

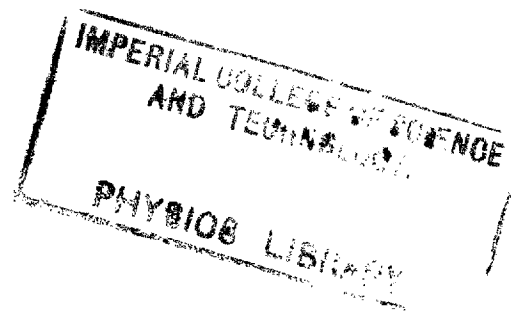


COSMIC RAY INTENSITY VARIATIONS
IN SOLAR AND SIDEREAL TIME

by

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Dissertation submitted for the degree
of D.I.C. in the Imperial College
of Science and Technology



September 1972

ABSTRACT

In this thesis underground and surface level observations of cosmic ray intensity variations are reported. Following a brief introduction the work is discussed in three sections.

The first part contains underground results relating to sidereal variations and their interpretations. Data from 1960 to 1971 has revealed a small sidereal variation of amplitude 0.009 ± 0.004 % at ~ 18.00 hrs L.Sid.T.. Modulation of the solar daily variation vector is shown to be inadequate to explain the sidereal observations. Instead trajectory calculations in a model interplanetary field are used to show that this sidereal variation is best explained in terms of solar motion. The implications of the high degree of isotropy obtained in this series of measurements are discussed.

The second section of this thesis relates primarily to surface level observations of the solar daily variation. Surface level data from 1965 - 1970 is used, in conjunction with underground data on the solar daily variation, to study long term changes in the solar vector during the solar cycle of activity. The changes are found to be best explained as due to a variation in the upper limiting rigidity of corotation. Surface level meson data and HEOS-A1 interplanetary field data are used together to study day to day variations in the diurnal vector.

The third part of this thesis describes the development of a new detector to be used in a future underground experiment. In the development of this detector an attempt has been made to produce a cheaper but more efficient detector than those presently in use so that more telescopes at a greater depth can be employed.

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ACKNOWLEDGEMENTS

Many members of the Cosmic Ray and Space Physics group of Imperial College have helped in the past three years, however, space allows me only to mention those, without whom, the production of this thesis would have been considerably more arduous, if possible at all.

For help with the physics, I am indebted to Professor H. Elliot under whose guidance and supervision this work has been carried out. For practical assistance and many helpful discussions I am sincerely grateful to Dr. T. Thambyahpillai and Mr. T. Miyazaki.

In the producing of this thesis, I am grateful for Sue Baker's help in typing. The financial support of the Science Research Council has been gratefully received.

For help which is difficult to classify I thank my parents and wife. Their encouragement and support was never-ending.

CHAPTER 1

INTRODUCTION

1.1 General introduction

Originally studied as an isolated phenomenon, cosmic rays are now part of high energy astrophysics and the information they transport is used to relate radio, optical, X-ray and γ -ray observations. Their relevance in high energy astrophysics lies in the fact that the cosmic ray energy density is comparable to that of the galactic magnetic field. Being comparable to the galactic magnetic field energy density probably implies that the cosmic ray energy density has a significant role in determining the behaviour of the interstellar gas.

Time variations of cosmic ray intensity cannot be studied independently of the many aspects of cosmic rays and to draw astrophysical conclusions from the results, estimates of the charge composition and energy spectrum must be used. Furthermore, the present theories for the origins of cosmic rays present limitations upon the time variations to be expected. In the following sections, the currently accepted ideas on the charge composition, energy spectrum, and age of the primary beam are given along with a brief discussion of the possible origins of the radiation. Relevant details of the apparatus used for monitoring the cosmic ray intensity and the analytical methods used to obtain anisotropy vectors are given in sections 1.2 and 1.3.

1.1.1 Chemical composition of the cosmic ray nuclei

Cosmic rays are the nuclei of different species of atom stripped of their electrons. Protons dominate the primary beam, contributing almost 90%; Helium nuclei (α -particles) contribute another 9% and the remaining 1% are heavier nuclei. A wealth of literature exists on the charge compo-

sition of the cosmic ray primary beam which is best presented in Fig. 1.1. This compares the cosmic ray charge distribution with the universal distribution of the elements. Although the general trends in both distributions are similar, important differences occur:-

- 1) Hydrogen and Helium have much lower relative abundances in cosmic rays.
- 2) Li, Be, and B which are comparatively rare on Earth have a much higher abundance in cosmic rays. It is now realized that these elements are produced by transmutation of the higher Z nuclei during their passage through interstellar space. By using an estimate for the density of interstellar matter and the increased abundance of Li, Be, and B an estimate of cosmic ray lifetime can be made. (See section 1.1.3.)
- 3) The very high Z nuclei are greatly enhanced in cosmic rays and as such provide limitations to the proposed origins of these particles. Sources rich in high Z nuclei immediately become favourite candidates.

About 1% of the cosmic ray particles are not nuclei, but electrons and their positively charged complement, positrons. The observed predominance of electrons argues that they come from the same sources as the nuclei. If they had a secondary origin in the collisions between the nuclei of the cosmic rays and those of the interstellar gas, the ultimate debris from the collisions would contain a greater proportion of positrons than electrons. It remains a fair assumption, of course, that the positrons in the primary beam (and a corresponding minority of the electrons) are generated by nuclear reactions in the travels of the cosmic rays.

1.1.2 Energy spectrum of cosmic ray nuclei

The energy spectrum for the nuclear component of the primary cosmic ray beam is given in Fig. 1.2. The spectrum extends smoothly from about

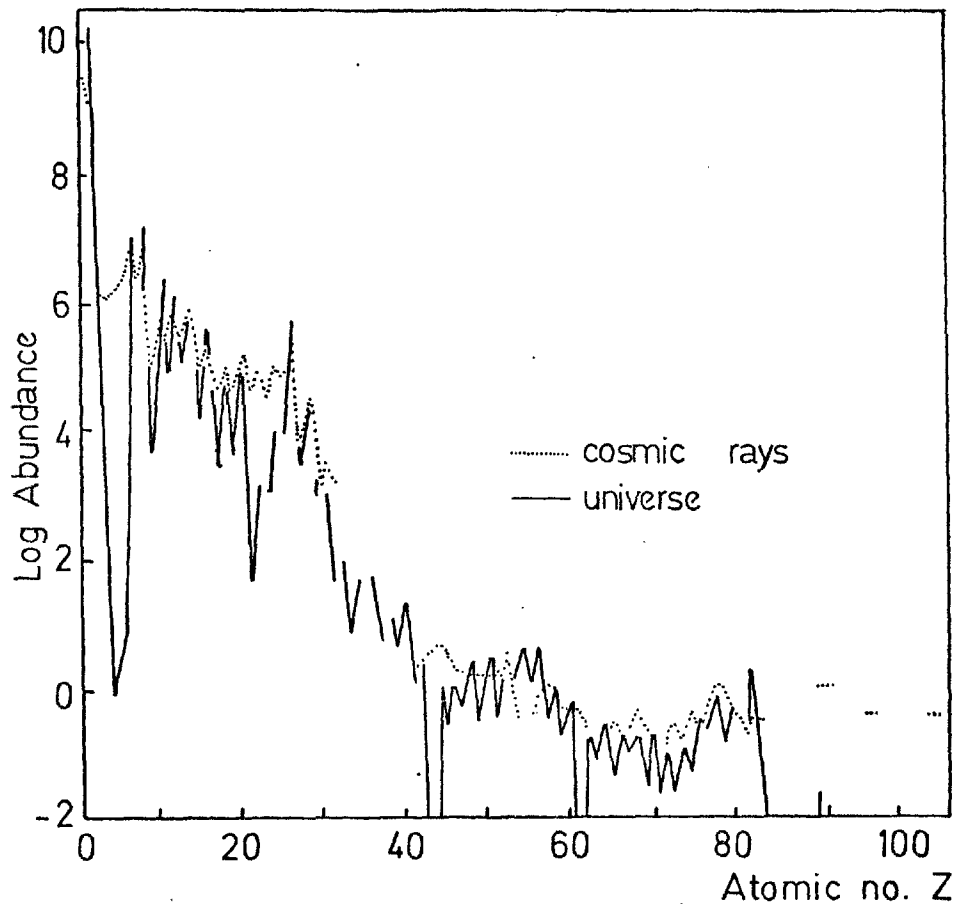


Fig. 1.1 Charge distribution of cosmic ray nuclei.

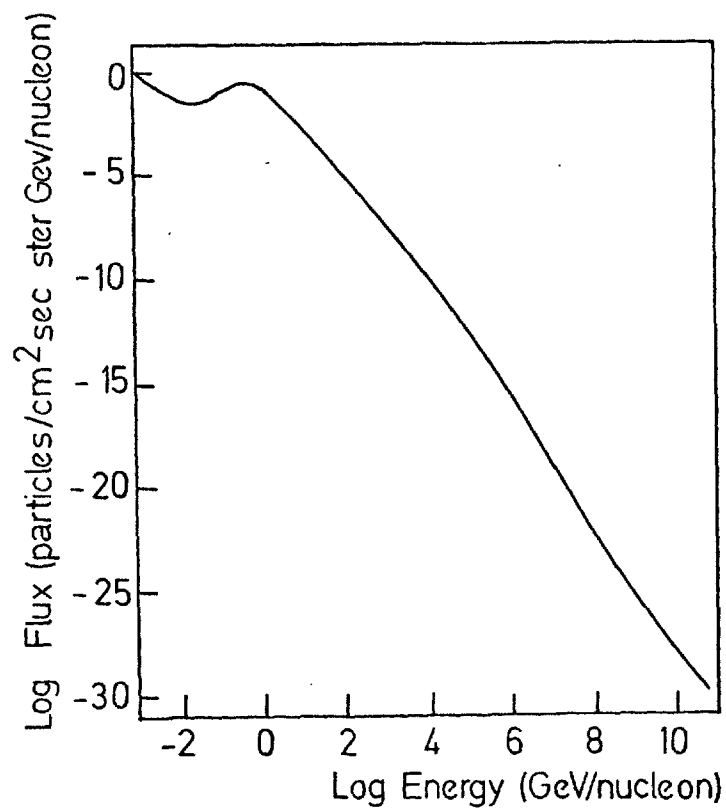


Fig. 1.2 Energy spectrum of cosmic ray nuclei.

10 MeV to 10^{20} eV and over most of this range it can be represented by a simple power law;

$$\frac{dI_R(E)}{dE} = A_R E^\gamma \quad (1.1)$$

where $I(E)$ is the intensity of particles per cm^2 -sterad-sec, E is the energy and A_R and γ are constants.

A_R determines the different absolute intensities of the various chemical components of the primary beam. The slope of the spectrum, γ , is not independent of energy but takes the value -2.6 for $10^{10} < E < 10^{15}$ eV, -3.2 for $10^{16} < E < 10^{18}$ eV and -2.6 for $E > 10^{18}$ eV. These irregularities in the slope may reflect a number of different mechanisms of generation, in particular the break at 10^{18} eV since this is the energy above which the galactic field cannot contain cosmic rays within the galaxy.

Below 10 GeV the power law relation breaks down and the spectrum peaks about 1 GeV or less. This peak is interpreted as being due to solar modulation and its position varies throughout the cycle of solar activity. The low energy end of the spectrum (~ 10 MeV) is dominated by energetic solar particles and, at times of solar flares, the sun can generate particles of up to 10 or 20 GeV. Clearly below 10 GeV this spectrum is not representative of that external to the solar cavity because of the solar modulation. However, above 50 or 100 GeV this spectrum can be regarded as the true galactic spectrum.

In the range of energies producing most of muons observed by the surface level and underground detectors (10 to 1000 GeV) the differential spectrum is well described by a simple power law with an exponent $\gamma = -2.6$.

1.1.3 Age of cosmic rays

In any of the theories for the origin of cosmic radiation estimates of the age of cosmic rays play an important role. Having been ejected from their source a variety of "forces" can act upon the general flux until

the cosmic rays arrive at their point of detection on the Earth. One important mechanism that can affect the cosmic ray composition is fragmentation of heavy ions into lighter ions in nuclear interactions with the interstellar hydrogen. The simplest propagation model is to assume that all nuclear species from the source region traverse the same amount of matter. Thus the anomalously high Li, Be, B percentage is naturally explained as secondary nuclei produced by fragmentation of the heavy nuclei having traversed $3 - 5 \text{ grm} \cdot \text{cm}^{-2}$. Assuming an interstellar hydrogen density of one proton/cc gives a cosmic ray lifetime of $\sim 3 \times 10^6$ years. This estimate of the cosmic ray lifetime is critically dependent upon the density assumed for the interstellar hydrogen. Ginzburg and Syrovatskii (1964) proposed that the galactic disc was contained within a spherical halo of tenuous gas and if cosmic rays could wander throughout the halo, the density being much less, the cosmic ray lifetime could be much longer $\sim 10^8$ years. However, polarization of distant starlight and Zeeman splitting of the 21 cm line have been used to determine the galactic magnetic field and in the measured field of $\sim 10^{-6}$ oe the vast majority of cosmic rays are confined well within the galactic disc. Therefore, it is interactions with the one proton/cc density that produces the distinctive charge distribution of the primary beam. Radioactive tracers have also been used to determine cosmic ray ages but inadequate statistics make the results inconclusive. All such methods do not contradict the result,

$$\text{Cosmic ray lifetime} = \tau_{\text{CR}} \approx 3 \times 10^6 \text{ years}$$

1.1.4 The origins of cosmic radiation

The present theories for the origins of cosmic rays fall into two broad categories, universal or galactic distribution of the radiation. Universal distribution of cosmic radiation is an attractive proposal because of the ease with which it can explain the measured high degree of isotropy. However, this proposal has been regarded as improbable due to the vast

amounts of energy it requires in the form of cosmic radiation, although recently some of the impact of this argument has been removed as pointed out by Setti and Woltzer (1971). A variant on the proposal of universal distribution was suggested by Scianna (1964). He supposed that cosmic radiation was confined to the local group or cluster of galaxies and although this could surmount energetic arguments the mechanism for containment could not be explained. The universal distribution of cosmic radiation has another problem when the primary electron component is considered. Due to the background 3°K radiation intergalactic space is opaque to relativistic electrons and hence, although the primary nuclei might be universal, the primary electrons cannot be. Certainly one part of the cosmic ray beam is extragalactic, that is those cosmic rays of energy $>10^{17}$ eV. To contain these particles within the galaxy would require a galactic magnetic field stronger than that deduced from other observations. Ginzburg and Syrovatskii (1964) suggest that the observed flux is essentially a galactic phenomenon and that the intergalactic flux is very small. Their theory represents a steady state where cosmic rays that slowly diffuse out of the galaxy are replaced by new ones produced in a set of discrete sources within the galaxy. Another proposal for the galactic origin of cosmic radiation is the "big-bang" theory. However, this model cannot supply long enough lifetimes for the observed high Z (~ 80) nuclei and again difficulty is encountered with the primary electron component. The major objection to the galactic origin of cosmic rays is the difficulty it has in explaining the high degree of isotropy. The galactic magnetic field means that cosmic rays are essentially confined to the disc and can only get out of the galaxy by travelling along the spiral arms. The isotropy implies low streaming velocities (<20 km/sec) and with a lifetime of $\sim 10^6$ years as deduced from the abundance of Li, Be, B, cosmic rays cannot reach the periphery of the galaxy. A possible solution to this problem has been given by Lingenfelter et al. (1971) by considering compound diffusion of cosmic rays.

However, Allan (1972) criticizes this result on the grounds that it applies to a very large effective detecting area which is not the case with observations made over a few years. The discrete sources that have been proposed to supply the cosmic rays for the galactic theory have been supernovae explosions, pulsars and more recently white dwarf stars. All have their advantages and disadvantages and possibly a summation of all three over their life histories as cosmic ray sources provides the best solution.

The implications of the results presented in this thesis upon these various theories are considered in greater detail in Chapter 2.

Clearly no firm conclusion has been reached as to how much of the cosmic ray flux at the Earth arises from sources inside our own galaxy and how much is of extra-galactic origin. Probably the most popular view is that most cosmic rays, with the exception of those of energy $\geq 10^{18}$ eV, are produced within our own galaxy in discrete sources such as supernovae explosions, pulsar relics or white dwarf stars. Subsequent motion within the galaxy for $\sim 10^6$ years renders the cosmic rays isotropic due to the galactic magnetic field believed to be of a few microgauss.

As indicated in Section 1.1.4 a study of the sidereal anisotropy can in theory make it possible to decide which of the two origin theories is most tenable. On the galactic theory the escape time from the galaxy and the source distribution govern the degree of isotropy; in general, the longer the cosmic ray lifetime, the higher the degree of isotropy. Independent estimates of cosmic ray lifetimes as given in Section 1.1.3 provide a test, therefore, for the internal consistency of the galactic origin theory. However, before inferring a particular isotropy from the observed data it is essential that this data be corrected in every sense. An essential correction of sidereal data, hitherto ignored, is the correction required to put the measured anisotropy into the frame of reference of the galaxy. The frame of reference in which the measurements are made has a velocity of

~ 20 km/sec relative to the galactic frame and the effect of this upon the observed data depends critically on the extent to which the particle trajectories are affected by the interplanetary magnetic field. At low energies, where the Larmor radii in the interplanetary field are small compared with 1 AU, any anisotropy existing in interstellar space is completely washed out by the local field. At higher energies where the Larmor radius is appreciably greater than 1 AU the interplanetary scattering can certainly be ignored but in this case the fraction of the total cosmic ray energy flux to which the measurements apply may be quite small because of the steepness of the intensity/rigidity spectrum. Primary cosmic rays with rigidity greater than 10^{11} V carry $\sim 10\%$ of the total energy flux and thus measurements in this region of the spectrum can be regarded as reasonably representative provided they are not invalidated by scattering in the interplanetary field. Trajectory integrations are used in this thesis to show that a genuine galactic anisotropy will not be obscured at these energies.

Primary cosmic rays with rigidity less than 10^{11} V provide measurements of the solar daily variation. Such measurements are useful for studying the changing conditions of the interplanetary plasma-field and these are presented and discussed in detail in Chapter 3.

1.2 The apparatus - introduction

The apparatus used in the present investigation has been described in detail elsewhere (Peacock (1967), Hashim (1968)) and only details relevant to the following work will be discussed.

The detectors used for monitoring the muon intensity were two-fold coincidence telescopes using one inch thick slabs of plastic scintillator arranged in cubical and semi-cubical geometry and viewed by 5 inch photomultipliers. The underground units were installed in a laboratory at the Holborn station of the London Transport Executive and each had a detecting

area of 1.44 m^2 . The surface level telescopes have a detecting area of 0.81 m^2 each and have been installed on the top floor of the Physics Department, Imperial College, London. Each telescope uses 1" NE102A plastic phosphor and E.M.I. S11 cathode, photomultipliers, type 9168B. The electronics and E.H.T. supplies are temperature and mains voltage stabilized and all the telescopes have given reliable operation over the entire period from 1961 to 1971. All the telescopes have a resolving time of about 70 n secs.

On the surface North and South, 45° inclined, telescopes have been operational from 1965 (August) up to the present (August, 1972) and underground vertical telescopes have operated from 1961 to 1971. From 1965 to 1969 45° inclined telescopes pointing in the North and East directions were installed in the underground laboratory; these were followed by South pointing telescopes inclined at 15° to the zenith which ran from 1969 to 1971. The total count rates over different periods are given in Table 1.1.

Direction	Period of Operation	Count Rate/hr	No. of Telescopes	Location
Vertical	Nov. 60 to Oct. 62	50,000	2	Under-ground
"	April 63 to July 64	150,000	6	
"	Oct. 64 to -	50,000	2	
North (45°)	Oct. 64 to Sept. 69	35,000	2	
East (45°)	Oct. 64 to Sept. 69	35,000	2	
South (15°)	Oct. 69 to April 72	105,000	6	Surface
North (45°)	Aug. 65 to -	90,000	1	
South (45°)	Aug. - 65 to -	90,000	1	

TABLE 1.1 - Telescopes supplying data used in this thesis.

The information relating to the detectors necessary for a knowledgeable

assessment of the data from each telescope is:-

- (a) The directional sensitivity
- (b) The differential or integral response function
- (c) The asymptotic directions of viewing outside the magnetosphere.

1.2.1 Directional sensitivity

The sensitivity of a telescope in a particular direction is given by the product of the secondary intensity and the effective detecting area in that direction. Taking the secondary intensity to decrease as $\cos^2 \lambda$ with zenith angle λ , underground and at surface level (George (1952)), the directional sensitivity patterns for the telescopes used in this thesis have been calculated and are given in Fig. 1.3. The vertical semi-cubic telescopes have a large "cone of acceptance" with an opening angle of $\pm 35^\circ$. Inclined telescopes give much better directional sensitivity. The 45° inclined detectors have an opening angle of $\pm 15^\circ$ at half maximum sensitivity with an effective telescope axis at 35° to the zenith. Knowing the effective axis of the telescope the asymptotic directions of viewing can be found and the response functions calculated.

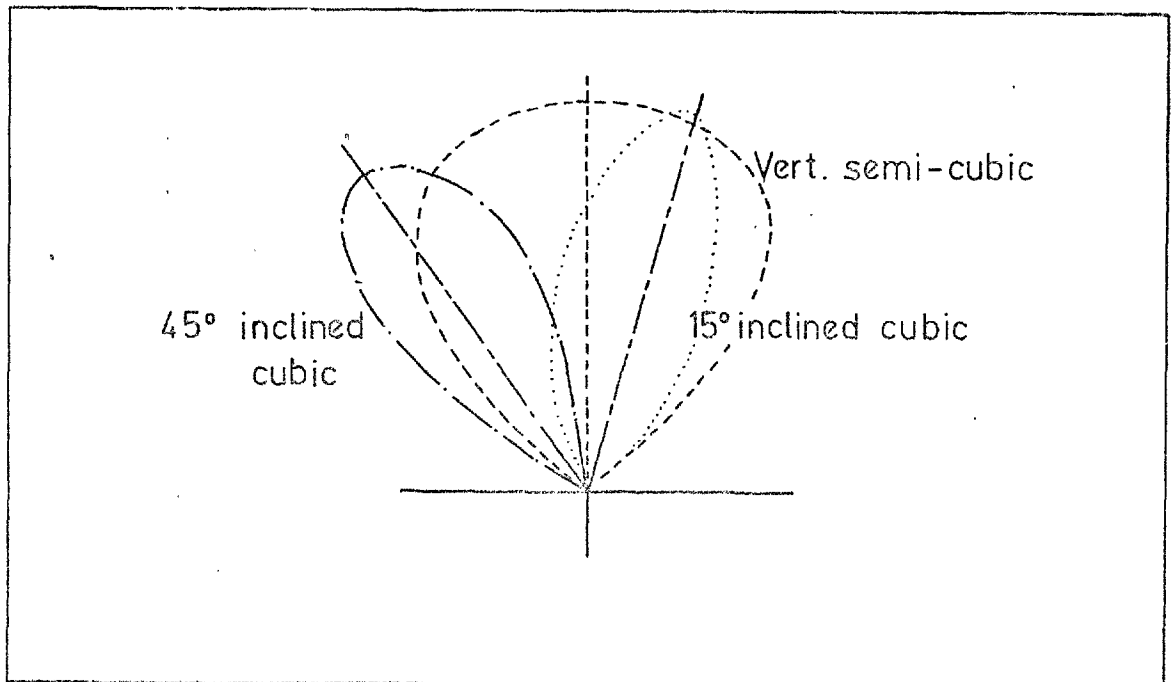


Fig. 1.3 Directional sensitivity patterns for the telescopes used in this thesis.

1.2.2 Response functions

Fig. 1.4 shows the integral response functions applicable to the inclined surface level and vertical underground telescopes. The integral response function gives the percentage of the total count rate due to primaries of a given rigidity or less and in the present application the integral response function is easier and quicker to use than the differential response function. Throughout this thesis, when considering rigidity dependent effects, rigidity ranges are selected and the mean rigidity of the range is used to investigate the effect under consideration. The percentage of the count rate due to that rigidity range can then be used to weight the individual results to enable a weighted mean value to be found for the detector for that effect.

Neutron monitor and surface level meson telescope response functions can be found experimentally by studying the variation of count rate with cut-off rigidity. This is done by a latitude survey, using a mobile detector, where cut-off rigidities range from <1 up to ~ 15 GV (Lockwood and Webber (1967) and others). Above ~ 15 GV (the maximum cut-off rigidity) an extrapolation is used to extend the response function to the full range of the detector. A response function for surface level detectors derived by Krinsky et al. (1965) is used for the North/South inclined telescopes throughout this thesis.

Underground response functions are a point of controversy. Two approaches can be made to derive them and these are discussed below. Firstly, empirical attempts to derive coupling coefficients have been made by Dorman (1967), Mathews (1962), Ahluwalia and Ericksen (1971) and others. These are essentially based on Dorman's (1957) suggestions that the coupling function for underground meson telescopes may be obtained from those applicable to sea-level meson telescopes after suitable scaling and renormalization. The scaling factor being derived from the amount of absorber above the detector.

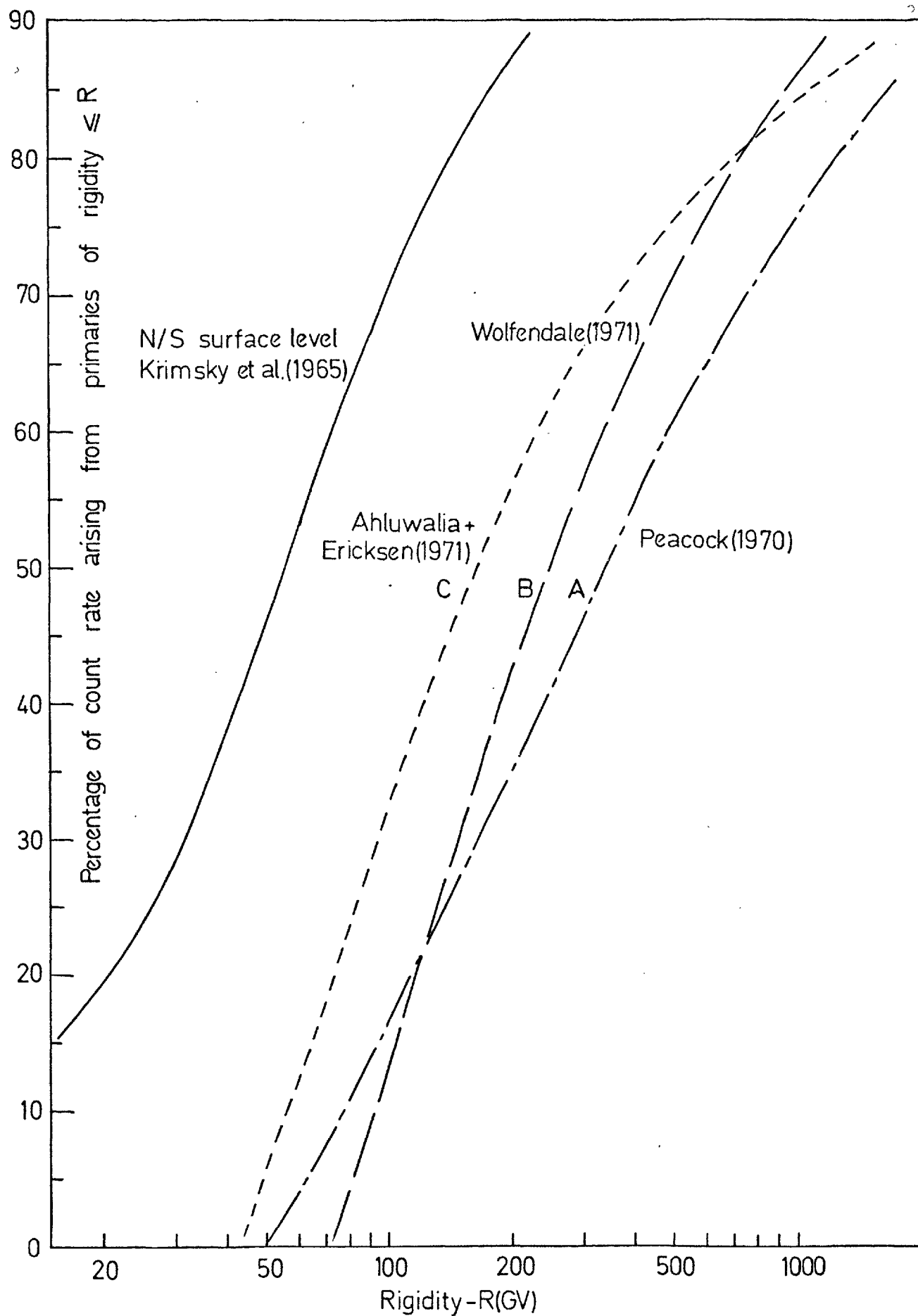


Fig. 1.4 Response functions for muon detectors on the surface and at a depth of 60 m.w.e.

Alternatively, coupling functions may be calculated on purely theoretical grounds (Fenton (1963), Peacock (1970), Wolfendale (1971) private communication). These methods require the use of a theoretical model of high energy nuclear interactions to extend the presently available experimental knowledge above 70 GeV. Knowing from the model the pion multiplicity over the full range of the detector and the integral primary spectrum, a theoretical estimate of the detectors response to a given energy primary can be made. Fenton (1963) used Fermi's model for the nucleon-nucleon collision in the extreme relativistic case. Peacock (1970) derived a response function for a depth of 60m.w.e. by using the Trilling formula to represent the pion multiplicity as a function of energy and a primary integral energy spectrum of the form $E_p^{-1.67}$. At high energies the Trilling formula asymptotically approaches a pion multiplicity which is proportional to $E_p^{\frac{1}{2}}$. Wolfendale (1971) has derived a response function applicable to 60 m.w.e. which is based on an integral energy spectrum of the form $E_p^{-1.5}$, a pion multiplicity given by $M = 0.8 E_p^{\frac{1}{2}}$ (E_p in GeV) and the CKP model of high energy interactions.

Plotted in Fig. 1.4 are three response curves that have been derived for meson telescopes at 60 m.w.e.. Each curve has been adjusted to take into account the primaries with $Z/A = \frac{1}{2}$ so that the response function can be plotted as a function of magnetic rigidity rather than the energy since it is the rigidity which governs the particle motion in the interplanetary field. Curve C was derived by Ahluwalia and Ericksen (1971) using the empirical method originally suggested by Dorman (1957). Curve A has been obtained using the same primary spectrum as Peacock but under the assumption that the Trilling formula applies at all energies whereas Peacock neglected all secondary production at $E_p > 2 \times 10^{12}$ eV. Curve B was obtained by Wolfendale (1971).

The assumptions made by Ahluwalia and Ericksen (1971) to derive the threshold energy of a detector leads them to the conclusion that up to a

primary energy of 400 GeV, the fastest daughter muon carries away 50% of the primary cosmic ray nucleon energy. This gives a low estimate of the threshold energy and due to the over estimate of the secondary muon energy, consequently adds too much weight to the low energy end of the response function. The choice between the various response functions is a little arbitrary. However, that derived by Ahluwalia and Ericksen (1971) would over accentuate the low energy end of the energy spectrum and that due to Peacock the high energy end. A compromise is found in the response function of Wolfendale and therefore this response has been chosen to best represent that relating to the Holborn detectors. It is shown that few, if any, of the conclusions drawn would be altered radically by using another response function.

1.2.3 Asymptotic directions of viewing

Fig. 1.5 contains the asymptotic directions of viewing, external to the magnetosphere, applicable to the underground and surface level detectors. These have been taken from two sources; model experiments by Brunberg and Dattner (1953) and digital computer trajectory integrations by McCracken et al. (1962).

Model experiments can only produce dipole field approximations to the geomagnetic field. Trajectory integrations use spherical polar, sixth harmonic representations of the field and consequently produce more accurate results. However, above ~ 30 GV the difference between the asymptotic directions obtained in these two ways become very small and in view of the other experimental errors it can be ignored. Therefore, for Holborn where the amount of response is negligible below ~ 50 GV, asymptotic directions obtained from model experiments are adequate. On the other hand, surface level meson telescopes have a large proportion of their response below 10 GV and here computer integrations of trajectories give more accurate results.

The plotted asymptotic directions of viewing are those that correspond to the "effective axis" of the telescope as given by the directional sensi-

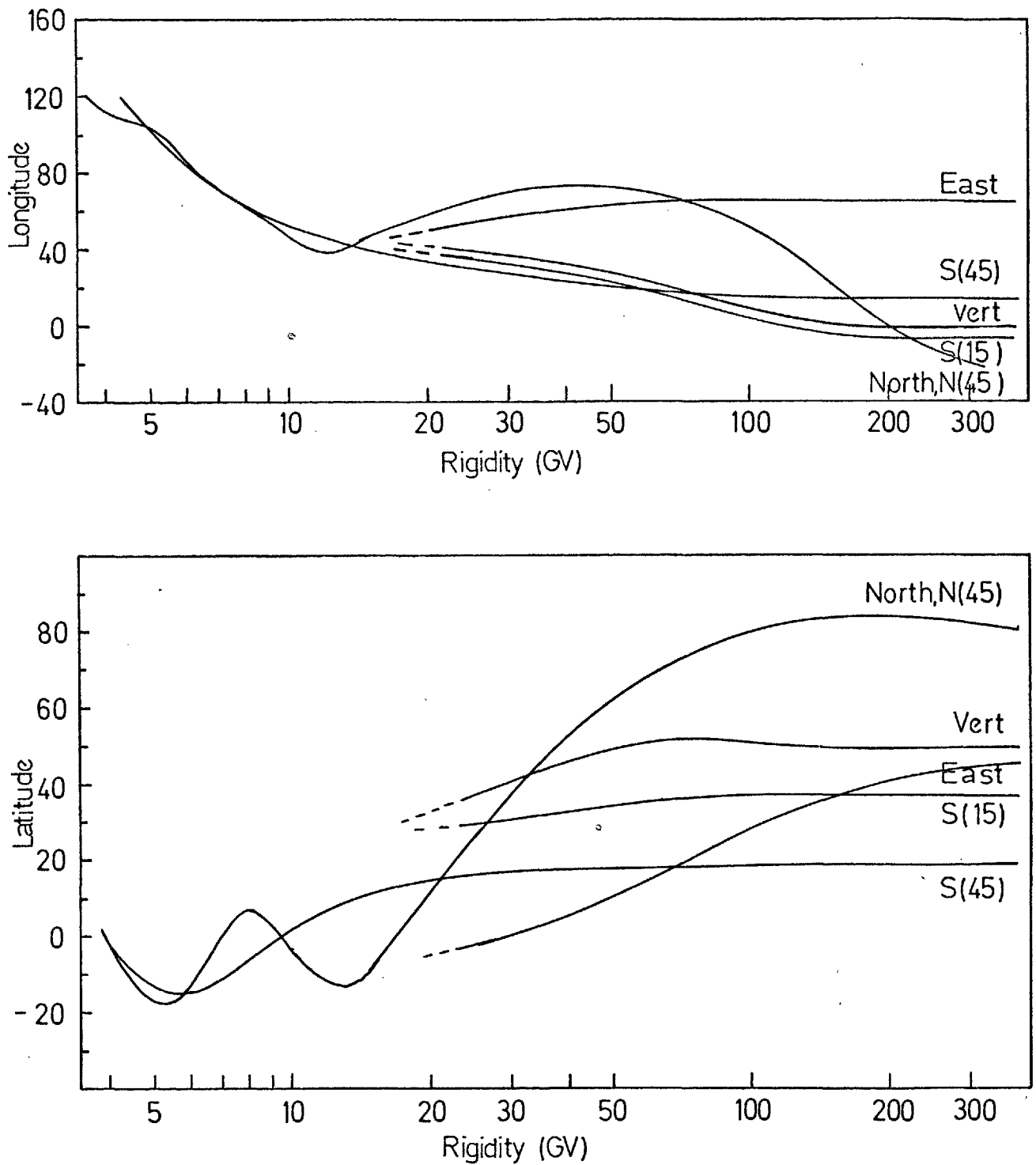


Fig. 1.5 Asymptotic latitude and longitude of viewing outside the magnetosphere for the telescopes supplying data used in this thesis. Longitude is measured eastwards from the recording station.

tivity patterns (Section 1.2.1) with the telescope located in London. Those labelled North, South (15°), Vert and East have been taken from the appropriate Brunberg and Dattner diagram and relate to the Holborn installation and those marked N(45) and S(45) are results from trajectory integrations by McCracken et al. (1962) and are to be used in interpreting the surface level data.

Using the results presented in Figs. 1.4 and 1.5, the effect of any anisotropy external to the magnetosphere upon the count rate of either the underground or surface level detectors can be found. The fractional change in counting rate $\Delta N/N$ arising from an anisotropy, A , can be expressed as,

$$\frac{\Delta N}{N} = A \int_{R_1}^{R_u} W(R) R^m F(\lambda) dR \quad (1.2)$$

where $W(R)$ represents the coupling coefficient or response function, R^m is the assumed variational spectrum of the anisotropy, R_1 and R_u are the lower and upper rigidity limits of the anisotropy and $F(\lambda)$ represents the latitude dependence of the anisotropy. Using this expression the expected variations for the solar daily variation are derived for the underground and surface level detectors (see Chapter 3), where $F(\lambda) = \cos \lambda$ and λ is the asymptotic latitude out of the ecliptic plane. In this case it is implied that the solar diurnal anisotropy has its axis in the ecliptic plane. For a vertical telescope at a mid-latitude station, this and associated effects, produce considerable geomagnetic smoothing of the anisotropy amplitude. For an anisotropy with its axis aligned with the effective axis of the telescope, geomagnetic smoothing will be reduced and, particularly at high mean rigidities, as in the case of the underground telescopes, any geomagnetic smoothing becomes negligible.

1.3 Analytical methods of data handling

1.3.1 Data reduction and harmonic analysis

For all the telescopes bi-hourly, scaled count rates have been pressure corrected using the barometer coefficients as given in Chapters 2 and 3 for the underground and the surface level data respectively. The data could not be temperature corrected due to lack of aerological data but an allowance for this will be considered more fully later. Non-cyclic variations, mainly due to ageing of the photomultipliers in the detector, are of the order of 0.5%/year and hence no correction has been applied for them. Only days of at least 20 hrs data have been used and any missing data has been interpolated. Furthermore, any day showing large anomalous departures from the mean have been removed from the analysis. Monthly mean departures of the bi-hourly values from the mean have been found and harmonically analysed according to the scheme of Chapman and Bartels (1940). Harmonic analysis produces the coefficients a_n , b_n in the equation representing the observed intensity;

$$I(t) = I_0 + \sum_{n=1}^{\infty} (a_n \cos(nt) + b_n \sin(nt)) \quad (1.3)$$

where $n = 1$ gives the first harmonic, $n = 2$ the second and so on. The clearest presentation of results in this form is obtained by using a harmonic dial where (a_n, b_n) are the co-ordinates of the end point of the vector representing the wave both in phase and amplitude. This type of representation has been used throughout this thesis.

1.3.2 Errors on the harmonic coefficients

Genuine day to day variations in the diurnal and semi-diurnal vectors cause the scatter of the results to be considerably greater than that due solely to counting rate statistics. In order to get a true estimation of errors in the daily variation the method of the "cloud of points" (Dorman

(1957), Chapman and Bartels (1940)) has been used. In Fig. 1.6 harmonic coefficients for 1970 from the North telescope, on a day to day basis, have been plotted along with the ellipse of probable error. This ellipse is typical of all those derived from the data to be considered. It can be seen that it is not very eccentric which implies the correlation between the a's and b's is small. This further implies that the standard deviations of the a_n 's and b_n 's can be used to obtain an approximate value for the two-dimensional standard deviation,

$$\sigma_{2-D} = \sqrt{\sigma_a^2 + \sigma_b^2}$$

where σ = standard deviation.

An analysis of this form by Dutt (1965) and Peacock (1967) has shown that for the underground data with a count rate of ~35,000 to 50,000 per hr the error on an annual mean vector is $\pm 0.013\%$. Subsequent analysis has confirmed this result, and hence the value of $\pm 0.013\%$ will be used throughout this thesis for the error on the underground data. However, the North/South surface level data is more variable, hence the error has been calculated by the above method for each period considered. Errors on the Deep-River data (Chapter 3) have also been estimated in this manner.

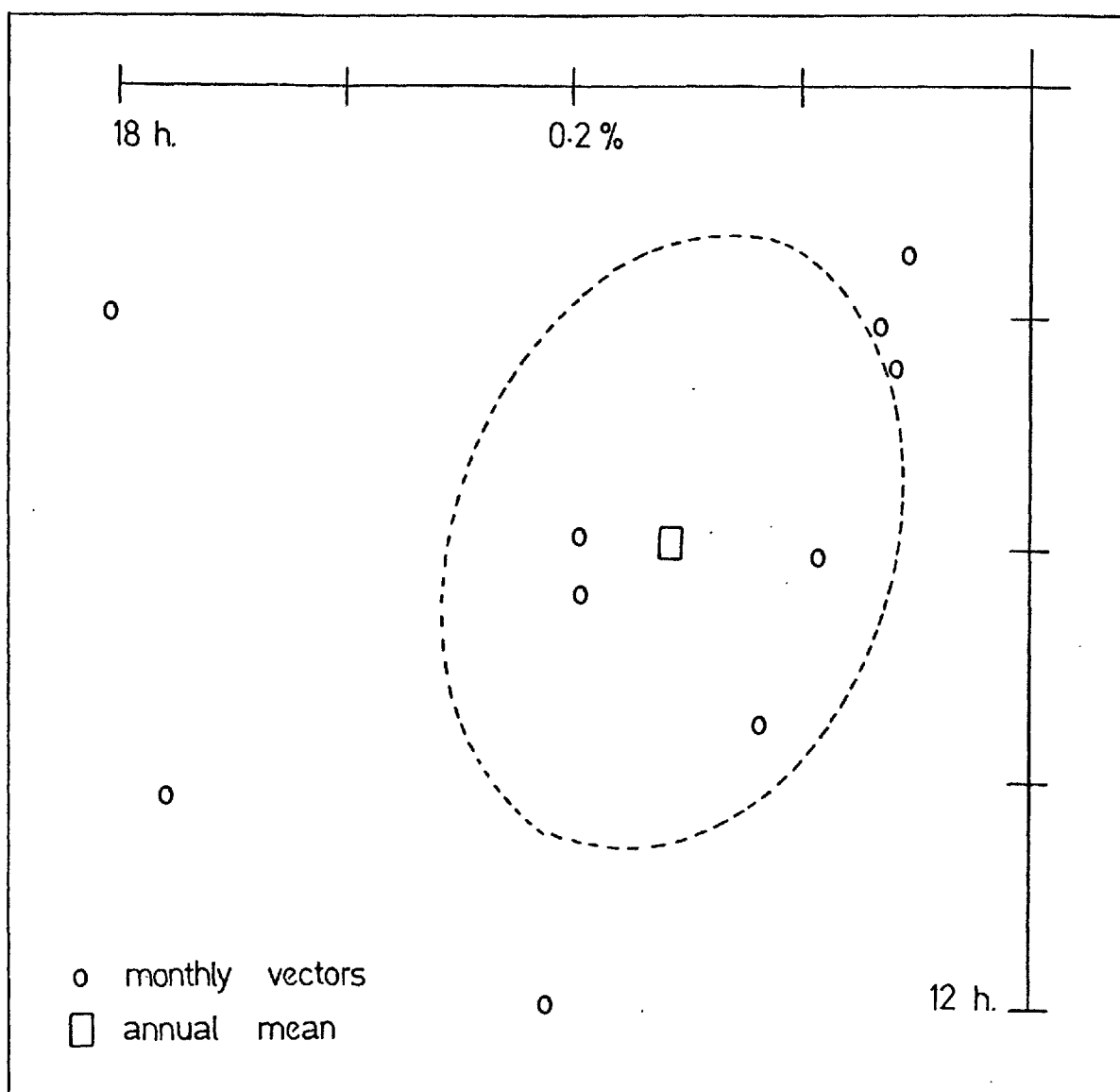


Fig. 1.6 1969 monthly vectors for the North telescope (only 11 months data available) along with the annual mean and the ellipse of probable error.

