COSMIC RAY INTENSITY VARIATIONS AT MEDIUM AND LOW LATITUDES

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Abstract

The time variations of Cosmic Ray intensity have been studied by means of two sets of directional meson telescopes situated at

1) London, U.K., a medium latitude station ($51^{\circ}32'$ N) and
2) Kampala, Uganda, a low latitude station (0.33 N).

At London two telescopes inclined at 45° to the zenith were made to point in the North and the South directions. At Kampala, two similarly inclined telescopes were directed in the East and West directions. The main purpose of using directional telescopes at the two locations was to separate out that part of the daily variation which is due to a primary anisotropy from that induced by atmospheric temperature effects, as the latter cannot be determined by direct methods.

Data from the North/South telescopes have been used to study the atmospheric effects on the particles recorded. Pressure and Temperature coefficients have been obtained by regression analysis between the atmospheric variables and the Cosmic Ray intensity. The different procedures normally employed for correcting meson data are compared and critically examined.

The London (North/South) data have also been used to study the characteristics of the solar anisotropy during the ascending phase of the present solar cycle. (After correction for atmospheric effects). The analysis revealed that the solar diurnal vectors had increased in going from 1965 to 1967, for both the North and South telescopes. A comparison of the observed diurnal vectors with the predictions of a free-space anisotropy of amplitude 0.4% and phase 1800 hrs. L.S.T., (as suggested to be obtaining in recent years by extensive neutron-monitor measurements), reveals that the observed changes in the diurnal waves over 1965-67 may be attributed to an increase in the upper limiting rigidity of co-rotation from about 40 Gv during 1965 to 80 Gv in 1967.

An extensive analysis has also been carried out to investigate the correlation on a day to day basis between the diurnal and semi-diurnal vectors as observed by the N/S telescopes with those observed by a high latitude neutron monitor. The correlation of the diurnal vectors with the level of geomagnetic activity has also been investigated. Data obtained from the Makerere, Kampala telescopes over the period July 1964-Apr. 67 have also been analysed for the solar daily variation.

It was observed that during the years 1964–65 the solar diurnal variations in the pressure corrected data, from both the recorders at Makerere, had an amplitude of 0.2% and a time of maximum at about 14.30 hrs. L.S.T. The absence of any appreciable phase difference between the E/W recorders at Makerere also suggests that there was no appreciable primary anisotropy in the medium range of energies, (50–150 Gv) at the minimum of the solar cycle No. 19. A gradually increasing phase difference observed over 1964–67 suggests a return of the diurnal anisotropy as the solar activity builds up. (It is found that a major part of the diurnal and semi-diurnal variations observed during this period can be attributed to instrumental temperature effects).

The results on the S.D.V. obtained by the London recorders have been compared with those obtained at Manchester over the period 1948–54 (i.e. the declining phase of the solar cycle No. 18).

It is found that the phase of the diurnal vectors observed during 1949–52 was significantly earlier that that measured more recently in London. Furthermore the azimuthal streaming of the cosmic rays in the solar system due to the co-rotation of the cosmic rays gives a time of maximum of 18.00 hr. to the diurnal variation at the earth. The Manchester data for the above period cannot be reconciled with the co-rotation theory. In fact it is necessary to postulate the presence of an anisotropy with an earlier time of maximum than 18.00 hr. to explain the Manchester data and it appears that this component may be present during certain portions of the solar cycle.

Data acquired from the Carnegie Institution stations (Ionization Chambers), over the period 1937–66 has been studied in conjunction with the predictions of the co-rotation theory. There appears to be a systematic difference between these data and the predictions of the theory. As in the case of the Manchester recorders, a vector with a time of maximum earlier than 18.00 hrs. is required to explain the results during some parts of the solar cycle. Apart from this discrepancy, both the Manchester data and the Carnegie Institution data indicate a reduction in upper limiting rigidity during years of the minimum of the solar cycle.

The onset recovery characteristics and the rigidity dependence of several Forbush decreases occurring during 1966–67 have been studied. For these investigations data from high counting rate neutron monitors have been used along with data acquired from the N/S recorders at London and the E/W recorders at Makerere. The results have been compared with those of earlier investigations and the areas of agreement and disagreement explored.

CONTENTS.

CHAPTER I

INTRODUCTION

1.1. General Introduction

The discovery that cosmic rays are charged particles of non-solar origin, opened up the possibility that the radiation could be used as an additional valuable tool for extending our knowledge of the electromagnetic conditions in space. With the advancement of our knowledge regarding the interplanetary medium and associated magnetic fields, it is now realized that the comparatively low energy radiation, (Energies up to a few tens of Gev) cannot tell us anything about the source distribution of the particles, since the scattering and deflections suffered by the cosmic rays in this energy range, during their interaction with the interplanetary magnetic fields will be very severe. In view of this, a study of the time variations of this comparatively low energy band of cosmic radiation (which forms the subject matter of this thesis) would be able to provide very little information as regards any anisotropic distributions, related to the location of sources, existing in interstellar space. However, such a study has been found to be of considerable help in building up a picture of the processes occuring in interplanetary space.

Thus, it is now realised that most of the time variations observed in the primary cosmic radiation (on the surface of the earth) are a direct consequence of the interplanetary magnetic fields, (e.g. the solar daily variation), or are caused by rapid changes in a part of the interplanetary medium following violent disturbances on the sun, (e.g. Forbush decreases and associated anisotropies), or are the result of slow changes in interplanetary conditions associated with the cycle of solar activity, (the solar cycle or 11 year variation).

Thus a study of the time variations of cosmic ray intensity can be regarded as a powerful, though indirect technique of investigating the interplanetary medium and associated magnetic fields.

With the advent of the new era heralded by the launching of artificial earth satellites and spaceprobes it has become possible to conduct "insitu" experiments in the interplanetary medium. At the present state of the art, however, these direct measurements yield data confined to a very localized region in space. On the other hand, the virtue of the technique of monitoring cosmic rays by a network of stations is that it can give information on the magnetic field configuration and other properties of the interplanetary medium over a much larger scale size. With the additional advantages afforded by continuity of observation and diversity of information (e.g. the detailed time, direction and rigidity dependence of the cosmic ray flux, at present not available with space probes etc.) it is justified to regard the technique as a necessary and useful means of supplementing the results obtained by satellite borne magnetometers etc. However, this study is rendered considerably more difficult in view of the fact that the primary cosmic ray particles are not only affected by the interplanetary magnetic fields, but are also influenced by the Geomagnetic field and interact strongly with the oxygen and nitrogen nuclei of the atmosphere producing a host of secondary particles. Detectors located on the surface of the earth mainly record these secondary particles. Moreover, the propagation of these secondary particles through the atmosphere is controlled by the state of the atmosphere, the flux of the particles observed on the surface of the earth is a function of the parameters (e.g pressure or temperature) which characterize this state.

In view of this, it is obvious that before we can arrive at any conclusions regarding the behaviour of the primary particles in the interplanetary magnetic fields, it is essential to:

1) establish accurately the effect of the Geomagnetic field.
2) correct the secondary intensity for any variations in the atmospheric elements.
3) establish a relationship between the variations exhibited by the primary particles and the secondaries actually observed.

In view of this, it is perhaps relevant to give a brief survey of the different techniques employed to isolate the effect of the atmosphere and the geomagnetic field before we discuss the interaction of the cosmic rays with the interplanetary magnetic fields.

1.2 GEOMAGNETIC EFFECTS:

For studies of time variations of cosmic rays, the two most important aspects of the geomagnetic effects on cosmic rays are:

1) The problem of determining CUTOFF-RIGIDITIES, i.e. the rigidity threshold at a particular point and direction of observation below which the geomagnetic field prevents the entry of the cosmic ray particle.

2) The calculation of the deflections of the primary cosmic ray particles by the geomagnetic field.

The basic problem to be considered here is that of the interaction of the primary cosmic rays with the geomagnetic field as the particle approaches the earth. For this purpose, as a first approximation, the earth's magnetic field may be assumed to be due to a Dipole of magnetic moment 8.1×10^{25} gauss-cm^3 embedded at the centre of the earth.

The trajectories of charged particles in a dipole field have been investigated by STORMER (1930). These calculations were extended by LEMAITRE and VALLARTA (1933). As a result of these studies several points became evident.

1) At a particular point on the earth there are allowed and forbidden directions of incidence for a given rigidity. These are the MAIN and STORMER cones respectively.

2) Certain trajectories though allowed by the geomagnetic field intersect the earth at another point and are therefore forbidden. This is the"shadow cone".

3) There exists considerable fine structure near the borders of the Main and Stormer cones. This is referred to as the "Penumbral region". In this region some trajectories are allowed and some forbidden. These penumbral effects have to be taken into account while considering the threshold rigidities at a particular point of observation. These effects are important for low and middle latitude stations (L.T. 60°). For high latitude stations the transparency of the penumbral region is nearly 100%.

However, considerable discrepancies are found to exist between the measured cosmic ray distributions over the surface of the earth and those to be expected from a pure dipole field, as assumed in the above calculations. These discrepancies were first noted by JOHNSON (1938). The introduction of nucleonic detectors enabled measurements to be made unperturbed by atmospheric effects and it became possible to determine the distribution of cosmic ray intensity with respect to latitude and longitude with far greater certainty. Results of latitude surveys conducted by several workers, e.g. ROSE et al (1956), Fenton et.al. (1958), Simpson et al.(1956) revealed serious discrepancies from values calculated on the basis of the dipole field.

Slightly better agreement was obtained by displacing the assumed dipole to about 450 Km from the centre of the earth. Such a representation introduces certain second order terms in the simulation of the geomagnetic field. Rothwell and Quenby (1958) showed that higher order terms are necessary for a complete representation of the geomagnetic field. The effect of these terms is considerable for certain places (e.g. in the region of the South African anomaly) and may cause errors of about 40% in calculated threshold rigidities. Quenby and Webber (1957), KELLOG and SCHWARTZ (1959), QUENBY and WENK (1961) have calculated new values of the threshold rigidities taking into account the higher order terms. The last group of authors have also introduced a correction for penumbral effects.

Deflection of primary particles in the geomagnetic field were initially determined by scale model experiments conducted by Malmfors (1949), Brünberg and Dattner (1954) etc. The cosmic rays are simulated by electrons fired outwards from the surface of a model earth (terrella). The magnetic field of the earth is simulated by means of magnetizing coils surrounding the terrella. For a given energy and direction of emission a definite path is obtained which approaches an asymptotic direction in the border region of the geomagnetic field. This ASYMPTOTIC DIRECTION corresponds to the direction of motion of the cosmic ray particle before it enters the earth's terrestrial magnetic field.

The asymptotic directions can be defined uniquely in terms of two angles $\varnothing_N$ and Y_E. Where $\varnothing_N$ represents the geomagnetic latitude at which in the absence of a magnetic field the cosmic ray particles would strike the surface of the earth. Y_E represents the longitude of the impact point relative to the meridian through the point of observation. The angle Y_E can be transformed into a time correction. By adding this correction to the local time of the point of observation, one obtains the asymptotic time of any anisotropy beyond the geomagnetic field. BRUNBERG and DATTNER have evaluated $\varnothing_N$ and Y_E for every 10° of geomagnetic latitude, for different azimuths and zenith of observation, for particles with rigidities from about 10 Gv to about 500 Gv. However, since these experiments were performed it has been realized that the simple dipole approximation assumed here is inadequate for a description of the geomagnetic field and the asymptotic directions determined on this basis may be in considerable error, especially for low energies.

With the advent of high speed digital computers, asymptotic directions may be calculated by numerical integration of the trajectories of cosmic ray particles in a high order simulation of the geomagnetic field, e.g. that due to Finch and Leaton. The procedure is as follows: a negative particle of a specified rigidity is assumed to originate from a point 20 km above a specific location on the earth and its path is traced through the assumed geomagnetic field, using the Gill modification of the Runge Kutta method of iteration. The orbit is traced to a distance of about 25 earth radii and the coordinates of the particle at this point are taken to be the Asymptotic latitude and longitude. In this manner asymptotic latitudes and longitudes have been calculated for a number of stations of geophysical interest, for a range of rigidities, azimuths and zenith angles-McCracken et. al.(1962) Shea et.al(1967).

This trajectory tracing process has also been employed to calculate cut-off rigidities. Corresponding to a particular direction and rigidity, if the trajectory can be traced to 25 earth radii then the corresponding direction and rigidity are considered to be allowed, otherwise forbidden. By considering rigidity intervals of 0.01 Gv it is possible to investigate the structure of the penumbral region. A beginning has been made to construct a world wide grid of trajectory derived vertical cut-offs by Shea et al. (1967)

1.3. EFFECT OF THE ATMOSPHERE

a) EFFECT OF A VARIABILITY IN ATMOSPHERIC PARAMETERS

In general, the composition of the secondary cosmic rays changes considerably during their traversal of the atmosphere. The interactions between the secondary cosmic ray particles and the atmosphere and the character of the changes taking place during these interactions will be a function of the chief parameters characterising the atmospheric conditions e.g. temperature and pressure. Consequently, a change in these parameters will cause a set of variations in the secondary flux observed at the ground level (or any other level) deep in the atmosphere. Such variations, termed the Atmospheric Effects, have been observed and are found to depend on the nature of the secondary particles recorded.

Deep in the atmosphere, the cosmic radiation is, in fact, found to consist of three major components.

1) The MU-MESON or the hard component, which constitutes the major part of the cosmic ray flux at sea level. This component is highly penetrating and survives down to considerable depths below the surface of the earth.

2) The electron-photon or the soft component, being so called because it is rapidly attenuated by an absorber.

3) The nucleonic component.

(The experimental arrangement employed in the present experiment records the total ionizing component. This is a combination of the hard and soft components above. At sea-level, the total ionizing flux normally observed consists of about 75% hard component and 25% soft component. In our case however, a large fraction of the soft component is filtered out and the ratios actually observed are 85% hard component, 15% soft component).

The atmospheric effects on the secondary cosmic rays are now relatively well understood, e.g. TREFALL (1955, a, b, c,), WADA (1961) and DORMAN (1957) and may be enumerated as follows for the hard and the soft components, which concern us in the present experiment.

The atmospheric effects of the hard component can be basically divided into a) A simple absorption effect due to ionization loss which increases with the amount of absorber and therefore with the pressure at the observation level.

b) Decay effects due to the unstable nature of the PI and MU-mesons. The first probability of a decay effect can be traced to the parent PI mesons. These PI mesons, produced at the top of the atmosphere can either decay into MU mesons or interact with the air nuclei in the region. As a result of such interactions the energy of the pions is distributed between many particles leaving the nucleus and such pions consequently become ineffective for formation of energetic mu-mesons. (DORMAN 1957). The number of pions which will be lost in this way will be directly proportional to the local atmospheric density and therefore inver[illegible]lly proportional to the temperature of the layer where these mesons are first produced. (200 - 50 m.b.) A positive temperature effect will therefore result.

A second temperature effect is associated with the mu-mesons produced from the decay of PIONS. The heights above S/L at which these mesons are produced are a function of the temperature distribution in the atmosphere. A rise in the temperature will cause an increase in the path length of the mu-mesons before they can be recorded. This in turn will result in a decrease in the survival probability, hence a negative temperature effect is introduced. These effects are the main temperature effects for the hard component of the cosmic ray intensity, however, some second order effects are also present which will be important for S/L observations.

The temperature effects of the soft component have not been studied in quite as much detail as those of the hard component, however, the nature of these effects is also known to fair degree of confidence. e.g. Dorman (1957), Trumpy and Trefall (1956). It is found out that the temperature effects for the soft component in fact balance out for the two constituents - the equilibrium and non equilibrium portions. However, a positive correlation is observed with the ground level temperature. In addition, the soft component exhibits strong attenuation with an increase in S/L pressure and the corresponding pressure coefficient is about twice that observed for the hard component.

The atmospheric effects of the cosmic ray intensity recorded by our recorders will be calculated in chapter III in order that variations of atmospheric origin may be effectively removed.

b) Differential response functions:

(Method of relating secondary and primary cosmic ray variations).

In order to gain a fuller understanding of the physical processes responsible for the observed variations in cosmic ray intensity, it is necessary to find out the relationship between the variations observed in the secondary component and those actually occuring in the primary cosmic rays. This is accomplished by the method of coupling constants (e.g. Dorman (1957) which enable us to evaluate the magnitude of the variations to be expected in the intensity recorded by a particular instrument, at a certain depth in the atmosphere, corresponding to a given variation in the primary flux outside the geomagnetic field.

In general, the total intensity N_L^i (ho) of a component "i", of the secondary cosmic rays, observed at a atitude L and atmospheric depth ho, may be written as:

$$N_L^i\ (ho) = \int_{e_\circ}^{\infty} D\ (e)\ m^i\ (e, ho) de.$$

where $D(e)$ is the differential energy spectrum of the primary cosmic rays.

m^i (e, ho), is called the MULTIPLICITY, and represents the number of i-type particles produced by a single primary particle of energy e.

e_o, is the geomagnetic threshold at the point of observation.

The intensity recorded at a particular place of observation will accordingly be a function of the variables, D(e), m^i (e, ho) and e_o, entering the above expression. The fractional variation recorded in the intensity due to variations in these parameters may be obtained by differentiation and is:

$$\frac{d\,N_L^i\,(ho)}{N_L^i\,(ho)} = -de_o\,W_L^i\,(e,h) + \int_{e_o}^{\infty} \frac{d\,D(e)}{D(e)}\,W_L^i\,(e,h)\,de + \int_{e_o}^{\infty} \frac{dmi\,(e,ho)}{mi\,(e,ho)}\,W_L^i\,(e,h)\,de, \text{ ---------(a)}$$

where,

$$W_L^i\,(e,h) = \frac{D(e)\,m^i\,(e,ho)}{N_L^i\,(ho).} \text{ ------(b)}$$

and is called the coupling constant. Curves giving W_L^i (e, h) as a function of energy are called the Differential response functions.

In the expression (a) above, the first term represents the variation in the intensity due to a change de_o in the geomagnetic threshold e_o. The second term provides a means of evaluating a change in the secondary intensity for a changed D(e) in the primary spectrum, and is the quantity usually of primary interest. The third term represents the effect of a change in multiplicity which may result from, say a change in atmospheric conditions.

Thus, in order to couple the variations of the primary and secondary cosmic rays, it is necessary to evaluate W_L^i (e, h). The coupling constants could in principle be evaluated from aknowledge of the differential energy spectrum D(e), and the multiplicity, m. However, a calculation of the multiplicity will require a detailed knowledge of the phenomenon of high energy interactions involving particles of 30 Gev or so. In view of the scanty knowledge about the nuclear processes at such high energies, frequently encountered in cosmic radiation, an indirect method is normally employed for a determination of the coupling coefficients. It can be shown quite simply that the function W_L^i (e, ho) can be expressed as:

$$W_L^i (e, ho) = \frac{1}{N_L^i (ho)} \frac{d Ni}{deo}$$

Since the right hand side of this equation, in effect represents the geomagnetic effect on a particular component, it is possible to evaluate W^i by determining the variation of the intensity of the component with geomagnetic latitude. By this procedure however, it is only possible to calculate W_i for primaries of energy up to about 20 Gev which are substantially affected by the geomagnetic field. Above this energy W^i is usually evaluated under certain simplifying assumptions (e.g. that the multiplicity varies ~~exponentially~~ as $E^{'4}$ with energy).

Differential response functions for the neutron and meson components observed at different depths in the atmosphere have been investigated using the technique described above, e.g. Dorman (1957), Quenby and Webber (1962), Lockwood and Webber (1966). The accuracy of the calculations depends on the accuracy with which the geomagnetic thresholds are known. Quenby et. al. have taken into account the higher order terms in a harmonic expansion of the geomagnetic field for the calculation of the geomagnetic thresholds. Lockwood et. al. have used the extensive data now available on the geomagnetic thresholds and the results of a recent latitude survey conducted during 1965 to re-evaluate the differential response functions for S/L neutron monitors. KRIMSKY et. al (1965) have calculated, theoretically, the differential response functions for S/L meson monitors inclined to the

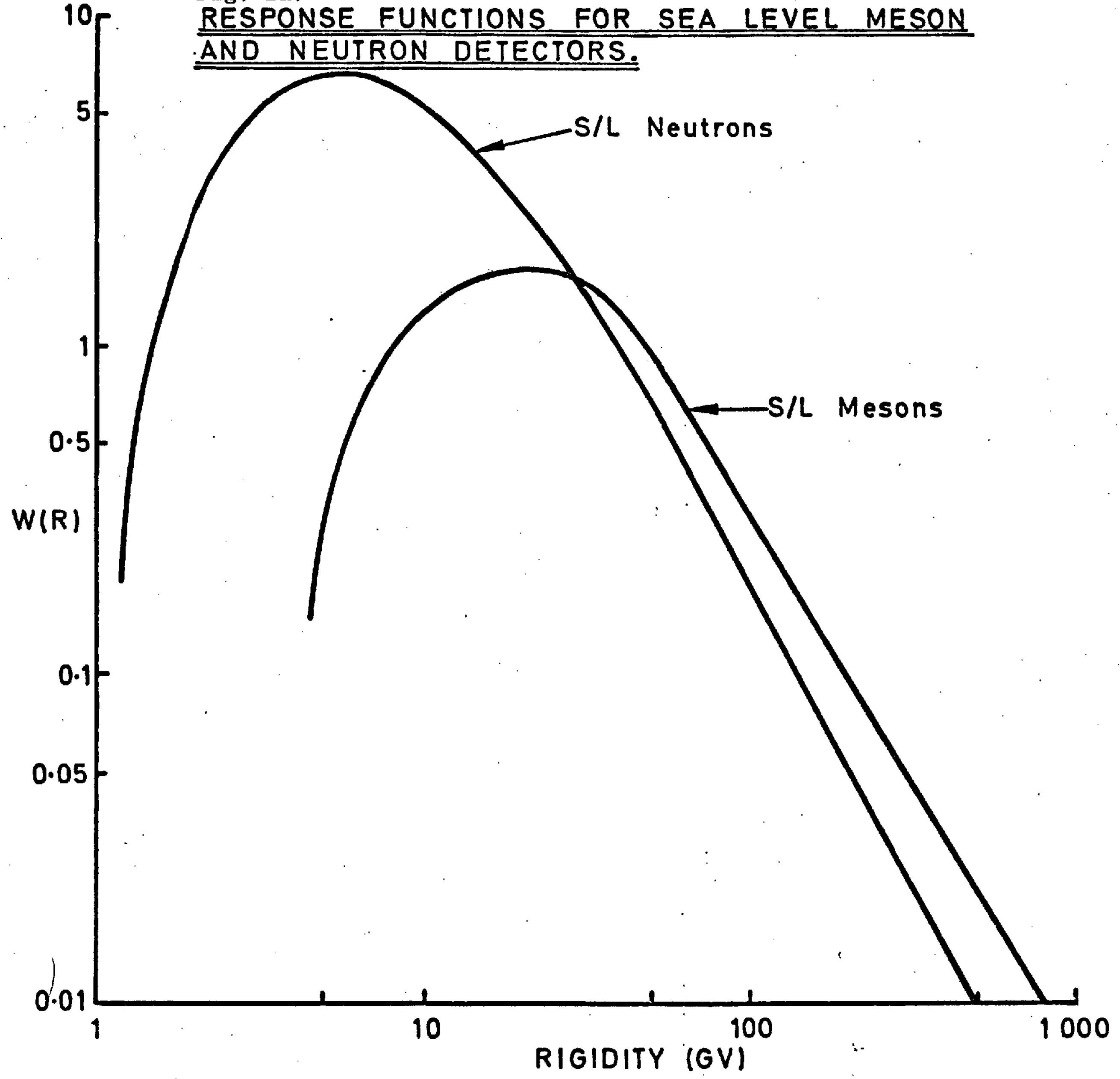
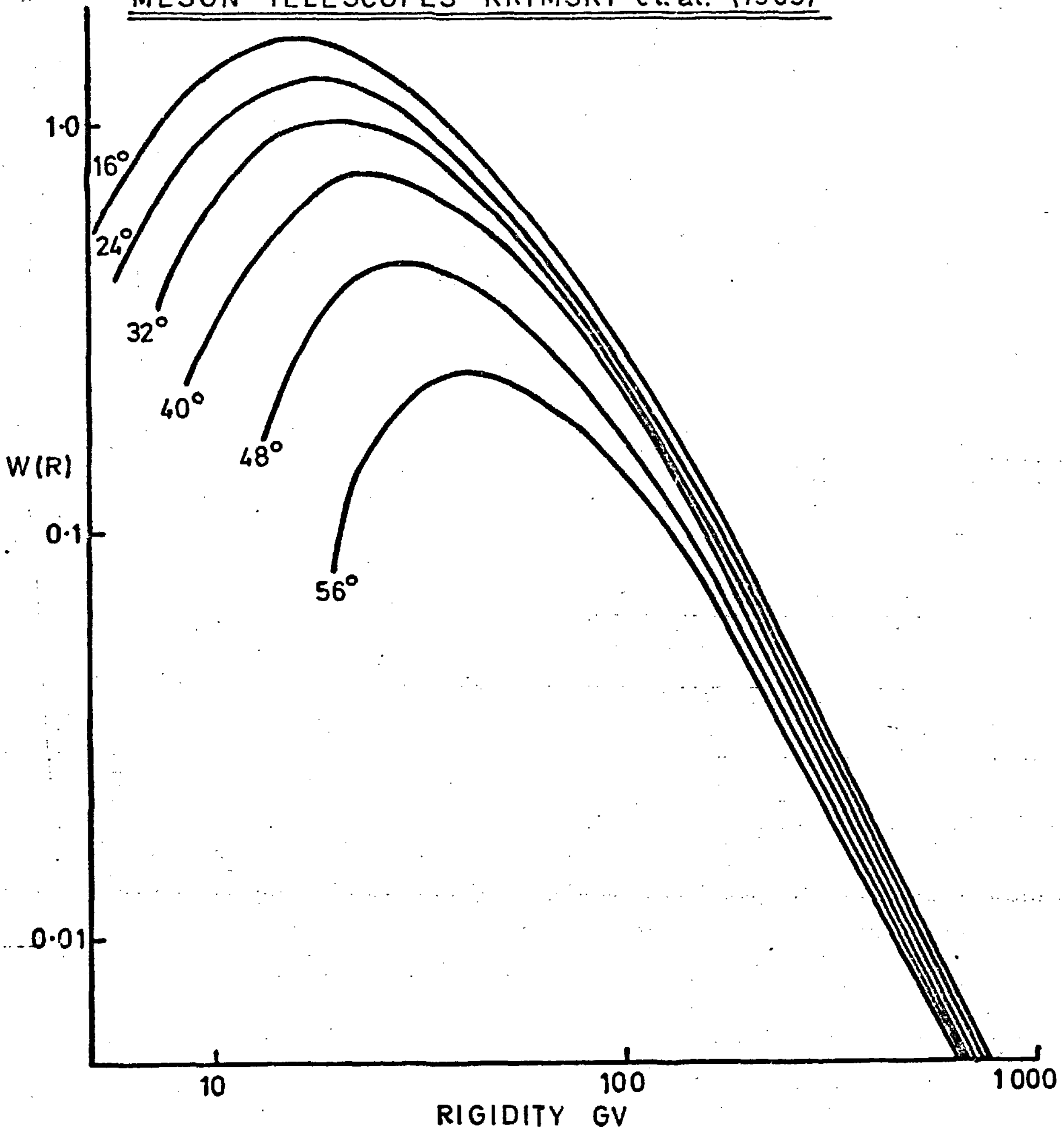


Fig. 1a.

