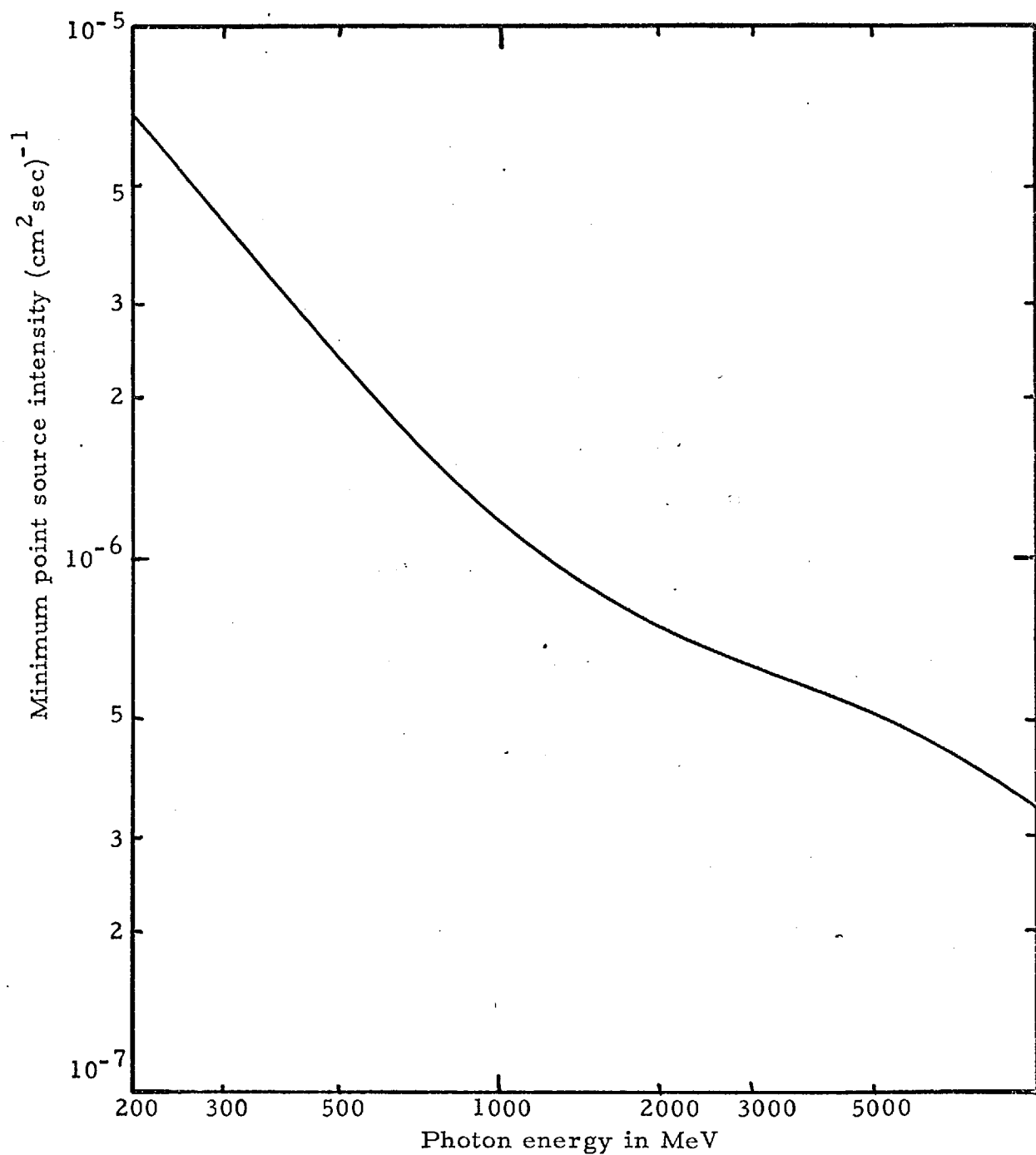


Figure 5.2
The minimum point source intensity as a function of energy

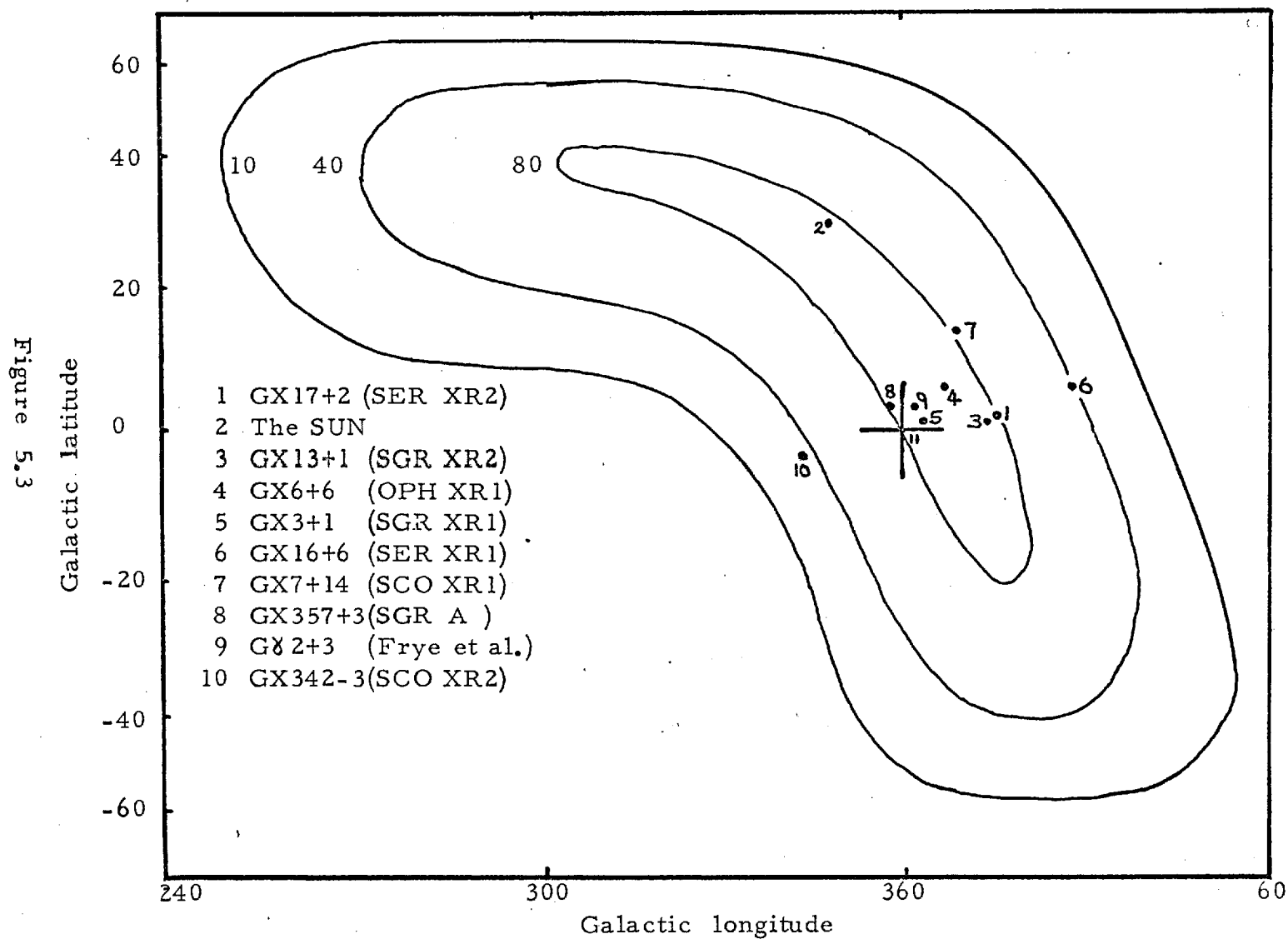


Figure 5.3
 The smoothed exposure contours for the flight together with the positions of some known hard X-ray sources.