CHAPTER 2

UNDERGROUND OBSERVATIONS OF THE SIDEREAL ANISOTROPY AND ITS INTERPRETATION

2.1 Introduction

This chapter deals with the series of muon intensity measurements made in the underground laboratory at Holborn, London. First atmospheric corrections are applied using the mean correction coefficients obtained by previous workers (Peacock (1967), Miyazaki (1972)). The pressure corrected results are then corrected to obtain the genuine galactic anisotropy by considering both Farley and Storey type and solar motion corrections. Finally, the implications of the results obtained are discussed.

2.2 Underground atmospheric effects

Correction of data from the underground laboratory for atmospheric effects has been studied in detail elsewhere (Peacock (1967), Miyazaki (1972)). Due to insufficient meteorological data, determination of the density of temperature coefficients in a Dorman (1957) type correction scheme has not been possible. Instead, an analysis based on a Duperier (1951) type regression equation has been studied. The variables that have been used in the correlation analysis are, the recorded intensity, surface level pressure, the difference in heights of the 1000 and 100 mb layers and the mean temperature of the 200 - 70 mb layer. Using a regression equation of the form:-

$$\frac{\delta I}{I} = \beta_P \delta P + \beta_H \delta H + \beta_T \delta T \quad (2.1)$$

where δ stands for departures from the monthly mean values,

P is the barometric pressure,

H is the difference in height of the 1000 and 100 mb layers,

and T is the mean temperature of the 200 - 70 mb layer.

The regression coefficients obtained are presented in Table 2.I.

As radiosonde balloon flights from Crawley only occur twice daily the data to be presented has only been pressure corrected using the values given in Table 2.I. Pressure data is supplied in hourly punched card form from Kew.

DIRECTION	$\beta_P(\%/mb)$	$\beta_T(\%/^{\circ}C)$	$\beta_H(\%/km)$
VERT.	$-.041 \pm .002$	$.036 \pm .004$	$-.35 \pm .17$
EAST	$-.037 \pm .001$	$.035 \pm .003$	$-.18 \pm .14$
NORTH	$-.037 \pm .002$	$.038 \pm .003$	$-.10 \pm .19$
SOUTH (15)	$-.041 \pm .002$	$.037 \pm .005$	$-.30 \pm .16$

TABLE 2.I - Mean values of the regression coefficients obtained from equation 2.1

2.3 Underground solar and sidereal results

Monthly averages of the pressure-corrected bi-hourly count rates were arranged in solar, sidereal, anti-sidereal, double sidereal and double anti-sidereal time and yearly mean values found for each even hour.

The use of yearly averages effectively removes all the other periodicities, which cancel out, leaving the particular side-band that we are interested in. The yearly bi-hourly values were harmonically analysed as described in Chapter 1 to give the first and second harmonics.

The statistical errors have been taken to be 0.013% for an annual vector (as found for the solar daily variation in Chapter 1) since the frequency difference between solar and the side-band frequencies is so small that any variation in one time scale will naturally be evident in the other.

2.3.1 Results from Holborn 1961 to 1971

Results have been obtained since 1960 and the present work has continued the analysis up to the end of 1971. The lack of significant variations in the results throughout this period justifies the taking of mean values and

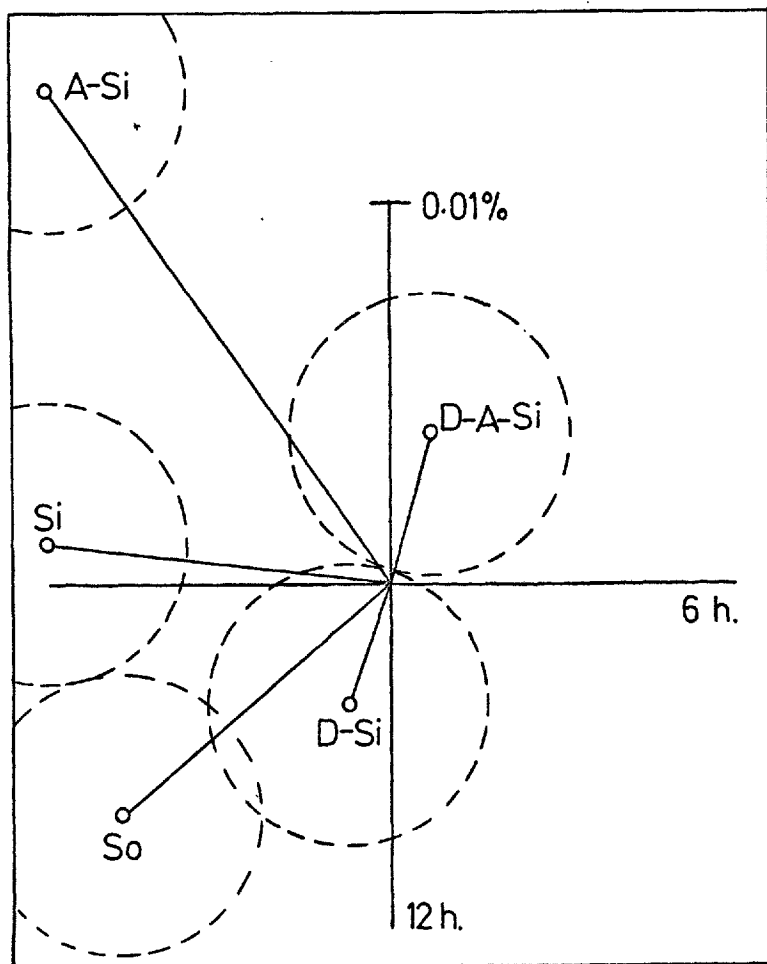
the total data are displayed on harmonic dials in Figs. 2.1 and 2.2. Only the first and second harmonics have any significance and studying Fig. 2.1 and 2.2 the following points are clear:-

(i) Only the sidereal and anti-sidereal diurnal vectors have any significance, indicating that a twice yearly modulation of the Farley and Storey (1954) type of the solar diurnal vector is not present. Insignificant anti-sidereal second harmonics further substantiate no twice-yearly modulations.

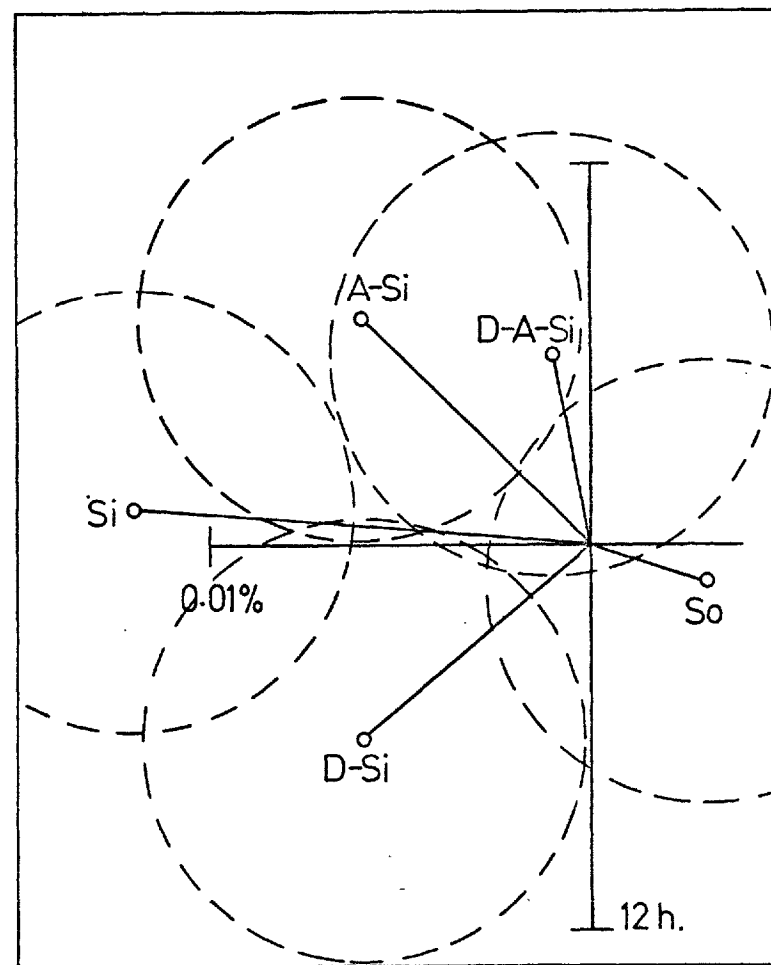
(ii) Despite large changes in the solar diurnal variation over the period 1961 to 1971 (see Chapter 3 Fig. 3.4), the sidereal diurnal wave observed by the vertical telescopes has shown remarkable constancy over the entire period, with an amplitude and phase in good agreement with other Northern hemisphere stations (see Section 2.3.2). The mean amplitude is $0.009 \pm 0.004\%$ at 18.00 hrs. During 1970 and 1971 the vertical sidereal vector did appear to go to earlier times, but the amplitudes are insignificant and so a mean vector for the entire period has been used. The mean vectors reveal a large anti-sidereal vector of amplitude about 4σ , and a sidereal vector of amplitude $\sim 2.5\sigma$.

(iii) The North telescope, surprisingly, reveals significant sidereal and anti-sidereal vectors for the period 1964 - 1969. However, the years 1967, 1968 and 1969 have indicated an insignificant sidereal vector (also plotted on the North harmonic dial in Fig. 2.1) and it is only the inclusion of the earlier years that produces the significant mean vector. Therefore, the large sidereal vector for 1965, 1966 could be due to the very large changes in the solar daily variation over the solar minimum period, producing spurious sidereal vectors. A 45° North telescope would not be expected to "see" a true anisotropy as it points in a fixed direction in space. However, it is noteworthy that the anti-sidereal vector is significant for all the periods but the solar vector is barely significant for any.

(iv) The East telescopes indicate a significant sidereal vector,

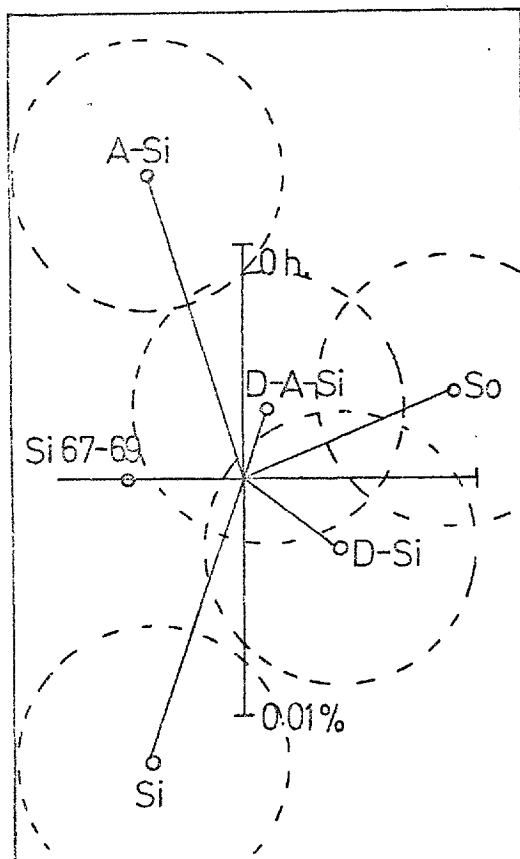


(a) Vertical 1961-71

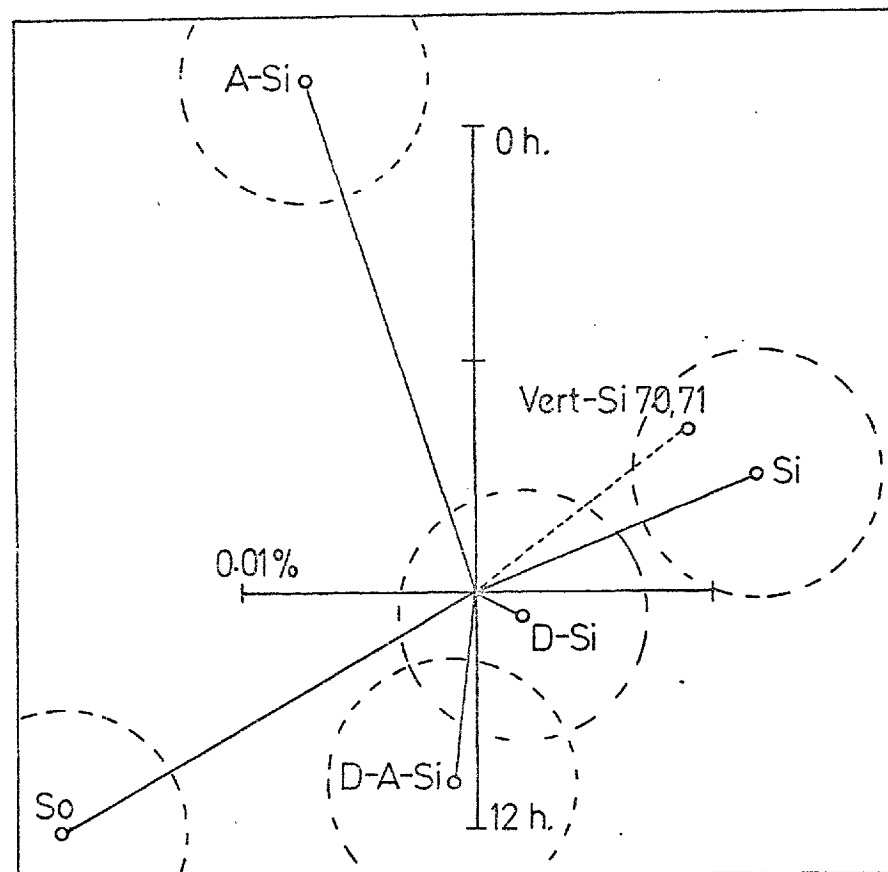


(c) East 1965-69

Fig. 2.1 (a) & (c) Diurnal harmonic dials for the underground Vertical and East telescopes for the time periods shown.

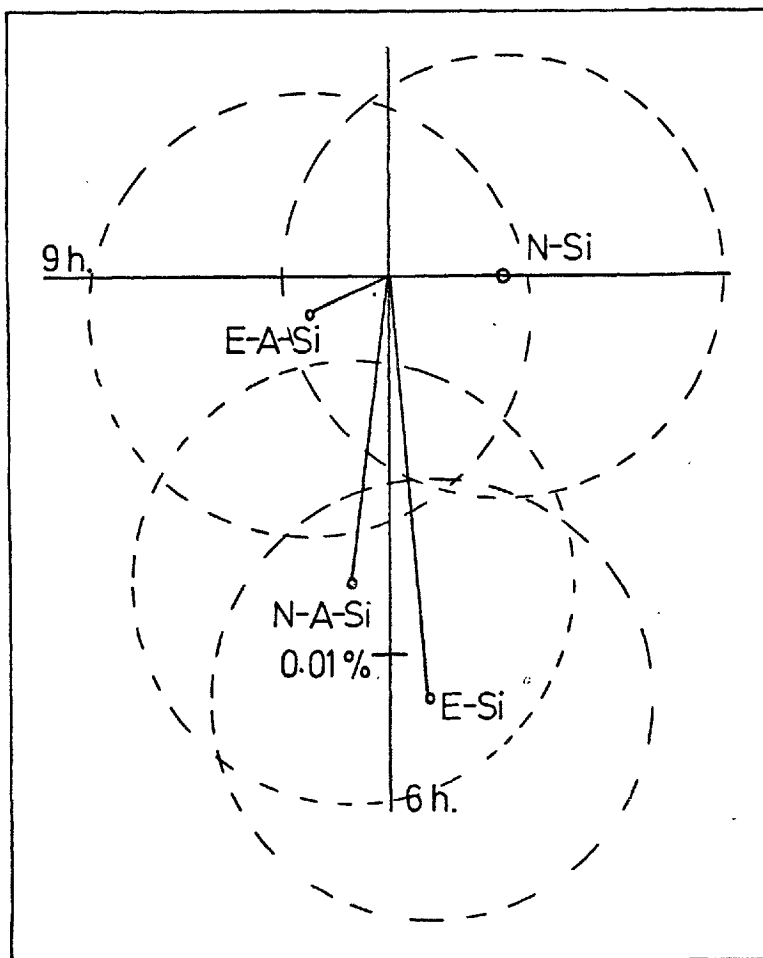


(b) North 1965-69

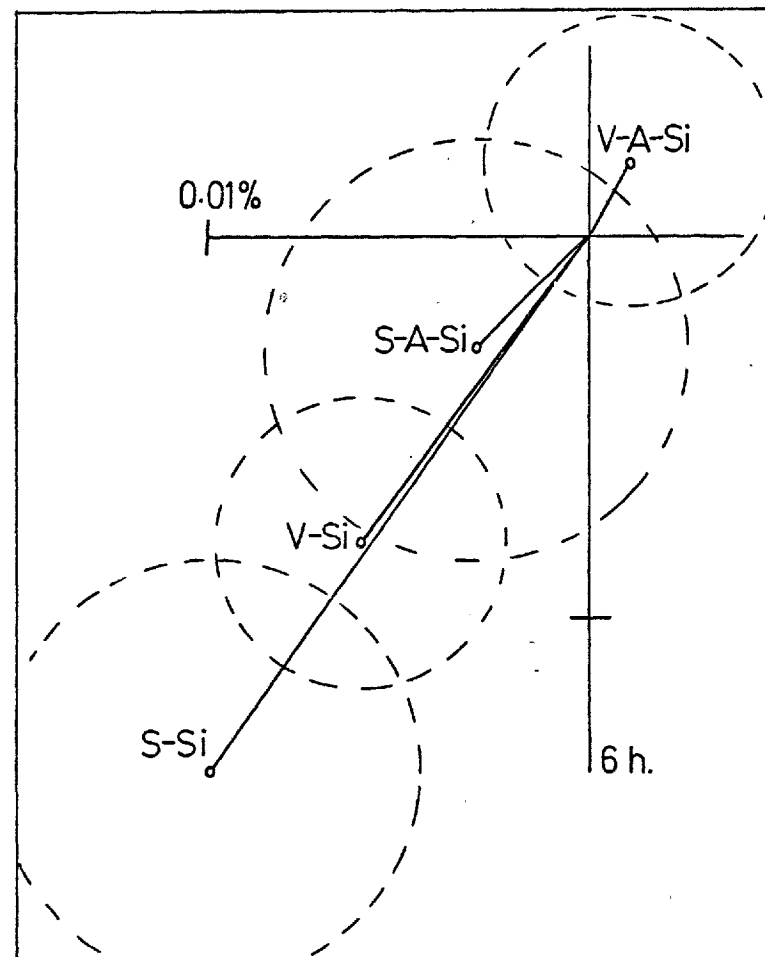


(d) South 1970-71

Fig. 2.1 (b) & (d) Diurnal harmonic dials for the underground North and South telescopes for the time periods shown.



North and East 1965-69



South 1970-71 and Vertical 1961-71

Fig. 2.2 Semi-diurnal harmonic dials for the underground North, East, South(15°) and Vertical telescopes for the time periods shown.

although the existence of the anti-sidereal vector must be doubted. A true sidereal anisotropy should be seen by the vertical and East telescopes with phase difference of 2 or 3 hrs. The large errors in the vectors make conclusions about any phase difference rather difficult and if no phase difference exists the observed vectors could be interpreted as an effect of local origin.

(v) The South (15°) telescopes reveal significant sidereal and anti-sidereal vectors with a phase for the sidereal anisotropy of ~ 06.00 hrs, i.e. opposite to that for the vertical telescopes. The South telescopes are only tilted at 15° to the zenith giving them a maximum sensitivity at $\sim 15^\circ$ to the zenith (see Section 1.2.1). Thus their response to any anisotropy should be similar to that of the vertical telescopes. Plotted on the South (15°) harmonic dial are the vertical vectors for the same period 1970 and 1971. Although the errors are large, the agreement is impressive and possibly a change of phase could have occurred; however, more data is required to establish such a change.

(vi) All the second harmonics appear to be insignificant with the possible exception of the South (15°) and vertical sidereal vectors. The double sidereal and double anti-sidereal second harmonics are insignificant, but have not been plotted in Fig. 2.2.

The rest of this chapter deals with the interpretation of the sidereal variation. The solar daily variation observed underground will be discussed more fully in Chapter 3 and only the mean solar vector, given in Fig. 2.1, will be used here in connection with the correction of the sidereal vector due to the solar modulation.

2.3.2 Comparison with other results

Tables 2.II and 2.III contain a brief summary of results published on the sidereal variation. No effort has been made to present a thorough and comprehensive list of all the investigations that have been performed;

rather, the aim has been to select what can be regarded to be typical results. Results from neutron monitors have not been included; they are numerous, but due to the low mean primary energy of response they are bound to be seriously affected by solar modulation. There is some doubt that even during periods of very low solar activity the results represent genuine sidereal effects (as reported by Conforto and Simpson (1957)). Table 2.II contains results from meson telescopes (MT) and ionization chambers (IC) operated on the surface, and, therefore, the results correspond to primaries of energy less than 50 GeV. Underground meson telescopes, air Čerenkov telescopes (CT) and extensive air shower (EAS) results are presented in Table 2.III. The mean primary energy of response of these detectors is probably ≥ 100 GeV, 200 GeV (Sekido et al. (1971)) and ≥ 500 GeV respectively. The value for the underground meson telescopes depends upon the depth and the response function considered, but 150 GeV is probably a reasonable estimate for a telescope at 40 or 60 m.w.e..

Table 2.II summarizes the results due to primaries of low energy and consequently are subject to some solar modulation. Apart from solar induced effects, atmospheric effects at the surface are large; careful allowances must be made for them, and extra caution must be exercised in interpreting the data. Generally it appears that with short periods of data (one or two years) the sidereal amplitude is $\sim 0.05\%$, with a time of maximum about 20.00 hrs L.Sid. time in both the Northern and Southern hemispheres. However, the 20 yrs data analysed by Nagashima et al. (1968) does indicate a smaller amplitude of about 0.02% and with a phase that depends upon the hemisphere in which the detector is located; (21.00 hrs for the Northern hemisphere and 07.00 hrs in the Southern). More recently, Messerschmidt (1971) has confirmed this result using very similar data. Most of the results quoted in Table 2.II have large errors associated with them, possibly for the reasons outlined previously, and more reliable results will be obtained from studying higher energy primaries.

Author(s)	Location	Latitude	Instrument	Period	Sidereal Amplitude	Time of max. L. Sid. T.
BALIGA & THAMBYAHPILLAI (1954)	HOBART	43°S	MT	54	0.06	23.5
	HUANCAYO	12°S	IC	54	0.06	19
	TOKYO	36°N	IC	54	0.06	21
BERCHICHEVSKAYA & ZHUKOVKAYA (1960)	MOSCOW	55°N	MT	53-57	0.05	22
	YATUTSK	62°N	MT	54-57	0.04	24
	TIKHAYA BAY	71°N	MT	53-55	0.03	23
	FREIBURGH	48°N	IC	52-54	0.03	21
NAGASHIMA et al. (1968)	CHEL TENHAM	38°N	IC	38-52	0.02 ±.004	21
	CHRISTCHURCH	43°S	IC	38-52	0.025 ±.004	7
KUSMIN (1968)	YAKUTSK	62°N	MT	61-62	0.26	21.3
DORMAN et al. (1967)	KRASNAYA PAKHRA		MT CROSSED	63-64	0.10 ±.01	21
	ITABASHI		MT CROSSED	60&62	0.10 ±.01	1
MESSERSCHMIDT (1971)	HUANCAYO	12°S	IC	37-65	0.034	00.30
	GODHAVN		IC	39-56	0.066	20.00
	HALLE		IC	57-69	0.026	17.40

TABLE 2.II Surface level measurements of the sidereal variation.

Author(s)	Location	Latitude	Instrument and Depth	Period	Sidereal Amplitude	Time of max. L. Sid. T.
HODSON (1951)	MANCHESTER	53°N	EAS		1.15 ±.61	23.30
FARLEY & STOREY (1954)	AUKLAND	37°S	EAS	51-52	1.43 ±.38	17.6
CHAPMAN & RYDER (1957)	WELLINGTON	41°S	EAS	55-56	0.88 ±.65	17.0
SEKIDO et al. (1968)	NAGOYA	35°N	CT	64-66	0.054 ±.04	18.5
JACKLYN (1965)	HOBART	43°S	MT 40 m.w.e.	58-62	0.054 ±.005	07
JACKLYN (1966)	HOBART	43°S	MT 40 m.w.e. VERT.	64	0.035 ±.010	05.5
	HOBART	43°S	MT 40 m.w.e. 70°N	64	0.10 ±.05	17.5
	BUDAPEST	47°N	MT 40 m.w.e. VERT.	59&61	0.030 ±.008	19
ELLIOT et al. (1970)	LONDON	52°N	MT 60 m.w.e. VERT.	60-68	0.015 ±.005	18
SWINSON (1971b)	BOLIVIA	16°S	MT 25 m.w.e.	65-70	0.035 ±.010	10
	EMBUDO	35°N	MT 25 m.w.e.	65-70	0.015 ±.005	18
SEKIDO et al. (1971)	NAGOYA	35°N	CT 35° to S	68-71	0.018 ±.014	23±4
	NAGOYA	35°N	CT 55° to S	68-71	0.042 ±.035	9±4
THOMSON & SUMNER (1971)	KILEMBE	0°	MT 40 m.w.e. CROSSED	71	0.03 ±.015	6
MESSERSCHMIDT (1971)	HALLE		IC 15 m.w.e.	57-64	0.05	10.40

TABLE 2.III Underground and EAS measurements of the sidereal variation.

Table 2.III summarizes the results of underground meson telescopes and extensive air showers experiments where the solar modulation should be small. It can be seen that there is some agreement on the magnitude of the effect, although, the amplitude appears to become smaller and not surprisingly more reliable the longer the period of analysis.

Northern hemisphere stations or detectors that "look" into the northern hemisphere show a common time of maximum L.Sid. time between 18.00 and 20.00 hrs, although an exception to this is the result of Thomson and Sumner (1971). (The Kilembe mine telescopes, due to their position within the mine, effectively look 16°N of the equator.) However, this result is from just one year's data and its significance must be doubtful. Results from apparatus that has been continuously operational for at least 5 years (i.e., London and Embudo), and therefore should provide more reliable results, show excellent agreement for amplitude (0.015%) and phase (18.00 hrs). Reliable results in the Southern hemisphere are few, either the period of data is short or the measured amplitudes are barely significant. Hobart (5 yrs) and Bolivia (4 yrs) have both recorded amplitudes greater than 0.03% with times of maximum around 07.00 to 10.00 hrs, respectively. However, large changes of phase occurred in the Hobart data during 1961 - 62 which were unconfirmed by any other station. Extensive air shower results are a little confusing and although they should eliminate any solar-induced sidereal variations the vast reduction in counting rate leads to large errors in the results. The phase recorded by the three experiments in Table 2.III are in reasonable agreement with a time of maximum of 18.00 to 20.00 hrs even though two of the experiments are in the Southern hemisphere. Despite the accord between the phase in these experiments, Delvaille (1959) using results from a number of EAS experiments concluded that the times of maximum were randomly distributed. Sakakibara (1965), using similar data, found that the phase depended upon the primary energy with a break between a phase of 20.00 hrs and 12.00 hrs L.Sid. time occurring at $\sim 5 \times 10^{15}$ eV.

The mean sidereal vertical vector observed at Holborn of $0.009 \pm 0.004\%$ at 18.00 hrs L.Sid. time is in good agreement with other Northern hemisphere stations although the amplitude is somewhat smaller. The North and East telescope data confirm the vertical observations, again, with quite small amplitudes.

A point of interest in the data is the change of phase of the sidereal vector in both the vertical and South (15°) telescopes during 1970 and 1971. Thomson and Sumner (1971) report that a phase of ~ 06.00 hrs during 1970 - 1971 occurred in their data from the Kilembe mine. Although situated on the equator, the telescopes, effectively scan at 16°N of the equator and hence their observation supports that made at Holborn.

2.4 Correction of the observed vectors

Various possible contaminations in the data must be considered and removed before any conclusions are drawn from the results. It is in this respect that analysis of sidereal data has its greatest uncertainty. In this thesis a new approach to these important corrections is made. Firstly, it is shown that Farley and Storey type corrections are inadequate and instead modulation of the sidereal vector itself is considered. Following this a detailed analysis of cosmic ray trajectories is used to indicate the source of this sidereal vector modulation and the magnitude of the effect is evaluated.

2.4.1 Vectors produced by "seasonal modulation"

Adoption of the procedure to correct the observed sidereal vectors for amplitude modulation of a component of the solar daily variation has been discussed by Farley and Storey (1954) and has been used by many workers since. Once yearly modulation of the solar daily variation would produce spurious sidereal and anti-sidereal vectors where the amplitude of the anti-sidereal vector (and the spurious sidereal vector) would be one quarter of the peak to peak modulation of the solar vector. Any twice yearly modula-

tions of the solar vector would produce double sidereal and double anti-sidereal vectors, whereas, a twice yearly modulation on the solar semi-diurnal vector would produce spurious semi-diurnal sidereal and anti-sidereal vectors. Only the once yearly modulation upon the solar diurnal variation seems to be applicable here since from Figs. 2.1 and 2.2 it is clear that all the double time and semi-diurnal vectors are insignificant.

There are two approaches to this correction problem:-

(i) As used by many workers, the existence of the anti-sidereal vector is assumed to be purely due to amplitude modulation of the solar diurnal vector throughout the year. Thus once the solar vector undergoing modulation has been found, reflection of the anti-sidereal vector in the solar vector gives the spurious sidereal component which can then be subtracted from the observed or apparent sidereal vector to give the true resultant. A correction of this sort has been carried out on the vertical data as indicated in Fig. 2.3. Two "genuine" sidereal vectors have been plotted; "(A)" is for the case where the solar vector has not been corrected for the orbital motion of the Earth around the sun and "(B)" is the resultant when this aberration effect is taken into account (see Chapter 3, Section 3.4.2).

(ii) As an alternative method of correction the component, or components, of the solar daily variation producing the modulation can be identified (Elliot et al. (1970)). Two possible components which could produce a modulation of the solar vector with an annual periodicity can be recognized,

- (a) the orbital motion of the Earth around the Sun,
- and (b) seasonal atmospheric temperature changes.

The phase of the atmospheric temperature effect is uncertain at 60 m.w.e.. The North telescope which should only measure meteorological effects shows an insignificant amplitude even when averaged over a period of four years (see Fig. 3.4, Chapter 3). The best estimate that can be made for the phase is from surface level observations where such effects are relatively large. Two possibilities have been suggested; one from Dorman's

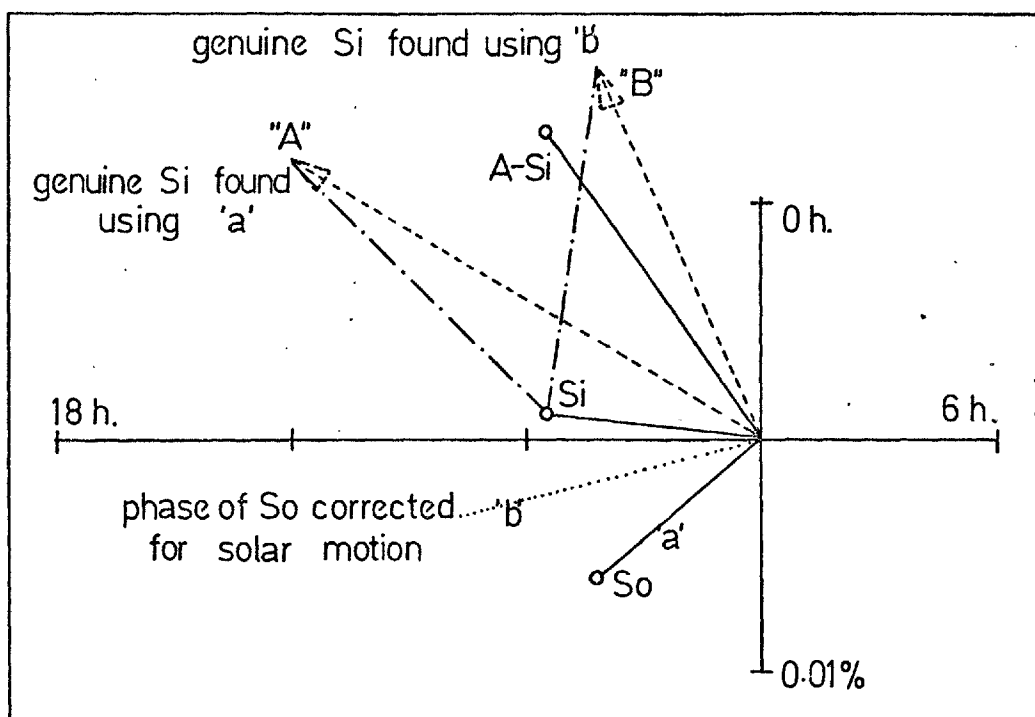


Fig. 2.3 Farley & Storey (1954) type corrections of the observed sidereal vector, Si. Two phases of the observed solar vector, So, have been used. The errors have not been plotted to avoid confusion but are the same as for Fig. 2.4. The spurious sidereal vectors are shown as — — — — —

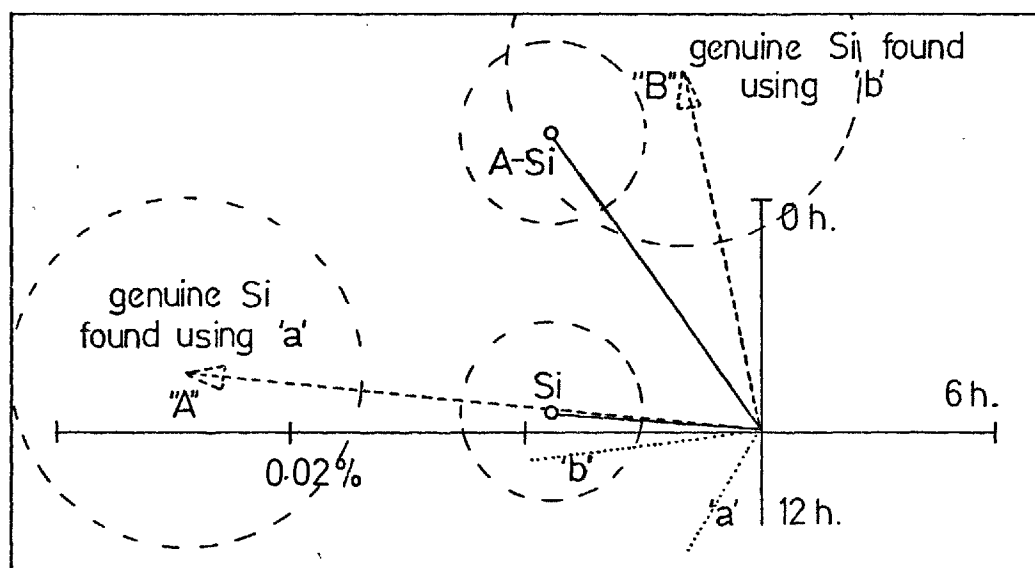


Fig.2.4 As for Fig. 2.3 although the modulating solar components have been identified giving rise to the two phases a & b . The spurious sidereal vectors have not been plotted.

analysis on an average atmosphere leads to a phase ~ 02.00 hrs. The other due to Quenby and Thambyahpillai (1960) suggests a later phase around 05.30 hrs. The phase of the orbital motion effect, after correcting for geomagnetic bending, is also ~ 05.30 hrs (see Chapter 3). Reflection of the anti-sidereal vector in the three possible vectors outlined above has been performed in Fig. 2.4. Only the phases are important to obtain the spurious sidereal vector in the diagrams; the magnitudes will be discussed below. Vector "(A)" assumes an early phase for the atmospheric effect whereas "(B)" assumes the later phase or the orbital motion effect.

In all cases (Figs. 2.3 and 2.4) the genuine sidereal vectors are larger than the apparent ones but since the errors are increased by a factor of $\sqrt{2}$ the significance levels remain approximately the same. The amplitude and phases of the corrected vectors agree well with results in Tables 2.II and 2.III, although the phases for the "(B)" vectors tend to be rather late.

However, consideration has to be given to the question of whether the modulation hypothesis possesses internal consistency. In order to produce the required spurious effects,

- (1) the solar daily variation vector must be sufficiently large compared to the anti-sidereal vector so that the spurious sidereal vector and the anti-sidereal vector can be produced by amplitude modulation of the solar vector, and,
- (2) the effect producing this modulation must be of sufficient amplitude to do so. The peak to peak variation of the modulating component has to be four times the amplitude of the anti-sidereal vector.

Without identifying the modulating components and studying Fig. 2.3 it is clear that the uncorrected solar vector is certainly too small to produce the anti-sidereal vector and even having corrected for the orbital motion of the Earth the resultant solar vector is still inadequate.

Alternatively, Fig. 2.4, the variation in the proposed modulated com-

ponent of the solar daily variation can be evaluated. The orbital motion vector (see Chapter 3, Section 3.4.2) has an amplitude at the detector of $\sim 0.03\%$. Thus the maximum possible variation in this component is $.03\%$ (without the Earth's orbital motion reversing!) and this is less than the $0.062 \pm 0.014\%$ required by the anti-sidereal vector, multiplied four times. Considering the atmospheric temperature effects the phase is irrelevant and only the magnitude will be considered. Meteorological data indicates a peak to peak variation in the amplitude of the diurnal variation of the upper atmosphere between summer and winter of approximately 0.5°C . Using the positive temperature coefficient (see Table 2.I, Chapter 2) of $\sim 0.04\%$ per $^\circ\text{C}$, gives a maximum range to this effect of about 0.02% which is well below the required magnitude. Thus, neither of the effects considered individually can account for the production of the anti-sidereal vector. Only if the orbital motion and atmospheric variations are considered together could the anti-sidereal vector be produced; however, this requires the full range of the orbital motion vector being utilized which seems very unlikely.

2.4.2 Modulation of the sidereal vector

Production of an anti-sidereal vector was suggested by Professor Somogyi to be due to the six monthly modulation of the sidereal vector (see Elliot et al. (1970)). In order to see if such a modulation is present the data for the whole period has been averaged in monthly batches and the harmonic coefficients have been determined for each month of the year. The results are plotted in Fig. 2.5 (a) and (b) in solar and sidereal time. It is clear that half the vectors are consistent with zero amplitude. The dotted circle represents the standard deviation calculated from the scatter of the monthly values. The vectors for January, February, March and July, August, September however are significant, indicating a twice yearly amplitude modulation of the sidereal vector.

In a Farley and Storey type expansion the sidereal vector is given as,

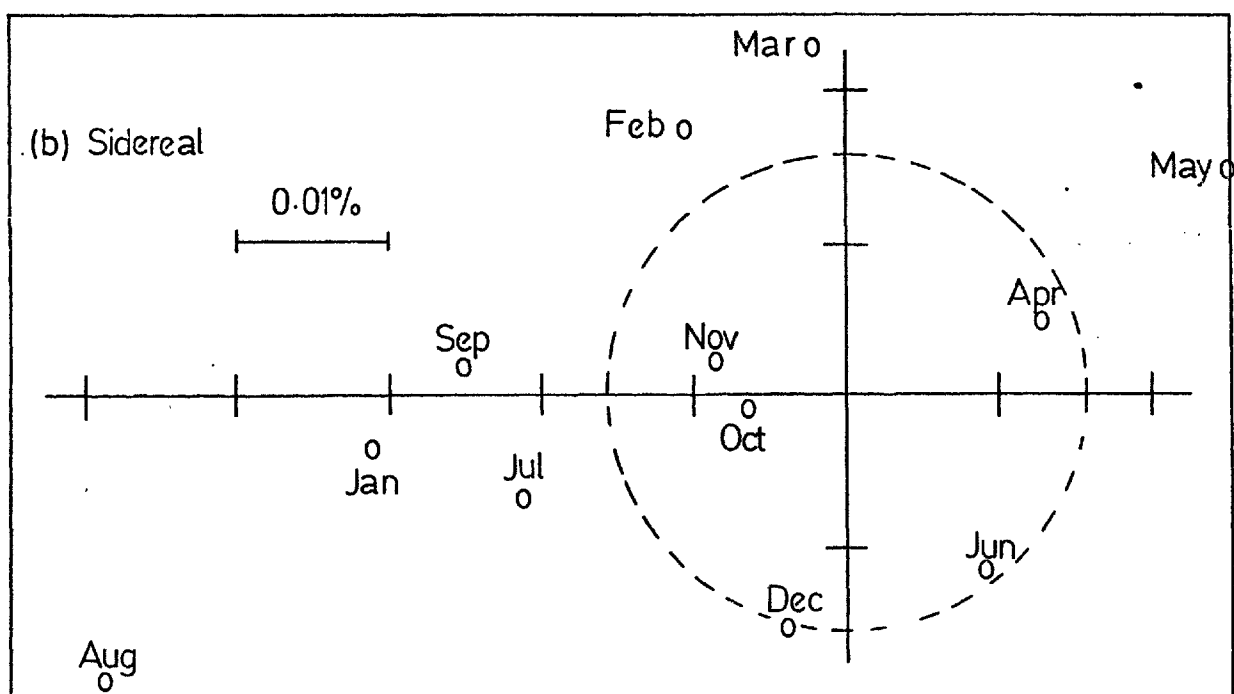
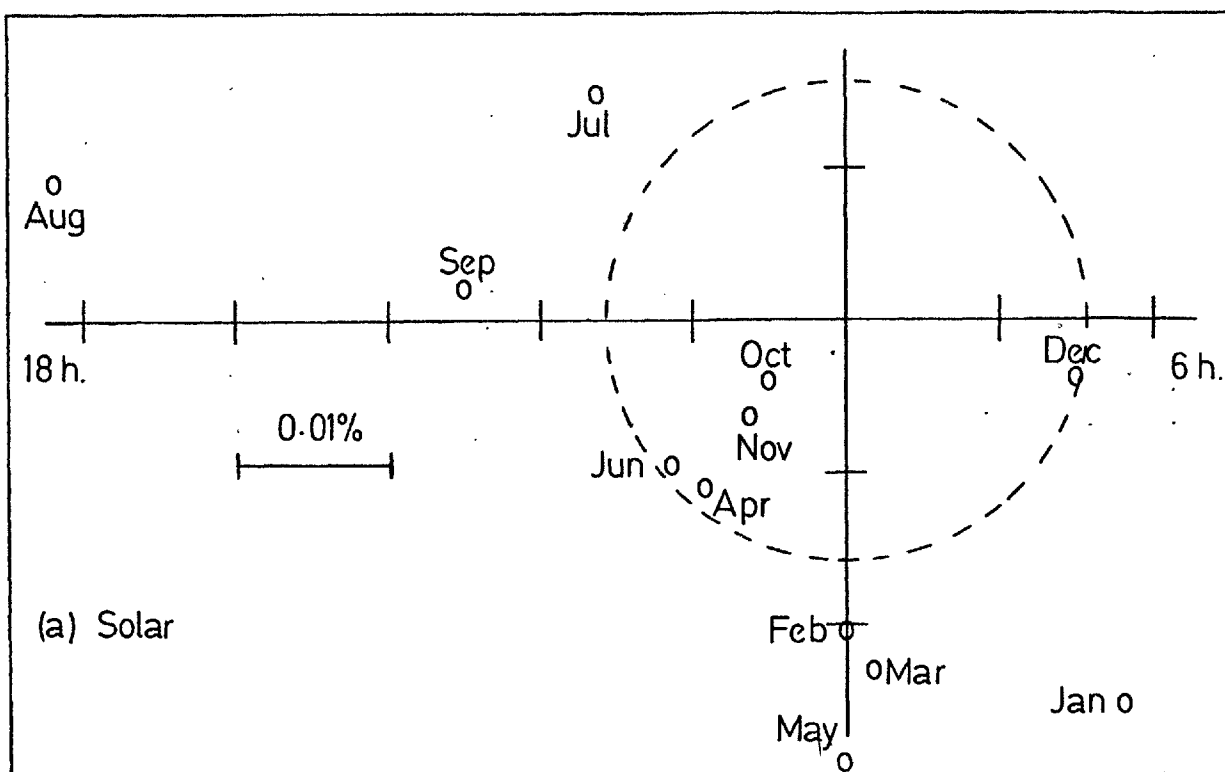


Fig. 2.5 Harmonic dials in sidereal and solar time showing the mean monthly first harmonics for the complete period of observation 1961-1971. The data have been corrected for pressure only.

$$C \cos 2\pi \{(N + 1) t + \phi_3\} \quad (2.2)$$

where C = the amplitude of the sidereal vector (assumed constant), the solar diurnal vector has a frequency of N/year and ϕ_3 is the phase of the sidereal vector. t , the unit of time is one year. If, however, C is modulated throughout the year equation 2.2 becomes,

$$\{C + D \cos 2\pi (mt + \phi_4)\} \cos 2\pi \{(N + 1) t + \phi_3\} \quad (2.3)$$

where D is the amplitude of the sidereal modulation at a frequency of m/year and phase, ϕ_4 . Expanding 2.3 gives,

$$C \cos 2\pi \{(N + 1) t + \phi_3\} + \frac{D}{2} \cos 2\pi \{(N + 1 + m) t + \phi_3 + \phi_4\} \\ + \frac{D}{2} \cos 2\pi \{(N + 1 - m) t + \phi_3 - \phi_4\} \quad (2.4)$$

In a similar manner to the modulation of the solar vector producing spurious vectors in sidereal and anti-sidereal time the modulation of the sidereal vector will produce sideband frequencies of $(N + 1 + m)$ and $(N + 1 - m)$. For the first harmonic $N = 365$ and if $m = 1$ we get sideband frequencies of 367 (double sidereal time) and 365 (solar time). Since in all the data considered the double sidereal vectors were insignificant it is concluded that no spurious solar vectors are produced due to modulation of the sidereal vector. If $m = 2$ spurious vectors of frequency 368 (ultra sidereal of order 2, USV2) and 364 (anti-sidereal) are produced. Further combinations are possible although from Figs. 2.5 (a) and (b) it appears that only the twice yearly ($m = 2$) modulation of the sidereal vector is important. To see if any spurious anti-sidereal vectors have been produced, the vertical data has been arranged in USV2 time and has been harmonically analyzed as before. Plotted in Fig. 2.6 is the result along with the sidereal vector and anti-sidereal vector. If twice yearly modulations have produced the USV2 vector then obviously a part of the measured anti-sidereal vector can be produced in this way.