RESPONSE FUNCTIONS FOR SEA LEVEL MESON AND NEUTRON DETECTORS.

RESPONSE FUNCTIONS FOR SEA LEVEL INCLINED MESON TELESCOPES KRIMSKY et. al. (1965) FIG. - 1,b



vertical at different angles.

The figure 1 (a, b) shows the differential response functions for the different cases of recording.

1.4. COSMIC RAYS AND THE INTERPLANETARY MAGNETIC FIELDS

Certain time variations observed in the cosmic ray intensity have been identified as a result of the modulation of the cosmic rays by the interplanetary magnetic fields, these are:

a) The 11 year variations
b) The Forbush decreases observed in cosmic ray intensity
c) The solar daily variations (Diurnal and semi-diurnal)
d) The 27 day variations.

In addition the chief propagation characteristics of the solar flare particles are also explained in terms of the structure of the interplanetary magnetic fields.

The main features of the 11 year variation are a reduction in intensity of cosmic rays as solar activity increases. For S/L meson recorders this reduction amounts to about 5%, however, for neutron monitors at a high latitude station it may be as large as 20%. Experiments with balloon borne detectors suggest that for the low energy particles recorded at these altitudes the reduction is considerably greater (50% or even more). It also seems to be true that the modulation processes never cease to be operative for the low energy particles which, consequently, cannot penetrate the inner solar system even at minimum solar activity. The Forbush decrease, on the other hand, is a relatively large intensity decrease of up to 15% (with high latitude neutron monitor) which occurs rapidly with a time constant of about a day and is followed by a relatively slow recovery of about ten days.

Forbush decreases are usually assocated with outbursts of solar plasma. The scale size of the effect is often greater than 0. 1 A. U. as is indicated from simultaneous observations of the effect in interplanetary space by satellites and on the surface of the earth. Unlike the sudden and large decreases in cosmic ray intensity during Forbush decrease events, the 27 day variations are characterized by slow and small increase and decreases which take place at 27 day intervals, i.e. with a time period corresponding to the synodic period of rotation of the sun. The solar diurnal variation is a small variation in solar time of an amplitude of about 0.2% and a time of maximum at about 1400 hours L.S.T. The amplitude of the variation is found to vary considerably about this average value and the phase also varies correspondingly. A detailed description of the chief characteristics of the diurnal variations and Forbush decreases which are the main aspects of cosmic ray modulation studied here is given in chapters 4 and 7.

With the advent of the satellite era, it has become possible to conduct insitu experiments on the nature and magnitudes of the interplanetary magnetic fields. With the knowledge so acquired, a beginning has been made along the lines of a unified theory of the modulation of the cosmic ray intensity by interplanetary magnetic fields, by which it may be possible to account for the major types of the cosmic ray variations observed.

In the following, we shall give a brief survey of the state of the interplanetary medium and a short qualitative description of the physical processes which lead to the modulation of the galactic cosmic ray intensity.

1.4.1 INTERPLANETARY MAGNETIC FIELDS AND THE SOLAR WIND

The notion of a solar corpuscular radiation emanating from the sun dates back some 40 years. Thus, BARTELLS (1949) defines the kp index as "designed to measure the varying intensity of solar particle radiation by its geomagnetic effects". BIERMANN(1951, 53, 57) advocated the concept of a continuous solar wind to explain the observed acceleration of gaseous comet tails.

Though Biermann's original explanation of comet tail behaviour were found to be wrong, PARKER (1958) proposed that Biermann's continuous solar - wind thesis could be accounted for by a simple hydromagnetic expansion of the solar corona. The essence of Parker's argument is that the solar corona is so hot that the solar gravity cannot contain it. The temperature of the lower layers of the corona is estimated to be about $1.5 * 10^6$ K°. At such a high temperature, though the average thermal velocity of particles within the inner corona is less than the escape velocity, their pressure nkT is greater than the weight of the overlying atmosphere. As a result, the corona expands continuously. If a gas is to be treated as a hydrodynamic fluid then the collision mean free path should be less than the local dimensions of the body of gas, i.e. the effect of randomizing collisions or some comparable process should be important. In the case of the solar corona, several mechanisms are present which may take the place of randomizing collisions, e.g. a magnetic field is present so that collisions can occur through long-range magnetic forces. Thus the corona can be described in terms of equations of hydrodynamics. Parker has considered the hydrodynamics of the solar corona and finds that the only stationary state for a corona strongly bound to the sun and with a temperature declining less rapidly than $1/r$, (where r is the distance from the sun) is one of supersonic expansion beyond a certain distance r_c, equal to a few solar radii. Thus, Parker's integration of the hydrodynamic equations for the solar corona leads to the conclusion that interplanetary space must be filled with a hot plasma which moves nearly radially from the sun with supersonic velocities of the order of several hundred kilometres/sec.

Parker also points out that this theory of coronal expansion immediately determines the nature of the interplanetary magnetic field. Inherent in this theory of the solar wind is a possibility of an extension of the solar magnetic fields as observed in the photosphere into interplanetary space.

On the basis of observations of the longitudinal Zeeman effect a photospheric field has been found with an average intensity of the order of one Gauss. In the absence of a solar wind, this magnetic field cannot give an appreciable magnetic intensity throughout the solar system. In fact, the general magnetic field of the sun would reduce to about 10^{-2} gamma at about 1 A.U. On this basis then, no appreciable magnetic field could be expected in the solar system.

However, ALFVEN (1950), has pointed out that a magnetic field embedded in highly conducting plasma tends to behave as if it were 'frozen in' the plasma. PARKER (1958) used this result and argued that solar plasma leaving the sun would carry with it a frozen magnetic field. On considering the effect of solar rotation on the outflowing solar wind it is easy to see (as explained by CHAPMAN (1929)), that gas issuing in a narrow stream, with constant velocity, from a particular region of the sun, will trace out an ARCHIMEDIAN SPIRAL, in interplanetary space. Though each element of the gas moves very nearly radially away from the sun, the turning of the sun will cause the locus of a line of moving particles to lie along a curved path. If we generalize this result for an isolated stream to a spherically symmetric solar wind we see that a collection of archimedes spirals results. In view of this and the fact that the magnetic field is 'frozen in' in the outflowing plasma the magnetic field lines will be stretched out along the archimedes spirals that represent the locus of a continuous stream of solar wind plasma.

PARKER (1958) has given an exact computation for the magnetic field to be expected in the interplanetary space. Expressed in the usual right handed system of spherical polar coordinates ($r, \theta,$) the interplanetary field components at a distance r are:

$$B_r = B_o \left(\frac{r_o}{r}\right)^2$$

$$B\theta = 0$$

$$B\phi = B_o \frac{r_o \Omega r_o}{V r} \operatorname{Sin} \theta$$

where θ is the angle measured from the polar axis and ϕ is the azimuth round this axis; r_o is the radius of the sun and Ω its angular velocity; B_o is the intensity of the radial field at the sun and V is the solar wind velocity.

The angle (often called the garden hose angle), between the plasma velocity vector and the magnetic field line at a distance r is given by

$$\operatorname{Tan} \psi = \cancel{V}\Omega r/V$$

with $\Omega = 3 \times 10^{-6}$ radians/sec, V = 400 km/sec and r = 1.5×10^8 km (corresponding to the orbit of the earth) ψ is about 45°. The existence, general description and temporal behaviour of the interplanetary magnetic field, had in the past been deduced from indirect terrestrial observations, e.g. from the study of solar flare particles incident on the Earth, McCRACKEN (1962). McCracken noted a preponderance of westerly flares. To account for this phenomenon, one must find some sort of a guiding mechanism for the particles to be bent to the earth, instead of travelling radially away from the sun. This strongly suggested the development of the Archimedes Spiral structure in the interplanetary field. However, since then it has become possible to make direct measurements in interplanetary space. The use of satellites and space probes during the last few years has now confirmed the existence of the solar wind and the nature of the magnetic fields as suggested by Parker. The general characteristics of the solar wind and interplanetary magnetic fields have now been established (NESS, 1965, 67), (WILCOX, 1966, 67) etc. and are summarized below.

1) The solar wind consists of a flux of Plasma with the principal positive ionic constituent as Hydrogen. About 5% of the positive particles are He.

2) At 1 A.U. the flux of particles has been measured to be about 10^8 to 10^{10} ions / cm^2 / sec. The average energy / ion is estimated to be about 1 kev/ion.

3) The solar wind appears to flow from about 1.5° east of the sun. This effect is thought to be due to the corotation of the solar corona to several solar radii beyond the sun.

4) The average solar wind velocity has been estimated to be 400/km/sec during quiet periods. The velocity has been found to be constant from 0.7 to 1 A.U. During periods of intense activity the solar wind velocity may however rise to 1500 / km / sec.

5) Embedded in the solar plasma has been found a magnetic field with an average magnitude of 6γ at 1 A.U. Considerable fluctuations are found to occur over this mean value and the actual amplitudes recorded range from 2γ to about 40γ. The large amplitudes are usually observed following strong solar flare activity.

6) The vector properties of the interplanetary field show characteristic patterns paralleling the expected Archimedian Spiral angle and are observed to be in either a positive ($a = 235°$) or a negative ($a = 315°$) sense at 1 A.U. The field is confined mainly to the plane of the eliptic though a small southward component has been reported by some workers.

7) For several days at a time, the field polarity is observed to be undirectional. After this the field direction reverses and stays as such for the

next several days. This large scale structure of the interplanetary field shows a recurrence period equal to the synodic period of rotation of the equatorial region of the sun. This implies that the interplanetary magnetic field co-rotates with the sun. Four sectors of the type mentioned above were observed during 1964.

Superimposed on the quiet time spiral field described above are a series of magnetic irregularities which result from turbulence or changes in the solar wind velocity. These irregularities move radially with the solar plasma at a relative speed of about 50 Km/sec with respect to the solar wind. These irregularities have amplitudes which sometimes approach the strength of the underlying field in which they occur. There is some evidence that these irregularities become more intense beyond the orbit of the earth.

As the solar plasma moves outwards its momentum / unit volume decreases and it is eventually slowed down by the interstellar fields. The position of the boundary is the result of a balance between the solar wind pressure and the magnetic pressure of the galactic fields. At the heliocentric distance R, at which this occurs, the solar wind will undergo a shock transition to subsonic flow and the plasma will disperse into the interplanetary medium. The interplanetary magnetic field in the boundary region beyond the shock is highly tangled and irregular, as a result of the turbulence induced by the shock and by instabilities occuring where the solar plasma interacts with the interstellar medium. The tangled fields in the boundary region form a sort of magnetic barrier. The exact size of the solar cavity is still under discussion, distances of about 10 to 100 A.U. are suggested. e.g. QUENBY (1964, 67).

1.4.2. MODULATION OF THE COSMIC RAY INTENSITY BY THE INTERPLANETARY MAGNETIC FIELDS:

The key to the physical processes responsible for the modulation of the galactic cosmic rays lies with magnetic irregularities superimposed on the regular spiral pattern of the interplanetary magnetic field and moving outwards with the radially outflowing solar plasma. PARKER (1965), AXFORD (1964), etc. have worked out the detailed mathematical theory of the modulation of the cosmic ray intensity by the regular and irregular components of the interplanetary magnetic fields, we shall however only consider briefly the main physical processes involved.

The recent observations by means of space probes have shown that the magnetic irregularities in the interplanetary magnetic field have typical scale sizes of 10^{10} to 10^{12}cms. These are comparable to the radius of gyration of protons in the energy range 10^{8} to 10^{10} eV, in a magnetic field of 5γ. The magnetic irregularities are therefore able to scatter particles in this energy range and the motion of the cosmic ray particles may be regarded as a random walk in a frame of reference moving with the irregularities. In an extreme case where the collision frequency is much greater than the gyro-frequency, the motion of the cosmic ray particles may be described by equations of isotropic diffusion. In the opposite case where the collision frequency is very much less than the gyro-frequency, the cosmic ray particles tend to follow the lines of the interplanetary field and their motion is describable in terms of the guiding centre approximation. It is possible to obtain an explanation of the major types of cosmic ray modulation observed by considering the motion of the cosmic ray particles in the spiral field and the effect of the magnetic irregularities.

The effect of the scattering of the cosmic ray particles by the magnetic field irregularities is that the motion of the particles coming into the solar system is in general impeded and the radial outflow of the irregularities tends to convect cosmic ray particles (in the range of energies stated) out of the solar system. The steady state obtaining at a particular time is the result of a balance between this radial outflow and an inward diffusion through the magnetic irregularities. In general, the density of the cosmic ray particles in the solar system will be lower than that obtained outside the solar wind cavity and a radial gradient will be expected.

For the simple case of a spherical cavity of radius R, a uniform solar wind velocity V and isotropic diffusion with a ~~coefficient~~ mean free path L, the cosmic ray number density at a heliocentric distance r can be written as:

$$n = n_0 \quad \exp \frac{-3V}{W} \frac{R-r}{L} \qquad (i)$$

and the magnitude of the radial density gradient calculated for this simple case is:

$$\frac{1}{n}\frac{dn}{dr} = \frac{-3V}{WL}$$

In the elementary theory that the diffusion coefficient is typically 10^{21} - 10^{22} cms^2 / sec based on a particle velocity W = c and a mean free path of the order of 10^{11} - 10^{12} cm. Typical values of the radial grandient predicted are about 10%/a.u.

The equation (i) above holds for low values of particle energy when each scattering centre (referred to as a thick scattering centre) can by itself give a large deviation of the cosmic ray particle. For higher energies Parker introduces the concept of thin scattering centres, a large number of which are required to give a sizeable deflection ($\pi/2$).

On this theory, time variations, such as the 11 year variation, are described as a result of a slow variation of the factor VR/L with the solar cycle. The 27 day variations, on the other hand, are described as being due to the variation of the Vr/L around the sun at any one time, so that the effective value of the exponent is different at any particular point in space and varies with the rotation of the sun, leading to a 27 day variation in the cosmic ray intensity.

Forbush decreases occur when conditions in the solar corona vary rapidly with time. Thus, during a solar flare, a sudden increase occurs in the coronal temperature which leads to an outward explosion of the corona with a velocity considerably greater than the mean solar wind velocity of 400 km/sec. This sudden outburst of solar plasma at high velocities scoops up the slower moving plasma and forms a shock wave travelling in space. The result is that the spiral magnetic field which was embedded in the slower solar wind is compressed as the solar wind moves out with the blast wave. A strong compression of the basic spiral field pattern seriously restricts the passage of cosmic rays through the wave. The passage is impeded by the same factor f by which the field is compressed and f may be about 10 in a typical situation. As the shock passes over the earth a sharp decrease in the cosmic ray intensity will be observed. The diurnal variation is explained as a result of a drift motion of the cosmic ray particles consequent on their co-rotation with the interplanetary magnetic field. (A more detailed discussion is given in Chapter IV).

The simple theory presented above is only a first approximation to the actual situation obtaining and is not able to explain all the facts about modulation. In practice, it is found that the diffusion of cosmic ray particles is usually highly anisotropic with K_{11} being greater than

$K_\perp$. Small angle scatterings are also quite common and the mean freepath L is a function of the form $L = A r^2 R^s$ where r is the distance from the sun and R the particle rigidity. s usually lies between 0 and L. QUENBY (1968).

1.5. SCOPE OF THE PRESENT INVESTIGATION

The technique of making measurements on the diurnal variation by means of directional counter telescopes pointing towards opposite azimuths has been used for a long time, e.g. MALMFORS (1948), DOLBEAR and ELLIOT (1951) etc. The chief advantage of this method is that is makes it possible to distinguish between primary anisotropies and these generated by atmospheric or geomagnetic effects. A detailed discussion of these features is included in CHAPTER IV.

We have set up two sets of directional meson counters, one each at a medium and a low latitude station at LONDON (51.53N, 0.09W) and MAKERERE (0.33N, 32.56 E) respectively. These directional telescopes have been operated over the period of the recent solar minimum and the ascending phase of the present solar cycle (no;20). A major purpose of this setup was to study the characteristics of the solar daily variation over the period of the solar minimum and the subsequent ascending phase of the solar cycle.

A similar experiment has been conducted at Manchester near the solar minimum of 1954. (POSSENER and VANHEERDEN (1956)) and interesting changes have been observed in the characteristics of the diurnal anisotropy at that time. The London telescopes are quite similar in geometry and response to the apparatus employed at Manchester. In view of this, the data obtained from the directional counters at London and Manchester are directly comparable and could also be used to study the differences in the behaviour of the solar daily variation during the two minima.

More recently an extensive network of neutron monitors has been set up under the auspices of the I.G.Y. and the I.Q.S.Y. These instruments respond to a mean primary energy someqhat lower than that monitored by meson counters. (In addition, the data from neutron monitors is free from uncertainties associated with temperature effects). Data obtained from meson telescopes can therefore be regarded as complementary to those obtained from neutron monitors. Since extensive data on the S.D.V. are now available from the neutron monitors and these data have been analysed to establish the average features of the diurnal anisotropy during recent years, it would be interesting to see how the results obtained from these two sources compare.

Several subsidiary pieces of information have also been obtained from the data acquired over three years from the directional telescopes. The long period records of the daily mean intensities obtained at London have been correlated with atmospheric variables (temperature and pressure) in order to determine the atmospheric effects on the intensities recorded by the London recorders.

Previous investigations of Forbush decreases have had to rely on data from the I.G.Y. type neutron monitors which had considerable statistical uncertainties associated with them. With the advent of high counting rate NM -64 neutron monitors and increased knowledge about the asymptotic directions it is now possible to study with greater confidence several characteristics of Forbush decreases, e.g. onset directions relative to the Earth - Sun line, direction of anisotropies associated with the recovery and Onset phases of the decrease, characteristics of storm time increases, rigidity dependence, etc. We have accordingly used data from a series of Super-Neutron monitors and other high counting rate monitors distributed in latitude and longitude along with the data obtained from the NORTH/SOUTH and EAST/WEST recorders to study the major characteristics of several Forbush decreases recorded during the present solar cycle.

CHAPTER II

THE APPARATUS

2.1 INTRODUCTION:

Ionization chambers, neutron monitors and meson telescopes are the principal instruments currently in use for a continuous monitoring of the cosmic ray flux. Each of these instruments has some characteristic features which are of use for particular experiments.

Thus, e.g. an examination of the differential response function, (which specifies the contribution to the counting rate from different primary energies) for the case of a neutron monitor and that for the meson telescope or ionization chamber shows that the neutron monitor has a considerable response for the lower energy range of the primary spectrum (less than 5GV) inaccessible with a meson telescope or an ionization chamber. Therefore, by placing a neutron monitor at a high latitude station, so that the lower energies are not excluded by the Geomagnetic field, it is possible to monitor a lower mean primary energy than is possible with, say a meson telescope.

Another important factor in favour of the neutron monitor is that the secondary particles recorded by the instrument are relatively unaffected by changes in atmospheric temperature, unlike the intensity recorded by meson telescopes or ionization chambers. This is of special advantage while studying the daily variation of the cosmic ray intensity, insofaras the magnitude of the temperature corrections for the hard component (recorded by meson telescopes and ionization chambers) are appreciable and uncertain, while the corresponding corrections for the neutron monitor data are very small. The uncertainty inherent in the application of temperature corrections can therefore be avoided in the case of the neutron monitor

The chief advantage obtainable with a meson telescope is that it enables a degree of resolution in directional characteristics. Since the meson telescopes consist of one or more trays of sensitive counter area placed parallel to each other and worked in coincidence, the geometry of the telescope defines a solid angle within which the response of the instrument will be restricted (i.e. it will only record particles within this solid angle as opposed to an omnidirectional instrument which records all particles within a hemisphere of directions). These directional properties of the telescopes can be used to distinguish between variations in the secondary component of the cosmic ray intensity, introduced by the atmosphere or the geomagnetic field and those caused by primary anisotropies. Thus (as is described in section 3.2) two telescopes inclined at 45° to the zenith and located at a medium latitude station like London and pointing in the North/South directions respectively will observe any primary anisotropies with a phase difference of about two to three hours, whereas they will show variations with no phase difference for atmospheric or geomagnetic effects. Besides this angular resolution available with meson telescopes, because of the coincidence technique employed it also becomes possible to make an effective discrimination against background radio-activity.

In the present thesis, we are chiefly concerned with a study of the daily variation of the cosmic ray intensity in the medium energy range (30 - 50 Gv) and have therefore employed two pairs of meson telescopes to study the diurnal and semidiurnal anisotropies in the cosmic radiation.

The earlier telescopes employed G-M counters for the detection of cosmic ray particles. However, the recent development of large area plastic scintillation counters has provided a method with distinct advantages over the G-M counter technique. The use of scintillation counters dispenses with the problem of complex circuitry associated with G-M counters and those of the stability and maintenance of the G-M tubes. The sensitive area of the scintillator telescopes and therefore, the counting rate, can be greatly increased without encountering problems of "Dead spaces" etc. High efficiency, long life, stability with regard to operational characteristics, high counting rates obtainable and the extremely high time resolution possible (10^{-9} secs) are the chief factors which have brought the scintillator telescopes into vogue.

A set of telescopes have been developed at IMPERIAL COLLEGE by MATHEWS (1963) and DUTT (1965) and have been used by DUTT (1965) and PEACOCK (1967) with satisfactory results. It was therefore decided to use the basic design as discussed by Dutt and Peacock for the present experiment.

In the following, we shall describe the instrumental and operational characteristics of the scintillation counter telescopes with a view to elucidating the different factors which determined the design of the apparatus and the methods used to ensure its proper operation.

2.2. SCINTILLATOR TELESCOPES

2.2.1 GENERAL PRINCIPLES:

A charged particle passing through a scintillator loses energy in ionizing, exciting and dissociating molecules in a column around its trajectory, to an extent depending on its energy and charge and average ionization potential of the scintillator material. This energy is finally transferred to the molecules of the scintillator and a part of it is reradiated by them as fluorescent radiation.