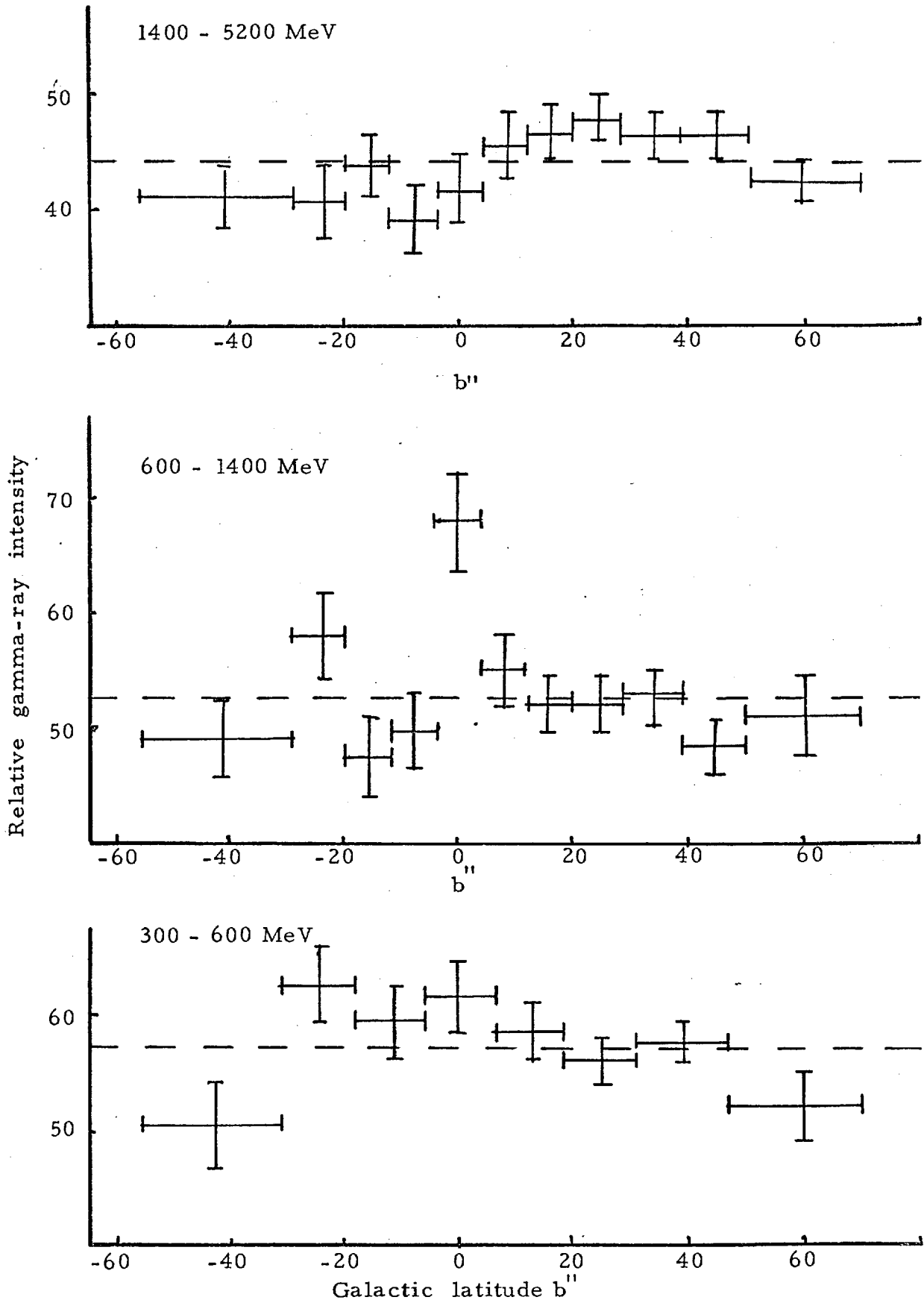


Figure 5.4

The average photon flux for strips summed in Galactic latitude before correction was made for the east-west variation, altitude, and geomagnetic latitude changes.

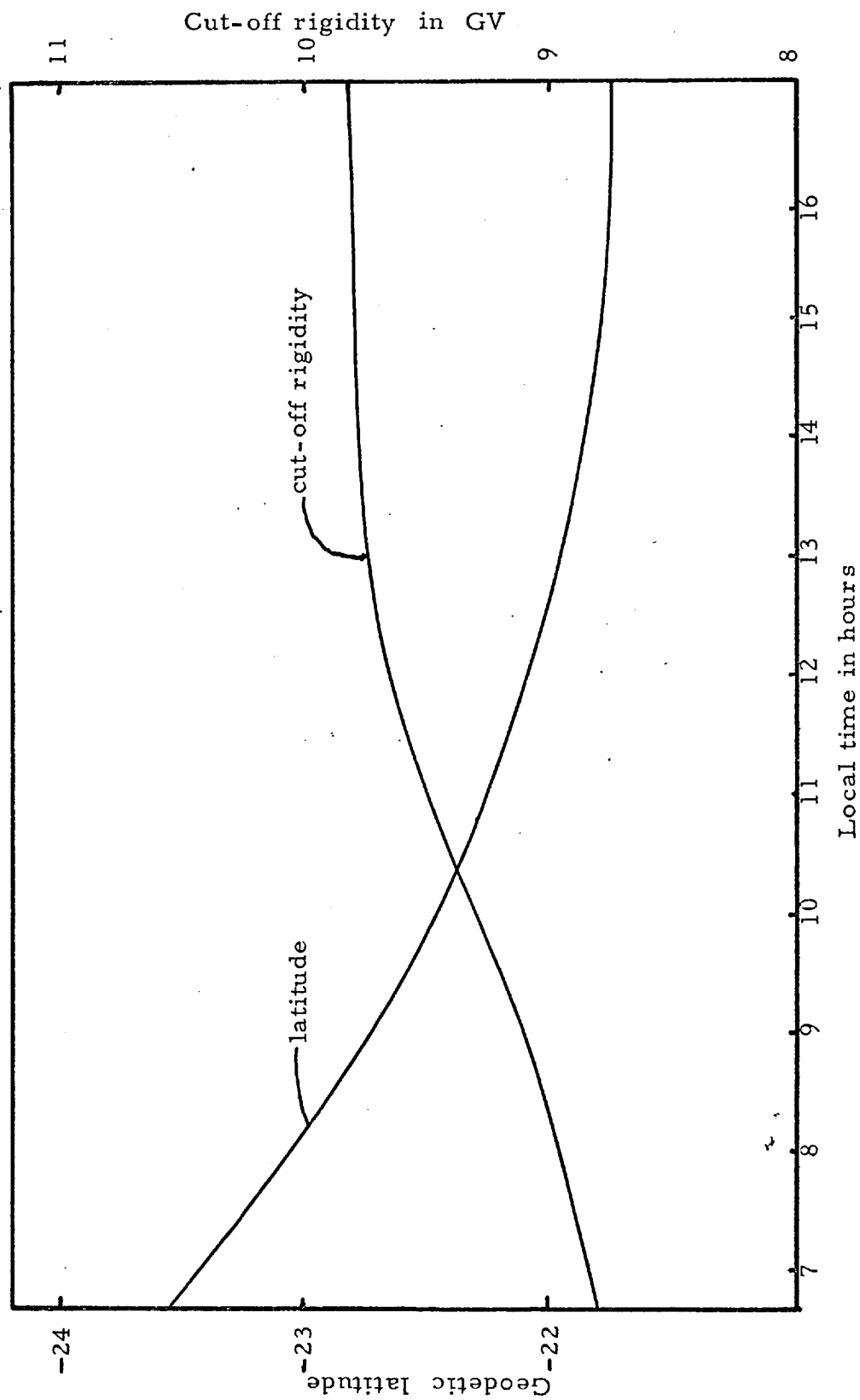


Figure 5.5
The variations in geodetic latitude and vertical cut-off rigidity as a function of local time.