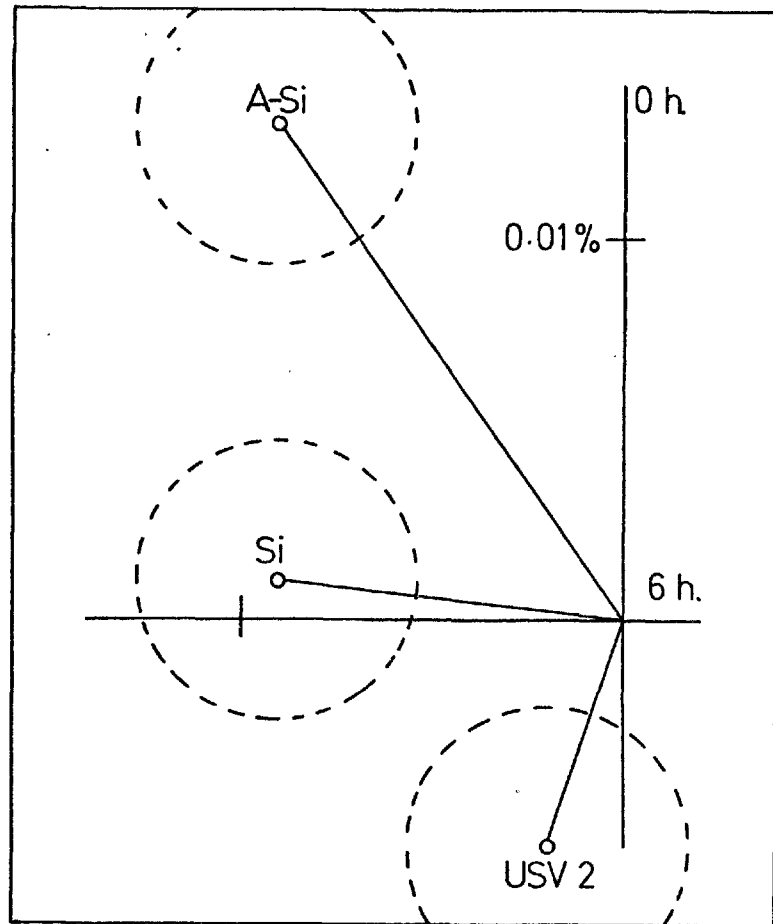


Fig. 2.6 Diurnal harmonic dial showing the observed sidereal, anti-sidereal and USV2 vectors for the underground vertical telescope.

A modulation of the solar daily variation could possibly produce a spurious vector with a frequency of the USV2 observation, but in order to do so, the modulation would have to be three cycles yearly and this seems very unlikely. Therefore, the observed USV2 vector would seem to have its only origin in the semi-annual modulation of the sidereal vector, and if this is the case, part or all of the large anti-sidereal vector can be attributed to the same cause. Amplitude modulations of the sidereal wave produces two vectors, the anti-sidereal and USV2, of equal amplitude and equally displaced either side of the sidereal vector. Clearly from Fig. 2.6 the observed anti-sidereal vector is twice the amplitude of the USV2 and amplitude modulation of the sidereal vector is not the only source of the anti-sidereal vector. In Section 2.4.1 it was shown that modulation of the solar vector was inadequate to produce the anti-sidereal vector and a correction of the Farley and Storey kind was not justified. However, phase modulation of the sidereal vector on a semi-annual basis is also present in the data (see Fig. 2.5) and a combination of phase and amplitude modulation of the sidereal vector could be the origin of the anti-sidereal vector. Certainly the combination of the anti-sidereal vector and USV2 on a sidereal time dial will cause the end point of the resultant sidereal vector to trace out an ellipse, one traversal of this ellipse being completed every six months. This behaviour is present in the data presented in Fig. 2.5.

Elliot et al. (1970) discuss this sidereal vector modulation using the trajectories of primary cosmic rays in the interplanetary medium, indicating that particles arriving on the night side of the Earth receive much less deflection in the solar field. So when the source or the sink of the sidereal anisotropy occurs on the night side of the Earth the sidereal vector will have its maximum value and this occurs twice yearly. A detailed analysis of the trajectories of cosmic rays in the interplanetary field is given in Section 2.7 but qualitatively it can be seen that such a modulation on the sidereal vector can exist and could be the explanation of the large anti-

sidereal vector observed at Holborn.

2.5 Summary of the sidereal observations

(1) Significant apparent sidereal and anti-sidereal vectors have been found in the data from all the telescopes over the period from 1961 to 1971.

(2) A significant sidereal vector for the North telescope is not to be expected as it looks in a fixed direction in space. The mean sidereal North vector for the years 1967, 1968 and 1969 is consistent with zero amplitude implying that the large apparent sidereal vector for 1965, 1966 could have been due to the large changes in the solar diurnal anisotropy over the solar minimum. If this is the case it would indicate that solar minimum is not a good time to study sidereal variations, as previously thought, since the large solar variations induce spurious sidereal variations.

(3) The errors on the East and Vertical telescope vectors are too large to decide whether a phase difference exists between them. A significant phase difference would confirm that the observed sidereal vectors arise from a primary anisotropy. The North telescope should be the best one to indicate a temperature effect as it "looks" in a fixed direction in space. Zero solar diurnal variations, for the North telescope, indicates that little, or no temperature effects are present, and a North apparent sidereal vector is observed for half the recording period with a large anti-sidereal vector for the entire period. Thus it must be concluded that part of the observed sidereal effects are external to the Earth's atmosphere.

(4) By using the vertical data it was shown that the large anti-sidereal vector cannot be explained entirely by modulation of the solar vector. Instead amplitude and phase modulation of the sidereal vector on a semi-annual basis, shown to be present in the data, if large enough, could account for the anti-sidereal vector.

(5) A possible phase reversal in 1970 and 1971 has been noticed but

needs confirmation with further data.

(6) No double sidereal or double anti-sidereal vectors were significant indicating that a semi-annual variation of the solar vector, possibly due to the Earth's elevation out of the ecliptic, does not exist.

(7) The results are in good agreement with all Northern hemisphere stations but disagree with those from Hobart, Tasmania in that a phase difference of 12 hrs exists between the two hemispheres.

2.6 Interpretation of the sidereal variation

2.6.1 Introduction

It has been shown that the sidereal variation observed at Holborn is, at least in part, external to the Earth's atmosphere. It was shown that seasonal atmospheric temperature changes were insufficient to cause a large enough modulation of the solar diurnal variation so that an anti-sidereal vector of the observed magnitude was produced. Considering bi-annual modulation of the sidereal vector it was indicated that if the modulation was large enough an anti-sidereal vector of phase and magnitude, in good agreement with the observed, could be produced. This leads to the conclusion that the observed sidereal vector could be entirely genuine, thus indicating a sidereal anisotropy of amplitude $0.009\% \pm 0.004$ at ~ 18.00 hrs L.Sid. time.

General agreement with this observation has been found by others in the Northern hemisphere although the Southern hemisphere results reveal a phase difference of ~ 12 hrs. The interpretation of these results has mainly been in two directions:-

(1) The sidereal anisotropy is locally produced due to a radial cosmic ray density, the corotating solar magnetic field and the inclination of the Earth's axis to the ecliptic. This explanation has been put forward by Swinson in several papers (1969, 1971a, 1971b).

(2) A two way anisotropy exists in the galaxy probably aligned along the spiral arm with a flow of the cosmic radiation both inward and outward

along the spiral arm. This idea was put forward by Jacklyn (1963).

The effect being studied is critically dependant upon the mean primary energy of response of the detector. Obviously a detector monitoring particles appreciably affected by the solar magnetic field will only indicate solar modulation processes and render little or no information about the galactic particle distributions. A detector (on the other hand) monitoring particles of energies above the limit of solar modulation i.e., >75 GeV should provide useful information about the galactic population of cosmic rays provided all the necessary corrections upon the observed effect have been evaluated.

With these points in mind the interpretation of the observed sidereal variations will be dealt with.

2.6.2 "The Swinson effect"

Swinson (1969, 1971a, 1971b) proposes a mechanism whereby spurious sidereal variations are produced by a particle density gradient, the interplanetary field and the inclination of the Earth's axis at $23\frac{1}{2}^\circ$ to the ecliptic.

If a radial cosmic ray density exists with number density increasing with radius from the Sun, then spiralling of particles around the interplanetary field will cause a nett streaming from above, or below, the ecliptic plane according to the direction of the interplanetary field. Over a long period (e.g. one year) the field points away from and towards the Sun for an equal number of days, so the total nett streaming would be zero. Even considering days of just one polarity, if the axis of the Earth was perpendicular to the ecliptic no variation would be introduced in the count rate due to this effect. However, the Earth's axis is tilted at $23\frac{1}{2}^\circ$ to the ecliptic in such a manner that in sidereal time a Northern hemisphere zenith has its maximum inclination to the plane of the ecliptic at 18.00 hrs. Similarly in the Southern hemisphere this maximum inclination occurs at 06.00 hrs L.Sid. time. Therefore, even over a period of equal but opposite

field polarities (i.e., equal periods of streaming of cosmic rays from above or below the ecliptic) a nett streaming will result from that direction in which the particular detector has maximum sensitivity or in other words maximum inclination from the ecliptic plane. That is to say, a Northern hemisphere detector records a bigger intensity at 18.00 hrs from above the ecliptic than it would at 06.00 hrs from below it if the field direction was opposite in each case. Just the reverse applies to a Southern hemisphere detector. Any geomagnetic bending has to be considered separately and the necessary adjustments of the phase made.

Swinson (1971a) indicates that the magnitude of the spurious sidereal variation should be constant up to a limiting value of rigidity of 75 GV, like all other solar modulation effects, and that the observed amplitude will be proportional to the percentage of the count rate of the detector due to particles of rigidity less than 75 GV. Using a response function due to Ahluwalia and Ericksen (1971) and threshold energies by the same authors Swinson (1971a) estimates that somewhere between 14 and 36% of the count rate is due to 75 GV or less particles at 60 m.w.e.. He further illustrates, by plotting the observed amplitude against threshold rigidity, for several stations, that the amplitude falls to zero at 75 ± 15 GV as expected.

More recently Ahluwalia (1971) has used a more reliable set of data considering only those cosmic ray stations that have been in continuous operation for at least 10 years and again plotting the observed amplitude against the threshold energy he obtains a cut off to the effect well above that of Swinson, so throwing doubt on the source being entirely solar modulation.

Swinson's results depend upon the response function used and the threshold energy considered. Obviously a detector on the surface, or at a shallow depth, will be under considerable solar influence and in that case the mechanism proposed by Swinson will be applicable. However, the response function he uses to represent the Holborn detectors would appear to over estimate the contribution to the count rate by low energy primaries.

Fig. 1.4 (Chapter 1) shows three separate response functions that have been proposed for the London vertical recorders at the depth of 60 m.w.e.. Curve B is considered to best represent the situation at Holborn while curve C due to Ahluwalia over emphasises the low energy end of the spectrum. According to B the percentage of particles that are within the solar modulation region proposed by Swinson (i.e., <75 GV) is 10%. This means that the measured sidereal variation of 0.009% only corresponds to 10% of the count rate if Swinson is correct. Normalizing this result implies an apparent sidereal variation, at all rigidities less than 75 GV, of 0.09%, and this should be comparable with the result from a detector that only registers particles of rigidity <75 GV.

A detector which should give a true measure of the Swinson effect would be either a surface level meson telescope or ion chamber, both having a maximum sensitivity ~20 GV well within the solar controlled regime. Nagashima et al. (1968) provide the most reliable estimate of the measured sidereal variation in this rigidity region by utilizing 21 yrs of ionization chamber data from Cheltenham and Christchurch. The measured sidereal amplitudes are 0.02% at Cheltenham and 0.025% at Christchurch, both well below the value inferred from the London results above. Alternatively, if this ionization chamber data is considered a reliable measure of the Swinson effect, then the contribution by an effect of this magnitude to the Holborn data would be ~14% assuming that ionization chamber data relates to primaries of rigidity $10^{10} - 10^{11}$ V. This implies a measured value of less than 0.005% in the Holborn data which is comparable to the statistical error.

Swinson has tested his model by analysing his data in two separate batches, one including days when the interplanetary field points away from the Sun, the other when the field points towards the Sun. If his interpretation is correct a Northern hemisphere telescope should see a larger anisotropy at 18.00 hrs when the field is towards the Sun and a smaller anisotropy at 06.00 hrs when the field is reversed. The opposite is applicable to a

Southern telescope. This effect has been illustrated in Fig. 2 of his recent paper (1971b) where he considers data from Bolivia and Embudo underground telescopes. However, it is important to realize that this data relates to vertical telescopes at only 25 m.w.e. or inclined telescopes at 40 m.w.e.. Thus for underground detectors at depths of ~ 30 m.w.e. analysis of data according to interplanetary magnetic field directions has revealed sidereal anisotropies with approximately opposite phases for different field directions. The critical question is whether or not this spurious sidereal variation extends up to the rigidities that are observed by the underground detectors at London (60 m.w.e.).

A test of the Swinson effect in the Holborn data has been carried out by Otaola (1972) where he uses vertical data for 5 yrs and inclined data for 4 yrs. The data has been split according to the interplanetary field direction obtained from several satellites over the period 1964 - 1969, and statistical tests have been carried out, first to find if the estimates for each year come from different populations for different field directions, and secondly to see if the difference between the two vectors for an individual telescope, when the field points in different directions, is significant. The former test revealed that for the East and Vertical telescopes the vectors that are produced, when the field is towards or away from the Sun were most likely from different populations. However, the difference between the vectors, which is really the important consideration, since this is what the different field directions should produce, was not found to be significant. In fact the probabilities that the difference arose by chance were 7.5% for the vertical telescopes and 12.1% for the East and he concluded that there is insufficient experimental evidence to indicate that the major part of the sidereal vector observed at Holborn is due to a Swinson type effect.

From the arguments presented it appears that the Swinson "sidereal" variation is not present in the Holborn data. Primarily, the difference

between the data presented by Swinson and the Holborn data must lie in the primary energy to which they relate. Bolivia and Embudo are at only 40 m.w.e. (inclined) and 25 m.w.e. (vertical) and hence possibly contain in their data a much larger proportion of sun-controllable cosmic rays. The only other Southern hemisphere underground meson telescopes that have been operational for any length of time are those at Hobart. Recently, Jacklyn (1970) has recalculated the overburden at Hobart and concludes that rather than the previously quoted figure of 40 m.w.e., the actual depth should be 31 m.w.e.. Thus up until the present there have been no long term measurements comparable in depth to Holborn (60 m.w.e.) in the Southern hemisphere, and really depths of 30 m.w.e. in the Southern hemisphere cannot be used for a direct comparison with the Holborn results.

Obviously an effect envisaged by Swinson will be present at smaller depths and ground level and possibly the observations of Jacklyn (1971) are best explained in this manner. Jacklyn proposes a two-way anisotropy along the local spiral arm of the galaxy to explain the observations of Southern and Northern hemispheres. This effect has a galactic origin and would explain different phases in different hemispheres. However, the phase differences of galactic particles has not been conclusively proven since all data to date in the Southern hemisphere does not relate to sufficiently high energy particles.

In conclusion it is found that:-

(1) Ahluwalia's result (1971) indicates that the sidereal anisotropy amplitude does not fall to zero inside the solar modulation region as indicated by Swinson (1971a) demonstrating that the measured sidereal variation cannot be entirely due to solar modulation.

(2) Using ionization chamber results as an indication of the magnitude of the Swinson effect, the expected magnitude of the Swinson effect in the Holborn data was found to be $\sim 0.005\%$ comparable with the statistical error of the data.

(3) Splitting Holborn data according to the sign of the i.m.f. does not indicate a significant difference between the two vectors.

Before inferring a degree of isotropy from a measured sidereal variation, the sidereal variation must be corrected so that it represents the anisotropy in the frame of reference of the galaxy. If we assume that the galactic field renders the cosmic ray gas isotropic in the galactic frame of reference then any motion that the solar system has relative to the galactic frame of reference will produce a sidereal variation due to a Compton-Getting effect external to the solar cavity, of the form,

$$I = I_0 \left(1 + (2 + \gamma) \frac{v}{c} \right) \quad \text{Gleeson \& Axford (1968)} \quad (2.5)$$

where I_0 = mean intensity

v = velocity of solar system

c = velocity of particles

where the factor $(2 + \gamma) \frac{v}{c}$ will have a time dependence with a period of one sidereal day.

The interpretation of this effect as an effect at the Earth depends critically upon the trajectories of the particles in interplanetary space and the response function of the detector. Trajectories of cosmic ray particles monitored at Holborn have been calculated in a model solar field. These have been used in conjunction with the response function of the detector and the solar motion correction has been evaluated, thus enabling the sidereal variation in the frame of reference of the galaxy, external to any smoothing produced by the interplanetary magnetic field, to be determined.

2.7 Cosmic ray propagation in the interplanetary medium

The arrival of a cosmic ray of sufficiently high rigidity that electric fields everywhere can be assumed to be zero, is initially affected by the interplanetary magnetic field and then the geomagnetic field. Previous workers Burnberg and Dattner (1953) and McCracken et al. (1962)) have only

evaluated the effect of the geomagnetic field and their "asymptotic directions" then apply to the arrival direction of the cosmic ray just prior to entering the magnetosphere. The effect of the geomagnetic field upon the particles monitored by the Holborn detectors is small. However, modulations introduced by the large scale properties of the interplanetary field have, up until now, remained unknown, but have been found to be considerable.

Following a brief discussion of the known properties of the interplanetary medium the model used will be presented. The types of calculations used in determining the trajectories will be given and the application of the results discussed.

2.7.1 Present knowledge of the interplanetary medium

In situ observations over the past decade of the interplanetary medium by various space vehicles has produced a wealth of data and a reasonably clear picture of the Earth's environment close to the ecliptic plane, between the orbits of Mars and Venus. Results of Wilcox and Ness (1965), Fairfield and Ness (1967), Coleman et al. (1967) and Sear (1971) all show that on average the field is reasonably consistent with the Archimedean Spiral configuration of Parker's model, having a magnitude of $5 - 6 \times 10^{-5} \text{oe}$ at 1 A.U. and making an angle with the Earth-Sun line of $\sim 45^\circ$. This "garden hose" angle corresponds to a solar wind velocity $\sim 400 \text{ km/sec}$ and this too has been confirmed. Two other features have also been observed:-

(1) In the plane of the ecliptic, the field generally has a large scale sector structure of alternate polarity (towards or away from the Sun). The number of sectors in 1962 was two, in 1964 four, followed by a period during which the sectors changed rapidly and then back again to two in 1968-1970. The source of these sectors is not entirely understood although Schatton et al. (1968) have observed the evolution of new sectors to be associated with enhanced activity at the solar surface.

(2) The spiral configuration is only meaningful for observations on a long time scale and day to day variations of both magnitude and direction are

very large. These irregularities on the ideal spiral will scatter cosmic rays from the guiding centre motion, determined by the large scale properties of the field, causing the particle to lose any information about its history.

The effects that these two properties of the interplanetary field will have upon cosmic rays is critically dependent upon their energy. A low energy particle would undergo guiding centre motion following the spiral field well, in which case, the polarity of the field will have very little effect on its motion, although, irregularities upon the ideal spiral will cause large scatterings and consequent loss of sidereal information. A particle of high energy, on the other hand, will not see such irregularities and will only be affected by the large scale polarity of the field. The Holborn detectors have very little sensitivity below 100 GeV, in fact from the threshold energy to 100 GeV accounts for only ~13% of the total count rate, and therefore effects on the total count rate due to scattering will be very small and can be neglected. The scattering mean free path, λ , has recently been determined by power spectral measurements of the interplanetary magnetic field. Reliable estimates have indicated that at ~100 GeV, λ is approximately 2 or 3 A.U., and therefore the only discontinuities that will affect such particles are liable to be the sector boundaries. Therefore, trajectory calculations for the Holborn detectors need only take account of the large scale sector structure.

2.7.2 Mathematical model of the spiral field

The large magnetic Reynold's number indicates that the solar magnetic field is frozen into the solar wind plasma and it is the combination of radial expansion of the plasma and rotation of the roots of the field which causes the interplanetary field lines to be drawn out into the spiral configuration shown in Fig. 2.7

$$\text{where} \quad \phi - \phi_0 = \Omega t = \Omega \frac{(r_0 - r)}{\omega} \quad (2.6)$$

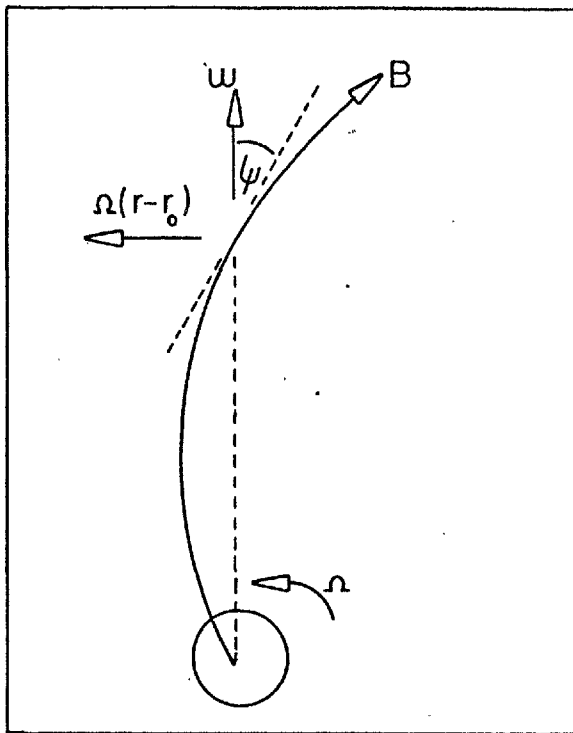


Fig. 2.7 The spiral form of the interplanetary magnetic field and the quantities used to describe it.

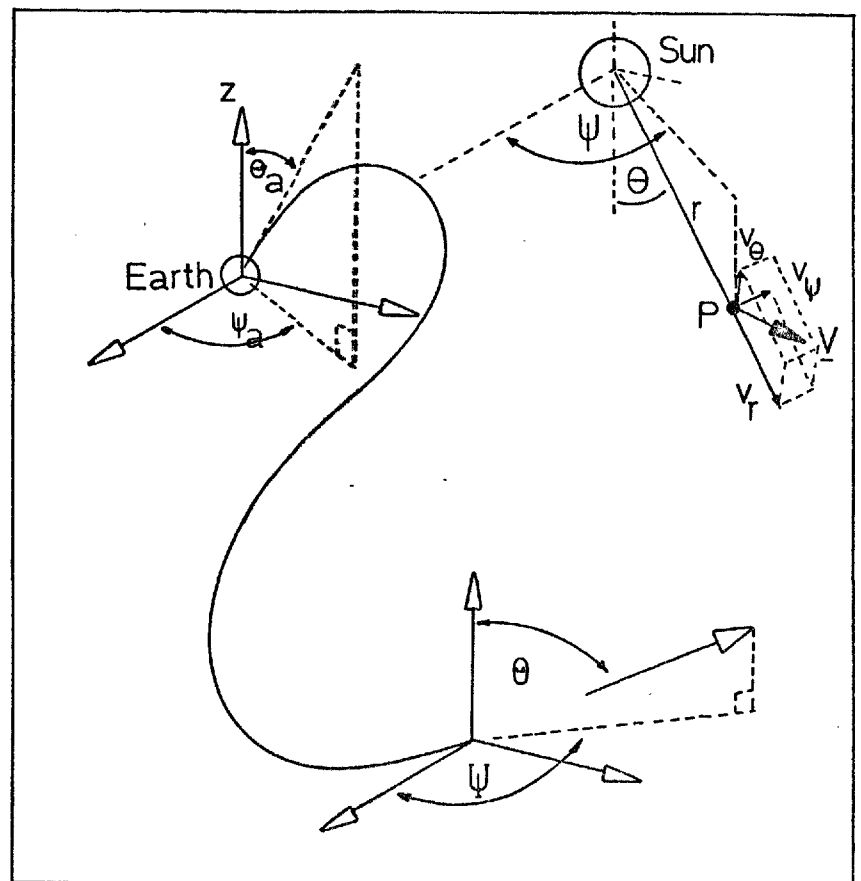


Fig. 2.8 Cosmic ray arrival direction (θ_a, ϕ_a) and asymptotic direction at the boundary of the solar cavity (θ, ψ) . The co-ordinate system used in calculating the trajectory is also given.

where ϕ = present longitude of field line
 ϕ_0 = original longitude of field line
 Ω = rotation period of Sun
 t = time between original and present
 r_0 = radius at which field line starts
 r = radius considered
 ω = solar wind velocity

and ψ the Garden hose angle is given by:-

$$\tan \psi = \frac{(r - r_0)}{\omega} \Omega \quad (2.7)$$

In the present analysis $\Omega = 27$ days, $\omega = 370$ km/sec and $r_0 = 6.69 \times 10^{10}$ cm, this gives at $r = 1$ A.U. $\psi = 45^\circ$, the observed Garden hose direction. Assuming that the solar wind velocity is independent of time and heliographic latitude and longitude, and that the root field is uniform and constant in time, the field components become independent of time. By using the observed values for the magnitude and direction we have,

$$B_r = \frac{3.5 \times 10^{-5}}{r^2}, \quad B_\theta = 0 \quad \text{and} \quad B_\phi = \frac{3.5 \times 10^{-5}}{r} \cos \theta \quad (2.8)$$

where r is in A.U. from the Sun, θ and ϕ are heliographic latitude and longitude respectively.

The results of the present calculations were to be used to interpret the vertical data at Holborn from 1961 to 1971, a time during which the sector structure changed from 2, to 4, to many, and back again to 2. In order to produce a representative sample of trajectories the sector structure chosen was for four sectors of equal extent; 90° in longitude, with the boundaries perpendicular to the ecliptic plane, for heliolatitudes between $\pm 60^\circ$. Above $+60^\circ$ the field was unsectored and positive, and below -60° it was negative. These unsectored polar regions seem to represent best the solar field as indicated during eclipses of the sun by the solar plumes. The choice of the number of sectors would alter the effects at the lower

rigidity end of the spectrum. However, the effects over the whole rigidity range of the detector would be small and would not change the final conclusions drawn.

2.7.3 The Equations of motion and the trajectory parameters

A particle of charge q , moving with a velocity $\underline{v}$, in a magnetic field $\underline{B}$ experiences a force $\underline{F}$ given by:-

$$\underline{F} = q(\underline{v} \times \underline{B}) \quad (2.9)$$

Applying Newton's second law, we get,

$$m \frac{d^2 \underline{r}}{dt^2} = q \frac{d\underline{r}}{dt} \times \underline{B} \quad (2.10)$$

where m is the mass of the cosmic ray and $\underline{r}$ is its position vector. The co-ordinate system used in the calculation of the trajectories was the spherical polar co-ordinate system with the sun at the centre as shown in Fig. 2.8.

At the point P (Fig. 2.8) the particle position is given by (r, θ, ϕ) and its direction of motion by (V_r, V_θ, V_ϕ) , thus by finding $r, \theta, \phi, V_r, V_\theta$ and V_ϕ at various points along the orbit, all the possible information about the particle trajectory has been found. Putting equation (2.10) into spherical polar co-ordinates gives,

$$\begin{aligned} \frac{dV_r}{dt} &= \frac{e}{m} (V_\theta B_\phi - V_\phi B_\theta) + \frac{V_\theta^2}{r} + \frac{V_\phi^2}{r} \\ \frac{dV_\theta}{dt} &= \frac{e}{m} (V_\phi B_r - V_r B_\phi) - \frac{V_r V_\theta}{r} + \frac{V_\phi}{r \tan \theta} \\ \frac{dV_\phi}{dt} &= \frac{e}{m} (V_r B_\theta - V_\theta B_r) - \frac{V_r V_\phi}{r} - \frac{V_\theta V_\phi}{r \tan \theta} \\ \frac{dr}{dt} &= V_r \\ \frac{d\theta}{dt} &= \frac{V_\theta}{r} \quad \text{and} \quad \frac{d\phi}{dt} = \frac{V_\phi}{r \sin \theta} \end{aligned} \quad (2.11)$$

and numerical integration with respect to time of equations (2.11) will yield $r, \theta, \phi, V_r, V_\theta, V_\phi$ at any desired point along the particle trajectory. From equation (2.9) it can be seen that if q is put as $-q$ and V as $-V$ all the equations following will be unaltered. This amounts to integrating the equations for a negatively charged particle emitted from the Earth which is a much simpler procedure than trying to follow particles arriving at the Earth. In the calculations the cosmic rays are ejected from a point corresponding to the centre of the Earth and are assumed to experience the interplanetary magnetic field immediately. For the physical situation the Earth's magnetic field can be accounted for; however, the correction at the energy of response of the Holborn installation is small, ($\sim \frac{1}{2}$ hr) comparable with other errors involved.

2.7.4 Numerical solution of the equations of motion

The basic programme was developed by McCracken et al. (1962) to find asymptotic directions of arrival for cosmic rays in the geomagnetic field represented by a sixth degree spherical harmonic expansion. The programme was altered so that the field model given in Section 2.7.2 could be used with the sun as the centre of the coordinate system.

The step length, which determines the separation of adjacent points along the trajectory, is a variable in the programme. The errors in the iteration increase strongly with increasing step length but the time to compute the orbit to the required distance increases with decreasing step length. A good compromise is reached by varying the step length as a function of the heliocentric radius of the point along the trajectory. Typically the step length is ~ 0.5 seconds at 1 A.U. giving point separations of $\sim 10^{-3}$ A.U..

The accuracy of the numerical solution was monitored along its orbit by calculating the fractional change in velocity that had taken place since its ejection from the Earth. Typically at the end of an orbit this fractional change was 10^{-9} . Changing this into a percentage change in rigidity

gives the error on a numerical solution as $\ll 1\%$.

2.7.5 The application of the numerical integrations

The Holborn data are only significant when used in sufficiently large batches. To study the sidereal variation, annual batches are used so that any constant solar variation will be eliminated. As indicated earlier the model used in the calculations only gives the idealized situation for the field which is most nearly achieved when the long term, or annual, characters of the interplanetary magnetic field are studied. Therefore the results of these numerical integrations will be used as annual averages and the effects studied will be concerned with the rotating sector structure upon the asymptotic directions at the boundary of the solar cavity. The solar cavity, or heliosphere, is the region that contains the solar plasma and magnetic field and the boundary will occur where the energy density of the interplanetary medium just balances that of the interstellar medium. Such a balance occurs at about 50 A.U. and so the integrations have been carried out to 50 A.U.. In practice the largest deflections between 10 and 50 A.U. can amount to $\sim 10^\circ$ and so were considered important.

Due to the high energy of response of the Holborn detectors, scattering by magnetic irregularities has not been considered and only the effect of the large scale sector structure is important. The method by which the sector structure was incorporated was as follows:-

At each point along the trajectory the value of the step length and magnetic field must be determined. The step length has been discussed previously and the components of the magnetic field have also been given. To find the polarity of the magnetic field the r component of the polar coordinates was used to determine the number of solar rotations required to produce a sector boundary at the required point. This effectively traces the sector, within which the cosmic ray lies, back to its root position and according to the quadrant of solar longitude in which this root field origi-

nated, so the polarity of the field is assigned.

The asymptotic direction of arrival is taken to be the direction of the velocity vector of the "traced" cosmic ray at 50 A.U.. This direction is found as latitude and longitude in the system of coordinates shown in Fig. 2.8. The sun is at the centre with the sun/earth line as the positive X-axis, the positive Z-axis being along the S/N axis of the sun and the Y-axis making up the right handed set of coordinates. In this set of coordinates the helio-latitude and longitude are given by:-

$$\begin{aligned}\theta &= \tan^{-1} \left(\frac{-V_{\theta_f} \sin \theta_f + V_{r_f} \cos \theta_f}{\sqrt{V_{\phi_f}^2 + (V_{\theta_f} \cos \theta_f + V_{r_f} \sin \theta_f)^2}} \right) \\ \psi &= \phi_f + \arctan \left(\frac{V_{\phi_f}}{V_{\theta_f} \cos \theta_f + V_{r_f} \sin \theta_f} \right)\end{aligned}\tag{2.12}$$

where θ and ψ are shown in Fig. 2.8.

2.7.6 Starting conditions for which calculations were made

Due to the dependance of the final asymptotic latitude and longitude upon the starting conditions, the tilt of the earth's axis at 23.5° to the ecliptic was included in all the calculations. The factors that alter the asymptotic directions are:-

- (i) different values of the cosmic ray rigidity
- (ii) different directions of arrival
- (iii) different positions of the earth with respect to the sectors
- (iv) different times of the year.

The rigidity dependance was studied by using rigidities in the calculations that covered the full range of the Holborn energy response. For this purpose rigidities of 100, 150, 200, 300, 500 and 9000 GV were used. The 9000 GV case served two purposes. Firstly it represented the high energy response (about 24% of the count rate) and secondly, since such a high rigidity would not be much affected by the interplanetary magnetic field, it

facilitated a check upon the validity of the results. In order that the results could be directly compared with observation, directions of arrival covered every even hour of the sidereal day. It was soon realized from the calculations that one of the most important factors affecting the final results was the position of the Earth with respect to the sector boundaries. Middle of sector positions allowed large deflections before encountering a field of opposite polarity, whereas, edge of sector positions caused different polarity fields to be sensed at different times of the day. The different times of year have been studied to see if the interplanetary magnetic field can produce an annual or bi-annual modulation. The inclusion of the tilt of the Earth's axis requires that for each position in the year the trajectories must be calculated separately since the initial pitch angle with the interplanetary magnetic field will be different for similar sidereal times. Solstitial and equinoctial positions of the Earth were chosen as the four different times throughout the year and in all sixteen different starting conditions have been used for each energy and for each time of the sidereal day.

This has produced a representative sample of cosmic ray trajectories relating to the vertical telescopes at Holborn throughout the year.

2.8 Results from trajectory integrations

Having integrated the equations of motion and found the asymptotic direction of arrival for a variety of energies, sector/Earth relationships, and times throughout the day and year the information obtained can be used in many ways. Looking at individual situations can only be satisfactory if interplanetary conditions prevailing upon that day conform to the ideal situation of the assumed Sun's field. For example, differences are easily seen between the different directions of view when a sector change occurs, or from being in a sector of different sign. However, the actual conditions prevailing, both in magnitude and direction of $\underline{B}$, will cause effects equally

as large as the observed ones mentioned before. Therefore, only averages of the asymptotic directions of view will be used, when it is hoped that the average properties of the interplanetary magnetic field will conform to the ideal situation assumed in the field model. Furthermore, the Holborn data are only significant if taken in long term batches and so daily correlations with field parameters are meaningless.

Three effects appear to be worth looking at:-

(1) The scan of the telescopes across the celestial sphere throughout a sidereal day. This can also be studied to see if the telescopes effectively "look" in different directions with different interplanetary magnetic field polarity.

(2) The smoothing effect the interplanetary magnetic field has upon a sidereal anisotropy external to the solar cavity. A phase shift like that caused by geomagnetic bending is not expected since the interplanetary magnetic field is not uni-directional. However, the interplanetary magnetic field will cause considerable smoothing and to see if a sidereal anisotropy will be detectable upon the Earth this smoothing must be evaluated.

(3) Correction of the observed sidereal anisotropy for the motion of the solar system. Also to see what, if any, annual modulation of the observed vector is caused by the interplanetary magnetic field.

2.8.1 Scans across the celestial sphere

Any particular arrival direction has had six trajectories calculated for a given set of starting conditions. The six trajectories correspond to rigidities 100, 150, 200, 300, 500 and 9000 GV and effectively cover the range of energies detectable by the Holborn installation. Each of those trajectories will, of course, have different asymptotic directions of viewing and in order to reduce the six to a mean direction for a given sidereal time, for a given set of starting conditions, the response function appro-

appropriate to the detector must be used to weight the individual results. Curve B is believed to be the best representation of the response of the Holborn detectors. Nevertheless, both B and C have been used in order to illustrate that even using curve C as the response function the interplanetary field is not completely successful in wiping out a genuine sidereal anisotropy as suggested by Swinson (1971a, b). The response function has been split into energy ranges where the trajectory energy (100, 150, 200 etc.) is the mean of the range and can therefore be considered representative of that range. The weights attached to the individual trajectories are listed in Table 2.IV below:-

WEIGHTS	Rigidity					
	100	150	200	300	500	9000
Curve <u>B</u> (Wolfendale) 1971	0.23	0.10	0.11	0.18	0.14	0.24
Curve <u>C</u> (Ahluwalia & Ericksen) (1971)	0.42	0.11	0.07	0.12	0.07	0.21

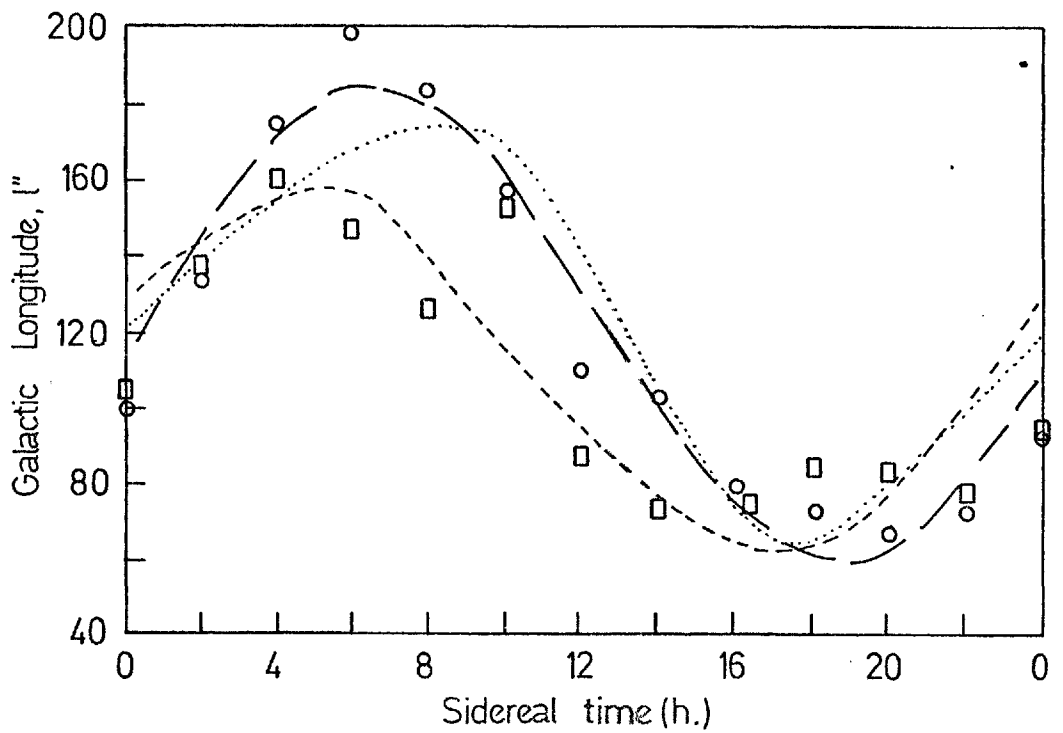
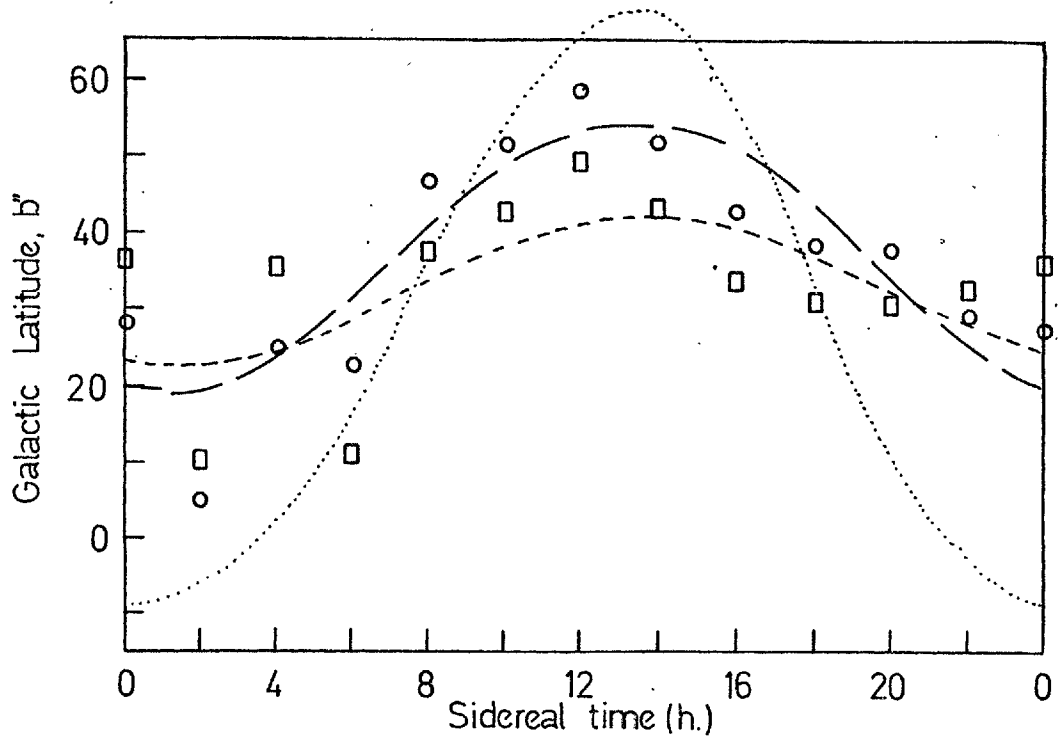
TABLE 2.IV

Despite the large weight given to the low energy end by the Ahluwalia weights, the smearing produced by the interplanetary magnetic field is not sufficient to obliterate a sidereal anisotropy entirely, as will be seen later.

Weighted results for a given time of year and Earth/sector position were then transformed from the solar equatorial system of co-ordinates into the galactic system using Euler angles. Mean values of the asymptotic galactic latitude and longitude were then found from the 16 different starting conditions for each bi-hour of the sidereal day. 8 of the starting conditions were for the Earth in the middle of a particular sector, positive

or negative. These 8 values were used to see if the interplanetary magnetic field polarity caused the direction of viewing to be substantially altered, in particular to see if it could cause a twelve hour phase difference between the observed anisotropy.