In a scintillation counter light output from the scintillator is guided to a photomultiplier. Scintillation light falling on the Photo-Cathode of the photomultiplier causes photoelectrons to be emitted; these are then accelerated and multiplied in the Dynode structure of the tube. A charge is collected at the anode of the photomultiplier and can be recorded by suitable electronic circuits.

The response of a scintillation counter to the passage of a charged particle is a function of several factors, as given below:

1) The energy deposited in the scintillator and the fraction of this energy which appears as scintillation light,

2) The transparency of the material of the scintillator to its own radiation.

3) The reflectivity of the container walls and the fraction of the wall area covered by photocathodes.

4) The photo-electric efficiency of the photocathodes and the electrical characteristics of the photomultiplier and the associated electronic circuits.

It has been shown by SWANK (1954) that the output pulse voltage amplitude at the anode may be written as:

$$V_{max} = \frac{N g \eta G}{C} \gamma^{\frac{1}{1-\gamma}}$$

where

N is the total number of excitations in the scintillator/passage,

η is the Quantum efficiency of the Photo Cathode,

G is the multiplication factor of the P.M. tube,

g is the fraction of the photons collected at the Photo Cathode,

$\gamma = \frac{Rc}{\tau}$ is the circuit time constant divided by the decay time of the fluorescence.

Since it is desirable from the electronic point of view to obtain an appreciable voltage pulse at the anode, the design of the scintillation counter is concerned with adjusting the different parameters enumerated above, with a view to obtaining a suitably high voltage output at the anode (0.2 Volts).

2.2. 2 THE SCINTILLATORS

The plastic scintillators used in our case are of the type NE 102A supplied by NUCLEAR ENTERPRISES Ltd. They consist of slabs of POLY-VINYL TO$\overset{u}{\wedge}$LUENE in which an organic scintillator P-Terphenyl is dissolved. The material has been doped with POPOP which causes a shift in the wave length of maximum emission from 3800A° to about 4500A°. This matches the output from the scintillator to the peak response of the photomultiplier used.

The chief physical characteristics of the scintillator are listed below:

1.	LIGHT OUTPUT:	65% of an Anthracene crystal of the same geometry.
2	DECAY CONSTANT:	3 nano secs
3	WAVE LENGTH OF MAX^{m} Emission:	4550A°
4	SP. GRAVITY:	1·032
5.	SOFTENING TEMP:	75°C
6	REFRACTIVE INDEX:	1·581
7	NO OF ATOMS / BARN:	H:0525 C:0475 N: $1.8 * 10^{+6}$ O: $1.8 * 10^{6}$
8.	NUMBER OF ELECTRONS/c.c.	$3.4 * 10^{23}$

The scintillators were employed in the form of slabs measuring 61 * 61 * 2.54 cms for the MAKERERE telescopes and 90 * 90 * 3·75 cms for the LONDON telescopes.

For design purposes a useful quantity is the number of photons emitted / passage of a charged particle through the scintillator. This may be worked out from the energy lost by a minimum ionizing particle in traversing the scintillator and the scintillation efficiency of the scintillator. The energy loss /gm-cm^2 for a material of NZ/A (electron-concentration) $3.4 * 10^{23}$ may be estimated from a relation given by ROSSI (1952) and is found to be 2.2 Mev / gm-cm^2. Hence the total energy loss in passing through 2.54 cms (for MAKERERE) of the material is about 5.5 Mev. We may estimate the number of photons emitted / vertical passage with a knowledge of this energy loss and the fact that the scintillation efficiency of the material is about 60% of that of ANTHRACENE. Anthracene converts about 4-6% of the energy lost in it to scintillation radiation. In our case this fraction will therefore be more like 2-3%. Therefore, about 120 eV will be expended per photon emitted, compared to 60eV in the case of ANTHRACENE. The total number of photons emitted will therefore be about $4.6 * 10^4$. A fraction of these photons will be collected at the photo cathode of the P.M. tube. This fraction will depend on the characteristics of the light guide system employed.

2.2 3 THE LIGHT GUIDE SYSTEM:

The coupling between the P.M. tube and the scintillator is an important factor in the design of the scintillation counter. In practice the design is approached with a view to maximize the light-collection at the Photo Cathode. A direct coupling would enable maximum collection, however, it would be unpractical with the large scintillator sizes being employed. We have relied on diffuse relection from the walls of the container boxes to provide the coupling required.

The scintillators were arranged on the base of a rectangular box from which all external light was excluded. For the MAKERERE telescopes four scintillator slabs, each measuring 61 * 61 * 2.54 cms were arranged round a 5" photomultiplier tube in an alluminium box measuring 54" * 54" * 17" as shown in fig. 1. The inside of the box has been lined with a diffusely reflecting white material DARVIC (with a reflection coefficient of about 0.750). Light emitted on the passage of a particle through the box is diffused and isotropically distributed in the box.

The arrangement was slightly different for the LONDON telescopes. Here two slabs of dimension 90 * 45 * 3·75 cms were placed in direct optical contact on the base of the box and the P.M. tube looked on to the scintillator from the top of the box. The inside of the box was made to approach a hemispherical shape by means of angular screens arranged in the interior. Such a procedure increased the uniformity of light collection over the entire area of the scintillator. The interior was lined with DARVIC as before.

DUTT (1965) has tested the uniformity of light collection as obtained in the rectangular boxes by measuring the dark current of the p.m. tube when a small tungsten lamp was moved across the box. He finds that the light collection efficiency remains within 15% of that obtained when the light flash occurs directly below the P.M. tube for appreciable portions of the scintillator and falls by only 30% at the extreme corners of the box. In the design of the LONDON telescopes this falloff at the corners is minimized by the hemispherical shape of the interior of the container box.

As mentioned earlier, the response of the scintillation counter will depend on the reflectivity of the walls of the container and the fraction of the wall area covered by photo cathodes. Starting with the total number of photons emitted / passage of a charged particle, as calculated earlier, an estimate may be made of the number of photons actually collected at the photo cathode for a particular geometry of the box and reflectivity of its walls. DUTT (1965) has made such a calculation and finds this number to be about 300 photons collected / vertical passage. A fraction of these photons will succeed in ejecting a photo electron, this fraction depending on the photosensitivity of the photo cathode.

2.2.4 THE PHOTOMULTIPLIERS:

Desirable features in the selection of a photomultiplier for scintillation counting are:

1) High photo sensitivity,
2) Uniformity of response of the photo cathode,
3) High blue sensitivity,
4) Good collection efficiency of the electrons from the cathode to the first Dynode,
5) High first dynode gain,
6) High stability against drift in gain,
7) Low noise characteristics (low dark current).

In our case, since the scintillators occupy a large area it is necessary to have a large photo sensitive cathode area, so as to ensure a uniform response of the P.M. tube to different portions of the scintillator.

The tubes for our telescopes are of the type 9618 supplied by EMI and are recommended for fast coincidence work (rise time of the pulses is 10 n secs and time spread on the pulses is 25 n secs), and low noise characteristics.

The tubes have a photo cathode of diameter 111mm made of Sb - Cs - 0 (S11). It has 11 dynodes. The dynode structure is of the venetian blind type recommended for high gain stability. They contain a focussing electrode to ensure maximum efficiency of electron collection from the anode to the first dynode. Dark current and photo sensitivity satisfy the general requirements of scintillation counting. The scintillator output is well matched with the photomultiplier response.

The overall gain of the photomultiplier is so critically dependent on the individual stage gain that it is impossible for all P.M. tubes, even of the same type, to have the same gain at the same voltage. Accordingly, matched pairs of tubes which satisfy this requirement to a degree were used for each telescope.

The photo cathode sensitivities quoted by the manufacturers were about 70 μa/Lm and the dark current at an operating voltage of about 1450 volts was 15 namps.

From a knowledge of the photosensitivity of the photo cathode an estimate may be made of the signal amplitude obtained on the passage of a minimum ionizing particle through the scintillator. As mentioned in section 2.2.3, about 300 photons are collected at the photo cathode per passage. With the values of photo cathode sensitivities quoted above, these will release about 35 photoelectrons. Since the interdynode capacitance is about 30 pf this will result in an output voltage of about 200 mv(per passage of a minimum ionizing particle) at the anode of the P.M. tube.

2.2.5 TELESCOPE GEOMETRY AND COUNTING RATES AVAILABLE:

An effective discrimination against background radioactivity can be achieved only if two or more counters are used in coincidence. Such an arrangement also introduces an amount of angular resolution in the directional characteristics of the instrument and is desirable for the reasons spoken of earlier. (See 2.1). A study of the voltage characteristics shows that an effective discrimination against background radioactivity is achieved with two scintillation counters working in coincidence. We have accordingly used two counters of the type described to form a telescope.

The size of the scintillators is slightly different for the Makerere and the London telescopes. In the Makerere telescopes, two scintillation counters of sensitive area 165 x 165 cms are mounted 165 cms apart, so as to give a cubical geometry. In the London telescopes, the size of the scintillators and the separation between the two counters is smaller.

They form a cube of size 90 x 90 x 90 cms. The sensitive areas for the two sets of telescopes are therefore 1.5 sq.metres (MAKERERE) and 0.81 sq. metres (LONDON), respectively.

With these sensitive areas it is possible to achieve a sufficiently high counting rate so as to obtain an adequate resolution against statistical and background fluctuations. The counting rates actually obtained at London and Makerere are 90,000 / hr. and 180,000 / hr. respectively. The statistical fluctuation on the counting rate for a particular period is SQRT (N). Where N is the counting rate during the period under consideration, the statistical fluctuations for mean monthly and yearly bihourly values, for Makerere and London are given below in TABLE 1.

TABLE I

ERRORS ON	LONDON (N/S)	MAKERERE(E/W)
BIHOURLY VALUES	0.225%	0.165%
MEAN MONTHLY BIHOURLY VALUES	0.045%	0.030%
MEAN ANNUAL BIHOURLY VALUES	0.013%	0.009%

Since the diurnal and the semi-diurnal waves at medium energies have amplitudes of about 0.2% and 0.05% respectively, it is possible to obtain accurate estimates of these variations with the counting rates achieved.

Both the Makerere and London telescopes are inclined at 45° to the zenith. The MAKERERE telescopes are made to point in the East and West directions, while the London telescopes point in the North and South directions for reasons explained in chapter I.

Fig. 2 shows a view of an inclined telescope.

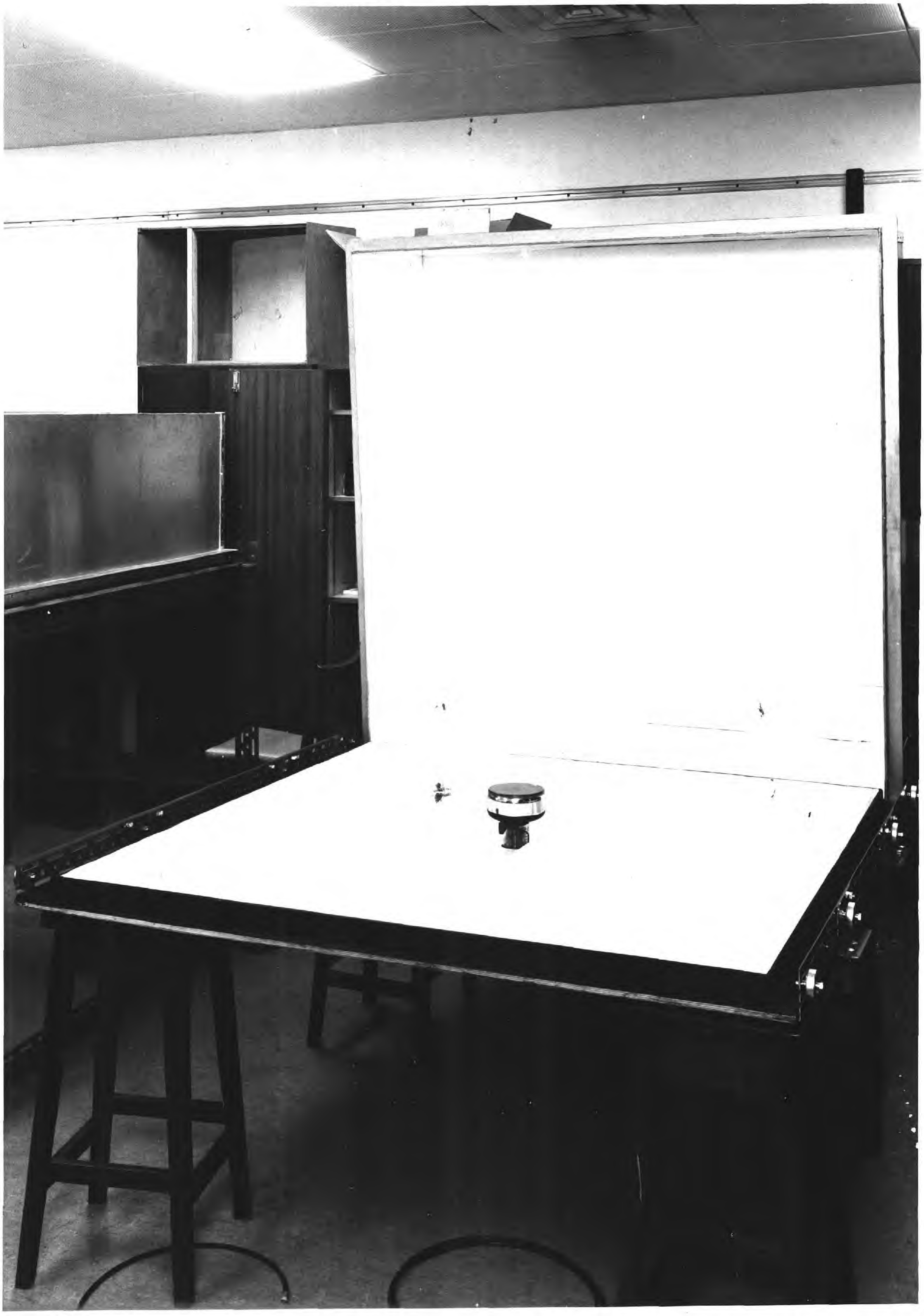


Fig. 1: Figure showing the arrangement of scintillators in a telescope.

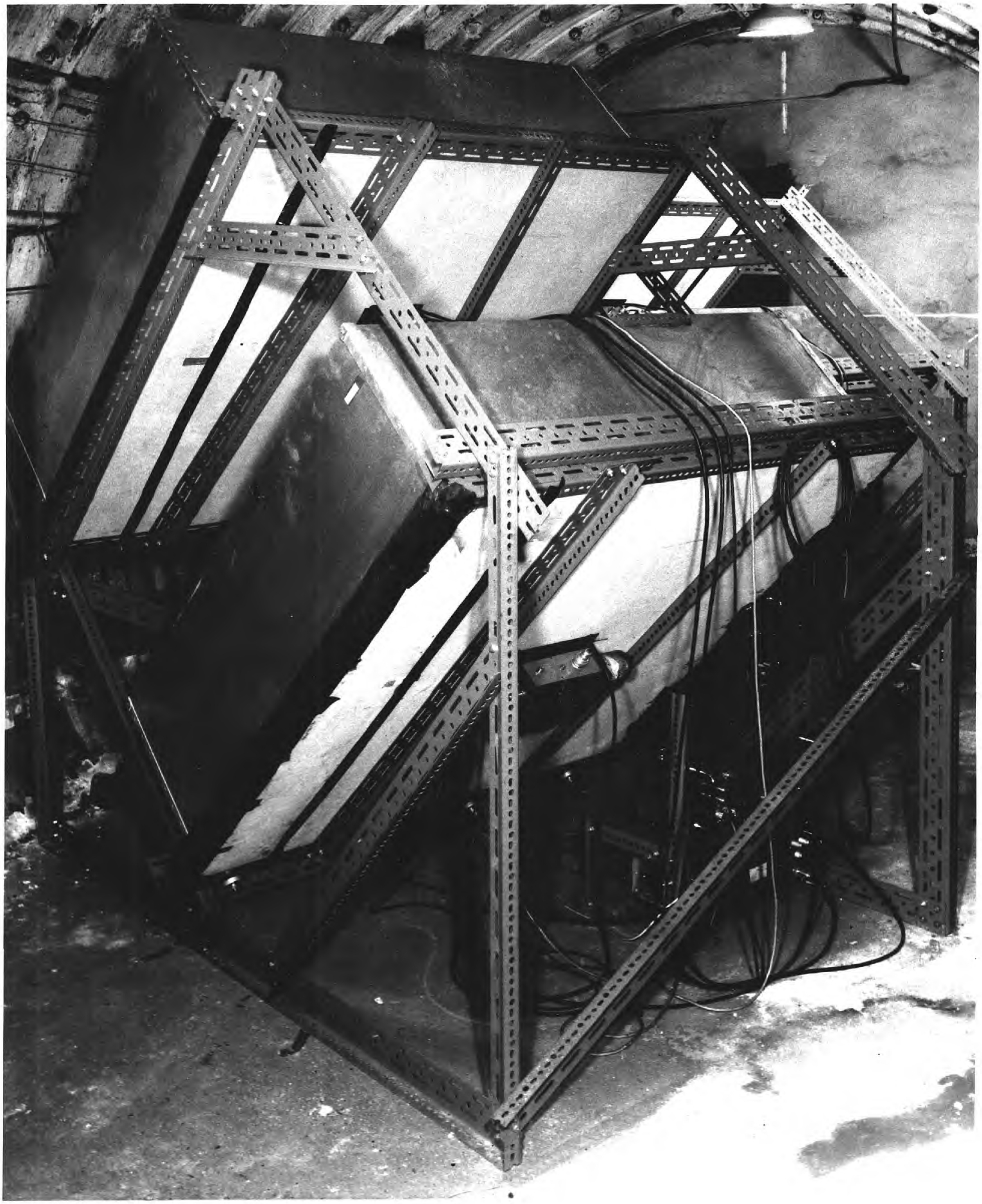


Fig. 2: View of an inclined telescope.

2.3 ELECTRONIC CIRCUITRY

2.3. 1 GENERAL REQUIREMENTS

The requirements of the circuit design follow from the general requirements of the experiment, these may be listed as below:

1) Sufficiently high counting rate to achieve an adequate resolution against statistical and background fluctuations.

2) High instrumental stability.

3) Uninterrupted operation over long periods of time.

4) Elimination of all periodic variations in instrumental stability which are likely to be confused with true variations of cosmic ray intensity.

Of these requirements, the counting rate is determined essentially by the size of the scintillator and has been discussed in the previous section. The primary considerations in the design of the circuit are those of the stability of the voltage supplies, discrimination levels and amplifications at different stages of the circuit. In this connection, it is important to mention two major sources which can produce variations in the operational characteristics over the period of a day, they are:

a) Variation in supply voltages due, for example, to alterations in consumer demand.

b) Changes in electronic characteristics due to variations in laboratory temperature over the day.

It is therefore necessary to ensure that all variations in voltage are smoothed and that the electronic circuits have a negligible temperature coefficient.

The extreme sensitivity of the photomultiplier gain to changes in applied voltage is brought about by the following equation:

$$\delta G/G = 0.7\, n \delta V/V$$

Where L.H.S. gives the fractional change in the gain G of the photomultiplier for a change δV in the applied voltage. The factor 0.7 n is about

10 in a typical situation. Special care is therefore necessay to minimize variation in the voltage applied to the P.M. tube. Such variations may result from a change of the mains supply to the E.H.T. power supply, or from a change in the performance of the power supply itself with a change in environmental conditions, e.g. temperature variations. In the present setup, both these sources of error have been accounted for.

The flow diagram of the power supply to the different parts of the circuit illustrates the precautions taken to account for variations in the mains supply voltages. The mains supply is in fact, stabilized in two stages. An A.C. Servomex stabilizer is responsible for smoothing mains fluctuations of 10% less than 0.25%. The smoothed output from the servomex is taken to a saturated core transformer which not only removes any sudden troughs or spikes, but also reduces any residual voltage fluctuations allowed through by the servomex. These transient fluctuations cannot be removed by the servomex because of its rather long time constant. The transformer reduces the sudden troughs or spikes of ± 15% to less than 0.1% It is also self protecting against short circuits and transient overloads.

The stabilized mains are then supplied to E.H.T. and L.T. units which supply power to the different parts of the circuit The E.H.T. units used are of the TYPE PW 4024 / 01 (PHILLIPS). These power supplies are themselves stabilized and for a change of 10% in the mains voltage, the output voltage changes by 0.05%. After these different stages of stabilization, a change of the mains voltage by, say 10 volts, will result in a change of the E.H.T. voltage by only 0.00075 volts The photomultiplier gain will change by 0.0035%. Thus the changes in gain are successfully minimized by the different stages of stabilization used.

The E.H.T. units have a low temperature coefficient of about 0·02% which is unlikely to cause any errors.

The L.T. to the different parts of the circuit is supplied from transistorized low tension units (Type TS 20 Venner Electronics) which are well stabilized against voltage fluctuations and are operated off the stabilized mains supply.

Most of the circuits utilized transistors to get reliability and troublefree operation over long periods of time. The use of transistors however, necessitated that greater care be taken in the design of the circuits to account for changes in voltage and temperature, because of the greater sensitivity of transistors to fluctuations in these parameters. Accordingly, at certain stages, special precautions were taken to minimize the effect of temperature on the performance of the circuits. These will be described in the stage by stage description of the circuitry that follows.

2.3.2 THE CIRCUIT

Figure 3 shows the block diagram of the circuit employed The different parts of the circuit will be discussed below.

The Head units contain the DYNODE CHAIN, an AMPLIFIER, a PULSE-HEIGHT LIMITER and a discriminator. The associated circuits are shown in Figures 4 and 5.

The DYNODE CHAIN resistors supply the H.T. to the various Dynodes of the P.M. tube. The optimum value of these resistors depends on the particular application, in particular, it is important that the electric field between the cathode and the first dynode should be high. This is ensured by providing a high voltage between the cathode and the first dynode. This provides the following advantages:

1) The gain of the first dynode is high. This is important at low levels of illumination and high frequencies where the statistics of photo-emission become important.

2) The time spread of electrons arriving at the anode after a very short light pulse is reduced. Thus, for fast pulses it is required to operate tubes with the maximum possible cathode to first dynode voltage.

In the present case a focussing electrode is built into the P.M. tube to ensure a high collection efficiency of the electrons by the first dynode.

Another consideration, more important for D.C. applications is that the chain resistors should be so chosen that the chain current is about ten times the expected mean anode current. If this is not so the Dynode voltages will vary with the changes in the mean anode current and therefore, the overall gain of the P.M. tube will not remain constant. In the present case, it was necessary to ensure that the dark current of the P.M. tube was negligible compared to the current in the chain. The low value of the dark current quoted by the manufacturers is likely to be exceeded if the box containing the P.M. tube is not absolutely light tight. A stringent test on the light tightness of the box was carried out to ensure that the operational dark current never exceeded one μamp at the operating voltage (1450 Volts) With the arrangement of the resistor chain shown in the figure the current in the chain was about 150μamps and therefore, a change in the dark current could not affect the gain of the P.M. tube.

The output from the anode of the P.M. tube goes to an amplifier through a coupling capacitor (1000 pf, 2.5 kW). The function of the amplifier is primarily that of impedance matching of the high input impedance of the P.M. tube to the low input impedance of the discriminator circuit following it. The amplifier used employs negative feedback for stability against L.T. and temperature changes and has an amplification factor of about 3. The amplified pulses are clipped to a maximum amplitude of about one volt by the pulse height limiter.

The inclusion of a dscriminator in the amplifier output circuit permits effective control of the background noise proffered to the coincidence circuit. In the present case the discriminator excludes pulses below 150m Volts. Since the pulse height obtained with a minimum ionizing particle is about 200mv, a major portion of the cosmic ray flux is counted. It is important from the point of view of the experiment that drift in discriminator level should be minimum, for any changes in this will be wrongly interpreted as changes in the cosmic ray intensity.

The discriminator used here uses a tunnel diode which does not fire below 150 mv. The tunnel diode (IN 2969 A G.E.C.) has been preferred here because of its temperature characteristics. Thus the manufacturers quote temperature coefficients of 60 Micro amps/°C for the peak current and 1.0 mv/°C for the forward voltage. The former determines the switching threshold,while the latter, the amplitude of the output voltage. Thus, in view of the low temperature coefficients, the output from the discriminator will remain uniform in its upper and lower limits irrespective of the temperature changes.

The output from the discriminator triggers an avalanche transistor (ASZ 23 MULLARD) to give pulses of about one volt amplitude and a width of about 20 nano secs which can be transmitted through an appreciable length of the coaxial cable without attenuation.

The electrical pulses from the head unit are transmitted via a coaxial cable to a coincidence unit (fig.6). To achieve a short resolving time, the signals are shaped into square pulses by reflecting them at the end of a coaxial cable. This also doubles the width of the pulses to 60n secs. The coincidence circuit used employs Diodes (OA 95 MULLARD). The circuit requires two one volt pulses to make the Diode conducting.