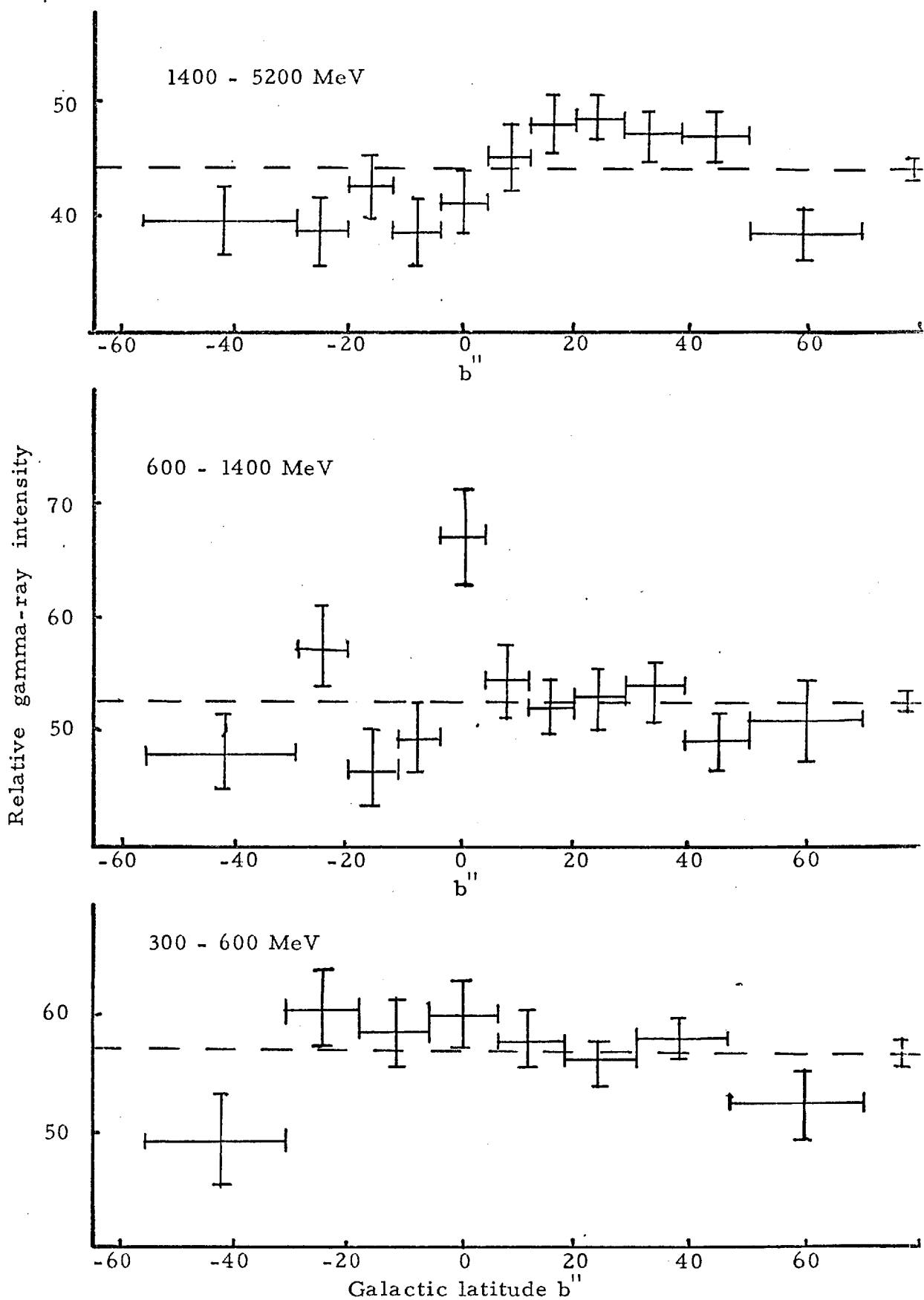


Figure 5.6
The average photon flux for strips summed in Galactic latitude after all the corrections to the background had been made.

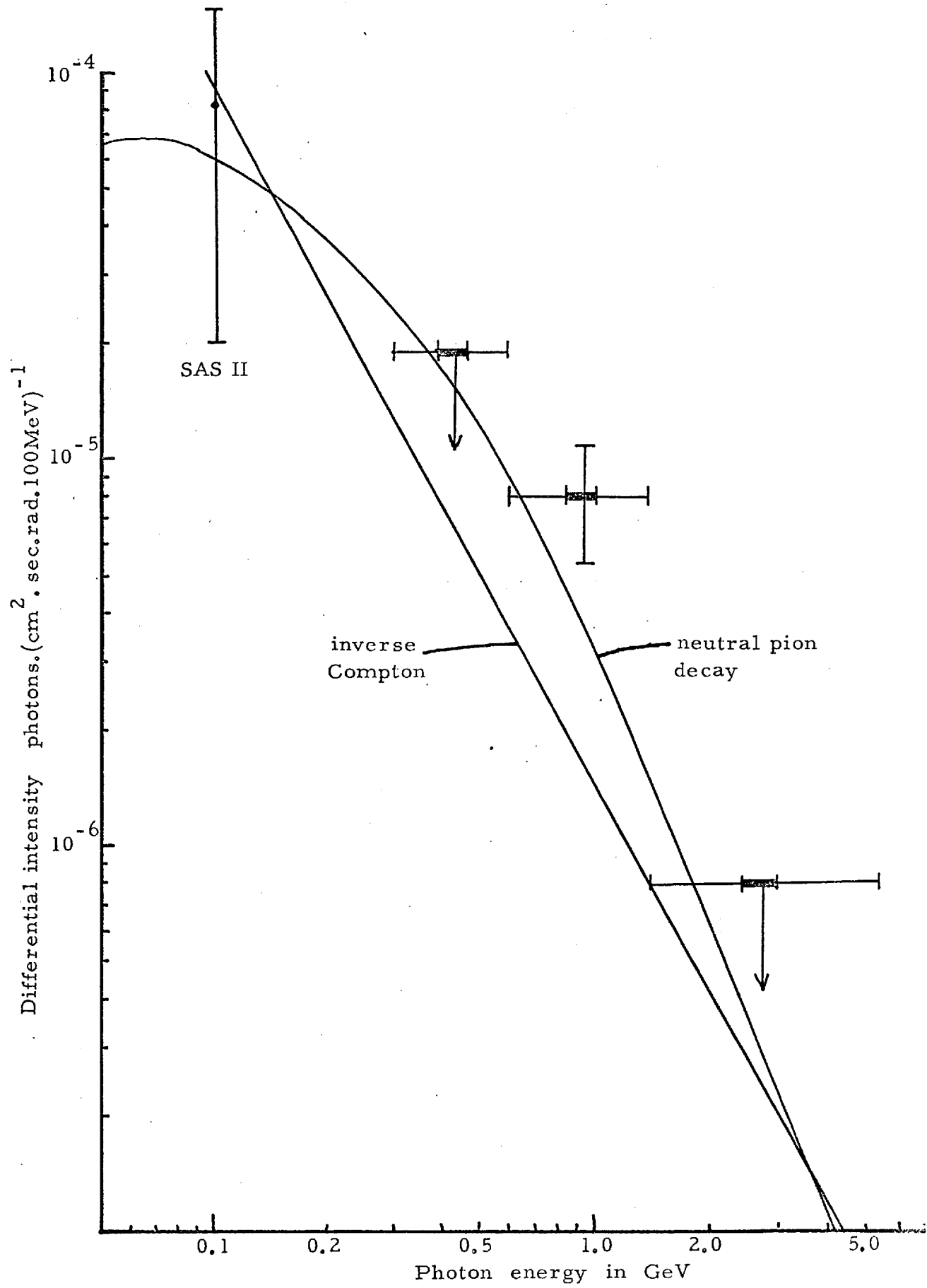


Figure 5.7

The differential energy spectrum for gamma-ray emission from the galactic plane.