Fig. 2.9 shows the galactic scans produced, assuming curve B and curve C weights, also the scan produced if the interplanetary magnetic field was not present. Each set of points has its corresponding best fitting sine curve plotted. Curve B has been used to produce Fig. 2.10 to illustrate the difference in scanning produced when the data are split according to the polarity of the field direction; again the first harmonics have also been plotted. Clearly, it can be seen, from Fig. 2.9 that the scans produced by assuming different response functions only reflect the emphasis put upon the low energy end of the spectrum. Using curve B, where the low energy contribution is believed to be small, the galactic scan is similar to that due to infinite energy particles, however, curve C, using a large proportion of low rigidity particles, smears out the variation expected. The possible phase lag introduced in the galactic longitude could be due to the "bunching" of asymptotic longitudes of particles (particularly low rigidity) when the Earth is in the middle of a sector. When a particle is in a sector and is travelling in such a direction that it will remain within that sector for some time, then the deflection produced can be large, depending upon the rigidity. In this way even relatively high energy particles (up to 300 - 500 GeV) can be caused to bunch in one particular galactic longitude. Obviously, the response function that favours lower energies will reflect such a behaviour in its final result. These results have been plotted on a galactic system of co-ordinates in Fig. 2.11. The scan plotted only indicates that produced for a detector of zero acceptance cone. In practice with an opening angle of $\sim 90^\circ$ and a cone of half width $\sim 15^\circ$ at half maximum sensitivity this thin line would become a broad band sufficient to encompass the majority of the celestial objects within the galactic co-



---□ Ahluwalia weights —○ Wolfendale weights

Fig. 2.9 Scans in galactic latitude and longitude as a function of sidereal time for a vertical telescope at London. Symbols are calculated values; lines are best fitting sine curves. The dotted line is the scan produced by considering only infinite energy particles.

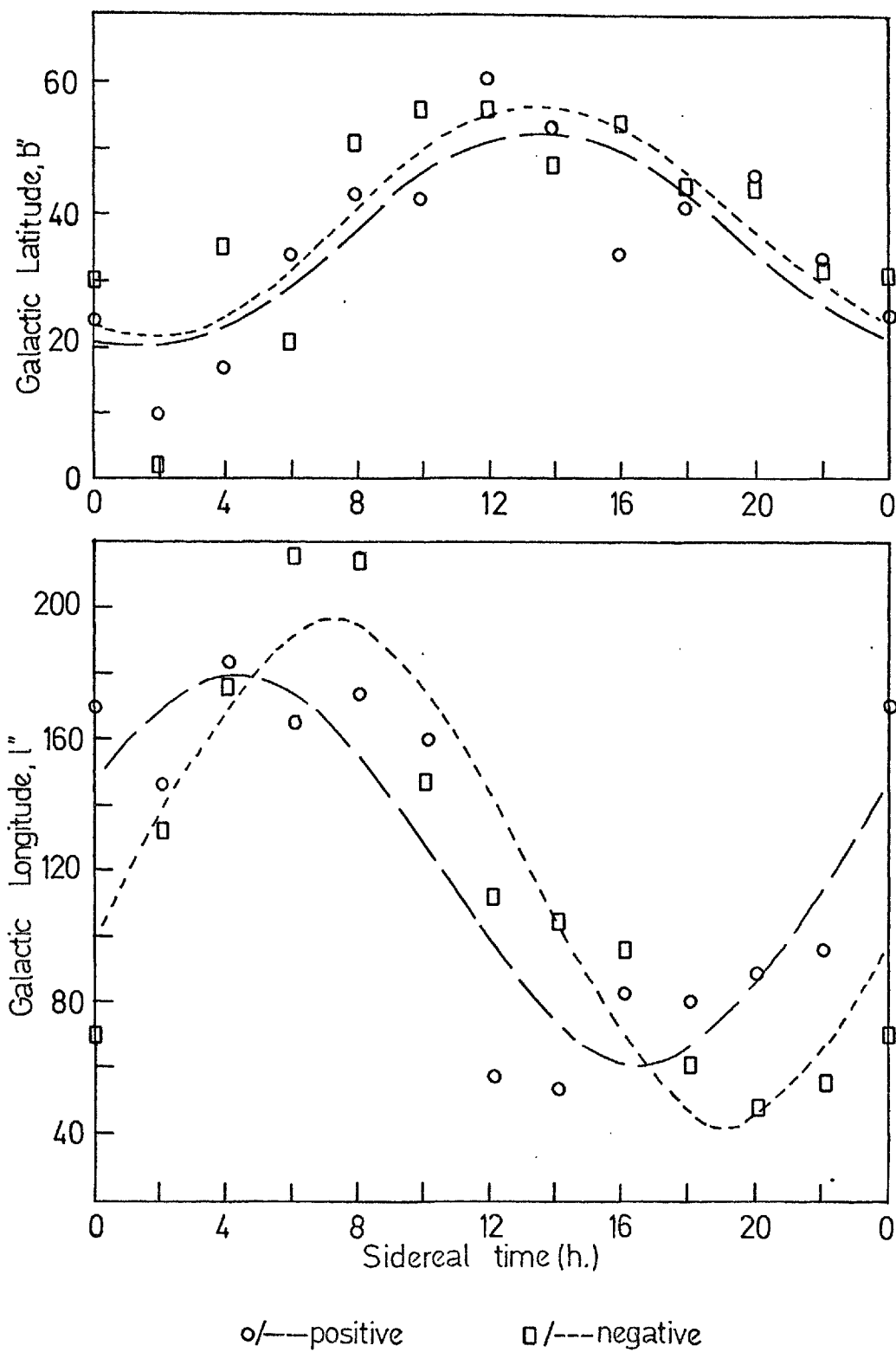


Fig. 2.10 Scans in galactic latitude and longitude as a function of sidereal time for different polarities of the inter planetary field. Symbols are calculated values; lines are best fitting sine curves.

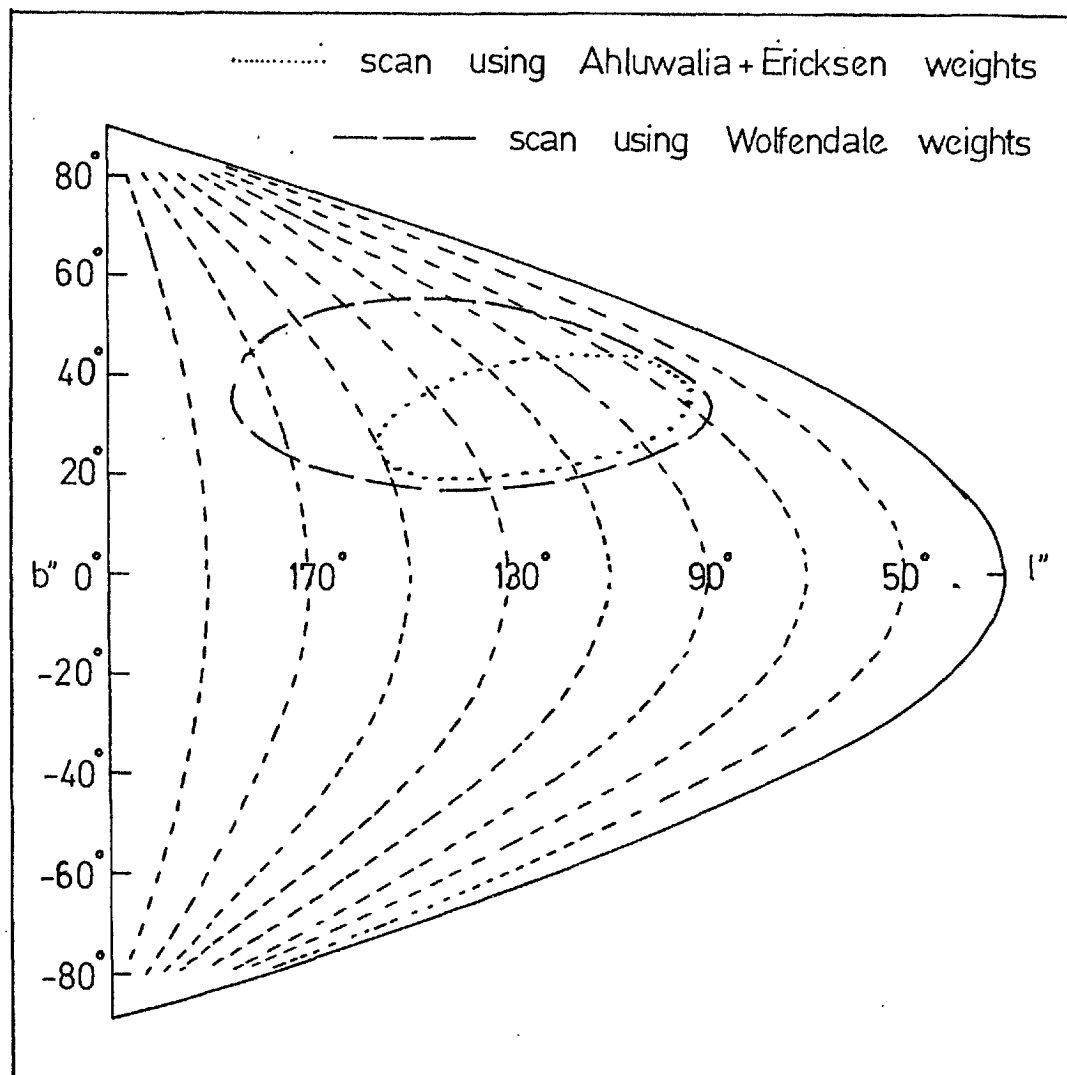


Fig. 2.11 Scans across the galactic sphere produced by the vertical telescopes in London assuming two different response functions.

ordinates $l'' = 0$ to 180° and $b'' = 0$ to 90° N. It is clear that the curve produced using the Ahluwalia response function does not have such a large scan nor does it encompass such a large area of the celestial sphere. However, it does still produce a scan sufficient to include a comparable area of the celestial sphere.

Fig. 2.10 indicates different viewing directions within the galaxy for different directions of the interplanetary magnetic field. The latitude scans are very little different, but, phase differences do appear in the longitude, of about 3 hrs. Swinson's effect produces a phase difference of about 12 hrs between data for different field directions. However, Swinson's effect is due to spiralling around field lines and has very little to do with guiding centre motion which is what the trajectories indicate. Nevertheless it is possible to imagine even greater phase differences being introduced into the directions of viewing if lower energy primaries are considered, as would be detected by Swinson at 25 m.w.e. (vertical). The separation indicated by Swinson (1971b) for both Bolivia and Embudo, when the interplanetary field is considered, is about 6 - 8 hrs and therefore the different directions of viewing when in different polarity interplanetary magnetic field, must also be considered in Swinson's data. In other words, if the source of the sidereal variation is external to the solar vacuity, a difference introduced by different polarity interplanetary magnetic field can be expected and must be accounted for.

2.8.2 The smoothing effect of the interplanetary magnetic field

In order to evaluate this smoothing effect one particular variation has been studied - that caused by the motion of the solar system relative to the galactic frame of reference. Any sidereal variation measured on the Earth must be corrected for this solar system motion before any useful deductions can be made concerning the origin of the sidereal variation. The magnitude of this correction depends upon the energy dependence of the

interplanetary smoothing effect and the response function of the detector.

The magnitude of a sidereal variation at any given time, t , is proportional to $\cos[\alpha(t)]$ where $\alpha(t)$ is the angle between the asymptotic direction of view of the telescope and the axis of the anisotropic flux. In the case of the solar system motion effect the axis of the Compton-Getting type flux is in the direction of the Solar Apex i.e., $RA = 18$ hrs, $\delta = 34^\circ N$. $\alpha(t)$ will vary throughout the day according to the scan the telescope axis makes upon the celestial sphere. However, the peak to peak variation is primarily a function of the rigidity of the particles considered and the inclination between the telescope axis and the axis of the rotating Earth. For the Holborn vertical telescopes the latter variable is fixed and the effect of the first can be evaluated. Values of $\cos(\alpha)$ were calculated for each even hour of the sidereal day for the 16 different starting conditions considered earlier and for each rigidity; 100, 150, 200, 300, 500 and 9000 GV. The 9000 GV values gave the maximum possible variation in the value of $\cos(\alpha)$ throughout the day, since, effectively these particles undergo rectilinear propagation and are unaffected by the solar field. These values of $\cos[\alpha(t)]$ have been plotted in Figs. 2.12, 2.13, 2.14. Individual results, mean values and best fitting sine curves have all been plotted for each individual energy. Clearly, the asymptotic directions of low rigidity primaries depend critically upon the rigidity and starting conditions, with the result that the interplanetary magnetic field can be expected to smear out any cosmic ray anisotropy dependant upon magnetic rigidities of less than ~ 150 GeV. This behaviour is indicated by the extreme scatter in the results and the relatively small amplitude of the mean expected curve. The amount of scatter diminishes, and can be seen to become quite small, at rigidities greater than ~ 300 GV. Thus, by using the 9000 GV trajectories as indicating the true magnitude of the $\cos(\alpha)$ variation, the smoothing effect at different ranges is indicated in Fig. 2.15. Clearly, a detector with very little response above 100 GV will see very little sidereal effects due to the

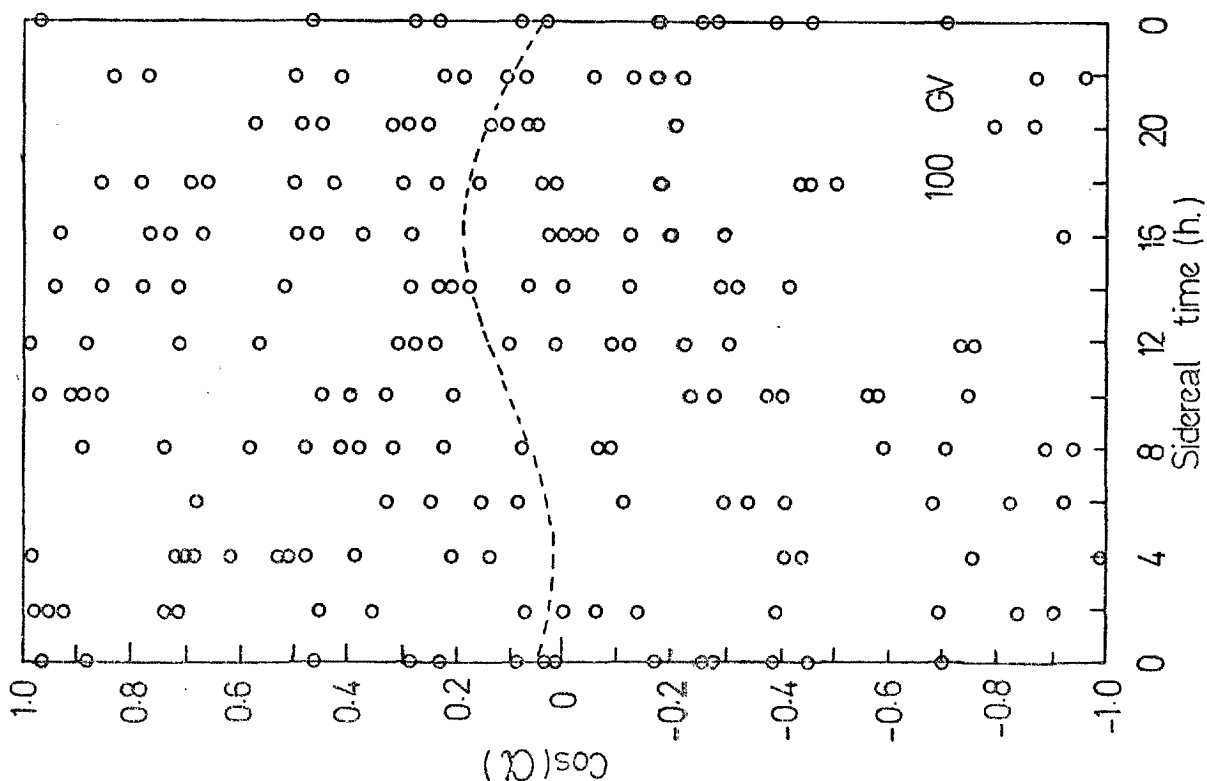
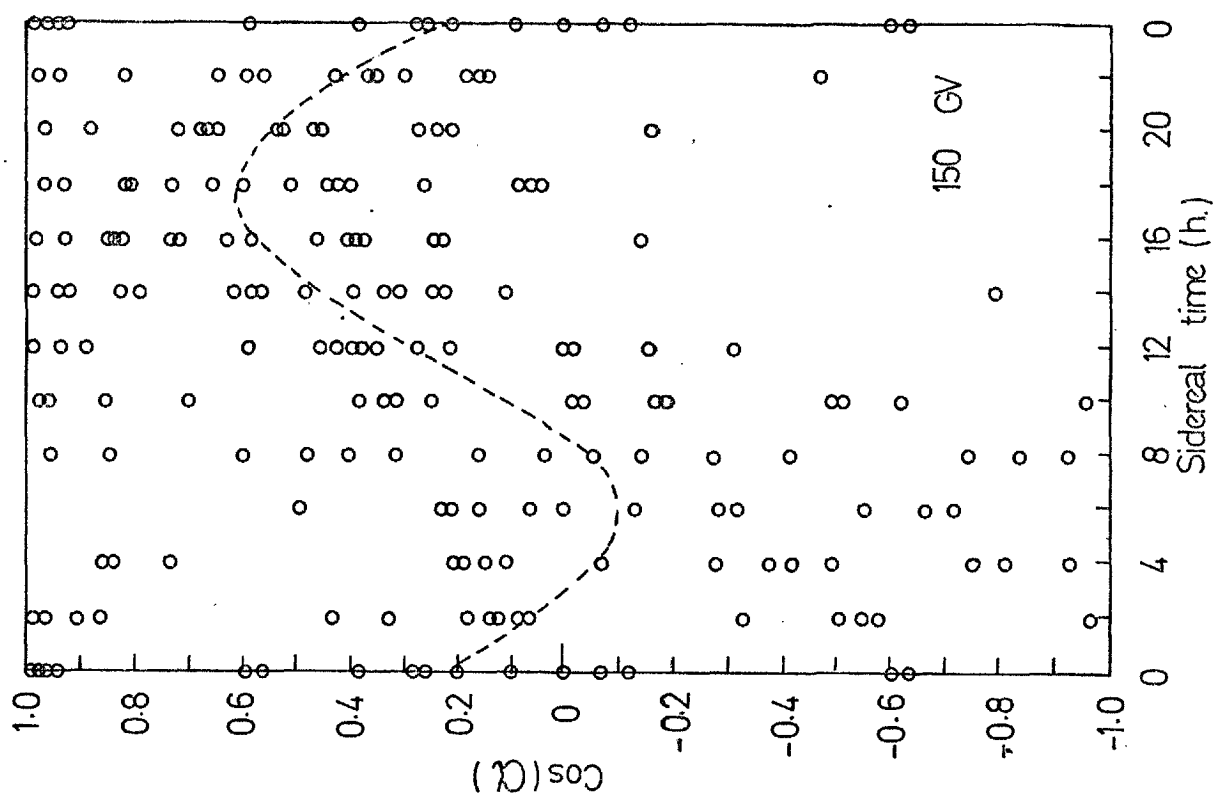


Fig. 2.12 Angular scans of a muon telescope at Holborn relative to the solar apex for primaries of rigidity 100 & 150 GV. " α " is the angle between the solar apex and the effective viewing direction for the 16 starting conditions given in the text. The curve is the best fitting sine curve of the mean values.

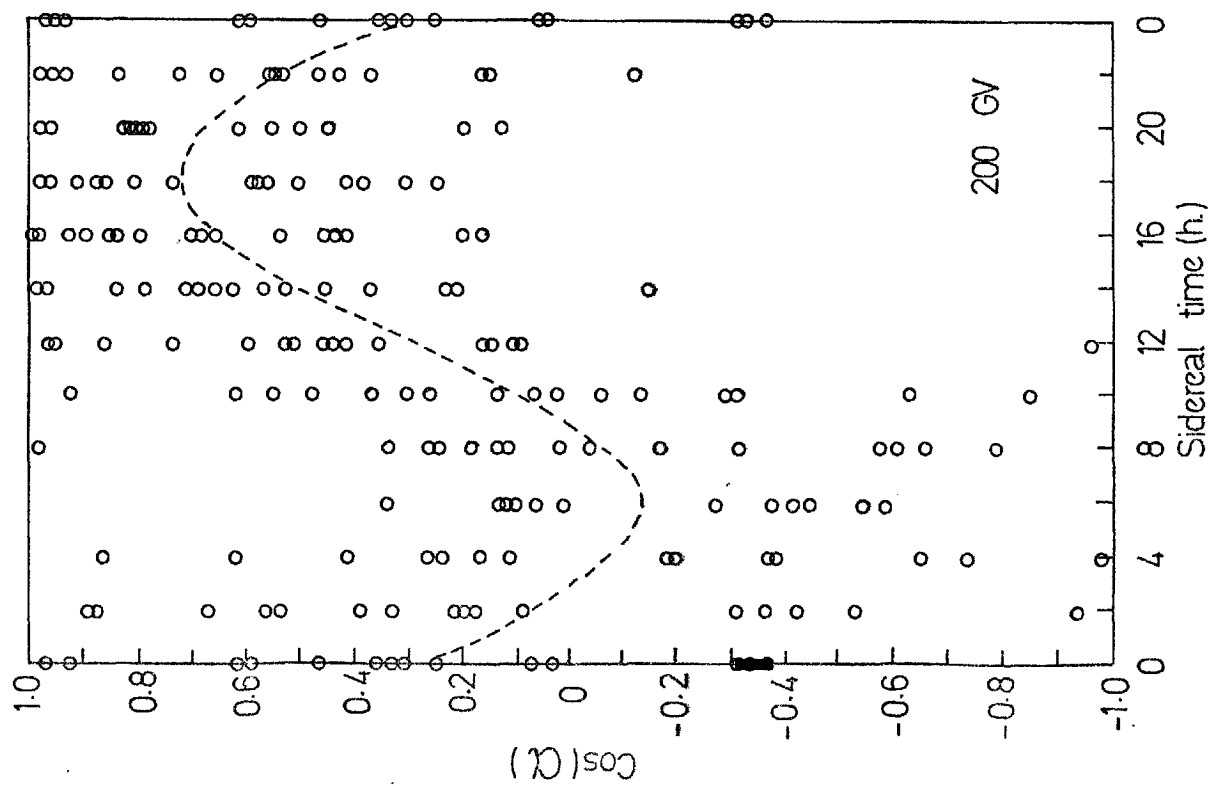
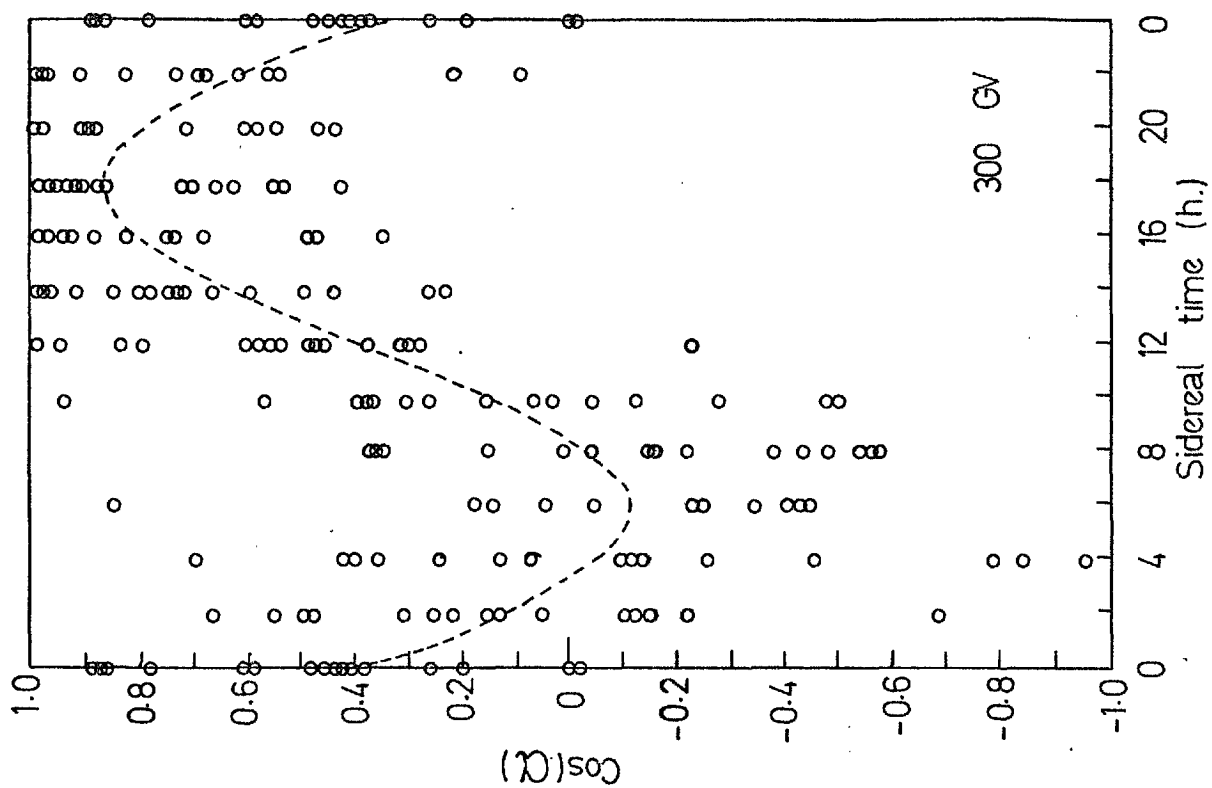


Fig. 2.13 As for Fig. 2.12 but for rigidities 200 & 300 GV.

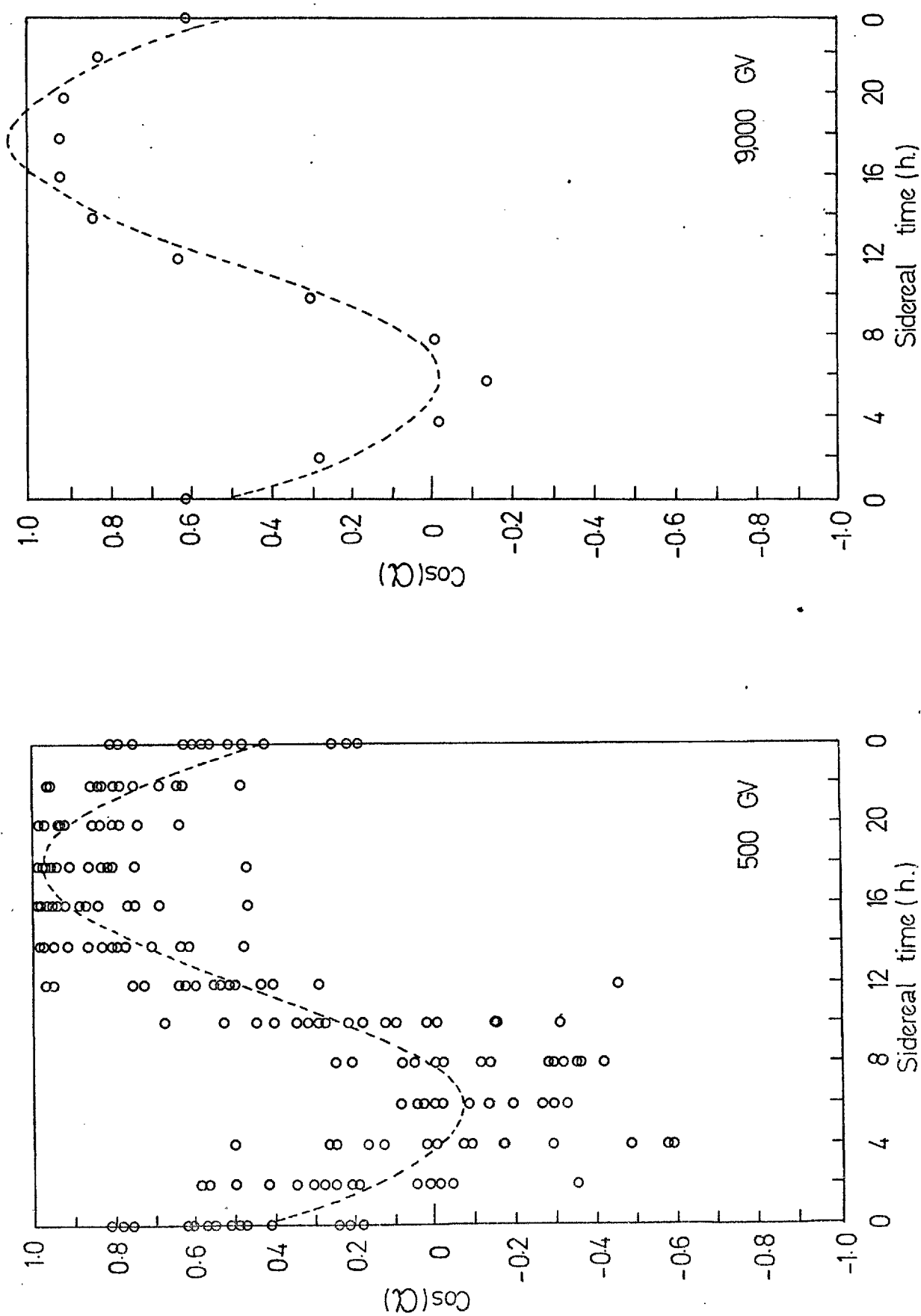


Fig. 2.14 As for Fig. 2.12 but for rigidities 500 & 9000 GV.

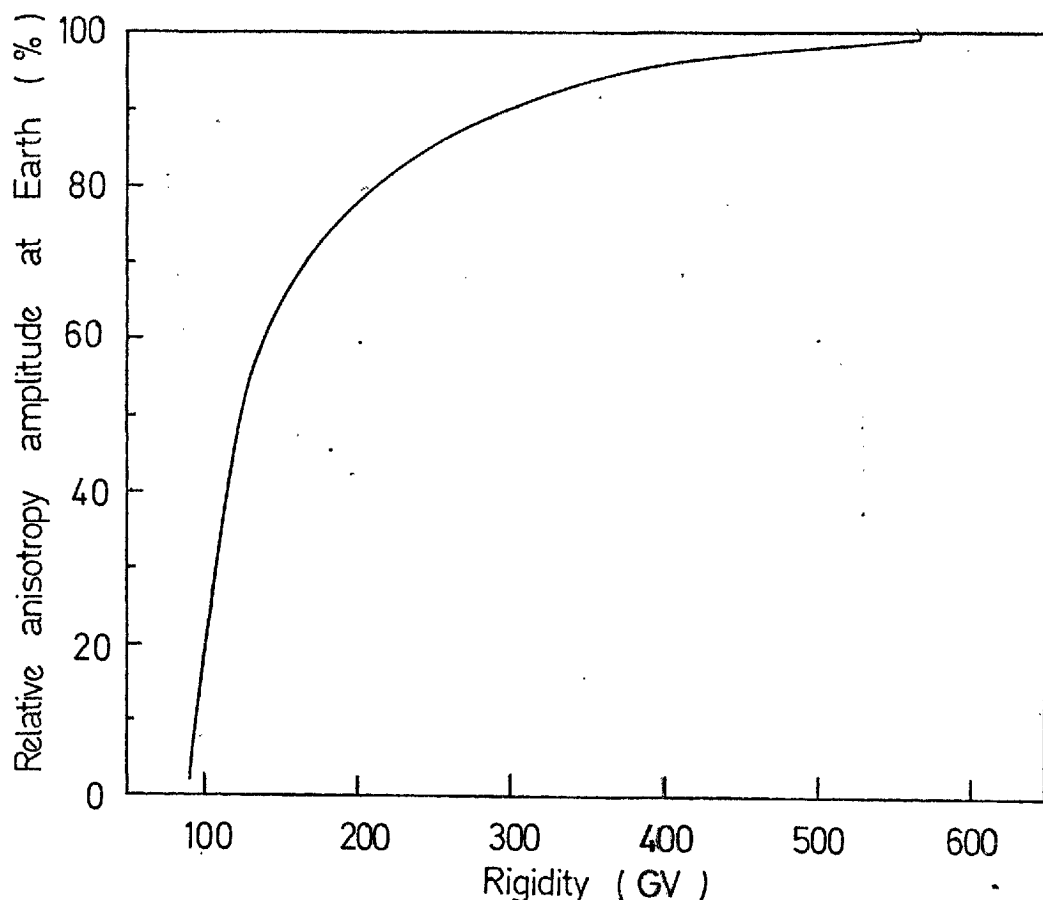


Fig. 2.15 The amplitude of the sidereal anisotropy at the Earth relative to the amplitude outside the solar cavity for different energy cosmic rays. Solar cavity radius = 50 A.U..

screening of the interplanetary magnetic field. However, a detector with a considerable portion of its response above 150 GV can hope to see a sidereal effect quite clearly, such is the case for the Holborn detector. Using the best fit sine curves to the values of $\cos(\alpha)$ for the different energy primaries, and the response function curve B , the mean value of $\cos[\alpha(t)]$ over the whole year, and energy range of the detector, can be found and this is plotted in Fig. 2.16. The 9000 GV curve is repeated for comparison. Again using the 9000 GV case as a measure of the maximum variation, and if a years data from the Holborn detector is considered, smoothing by the interplanetary magnetic field will reduce the observed amplitude by approximately 25%. Thus it has been shown that provided the response of the detector extends well beyond 150 GV the smearing of a genuine sidereal variation is only a minor perturbation upon the overall observations. On the other hand, detectors monitoring particles in the range 1 - 100 GV can

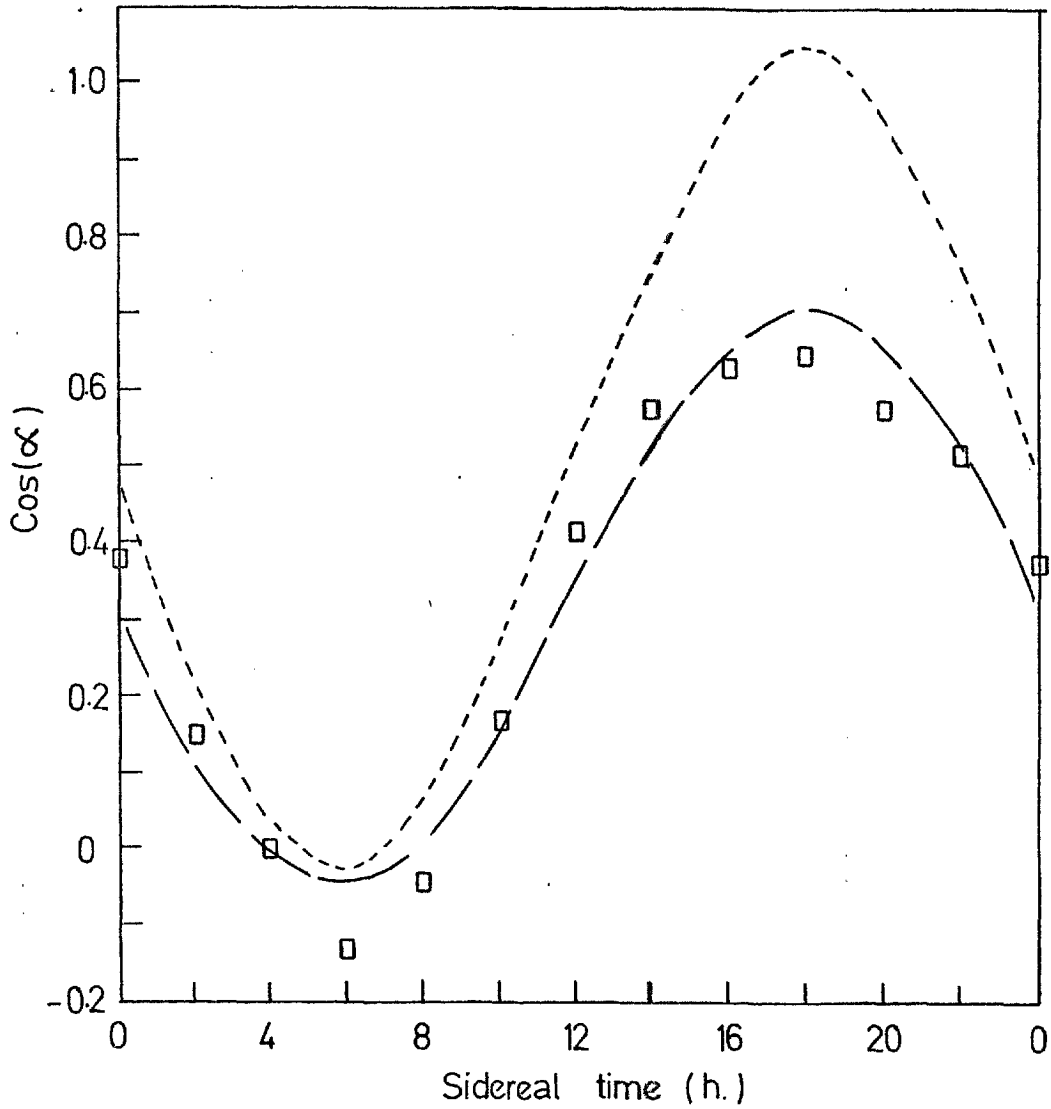


Fig. 2.16 Mean response function weighted values of $\cos \alpha$ (□) throughout the sidereal day. For comparison the 9000 GV case is included (-----).

have little hope of seeing a sidereal anisotropy external to the solar cavity.

2.8.3 Correction of the observed sidereal vector for the solar system motion

If the radiation is assumed to be completely isotropic in the frame of reference of the galactic rotation then the angular distribution seen by an observer in the solar system is,

$$I(t) = I_0 \left[1 + (2 + \gamma) \frac{v}{c} \cos(\alpha(t)) \right] \quad (2.13)$$

where I_0 = mean intensity, γ = exponent of the differential energy spectrum
 v = the velocity of the solar system relative to the galactic frame and α is

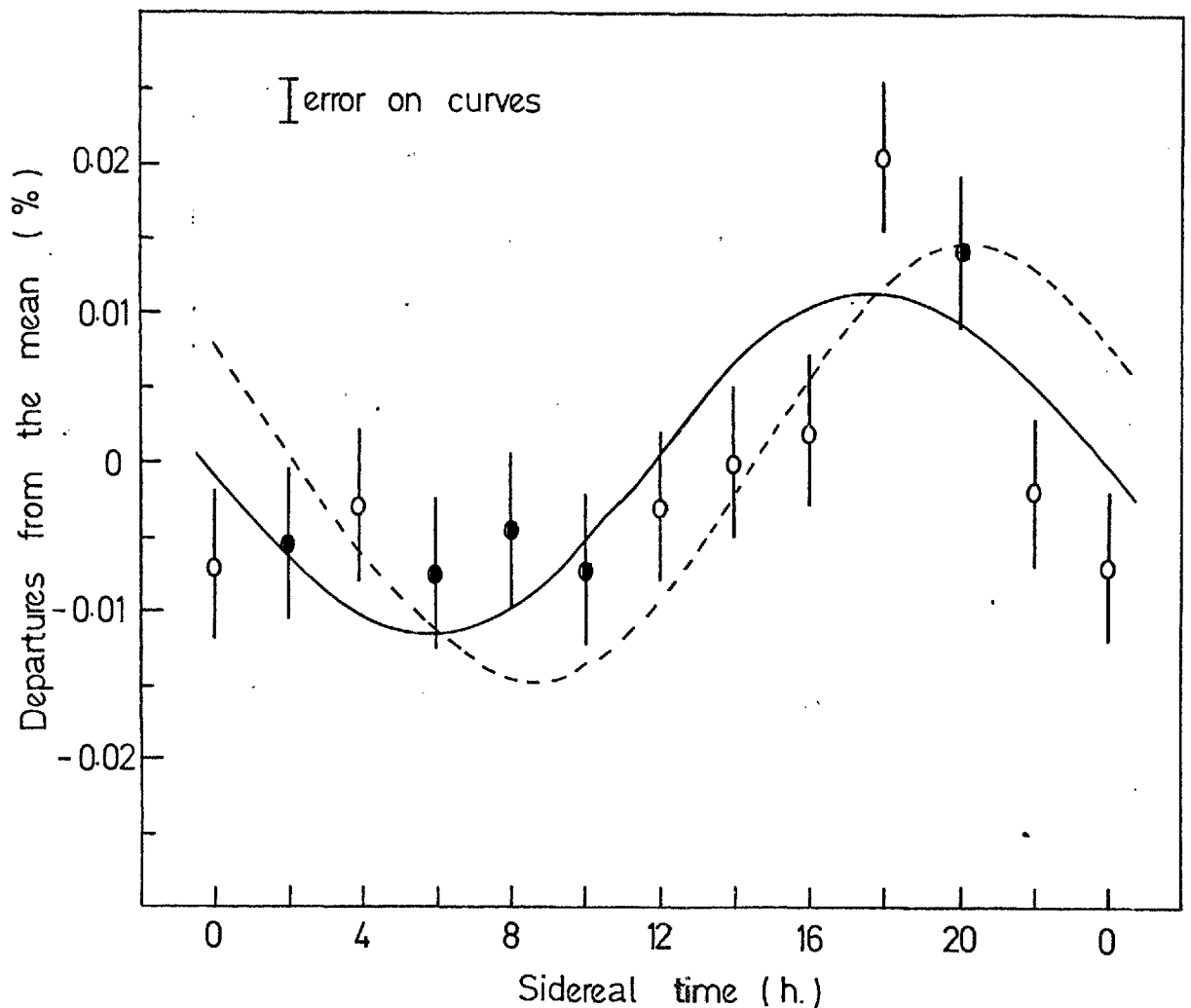


Fig. 2.17a Comparison between the bi-hourly cosmic ray departures from the mean observed at 60 m.w.e. depth and the variation to be expected in the basis of solar motion towards the generally accepted apex (—) and that corresponding to the streaming of interstellar hydrogen deduced from Lyman α observations (---). [Using Wolfendale response function.]

the angle between the direction of viewing and the direction of the solar system motion. Using the mean response function weighted values of $\cos \alpha$ from Fig. 2.16, $\gamma = 2.5$ and $v = 20$ km/sec, values of $I(t)$ have been found and these are plotted in Fig. 2.17a as the solid line. For this curve the generally accepted direction of solar motion has been used; the solar apex. Recently Lyman α observations of interstellar hydrogen that has penetrated the solar system have suggested that the interstellar medium appears to be streaming from a direction $\sim 50^\circ$ distant from the apex (Chambers et al. (1970), Thomas and Krassa (1971), Bertaux and Blamen (1971)). If this neutral hydrogen represents the interstellar medium in the galactic frame of reference

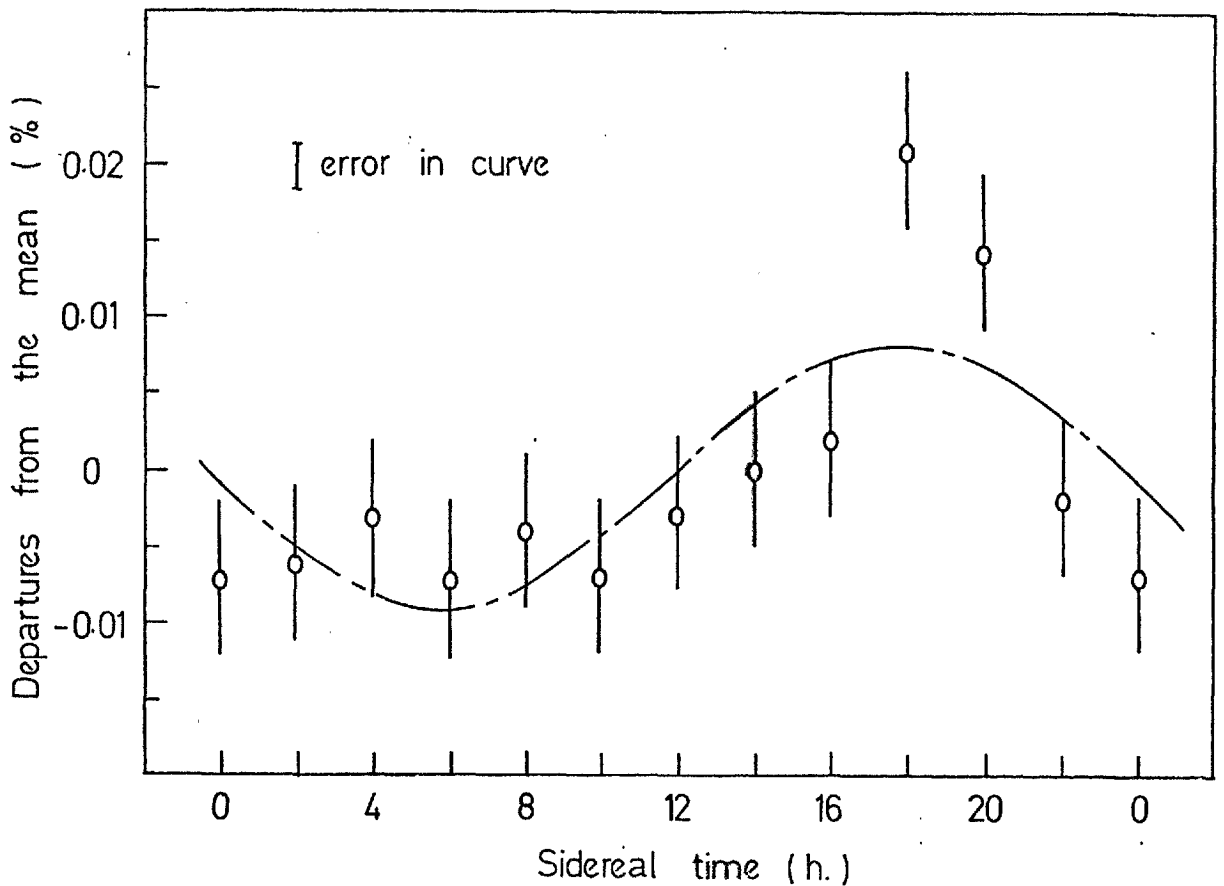


Fig. 2.17b Comparison between the bi-hourly cosmic ray departures from the mean observed at 60 m.w.e. and the variation to be expected as the basis of solar motion towards the generally accepted apex. [Using Ahluwalia response function.]

then the Compton-Getting effect will again be given by equation (2.13) but with α equal to the angle between this interstellar hydrogen streaming direction and the direction of viewing. Using this new solar motion direction produces the dotted curve of Fig. 2.17a. Also given in Fig. 2.17 are the average bi-hourly departures from the mean plotted in sidereal time for the whole period of observation. The data have been corrected for variations in barometric pressure and the error bars are standard deviations appropriate to the bi-hourly count rate. The errors in the calculated curves have been obtained from the scatter in the results of Figs. 2.12, 2.13 and 2.14 and are indicated in the top left hand corner of Fig. 2.17. A further curve has also been found using the solar apex as the direction of the solar system motion but using values of $\cos(\alpha)$ that have been weighted with Ahluwalia's response function. This curve is plotted in Fig. 2.17b.