Fig 3.

BLOCK DIAGRAM OF A TYPICAL TELESCOPE

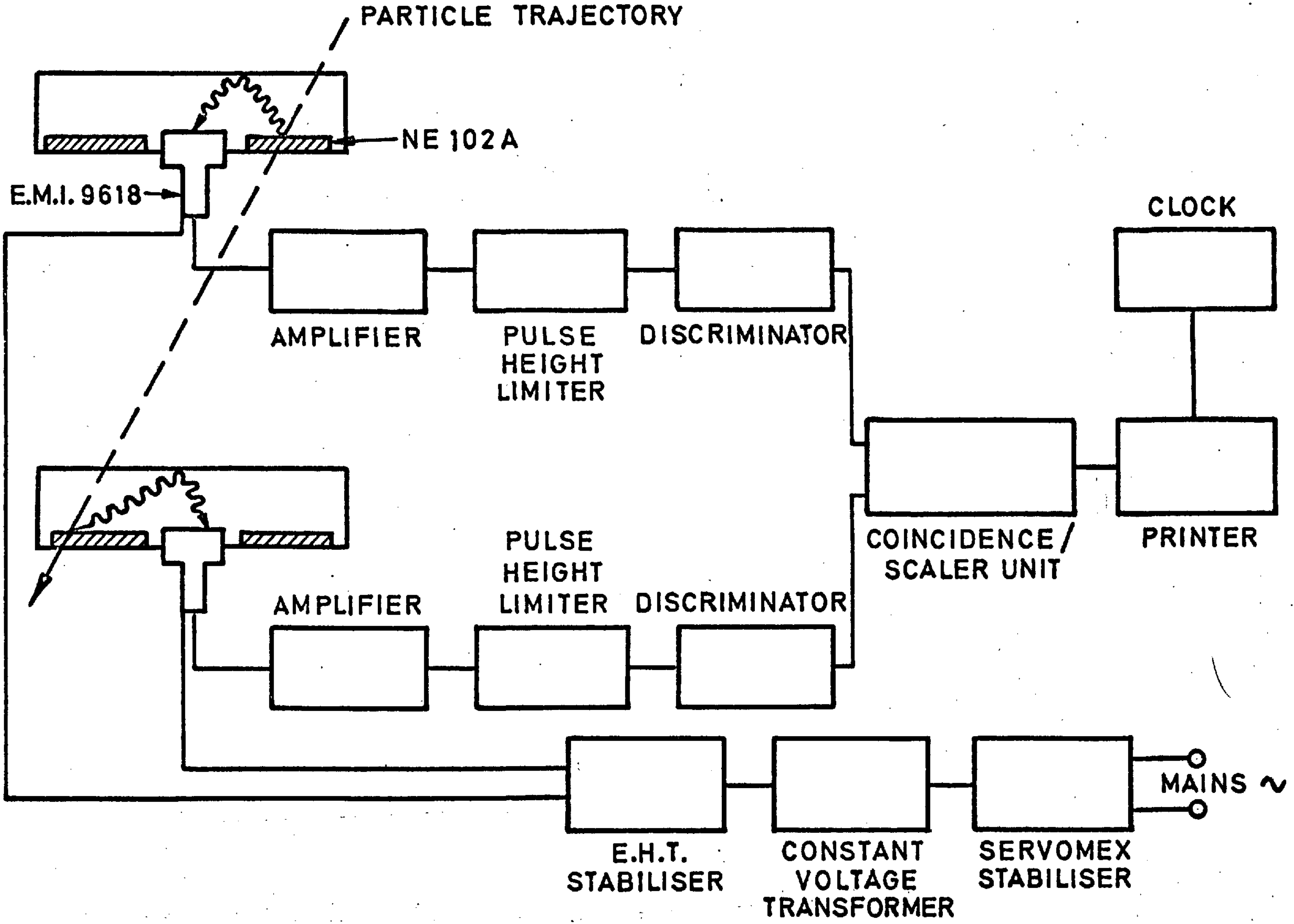


Fig. 4.

CIRCUIT FOR INITIAL PROCESSING OF P.M. TUBE PULSES

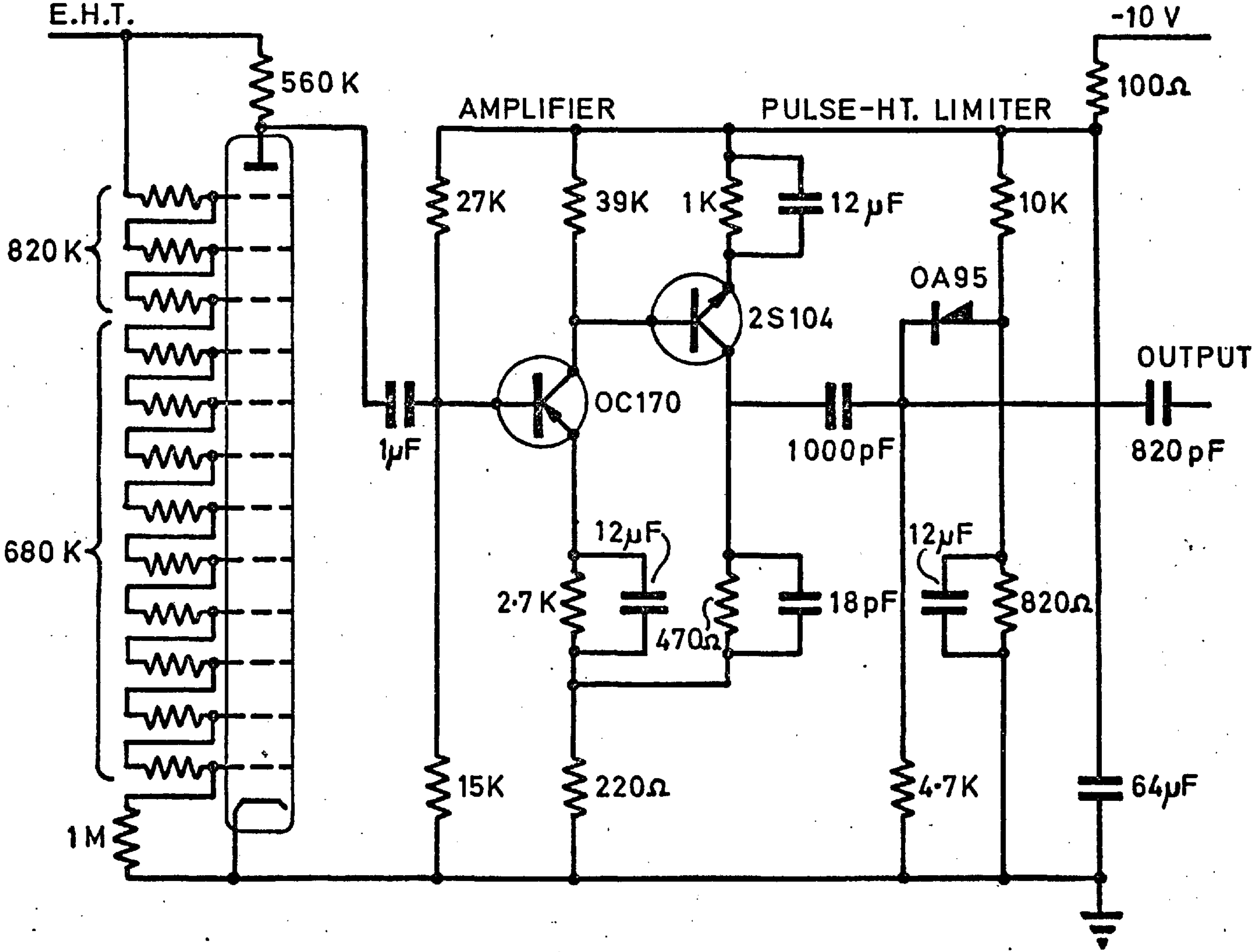
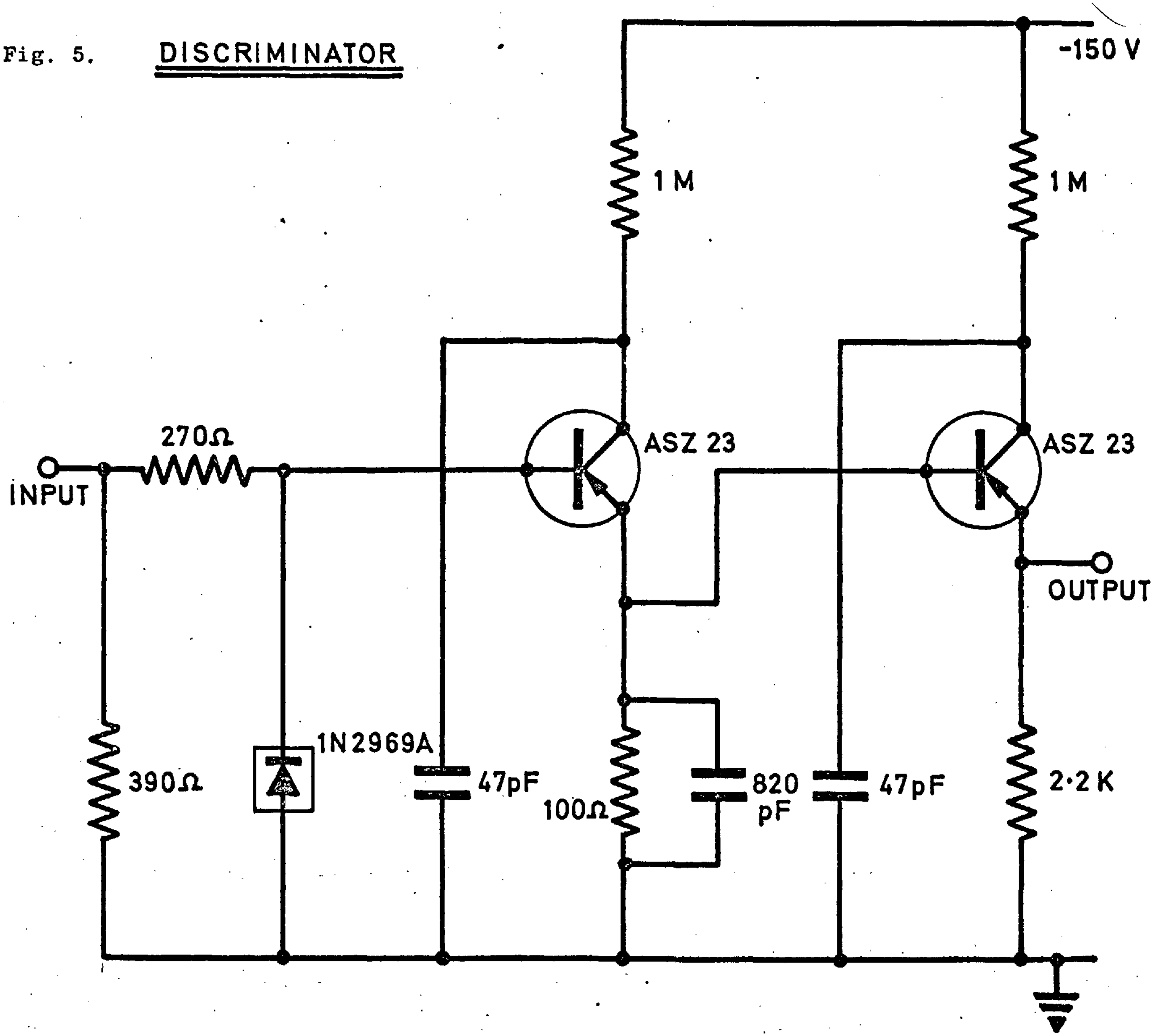


Fig. 5. **DISCRIMINATOR**



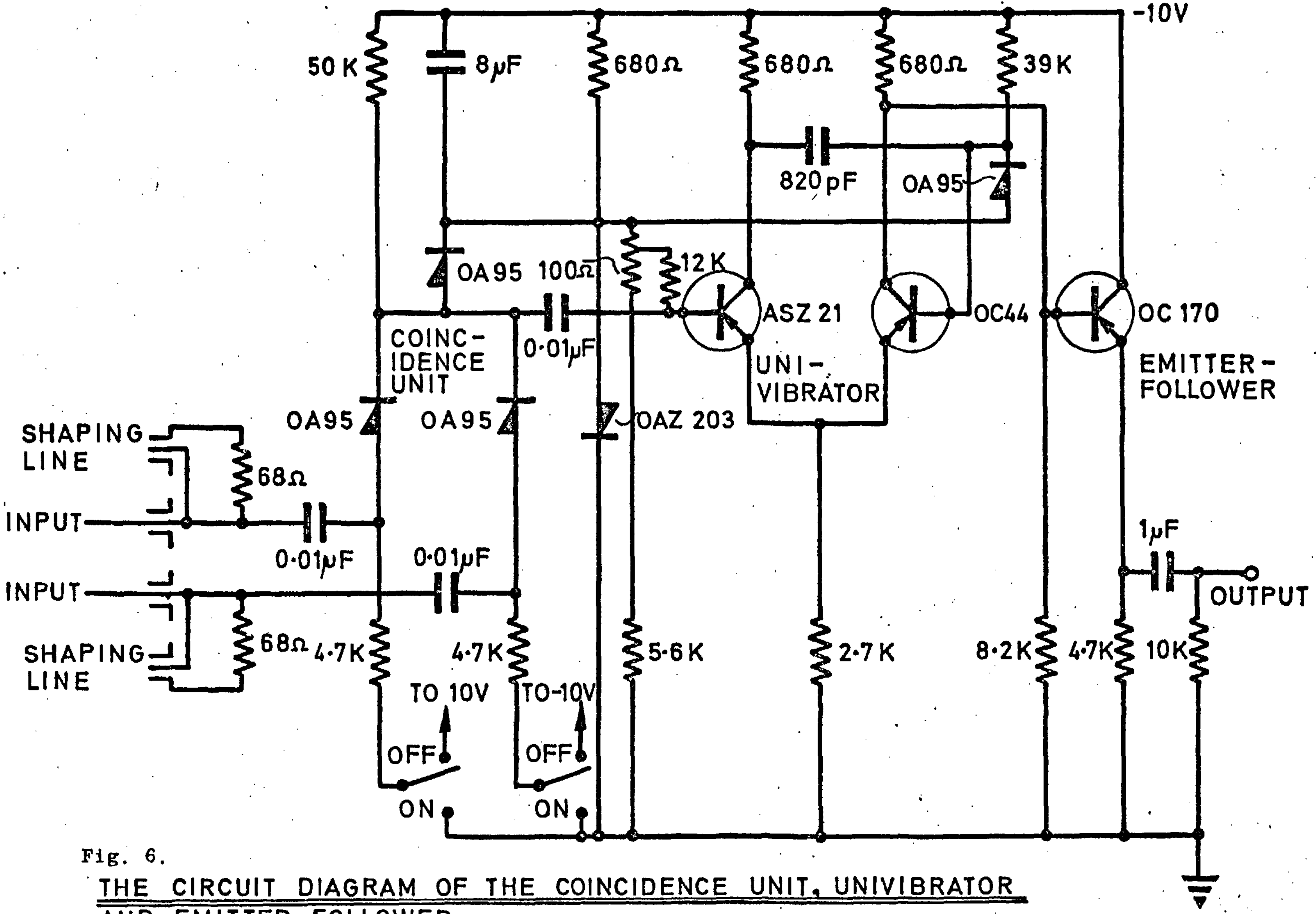


Fig. 6.

THE CIRCUIT DIAGRAM OF THE COINCIDENCE UNIT, UNIVIBRATOR AND EMITTER FOLLOWER

(The voltage amplitude obtained from the coincidence unit after a coincidence is about three times the value of a single pulse). The coincidence output is fed into a univibrator which switches states when it receives a coincidence pulse from the coincidence unit. A single pulse has no effect on the univibrator. The resolving time of the coincidence unit is about 70n secs.

On receiving a coincidence pulse from the coincidence unit, the univibrator gives out a square pulse of amplitude 1 volt and a width of about 6 micro secs (which can drive a venner decade unit). An emitter follower used at the end of the univibrator matches the output impedance of the circuit to that of the coaxial cable which transmits the pulses to the scaling and recording units.

Before recording, the pulses are scaled by factors of 100 and 1000 respectively, for the London and the Makerere recorders, by means of VENNER DECADE UNITS. After 100 (/1000) coincidences are recorded by a telescope, a transistorised relay (TYPE TS 13) closes a pair of contacts. The signal from a relay causes a count action in an electromagnetic printer. After every half hour a clock closes a pair of contacts and the electromechanical counters are made to print out the contents of their registers on a paper tape. Records from the printers are collected regularly and are transferred to I.B.M. data cards for analysis by an electronic computer.

2.4.1.

OPERATIONAL CHARACTERISTICS

The performance of the telescopes is a function of several experimental parameters, e g :

1) The operating voltage of the photomultiplier tubes.
2) The amplification of the electronic circuits.
3) The discrimination levels of the tunnel diode and coincidence discriminators.

The practical setting of the telescopes is approached with a view to obtaining:

1) Maximum stability of the counting rate against instrumental drift.
2) Good discrimination against background radio activity and noise

In practice, the coincidence discriminator is first adjusted to give an effective rejection of the singles counting rate. The voltage-vs-counting rate characteristic of the telescope is then studied to ascertain the optimum operating position.

The counting rate from the two channels of a telescope can be studied as a function of the E.H.T. voltage applied to the photomultiplier. The curves a and b illustrate the variation exhibited by a typical telescope. Curve c of the same figure (7) illustrates the variation of coincidence rates with the voltage.

The singles counting rate is seen to increase with voltage without an indication of a plateau. This is evidence of the fact that there is an almost continuous distribution of pulses from cosmic rays and background radio activity and it is not possible to achieve an adequate resolution between the two by means of a single counter.

The variation of the coincidence counting rate against voltage, however, exhibits a plateau extending over 100 volts. This corresponds to the fact that with the photomultiplier voltage at this level all cosmic rays passing through the boxes are being counted. In practice the photomultiplier is operated at the middle of the plateau.

The slope of the counting rate/voltage characteristic at the operating point is direct measure of the stability of the instrument against drift in photomultiplier voltage. A figure indicative of the stability obtained is the percent change of the counting rate per 10 volts change of the photomultiplier voltage. In our case, this figure is 0.14% / 10 volts.

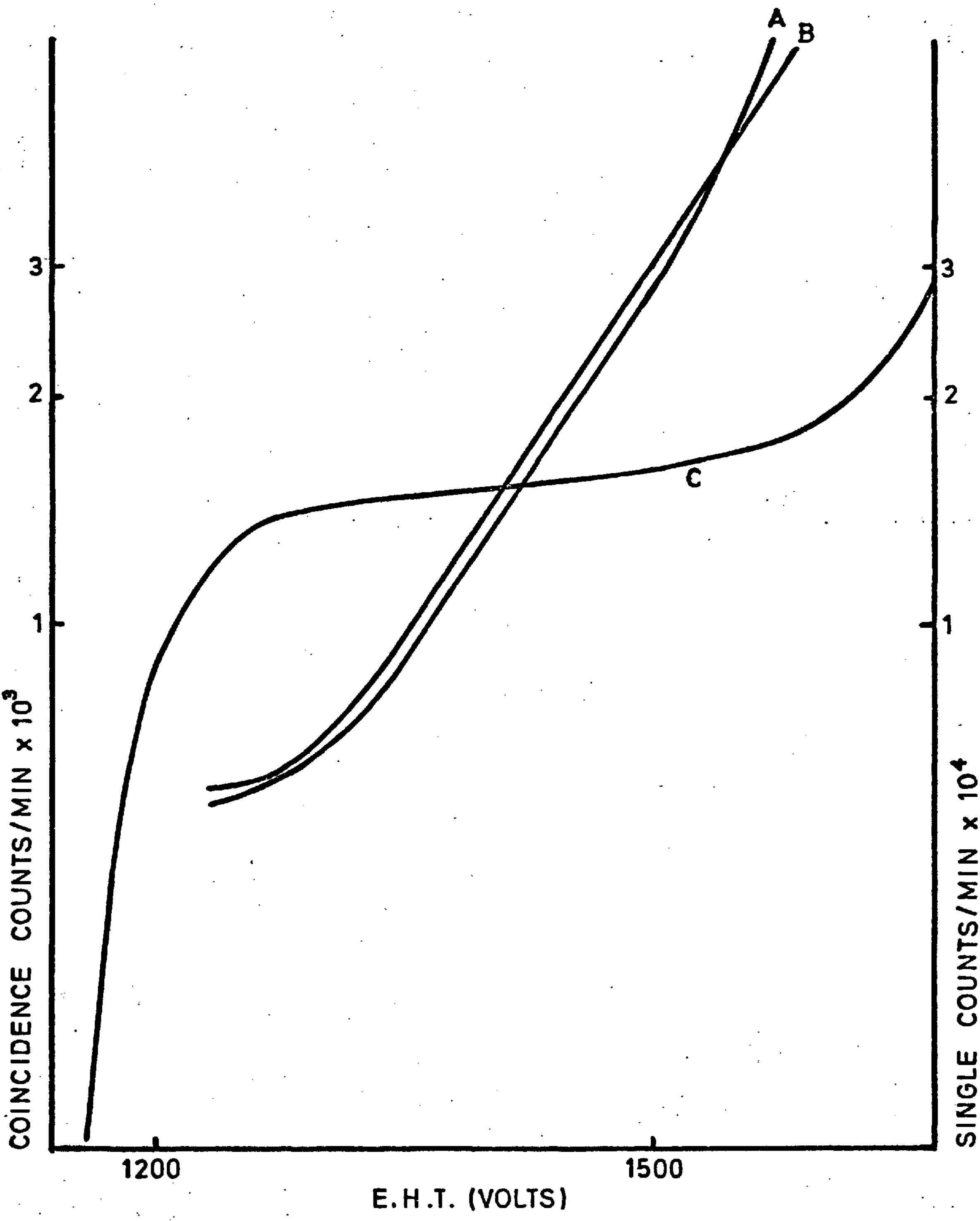


Fig. 7 – VOLTAGE CHARACTERISTICS OF MESON TELESCOPES.

The finite slope of the curve in the plateau region is due to increasing chance coincidence with an increase in the singles counting rate at these voltages. The increase in the counting rate beyond the plateau is likewise due to this increased chance coincidence and contributions from background GAMMA counts.

Since the same E.H.T. unit was employed for the two counters of a telescope, matched pairs of photomultipliers were used in each unit. The selection criterion was that the two multipliers of a telescope should have the same singles counting rate at the operating voltage. Pairs selected on this basis were supplied by the manufacturers. Any residual differences were removed by including a resistor in series with the E.H.T. supply to the P.M. tube.

2.4.2 ROUTINE CHECKING PROCEDURE

As mentioned earlier, the slope of the counting rate / voltage characteristic is indicative of the stability of the apparatus. It is therefore advisable to keep a check on the plateau at regular intervals.

However, routine checks on the performance of the apparatus consist of the comparison of the records from the two channels. Such a procedure provides a means of recognizing short term instrumental aberrations. Changes in the amplification of the system may be checked by the counting rates from the individual counters of a telescope at the operating voltage.

2.4.3 TEMPERATURE CHARACTERISTICS

As decribed in an earlier section, several precautions have been incorporated in the design of the scintillation counters to minimize any dependence on environmental temperature. In order to test the effectiveness of these methods for controlling the temperature coefficient of the apparatus, we have also carried out an extensive investigation of the temperature characteristics of the telescopes installed at London.

The temperature characteristics of the telescope were studied by comparing the counting rate of one of the telescopes (UNIT I) with that of the other (UNIT II), while the temperature of UNIT II was varied from 20°C to 35°C in alternate cycles of 48 hours duration over a period of two months.

Both of the telescopes were first made to point in the same direction so as to make their response to primary and atmospheric variations the same. UNIT II was then enclosed in an insulated hut made of polystyrene. The temperature of this hut could be raised by means of electrical heaters. A uniform temperature distribution was ensured by means of a fan mounted in the hut which could blow air uniformly all over the hut. By this means it was possible to heat the different parts of the hut simultaneously to a high temperature, with the temperature difference between the different parts of the hut not exceeding 1°C. A thermograph kept in the hut, maintained a record of the temperature variations. The telescope enclosed in the hut was heated to a temperature of about 35°C for periods of 48 hours and cooled and maintained at room temperature for the next 48 hours. A uniformly high temperature could be achieved fairly quickly (2 hours) and could be maintained at this value by means of a thermostat. The period of 48 hours was chosen so that the different parts of the telescope had sufficient time to attain the high temperature and any diurnal variations can be averaged out by taking daily means.