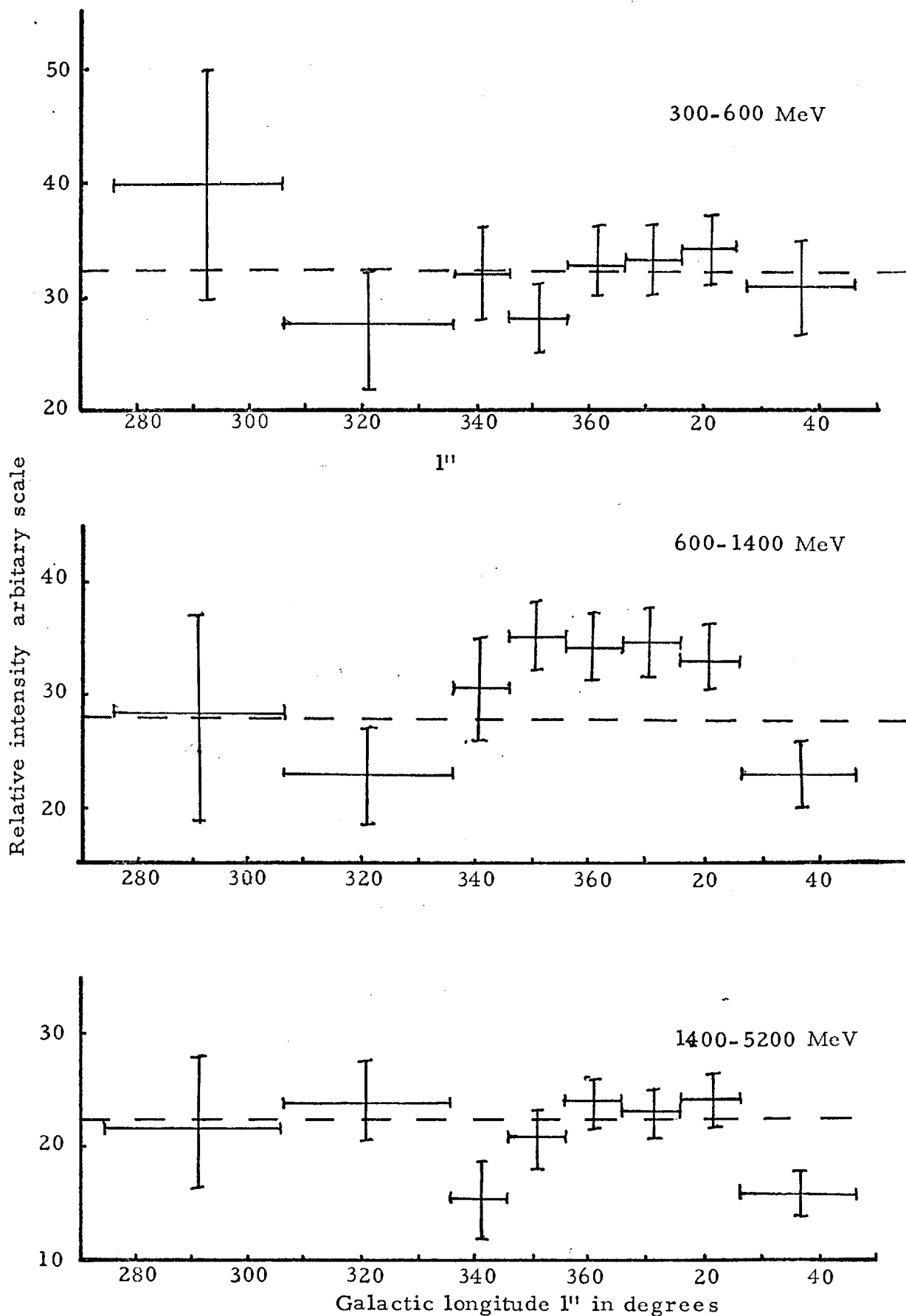


Figure 5.8
The average photon flux summed in Galactic longitude,
for the interval b'' less than 10° .

CHAPTER VI

DISCUSSION

The observed enhancement in gamma radiation in the plane of the Galaxy towards the Galactic centre region is now well established. Table 6.1 summarises the results of several experiments. It can be seen that the results are in good agreement except for the results of Frye et al. (1971, 1974) whose upper limit and subsequent data point are low by comparison.

Figure 6.1 shows these results plotted on an integral spectrum together with the theoretical curves for π^0 decay and inverse Compton production mechanisms. It can be seen that the data favour a π^0 decay mechanism, especially at high energy, although there seems to be some evidence for a softer component at lower energies (e.g. the differential data of Samimi et al. 1974). Stecker (1971) suggested a two component model comprising 70% π^0 and 30% inverse Compton. However, there is no evidence for inverse Compton gamma-rays in the SAS-2 longitude data where such an emission should show up as a definite peak at $l'' = 0$. Furthermore, Fichtel et al. (1972) have compared the number of events in the 50 - 100 MeV interval with those > 100 MeV and have concluded that the ratio was inconsistent with any production mechanism other than that of π^0 decay.

Shivanandan et al. (1968) and Houck and Harwitt (1968) measured an unexpectedly high infra-red flux emanating from the centre of the Galaxy. An isotropic flux at 100μ was also reported by Hoffman and Frederick (1969). These observations were later fitted to a greybody curve with a characteristic temperature of 16°K and representing the enormous energy density of 53 eV/cm^3 .

Shen (1969) and Cowsik and Pal (1969) derived, from this radiation field, a flux of gamma-rays greater than 100 MeV approximately equal to the original OSO-3 measurement. However, the existence of the infra-red field and the validity of these two models has been disputed (e.g. Ipavich and Lenchek, 1970, and references therein). Indeed, in a recent paper, Cowsik and Voges (1974), the authors do not take the greybody into account at all. If they did so it would represent a serious contradiction to the present SAS-2 longitude data.

However, Cowsik and Voges (1974) maintained that the inverse Compton effect was more important than π^0 even at 100 MeV. This was disputed by Stecker who estimated (Stecker 1975) that the inverse Compton mechanism could not be expected to produce more than 6% of the gamma-rays of energy > 100 MeV. The upper limit set by the present experiment on the Galactic centre region (equivalent to 9.74×10^{-7} photons $(\text{cm}^2 \text{sec str MeV})^{-1}$ at 950 MeV for a region $4^\circ \times 4^\circ$ around the centre) was used to clarify this discrepancy. By using the expression in section 1.2.2.2 the calculated total intensity of gamma-rays from inverse Compton interactions between cosmic ray electrons and the starlight and 2.7°K radiation fields, was 5.93×10^{-9} gammas $(\text{cm}^2 \text{sec str MeV})^{-1}$ at 950 MeV. This is only 0.6% of the upper limit flux value quoted above. Further, by comparing the energy density used by Cowsik and Voges with that required to produce the experimental upper limit flux value, it was possible to estimate an upper limit inverse Compton spectrum from that obtained by Cowsik and Voges (1974). This spectrum is shown in figure 6.1. It can be seen that this is in very good agreement with Stecker's predictions of the inverse Compton contribution and shows that

this interaction does not contribute significantly above 100 MeV where the π^0 mechanism clearly dominates.

The π^0 decay line (solid) shown in figure 6.1 is that calculated by Stecker (1969) assuming an average hydrogen density of 0.7 cm^{-3} (for atomic hydrogen alone). Also shown is the π^0 decay spectrum (dashed) for $n_H = 1.2 \text{ cm}^{-3}$ (which requires some H_2) which gives very good agreement with the experimental data, especially at high energies where only the π^0 mechanism is of importance.

The early predictions of Galactic anisotropy (e.g. Hayakawa, 1964) were based on the density of atomic hydrogen estimated from the 21 cm radio observations of the Galaxy. It was assumed that the atomic hydrogen observed was the full content of hydrogen gas in the Galaxy, giving a resultant gamma-ray emission, from π^0 decay, for gamma-rays of energy greater than 100 MeV of $3 \times 10^{-5} \text{ cm}^{-2} \text{ sec}^{-1} \text{ rad}^{-1}$. However, when the enhancement was first observed, (Clark et al.), the observed fluxes were an order of magnitude higher than this. Clark et al. suggested that these fluxes may originate mainly from unresolved discrete sources (a suggestion which was further explored by Ogelman, 1969, but has not stood the test of time and better resolution detectors). However, they were careful to point out that large amounts of undetected hydrogen might also account for these enhanced fluxes.

The results obtained by the gamma-ray detectors flown on the SAS-2 and OSO-3 satellites provide the strongest evidence for the enhancement of the gamma-ray flux towards the Galactic centre region. Also, the present experimental results show good agreement with these measurements although the observing time of the present detector was considerably less than these satellite borne experiments.