Very little difference exists between the calculated curves indicating that even if Ahluwalis's response function for the Holborn detector is regarded to be correct, the observation of a sidereal anisotropy due to solar motion is little affected. The different assumed direction of solar motion has little affect upon the predicted variation and within the errors neither can be chosen as more correct. The agreement between the data and the calculated curves is good. Fig. 2.18 shows the residual variations after subtracting from the data those variations expected from solar motion in the apex direction. These residuals can now be considered as the sidereal variation that exists external to the solar cavity and in the galactic frame of reference. Harmonic analysis of these residuals yields the vectors plotted in Fig. 2.19. Clearly from Figs. 2.18 and 2.19 any residual variation left in the data, after correction for the motion of the solar system, falls within the errors and hence below the level that is detectable at Holborn.

2.8.4 Bi-annual modulation of the sidereal vector due to the rotating solar structure

It was shown in Section 2.4.2 that the measured amplitude of the sidereal variation had a twice yearly modulation and this was shown to be plausible when one considered the large deflections of cosmic rays from the sunward direction. The anisotropy is given by,

$$\delta = \frac{I_{\max} - I_{\min}}{\frac{1}{2}(I_{\max} + I_{\min})} = \frac{(I_{\max} - I_{av}) - (I_{\min} - I_{av})}{\frac{1}{2}(I_{\max} + I_{\min})} \quad (2.14)$$

and this will have its maximum values where either $(I_{\max} - I_{av})$ has its maximum value or $(I_{\min} - I_{av})$ has its minimum value and this will occur twice yearly when the directions of $I_{\min}$ and $I_{\max}$ are sun or anti-sunward.

The trajectory calculations have been used to see if they predict such an effect if the motion of the solar system is assumed to be the cause of

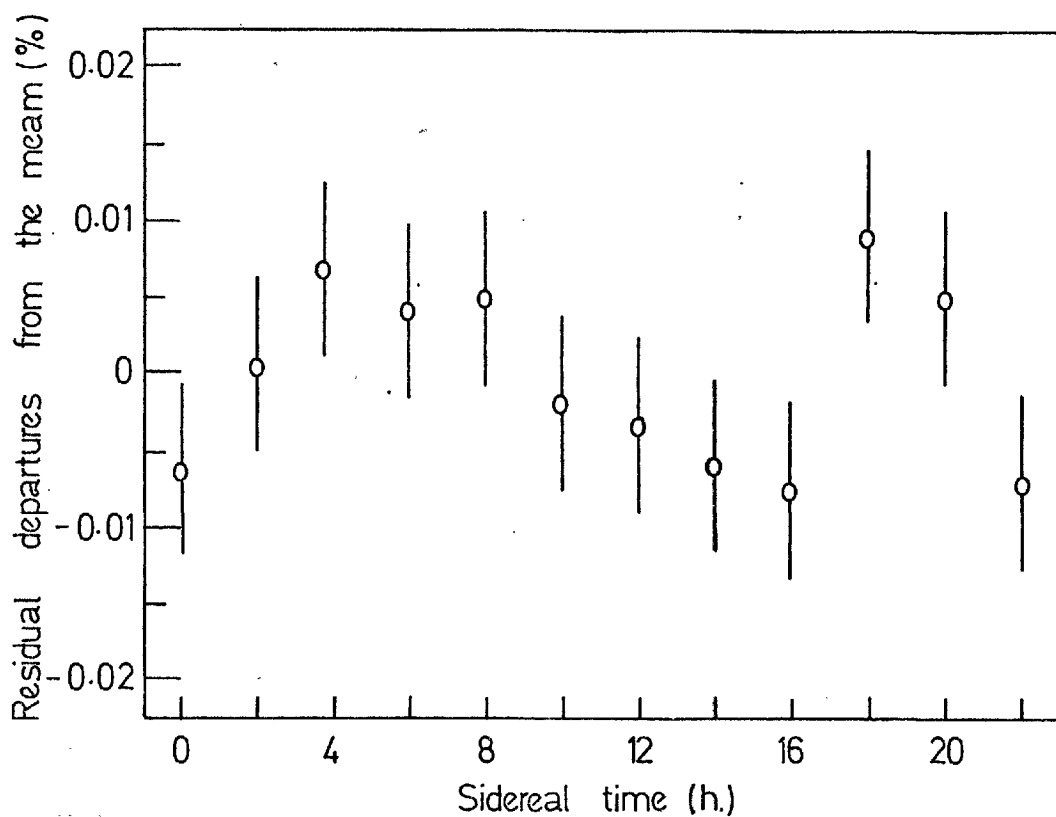


Fig. 2.18 The bi-hourly residual departures of the muon intensity at 60 m.w.e. after correction for solar motion.

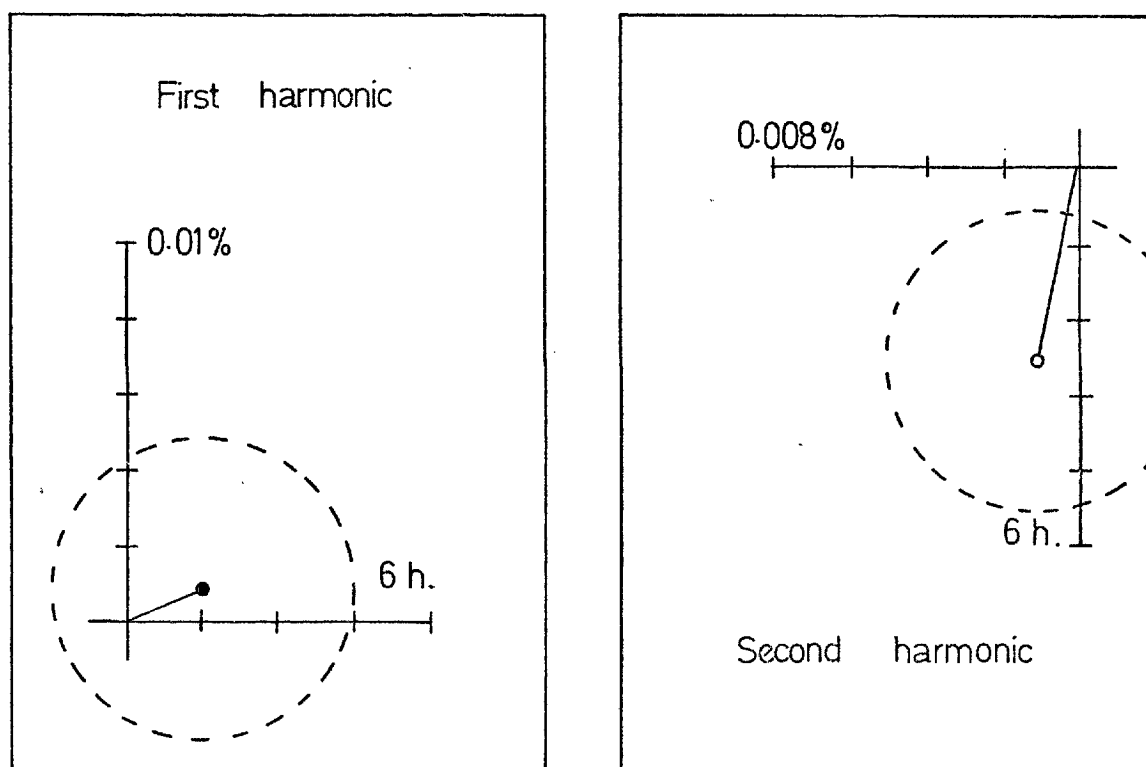


Fig. 2.19 Sidereal time dials showing the first and second harmonics of the residual bi-hourly departures of Fig. 2.18 after correcting for solar motion.

of the observed sidereal variation. The mean response function weighted values of $\cos[\alpha(t)]$ have been found for the four times throughout the year considered. The amplitudes of the curves indicate a modulation throughout the year although harmonic analysis of the modulation cannot be carried out on only four values.

To indicate this behaviour more clearly the amplitude in arbitrary units has been plotted against the time of year in Fig. 2.20; also plotted for comparison are the observed amplitudes of the months for which trajectory calculations have been carried out. The correlation is impressive. The calculated amplitude modulation indicates an annual, as well as bi-annual, modulation. However, the errors involved in the observed data are too large to indicate if this annual modulation is also present. Such an annual modulation would be expected to be present if the axis of the anisotropy is not in the ecliptic plane, and such is the case for the solar system motion. Further data might reveal the presence of this annual modulation, however, since the anisotropy axis is only inclined at $\sim 10^\circ$ to the ecliptic it seems unlikely that this would be detectable.

2.8.5 Summary of results for trajectory calculations

(1) Only mean values from several starting conditions seem sensible due to the large dependence upon the starting conditions.

(2) Little difference occurs between the conclusions drawn whatever form one assumes for the response function i.e., either curve B or C.

(3) Scans across the celestial sphere appear energy dependent as expected, also phase lags in longitude can occur for different polarities of the interplanetary magnetic field.

(4) The smoothing of the interplanetary magnetic field was shown to be considerable for a telescope with response in the range 1 - 100 GV: however, if a large proportion of the count rate is due to primaries above 150 GV a sidereal variation can still be observed. For Holborn the interplanetary magnetic field causes a reduction in amplitude of an anisotropy

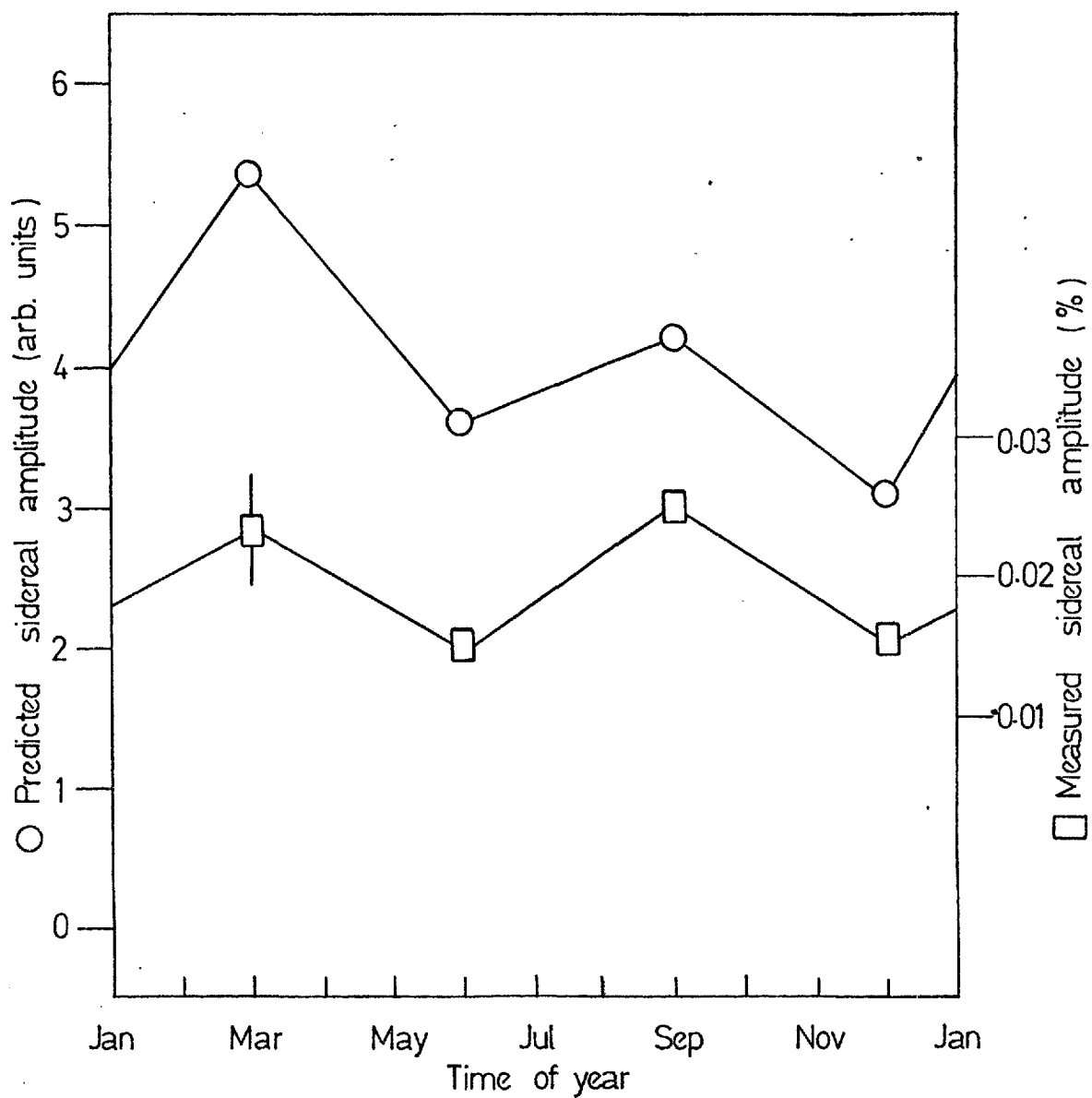


Fig. 2.20 Comparison between the observed and predicted bi-annual modulation of the sidereal vector.

external to the solar cavity by about 25%.

(5) The correction of the Holborn data for the solar system motion gives zero amplitude to the sidereal anisotropy in the galactic rotation frame. Further, bi-annual modulation is predicted in the Holborn data as seen in the observed results and correlation between the predicted and observed results is impressive. It is this modulation which produces part of the observed anti-sidereal vector.

2.9 The implications of the high degree of isotropy and the possible origins of cosmic rays

The high degree of isotropy ($0.002 \pm .004\%$) obtained from the corrected Holborn data puts severe limitations upon cosmic ray production and propagation. Two alternatives exist, one that cosmic rays of 100 to 1000 GeV are essentially galactic "citizens" or two, such particles exist throughout the universe. These two possibilities will be examined separately.

2.9.1 Galactic origin of cosmic rays

If cosmic rays are produced and contained within the galaxy then the observed isotropy has to be explained by diffusion and containment in the galactic field with a suitable source distribution. The cosmic ray anisotropy is given by the Compton-Getting relation:-

$$\delta = (2 + \gamma) \frac{v}{c} \quad (2.15)$$

where v is the bulk streaming velocity

c is the velocity of the particles

and γ is the exponent of the differential energy spectrum

As $\delta \leq 10^{-4}$ (using the upper limit of the Holborn observations) and $\gamma \approx 2.5$ this gives $v < 10$ km/sec.

The life-time of cosmic rays is usually estimated as that amount of time required to produce the high relative proportion of Li, Be and B in the

primary beam by fragmentation of the heavier cosmic ray nuclei. The high proportion of these elements indicates that approximately 3 gm cm^{-2} of material has been traversed. The density of interstellar hydrogen is believed to be ~ 1 hydrogen atom/cc which indicates that the cosmic ray nuclei have travelled approximately $2 \times 10^{24} \text{ cm}$. For relativistic particles, their velocity being equal to c , this distance gives a lifetime $\tau = 7 \times 10^{13} \text{ secs}$ $\sim 2.5 \times 10^6$ years. A cosmic ray of $3 \times 10^{11} \text{ eV}$ in a field of 10^{-6} Oe (believed to be the magnitude of the galactic field) has a cyclotron radius of $\sim 10^{15} \text{ cm}$ which is much less than the thickness of the galactic disc, $\sim 10^{21} \text{ cm}$. Thus such a cosmic ray is deeply embedded in the galactic disc, effectively trapped and has as its only exit, the ends of the spiral arms. The upper limit on the bulk streaming velocity of 10 km/sec in a lifetime of $\sim 10^6$ years allows a mean traversal of $\sim 10 \text{ pc}$, however, the only exit is $\sim 5 \times 10^4 \text{ pc}$ away, the length of the spiral arms, and therefore the escape of cosmic rays within 10^6 years seems impossible. That is, with a magnetic field everywhere parallel to the plane of the disc, it is not possible for cosmic rays to escape from the galaxy rapidly enough to account for their observed lifetimes and still be consistent with the observed upper limits on anisotropies.

Lingenfelter et al. (1971) have resolved this problem by assuming compound diffusion (diffusion of cosmic rays along the field lines with the diffusion of the field lines themselves) in a stochastic field of the kind discussed by Jokipii and Parker (1969). Previous attempts using streaming of cosmic rays along 3-dimensional-random-walked field lines, Ramaty et al. (1970), requires irregularities in the interstellar medium of $\lesssim 10^{-1} \text{ pc}$ which is much less than the observed interstellar gas clouds of diameter 10 pc with separation $40 - 100 \text{ pc}$ (Allen (1963)). The turbulent motions of these gas clouds cause the galactic field lines to diffuse in three dimensions with the result that field lines will reach the edge of the galactic disc every few thousand light years. The cosmic ray pressure in a flux

tube near the surface of the disc is sufficient to cause the tube to expand, penetrating the galactic halo, and allowing the cosmic rays to escape from the galactic disc much earlier than if they had to travel the length of the spiral arm. Lingenfelter et al. (1971) show that compound diffusion of this type leads to a lifetime of

$$\tau = \frac{L^4}{l_1 l_2^2 c} \quad (2.16)$$

where L is the distance between escapes of the cosmic rays into the halo, and l_1 = scattering mean free path for one dimensional diffusion of cosmic rays and l_2 = characteristic length of the random interstellar field distribution. Using $L = 1,500$ light years, reasonable values for $l_1 = l_2 = 100$ l.yrs. gives $\tau = 5 \times 10^6$ yrs, which is the lifetime required to explain the properties of Li, Be and B in the cosmic ray beam. Furthermore; using the ideas of compound diffusion with a statistical source distribution of supernovae once every 100 yrs in the galaxy, Lingenfelter et al. predict anisotropies of:-

$$\begin{aligned} \delta &= [1.4 \quad +3.1 \\ &\quad -0.9] \times 10^{-4} \quad \text{for } \tau = 5 \times 10^6 \text{ yrs} \\ \delta &= [0.75 \quad +1.9 \\ &\quad -0.5] \times 10^{-4} \quad \text{for } \tau = 15 \times 10^6 \text{ yrs} \end{aligned} \quad (2.17)$$

for $l_1 = l_2 = 100$ l.yrs, where the limits are 1σ levels and reflect the uncertainty in the positions and ages of the closest cosmic ray sources. It is clear that the upper limit to δ measured at Holborn is consistent with both these lifetimes and therefore compound diffusion appears to supply the explanation of the very high degree of isotropy. However, although supernovae have long been favourite candidates as cosmic ray sources as assumed in the calculations above, Gold (1969) has suggested that pulsars could be possible sources of cosmic rays. If this is the case, due to the proximity of some of the pulsars, the statistical source distribution assumed above is no longer valid and Lingenfelter (1969) has considered the possible effects

such objects could produce in an Earth-sited detector. Using supernovae remnants as indicators of pulsars he obtains a table of pulsar ages and distances and by using simple diffusion he estimated the contribution to the local cosmic ray energy density due to each pulsar. Of all the pulsars, PSR 1929 + 10 with an estimated age of $\sim 6 \times 10^4$ yrs was the most prominent and should provide approximately 20% of the presently observed cosmic ray flux. Other possible sources, with their contributions to the count rate are PSR 1451 ($\sim 9\%$), PSR 1642 ($\sim 4\%$), PSR 0736 ($\sim 3\%$) and PSR 0950 ($\sim 1\%$). The flux suggested for PSR 1929 would produce an anisotropy $\delta \approx 4$ to 10×10^{-4} which should easily be observable in this experiment. However, further evidence on PSR 1929 (Hunt (1971)) has put the lifetime nearer 3×10^6 yrs, in which case, the flux due to the pulsar is below the statistical noise level of the experiment.

Therefore it has been shown that statistical source distributions with no strong nearby sources and compound diffusion can explain the observed isotropy. However, the other source characteristics required for a complete explanation of the origin of cosmic rays need to be considered. The method of acceleration of cosmic rays to the extremely high energies observed has long been a source of investigations. Fermi suggested a process whereby cosmic rays are accelerated by repeated scattering off of moving magnetized plasma clouds throughout the galaxy. However, the observed properties of the gas clouds implies too long a cosmic ray lifetime to produce the required effects and instead it has been suggested that regions of more violent plasma motions must be sought. Violent motions of magnetized plasma occur in active objects in the galaxy, e.g., supernovae explosions, pulsars and white dwarf stars. Furthermore, with an energy density in the galaxy of ~ 1 eV/cm³ ($= 10^{-12}$ ergs/sec) and a galactic volume of 10^{67} cm³ the total energy within the galaxy is $\sim 10^{55}$ ergs. This energy must be replaced every 7×10^{13} secs (the cosmic ray lifetime) and therefore requires from the cosmic ray source an energy production rate of $\sim 10^{41}$ ergs/sec.

The natural high abundance of $Z > 10$ nuclei and the observation of very high energy electrons in their remnants make supernovae an attractive candidate for the source. With an energy output of $\sim 10^{51}$ ergs per explosion and a frequency of one every 50 yrs (1.5×10^9 secs) the energy output per sec is $\sim 6 \times 10^{42}$ ergs/sec and with approximately 1% conversion efficiency this just makes supernovae possible sources. However, explosions only once every 50 yrs within the whole galaxy implies that at any one time only ~ 30 supernovae would be active. With galactic length approximately 30 times galactic thickness, the cosmic ray flux monitored at the earth is likely to be due to just one supernova and in this case isotropy would not be observed.

Pulsars, being the remaining, revolving neutron star left after a supernova explosion have been proposed as possible cosmic ray sources due to the intense ($\sim 10^{12}$ gauss) surface fields and the large quantity of stored rotational energy ($\sim 10^{50}$ ergs). A loss of energy per second arises due to the rapid (on an astronomical scale) retardation of the rotating star and calculations on the braking of these pulsar relics have shown that high energy cosmic rays can be produced. Isotropy does not pose such a great problem as for the supernovae explosions since the production of cosmic rays from pulsars would be a continuous process and, due to observational difficulties, undiscovered pulsars, strong enough to produce considerable cosmic rays, could still be present. However, the mechanism of cosmic ray production in the pulsar is not very efficient below 10^{14} eV, and the majority of cosmic rays have energies of $10^9 - 10^{12}$ eV. The discovery of a pulsar at the centre of Crab Nebula links supernovae explosions and pulsars strongly together and possibly a combination of the two types of source, forms a strong case for the cosmic ray origin.

White dwarfs as possible cosmic ray sources immediately solve the isotropy problem due to their much greater abundance throughout the galaxy. Cowsik and Price (1971) calculate that cosmic rays of $10^8 - 10^{14}$ eV of energy can be accelerated and with 10^{10} such objects, each of rotational

energy $\sim 10^{48}$ ergs, just sufficient cosmic ray power could be supplied over the life of the galaxy.

It is clear that each type of source is possible although they all have difficulties in one respect or another, however, a combination of the three possibilities outlined above, summed over their life history as cosmic ray sources could provide the answer.

2.9.2 Universal distribution of cosmic rays

Compton and Getting (1935) had originally suggested that if cosmic ray particles had much the same density in intergalactic space as measured at the earth i.e., they were evenly distributed in the universe, galactic rotation of 300 km/sec at the solar system would produce an anisotropy to be measured in sidereal time. Such an effect would be of an order of magnitude larger than that due to the solar system motion in the galaxy and would easily be observable at Holborn, however, the galactic field aligned along the spiral arm would ensure that as cosmic rays entered the galaxy they would be caused to corotate with the galaxy and no such galactic rotation effect could exist. Thus the observed isotropy is easily explained if cosmic rays are assumed to be a universal phenomenon and particles of $E \geq 10^{17}$ eV are certainly metagalactic since they cannot be contained within the galaxy by the galactic magnetic field.

The argument usually advanced against the universal distribution of such particles is the enormous amounts of energy required by the sources to fill the whole universe with cosmic rays at the observed energy density. With any galactic origin of cosmic rays the sources make up for any loss of cosmic rays into metagalactic space. For the universal distribution of cosmic rays the sources of cosmic rays must make up for the loss of cosmic ray density due to the expansion of the universe. The radius of the universe where the energy flux is still measurable occurs approximately where the velocity of recession, u , is $\sim c/2$. This radius is given by,

$$r = \frac{u}{h}$$

where r = distance from the earth

h = Hubble's constant = $100 \text{ km sec}^{-1} (\text{Mpc})^{-1}$

Therefore $r_{\text{'universe'}}$ = $\frac{c}{2h}$

$$= 5 \times 10^{27} \text{ cms}$$

Therefore The Volume of the universe = $V_u = 5 \times 10^{83} \text{ cm}^3$

and The lifetime of the universe = the time taken to expand to r_u

$$= \frac{r_u}{c/2} = \frac{5 \times 10^{27}}{1.5 \times 10^{10}} \approx 3 \times 10^{17} \text{ sec}$$

$$\approx 10^{10} \text{ yrs.}$$

If the energy density at the earth ($\sim 1 \text{ eV/cm}^3$) is representative of the universal density then,

$$\begin{aligned} \text{Total cosmic ray energy in the universe} &= 5 \times 10^{83} \times 10^{-12} \text{ ergs} \\ &= 5 \times 10^{71} \text{ ergs} \end{aligned}$$

and this has been produced in the lifetime of the galaxy hence,

$$\text{Energy production} \approx 2 \times 10^{54} \text{ ergs/sec.}$$

Assuming that cosmic rays can only be produced in galaxies (as these contain matter) and a galaxy has a volume of 10^{74} cm^3 there are 5×10^9 cosmic ray sources per universe. Therefore the cosmic ray energy that must be produced per galaxy is, $\sim 4 \times 10^{44} \text{ ergs/galaxy/sec}$. Radio galaxies and quasars could possibly produce such large quantities of energy, however, the density in the universe of these objects is such that each of them has to inject $\sim 3 \times 10^{48} \text{ ergs/sec}$ which would seem excessive. Recently, Setti and Woltzer (1971) have indicated that infrared emission by a source is a direct measure of its cosmic ray production and if this is the case objects that were thought to be "inactive" as cosmic ray sources could produce substantial quantities of these particles. If this is the case, the energetic argument usually

advanced against the universal theory of cosmic rays is diminished. However, the discovery of an all pervading 3°K thermal radiation imposes a further condition upon the universal theory of cosmic radiation. Such a radiation would interact with relativistic electrons producing X-rays meaning that metagalactic space would be opaque to such a radiation. Therefore, even if it is proposed that the proton component of cosmic radiation is extragalactic the electron component most certainly cannot be, inferring that the two components would have different sources.

2.9.3 Summary

- 1) Correction for the solar system motion leaves an anisotropy of amplitude $\sim 0.002 \pm 0.004\%$ in the rotational frame of the galaxy.
- 2) Such a high degree of isotropy is easily explained on the universal theory of cosmic rays but such a theory has to explain the dual nature of the proton/electron sources and the high energy resources required to fill the whole universe. The latter of these arguments has been diminished recently by the connection of infra-red emission and cosmic ray production.
- 3) Galactic theory for the origins of cosmic rays require the explanation of the very small streaming velocity < 10 km/sec and the lifetime of $\sim 10^6$ yrs. This can only be effectively explained by considering compound diffusion and a statistical source distribution due to supernovae explosions. Using energy considerations ordinary stars or galactic core explosions seem untenable due to a lack of energy or the inability to produce high energy electrons over a long period of time. Pulsars are possible sources for particles of energy $> 10^{14}$ eV and white dwarfs at energies of 10^8 to 10^{14} eV, therefore a combination of supernovae, pulsars and white dwarfs seems the best explanation for the galactic origin theory.

CHAPTER 3

SURFACE LEVEL AND UNDERGROUND MEASUREMENTS OF THE SOLAR DAILY VARIATION

3.1 Introduction

An intensive study of the variation in cosmic ray secondary intensity with the period of a solar day, corrected for any geomagnetic or atmospheric effects, provides a means for understanding the electromagnetic conditions of interplanetary space. Methods of removing any atmospheric contribution to the variation have been discussed. In the present chapter allowances will be made for geomagnetic effects and the remaining variations will be used to study the conditions in interplanetary space over the period 1961 to 1971.

Circa 1930, attempts were made to explain the measured solar daily variation solely in terms of atmospheric effects, but the use of crossed telescopes (Alfven and Malmfors(1948), Elliot and Dolbear(1950)) in which the atmospheric effects should be the same, showed clearly that a primary anisotropy, following solar time, existed. The development of the neutron monitor in which the data are not affected appreciably by temperature effects confirmed that the diurnal variation was due to a primary anisotropy. The existence of a semi-diurnal component of primary origin was accepted when it was realized that atmospheric oscillations could not totally account for the 12 hr. wave (Elliot and Dolbear(1950,1951)). The following characteristics have emerged from the researches carried out over the last 50 years, in particular, during the past 15 years when a world-wide net-work of stations operating different types of detector has been established

- (1) Diurnal and semi-diurnal periodicities exist in L.S.T. and are of primary origin.
- (2) The amplitude of the 24 hr. wave depends upon the mean rigidity

- of the primaries, being $\sim 0.3\%$ in surface recorders and $\sim 0.05\%$ in detectors at moderate depths underground. The time of maximum usually lies between 12.00 and 16.00 hrs. L.S.T. before geomagnetic correction.
- (3) The amplitude of the 12 hr. wave increases with mean primary energy up to some limiting energy.
 - (4) Geomagnetic deflection reduces the amplitude and alters the phase from the free space values. The amplitude also has a dependence upon the angle between the asymptotic direction of viewing and the solar equatorial plane. Trajectory calculations have enabled these effects to be accounted for and give the free space amplitude of the diurnal anisotropy as $\sim 0.4\%$ at 18.00 hrs. L.S.T. with a $\cos(L)$ dependence, where L is the declination from the ecliptic plane. (McCracken and Rao(1965), Jacklyn et al(1970)).
 - (5) The diurnal wave is rigidity independent up to some limiting value, P_u of the order of 100-200 GV.

In this chapter, data from both the surface level and underground telescopes is used to study the solar daily variation. The long term changes in the solar vector are shown to fit the presently accepted model of the daily variation provided the upper limiting rigidity of corotation varies over the solar cycle of activity. A study of day to day variations in the solar vector is also made in conjunction with measurements of the interplanetary field.

3.2 Surface level atmospheric corrections

Correction of surface level muon data for atmospheric effects has been reported elsewhere, Hashim, Speller & Thambyahpillai(1972). Inadequate radiosonde flights do not allow temperature correction of the data although allowances are made for this effect when interpreting the results. Barometric pressure correction of the data has been carried out using a pressure coefficient of $-0.185\%/mb$.

3.3 Results from 1961 to 1971

The results for the underground and surface level detectors are presented in tables 3.I and 3.II respectively, and the vectors have been plotted on harmonic dials in Fig. 3.1 and 3.2. Annual grouping of data has the advantage of eliminating any seasonal modulation due to atmospheric effects or any constant sidereal variation due to a flow of particles from one fixed direction. From Fig. 3.2 it can be seen that the underground vectors have made large phase changes, particularly during 1965 to 1967 and for this reason the results have been replotted in Fig. 3.3 in the form of a summation dial. For such a figure the end point of the previous vector is used as the origin for the next vector and enables phase changes, such as those observed, to be followed more closely. During the years 1965 to 1969 North pointing telescopes at 45° to the zenith were operational at the underground laboratory and the 4-year average vector is also plotted in Fig. 3.3. The mean 2nd harmonic is smaller than the 1st harmonic which is plotted. From a study of tables 3.I and 3.II and Figs. 3.1, 3.2 and 3.3 it can be seen that;-

- (1) During the period 1961 to 1964 both the phase and amplitude of the diurnal vector were essentially invariant.
- (2) For the 24 hr. wave a sudden phase change occurred in the underground data for 1965, followed in 1966 and 1967 by changes of both amplitude and phase. Surface level observations did not start until the middle of 1965 but the diurnal vector clearly shows a reduced amplitude for 1965 compared to later years.
- (3) A recovery period from 1968 to 1970 with increasing amplitude, and later phase is evident in both the underground and surface level observations
- (4) 1971 appears to mark the end of the increase in amplitude of the diurnal vector and possibly it tends to an earlier phase. This is only clearly evident in the surface and underground South(15°)

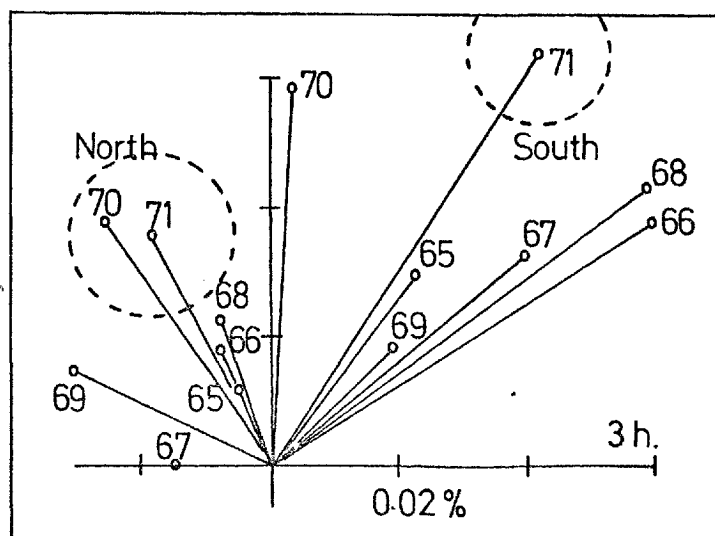
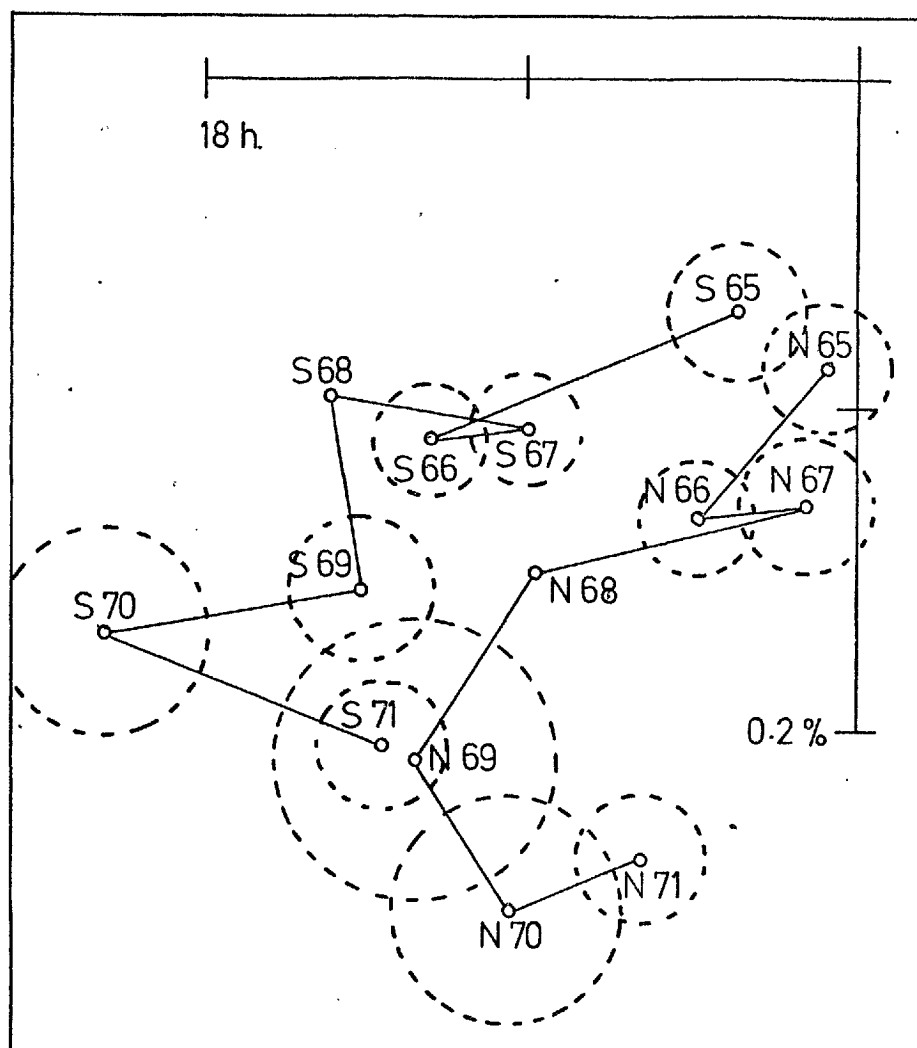
VERTICAL					EAST or SOUTH			
First harmonic		Second harmonic		First harmonic		Second harmonic		
Year	Amp. %	Phase hrs.	Amp. %	Phase hrs.	Amp. %	Phase hrs.	Amp. %	Phase hrs.
1961	0.023	14.3	0.017	2.0				
1962	0.020	13.8	0.021	1.0				
1963/4	0.016	13.3	0.013	2.1				
EAST								
1965	0.023	6.0	0.016	1.6	0.043	2.0	0.012	8.9
1966	0.012	22.0	0.023	2.6	0.012	5.2	0.043	11.9
1967	0.015	3.6	0.013	1.4	0.023	6.5	0.017	0.3
1968	0.017	14.5	0.030	1.6	0.026	15.6	0.029	11.9
1969	0.034	16.2	0.029	1.8	0.032	14.5	0.044	0.2
SOUTH								
1970	0.026	16.9	0.024	2.5	0.027	16.9	0.036	2.8
1971	0.010	20.6	0.024	1.6	0.018	12.9	0.019	1.2

TABLE 3.I Underground observations of the solar daily variation.

NORTH					SOUTH			
First harmonic		Second harmonic		First harmonic		Second harmonic		
Year	Amp. %	Phase hrs.	Amp. %	Phase hrs.	Amp. %	Phase hrs.	Amp. %	Phase hrs.
1965	0.090 ±.019	12.2	0.013 ±.016	11.3	0.080 ±.023	13.9	0.037 ±.016	1.3
1966	0.142 ±.016	13.3	0.020 ±.010	11.3	0.171 ±.016	15.5	0.071 ±.011	1.9
1967	0.137 ±.019	12.5	0.014 ±.013	9.0	0.148 ±.017	15.1	0.046 ±.011	1.7
1968	0.180 ±.022	14.2	0.023 ±.016	11.3	0.186 ±.019	16.0	0.073 ±.013	1.8
1969	0.251 ±.042	14.2	0.034 ±.023	9.8	0.219 ±.021	14.9	0.028 ±.015	1.6
1970	0.276 ±.035	13.5	0.049 ±.026	10.9	0.285 ±.032	15.5	0.058 ±.030	0.2
1971	0.229 ±.019	12.9	0.040 ±.012	11.2	0.248 ±.019	14.3	0.076 ±.011	1.1

TABLE 3.II Surface level observations of the solar daily variation.

First
harmonic



Second
harmonic

Fig. 3.1 Surface level observations of the first and second harmonics in the North and South directions for the years shown (solar time).

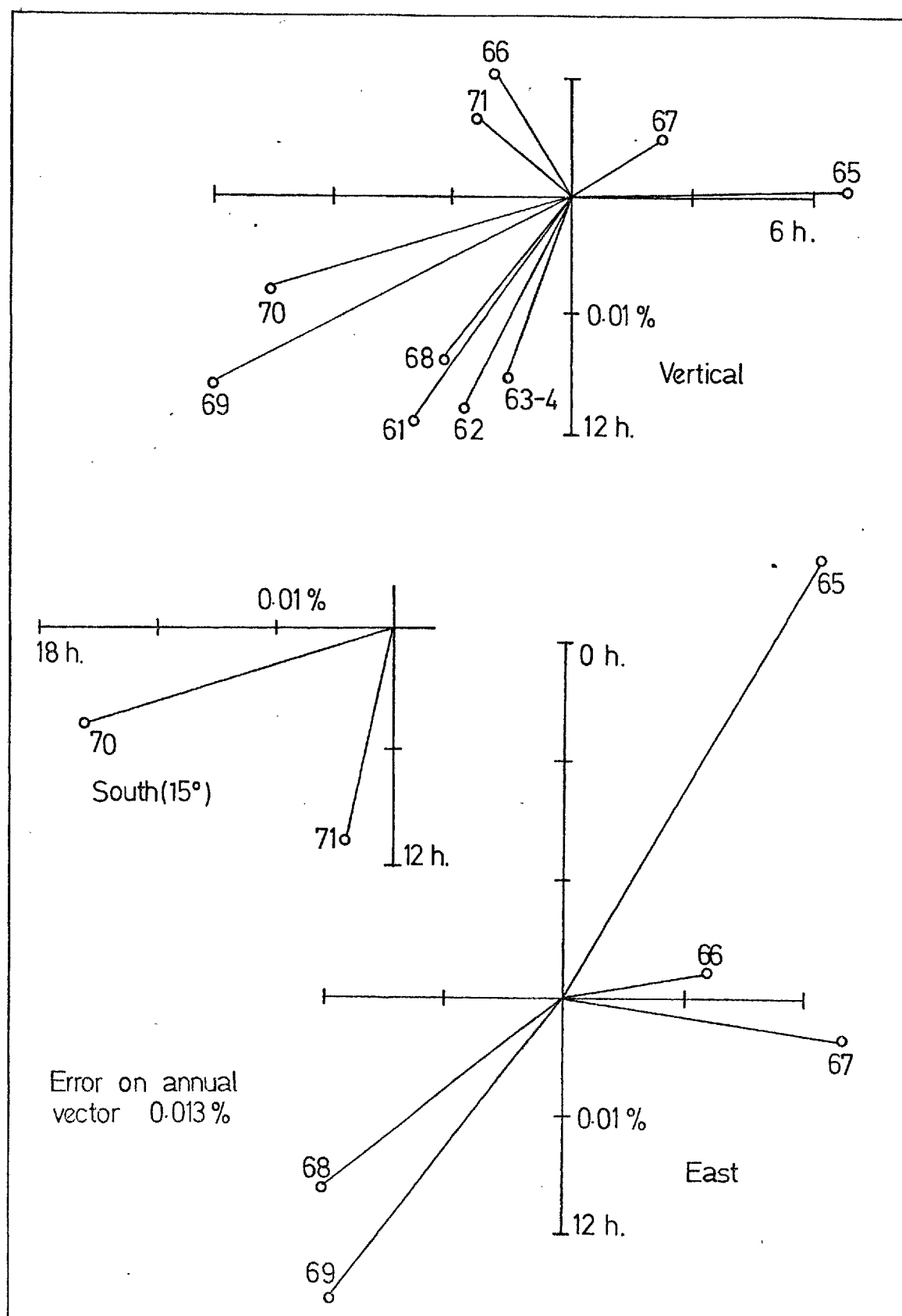


Fig. 3.2 (a) Underground observations of the first harmonic in the Vertical, East and South(15°) directions for the years shown (solar time).