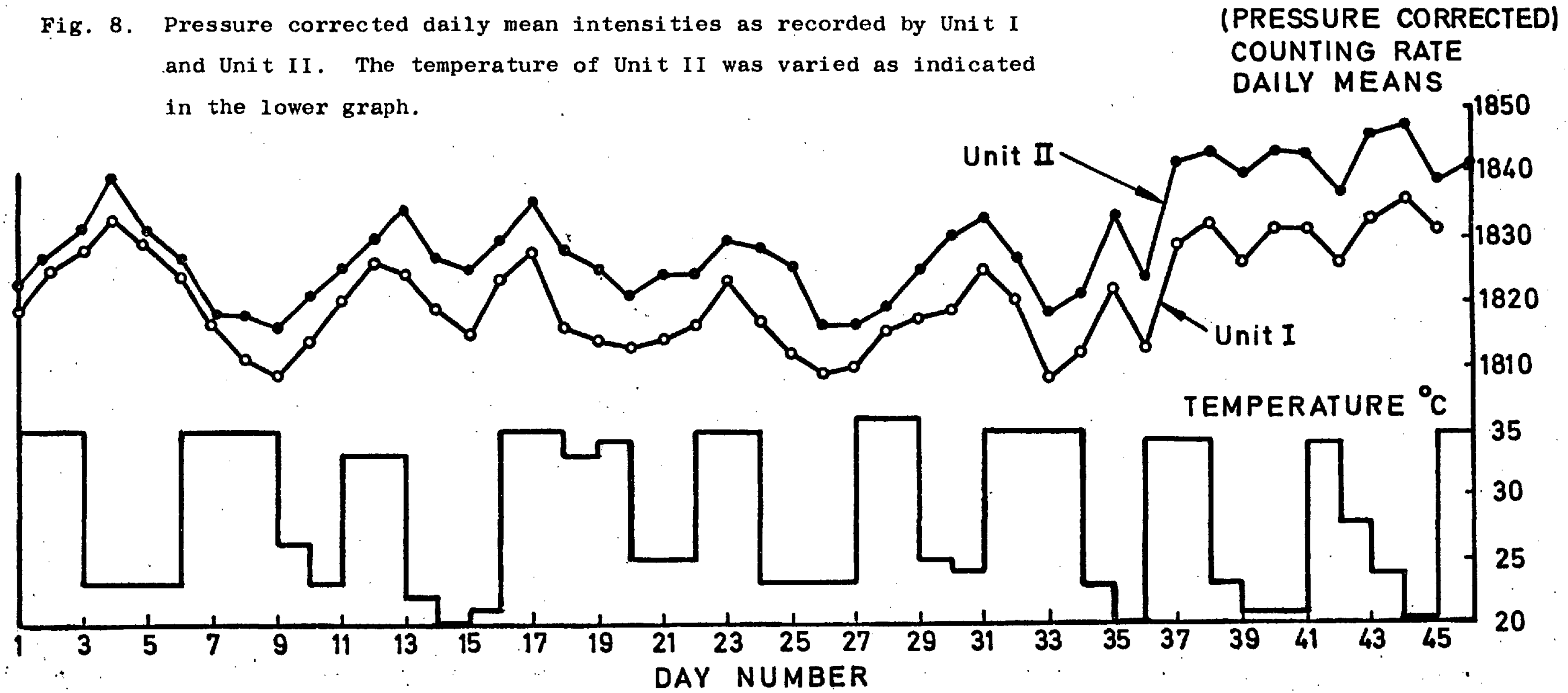
During the process of heating and cooling that unit II was taken through, unit I was maintained at the room temperature. A thermograph kept a record of the room temperature so that any difference of temperature of the two telescopes could be calculated.

Under normal conditions of operation at room temperature Unit I had a slightly higher counting rate than Unit II. Any changes of the counting rate of unit II because of temperature variations would therefore be reflected as changes in this difference between hot and cold days. The fig. 8 shows a plot of the 24 hour means of the two units for the period of the experiment. (Since the heating and cooling processes were started at 1200 hours every day, the means were computed starting from 1200 hours each day). The days on which the temperature of unit II was high have been plotted with a cross. An examination of this figure shows that unit I and unit II track very well, irrespective of the temperature of unit II. Any large temperature effect is therefore absent.

In order to make a quantitive estimate of the temperature coefficient a mean value for the difference of rates between the two units was computed for hot and cold days to increase the statistical accuracy of the results. A difference of these mean values was interpreted as being due to the temperature effect. Such an assumption was justified since the two telescopes would show the same variations for atmospheric and primary anisotropies and a subtraction of the counting rates of the two telescopes would eliminate these variations.

As a result of these calculations it was found that the counting rate of unit II decreased by 0.05% on average for the whole period for an average temperature increase of about 10°C. The Poissonian fluctuation on the mean difference of the counting rate has been estimated and is 0.03 % for the whole period of the test. The decrease in the counting rate is therefore only marginally sufficient. The temperature coefficient of the apparatus is therefore $-0.0055 \pm 0.0030\%/^{\circ}C$. Since the temperature of the laboratory is stabilized and diurnal temperature wave in the laboratory has an amplitude of only about 1.5°C, the observed value of the temperature coefficient will cause a temperature induced diurnal variation of about 0.015%.

Fig. 8. Pressure corrected daily mean intensities as recorded by Unit I and Unit II. The temperature of Unit II was varied as indicated in the lower graph.



Since the errors on the first harmonic of the diurnal variation are themselves of this order (see CHAPTER IV), this small temperature coefficient does not cause any difficulties.

2.4.4 DIRECTIONAL CHARACTERISTICS:

In order to relate the variations observed in the secondary component to primary anisotropies, it is necessary to know the response characteristics of the counter telescopes as a function of the zenith and azimuth angles. These characteristics are called the directional sensitivity patterns of the counter telescopes.

The directional sensitivity in a particular direction is equal to the product of the cosmic ray ~~density~~ intensity in that direction and the projection of the effective area in a particular direction. Since the cosmic ray intensity is known to decrease as COS$^{2}\theta$, where Θ is the angle from the vertical the directional sensitivity at an angle Θ to the vertical will be the product of the effective area and COS$^{2}\Theta$.

We have calculated the effective sensitivity patterns for the telescopes at MAKERERE and LONDON in the E/W and the N/S planes respectively and these diagrams are shown in fig. 9.

An examination of the figure shows that the maximum sensitivity is at an angle of about 35° to the vertical. The sensitivity is seen to fall to about half of this value at about 10° on either side of this. Thus the direction of maximum sensitivity is in fact confined to a small cone of semi-angle 16°, though the opening angle of the telescope is large (90°). In the following pages, we shall often have to assume that the actual telescope can be approximated by a narrow angle telescope looking at about 35° to the vertical. The above calculations show that such an assumption is justified.

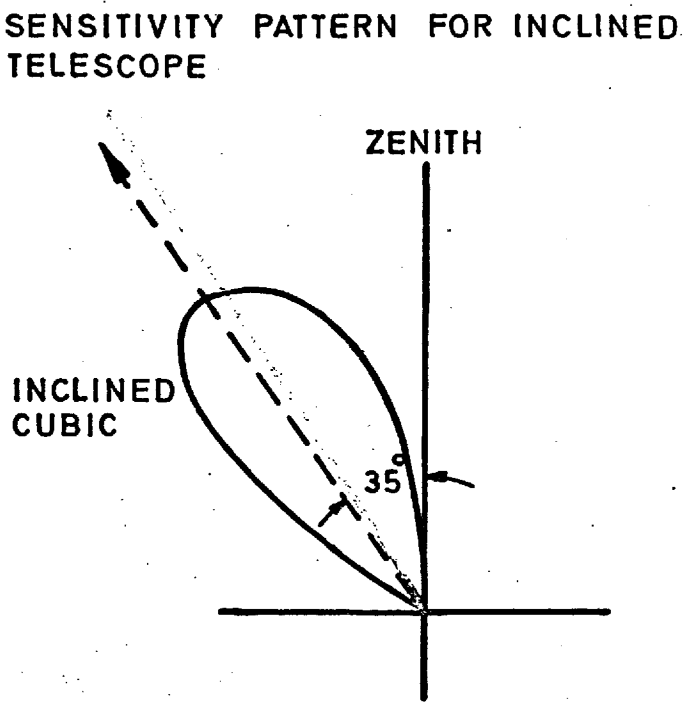


Fig. 9. Directional sensitivity pattern for a cubic telescope inclined at 45° to the vertical.

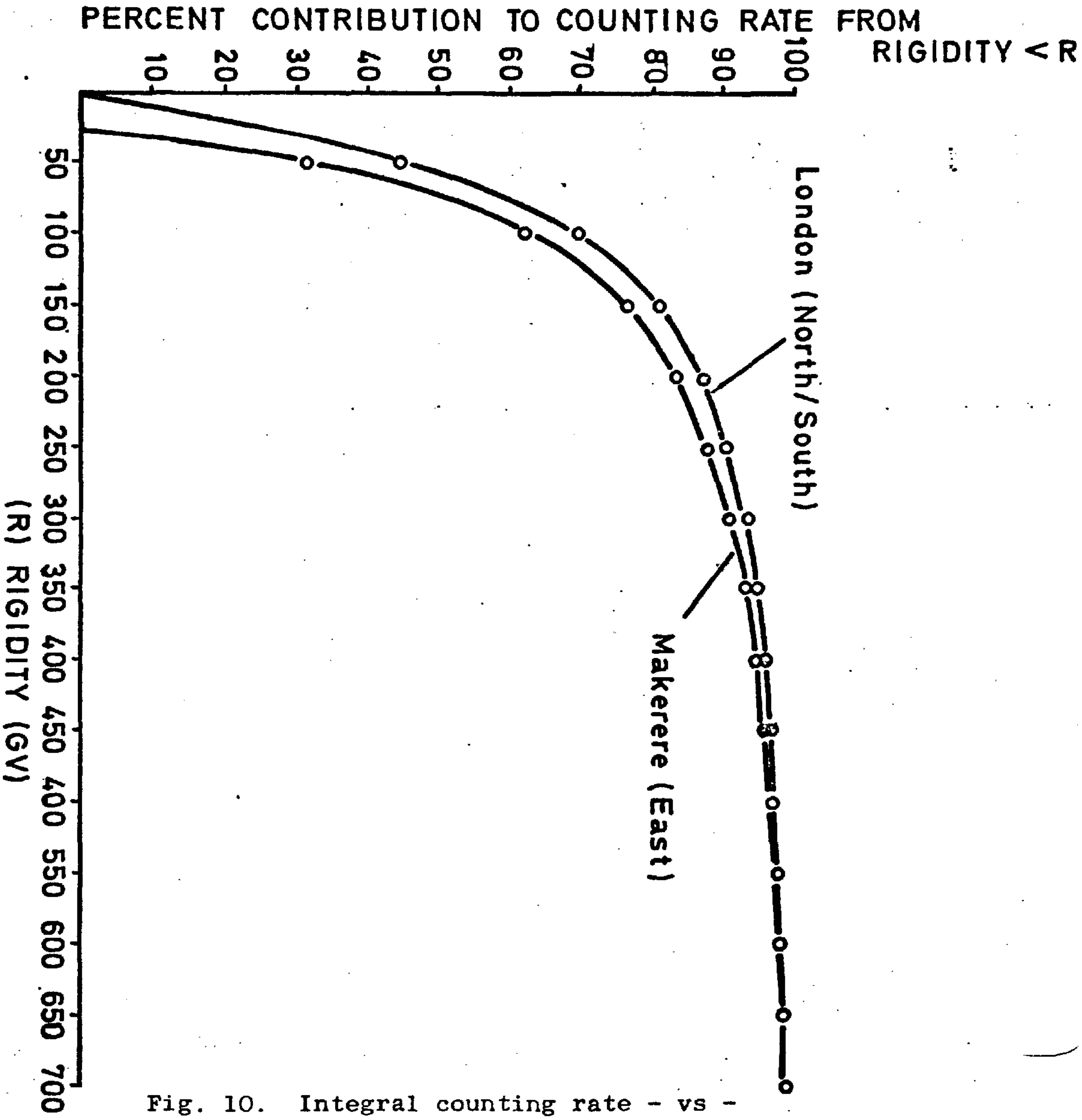


Fig. 10. Integral counting rate - vs - Primary rigidity for the directional recorders at London and Makerere.

2.4. 5 ENERGY CHARACTERISTICS

The counting rate of the meson telescopes is due to primary particles of different energies impinging at the top of the atmosphere. The contribution to the counting rate from different primary energy ranges is given by the DIFFERENTIAL RESPONSE FUNCTIONS for inclined telescopes described in Chapter I. These curves give the ratio of the number of particles recorded by the detector originally from primary particles of a given energy to the total counting rate of the detector.

With a knowledge of the differential response functions we can calculate several energy characteristics which are of interest. e.g. THE MEAN PRIMARY ENERGY will be given by:

$$R_{mean} = \int_{e_0}^{\infty} R\, W(R)\ dR \Big/ \int_{e_0}^{\infty} W(R)\ dR$$

Where W(R) is the response function of the detector. The integration is carried out from the Geomagnetic cutoff to very high energies till the response of the detector becomes negligible. This calculation has been carried out for the LONDON and MAKERERE recorders and the mean energy of response in these cases are presented in tabular form below. The lower limits of integration are also indicated.

Another important characteristic is the INTEGRAL COUNTING rate spectrum of the recorders. The figure 10 indicates the percentage contribution to the counting rate from particles of energy below a certain energy E against the energy E.

TABLE III

Station	Direction	Mean Primary Energy	Cutoff	% contribution below 100 Gv
London	North/South	101.74 Gv	3.5 Gv	70%
Makerere	West	107.00 Gv	13.0 Gv	68%
	East(16°)	114.65	19.0 Gv	65%
	East(24°)	118.5	21.0 Gv	65%
	East(32°)	123.78	25.0 Gv	62%

2.5 ERRORS OF MEASUREMENTS

The design of the apparatus made sure that no systematic errors arise in the data due to fluctuations in the mains voltage and laboratory temperature.

Any possible systematic differences existing between the telescopes due to slight differences in efficiency or geometry are taken care of by rotating the telescopes through 180° about a vertical axis at fortnightly intervals. As a check on the performance of the equipment, the daily variation data have been added together for each of the two telescopes operating at IMPERIAL COLLEGE, LONDON for a period of one year. Each telescope having spent the same length of time looking NORTH and SOUTH, any instrumental difference would be revealed as a difference between the average daily variation measured by the two counter sets. A harmonic analysed on the data thus averaged shows that the daily variation as obtained by the two recorders agrees within the limits of the errors. We can therefore safely conclude that any systematic difference due to instrumental defects is negligible.

Several statistical sources of error exist and are discussed below.

1) Errors due to the scaling factor.
The grouping of data in units of 100 will, according to Shepard, introduce an error of $100^2/12$ in the variance. The influence of this factor is negligible.

2) Errors due to the registration time.
The printers used for the recording of the data have a dead time of about 0.2 secs which may result in a loss of counts. However, since the scaled counting rate is about 0.25 counts/sec, this factor introduces only a negligible loss.

3) Chance coincidence.
The chance coincidence rate C is given in terms of the counting rates C_1 and C_2 of the two counters and the resolving time T of the coincidence system as:

$$C = 2 \cdot C_1 \cdot C_2 \cdot \tau$$

with the values of $15 \cdot 10^{2}$ counts / mt for C_1 and C_2 and about 70n secs for the resolving time of the coincidence unit the excess counting rate due to chance coincidence is negligible.

4) The accuracy of the data from the recorders is further limited by the inherent statistical fluctuations in the cosmic ray intensity. The counting rates of the detectors are normally assumed to have a Poissonian distribution. The spread about the mean is therefore given by $\sqrt{N}$ where N is the counting rate.

The errors on a mean daily counting rate are therefore .05% and those on a mean monthly and yearly values are .003% and .009% respectively. The statistical fluctuations on a mean monthly and yearly bihourly value sets a limit on the accuracy with which the daily variation can be measured.

The corresponding fluctuations for the case of the MAKERERE and the LONDON recorders have been presented in table II and are seen to be sufficiently small so that an accurate estimate of the diurnal and semi-diurnal variations can be made.

CHAPTER III

ATMOSPHERIC EFFECTS ON THE COSMIC RAY INTENSITY:

3.1. INTRODUCTION:

In order to separate out that part of the variation in the secondary cosmic ray intensity observed on the surface of the Earth which is induced by primary variations (these being of interest for an understanding of the way in which cosmic ray modulation is produced by interplanetary conditions), it is necessary to know how the various atmospheric factors control the secondary intensity, and to introduce suitable corrections to eliminate the variations of atmospheric origin.

A survey of the historical development of the subject of atmospheric effects on cosmic ray intensity will be given at first to gain an insight into the manner in which our understanding of the various atmospheric effects has progressed in the past few decades.

MYSSOWSKY and TUVIM (1928), first observed a negative correlation of the cosmic ray intensity with sea-level barometric pressure. COMPTON and TURNER (1935), using ionization chambers of improved design, were able to detect in addition to the barometric effect, a negative correlation with ground level temperature. BLACKETT (1938), interpreted the temperature effects as being the result of the finite life-time of the MU-MESON.

He also emphasized that it is the temperature up to the mean layer of meson production (16 km), rather than the ground level temperature which determines the temperature effects.

DUPERIER (1944), initiated a detailed study of the atmospheric effects of the hard and the total components of the secondary intensity, using methods of regression analysis. He pointed out that a direct correlation between cosmic ray intensity and pressure yields a regression coefficient that includes, in addition to the effects of mass absorption, decay effects due to the instability of the MU-MESON.

The height above sea-level, of a level of pressure B, is given in terms of the sea-level pressure B_o and the mean temperature T of the atmosphere up to B by,

$$H = (1 + aT)\,\mathrm{Log}(B_o/B) \quad \text{where} \quad a = 1/273.$$

Thus an increase in the S/L pressure will cause an increase in H even if the atmospheric temperature remains constant. This increase in the height of the mean layer of muon production will result in an increased probability of decay of the mu-mesons recorded at sea-level. Thus an increase of atmospheric pressure means that not only is the amount of absorber increased but the probability of decay is also increased.

DUPERIER (1944), therefore introduced the height of the mean layer of meson production as a second independent variable so that MUON decay effects could be separated. The regression equation can be written as,

$$dI/I = \beta_b \, dB + \beta_h dH$$

where I is the cosmic ray intensity, B the pressure at the observational level and H the height of a reference layer, which is assumed to be a mean production level for mesons. After an extensive investigation DUPERIER finally chose the 100 m.b. layer to be this level. Further investigations (DUPERIER (1949)), with shielded telescopes showed that it was necessary to include yet another temperature variable for a proper representation of the changes taking place in the cosmic ray intensity. This was the mean temperature of the layer between 100 m.b. and 200 m.b., which was assumed to be the level of meson production. The regression equation is now written as,

$$dI/I = \beta_b \, dB + \beta_h dH + \beta_t dT \, .$$

The regression coefficient corresponding to the last term was found to have a positive value and was interpreted as being due to a competition between $\pi - \mu$ decay and π capture, as described in Chapter I. Each of the regression coefficients obtained from the DUPERIER equation were thus taken to have a unique significance. The first term was thought to represent an effect of absorption, the second that of μ - e decay and the last that of competition between $\pi - \mu$ decay and π capture.

That such an assumption was erroneous was soon realized when DUPERIER (1951) found that the observed positive temperature effect was about three times the value expected on theoretical grounds.

Then TREFALL (1955, a,b,c), whilst attempting a theoretical interpretation of the barometer and decay coefficients, found by experimenters working with the DUPERIER model, showed that both the barometer and positive temperature coefficients have contributions resulting from second order $\mu - e$ decay effects.

TREFALL's chief conclusions may be summed up as follows:

1). The regression coefficient obtained by a two fold correlation analysis between cosmic ray intensity and barometric pressure yields a TOTAL BAROMETER COEFFICIENT that includes decay effects. This is so because there exists a systematic correlation between the barometric pressure and the height of the layer of meson generation.

2). The PARTIAL BAROMETER COEFFICIENT obtained by analysis using the height of an upper atmospheric isobar, where the decay effects have been apparently separated by the height variable, still includes a portion of these effects. This is a consequence of the fact that the mean life of relativistic particles is a function of their energy because of the phenomenon of relativistic time dilation. An increase in the sea-level pressure corresponds to an addition of absorber in the meson path and therefore to an increase in the energy loss by the meson. The survival probability of the mesons traversing the atmosphere will therefore go down and a decrease in mesons recorded at S/L will occur with an increase in pressure. This negative pressure effect will occur simultaneously with the mass absorption and the regression coefficient will include a component on this account. The contributions due to this effect may be as large as 1/2 of the pure mass absorption effect for S/L observations. A comparison between theory and experimental values leads to agreement only if this effect is included.

3). The main features of the positive temperature effect observed at surface level can be explained only by considering two second order effects of muon decay. a) The non-coincidence of the standard pressure levels normally taken to represent the mean layer of meson generation with the actual mean layer leads to an artificial temperature effect when the heights of these isobars are used as variables in the correlation analysis. The sign of the effect depends on the reference level used, being always positive for the 50 m.b. level and always negative for the 200 m.b. level. b) A redistribution of the air masses in the atmosphere causes a positive temperature effect. The survival probability of the mesons along a certain path will also depend on the way the absorber is distributed along its path because of the dependence of the life-time on energy. Thus if some of the absorber is transferred from the initial portion of the meson path to a latter portion an increase in survival probability will occur. Such a redistribution can arise as a result of temperature changes in the atmosphere. On the DUPERIER model it is assumed that the stratospheric temperature is independent of the pressure and height changes. Thus, if the stratospheric temperature increases and the pressure and height of the tropopause are to remain constant, in accordance with the model, the temperature of the lower atmosphere will decrease. As a result some air mass will be transferred towards the end of the path which in turn will result in an increase in the flux of the cosmic rays at sea-level. A positive correlation will thus be observed with the STRATOSPHERIC temperature.

Agreement between theory and experiment is obtained only if the above effects are invoked. Underground results, eg. MACANUFF (1954), may, however, be explained purely on the basis of the competition between $\pi - \mu$ decay and π capture, as the second order effects diminish to small values at high energies.

4). TREFALL's calculations for the decay effects due to changes in the height of the meson producing layer yield values of approximately 6-7%/km for sea-level measurements, compared to typical experimentally obtained values of 5%/km. This calculation however, invokes the use of a model atmosphere with constant Stratospheric temperature. The disagreement suggests a weakness in the model chosen.

MAEDA and WADA (1954), DORMAN (1957), MAEDA (1960), have approached the problem on a more general basis. Their procedure is based on a complete treatment of the diffusion processes of mesons in the atmosphere. On the basis of such a calculation DORMAN derived the temperature coefficient as a function of atmospheric depth. His final results for the atmospheric effects may be expressed as:

$$dI/I = \beta_b \, dB + \int_0^{h_0} W_t(h) \, dT(h) \, dh$$

where dI/I is a fractional change in the counting rate due to a change dB in pressure at the observational level and changes dT (h) in the atmospheric temperature at different heights h above the observational level. $W_t(h)$ is known as the density of temperature coefficient and gives the change in intensity due to a 1°C variation in air temperature at a depth h. The integral has to be evaluated from the top of the atmosphere to the observational level h_o.

DORMAN's chief findings may be summarized below:

1). The temperature effects in the atmosphere as expressed in terms of the density of temperature coefficients $W_t(h)$ are a combination of two effects of opposite sign. Thus,

$$W_t(h) = W_t(h)_\pi + W_t(h)_\mu$$

2). $W_t(h)_\pi$ is due to a competition between $\pi - \mu$ decay and π capture and is appreciable only in the upper atmosphere (250 m.b. or above) and vanishes at about 500 m.b.

3). $W_t(h)_\mu$, the component due to the unstable nature of the μ mesons, is also highest in the upper layers of the atmosphere, but decreases only by about 50%, even for layers deep in the atmosphere (1000 m.b.), for the case of S/L measurements. For observations deep underground, however, $W_t(h)_u$ is appreciable only in the upper-most layers of the atmosphere.

4). With increasing energy of the recorded particles, $W_t(h)_u$ decreases whilst $W_t(h)_\lambda$ increases. As a result, while the total temperature effect is negative throughout the atmosphere for S/L observations, that observed at even moderate depths underground (55 m.w.e.) is large and positive in the upper layers of the atmosphere and low and negative in the lower atmosphere.

5). DORMAN also pointed out that the DUPERIOR method for correcting the intensity of the hard component using the height of an upper atmospheric isobar is equivalent to the adoption of an arbitrary density of temperature coefficient. For S/L observations the DUPERIER coefficient is very much larger than the Dorman value in the upper-most layers of the atmosphere and slightly lower than the Dorman value in the lower atmosphere. This difference is due to the fact that the DUPERIER method does not take into account that the meson generation processes are in fact spread over the atmosphere (the blurring of the generation layer) and that there is a contribution to the temperature effect from the mass redistribution in the atmosphere. The first factor gives undue weight to the upper atmospheric layers and increases the temperature effect in the upper atmospheric region. Neglect of the second factor results in too small a value for the lower atmosphere.