Puget and Stecker (1974) have geometrically unfolded the SAS-2 longitude distribution (given by Kniffen et al., 1973) and the resultant emissivity as a function of galacto-centric distance is shown in figure 6.2a. They plot the product of emissivity and the half width of the gas disc (h , taken to be 140 pc) against galacto-centric distance. Strong (1974) has performed a corresponding unfolding of the combined data from OSO-3 and SAS-2 as shown in figure 6.2b. It can be seen that these two distributions are very similar, showing a marked peak in gamma-ray emissivity at ~ 5 kpc and a reduced emissivity within 3 kpc of the Galactic centre.

Also shown on figure 6.2b are the distributions of radio emissivity (150 MHz) derived by Ilovaisky and Lequeux (1972) (upper curve) and by Price (1974) (lower curve) using the observations of Landecker and Wielebinski (1970). By comparing the radio emissivity ϵ_r with the relative gamma-emissivity $w(R)$ in figure 6.2b, it can be seen that if all the increase in ϵ_r were due to the electron flux (rather than an increased magnetic field), a corresponding increase in the proton intensity falls short of explaining the $w(R)$ distribution by a factor of 2 - 3, for a π^0 decay mechanism.

It is now well known that the observed distribution of neutral hydrogen in the Galaxy (figure 6.3a) can not account for the form of the plot of emissivity against galacto-centric distance (figures 6.2a, 6.2b). A considerable quantity of molecular hydrogen in the interstellar medium had been considered a likely possibility until Stecher and Williams (1967) found an effective mechanism for its photodestruction. It now appears that in the presence of an average interstellar radiation field, the amount of molecular hydrogen expected to be present will be

negligible. In dark clouds, however, the rate of molecular hydrogen formation is expected to exceed the photodestruction rate and essentially all the hydrogen in these clouds is expected to exist in molecular form.

Molecular hydrogen is very difficult to detect directly as this would entail monitoring its Lyman absorption bands in the ultra-violet. Unfortunately, ultra-violet observations of H_2 at distances greater than ~ 1 kpc and in any cloud with greater than two magnitudes of visible extinction are not feasible. This is due to the large extinction of ultra-violet by interstellar dust grains. However, since collisions between H_2 and CO molecules is the most important source of excitation of CO in molecular clouds, measurement of the radio emission from CO molecules (2.6 mm emission) affords an insight into the density and distribution of H_2 in the galaxy. This has been done recently by Scoville and Solomon (1974). This data was used by Solomon and Stecker (1974) to estimate the mean density of molecular hydrogen. They show a striking correlation between the unfolded measurements of Galactic CO emission (figure 6.3b) and the unfolding of the SAS-2 measurements of Galactic gamma-ray emission (figure 6.2a). Both distributions could be indicative of a ring shaped distribution or arm feature consisting of cool clouds of molecular hydrogen at a Galacto-centric distance of ~ 5 kpc. Solomon and Stecker estimated the mean density of H_2 to be between 1 and 5 cm^{-3} in the 5 kpc region this density being estimated to be a factor of 7 greater than the local value. For a $\bar{n}_{H_2} = 5 \text{ cm}^{-3}$ the mass of molecular hydrogen would be large enough to account for the gamma-ray emissivity shown in figure 6.2a and in this case the cosmic rays could be either Galactic or extra-galactic in origin. Even though the results obtained

for the 5 kpc region may be compatible with the assumption of a uniform cosmic ray distribution, it appears that the cosmic ray intensity would have to decrease at the Galactic centre. This is necessary because the gas density appears to have a maximum there (after Solomon and Stecker, 1974, and references therein) but the gamma-ray emissivity does not. However, at present, the interpretation for the Galactic centre (as shown in figure 6.2a) is much more uncertain (Puget and Stecker, 1974) and this may not be the case.

Bignami and Fichtel (1974) in pursuing the problem of Galactic gamma radiation have put forward a model based on the spiral arm structure of the Galaxy (figure 6.4). They have pointed out that the observed intensity of a feature, with a thickness comparable to the disk of the Galaxy will decrease approximately as one over the distance, once it is more than 2 kpc away from SAS-2 and faster if it is also small in extent within the plane. Hence more remote parts of the Galaxy would have to be substantially more intense than local features to explain an observed intensity of gamma-rays in any direction.

Bignami and Fichtel assume that the cosmic rays and magnetic fields are Galactic and not universal, also that the fields are tied to the interstellar matter producing greatest field intensities where the matter density is greatest. The Galactic cosmic rays are confined to these field lines, being confined there up to an energy density of the order of the confining field energy density ($B^2/8\pi$). These assumptions combine to produce a n_H^2 dependence in the gamma-ray intensity, where n_H is the number density of hydrogen. In constructing the hydrogen distribution for the Galaxy they have taken three

main arm features: the 4 kpc dispersion ring, the Norma-Scutum arm and the Sagittarius arm. The arm/interarm density ratio they have proposed to be 5:1, with the density of an arm being 2 cm^{-3} . Outside the local arm they place no well defined feature and have a smooth decrease in density up to 16 kpc. On the basis of these assumptions, Bignami and Fichtel have obtained a very good fit to their longitude distribution with the major contribution to the flux coming from the Sagittarius arm.

Strong et al. (1974) considered a model similar to that proposed by Bignami and Fichtel (1974) by proposing a large scale variation in the magnetic field in the Galaxy which could be responsible for the variation in cosmic ray containment. They took $I_{\text{cr}} \propto B^2$ and using a field model derived by Thielheim and Langhoff (1968) found good agreement with observation. However, there is an objection here arising from the synchrotron emission measurements. If the cosmic ray electrons increase in the same way as the protons (as would be expected in this model), then the combined effect of field and electron enhancement would give the radio emissivity $\epsilon_r \propto B^4$ which implies a higher ϵ_r towards the centre than is allowed by radio observations. The conclusion would be that the ratio of e-sources to p-sources decreases towards the Galactic centre which seems unlikely.

Dodds et al. (1974) discuss various models for explaining the form of $w(R)$ derived by Strong and shown in figure 6.2b. These involve models suggested for the variation of cosmic ray flux in the Galaxy divided into those involving source density, containment of cosmic-rays and large scale accelerations on the cosmic ray particles.

Dodds et al. have examined the possibility of the distribution of super nova remnants (SNRs) as a possible source

distribution, after the identification of the Vela SNR as a gamma-ray source (observed by SAS-2). However, using the SNR distribution of Ilovaisky and Lequeux (1972), it was clear that this model gave too small an enhancement to account for the observed gamma fluxes. In contrast, when considering the possibility that the number of cosmic ray sources was proportional to the total mass density in the Galaxy and using the model of Perek (1962), they found good agreement with the observations. Although this model gave a mass density increasing towards the Galactic centre to 60 times that at the sun, this was offset by the lower neutral hydrogen densities for $R \sim 4$ kpc and the increasing distance of the more dense regions.

Puget and Stecker (1974) showed that the distribution of Galactic gamma-rays production rate (figure 6.2a) exhibits a striking similarity to that observed for ionised hydrogen in the Galaxy and also the radio emission model of Price (1974), although not correlating with the 21 cm atomic hydrogen distribution (figure 6.3a).

Stecker et al. (1974) and Puget and Stecker (1974) have suggested that the rapid decrease in outward radial velocity of gas observed between $R = 3$ and $R = 5$ kpc could be expected to lead to compression and acceleration of the cosmic rays in this region. However, Dodds et al. comment that although they (Puget and Stecker) have a consistent picture in which the required enhancement was obtained after 10^7 years, comparable with the lifetime of the expansion features, Dodds et al. doubt if it agrees with the radio data. The required compression would cause enhancement of both the magnetic field and cosmic ray electron density. Dodds et al. find that $\mathcal{E}_\gamma \propto w^\beta$ where $\beta = 1.3$

for a one dimensional compression. Using the form of $w(R)$ in figure 6.2b, they find a marked inconsistency with the distribution given by Price (1974). This remains even when $\beta = 1$, i.e., there is no compression of the magnetic field. Thus for this model to work the ratio of e-sources to p-sources would have to decrease towards the Galactic centre.