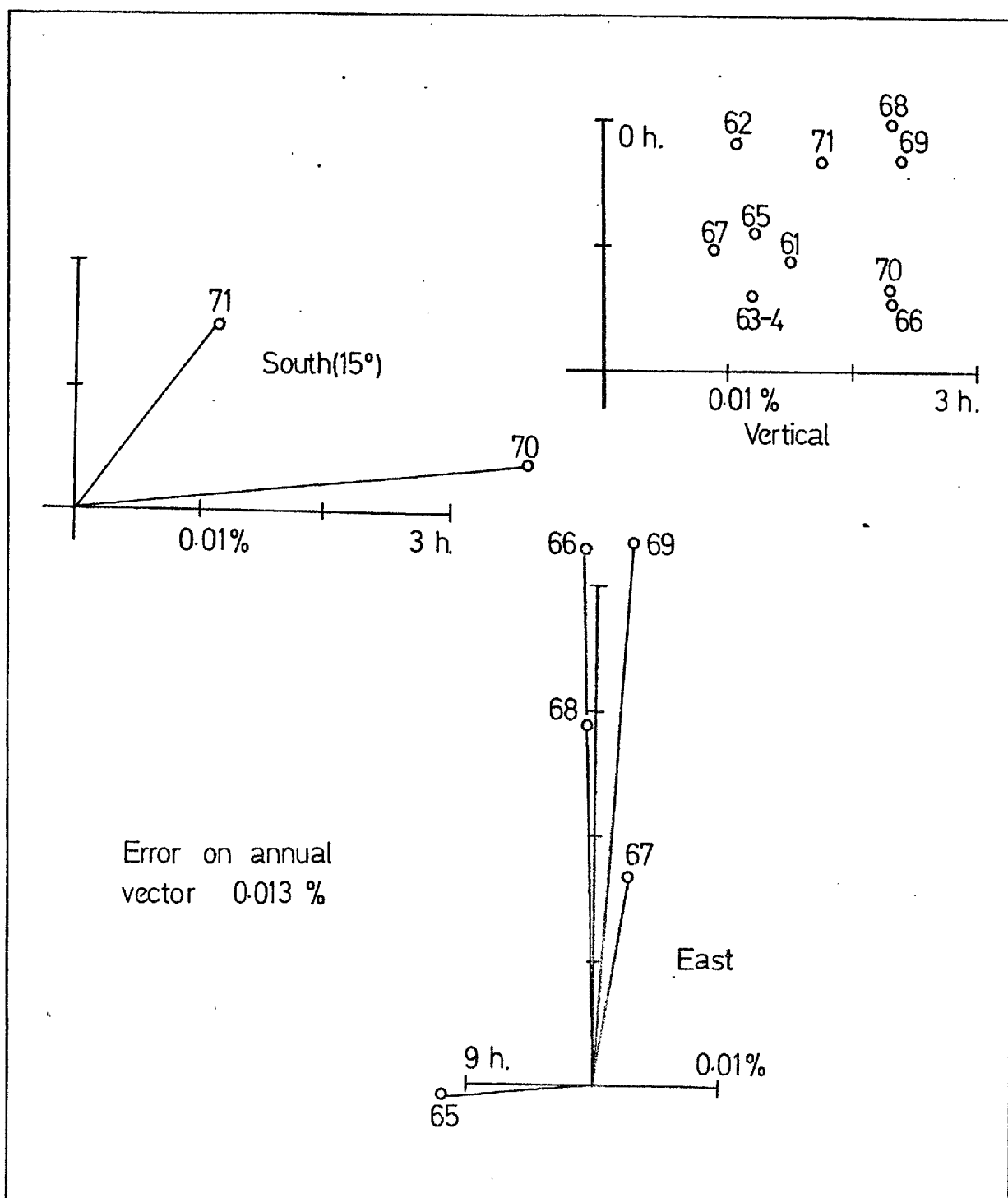


Fig. 3.2 (b) Underground observations of the second harmonic in the Vertical, East and South(15°) directions for the years shown (solar time).

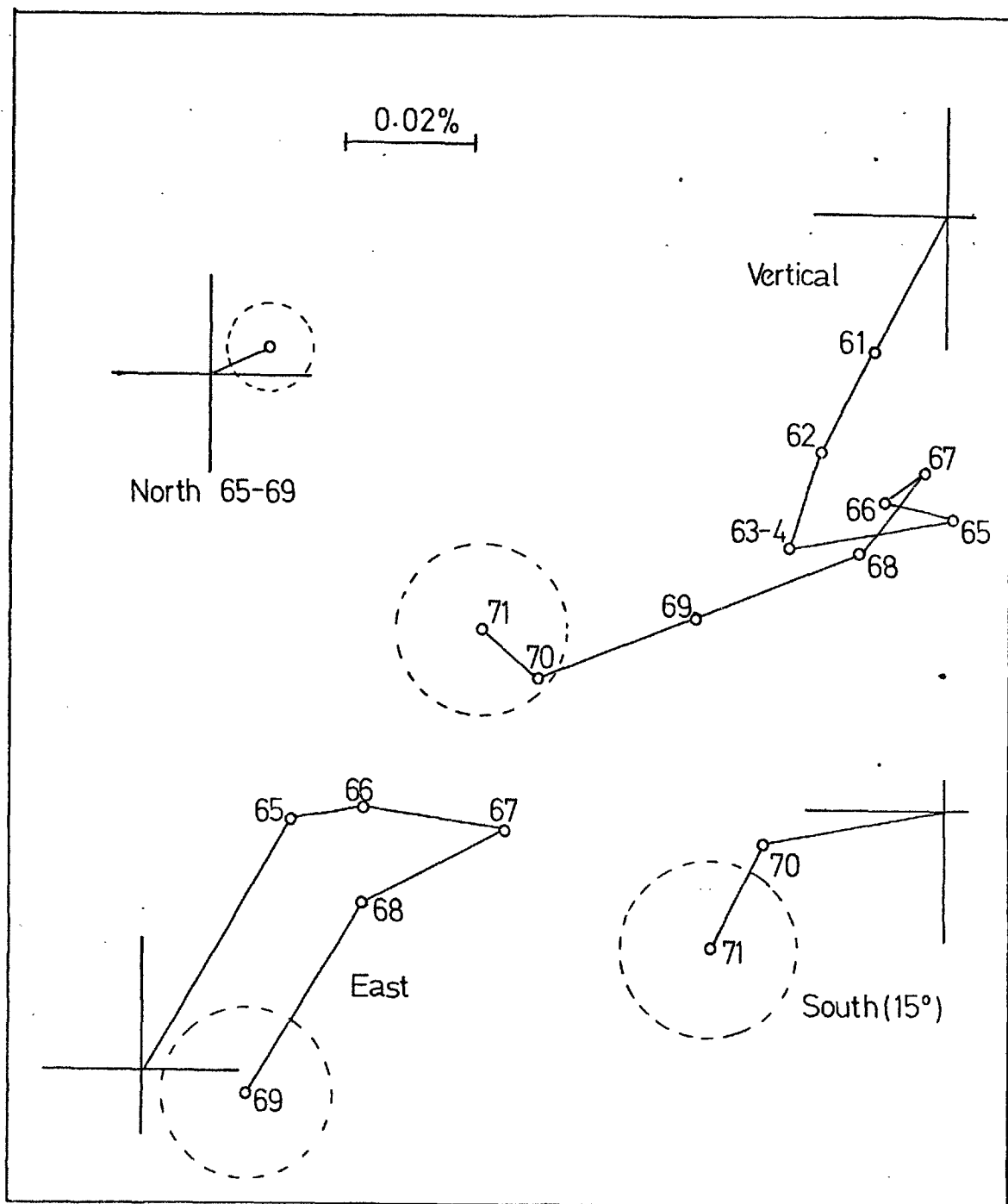


Fig. 3.3 First harmonic summation dials for the Vertical, East and South(15°) direction underground telescopes and the 5 year average for the North underground telescope.

results as the Holborn 1971 vertical vector is insignificant.

- (5) Throughout the whole period of operation the diurnal and semi-diurnal vectors for the North pointing underground telescope were insignificant and even the four year average, plotted in Fig. 3.3, produces a barely significant result. The implications of such a result are deep. Due to the relatively high mean primary energy of response such a detector essentially "looks" along the rotational axis of the Earth and hence any solar daily variation in the ecliptic plane will be reduced to zero. All that will be recorded is an atmospheric induced variation and the insignificant result of the North pointing telescope indicates that any atmospherically induced solar daily variation in the Holborn data is negligible.
- (6) Throughout the period considered the semi-diurnal vector for all the telescopes has undergone only small changes in amplitude and phase. From surface level measurements it is clear that the South telescope sees a larger second harmonic than the North telescope which is in accord with the underground data where the North telescope sees an insignificant second harmonic.
- (7) Although the errors are large it is possible that the second harmonic has increased in amplitude since 1967.

3.3.1 Comparison with other results

Peacock(1967) and Hashim(1968) have compared the underground and surface level measurements up to 1966 with those from other stations. They conclude that as far as the 24 hr. wave is concerned approximately constant phase and amplitude were measured between 1961 and 1964. There were radical changes in phase and amplitude during 1965. More recent results indicate that the behaviour found in London between 1967 and 1971 is seen elsewhere. Thomson & Sumner(1971) using east-west recorders at 40 m.w.e. report that the amplitude for 1971 appears smaller than in earlier years.

Ahluwalia(1971) and Agrawal et al(1971) both report an increase in the upper cut-off rigidity to corotation which implies an increase in the observed diurnal vector for the years from 1965 to 1969. Thus the general behaviour of the solar daily variation has been well recorded with agreement upon major changes between the years 1961 to 1971.

Following a short discussion on the theoretical model proposed to explain the solar daily variation the results presented thus far will be used to see if there is agreement between the observed and predicted effects.

3.4 Theory of the solar diurnal anisotropy

Following the development of the presently accepted model of the interplanetary field (Parker(1960)), Ahluwalia & Dessler(1962) proposed that the source of the diurnal variation was to be found in the electric field produced by the rotating magnetic field lines in the ecliptic plane. This electric field caused the cosmic rays to drift from the 15.00 hr. direction under the induced $\underline{E} \times \underline{B}$ force. Such a model, however, using the assumption that the solar field is time independent and hence conservative, violates Liouville's theorem (Stern(1964)) and in fact this $\underline{E} \times \underline{B}$ streaming must be cancelled by an equal and opposite streaming due to the density gradient induced by the electric field.

Parker(1964) and Axford(1965) independently showed that magnetic irregularities in the interplanetary field render $\frac{\partial B}{\partial t} \neq 0$ and hence cancel the density gradient leaving just azimuthal streaming at a velocity that corresponds to rigid rotation of the cosmic ray gas with the sun. Hence the term corotation. In the case of rigid rotation the amplitude of the anisotropy is given by,

$$A(r) = \frac{3CV_r}{v} \quad (3.1)$$

where C is the Compton-Getting factor

V_r is the velocity of the rotating magnetic field

and v is the particle velocity.

At the Earth for relativistic particles (3.1) becomes,

$$A(r_e) = \frac{(2 + \gamma)V_{re}}{c} \quad (3.2)$$

for $V_{re} = 400$ km/sec and $\gamma = 2.5$ gives $A(r_e) = 0.6\%$. This value appears to be systematically larger than the observed value of $\sim 0.4\%$ and Parker(1967) explained the discrepancy by introducing diffusion of cosmic ray particles perpendicular to the field lines causing the density gradient to be only partially cancelled. Random-walk of the field lines themselves increases the value of $K_{perp.}$, the perpendicular diffusion coefficient, (Jokipii & Parker(1969)). The inclusion of both $K_{par.}$ and $K_{perp.}$ into the theory leads to the amplitude of the anisotropy being given by,

$$A(r_e) = \frac{3CV_w}{v} \left[\frac{(K_{par.} - K_{perp.}) \tan \psi_B}{K_{par.} + K_{perp.} \tan^2 \psi_B} \right] \quad \text{Forman \& Gleeson(1970) (3.3)}$$

where ψ_B is the garden hose angle. This expression gives $A = 0.44\%$ for $\psi_B = 45^\circ$ which is in reasonable agreement with the observed amplitude.

Over recent years results indicate (Jacklyn et al(1970), McCracken and Rao(1965) and others) that the primary anisotropy observed at the Earth agrees with this Parker-Axford model. The observed anisotropy has rigidity independent free-space amplitude of $\sim 0.4\%$ with a time of maximum about 18.00 hrs. and an amplitude dependence of $\cos \lambda$ where λ is the declination in the ecliptic. The upper limiting rigidity, P_u , above which corotation ceases, being a variable parameter. Jacklyn et al(1970) report that P_u was ~ 100 GV in 1960 but fell to 60 GV in 1965, a similar effect being noticed by others; thus a reasonable range for P_u would be 30 up to 300 GV. Therefore recent results indicate that the solar daily variation is well represented by,

$$\begin{aligned} A(P) &= 0.4 \cos(\lambda) & \text{for } P < P_u \\ \text{and } A(P) &= 0 & \text{for } P > P_u \end{aligned} \quad (3.4)$$

where A = amplitude and λ is the angle between the ecliptic plane and the particle asymptotic direction. Using the measured properties given above and geomagnetic deflections by Brunberg & Dattner(1953) and McCracken et al (1962) the expected amplitude and phase have been found for different values of P_u . The components of the diurnal vector are given by,

$$\begin{aligned} \delta a_1 &= A \cos(\lambda) \sin(\psi) W(P) \delta P \\ \text{and} \quad \delta b_1 &= A \cos(\lambda) \cos(\psi) W(P) \delta P \end{aligned} \quad (3.5)$$

where ψ is the particle deflection east of the recording station and A takes the value 0.4. Integrating the expressions over the required rigidity range, squaring, adding and normalizing gives the amplitude of the first harmonic as,

$$A_1 = \frac{\{ [\int_{P_0}^{P_u} \delta a_1]^2 + [\int_{P_0}^{P_u} \delta b_1]^2 \}^{0.5}}{[\int_{P_0}^{P_u} W(P) \delta P]} \quad (3.6)$$

and the phase advance over the free space anisotropy is,

$$\psi = \tan^{-1} \left(\frac{[\int_{P_0}^{P_u} \delta a_1]}{[\int_{P_0}^{P_u} \delta b_1]} \right) \quad (3.7)$$

in degrees where P_0 is the threshold rigidity.

For the surface level data, response functions due to Krimsky et al (1965) have been used. As discussed in chapter I the response function most suitable to the Holborn detectors is that due to Wolfendale (curve B in Fig. 1.4 chapter I) and has been used here.

In Fig. 3.4 and 3.5 the expected end points of the vectors have been plotted as a function of P_u for the surface level and underground vectors

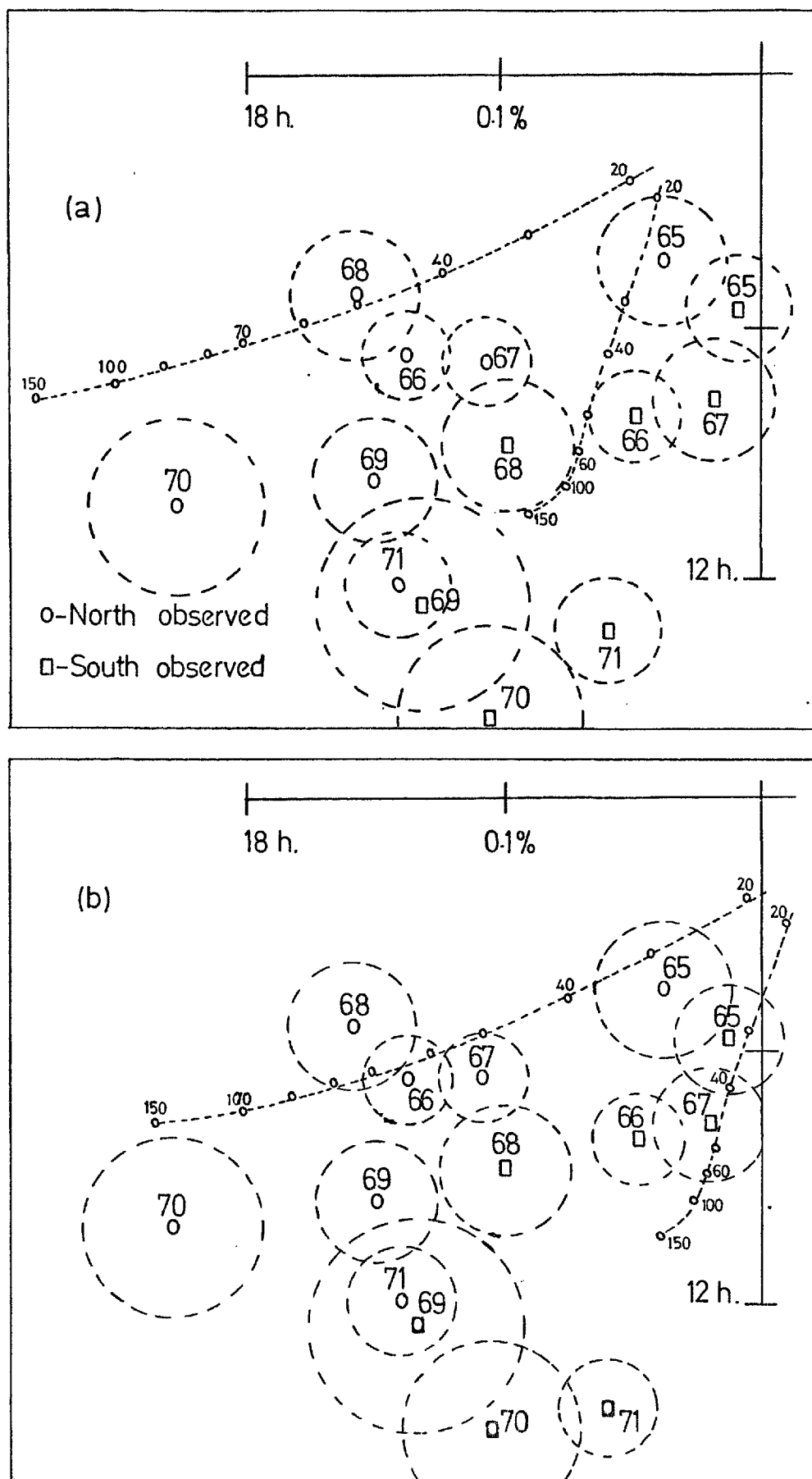


Fig. 3.4 Observed and predicted surface level diurnal vectors. (a) the data are just pressure corrected. (b) the predicted vectors include an allowance for temperature effects.

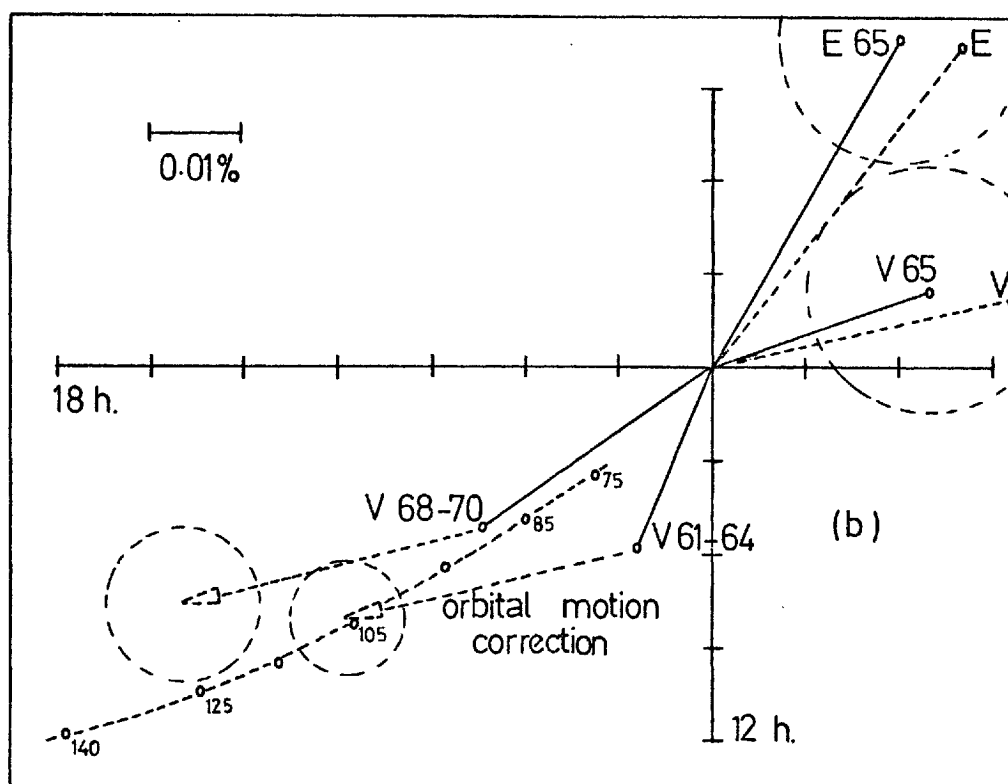
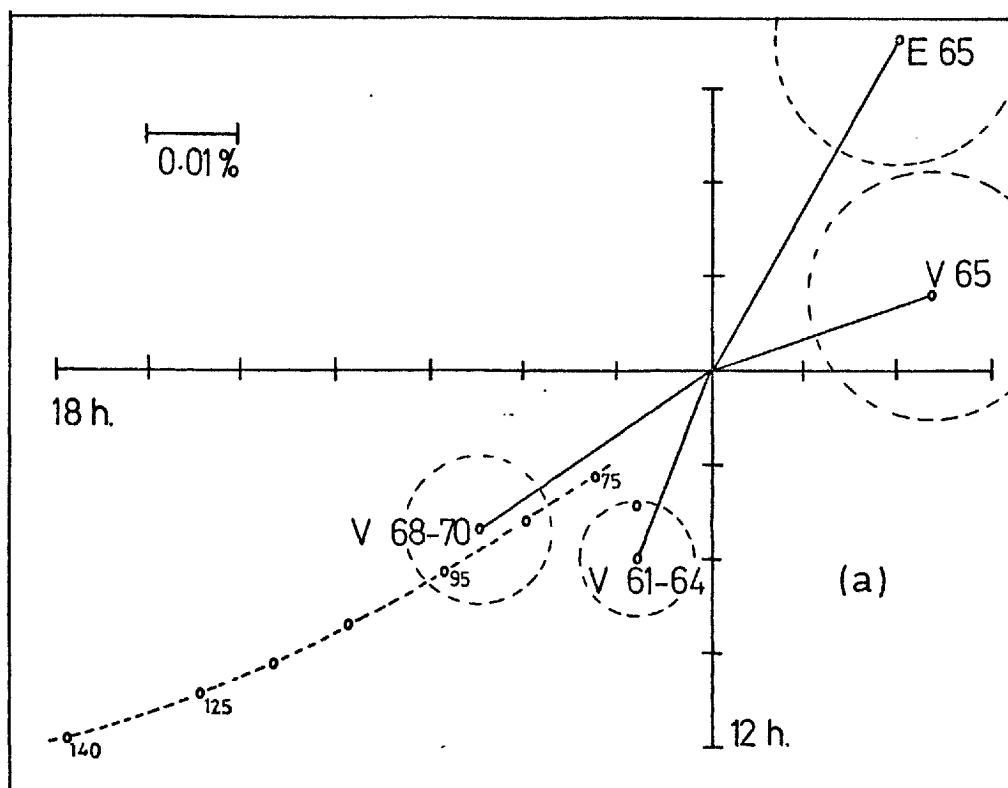


Fig. 3.5 Observed and predicted underground solar diurnal vectors. (a) observed data. (b) a correction due to the Earth's orbital motion has been included.

along with the observed vectors. The small figures printed along the curve are values of P_u in GV. The surface level data has been presented as annual vectors but to improve the statistical accuracy of the underground data, the vertical results have been grouped in 2 or 3 year batches after carefully studying Fig. 3.3. The groups have been selected according to the phase changes in the diurnal vector. 1961 to 1964, 1965, 1966 to 1967 and 1968 to 1970 have been chosen as groups on the basis that 1965 shows a complete phase reversal and 1966 to 1967 also has large phase changes. The remaining periods are more stable.

3.4.1 Comparison of predicted and observed vectors: surface level

From Fig. 3.4(a) it can be seen that there is general disagreement between the predicted and observed North and South vectors. Since the data are only pressure corrected the discrepancy could well be due to the remaining atmospheric effects included in the results. Using a suggestion by Quenby & Thambyahpillai(1960), a temperature correction with a time of maximum close to 06.00 hrs. would certainly improve the fit. The correct amplitude of this correction would be determined by a least squares fit between the observations and theory. A correction of 0.05% has been estimated to give the best fit and such a correction has been applied to the expected vector locii in Fig. 3.4(b). The fit between predicted and observed vectors is improved and in fact the South telescope observations (except for 1971) are in reasonable agreement with theory. The North vector also agrees except for the years 1969, 1970 and 1971.

The amplitude of the North telescope saturates above 60-70 GV since at this rigidity the viewing cone of the detector becomes almost parallel to the rotational axis of the Earth. Under these circumstances the only effect that will change the observed vector would be an increase in the free-space anisotropy. Therefore, the expected end points of the vectors, assuming a free-space amplitude of 0.7% and temperature corrected as before, are plotted in Fig. 3.6(a). Agreement for the years 1969 to 1971 for the

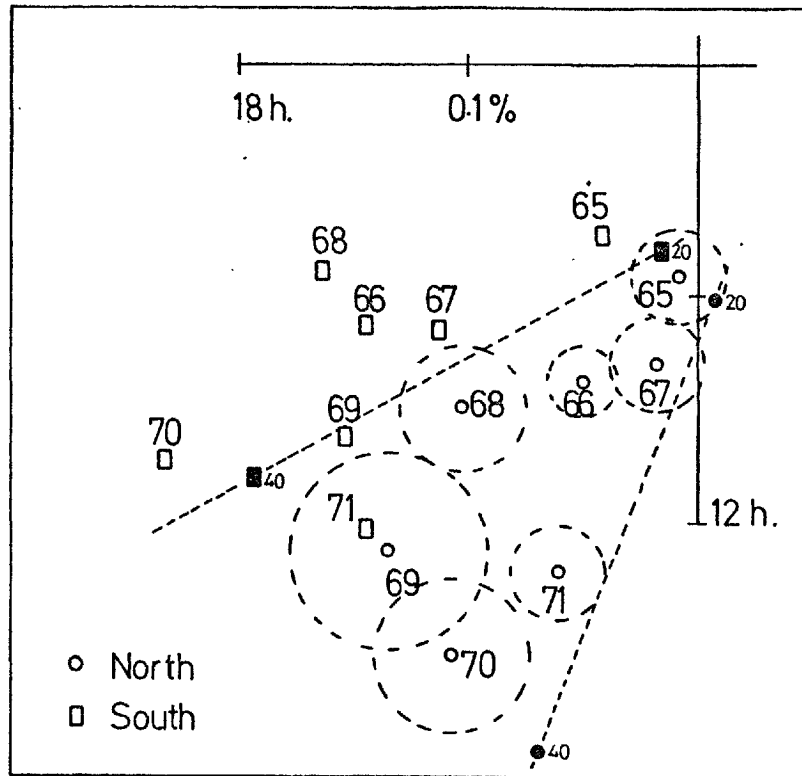


Fig. 3.6 (a) Observed and predicted surface level first harmonics. The predicted vector locii have been calculated assuming a free space anisotropy of 0.7% and have been temperature corrected.

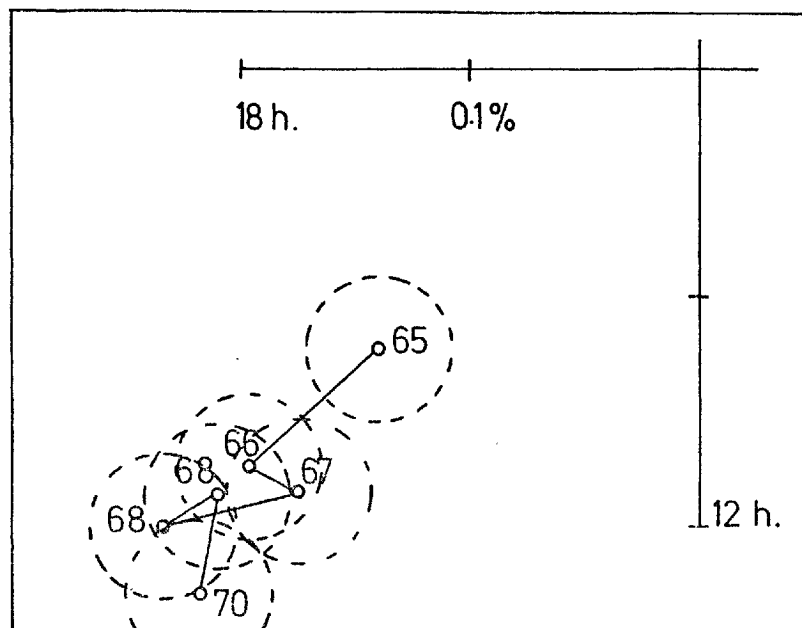


Fig. 3.6 (b) Deep River neutron monitor first harmonics for the period 1965-1970.

South telescope does appear to have improved and similarly for the North 1971 vector. However, for the other years the agreement is worse. As a further check to see if the free-space anisotropy has increased in amplitude Deep River neutron monitor data has been analysed. The sensitivity of a high latitude neutron monitor decreases rapidly above 60 GV so when P_U reaches 60-70 GV it also should saturate and only will the observed amplitude increase if the free-space amplitude does. The data have been grouped in annual batches for the years 1965 to 1970 and plotted on the harmonic dial in Fig. 3.6(b). Apart from the reduced amplitude in 1965 the diurnal vector has remained almost invariant during 1966 to 1970 within the statistical fluctuations and so does not indicate any large increase in the free-space anisotropy.

Summarizing the surface level results it appears that during 1965 P_U had fallen to a value ~ 30 GV but in 1967-68 increased to a value of 70 GV and reached a maximum value of ~ 140 GV in 1969-70. Also, fluctuations in the free-space amplitude may have occurred during 1969 to 1971 although such fluctuations have not been evident in neutron monitor data from Deep River. The rising trend in P_U may have ceased in 1970-71.

3.4.2 Comparison between predicted and observed results: underground

From Fig. 3.5(a) it can be seen that the fit between the predicted and observed vectors is generally poor; particularly the vectors for 1965 and 1961-64 which lie well away from the predicted curve. Due to the much smaller amplitude observed underground at the higher mean primary energy of response, the discrepancy could be either due to atmospheric temperature contributions or due to the orbital motion of the Earth around the sun (Peacock(1967)). Atmospheric contributions to the data are negligible (as indicated by the North telescope underground data presented earlier) and leaves just the Earth's orbital motion to be taken into account. The fact that the Earth is moving in the 06.00 hr. direction with a velocity of 30 km/sec through the randomly distributed cosmic ray gas produces a Compton-Getting type effect whose

magnitude is given by;-

$$\xi = (2 + \gamma) \frac{v}{c} \quad (3.8)$$

where $\gamma = 2.5$ and $v = 30$ km/sec. Using these values gives $\xi = 0.045\%$.

The orbital motion vectors have been calculated and plotted for the East and Vertical directions in Fig. 3.5(b) as dotted vectors marked E and V respectively. It is clear that there is very good agreement between these orbital motion vectors and the observed vectors for 1965 indicating that during this period the corotating vector had fallen to such a small value that only the orbital motion could be detected. Further, applying the orbital motion correction to the observed vectors for the periods 1961-64 and 1968-70 brings both these results into agreement with the predicted vectors.

Summarizing the underground data it can be said that, provided the orbital motion correction is applied, the data are consistent with $P_U \approx 105 \pm 8$ GV. for the period 1961 to 1964 and rising to $\sim 125 \pm 10$ GV. for the period 1968 to 1970, but for 1965 P_U had dropped so low (< 60 GV) that the corotation vector could not be observed and only the orbital motion of the Earth was detectable.

These results are consistent with the surface level data in the observation that P_U had fallen to ~ 30 GV. in 1965 and risen since then to a maximum value in 1969-70. In both the surface level and underground data the vector for 1971 appears to be tending to smaller values and hence possibly the upper limiting rigidity reached its maximum value in 1970, approximately coinciding with the maximum of the solar cycle. This variation of P_U has recently been reported by Ahluwalia(1971) and Agrawal et al(1971). Using underground and surface level meson data respectively, they have found values of P_U for 1965 to 1969. Thomson & Sumner(1971) also report a value of $P_U \sim 90 \pm 20$ GV. for the year 1970-71 and suggest that P_U may be falling in 1971. Using available data the values of P_U for 1959-1971 have been plotted in Fig. 3.7. Error bars could only be placed on the London data since values were not quoted for the other results. Clearly all the data are consistent with

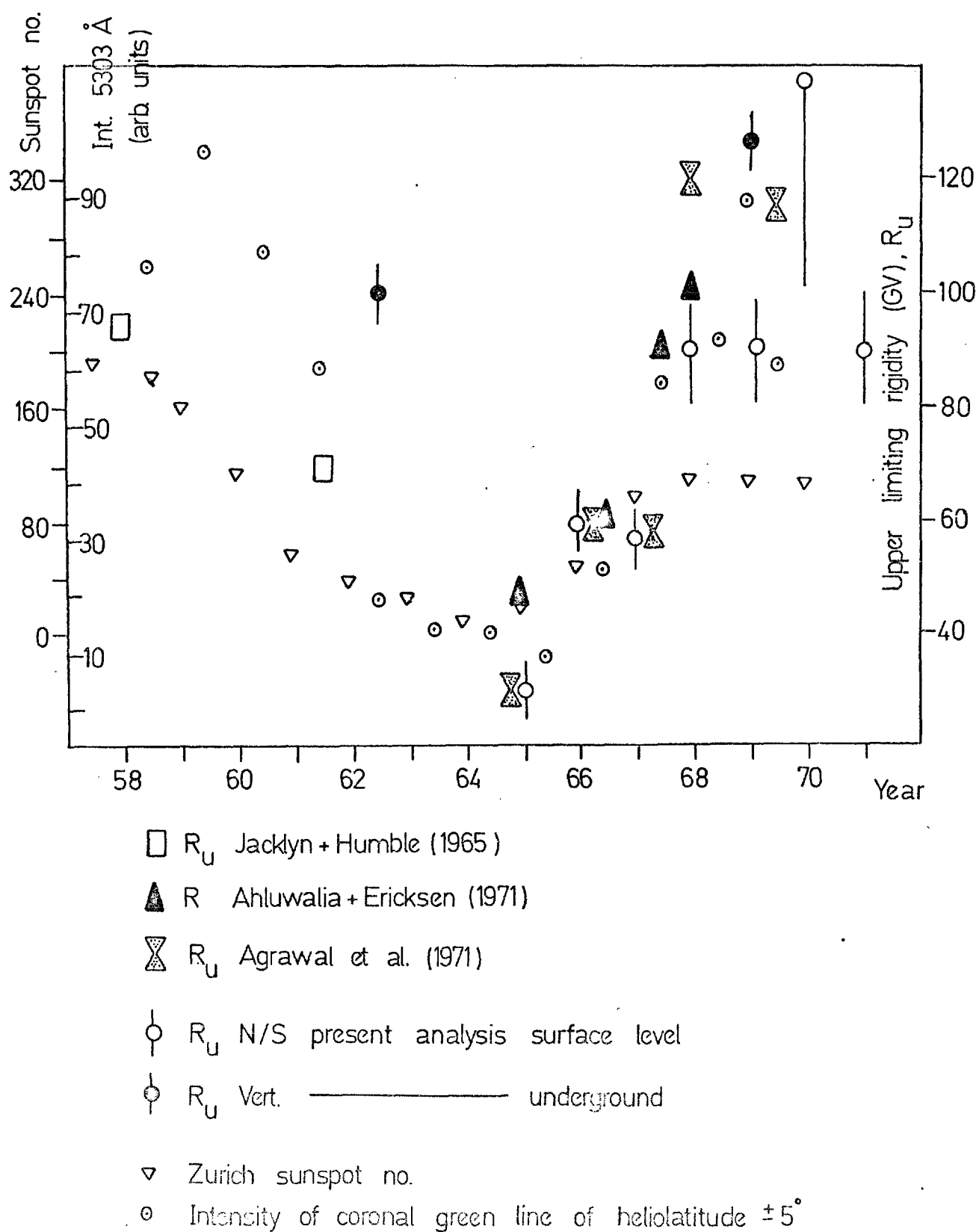


Fig. 3.7 Variation of the upper limiting rigidity, R_U , over the period 1958-1971. For comparison the sunspot number and the intensity of the green coronal line have also been plotted.

a variation of P_u over the solar cycle having a minimum value at around solar minimum and Ahluwalia(1971) shows that P_u correlates better with the intensity of the coronal green line (5303 Å) around the solar equator than the sunspot number. Plotted in Fig. 3.7 (from Ahluwalia's paper) are both the Zurich sunspot number and the intensity of the coronal green line. The correlation does seem better between P_u and the coronal green line, rather than the sunspot number for two reasons:-

- (1) The maximum and minimum in the sunspot number occur approximately 18 months before the maximum and minimum values of P_u , whereas the minimum intensity of the coronal green line occurs at the same time as the minimum value of P_u .
- (2) Successive maxima in sunspot number are widely unequal, unlike the green coronal line intensity or P_u .

The positive correlation between P_u and the intensity of the green coronal line is better throughout the whole period and it could be implied that such an intensity is a consistent measure of the solar modulation of cosmic rays.

3.5 The theory of the semi-diurnal anisotropy

The essential ingredient in all models of the semi-diurnal anisotropy proposed thus far is a gradient of cosmic rays perpendicular to the solar equatorial plane. Subramanian & Sarabhai(1967) propose a density gradient which has a form corresponding to the solar activity in either the Northern or Southern hemisphere. Lietti & Quenby(1968), however, propose a density gradient, produced by easy access of cosmic rays at the solar poles, rising equally on both sides of the solar equatorial plane. Both models propose larger densities of particles away from the ecliptic plane. For either model, viewing along the interplanetary field a telescope samples cosmic rays characteristic of the ecliptic plane, whereas 6 hrs. later the detector records particles that have reached it by spiralling around the interplanetary field from a higher heliolatitude. The cosmic ray density at this higher

heliolatitude is greater than in the ecliptic plane and this higher density is sampled twice daily, thus producing a semi-diurnal wave. The heliolatitude sampled being dependent on rigidity, the model readily explains the time of maximum and indicates a P^1 dependence of the semi-diurnal amplitude.

3.5.1 Comparison of predicted and observed semi-diurnal vectors

From Figs. 3.1 and 3.2 it is clear that throughout the period of observation the second harmonic in all the telescopes has remained essentially constant in both amplitude and phase within the errors. The surface level semi-diurnal vectors have tended to larger amplitudes since 1969 but the errors are rather large and other recent results (Sarabhai & Karagathra(1971) and Sekido et al(1971)) indicate a constant second harmonic for the period 1964 to 1971. Therefore the weighted mean values of the data have been calculated for the whole period of observation and the vectors have been plotted in Fig. 3.8. Only Vertical data from the underground telescopes have been

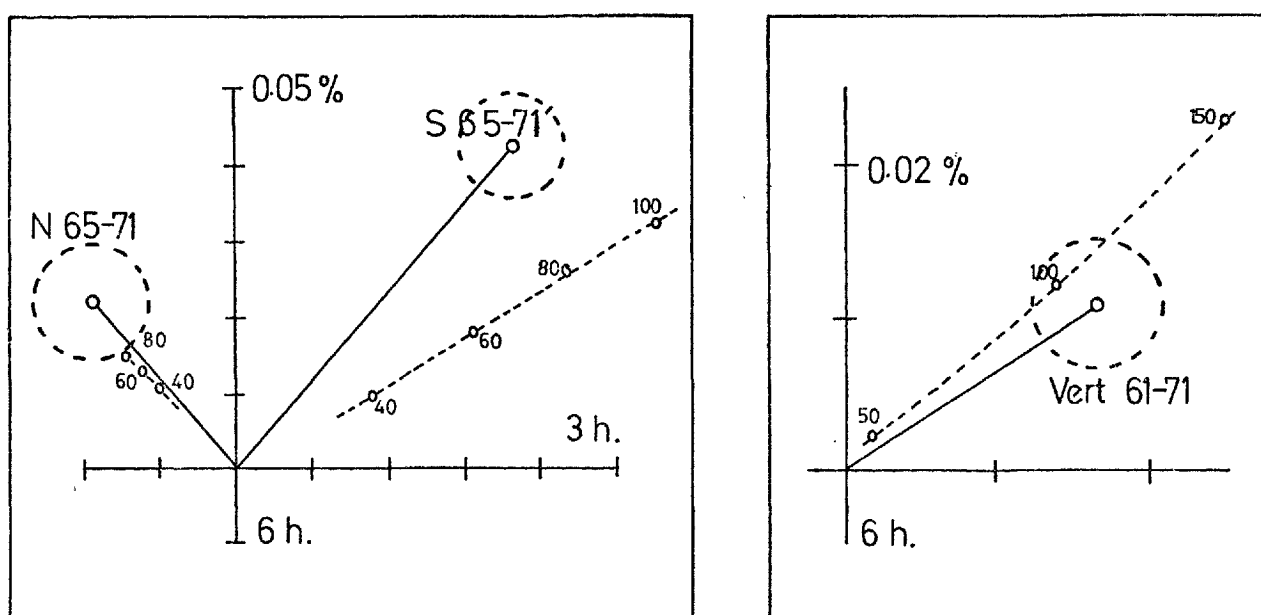


Fig. 3.8 Underground and surface level observations and predictions of the solar semi-diurnal vector for the periods shown.

used as they provide the largest data sample and hence the most significant result. Correction for geomagnetic bending requires an assumed rigidity and latitude dependence for the effect, and Hashim et al(1969) using the model

proposed by Lietti & Quenby(1968) have calculated the expected vectors as a function of the upper cut-off rigidity. The model includes the observed rigidity and asymptotic latitude dependence (Rao(1971)), and the calculated vectors have also been plotted in Fig. 3.8 where the small figures represent the limiting rigidity to the effect.

Due to the rigidity dependence of the effect a North pointing telescope scans a more restricted view of the solar system as the limiting rigidity and therefore the size of the effect increases. Thus the North pointing telescope should show little response to the predicted effect. The observed semi-diurnal variation will be due mainly to any residual atmospheric temperature effects which should be subtracted from the South result. Clearly a correction to the South results of this phase will improve the fit to the predicted values and give a value to the upper cut-off rigidity of 85 ± 15 GV. The underground North pointing telescope indicates that no correction is needed for residual atmospheric effects in the Vertical data and its agreement with the predicted vectors for an upper cut-off rigidity of 105 ± 15 GV. is impressive. Thus the results at two different mean primary energies of response provide clear evidence for the $+1$ rigidity dependence to the effect and the model proposed to fit the data. In all the models using a density gradient as the source of the semi-diurnal variation it is implied that the magnitude of the gradient is dependent upon the diffusion coefficient. Thus studies of the semi-diurnal variation provide a source of information about the diffusion coefficient at high energies and over the period of the data considered, the invariance of the amplitude of the semi-diurnal variation points to the constancy of the diffusion coefficient during 1961 to 1971.

3.6 Day to day variations of the diurnal anisotropy

Large day to day variations about the mean value of the anisotropy, in both amplitude and phase, have long been observed. Modern, high count rate detectors enable such variations to be studied and correlated with various parameters of the interplanetary medium.