Dorman's temperature coefficients are available for different cases of recording at S/L and underground. In a practical application of the Dorman method the integration is replaced by a summation of the type,

$$dI/I = \sum_i k_i \, dT_i$$

where dT_i is the change of temperature at the ith standard isobaric level, k_i is a weighting factor which is actually the integral of $W_t(h)$ for the ith level. For S/L observations the summation is carried over 11 standard isobaric levels from 1000 m.b. to 30 m.b.

MAEDA has extended Dorman's calculation to zenith angles other than the vertical and has considered effects due to the curvature of the isobaric levels and the curvature of the path of the mesons in the Geomagnetic field. His values are slightly smaller (12%) than Dorman's.

3.2 METHODS OF ANALYSIS:

Though Dorman's results rest on a more sound physical basis than the empirical given by Duperier, they have been based on certain assumptions regarding the behaviour of the atmosphere, the nature of the high energy interactions which produce the secondary particles observed at S/L and the subsequent interactions of these particles with the atmosphere. (Thus eg. Dorman has assumed a certain temperature distribution in the atmosphere in which the temperature is assumed to decrease linearly from sea-level to the 200 m.b. level and then to remain constant above this layer. It has also been assumed that the PION attenuation length is just twice its interaction length, i.e. has a value of 120 gm-cm^2). The inadequacy in our knowledge of the parameters, invoked for the calculation of the density of temperature coefficients leads an element of uncertainty to the result. In fact a different choice of these parameters as used by MAEDA actually lowers the integral effect, throughout the atmosphere, by about 10%.

Experimental tests carried out by MATHEWS (1959), LINDGREN and LINDHOLM (1960), etc. seem to indicate that the temperature coefficients as given by Dorman have been overestimated by about 25%. These results compare the cumulative effect of the atmospheric variations as given by theory and say nothing about the way in which the temperature effects are distributed in the atmosphere.

An important result of the Dorman theory is that it predicts a uniform distribution of the temperature effects throughout the atmosphere. Lindgern and Lindholm (1960) have attempted to test the shapes of the Dorman curve throughout the atmosphere.

They find that the temperature effect is about twice as great as that given by Dorman for the upper atmospheric layers, (greater than about 300 m.b.) while it is considerably smaller than Dorman's prediction in the lower atmosphere. Though nothing definite could be said for the intervening layers, because of large errors, the values obtained for the upper and lower regions of the atmosphere seemed to favour the dependence implicit in the Duperier method, where the upper atmosphere is assumed to play the dominant role in determining the temperature effect on the meson intensity. Though several other attempts have been made to perform a similar test on the Dorman temperature coefficients eg. WADA (1961), EHMERT (1959), etc., it was not possible to draw any reliable conclusions since most of the analyses were restricted to short periods and the errors were consequently rather large.

In view of these results it appears that the accuracy to be attached to the temperature coefficients given by Dorman may not be better than 25%. The shape of the Dorman curve too seems to be uncertain. It appears desirable therefore that a reliable experimental test be performed which can establish the magnitude of the temperature effect throughout the atmosphere.

We have accordingly used data from two cubical telescopes, inclined at 45° to the zenith, pointing in the NORTH/SOUTH directions, operating in London, to examine the Dorman curve and establish the temperature effects in the atmosphere. We find that the errors on the mean temperature coefficients over the period of analysis are reasonably small so as to make it possible to draw reliable conclusions with regard to the distribution of the temperature effects in the atmosphere. Since the telescopes do not contain any lead absorber, they will record both the hard and the soft components of the secondary intensity. However a considerable amount of the soft component will be filtered out due to the fact that the telescopes look through rather thick concrete walls. The intensity actually recorded will therefore be a combination of the hard component together with a small portion of the soft component. Effects of the inclusion of this portion of the soft component on the temperature coefficient will be taken into account.

The data has also been analysed by two modifications of the Duperier method often used in practice as suggested by Mathews (1959) and WADA (1961). A comparison of the Dorman and Duperier type methods has been attempted by comparing the goodness of fit obtained with the variables used in the different cases. The criteria of the goodness of fit are the multiple correlation coefficients obtained by the different procedures.

Atmospheric coefficients obtained by both type of procedures have been used to correct the daily mean intensities as recorded by the telescopes and the effectiveness of the two methods to remove the variability introduced in the data because of atmospheric variations, is compared. Analysis by the Dorman and Duperier type procedures is described below in separate sections.

3.3 REDUCTION OF LONDON DATA:

3.3.1 DORMAN TYPE ANALYSIS

Since according to Dorman the temperature effects on the mesons are distributed throughout the atmosphere, the technique employed is to divide the atmosphere into a number of characteristic regions. The temperature effects in each of these regions are determined by methods of regression analysis. In such a procedure the number of layers into which the atmosphere is to be divided is a problem. The greater is the number of layers the more accurate is the functional form of the coefficient against depth. On the other hand, however, because of the greater correlation between the temperatures of neighbouring layers errors on the regression coefficient will become large. Moreover, the complexity of the correlation analysis will increase greatly with an increase in the number of the independent variables. A compromise has therefore to be made.

An examination of the Dorman temperature curve for a S/L recorder shows that the temperature effects are more or less uniform throughout the atmosphere. We have therefore divided the atmosphere into three layers. The topmost layer extends from 100 m.b. to 400 m.b. and is characteristic of the uppermost regions of the atmosphere. The middle layer extends from 400 m.b. to 700 m.b. and is supposed to give the effect of the middle region of the atmosphere. The Dorman curve is very flat in this region of the atmosphere. The bottom layer is taken from 700 m.b. to 1000 m.b. and is representative of the lowermost regions of the atmosphere. The layer above 100 m.b. was omitted because temperature data for regions above this level are not available regularly. Such a procedure however means that the three layers are made to share the contributions for this layer to the intensity variations.

In each layer the temperatures of the composite isobaric levels have been weighted so as to give maximum weight to the middle of each layer. These weighted mean temperatures, along with the barometric pressure form the variables of correlation.

The regression equation used is;

$$dI/I = \beta_b \, dB + \sum \beta_i \, dT_i$$

where I is the recorded daily mean intensity.

B is the barometric pressure at KEW about ten miles from the cosmic ray recorders.

T_i are the temperature variables corresponding to the 3 atmospheric layers.

The temperatures corresponding to the various isobaric levels were obtained from twice daily (00.00 G.m.t. and 1200 G.m.t.), radio sonde balloon ascents from CRAWLEY about twenty-five miles from the recording station. For each of the variables daily centred on midday were calculated and used for correlation analysis. Days on which the cosmic ray intensity showed anomalous variations of primary origin were excluded from the analysis.

Day to day correlation analysis was performed for about 45 fortnightly batches for each direction over the period Aug. 1965 to Dec. 1967. It was convenient to analyse the data in fortnightly rather than monthly batches because the recorders were turned about a vertical axis through 180° at fortnightly intervals. (This was done to smooth out possible systematic errors from the daily variation.)

The average regression and correlation coefficients for the whole period of analysis have been calculated and are given in table 1. The errors have been calculated from the scatter of the individual results about the mean over the period. The means listed in the table have been obtained from the individual points after weighting each point by $1/s^2$ where s is the error on an individual point. The calculation of the error s from the scatter of the points enables an independent estimate to be made of this quantity, since the errors given by correlation theory are effected by the intercorrelation of the variables.

An examination of table 1 shows that the errors on the mean temperature coefficients for the three layers are of such a magnitude that reliable estimates may be made of the temperature effect. A detailed comparison of the regression coefficients calculated here with the theoretical values will be given in section 3.4.3.

TABLE 1

a) REGRESSION COEFFICIENTS:

CHANNEL	B_{IP}(%/m.b.)	B_{IT1}(%/^{o}C atm)	B_{IT2}	B_{IT3}
NORTH	-0.1906 ±0.0038	-0.1485 ±0.044	-0.256 ±0.037	-0.305 ±0.060
SOUTH	-0.182 ±0.0034	-0.127 ±0.046	-0.286 ±0.042	-0.291 ±0.062

b) CORRELATION COEFFICIENTS:

CHANNEL	r_{IP}	r_{IT1}	r_{IT2}	r_{IT3}
NORTH	-0.927 ±0.012	-0.201 ±0.051	-0.360 ±0.035	-0.273 ±0.055
SOUTH	-0.945 ±0.010	-0.134 ±0.051	-0.425 ±0.038	-0.226 ±0.061

The regression coefficients obtained from the 45 batches have been averaged over three monthly periods for the two telescopes and are given in table 11. The averages have been calculated with a view to detect any seasonal dependence in the temperature coefficients which may result from differing amounts of inter-correlation between the variables used in the analysis or from a seasonal variation in the mean temperature of the atmosphere.

TABLE II

SEASONAL VARIATION OF REGRESSION COEFFICIENTS (3-T method).

MONTHS	B_{IP}(%/m.b.)	B_{IT1}(%/°C-Atm)	B_{IT2}	B_{IT3}
a) CHANNEL NORTH:				
Aug-Sep-Oct	-0.1876 ±0.006	-0.160 ±0.095	-0.287 ±0.102	-0.332 ±0.141
Nov-Dec-Jan	-0.193	-0.214 ±0.079	-0.308 ±0.065	-0.524 ±0.104
Feb-Mar-Apr	-0.1938	-0.114 ±0.089	-0.180 ±0.037	-0.247 ±0.096
May-Jun-Jly	-0.187	-0.124 ±0.074	-0.251 ±0.049	-0.015 ±0.078
b) CHANNEL SOUTH:				
Aug-Sep-Oct	-0.178	-0.086 ±0.082	-0.389 ±0.102	-0.279 ±0.125
Nov-Dec-Jan	-0.183	-0.063 ±0.096	-0.363 ±0.052	-0.399 ±0.131
Feb-Mar-Apr	-0.191	-0.132 ±0.110	-0.181 ±0.060	-0.309 ±0.106
May-Jun-Jly	-0.179	-0.150 ±0.063	-0.287 ±0.057	-0.040 ±0.092

3.3.2. DUPERIER TYPE ANALYSIS.

Two modifications of the Duperier method, which are known to give better results than the original method, (WADA (1961), MATHEWS (1959)), have been used to investigate the atmospheric effects on the S/L intensity at LONDON. a) WADA (1961), has suggested that the difference of the height of the 100 m.b. and 1000 m.b. layers replace the height of the 100 m.b. layer as a variable of correlation in analysis based on the Duperier equation. Since this distance varies with the temperature of the layer between the isobaric levels chosen, regardless of the pressure changes, the condition that the temperature distribution is independent of pressure can be approximately satisfied. WADA also finds that the barometer coefficient thus obtained displays a stability with respect to the choice of the upper isobar, a factor which the ordinary barometer coefficient, obtained by means of a straight forward correlation analysis using the height of the 100 m.b. level from the ground, lacks.

The regression equation used was,

$$dI/I = \beta_b\, dB + \beta_h\, dH + \beta_t dT$$

where I is the cosmic ray intensity, B the barometric pressure, H the difference in heights of the 100 m.b. and the 1000 m.b. layers and T is the mean temperature of the atmospheric layer between 200 m.b. and 70 m.b. The pressure and atmospheric temperature and height data were obtained as before from KEW and CRAWLEY respectively.

Daily means centered at midday were evaluated for all the variables and regression and correlation coefficients were calculated by means of the equation above. Day to day correlation analysis was performed for 45 batches of about 15 days each. Averages of the regression and correlation coefficients over the period of the analysis are given in Table III. As before the errors have been evaluated from the scatter of the points about the mean. The mean values listed have been weighted by $1/s^2$, s being the error on an individual point

TABLE III

a) REGRESSION COEFFICIENTS:

CHANNEL	B_{IP} (%/m.b.)	$B_{IT(200-70m.b.)}$ (%/°C)	$B_{IH(1000-100m.b.)}$ (%/Km)
NORTH	-0.1896 ±0.0039	+0.0538 ±0.0106	-3.30 ±0.410
SOUTH	-0.1821 ±0.0037	+0.0578 ±0.0083	-3.30 ±0.470

b) CORRELATION COEFFICIENTS:

CHANNEL	r_{IP}	r_{IT}	r_{IH}
NORTH	-0.935 ±0.010	+0.387 ±0.054	-0.527 ±0.050
SOUTH	-0.941 ±0.011	+0.473 ±0.045	-0.474 ±0.063

b) The other modification of the Duperier method used here is the one suggested by Mathews (1959). An objection often levelled against the Duperier method is that it gives too much weight to the upper atmospheric layers and insufficient weight to the lower atmosphere. Mathews meets this criticism by including the temperature of a layer in the lower atmosphere as a variable of correlation. This tends to give greater weight to the lower atmosphere. The 800 m.b. layer is often used for this purpose.

The regression equation used in this case may be written as:

$$dI/I = \beta_b \, dB + \beta_h \, dH + \beta_t \, dT.$$

where T represents the temperature of the 800 m.b. layer and the other variables have the same meaning as the earlier equation.

The correlation analysis has been carried out for 18 months up to Feb. 1967 in 36 fortnightly batches. The averages for the correlation and regression coefficients and their errors, calculated as before are given in table IV.

TABLE IV

a) REGRESSION COEFFICIENTS:

CHANNEL	B_{IP} (%/m.b.)	B_{IT} (800 m.b.) (%/°C)	$B_{IH(1000-100\ m.b.)}$ (%/km)
NORTH	-0.197 ±0.005	-0.059 ±0.011	-2.3 ±0.068
SOUTH	-0.194 ±0.0038	-0.054 ±0.0094	-3.0 ±0.059

b) CORRELATION COEFFICIENTS:

CHANNEL	r_{IP}	r_{IT}	r_{IH}
NORTH	-0.945 ±0.012	-0.372 ±0.053	-0.336 ±0.073
SOUTH	-0.956 ±0.009	-0.374 ±0.059	-0.384 ±0.068

3.4. DISCUSSION:

The results obtained in the preceding section will now be compared with those obtained by other workers and those expected from theoretical calculations as given by WADA (1961), TREFALL (1955) and DORMAN (1957).

3.4.1. THE BAROMETER COEFFICIENT. (comparison with theory).

WADA (1961), has shown that the barometer coefficient obtained by regression analysis in which the difference in heights of the 100 m.b. and 1000 m.b. layers is used as a variable, is the TOTAL BAROMETER coefficient, as opposed to the PARTIAL BAROMETER coefficient obtained when simply the height of the 100 m.b. is used for the height variable. The analysis described above where the temperatures of three atmospheric layers are used to describe the temperature effects on the cosmic ray intensity, also gives the total barometer coefficient. The pressure coefficients obtained by the different methods described above are therefore directly comparable. Within the limits of the errors quoted in tables I, III and IV, the three values agree with each other. The values of the pressure coefficients for both the NORTH and the SOUTH directions also appear to be the same within the limits of error. A mean value of 0.186%/m.b. has therefore been adopted to represent the mean total barometer coefficient for both directions.

WADA (1961), has extended Trefall's calculation for the total barometer coefficient to include the effect of contributions from inclined directions. We shall use his results to compare the barometer coefficient obtained in our case.

The barometer coefficient for a S/L meson detector consists of two parts, one due to mass absorption in the atmosphere and the other due to decay effects of the u meson. Thus,

$$\beta_{tot} = \beta_{abs} + \beta_{dec}$$

The decrease in µ meson intensity due to absorption for mesons coming at an angle θ to the vertical may be written as;

$$\beta_{abs} = -\,(n(p_c,\theta)/N(p_c,\theta))\ dp_c/\,dB$$

where $n(p_c,\theta)$ and $N(p_c,\theta)$ are the differential and integral intensities at an angle θ to the vertical. (The path length of the mesons and therefore the amount of absorber is increased for inclined paths through the atmosphere.)

The contribution from µ - e decay can be calculated quite readily on the assumption that an increase in S/L pressure means that the whole atmosphere is lifted a certain distance dH upwards. This will result in a change in the survival probability of the mesons and therefore a change in the intensity of these mesons as recorded at S/L. The effect may be represented in terms of the differential momentum spectrum of the mesons as follows:

$$\beta_{dec} = \frac{mu}{\rho x\,\tau c} \int_{p_c}^{\infty} \frac{n(p_u,\theta)}{p_u}\ dp_u \Big/ \int_{p_c}^{\infty} n(p_u,\theta)\ dp_u$$

where p_c represents the cutoff momentum of the recorder

$\rho(x)$ the density of air at a depth x (gm-cm^2),

m_u, p_u the muon momentum and rest mass respectively,

τ the proper life of the µ - meson.

A knowledge of muon spectra is thus required for a calculation of the barometer effect. WADA has used the muon spectra given by ROSSI (1948) in the vertical direction and OZAKI (1959) for a direction at about 68° to the vertical. Using these results he has obtained the spectra at 30° and 60° to the vertical by interpolation. Using these values for the muon spectra he has then calculated the absorption and decay components of the barometer effect as a function of the cutoff momentum of the recorder for 30° and 60° to the vertical. The net effect has also been calculated. The barometer coefficient for a particular detector may be obtained by integrating the contributions from different zeniths over the polar diagram of the detector. WADA gives the barometer coefficient for the I.G.Y. type meson detector, located at a medium latitude to be -0.165%/m.b.

The coefficient obtained from the present analysis is -0.186%/m.b. and is significantly higher than the theoretical value. This high value obtained may be explained by including possible contributions from the soft component. Since no lead absorber has been used the telescopes monitor the total ionizing component of the cosmic radiation, which normally includes a contribution of about 25% from the soft component, at S/L.

We may estimate the contribution from the soft component to the counting rate observed with the LONDON telescopes in an approximate manner by comparing the experimentally observed value of the

Barometer coefficient with that given by theory and using the known value for the soft component Barometer coefficient.

Several workers, eg. TRUMPY (1958), DAWTON and ELLIOT (1953), HYNDS (1961), have studied the atmospheric effects of the soft component. The values that they obtain for the barometer coefficient agree within the limits of error and an average value may be taken to be -0.35%/m.b.

The contribution, X, from the soft component may now be obtained from the equation

$$0.35\ X + 0.165\ Y = 0.186\ (X + Y).$$

where Y is the percent contribution from the hard component. From this we obtain the following values for the hard and the soft components

$X = 12\%$, $Y = 88\%$.

An estimate of the uncertainty on the percentages calculated above may be made from the errors on the regression coefficients and is found to be of the order of ±4%.

The estimate of the soft component obtained above, viz 12 ± 4%, though lower than the normal estimate of 25%, appears to be reasonable since the North/South telescopes look through rather thick concrete walls. The absorber for inclined paths especially will be considerable and will attenuate the soft component.

3.4.2. COMPARISON WITH EARLIER RESULTS.

Several workers have studied the atmospheric effects on the total component of the cosmic radiation usually using a procedure based on the Duperier method. It will be interesting to compare the results of the present analysis with those obtained by them. However, while doing this comparison it should be remembered that the telescopes in the present experiment have a smaller contribution from the soft component than is normally obtained as has been shown in the previous section. This will tend to lower the value of the barometer coefficient. It may also be pointed out at this stage that the results obtained in the present experiment are for inclined observations whereas those of the other workers to be described below are for the vertical direction. To facilitate comparison, earlier results of the total component are presented along with those obtained here in a table (No. V) below. The variables used in the correlation analysis have also been listed. An examination of this table shows that all the other results quoted have been obtained by a correlation analysis using the height of the 100 m.b. layer rather than the difference in heights of this layer from the 1000 m.b. layer. The corresponding barometer coefficients listed are therefore Partial barometer coefficients as defined by Trefall. The barometer coefficients obtained in the present case, as explained earlier, are the Total barometer coefficients.

An examination of the table shows that the value obtained for the total barometer coefficient in our case is equal to that of the

Partial barometer coefficient obtained by other workers. This apparent discrepancy is resolved if we remember that we are monitoring only about half to 2/3rds of the contribution from the soft component normally present, because of the concrete absorber in the viewing angle of our telescopes.

EKSTROM (1966), has recently carried out a study of the atmospheric effects of the total component at a high latitude station. He finds a value of -0.20%/m.b. for the total component barometer coefficient. Ekstrom estimates the value of the cut-off momentum of his recorders to be 15MeV. A comparison with the present value shows that Ekstroms value is higher than in our case. In the present set-up the cut-off momentum may be taken to be about 70 - 100MeV, because of the concrete roof over the recorders. The increased absorber attenuates the contribution from the soft component and lowers the value of the pressure coefficient.

A comparison with the height and temperature coefficients obtained earlier shows that our values agree with those of other workers. WADA has in fact shown that the height coefficient obtained when the difference of the heights of the 100 m.b. and 1000 m.b. is used as a variable of correlation is directly comparable with the height coefficient ordinarily obtained with the height of the 100 m.b. layer as a variable of correlation. Our results thus confirm his findings.

TABLE V:

WORKERS	VARIABLES USED	B_{IP} (%/m.b.)	B_{IH} (%/km)	B_{IT} (%/°C)
DAWTON and ELLIOT (1953)	$B, H_{100} T_{100}$	-0.184±0.013	-3.02±0.4900	+0.054±0.01
TRUMPY and TREFALL (1953)	$B, H_{100} T_{100-200}$	-0.190±0.007	-3.[illegible] ± 0.50	+0.050±0.020
TRUMPY (1954)	$B, H_{100} T_{100-200}$	-0.196±0.007	-3.68±0.41	+0.028±0.011
PRESENT (1968)	$B, H_{100-1000}$, T_{200-70} m.b.			
a) CHANNEL NORTH		-0.1896±0.0039	-3.30±0.410	+0.0538±0.0106
b) CHANNEL SOUTH		-0.1821±0.0037	-3.30±0.470	+0.0578±0.0083

3.4.3. EXAMINATION OF THE DORMAN TEMPERATURE CURVE.

Dorman's density of temperature coefficients giving the change in intensity due to a 1°C change in temperature at a particular depth h, are available as a function of atmospheric depth and for four different zenith angles of incidence. The total effect to be expected for any experimental set-up may be obtained from these curves by integrating over the directional intensity patterns of the recorder. Curves giving the total density of temperature coefficient as a function of atmospheric depth, for an I.G.Y. type vertical meson telescope, have been published by DORMAN and those for a cubical telescope inclined at 45° to the vertical have been obtained by us in the manner described. The two curves are shown in figure 1.

The chief feature of the curve is its flat shape throughout the atmosphere, which suggests that the contribution to the temperature effect /°C variation of temperature is almost equal throughout the atmosphere.

Regression coefficients obtained by the analysis described earlier (in section 3.3) are plotted at positions corresponding to the centres of the three atmospheric layers into which the atmosphere had been divided. It is obvious from the figure that the temperature effect as obtained in the present experiment, agrees with that obtained by Dorman for the upper and middle regions of the atmosphere. In the lowermost region corresponding to the layers between 700 m.b. and 1000 m.b. there is a tendency for the temperature effect to be smaller than that predicted by Dorman. It is also to be noted that the error tails are of such a magnitude that reliable agreement with Dorman's curve can be established in the upper and the middle regions of the atmosphere. However, EKSTROM (1966) has recently carried out an examination of the Dorman temperature curve in a similar manner, using one years data from inclined and vertical meson telescopes. The telescopes record the total component of the C.R. intensity. EKSTROM finds that the temperature effects observed in the upper and the middle regions of the atmosphere are almost equal and within the limits of errors are the same as those predicted by Dorman. There is no evidence of a high temperature effect in the upper atmosphere as reported by Lindgren et. al.

In the lowermost regions of the atmosphere, however, the value is smaller than the Dorman prediction. These results compare very favourably with those obtained by us.

It has thus been observed that the Dorman calculations succeed in predicting temperature effect in the upper and middle regions of the atmosphere, while there appears to be an apparent discrepancy in the lower atmosphere. It is however possible to explain the lowering of the temperature coefficient in the lower atmosphere from the theoretically expected value, in a qualitative way, by considering the contributions from the soft component, which will be present both in Ekstrom's case and in ours.