Thus it can be seen that at the present time a high density of molecular hydrogen seems to be the most likely explanation for the gamma-ray fluxes towards the Galactic centre. An extragalactic origin for the protons would then allow the proton flux to be uniform while the (necessarily Galactic) electron flux increases as indicated by the electron radio data. Alternatively, if the protons are Galactic and the ratio of p-sources to e-sources is constant, then the models involving only increased cosmic ray fluxes lead to conflict with the data. In this case a more moderate increase in both gas density and cosmic ray flux would give the most consistent picture.

Reference	Energy of Measurement MeV	Width Of Emitting Region	Line Flux x 10 ⁻⁴ γ (cm ² sec.rad) ⁻¹
Clark et al. (1968)	> 100	$ b'' < 15^\circ$	5.0
Kraushaar et al. (1972)	> 100	$ b'' < 15^\circ$	1.3 ± 0.3
Fichtel et al. (1969)	> 50	$ b'' < 3^\circ$	4.4*
	> 100	$ b'' < 3^\circ$	2.2 ± 1.1
Fichtel et al. (1973)	> 100	$ b'' < 6^\circ$	2.0 ± 0.6
Kniffen et al. (1973)	> 30	$ b'' < 6^\circ$	2.0 ± 0.6
	> 100	$ b'' < 6^\circ$	1.15 ± 0.45
Share et al. (1974)	> 15	$ b'' < 3^\circ$	3.5 ± 1.2
Bennett et al. (1972)	> 200	$ b'' < 9^\circ$	2.8 ± 1.4
	> 1000	$ b'' < 9^\circ$	1.25*
	> 2000	$ b'' < 9^\circ$	0.76*
Frye et al. (1971)	> 100	$ b'' < 6^\circ$	0.53*
Frye et al. (1974)	> 100	$ b'' < 3.5^\circ$	0.38 ± 0.14
Sood (1969)	> 50	$ b'' < 15^\circ$	5.0 ± 1.5
Valdez et al. (1970)	> 100	$1.5 < b'' < 4.5^\circ$	3.0 ± 1.5
Cooke et al. (1969)	> 10 KeV	—	10.0×10^{-1}

* indicates a 95% confidence upper limit

TABLE 6.1

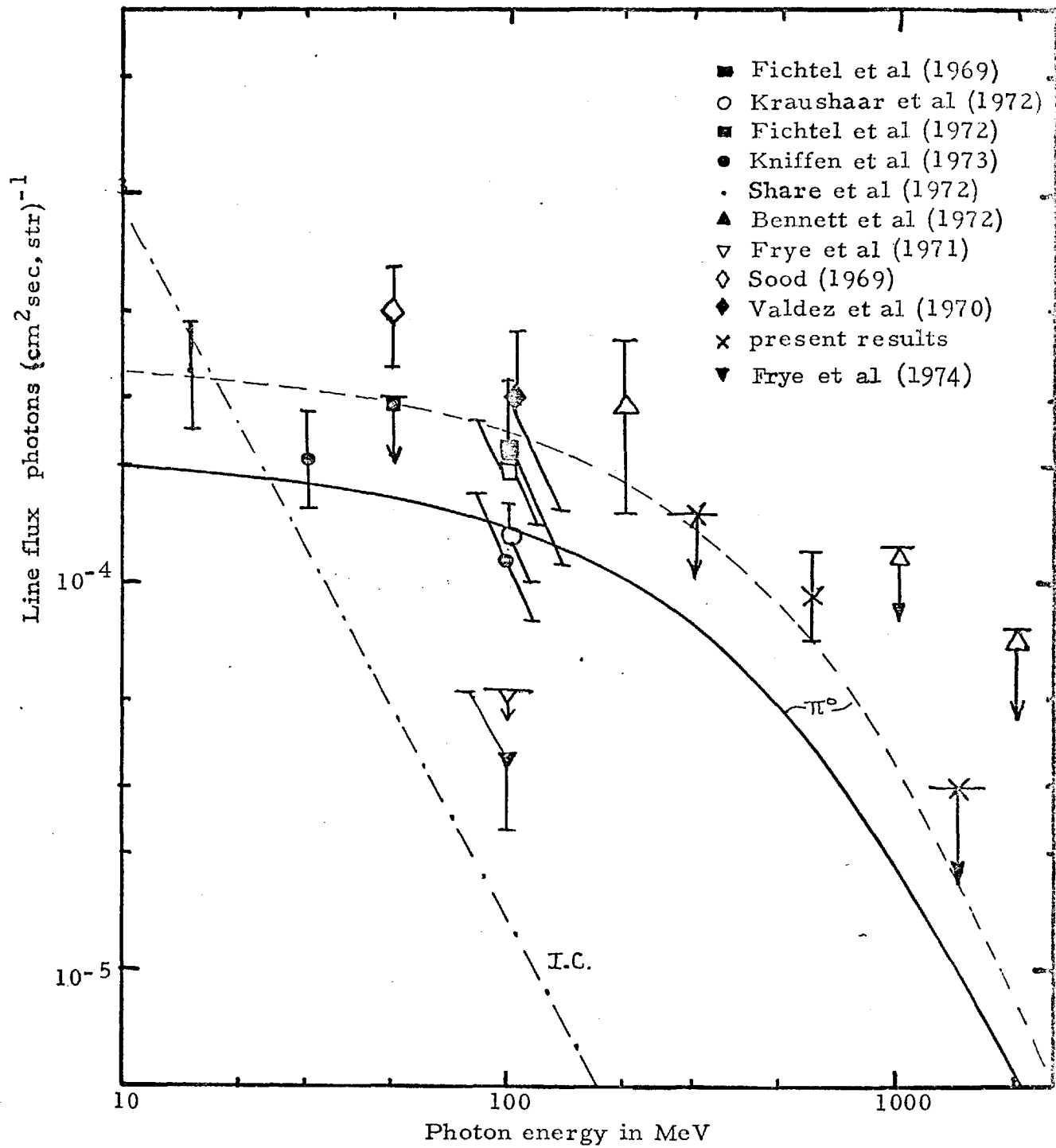


Figure 6.1
Comparison of the results of several experimental measurements
of the gamma spectrum from the Galactic centre region