Explanation of such large variations in terms of the Parker-Axford model are difficult in view of the large changes in the macroscopic structure of the interplanetary medium required. Streaming in the longitudinal sector structure and scattering at magnetic field irregularities, causing short circuiting of latitudinal gradients, have been mechanisms proposed. A further possible source of variation is due to an asymmetrical density gradient perpendicular to the ecliptic plane (Marsden(1967)). Such a gradient produces a flow of particles $\underline{B} \times \nabla n$ (where ∇n is the density gradient) which has to be vectorally added to the corotation vector and the sense of this additional vector depends on the direction of the interplanetary field. As the field reverses or changes direction at all, so does this $\underline{B} \times \nabla n$ streaming and hence the amplitude and phase of the "total" diurnal vector alters.

Recently Forman & Gleeson(1970), Rao et al(1971) and Hashim et al(1971) have attempted to provide a unified model of the diurnal variation to explain both average and day to day characteristics. It involves ideas of simple convection in the solar wind and field aligned diffusion. Consider the model drawn in Fig. 3.9. Obviously variations in $\underline{A}_d$ or $\underline{A}_c$ in both direction and magnitude can easily explain the day to day variations of $\underline{A}_0$. Since the long term means of $\underline{A}_d$ and $\underline{A}_c$ are well aligned radially and along the Archimedian spiral respectively, the average properties of $\underline{A}_0$ are well accounted for.

Using data from the North and South telescopes both models have been studied. Firstly, data for the years 1966, 67, 68 and 69 have been split according to the direction of the interplanetary field in order to see if a different phase and amplitude are found for different field directions, thus indicating the existence of a North-South density gradient. Secondly, data for 1969 was selected for days when interplanetary field measurements were available and a correlation between the field direction and the phase of the anisotropy has been carried out to see if a unified model can be

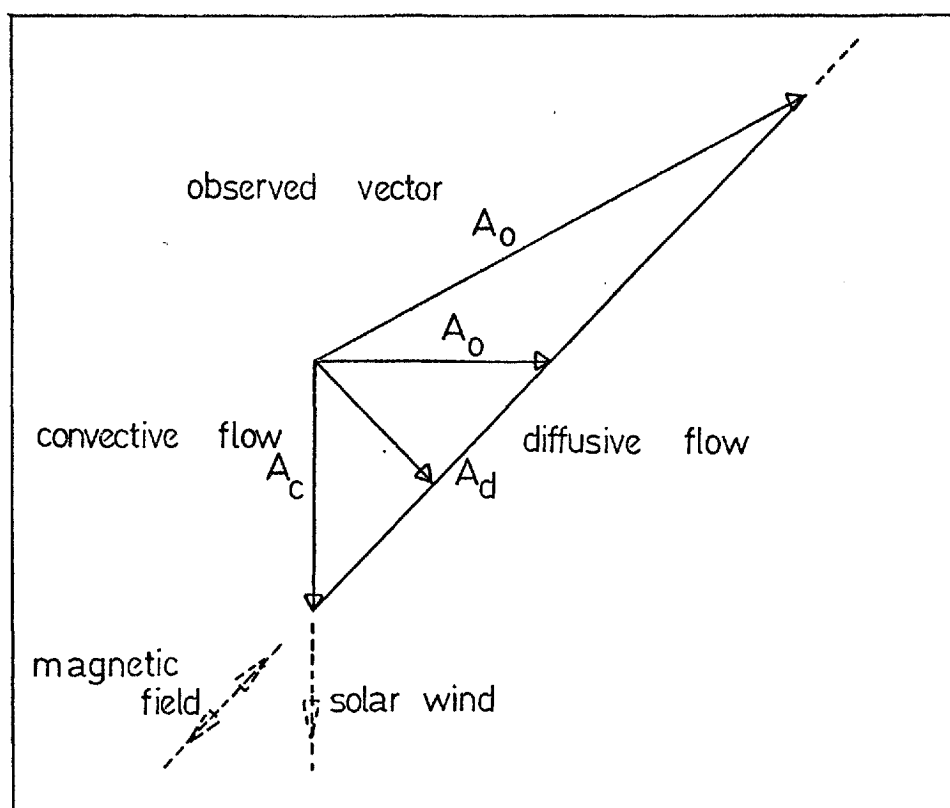


Fig. 3.9 Resolution of the observed anisotropy A_0 into components corresponding to radial convective flow A_c and diffusive streaming A_d .

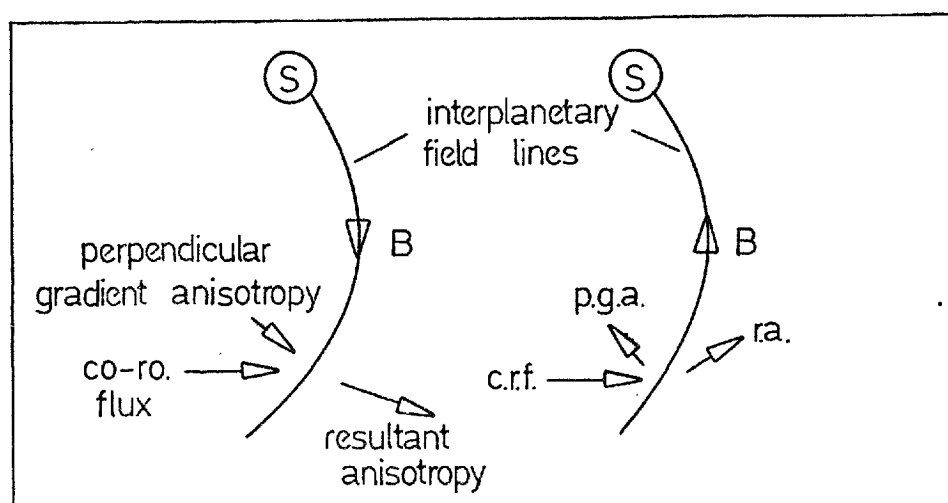


Fig. 3.10 Resultant anisotropies due to corotation and a perpendicular density gradient of cosmic rays for different directions of the interplanetary magnetic field.

found to fit the data.

3.6.1 A gradient perpendicular to the ecliptic

A marked asymmetry in activity on the Sun has been noticed with more activity since 1958 in the Northern hemisphere. Sarabhai & Subramanian(1966) conclude that this would produce a cosmic ray density gradient with increasing number density in a southward direction. Such a gradient coupled with the interplanetary field will produce diurnal anisotropies due to the addition of a corotational vector $\underline{A}_{co}$ and a gradient induced vector $\underline{A}_g$ as indicated in Fig. 3.10. From Fig. 3.10 it is clear that $\underline{A}_0$ changes in both magnitude and phase with the reversal of the field. Any radial cosmic ray gradient will produce another vector perpendicular to the ecliptic plane but since such a direction would be fixed in solar time it would not contaminate the results analysed in solar time.

The harmonic coefficients obtained on a daily basis have been split according to the interplanetary field direction on that day and the mean vectors for the North and South telescopes are plotted in Fig. 3.11. For the South telescope a significant difference in amplitude is seen for different field directions although the phase difference is covered by the errors. Due to the errors, the results for the North telescope are inconclusive, but the amplitude does appear to be larger for the positive field direction as in the South telescope.

Swinson(1971c), Hashim & Bercovitch(1971) and Hatton & Barker(1971) all report a similar effect i.e, for the field away from the Sun the amplitude does increase and goes to later phase. The present analysis is not inconsistent with these results in view of the fact that the phase difference cannot be regarded as significant. An estimate of the magnitude of the perpendicular gradient anisotropy can be obtained as half the difference between the amplitudes for negative and positive field directions. For the South telescope this gives a value of $0.027 \pm 0.018\%$ at the detector which agrees very well with the result of Swinson(1971c). The small value for the North

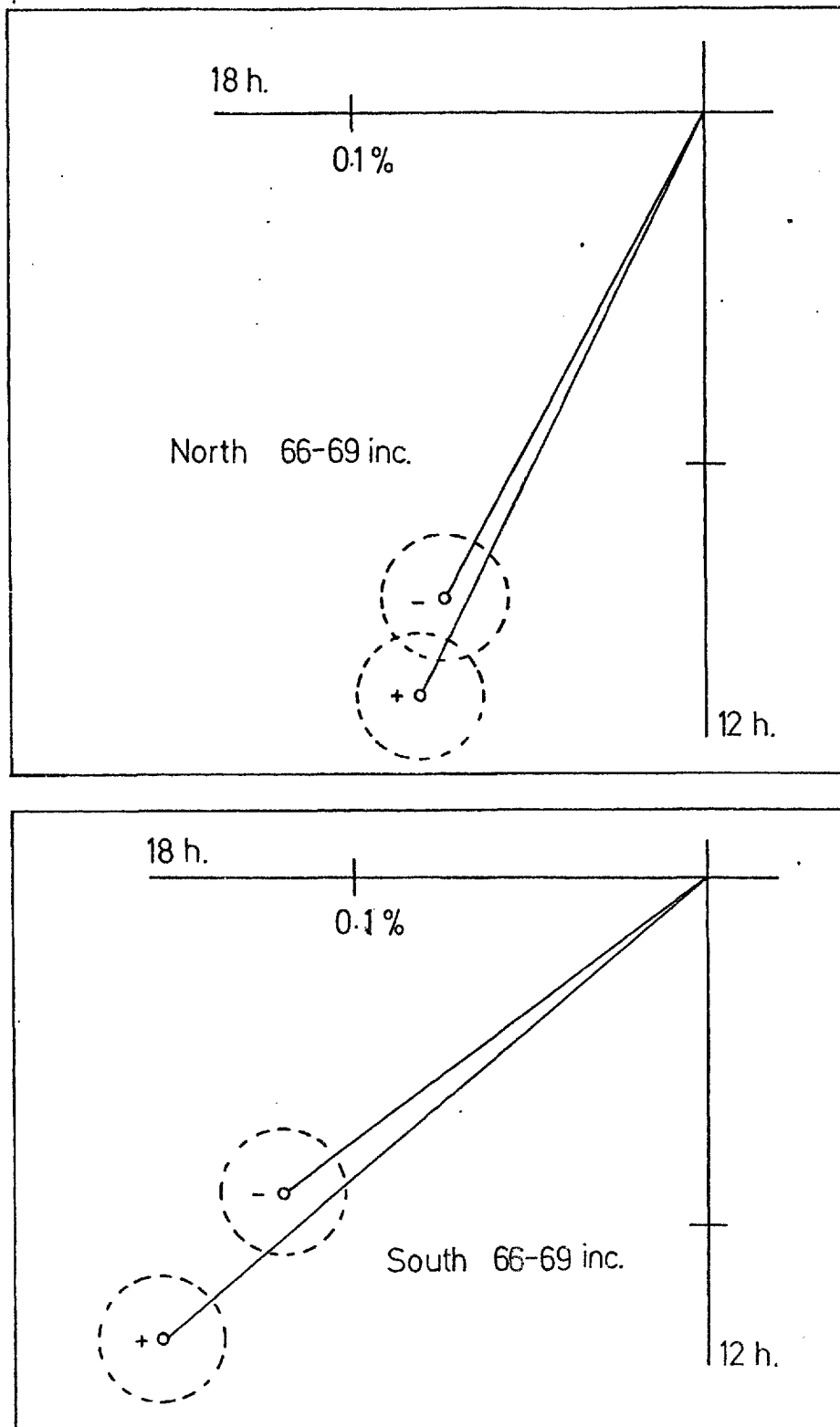


Fig. 3.11 Harmonic dials showing the effect of separating the solar diurnal variation data according to positive (B pointing away from the sun) and negative field directions for the surface level N/S telescopes.

telescope is understandable as in fact it does not "look" exactly in the ecliptic plane and under these conditions only a component of this $\underline{B} \times \nabla n$ streaming will be recorded and due to the errors such a component cannot be resolved.

Summarizing it can be said that the data presented for the period 1966 to 1969 does support the hypothesis that a perpendicular density gradient exists with the number density increasing southwards. This is in agreement with other recent results.

3.6.2 A unified model

A simple convection and field aligned diffusion model can explain both average and day to day characteristics of the solar daily variation. In order to test this model, which has been used effectively by Hashim et al (1971) on neutron monitor data, a correlation analysis between the direction of the interplanetary field and the time of maximum of the 24 hr. wave on a daily basis has been carried out. Daily averages are required since a period must be chosen that is representative of the prevailing conditions. Jokipii(1966,1967) suggested that the effective guiding field would be the average over a region $2\pi\rho$ where ρ is the particle gyroradius. For cosmic rays of rigidity 10-20 GV. this makes the "domain" size ~ 0.5 A.U. and as the solar plasma has a velocity ~ 0.01 A.U./hr. the period for a representative field average is of the order of one day. Daily average data for 1969 has been used from the South surface telescope and the fluxgate magnetometer on board HEOS-A1. Consider the model drawn in Fig.3.9. Mathematically we have;-

$$\underline{A}_0 = \underline{A}_c + \underline{A}_d \quad (3.9)$$

but it is required to show that;-

$$\underline{A}_0 - \underline{A}_c = \underline{A}_d = f\left(\frac{\underline{B}}{B}\right) \quad (3.10)$$

Thus assuming some magnitude and phase for $\underline{A}_c$, the fit to relation 3.10 can be tested by splitting the vector $(\underline{A}_0 - \underline{A}_c)$ into components parallel and perpendicular to the field direction on that particular day. The variance

formed by the perpendicular component is required to be a minimum, i.e., $(A_0 - A_C)_{\#}^2 = \sigma_{\#}^2$ (where the subscript $\#$ means the component perpendicular to the interplanetary field) should be a minimum. The amplitude and phase of A_C was allowed to take values from 0.1 to 0.6% with a phase from 06.00 to 18.00 hrs. L.S.T.. For each case $\sigma_{\#}^2$ was calculated and the results are plotted in Fig. 3.12 as a function of phase of A_C . The A_0 vectors have been corrected for geomagnetic bending assuming the value of P_U obtained for the yearly average of 1969. From Fig. 3.12 it can be seen that $\sigma_{\#}^2$ goes through a minimum for every value of A_C . Although there are large errors and a rather flat variation of $\sigma_{\#}^2$ for small values of A_C , the minimum variance occurs for $A_C \sim 0.2$ to 0.3% and a phase of 12.00 hrs. L.S.T.. Correction of the magnitude for geomagnetic smoothing yields the free-space value of $A_C \sim 0.4\%$ which corresponds to a streaming velocity of ~ 300 km/sec in approximate agreement with the measured solar wind velocity.

Unfortunately the data sample (only 108 days when both sources of data were available) was too small to allow the selection of a particular type of daily variation, small or large, late or early phase, to see if the model could cope with these different situations. However, the data spans the solar maximum with the expected large variation in solar wind parameters and although individually the fit of the model has not been tested, many types of variation should have occurred and collectively the model is adequate.

3.7 Summary and conclusions

The results of the surface level and underground measurements are consistent with the Parker-Axford model of the solar diurnal variation. The long term changes of amplitude and phase are well accounted for by a change of P_U , the upper limiting rigidity over the solar cycle, although the surface level data points to fluctuations in the free-space amplitude. P_U shows a correlation with solar activity and correlates best with the intensity of the coronal green line. The long term average of the stable semi-diurnal component is consistent with a cosmic ray density gradient perpendicular to the

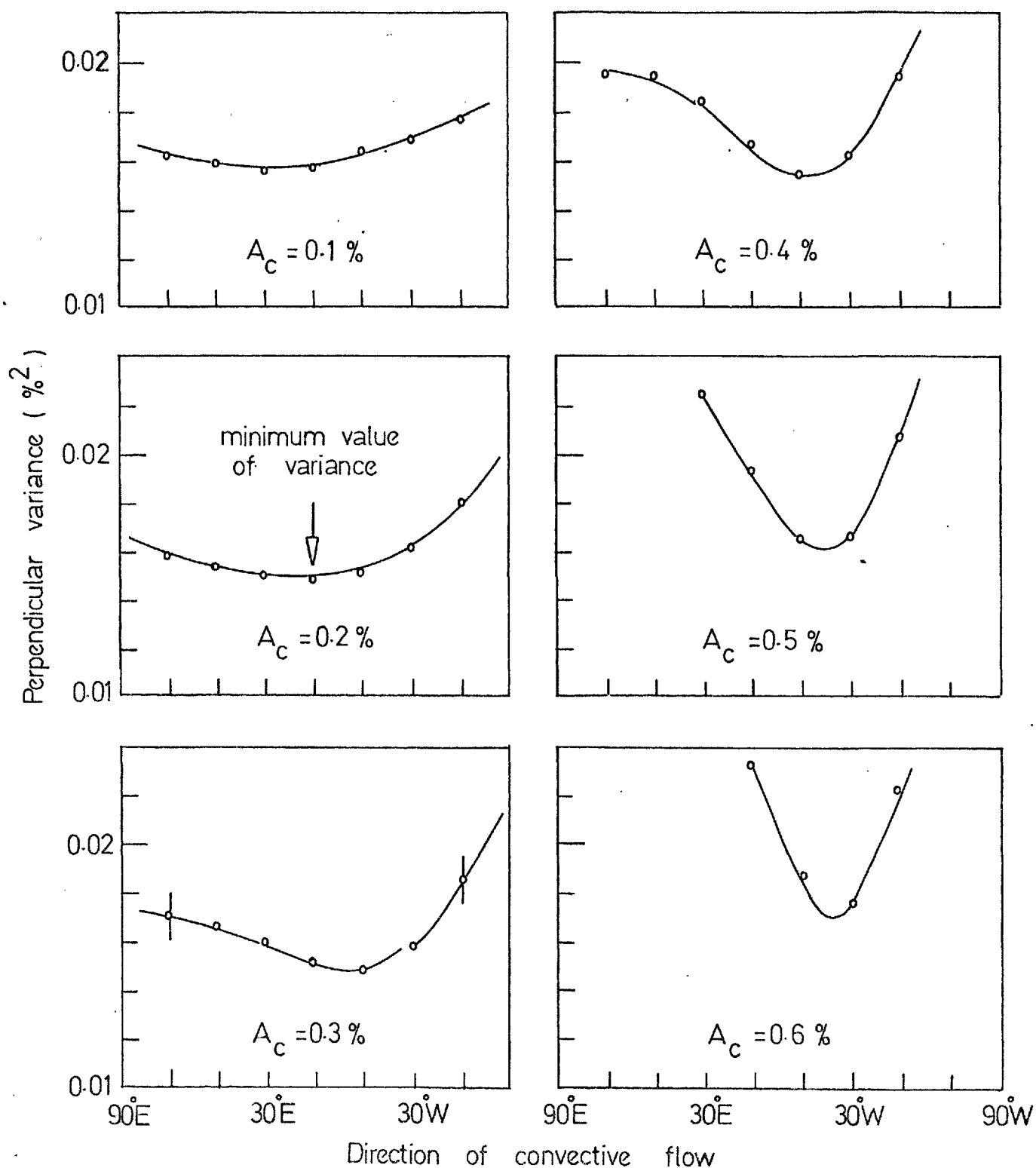


Fig. 3.12 Perpendicular variance as a function of the direction of the non-field-aligned vector A_C relative to the Sun-Earth line for various values of A_C .

ecliptic plane.

Day to day variations have been studied according to two different models. The split in the vectors for different sectors of the interplanetary field was interpreted as being due to a density gradient perpendicular to the ecliptic plane, as seen by other workers. The idea of convection and field aligned diffusion forming a unified model of both average and day to day variations was shown to be possible, however, the small data sample did not allow different types of variation to be studied in detail.

CHAPTER 4

A NEW DETECTOR

4.1 Introduction

The experiment at Holborn must be continued; firstly to confirm the phase reversal for 1970-71 as seen by the South(15°) and Vertical telescopes and secondly to substantiate the results found in the last ten years. However, a further experiment needs to be performed to decide the interpretation that should be applied to the above results. Southern hemisphere results, although as yet only obtained at shallower depths than Holborn, require different interpretations to those applied to northern hemisphere results. What is needed is an experiment that can decide between the three proposed interpretations; a genuine galactic effect of a 2-way anisotropy or solar system motion, or a solar modulation induced effect of the Swinson type. Such an experiment would be the operation of a vertical telescope at 60-100 m.w.e. situated at the equator. For an equatorial station the mechanism proposed by Swinson produces zero anisotropy and a 2-way sidereal flux would produce a large second harmonic but no first harmonic. However, the solar motion effect would be increased due to the greater scan of the telescope across the celestial sphere.

4.2 Expected results from an equatorial station

To evaluate the expected anisotropy further trajectories have been calculated for such an equatorial station. The same starting conditions have been used as in the previous integrations although only mid-sector positions of the Earth have been used. Altogether eight different starting conditions for each rigidity and each even hour of the sidereal day were chosen. Several interesting points arise in the results;-

- (1) At a depth of 60 m.w.e. approximately 24% of the total count rate of the telescope is due to particles of rigidity ≥ 9000 GV. Such

particles are virtually unaffected by the solar field at 1 AU. and it is only when such particles get very near the Sun will considerable deflections occur and at such close proximity the validity of the assumed model must be doubted. In practice for the times of the year when these close passages to the sun occur (September & March around 12.00 hrs. L.S.T.) the integrations were not completed in even 50,000 integrating steps due to the dependence of the step length on the radial distance from the Sun. The uncertainty in the asymptotic directions for such particles means that for a telescope relying upon such particles for a reasonable proportion of its count rate certain periods of data must be considered with extra caution. In practice the removal of the months September & March would be adequate.

- (2) The asymptotic directions have been transformed into the galactic system of co-ordinates and the results for a particular time of day have been used in conjunction with the weights given in table 2.IV chapter 2 to produce weighted mean values of galactic latitude and longitude throughout the sidereal day. The results are plotted in Fig. 4.1 along with the scan produced assuming the interplanetary field did not exist. These scans are to be compared with those for the London vertical telescopes given in Fig. 2.7 chapter 2. The scan produced at the equatorial station covers the full extent of galactic longitude whereas the present telescopes effectively "look" in just one quadrant. Furthermore, both north and south galactic hemispheres will be scanned quite effectively despite the depth of the telescope being assumed to be only 60 m.w.e.. The increase in the scan between the infinite energy case and the actual one at 60 m.w.e. is small, only $\pm 15^\circ$ in latitude. The sacrifice in counting rate and representability that would be needed to get this extra 15° scan does not really seem worthwhile. At a depth

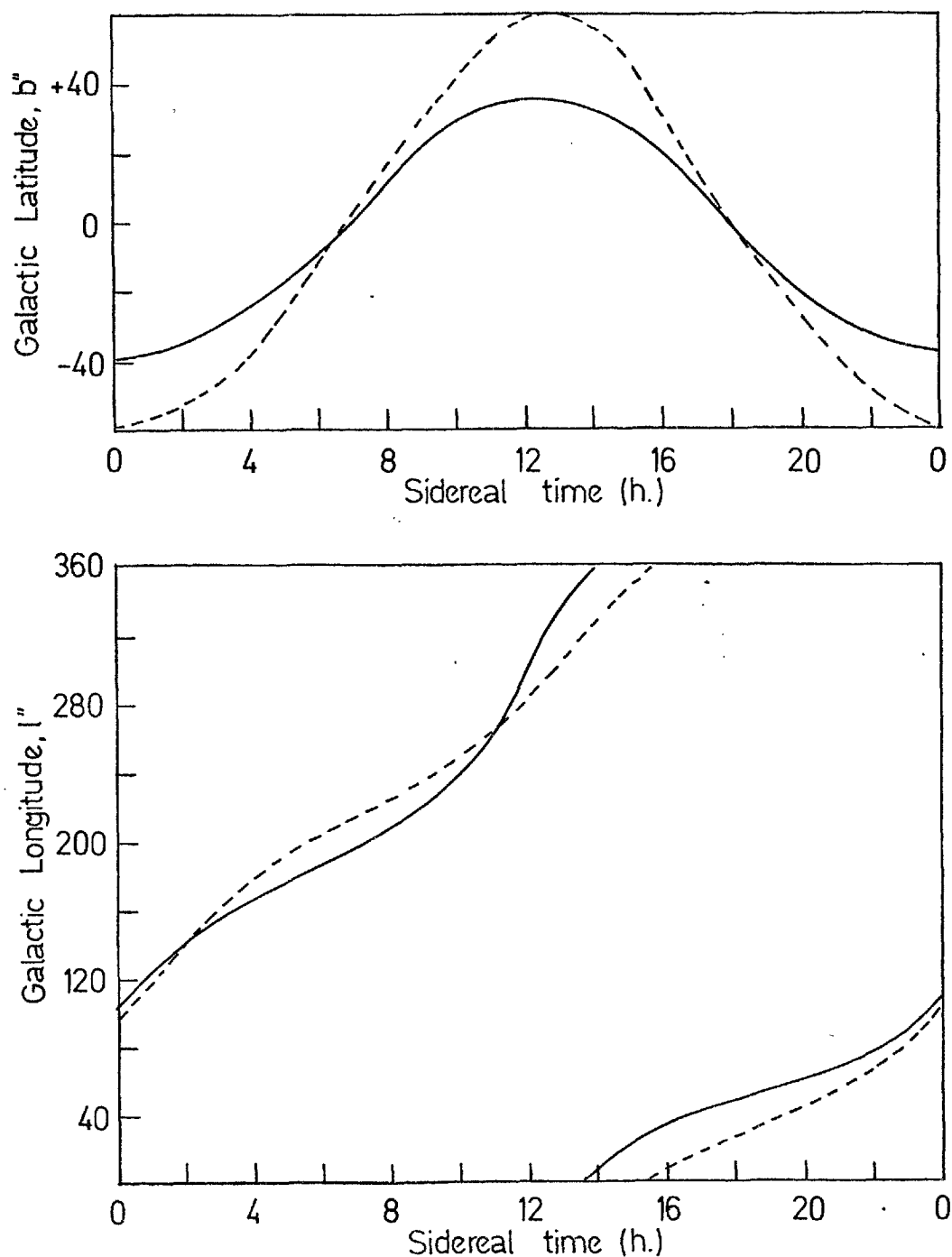


Fig. 4.1 Scans in galactic latitude and longitude as a function of sidereal time for a vertical telescope at the equator. The solid line is for a telescope at 60 m.w.e. and the dotted line is the scan produced by considering only infinite energy particles.

- of 350 m.w.e. the integral response function would have a form like that in Fig. 4.2 (Thambyahpillai(1971)). Using such a response function to weight the results produces the latitude scan in Fig. 4.3 which is very little different from that expected without the interplanetary magnetic field. At such a depth the count rate, and hence the statistical quality of the data would be very low and such a disadvantage has to be weighed against the reduced scatter in the results. Whether such a sample is representative of the general cosmic ray beam; the increased magnitude of the effect described in (1) plus the vast number of telescopes at 350 m.w.e. required to give statistical meaningful results would tend to indicate that 60-100 m.w.e. would be the best choice of depth.
- (3) Using the above scans in galactic longitude and latitude the magnitude of the solar motion effect has been evaluated for the equatorial station in the same manner as it was for the London vertical telescopes. The response function (60 m.w.e.) weighted values of $\cos(\alpha)$ have been used where α = the angle between the asymptotic direction of viewing and the solar apex in equation 2.13 of chapter 2. The resultant curve is plotted in Fig. 4.4. The expected amplitude of the effect at the equator is $\sim 0.026\%$ compared with $\sim 0.011\%$ at London and hence the observation of a first harmonic of increased amplitude can be expected if the solar motion interpretation is correct. The bi-annual modulation introduced due to large deflections in sunward looking directions can be expected to increase at the equator due to the more direct effect of the point discussed in (1). Thus, this modulation being larger one would expect a larger anti-sidereal effect.

Therefore the case for an experiment at an equatorial station at about the same depth as at Holborn has been made. For this purpose a new type of telescope had to be developed. It had to be cheap to build, so that a large

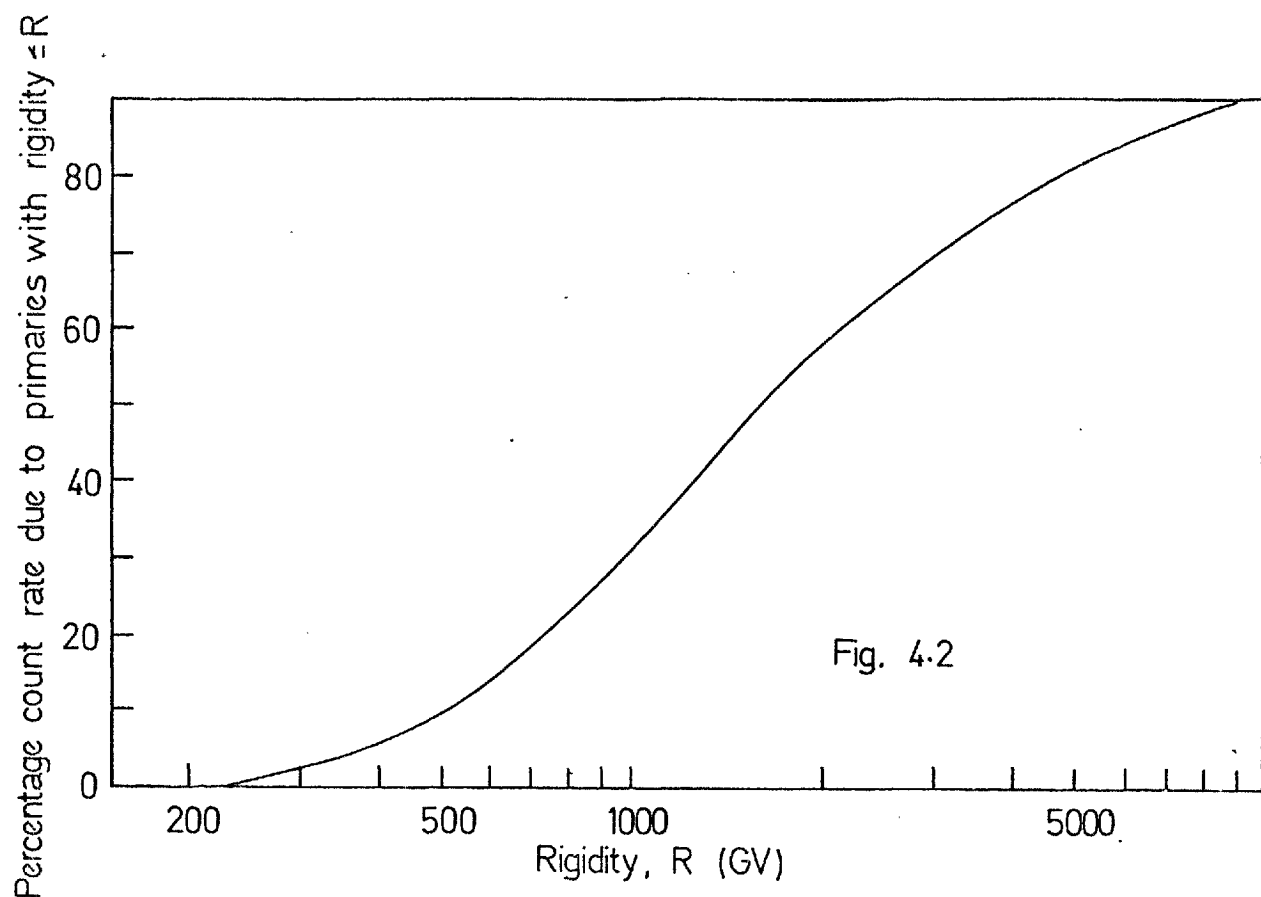


Fig. 4.2 Response function for a muon detector at a depth of 350 m.w.e. (Thambyahpillai [1971]).

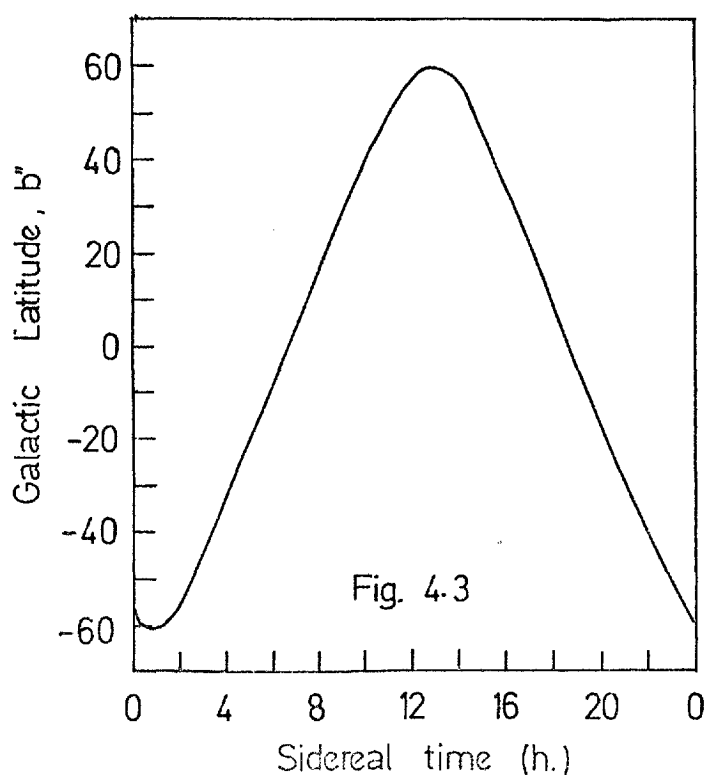


Fig. 4.3 Scan in galactic latitude as a function of sidereal time for a vertical telescope at the equator assuming the response function in Fig. 4.2 applies.

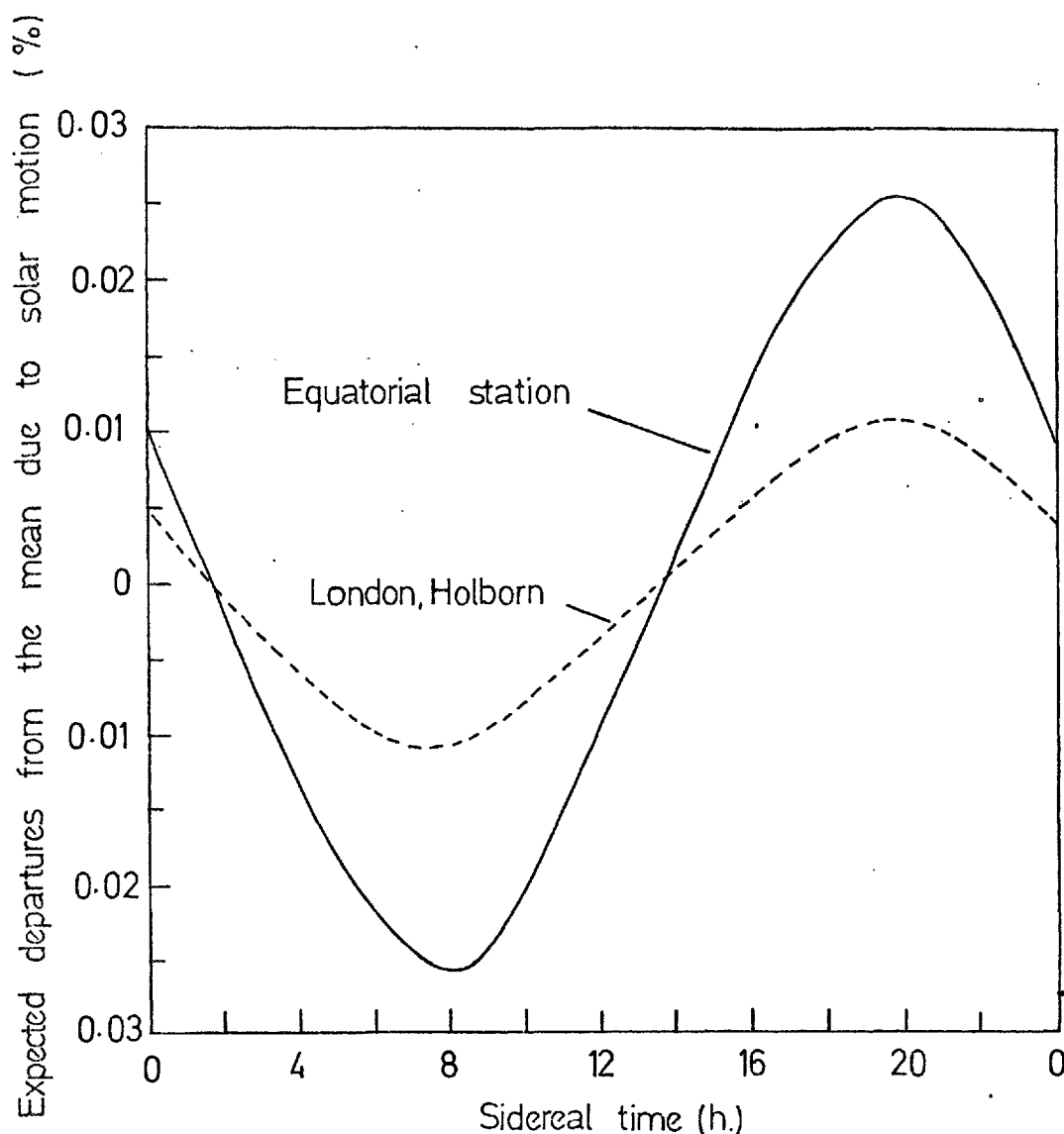


Fig. 4.4 Expected muon intensity departures from the mean throughout the sidereal day due to the solar motion effect at 60 m.w.e.. Vertical telescopes at two locations have been considered.

number could be used, and with very good resolution against background radioactivity so that it could be used at a greater depth if it was found necessary or useful.

4.3 The "Tank"

4.3.1 The "Tank" - general considerations

The fundamental considerations underlying all studies of time variations of cosmic rays is that of achieving adequate resolution against statistical and instrumental background fluctuations. Adequate statistical resolution can usually be found by using a large enough detecting area. However, at the same time, the cost of the experiment is an important consideration and the choice of components governs the cost of individual telescopes. Efficient use of the cheapest components should fulfil the required conditions. High

efficiency, long life, stability, high counting rates and extremely high time resolution are the main advantages of scintillator telescopes and therefore the design considerations of such a telescope have been carefully studied to produce a cheap efficient unit.

4.3.2 Scintillator telescope design considerations

Reliability, long term stability of the telescope components and associated electronics, low environmental temperature coefficient and discrimination against background radioactivity are all important factors. Particularly important is the last factor since at greater depths the meson count rate becomes very low and possibly at 300 m.w.e. the background radioactivity could be comparable. Long-term stability and low environmental temperature coefficient are governed by the magnitude of the effect to be measured. A low temperature effect in the associated electronics can be fulfilled by careful choice of the components and compensating feed-back loops, however, the temperature effects of photomultiplier/scintillator combinations can only be effectively overcome by the use of constant temperature environments. Ball et al(1957) show that temperature coefficients for photomultiplier/plastic scintillator combinations can be as large as -0.1% in pulse height/ $^{\circ}\text{C}$ and if the operating plateau of the telescope is short large changes in temperature need careful compensation.

The efficiency of the telescope is determined by the production of the scintillation light, its transmission and finally the detection of the light pulse after its transmission. The passage of a charged particle through the scintillator causes photons to be emitted. These photons are then "guided" to the photocathode of the photomultiplier where photoelectrons are produced. These photoelectrons cause an avalanche of secondary electrons in the dynode chain producing a pulse at the anode of the photomultiplier and such a pulse is registered by suitable electronics. The telescopes used at Holborn were built by Dutt(1965) and Peacock(1967) and those at the surface by Hashim(1968) The design has operated well over the past ten years but since they utilized

plastic scintillator(NE102A) they are expensive to build and their rejection of background radioactivity, if used at greater depths, is suspect. The electronics has proved reliable and being fully transistorized variations of temperature have little effect. The new telescope has been designed to use similar electronics but to give a superior performance from cheaper active components.

4.3.3 The scintillator

Modern liquid and plastic phosphors all have fairly similar efficiencies; the choice between them is usually determined by the relative importance of cost, convenience, fire hazard and long term stability. Plastic scintillators are convenient in use but their initial cost is high whilst liquids like Xylene or Toluene have such low flash points (17°C and 5°C resp.) that they present considerable fire hazards if used in large quantities. Barton et al(1962) have reported the use of medicinal paraffin as a solvent for p-terphenyl and POPOP and find that it is cheap, reasonably safe (flash point 229°C) and has a high transparency. They also find that using a concentration of 0.8 gm./litre of p-terphenyl gives an efficiency of about 600 eV per photon (i.e, approximately one third as efficient as NE102A) but its cost is $\sim \frac{1}{80}$ th that of the plastic.

In general terms, the passage of a charged particle through the scintillator causes a primary excitation of the solvent molecules. This excitation energy can migrate through the solution and some of this energy will be transferred to the primary solute molecule (p-terphenyl). Further transfer of excitation energy from the primary solute to the secondary solute (POPOP) molecules occurs and radiation from the secondary solute leads to scintillation light which is allowed to escape from the scintillator due to the low density of the primary and secondary solute molecules. The spectrum of the scintillation light observed is thus characteristic of the secondary solute molecules. POPOP gives an output wavelength well matched to the peak response of the photomultiplier.

For design considerations a useful figure is the number of photons produced by the vertical passage of a minimum ionizing charged particle through the scintillator. The most probable loss of energy by μ -mesons passing through one cm. of the phosphor is ~ 1.56 MeV. (Barton et al(1962)), thus the number of photons produced per cm. of track is,

$$\frac{1.56 \text{ MeV.}}{600 \text{ eV.}} = 2.5 \times 10^3 \text{ photons}$$

The fraction of these that reach the photocathode is determined by the light collection efficiency and the absolute number of photons at the photocathode will obviously depend upon the thickness of scintillator used. In turn the number of photoelectrons produced will depend upon the transparency of the photomultiplier window and the photoconversion efficiency of the photocathode. Birks(1953) estimates that due to thermal emission from the photocathode up to 8 photoelectrons can be produced so for effective discrimination against background noise the photoelectron emission due to a μ -meson needs to be an order of magnitude larger than that due to noise. During operation of the telescope a further discrimination needs to be made; that is discrimination against background radioactivity. A γ -ray of an MeV or so produces excitation of the solvent molecules by Compton scattering which is not a continuous process along the particle trajectory in the phosphor. Greater depth increases the number of Compton scatterings and subsequent loss of γ -ray energy, although at the same time the photon production for a meson also increases. Barton et al(1962) estimate that approximately 80 photons are produced per cm. of track for a 1 MeV. γ -ray in medicinal paraffin. Ideally the choice of light collection system and scintillator thickness should be such that the number of background radioactivity-produced photoelectrons is comparable to the noise of the photomultiplier but genuine μ -meson traversals at any point in the scintillator should produce a number of photoelectrons easily detectable above the noise.

The scintillator was mixed in 40 gallon drums to a recipe given by

Barton(1970). A concentration of 0.6 gms. per litre of p-terphenyl was used since the efficiency was still quite high but there was less risk of precipitation if the environmental temperature dropped too low. 0.006 grms. per litre of POPOP was used as the secondary solute to give an output wavelength of $\sim 4250 \text{ \AA}$. The paraffin was heated to $\sim 70^\circ\text{C}$ and maintained at this temperature for four hours while a small electric paddle ensured that the added chemicals dissolved. While the mixture was still hot and therefore less viscous, it was pumped into the scintillator boxes. This concentration of p-terphenyl yields an efficiency of $\sim 800 \text{ eV. per photon}$ giving $\sim 1.9 \times 10^3$ photons per cm. of muon track.

4.3.4 Light guiding system

Large area scintillators do not allow direct contact between the photocathode and the scintillator. Methods whereby the trapped photons are detected by employing light guides attached to the thicker edges of the scintillator sheets can produce non-uniformity of light collection or to overcome this a larger number of photomultipliers are used (e.g, Meyer & Wolmarans(1963), Barton et al(1962)). Indirect coupling has been used in the Holborn telescopes where the scintillator is contained in a large light tight box covered with highly reflective inner walls. Diffuse reflection over a sufficiently large area ensures reasonably uniform light collection and in practice aluminium boxes of dimensions $54" \times 54" \times 17"$ lined with I.C.I. Darvic have been used. These trays were further lined with one large sheet of polythene in order to contain the liquid phosphor. If the final telescope was to be used in an inclined position, perspex tanks would have to be used to hold the scintillator. However, as cost was a prime consideration and as a vertical telescope at the equator served the purpose, polythene sheet provided a cheap, efficient method to hold the scintillator.