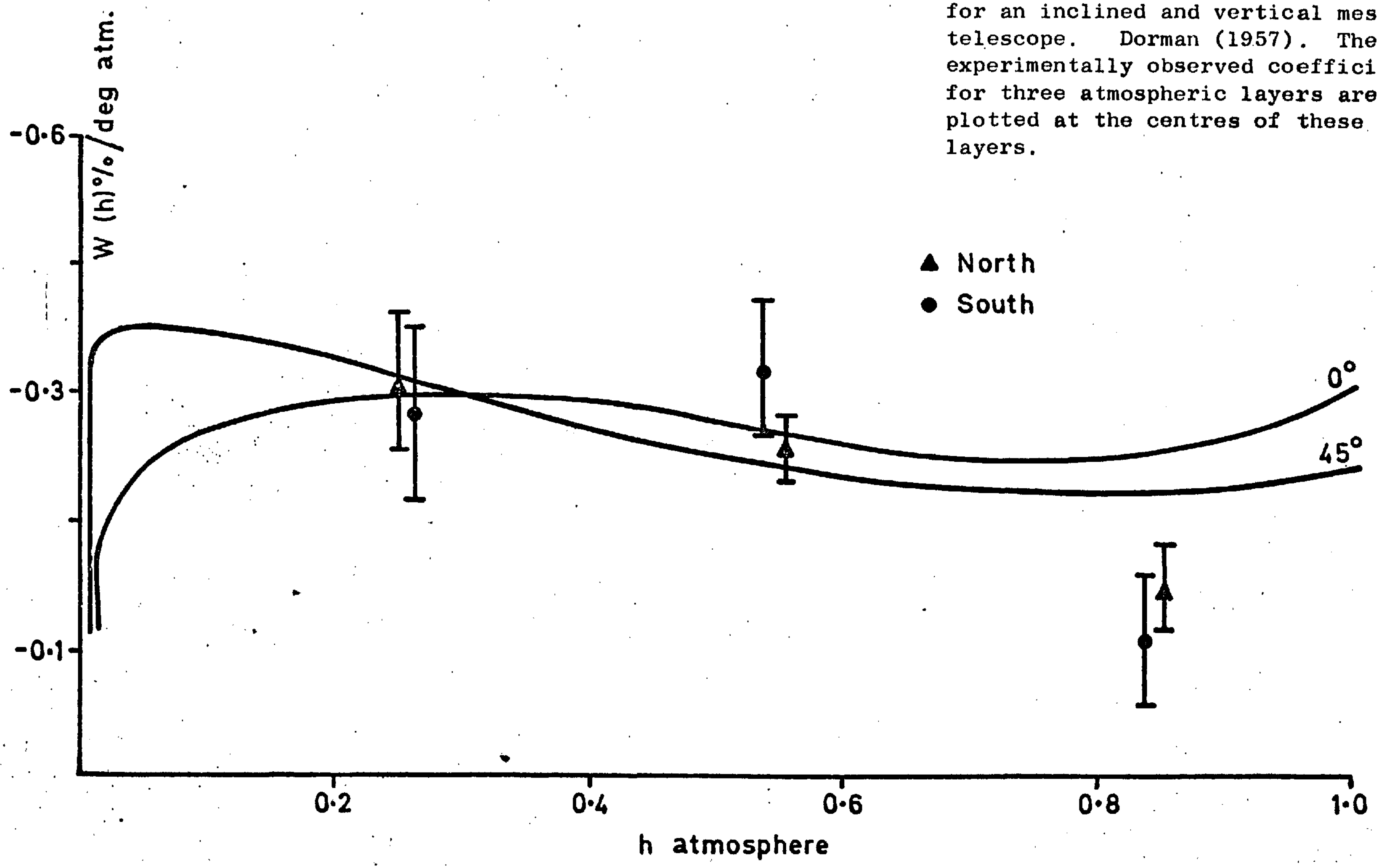
The soft component at S/L consists mainly of the so called EQUILIBRIUM PORTION of electrons and also has a small contribution (10% of the soft component) from the soft μ mesons. The equilibrium portion of the soft component consists of electrons resulting from the decay of the μ mesons and those from the passage of these mesons in the atmosphere (the so called δ-electrons).

The atmospheric effects of the soft component have been investigated by Dorman and he has described the nature of these effects for the composite parts of the soft component. Dorman finds that the soft component exhibits the usual barometer effect with a coefficient of about -0.35%/m.b. There are two components to the temperature effect. Firstly the soft component repeats the variations of the μ-mesons. There is however an additional positive temperature effect associated with the decay electrons. The net temperature effect for the soft component is small over the atmosphere. However the soft component exhibits a positive correlation with the surface temperature, with a coefficient of about +0.15%/°C.

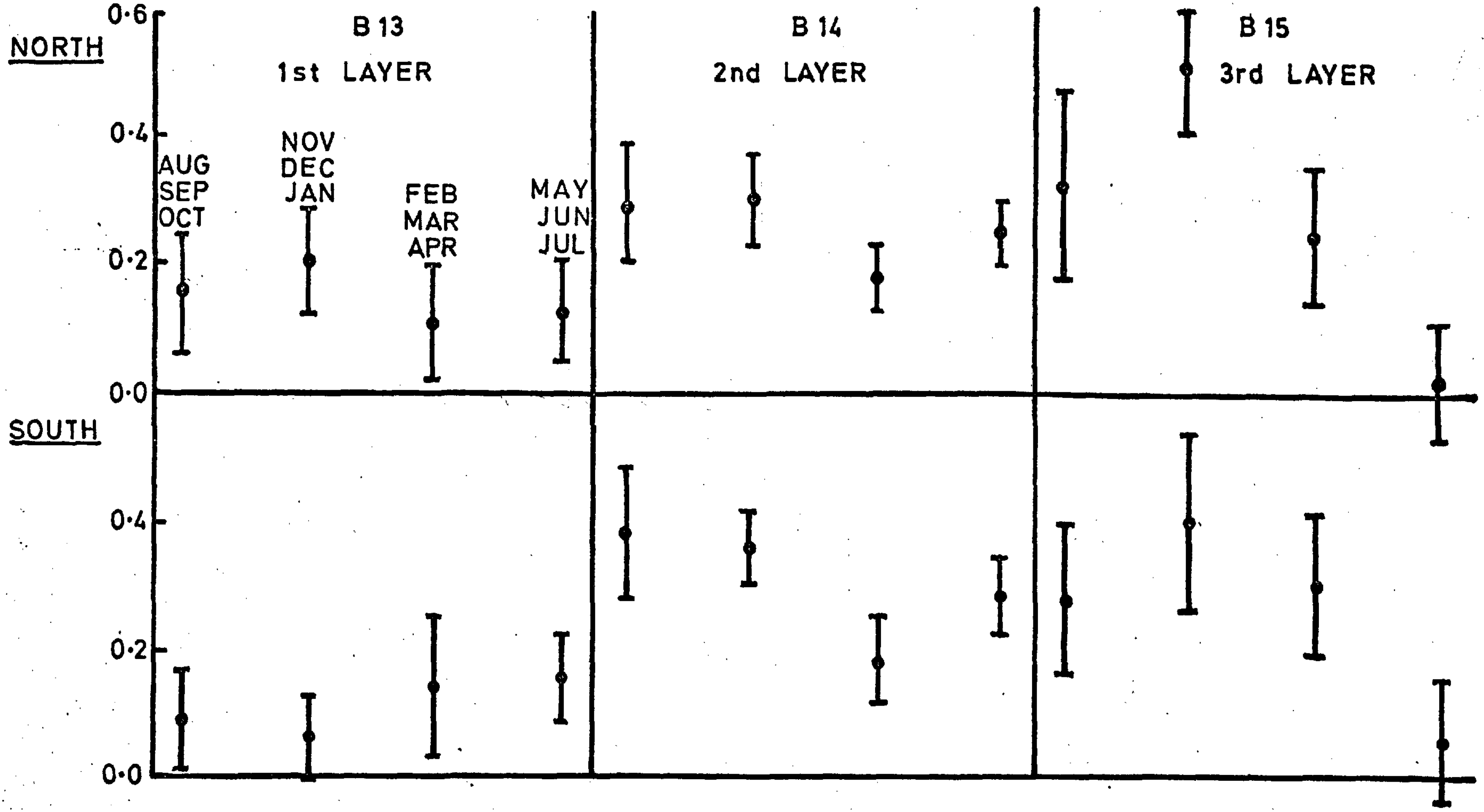
In the present analysis the temperature of the 1000 m.b. layer has been used to construct the temperature variable for the lower atmosphere. Therefore this positive temperature effect will tend to offset the negative temperature effect due to the μ mesons and a correlation of the intensity with the temperature variable corresponding to the lower atmosphere will result in a smaller value for the negative temperature coefficient. It is not possible to estimate the actual lowering of the negative temperature effect from the surface positive temperature effect exhibited by the soft component in a straight-forward manner, because of the fact that the negative temperature coefficient is a density of temperature coefficient, giving the temperature effect as a function of depth, while the positive coefficient applies only to the temperature of a single level, viz. that of the ground. The reasoning employed here however does give a qualitative explanation of the low temperature coefficient in the lower atmosphere. A direct confirmation, however, can only be made by studying the temperature effect after excluding the soft component by including 10 cms of lead in the recorders. Such a confirmation has, however, not been carried out by us.

As mentioned in section 3.3.1., we have investigated any possible

Fig. 1. Density of temperature coefficients for an inclined and vertical meson telescope. Dorman (1957). The experimentally observed coefficients for three atmospheric layers are plotted at the centres of these layers.



SEASONAL VARIATION IN TEMPERATURE COEFFICIENTS "DORMANS METHOD" FIG. 1-A



seasonal variation in the temperature coefficients. The results have been presented in Table II and the coefficients are plotted in Fig. 1-A. An examination of this figure shows that in view of the errors no large seasonal variation in the temperature coefficient is evident for the lower and the middle regions of the atmosphere. However there is a slight tendency for the temperature coefficient in the topmost region of the atmosphere to have a lower value in the summer months MAY, JUNE, JULY as compared to the winter months NOV., DEC., JAN. It is not possible to resolve the values for the intervening months in view of the large errors.

3.4.4. Comparison of the Dorman and Duperier type correction procedures:

From the experimentalists point of view the primary aim of a study of the atmospheric effects is to find a suitable way by which the most reliable correction can be affected in the cosmic ray intensity for variations of atmospheric origin. In this section we shall accordingly use the results obtained earlier to attempt to establish whether the use of the Dorman type equation, in which the temperature distribution throughout the atmosphere is considered to be relevant while attempting a correction for atmospheric variations, does in fact lead to any significant improvement on the case represented by the Duperier type methods where the temperature of certain represented levels is considered sufficient to account for the atmospheric variations.

Mathews (1959), has advocated the use of the multiple correlation coefficients, an index of the combined effectiveness of all terms of the regression equation, for comparison between different methods. Accordingly multiple correlation coefficients were evaluated for each month of analysis along with the regression and correlation coefficients, for all three methods of analysis employed. The mean values of the multiple correlation coefficients for the 2-year period of analysis are given in a tabular form below. (Table VI).

TABLE VI

MULTIPLE CORRELATION COEFFICIENTS:

CHANNEL	DORMAN	DUPERIER	MATHEWS
NORTH	0.9821	0.9778	0.9750
SOUTH	0.9856	0.9790	0.9790

An examination of this table shows that the multiple correlation coefficient is in fact higher for the method based on the Dorman type analysis where the temperatures of three atmospheric layers have been used for representing the temperature effects. It therefore appears that the three-temperature layer method based on the Dorman reasoning, does in fact lead to a better fit among the variables than the Duperier type methods.

The variability of the secondary cosmic ray intensity is due to a variability of the primary intensity together with that due to atmospheric effects. It is the function of the different correction procedures to remove the variability due to atmospheric effects.

TABLE

SCATTER ON UNCORRECTED DATA: (DAILY MEANS):

NORTH	1.83%
SOUTH	1.80%

SCATTER ON PRESSURE CORRECTED DATA:

NORTH	0.54%
SOUTH	0.55%

SCATTER ON TEMPERATURE AND PRESSURE CORRECTED DATA:

NORTH	0.35%	
SOUTH	0.34%	(3 - TEMP LAYER METHOD.)
NORTH	0.41%	
SOUTH	0.40%	(DUPERIER METHOD)
NORTH	0.39%	
SOUTH	0.38%	(MATHEWS METHOD)

Thus a valid criterion for distinguishing between different methods of correction for atmospheric effects would be to consider the effectiveness of the three methods to remove the variability due to atmospheric variations from the data.

We have accordingly corrected the daily mean intensities as obtained from the telescopes operating in London for atmospheric variations by using the atmospheric coefficients obtained in section 3.3. One year's data has been used for this purpose (1966).

The standard deviation of the daily mean values, a measure of the variability of the data, has been calculated on a month by month basis for the uncorrected, pressure corrected and the temperature+ pressure corrected data. The mean values of the standard deviation on the daily values for the whole year after correcting for the three different methods are given below.

An examination of the table shows that the pressure correction and temperature correction by any method causes a considerable reduction in the scatter. It is also evident that the least scatter is obtained if the daily values are corrected by the Dorman type procedure.

In view of the above analysis it is obvious that the Dorman type correction procedure is to be preferred for a routine correction of the cosmic ray data.

3.5. REDUCTION OF MAKERERE DATA:

Two other telescopes, tilted at 45° and pointing in the East and the WEST directions, have been set up at an equatorial station at MAKERERE in Uganda. These telescopes are similar in design to the London North/South telescopes are record the total ionizing component of the cosmic radiation. They have counting rates of 165000 and 185000/hr in the East and West directions respectively. The telescopes have been in operation since JLY 1964 and the data obtained from them have been analysed for atmospheric effects up to JUN 1966.

The atmospheric effects to be expected in this case also are a barometer effect and a negative temperature effect associated with the decay of the mesons.

Hourly recordings of pressure were available from Entebbe approximately 20 miles from MAKERERE, and the barometer effect could be studied in some detail. However the decay effects associated with temperature changes in the atmosphere could not be established with any great accuracy because of the scanty nature of the temperature and height data available. A Duperier type correlation analysis using the barometric pressure, the temperature of the atmospheric layer bounded by 200 m.b. and 100 m.b., and the height of the 100 m.b. as variables was in fact attempted. However because of the small number of days for which temperature and height data were available and also the absence of adequate variability in the parameters associated with the temperature, a characteristic of equatorial latitudes, no conclusive results could be obtained.

Since the data obtained from these telescopes were to be used primarily for a study of the daily variation it was thought adequate to establish an accurate value of the barometer coefficient for correcting the data for atmospheric effects.

The barometric effect was investigated by carrying out a two-fold correlation analysis between cosmic ray intensity and barometric pressure. Daily means of both the variables were used. At equatorial latitudes, however, the determination of the barometer coefficient poses a problem since the day to day variation in pressure is quite small (of the order of a few m.b.) while statistical fluctuations and primary variations are larger than the pressure induced variations and tend to mask the correlation between cosmic ray intensity and pressure.

FORBUSH and LANGE (1948), have also noted this difficulty and advocate selection of groups of days on which the pressure varies by large amounts. We have used this method for the determination of the barometer coefficient. We have also attempted a straight forward correlation analysis using all the pressure and cosmic ray data. The results obtained are described below and discussed in a later section.

3.5.1. High correlation method.

While analysing the data by this method a selection was made of groups of days on which the daily mean pressure as calculated from the hourly records obtained from Entebbe, increased or decreased monotonically for at least four days. The majority of intervals comprised four days; however some were longer. For each group the average of the barometric pressure and the cosmic ray intensity were obtained. Daily departures of the pressure and intensity from these means were calculated for each group. The departures of pressure were ranked by magnitude and sign into 12 intervals. The cosmic ray intensity departures were ranked according to the corresponding pressure departures. Averages of all departures were then obtained for the pressure and cosmic ray intensity.

The procedure described above was carried out in two yearly batches of data. The first batch of data extends from JLY 1964 to JUN 1965 and the second from JLY '65 to JUN '66. The two batches of data contain 21 and 25 groups (of four or more days) satisfying our requirements. Least square regression lines have been fitted to the two batches of data and the corresponding regression and correlation coefficients are listed in TABLE VII below.

It is evident from these results that a high correlation coefficient (0.950) can be obtained between the cosmic ray intensity and the barometric pressure by this method and therefore an accurate value of the pressure coefficient can be established. Since there do not appear to be any significant differences between the coefficients obtained for the two channels an average value of -0·210 210%/m.b. has been adopted as the pressure coefficient for the two telescopes.

TABLE VII

REGRESSION AND CORRELATION COEFFICIENTS (HIGH CORRELATION METHOD):

CHANNEL	REGRESSION COEFFICIENT	CORRELATION COEFECIENT
WEST	-0.2199 ± 0.010	-0.960
EAST	-0.2084 ± 0.010	-0.960

3.5.2. LOW CORRELATION METHOD:

A two fold regression analysis was also carried out using the regression equation

$$dI / I = \beta_p \, dP$$

where,

I is the cosmic ray intensity measured by the E/W recorders.

P is the barometric pressure as determined at Entebbe.

β_p is the barometric coefficient.

Daily means of the cosmic ray intensity and barometric pressure were used for the analysis. Data were analysed in monthly batches from Jly 1964 to Jun 1966 for the east and west telescopes and regression and correlation coefficients calculated for each month.

Averages of the correlation and regression coefficients have been obtained for the two telescopes for the two year period and are listed in TABLE VIII below. Errors on the individual values have been obtained from the scatter of the individual values about the mean. The means listed have been derived from the individual points by weighting each point by $1/s^2$, where s is the error on an individual point.

TABLE VIII

REGRESSION AND CORRELATION COEFFICIENTS (LOW CORRELATION METHOD)

CHANNEL	REGRESSION COEFFICIENT	CORRELATION COEFFICIENT
WEST	-0.2270 ±0.0185	-0.734 ± 0.032
EAST	-0.2332 ±0.01460	-0.7738 ± 0.031

3.5.3. DISCUSSION

A comparison of the results obtained by the two methods as listed in tables 7 and 8 shows that the correlation coefficients obtained by the first method, which involves selection of data, are much higher than those obtained by the second. The correlation coefficients obtained in the two cases are about 0.95 and 0.70 respectively. The reason for the low correlation coefficient is the low variability of the pressure at equatorial latitudes. The consequently low correlation between the cosmic ray intensity and pressure results in a considerable scatter on the regression coefficient as obtained on a month by month basis by the second method. Thus it is found that the monthly values of the regression coefficient obtained vary from -0.35%/m.b. to -0.05%/m.b., in the two years data analysed. The errors on the mean regression coefficient for the two year period are consequently larger in the second method. It appears therefore that the first method must be used for the determination of the pressure coefficient.

The pressure-coefficient as obtained by either of the two methods is the total barometer coefficient as defined by TREFALL (1955c). WADA (1961) has calculated the total barometer coefficient for inclined directions as described in section 3.4.1. An approximate value of the pressure coefficient for the hard component at Makerere has been obtained by him after taking into account the altitude variation of the barometer coefficient. He quotes a value of -0.16%/m.b. for vertical measurements. The value for inclined directions will be slightly smaller. In view of the errors involved in our measurements, however, such differences cannot be detected.

The coefficient obtained as a result of the present analysis is -0.210%/m.b. and is seen to be significantly different from the theoretical value. However, as we have mentioned, the telescopes record the total ionizing component of the cosmic radiation. Since Makerere is at a moderately high altitude (about 1,100 metres above S/L) the contribution from the soft component will actually be higher than that obtained at LONDON. The high value for the pressure coefficient can therefore be explained as a result of contributions from the soft component (which has a higher pressure coefficient of about -0.35%/m.b.). On the basis of the known value of the pressure coefficient e.g. DAWTON and ELLIOT (1953) etc., and the theoretical estimates by Wada for the barometer coefficient expected at Makerere for the hard component, we may use the experimentally observed values to make an approximate estimate of the contribution present from the soft component, in a similar manner to that used for the London telescopes in an earlier section.

If A and B are the proportions in which the hard and soft components contribute to the counting rate at Makerere then we must have

$$0.35\,A + 0.16\,B = 0.21\,(A + B)$$

Thus

$$A = 0.35\,B$$

$$A : B :: 74.1 : 25.9$$

The errors on these values can be similarly calculated from the errors on the observed regression coefficients and are about ±4%. Thus about 26% of the counting rate at Makerere is due to contributions from the soft component.

3.6. SUMMARY: a) LONDON RESULTS:

1) A mean value of -0.186%/m.b. has been obtained for the pressure coefficient for the secondary intensity as recorded by two cubical meson telescopes at LONDON. This is consistent with theoretical estimates if it is assumed that about 12% of the counting rate is due to contributions from the soft component.

2) Temperature effects on the ionizing component have been investigated for the intensity recorded at London. It is found that the experimentally observed values agree with the theoretically calculated values given by Dorman in the upper and the middle regions of

the atmosphere (up to about 700 m.b.). The experimentally observed values are lower than the theoretical values in the lower atmosphere. This reduction is thought to be due to the negative temperature effect being offset by the positive temperature effect associated with the soft component and localized to the lower regions of the atmosphere.

3) Analysis of the temperature effect by procedures based on the Duperier method yield values of-3.5%/km for the decay coefficient and about 0.05%/°C for the positive temperature coefficient. These values agree with those obtained by other workers at middle latitude S/L stations.

4) Methods based on the Duperier and Dorman procedures have been tested for their effectiveness in providing a goodness of fit amongst the variables (by comparing the multiple correlation coefficients in the two cases), and for their effectiveness in removing the variability introduced in the cosmic ray data due to atmospheric variations (by comparing the scatter obtained in the data after correcting for atmospheric variations using coefficients obtained by the different procedures). As a result of this analysis it has been found that the analytical procedures based on the Dorman method yield a better fit amongst the variables of correlation and are also more effective than the Duperier method for removing the variability in the data due to atmospheric variations.

b) MAKERERE RESULTS:

1) A value of -0.21%/m.b. has been found for the ionizing component of the cosmic ray intensity recorded by the two directional recorders at MAKERERE. A comparison with the theoretically expected values for the hard and the soft component suggests that about 25% of the counting rate at Makerere is due to contributions from the soft component.

2) It is found that correlation analysis on selected groups of days when the pressure changes are greatest provides a reliable value for the pressure coefficient. An analysis using all available data increases the scatter on the results. This is due to the fact that the variability in atmospheric variables is low at equatorial latitudes and statistical fluctuations and primary variations superposed on the data, spoil the correlation with pressure thereby increasing the errors.

CHAPTER IV

(SOLAR DAILY VARIATION I)

4.1. REVIEW OF EXPERIMENTAL RESULTS:

4.1.1. INTRODUCTION:

It has been established that at least part of the solar daily variation of the secondary cosmic ray intensity is due to anisotropic distributions of the primary radiation incident on the Earth's atmosphere, such distributions being produced by the modulation of the galactic cosmic rays by the interplanetary magnetic fields. The chief interest in an investigation of the solar daily variation lies in the important information it can yield about this anisotropy and the modulation mechanisms responsible for its production.

In the following paragraphs a brief summary will be given of the present state of our knowledge on the solar daily variation and the chief landmarks in our progress to date in this field.

A cosmic ray intensity variation with the period of a solar day has been known from the time when cosmic ray intensity monitoring apparatus was first commissioned for a long term study of the time variation of the secondary intensity. LINDHOLM (1928), noticed a 24 hour periodicity in the secondary cosmic ray intensity as recorded by an ionization chamber with an amplitude of 0.5%. His observations were confirmed by several other workers e.g. COMPTON et.al.(1932), HESS and GRAZIADEI (1936), SCHONLAND (1937), FORBUSH (1937). These results indicated a smaller amplitude of 0.2% to 0.3% and a time of max between 1000 Hours and 1600 hours L.s.t. A 12 hour wave was also detected with a smaller amplitude of 0.05% and a time of maximum of about 0 200 hours l.s.t.

Earlier efforts were directed at explaining these periodicities in terms of the diurnal and semi-diurnal variations of the atmospheric elements, in particular those of the barometric pressure and the temperature of the atmosphere.

Though variations in the cosmic ray intensity induced by variations in barometric pressure could be accounted for reasonably accurately, an adequate knowledge of the processes responsible for the temperature effect on the ionizing component of the secondary radiation prevented accurate temperature corrections being applied to the data. Since all the above measurements pertained to data obtained from ionization chambers, there were additional doubts about the variation being due to fluctuations in the Radon content of the atmosphere, i.e. due to fluctuations in the background radio-activity.

4.1.2. THE USE OF CROSSED TELESCOPES

The introduction of G-M counters for cosmic ray measurements enabled an effective discrimination against background radio activity. DUPERIER (1945,46) verified the existence of the diurnal and semi-diurnal waves using an unshielded threefold coincidence counter telescope. However, the temperature effects on the data were still uncertain.

In order to remove the uncertainty in the interpretation of the results caused by an inadequate knowledge of the atmospheric temperature effects, attempts were made to separate the part of the cosmic ray variation due to atmospheric effects from that due to any possible variations in the primary intensity by indirect means using pairs of inclined telescopes pointing towards opposite azimuths.