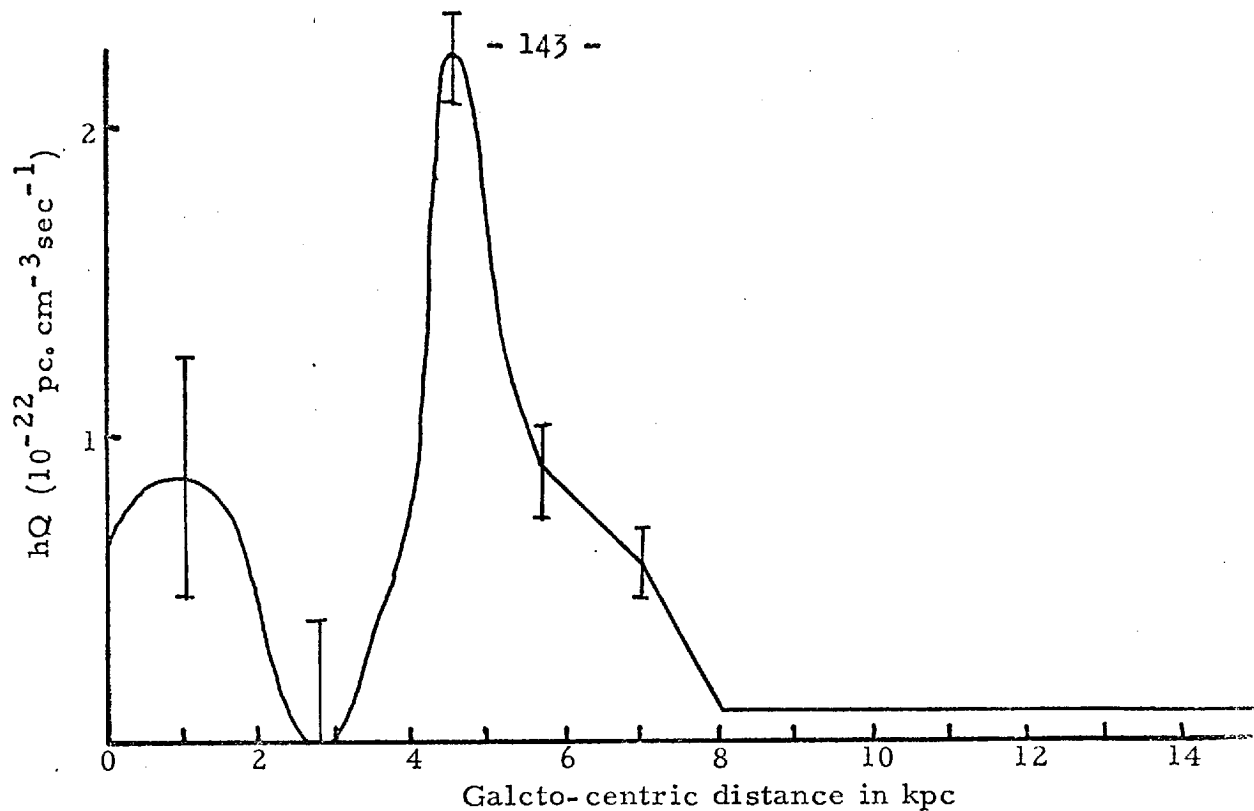


Figure 6.2a

The variation of hQ (gamma-ray production rate times the half width of the gas disc) with galacto-centric distance

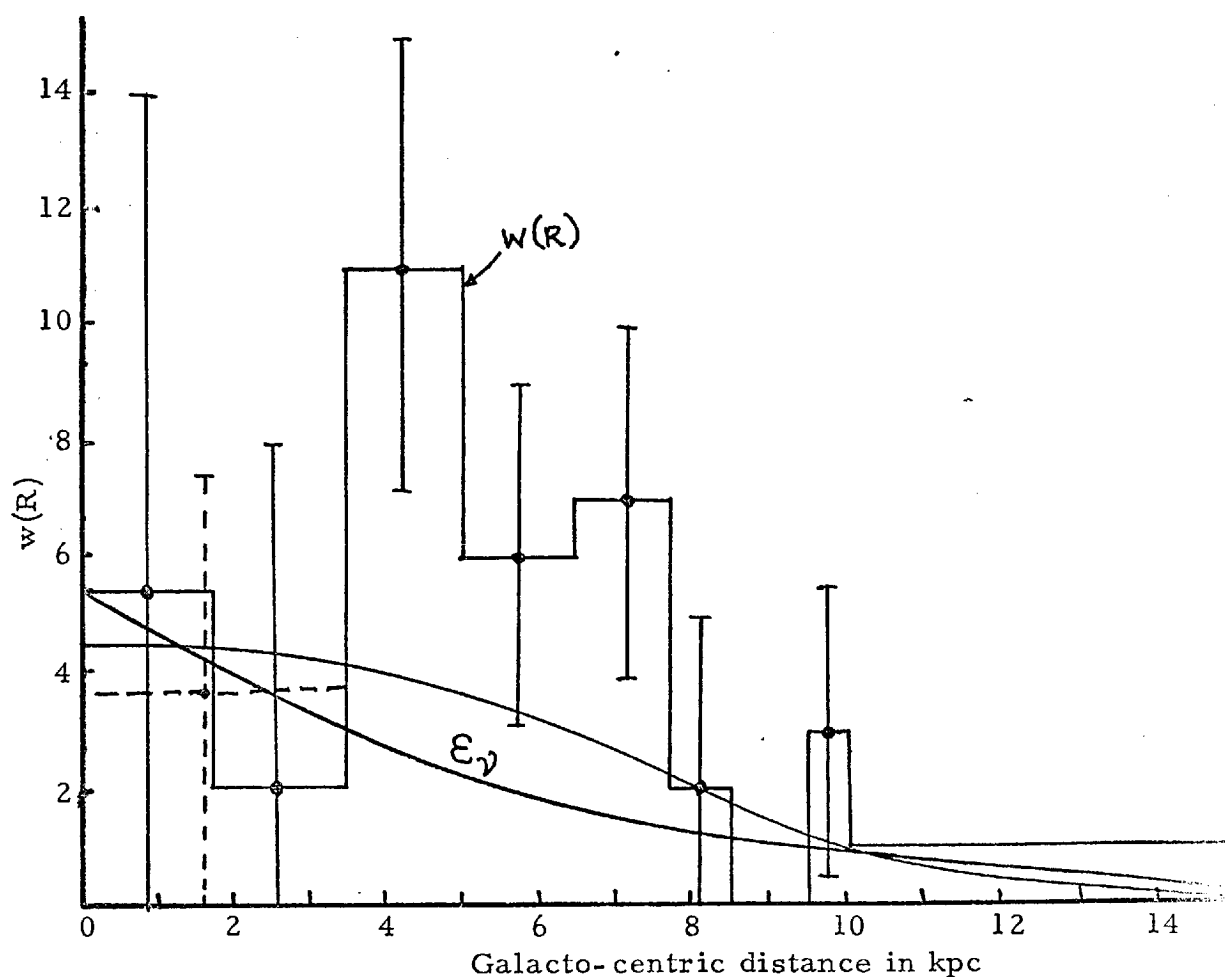


Figure 6.2b

The distribution of relative gamma-ray emissivity $w(R)$ in the Galaxy. Also shown are the distributions of radio emissivity derived by Ilovaisky and Lequeux(1972) and Price (1974)

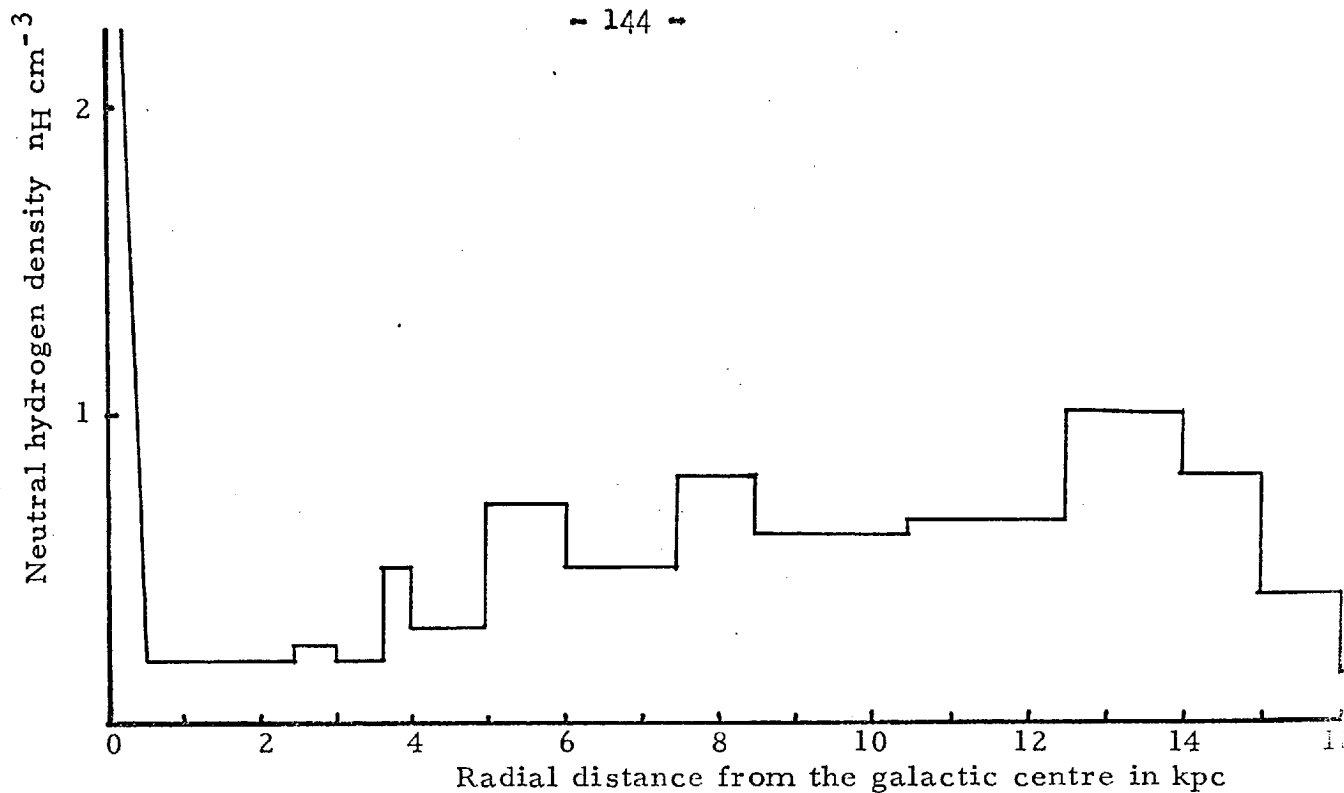


Figure 6.3a

The neutral hydrogen density as a function of galacto-centric distance (Stecker, 1974)