Large scintillators emphasize the importance of the reflectivity of the container walls and the absorption of the fluorescent light within the scintillator. Pure medicinal paraffin is highly transparent and with

thicknesses up to 12" the absorption should be small. The reflection coefficient of Darvic is ~ 0.75 in the wavelength region of importance and Barnaby & Barton(1960) show that diffuse reflection is considerably better for uniform light collection than specular light collection. The light collection efficiency depends on both the reflectivity of the surfaces and the area of the photocathode. Fan(1964) has shown that ϵ , the light collection efficiency for a diffusely reflecting counter is given by;-

$$\epsilon = fk \left(\frac{A}{A_0} \right) \left(1 - \eta \left(1 - \left(\frac{kA}{A_0} \right) \right) \right)^{-1}$$

where η = reflectivity of the container walls

A = area of photocathode

A_0 = total area of reflecting surfaces

k = probability that a photon hitting the glass window of the photomultiplier passes through.

f = fraction of light that escapes from the scintillator.

In the present case all the edges of the scintillator are in direct contact with the diffusely reflecting Darvic and hence very little light will remain trapped due to internal reflection, giving $f \sim 1.0$. Using $\eta = 0.75$ and assuming that scintillator may occupy half the tray $A/A_0 = 0.45 \times 10^{-2}$ which gives $\epsilon = 1.8 \times 10^{-2}$ if $k \approx 1.0$. Transmission curves supplied by E.M.I. show that for the type of window used in the photomultiplier approximately 86% of the incident light is transmitted at normal incidence, however, oblique incidence will reduce this figure considerably. A more realistic value of k would reduce ϵ to $\sim 1.0 \times 10^{-2}$. For resolution between photomultiplier noise and the signal produced by a meson the depth of scintillator must be such that an order of magnitude exists between these two cases. If n = the number of photons produced by a minimum ionizing particle per cm. of track and q = the conversion efficiency of the photocathode, then the number of photoelectrons produced at the cathode is, m_{pe} and given by,

$$m_{pe} = n \times d \times q \times \epsilon \quad (4.2)$$

where d is the depth of phosphor. For the conditions outlined above $m_{pe} \approx 80$ and using the values for n and ϵ above, a value of $q \sim 15\%$ (as quoted by E.M.I.) yields a value for the depth $d \sim 28$ cms. Therefore a depth of phosphor of 10" was chosen to fulfil the above conditions and to ensure efficient detection of mesons passing through the scintillator.

4.3.5 The photomultipliers

Each scintillator tray has one photomultiplier mounted in the middle of the face opposite the scintillator with the window of the photomultiplier flush with the Darvic (see Fig. 4.5). The uniformity of light collection was found to be best when the tube face was flush with the surface. A large photocathode is desirable due to the large area of the scintillator. E.M.I. type 9618 have 111 mm. diameter Sb-Cs-O(S11) photocathodes and are recommended for fast coincidence work due to their fast pulse rise time and their low noise characteristics and were chosen for the present experiment.

4.3.6 Construction of the telescope

Possibly the telescope was to be used at great depths underground (up to 1,000 m.w.e.) where the meson count rate was likely to be comparable to the background radioactivity. So that effective discrimination can be made between these two effects it is necessary to run several scintillators in coincidence. The telescopes used at the surface in double coincidence would be seriously affected by a radioactive background producing comparable counts as the sea level mesons so triple coincidence with larger thickness scintillators has been used in the present telescope. A schematic diagram of the telescope is drawn in Fig. 4.5. Photomultipliers which were matched as nearly as possible to have the same gain at the same voltage were chosen from the information given by the manufacturers. The electronics used is the same as for the underground telescopes with a slight modification to facilitate three-fold coincidence. The electronics have been described

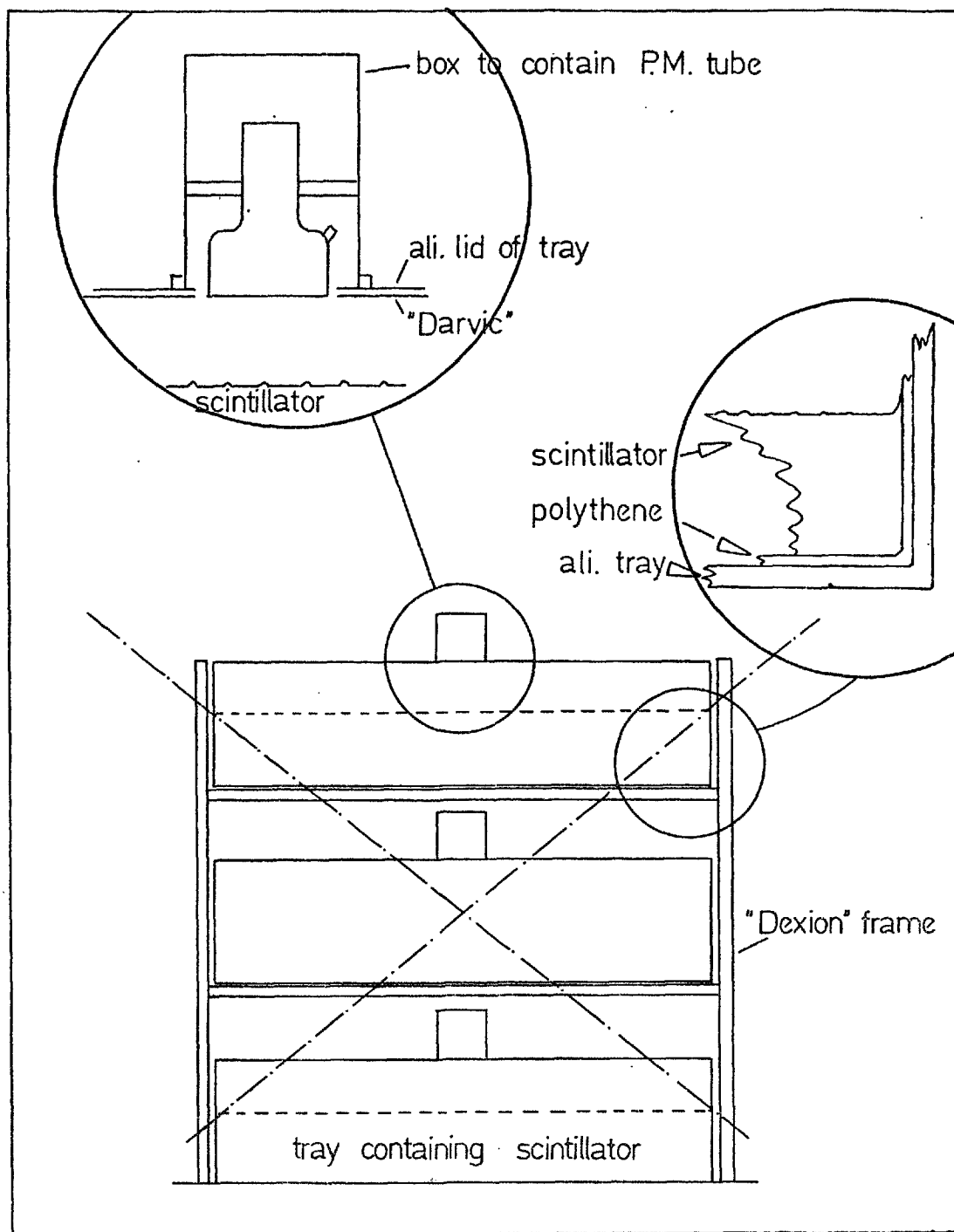


Fig. 4.5 Schematic diagram of the three-fold telescope.

before by Dutt(1965), Peacock(1968) and Hashim(1968) and only a brief outline will be given. The circuitry has been designed with a view to high stability long term reliability and elimination of any periodic variations, e.g, supply voltage variations or temperature variations of the environment. To avoid supply voltage variations an AC Servomex stabilizer and a saturated core transformer are used in series. These units supply the power to the stabilized E.H.T. and L.T. units and the overall stabilization is such that a 10 volt change in the supply results in a 0.00075 volt change in the E.H.T. output. The circuitry for each phototube consists of a dynode chain using high stability resistors and giving a chain current about ten times the expected anode current to ensure that changes in the anode current (i.e, change in dark current) could not interfere with the dynode voltages. The output pulse from the anode is coupled via a capacitor to an amplifier which effectively matches the output of the photomultiplier to the discriminator that follows. The amplifier has an amplification $\sim \times 3$ and uses negative feed back for stability. A pulse height limiter of ~ 1 volt is included in the output. This output is fed into a discriminator that does not fire below 150 mv. and therefore removes all pulses due to noise but allows those produced by mesons to be counted. The discriminator output triggers an avalanche transistor giving a pulse large enough to be transmitted along long lengths of co-axial cable. The output pulses (~ 1 volt) from each of these units are fed into the coincidence unit which requires three such pulses to make the diode (0A95) conducting. When it conducts it causes a univibrator to switch states giving an output of approximately 1 volt. An emitter follower is used to match this output to the following parts of the circuit usually being scaling units and electromechanical printers.

4.4 Performance of the telescope

The performance of a telescope is a function of two instrumental parameters; the operating voltage of the photomultipliers and the level of the coincidence discriminator. An optimum combination of these parameters is

required to provide:-

- (1) Maximum meson count rate
- (2) Maximum stability of the counting rate against instrumental drift
- (3) Minimum background count due to noise and radioactivity.

Therefore the characteristic dependence of the count rate upon these functions must be determined. Once having determined the operating point of the telescope the proper assessment of the instrument requires that the resolution of the telescope and the uniformity of response be measured.

The resolution of a particular peak is the full width of the differential pulse height distribution at half maximum height, expressed as a percentage of the position of the peak. The width of the resulting pulse height distribution will depend upon:-

- (1) Non-uniformity of photon collection
- (2) Non-uniformity of the conversion efficiency of the photocathode
- (3) Variable path lengths in the scintillator
- (4) Landau statistics of the energy loss by the particles in the scintillator

and (5) The energy spectrum of the particles.

Obviously the uniformity of response is an important, controllable factor, however, there is little advantage in having the non-uniformity much less than the resolution of the counter, as limited by the Landau and photomultiplier effects

4.4.1 Operating point of the telescope

In order to study the effects outlined above the operating point of the telescope had to be determined and the procedure adopted was:-

- (1) The scintillator trays were closed and sealed with the photomultipliers in place and the whole telescope was enclosed in black cloth.
- (2) The count rate versus photomultiplier voltage characteristics were determined for each tube and the individual E.H.T.'s were adjusted by the inclusion of resistors in series with the power supply, to

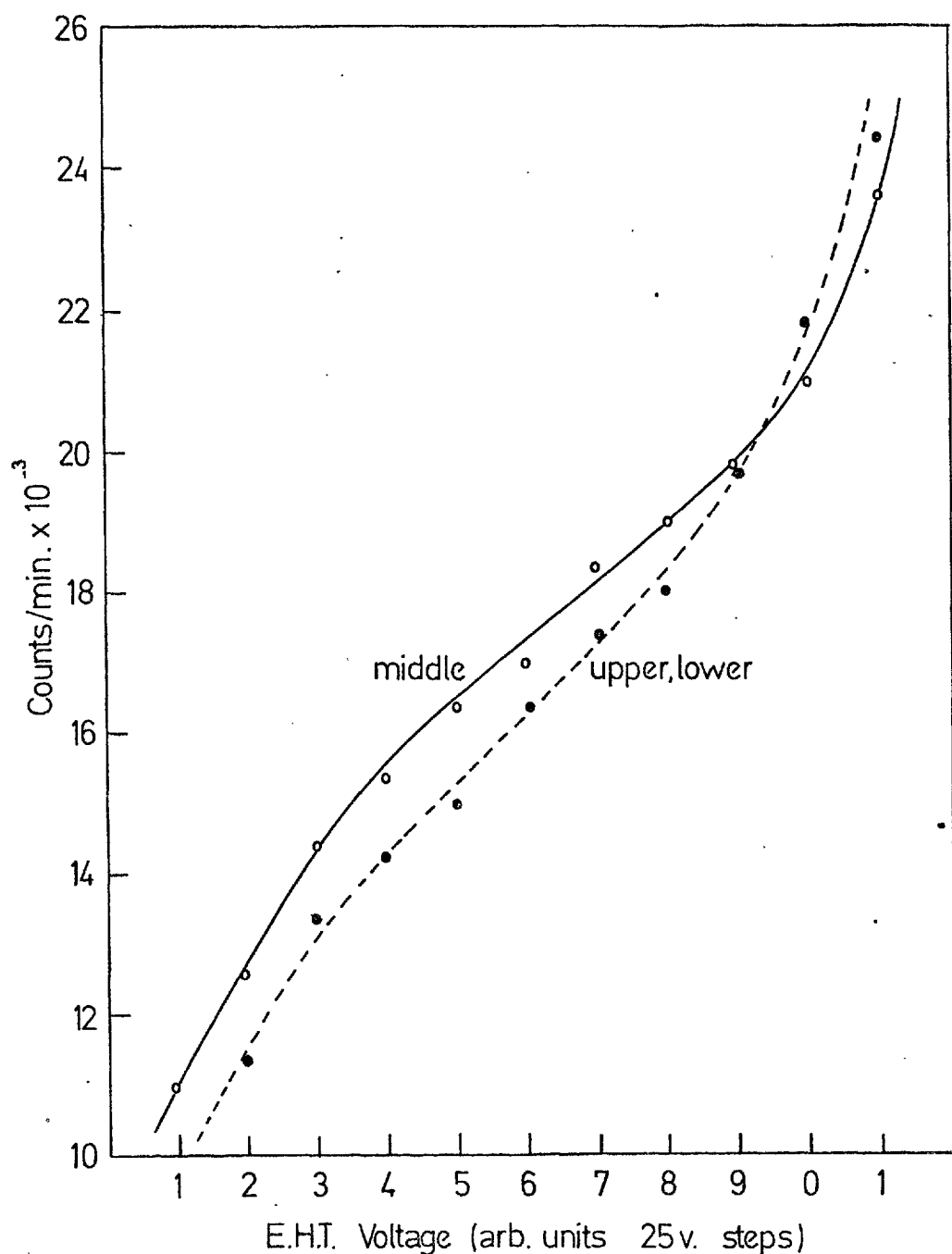


Fig. 4.6 Singles count rates as a function of E.H.T. voltage for each unit of the telescope.

give equal count rates at one setting of the E.H.T. supply. This allowed all three units to be run from one power supply. These characteristics are plotted in Fig. 4.6 and it is interesting to note that slight tendencies for a plateau are evident. This indicates that even though noise and background radioactivity counts are present in very large numbers some attempt at discrimination

is being made.

- (3) The three outputs were fed into the coincidence unit and with the E.H.T. set at the manufacturers recommended photomultiplier operating voltage (~ 1500 v.) the setting of the discriminator was investigated. The count rate versus discriminator setting characteristic is plotted in Fig. 4.7(a) showing that an initial increase of the discriminator level removes just the noise pulses. A flat section in this characteristic indicates that noise pulses are effectively removed but all the cosmic ray pulses are being recorded. Further increases of the discriminator level start to remove the weaker cosmic ray pulses with a subsequent loss of count rate. The correct setting of the discriminator, indicated in Fig. 4.7(a), ensures that only cosmic rays are recorded but none are removed.
- (4) Finally to determine the optimum operating voltage of the photomultipliers the coincident count rate versus E.H.T. characteristic was determined. This is plotted in Fig. 4.7(b). The important part of this characteristic is the plateau since it is a direct measure of the stability of the instrument against a drift in the E.H.T. voltage. In this region, although the sensitivity of the photomultiplier is increasing i.e., the detecting threshold is decreasing, the count rate is stationary. This can only happen if all the photon intensity output due to the measured radiation is above a certain threshold, which is the case for mesons traversing the phosphor. However, background radiation imparts its excitation energy to the solvent molecules by Compton scattering and therefore has a continuous spectrum from zero intensity up to some upper limit. The nearly flat plateau therefore indicates that only cosmic rays are being counted and radioactivity is having little effect. The very slight increase in count rate is due to the vast

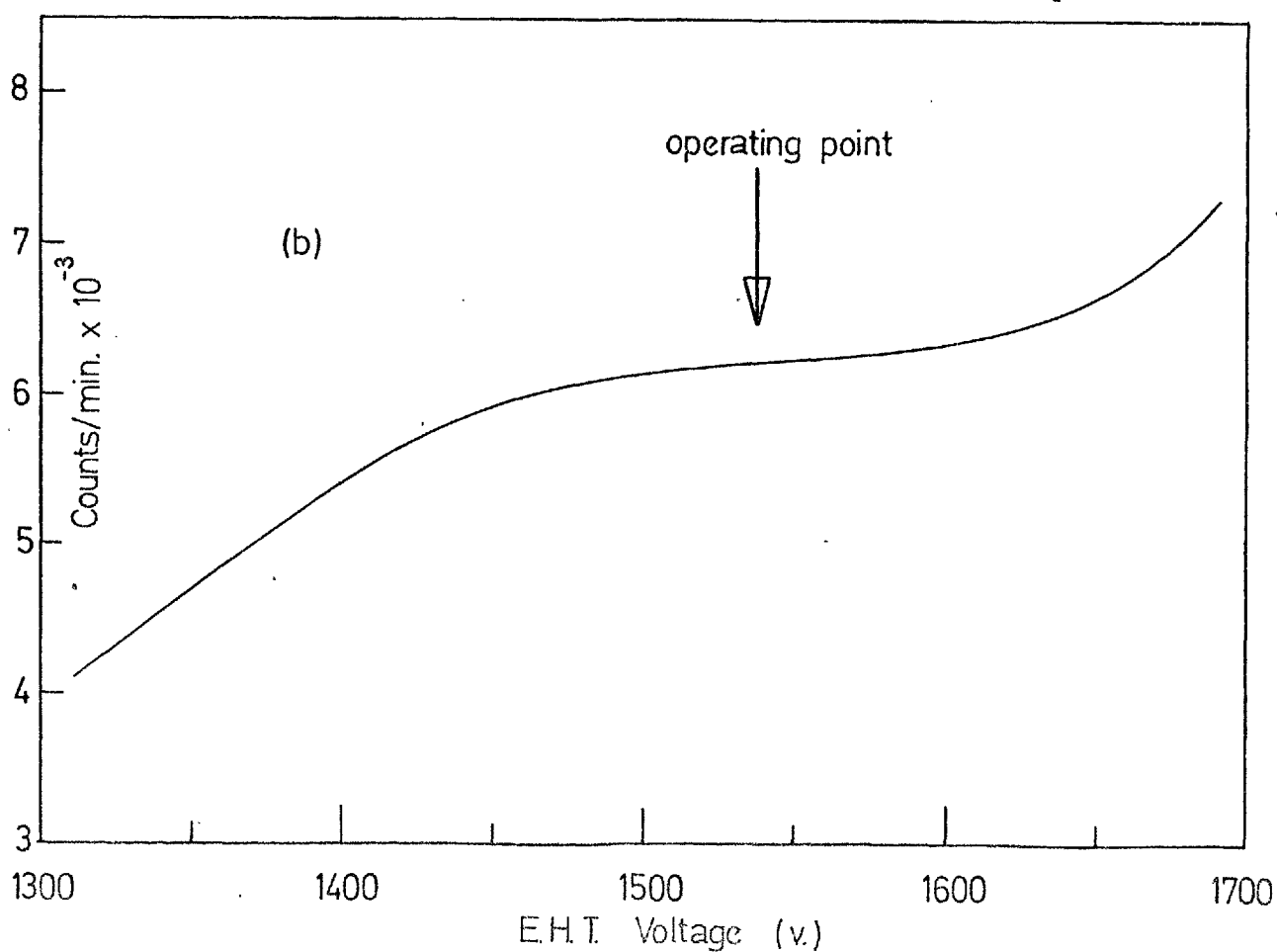
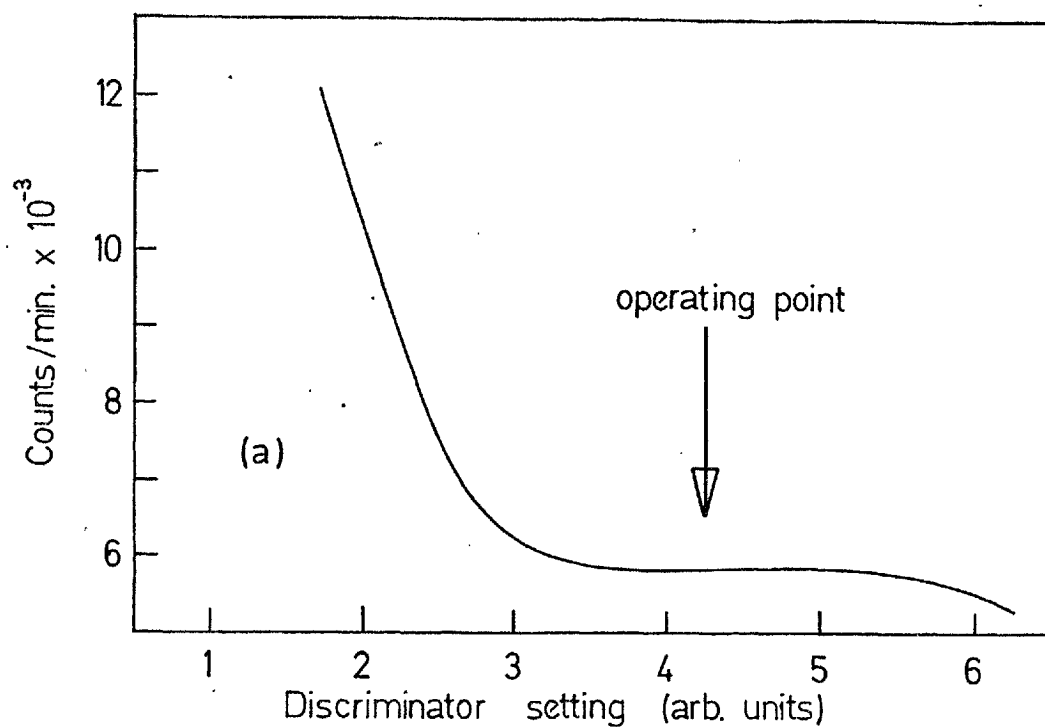


Fig. 4.7 Operational characteristics of the three-fold coincidence telescope.

(a) Count rate as a function of discriminator setting.

(b) Count rate as a function of E.H.T. voltage.

increase in the noise of the photomultiplier as the E.H.T. increases. An important figure is therefore the slope of the plateau as a percentage of the mean count rate for a given voltage step. From Fig. 4.7(b) this $\sim 4\%$ per 100 v. and for comparison, Holborn plastic telescopes give $\sim 8\%$ per 100 v. (Peacock(1967)). For long term operation the telescope is set to operate at the E.H.T. corresponding to the middle of the plateau, and it was at this voltage that the assessment of the telescope was made.

4.4.2 The uniformity of response

The uniformity of response was measured by operating a small area plastic scintillator counter in coincidence with the lower tray. These coincident pulses were used to gate a 100 channel pulse height analyser (P.H.A) and by moving the small counter over the area of the upper tray the meson peak was obtained for only a small region of the upper scintillator. By comparing the pulse heights corresponding to the peaks of the curves the variation in response was obtained and this is plotted in Fig. 4.8. The uniformity of response had been estimated for this type of container by Dutt(1965) by using a small electric light bulb. However, this method reproduces a more realistic situation and enables the measurements to be taken with the scintillator in position and, due to its thickness, differences could be introduced if it were removed. The errors have been determined from the spread of the μ -meson peak and hence contain many broadening effects. It can be seen that the present arrangement gives a uniform response over the large detecting area, only falling to 60% of the central value even at the extreme corners. The non-uniformity could be reduced by increasing the scintillator thickness towards the edges. For the present liquid scintillator this could be achieved by placing an inverted funnel made of Darvic on the base of the tray. However, from the subsequent performance of the telescope it does not appear to be necessary.

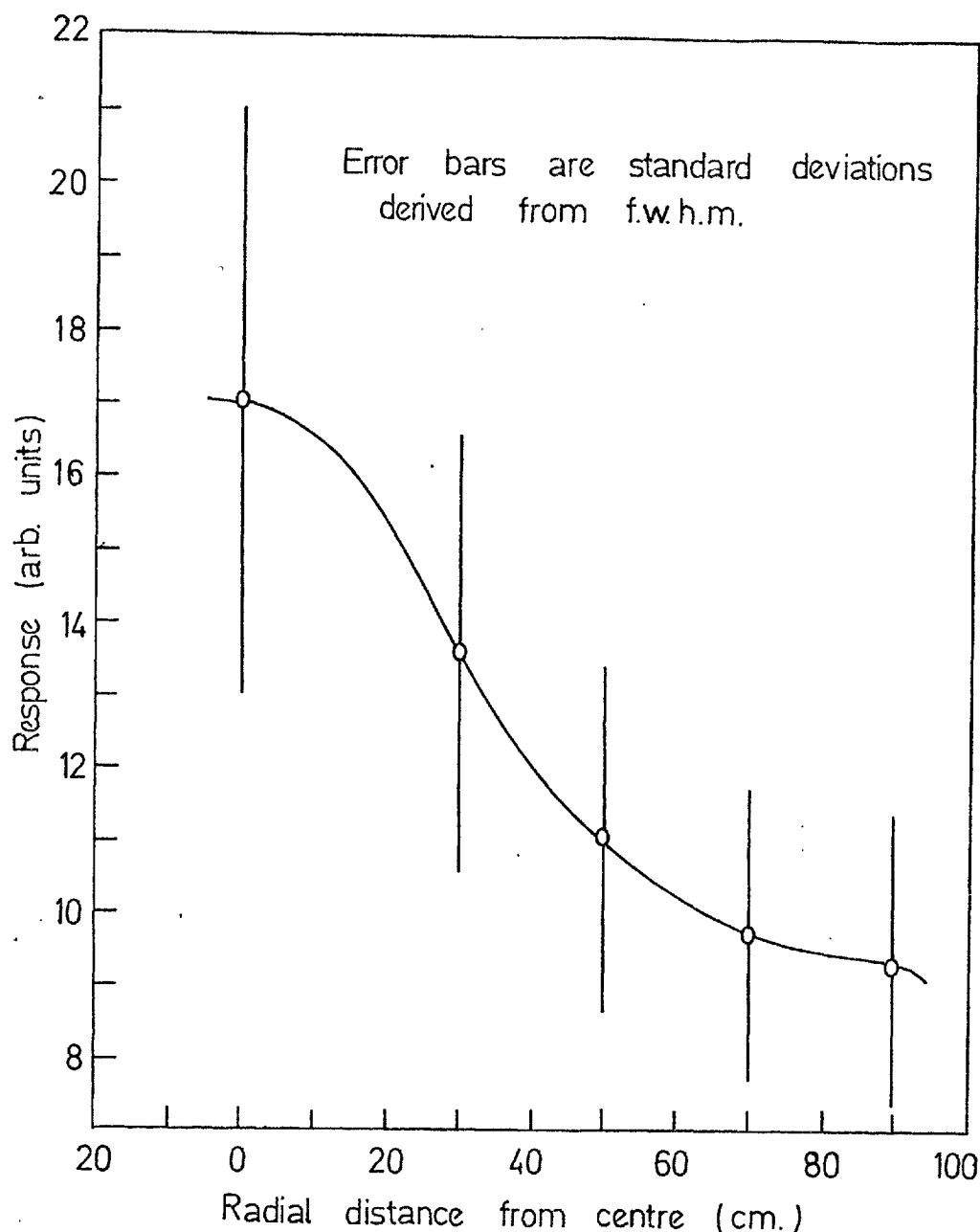


Fig. 4.8 The uniformity of response of the individual counter trays.

4.4.3 Resolution of the telescope

The resolution of the telescope was investigated under several conditions using a 100 channel P.H.A. Initially all three trays were run in coincidence and these coincident pulses were used to gate the P.H.A. to look at just one of the trays. The pulse height distribution for the telescope operating at the middle of the plateau is shown in Fig. 4.9. From this the resolution obtained is 64%. However, due to the asymmetry of the curve the width of the peak could be taken as twice the distance from the energy at

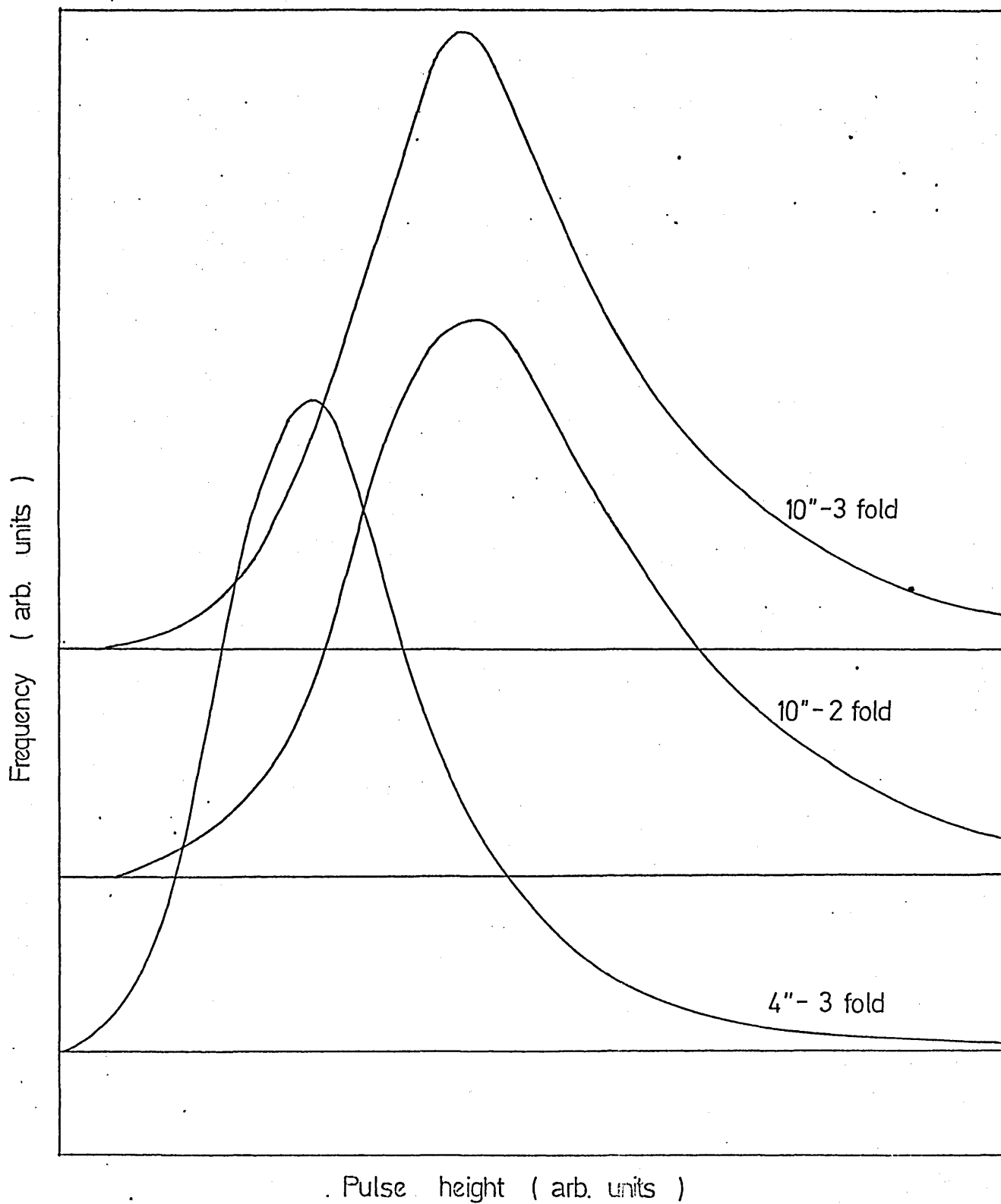


Fig. 4.9 Cosmic ray meson pulse height distributions for various thickness scintillators and conditions of coincidence.

half amplitude on the low energy side to the energy at the peak and this gives a resolution of 56%. Two-fold coincidence gives the pulse height distribution indicated in Fig. 4.9 and the resolution using the width of the measured distribution has fallen to 78%. Further tests with only 4" of scintillator in three-fold coincidence revealed that the resolution falls even further to 88%. As stated before the width of the pulse height distribution and hence the resolution depends upon;-

- (1) Variations in the directions and energies of cosmic rays entering the counter
 - (2) The Landau contribution due to the absorption of the meson energy in the scintillator
 - (3) Non-uniformity of light collection
- and (4) The statistical spread in the number of photoelectrons produced by the photocathode.

If the width of the pulse height distribution is due solely to the statistical spread in the number of photoelectrons then the mean number of photoelectrons is given by ;

$$n_{pe} = \left(\frac{2.69}{\text{resolution}} \right)^2 \quad (4.3)$$

and using the value of the resolution obtained from the pulse height distribution this gives $n_{pe} \sim 20$ which is well below the estimated 50 photoelectrons. To reconcile the two, estimates of the contributions to the width of the pulse height distribution given above must be made. Barton et al(1962) estimate that the contribution due to Landau fluctuations is around 20% and other perturbations might add up to 10%, however, more reliable estimates of the fluctuations due to the contributing factors have been made by Agrawal & Kunte(1968). They find that σ_L (Landau fluctuations) is about 24%. σ_p (variations in path length) is about 16% for an opening angle of 45° and the variation in the uniformity of light collection, σ_{non} was measured to

be 40% from the centre to the extreme edge. Thus the full width at half maximum, σ_t , will be given by;

$$\sigma_t^2 = \sigma_L^2 + \sigma_p^2 + \sigma_{\text{non}}^2 + \sigma_{\text{pe}}^2 \quad (4.4)$$

where, σ_{pe} is the variation in the number of photoelectrons produced at the photocathode. Putting in the measured value of $\sigma_t = 62\%$ and the values for σ_L , σ_p and σ_{non} given above yields $\sigma_{\text{pe}} \approx 37\%$. Using this value for the resolution due purely to variations in n_{pe} in equation 4.3 gives a mean value for the number of photoelectrons produced as ~ 50 . The agreement between the calculated and measured values of n_{pe} is impressive, indicating that any assumptions made about the design of the counter were justified. It is clear from the characteristics displayed in Figs. 4.7(a) & (b) and the resolution obtained from the pulse height distribution that with three-fold coincidence and 10" of scintillator there exists an efficient telescope to monitor muons. However, all the tests carried out so far have been on the surface with a cosmic ray count of approximately 6,000 counts per min. and a background radioactivity of very much less. At a deep site the meson count rate could be comparable to the background and therefore an important test is to simulate a background, comparable to or in excess of the cosmic ray count and to measure the telescope response to such a perturbation.

4.4.4 Response to background radioactivity

The background radioactivity response was found by measuring the pulse height distribution when a radioactive source was held approximately four feet above the detector. Such a source produced a singles count rate in the upper tray approximately 10 times the normal meson rate. Four pulse height distributions were recorded; 3 and 2-fold using 10" of paraffin, 3-fold with 4" of paraffin and 2-fold using 1" of plastic scintillator. The results are plotted in Fig. 4.10. The decline in the resolution between the two peaks (meson and γ -ray) and the overlap of the two distributions is clear as one goes from 3 to 2-fold coincidence and from 10" to 4" to 1" plastic scintillator.

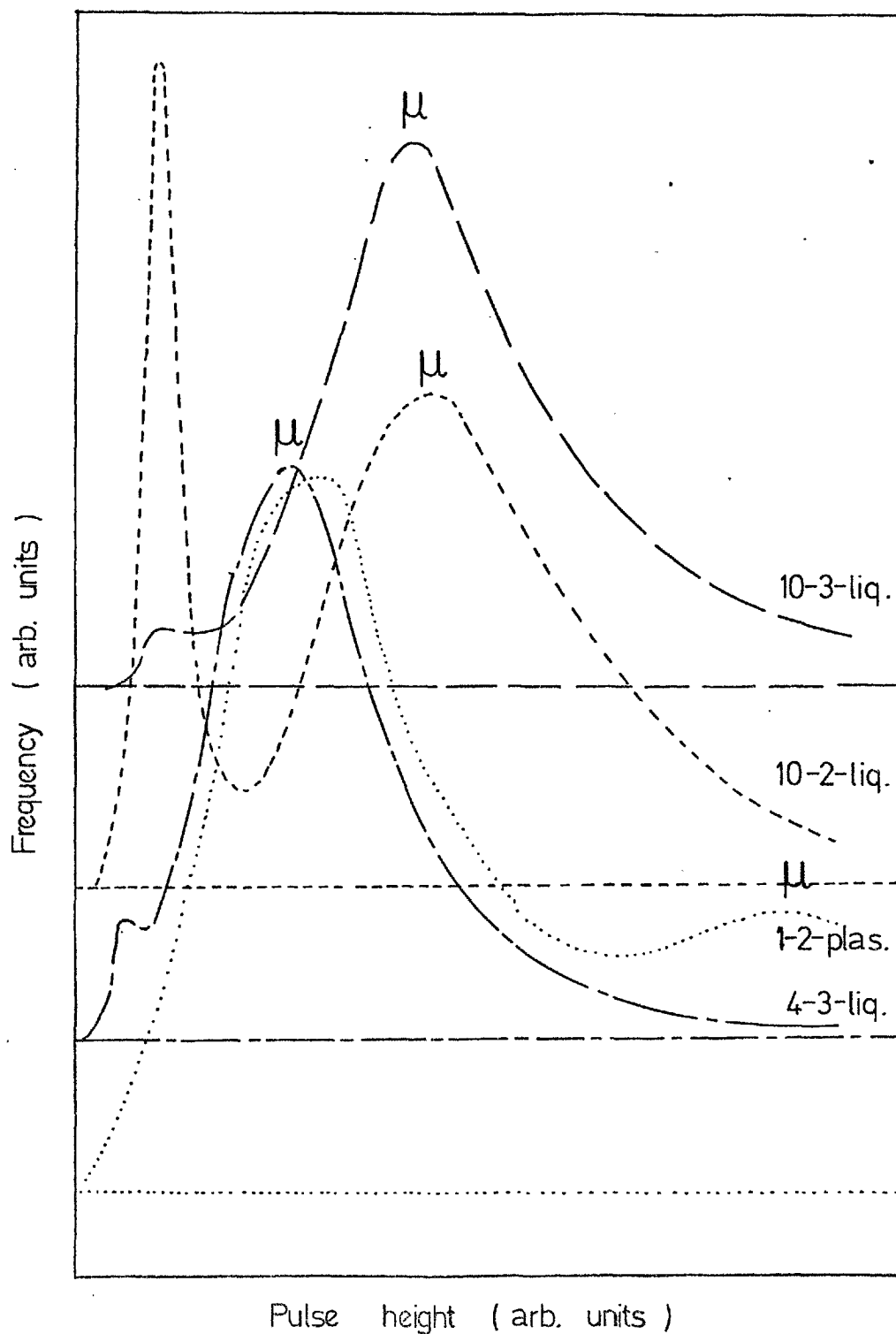


Fig. 4.10 Pulse height frequency distributions for various thicknesses of scintillator and conditions of coincidence when the background radio-activity is ~ 10 times greater than the cosmic ray meson intensity.

However; the 10" scintillator 3-fold coincidence curve indicates quite clearly that even under such adverse background radioactivity as produced in this test very few γ -rays are counted as cosmic rays. The 1" plastic scintillator pulse height distribution is not directly comparable with the other distributions since it was obtained using the North/South telescopes at the surface and these telescopes have a smaller detecting area, however, the curves are sufficient to demonstrate the superior discrimination between 3 and 2-fold coincidence.

4.5 Summary

A telescope has been designed for efficient detection of cosmic ray muons at a depth of up to 500 m.w.e.. At the same time the components have been chosen for their low cost to enable a large number of the telescopes to be built.

Apart from the usual design considerations of stability and long term reliability particular care has been taken to enable the cosmic ray meson peak to be distinguished from background radioactivity even when the count rates of the two effects are equal.

Having decided upon the design subsequent tests have indicated that;-

- (1) The uniformity of response over the scintillator of dimensions 54" $\times$ 54" is $\pm 20\%$ even at the extreme corners.
- (2) Using 10" of scintillator and three-fold coincidence the resolution of the μ -meson peak is $\sim 64\%$ which after correcting for various broadening effects corresponds to approximately 50 photoelectrons per meson track. This figure agrees well with the design figure and is approximately an order of magnitude larger than effects due to noise in the photomultiplier and background radioactivity.
- (3) Even with background radioactivity so adverse as to cause a γ -ray count rate ten times the cosmic ray count rate, 3-fold coincidence adequately distinguishes between γ -ray and cosmic rays.

The performance of this 3-fold, 10" liquid scintillator telescope is far superior than that of the 2-fold, 1" plastic scintillator telescopes used in Holborn from 1961 to 1971 even though the cost is comparable. Furthermore, this telescope has the advantage that it could be used at much greater depths even to the point where the background radioactivity is comparable to the meson count rate and still provide good discrimination between the two effects. The disadvantages of the telescope are the inconvenience of the liquid scintillator and its unknown long term performance. Deterioration of the performance has not occurred over the last year despite several refillings of the scintillator trays with the same phosphor, each involving possible contaminations by oxygen and other impurities. The telescope as tested is only suitable for vertical operation and to study the proposed effect this requires the telescopes being installed at an equatorial site. Such a site poses many problems none of which are due to the physics involved and as an alternative it has been proposed that a telescope sited in London and tilted sufficiently would have an equivalent equatorial scan. Fig. 4.11 shows the polar diagram for a cubical telescope tilted at 70° to the vertical and with a maximum sensitivity at 50° to the zenith such a telescope pointing south would "look" into the equator. The major problem with such a large inclination to the vertical is the amount of absorber introduced above the telescope. The wedge shaped overburden makes the response function a little uncertain but a mean depth of approximately 100 m.w.e. seems to be a reasonable assumption, and if this is the case the scans and effects predicted in Figs. 4.1 and 4.4 should apply. Such a disadvantage has to be weighed against the transportation and maintenance problems of a recording station many miles away at the equator.

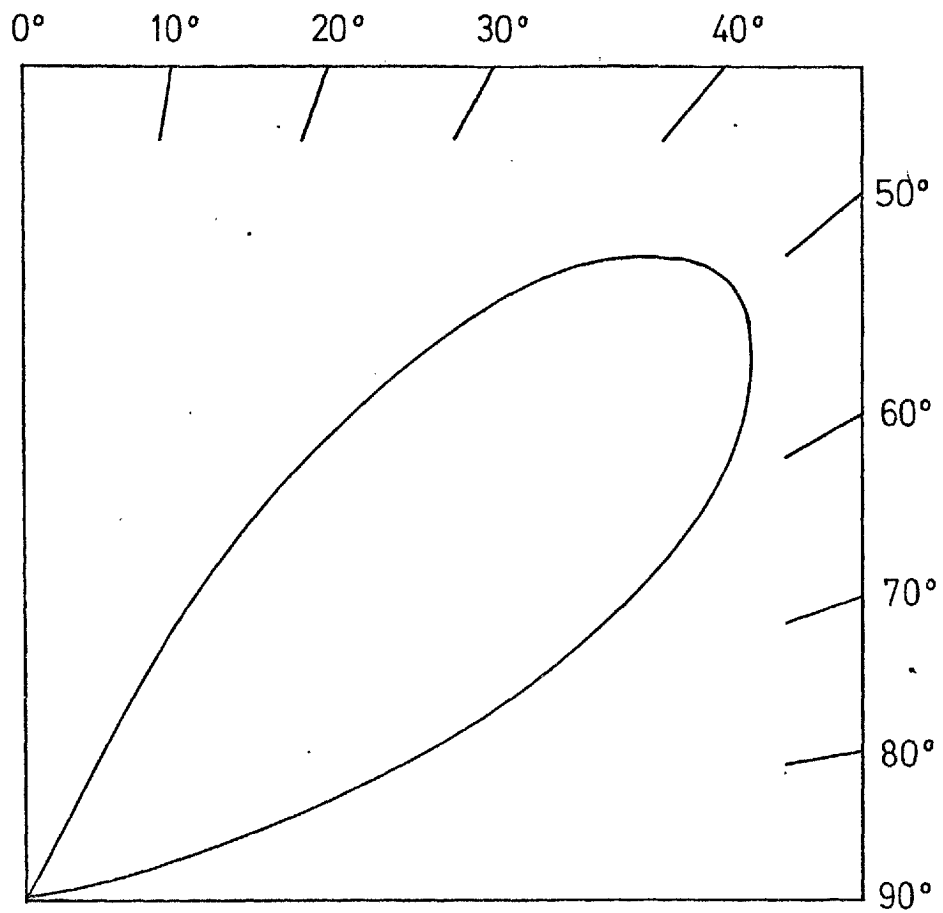


Fig. 4.11 Directional sensitivity pattern for a cubical telescope tilted at 70° to the vertical.

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