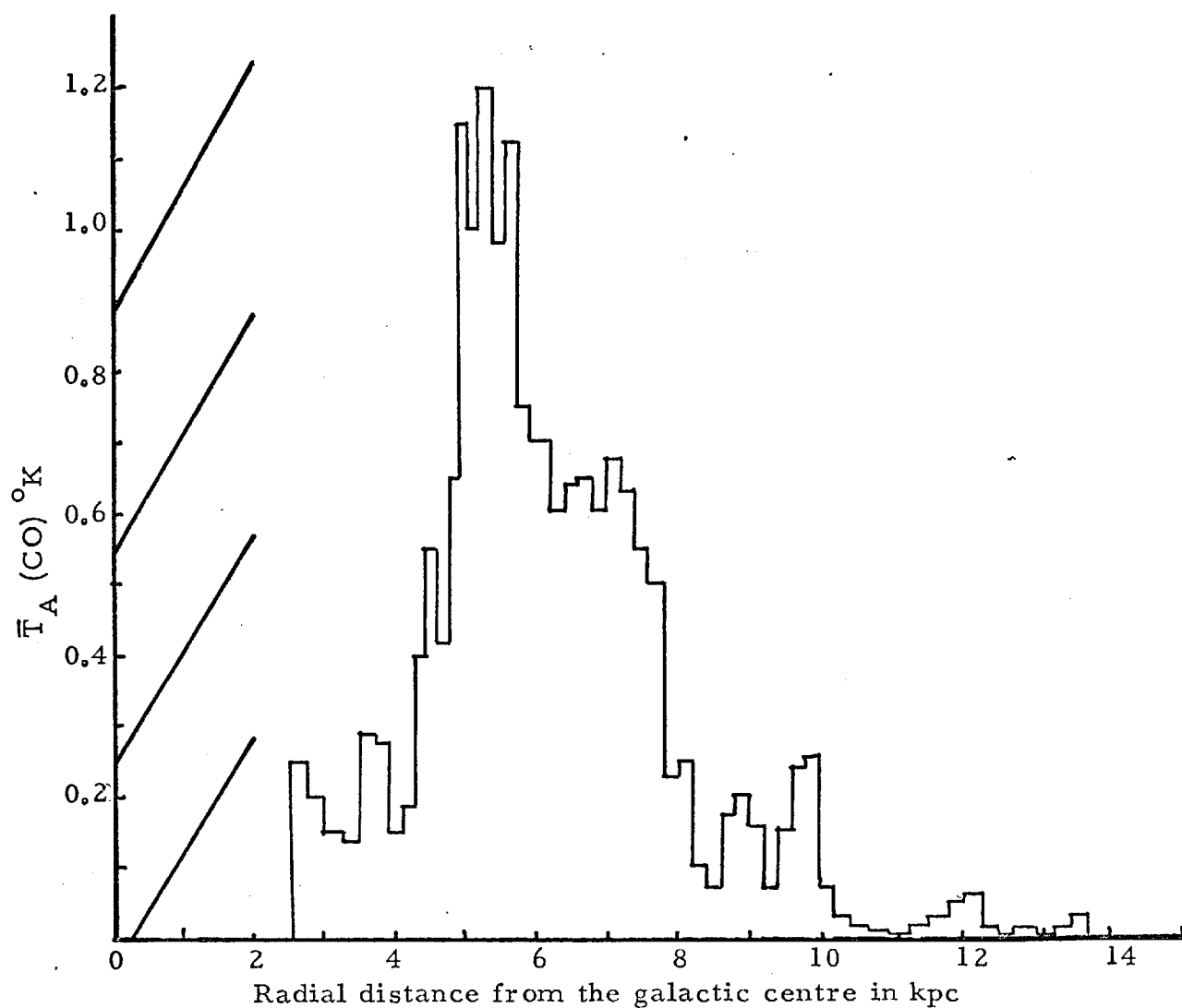


Figure 6.3b

The distribution of CO line emission as a function of galactocentric distance in kpc. The Galactic centre region has not been included.

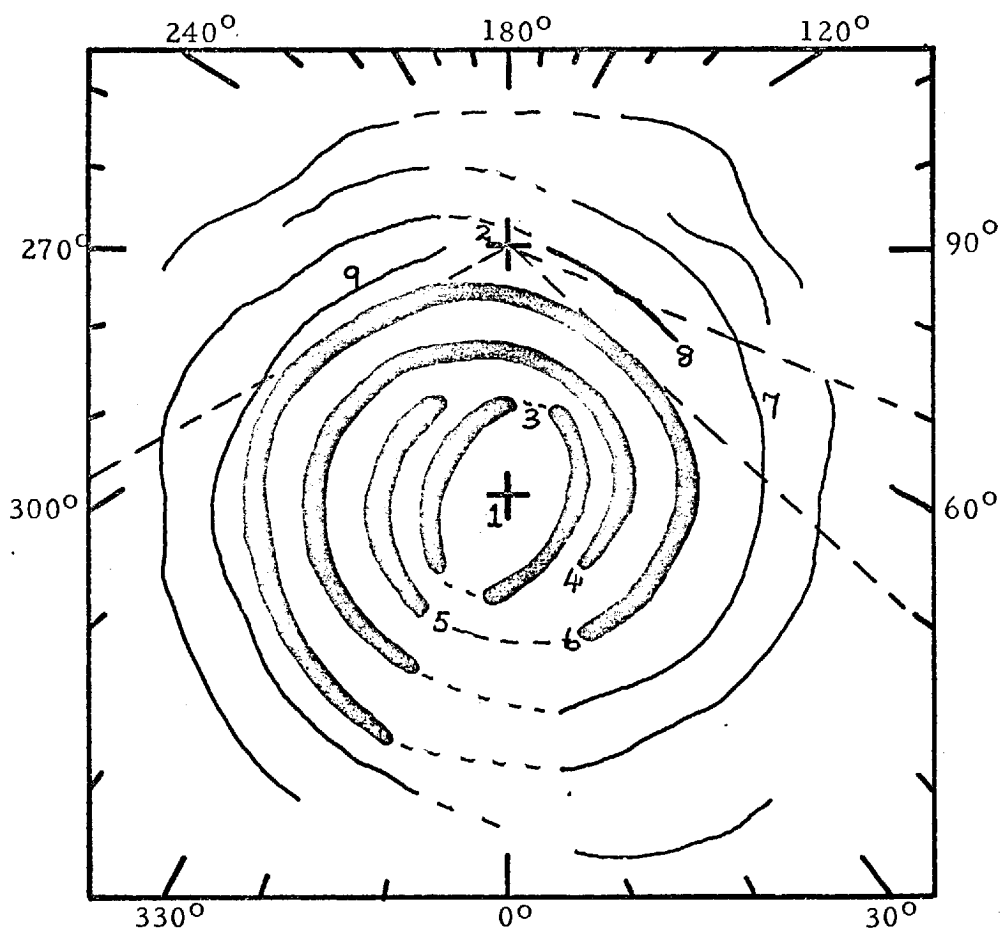


Figure 6.4

A smoothed spatial diagram of the location of the maxima of the matter density deduced from the 21 cm neutral hydrogen line measurements and the density wave theory by Simonson (1974)

The spiral arm features are as follows:

- 1 the Galactic centre
- 2 the Sun
- 3 the 4-kpc ring
- 4 the Scutum arm
- 5 the Norma arm
- 6 the Sagittarius arm
- 7 the Perseus arm
- 8 the Orion arm
- 9 the Carina arm

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