In practice, pairs of telescopes are so arranged that they record radiation arriving from quite different parts of the celestial sphere and therefore have a different response to any anisotropic components of the primary radiation, whereas, they respond in an identical manner to variations in intensity due to atmospheric temperature and pressure changes. Thus, consider two telescopes tilted symmetrically with respect to the vertical at an angle of about 45° and pointing towards opposite azimuths. If we construct an imaginary cylinder of about 10 miles radius around these telescopes with its axis vertical, then about 95% of the atmosphere traversed by the primary and secondary cosmic rays contributing to the counting rate of these telescopes is enclosed in this cylinder. Since the effective longitude or latitude change at the edges of this cylinder is only about 20' of the arc, the atmospheric conditions within the portion of atmosphere enclosed in this cylinder may be regarded as uniform. Therefore, the atmospheric contributions to the daily variation can be assumed to be the same for both telescopes. Such a pair of crossed telescopes, inclined at 45° to the zenith and pointing in the North and South directions respectively and situated at a middle latitude station, can in principle be used to separate out an anisotropy confined primarily to the ecliptic plane, from any variations due to atmospheric effects. The north telescope will look along the axis of rotation of the Earth while the south telescope will scan the sky ina strip near the ecliptic as the earth rotates. The north telescope will therefore see only the atmospheric parts of the variations, whereas the south telescope will record both the atmospheric and the anisotropic parts. A vector difference of the variations observed by the two telescopes should therefore yield the true extra-terrestrial anisotropy.

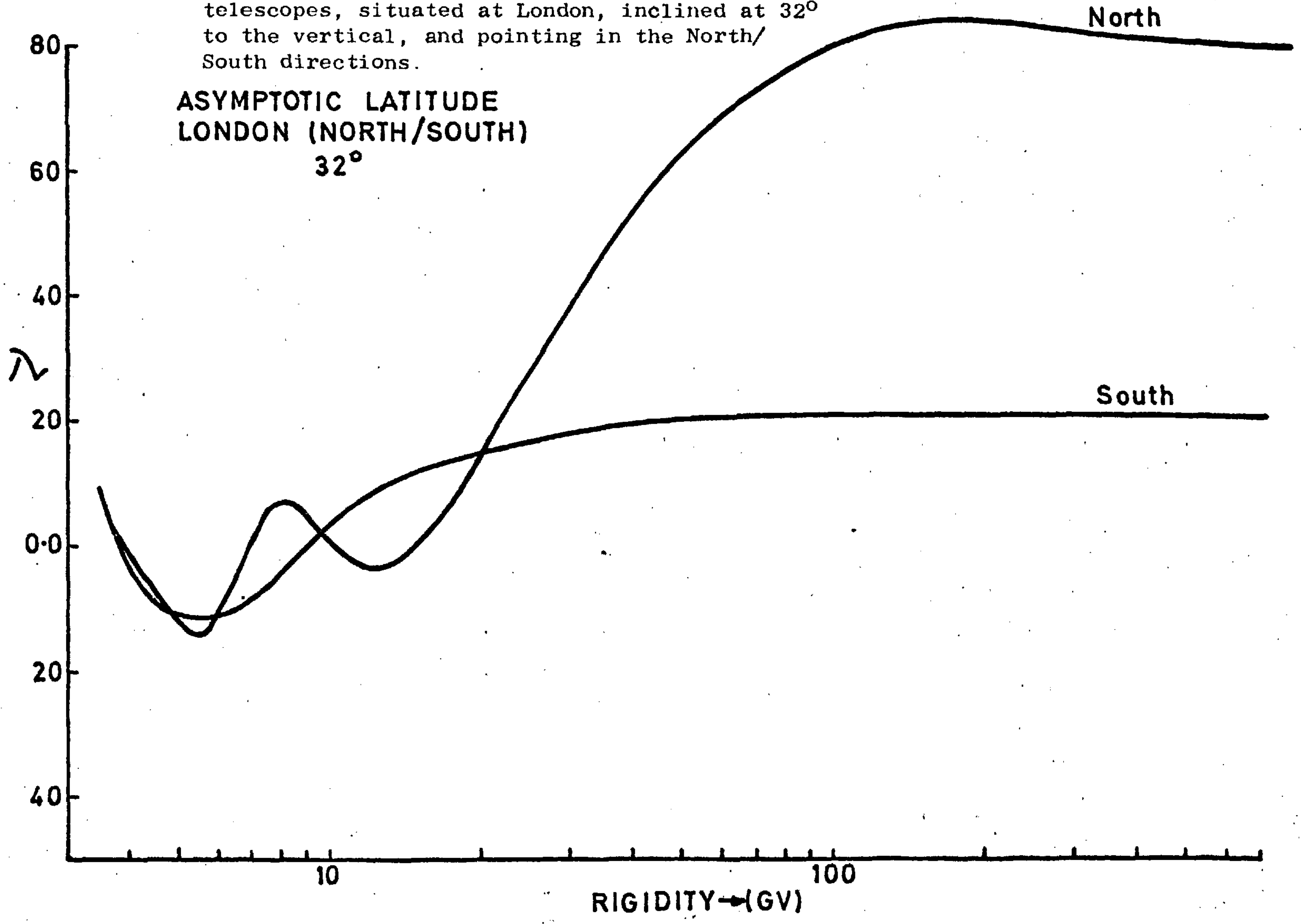
However, implicit in this interpretation is an assumption that the trajectories of the primary cosmic ray particles involved are not seriously effected by the geomagnetic field. It turns out that this assumption is not valid at the primary energies where the solar variation is greatest.

The model experiments on the geomagnetic deflection of the primary cosmic rays (BRUNBERG and DATTNER (1954)) and the detailed calculations of the trajectories of the primary particles (McCRACKEN et.al, (1962, 65, 67)) have shown that in the low and medium range of primary energies (5 - 30 Gev) the effective latitudes of viewing for both the North and South pointing telescopes are in fact quite similar. This is illustrated by figure 1a where we have plotted the asymptotic latitude -vs- rigidity for a narrow angle telescope inclined at 32° to the zenith and pointing in the north and south directions respectively. The asymptotic latitude for particles up to about 30 Gv is seen to be less than 30° from the equator for the north telescope. Therefore, any anisotropy present in this energy range and confined to the lower latitudes will be observed by both the north and the south telescopes. It is only at much higher energies (about 80 GV) that the north telescope starts looking along the rotational axis of the earth and therefore becomes insensitive to anisotropies confined mainly to the lower asymptotic latitudes. Since it is now established that the diurnal variation of the cosmic ray intensity is primarily due to contributions from medium energies (e.g. BRUNBERG and DATTNER (1954)), McCRACKEN et.al. (1963, 65)), a simple vector difference as ..ioned above, cannot be taken to be the true extra terrestrial anisotropy for sea level measurements. For measurements at high energies(at say 55m.w.e. Underground) the lower energy parts (less than about 50Gv) of the cosmic ray spectrum is filtered out and the approximation is more justified. However, even at sea level, though both the north/south telescopes look at equatorial latitudes for medium energies, the longitudinal deflection for particles of L.T.25Gv is different for the two being greater for the north than for the south telescope. This is illustrated by the plot of asymptotic latitude-vs- rigidity (fig. 1b) for two narrow angle N/S telescopes inclined at 32° to the vertical. The longitudinal deflection is about for the north telescope, compared with for the south telescope. In view of this any anisotropy will be observed with a phase difference of about 2 to 3 hours by the N/S telescopes, the North telescope showing a variation earlier in time.

Crossed telescopes are often made to point in the East/West directions. At a middle latitude station such an arrangement enables a more effective discrimination between the atmospheric and the anisotropic parts of the daily variation. Data on the geomagnetic deflection of the primary particles shows that a telescope pointing at 45° to the WEST collects radiation from very nearly the same direction throughout the day and therefore shows primarily the atmospheric parts of the variation. The east telescope however, samples particles which had their initial directions in the equatorial plane; consequently, as the earth rotates, this telescope will scan a strip around the celestial sphere and will record variations induced by atmospheric changes along with those due to any anisotropies in the primary radiation.

EAST/WEST counter arrangements of this type, located near the geomagnetic equator however, scan the same parts of the celestial sphere in succession as the earth rotates. The difference in time between any part of the sky appearing in the viewing cone of the telescope should, in principle, depend on the angle between the direction of maximum sensitivity for the two arrays and the time difference between any anisotropic components being registered should be $t = 0 / 15$ hours. (0 being the angle between the directions maximum sensitivity between the two recorders. In practice this simple phase separation is not obtainable because of the geomagnetic effects. Firstly the EAST/WEST asymmetry is pronounced at equatorial latitudes and causes the east telescope to

Fig. 1(a) Asymptotic latitude as a function of rigidity for narrow angle telescopes, situated at London, inclined at 32° to the vertical, and pointing in the North/South directions.



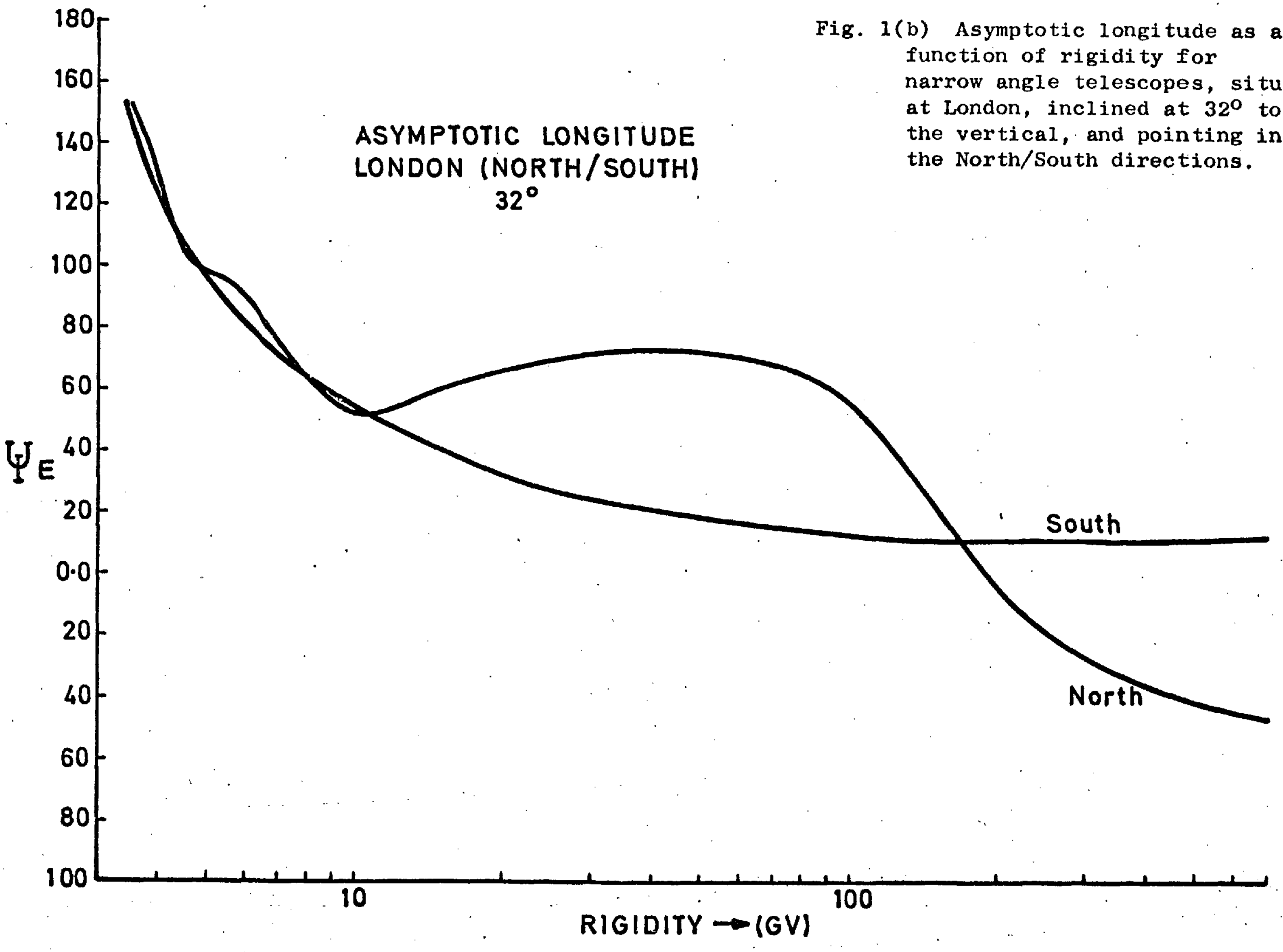


Fig. 1(b) Asymptotic longitude as a function of rigidity for narrow angle telescopes, situated at London, inclined at 32° to the vertical, and pointing in the North/South directions.

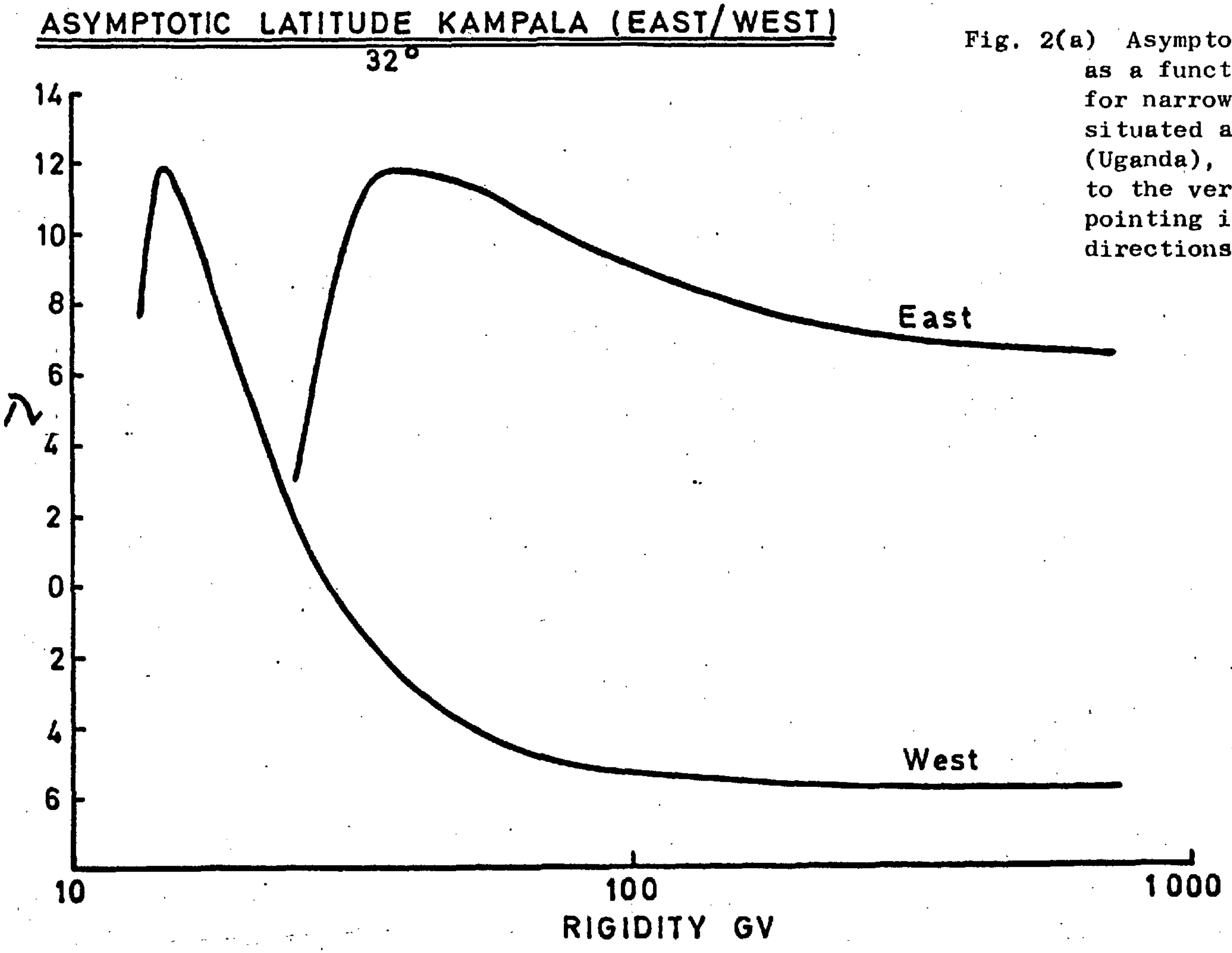


Fig. 2(a) Asymptotic latitude as a function of rigidity for narrow angle telescopes situated at Kampala, (Uganda), inclined at 32° to the vertical and pointing in the East/West directions.

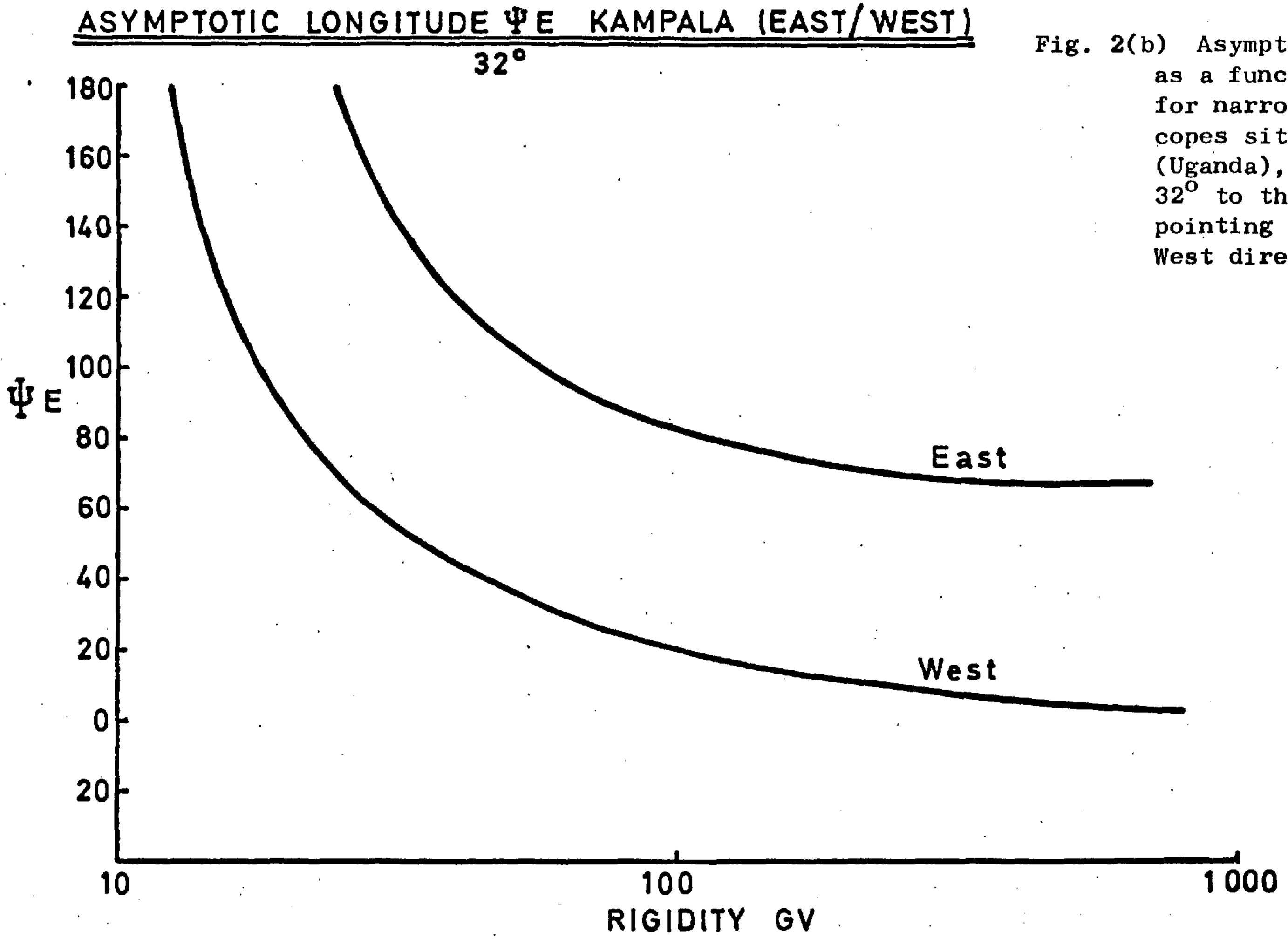


Fig. 2(b) Asymptotic longitude as a function of rigidity for narrow angle telescopes situated at Kampala (Uganda), inclined at 32° to the vertical and pointing in the East/West directions.

have a higher mean energy than the west. Secondly, the deflection being a function of energy, the phase difference between the two recorders is energy dependent. In practice, the phase difference is also smaller than the simple geometrical illustration above because of smoothing in the broad asymptotic cones of the recorders. Nevertheless, a phase difference of about three to four hours is normally obtained between E/W recorders placed at an equatorial station. The presence or absence of this phase difference will be indicative of any extra terrestrial anisotropy. Fig.2 (a,b).

ALFVEN and MALMFORS (1943), KOLHORSTER (1941), MALMFORS (1949), DOLBEAR and ELLIOT (1950) were pioneers in the practice of crossed telescope measurements for the study of the diurnal variation. They definitely established from the phase differences observed between different azimuths that the cosmic radiation is not entirely isotropic in the vicinity of the earth.

The development of the NEUTRON monitor as an intensity monitoring device made it possible to study the daily variation free of the influence of the atmospheric temeprature effects. Since the secondary particles recorded by the neutron monitor are relatively unaffected by variations in atmospheric temperature and the variations due to changes in barometric pressure can be accounted for accurately, it became possible to establish the amplitude of the diurnal variation without any uncertainty due to temperature corrections, e.g. McCRACKEN et.al. (1965).

4.1.3. PRINCIPAL CHARACTERISTICS OF THE DAILY VARIATION

With the help of vertical and inclined meson telescopes situated at different geographical locations on the surface of the earth and at various depths underground and with neutron monitors spread widely in latitude and longitude it has become possible to study the daily variation of the cosmic ray intensity in different energy ranges and several average characteristics of the daily variation have been established. A great deal of information has also been obtained on the effect of the geomagnetic field and atmospheric parameters on the cosmic ray intensity. A combination of these factors has enabled an understanding of the principal features of the daily variation.

In the following we list the main results obtained from extended observations on the S.D.V. using the techniques enumerated above and the effects of the geomagnetic field and atmospheric temperature on these observations.

1) In general the cosmic radiation measured on the surface of the earth and underground exhibits significant diurnal and semi-diurnal periodicities in local solar time, neither of which can be explained in terms of variations of the atmospheric elements, i.e. temperature and pressure.

2) The amplitude of the diurnal wave depends on the mean primary energy of the particles being monitored. Thus for lower mean primary energies L.T. 15Gev as recorded by a neutron monitor at a high latitude the diurnal amplitude has a value of about 0.3%. For medium primary energies as recorded by meson telescopes and ionization chambers the average amplitude is 0.15% and for high mean energies (100Gev) as recorded by meson telescopes located underground (50 m.w.e.) the mean amplitude is 0.05%, e.g. DORMAN (1957), KATZMAN et.al. (1960), SANDSTROM (1962), DUTT and THAMBYAHPILLAI (1965) etc. The time of maximum varies considerably from station to station (see 3) and ranges typically from 1200 hours L.S.T. to 1600 hours L.S.T.

The semi-diurnal wave is smaller than the diurnal wave and has a magnitude of about 0.05% for a neutron monitor at a medium latitude station. It is however found to increase with the mean primary energy of the particles being monitored, e.g. LIETTI et.al. (1967).

3) The amplitude of the daily variation and its time of maximum when measured by say a vertical cubical meson telescope or a neutron monitor located at different places on the surface of the earth are found to be a function of the geomagnetic coordinates of the place of observation.

It has been found, e.g. KANE and THAKORE (1960), SCHWACHIEM (1960) that the amplitude of the diurnal wave as measured by a neutron monitor increases from the equator where it is about 0.26% to medium latitudes (50° to 60°) where it becomes about 0.35% and then reduces in going to very high latitudes (0.15%). The amplitude of the semi diurnal wave is found to increase with increasing latitude. At the same geomagnetic latitude the times of maximum remain the same in l.s.t.

More recently KITAMURA (1965) has analysed data from the network of neutron monitor stations obtained during the I.G.Y. to obtain the latitude effect of the daily variation. He finds that the amplitude observed at 50° to 60° geomagnetic latitude is larger than in any other range. The latitude dependence of the time maximum between 0° and 60° in both the northern and southern hemispheres is found to be given by:

$$\mathrm{TMAX} = 10.12 + 0.08\,L \text{ hours} \qquad (L = \text{latitude})$$

$$\text{error} = 0.55 \text{ hours.}$$

4) Due to the deflection of the primary particles in the geomagnetic field the amplitude observed on the surface of the earth will be smaller than the primary anisotropy outside the geomagnetic field and the phase will be shifted to earlier hours.

The change in the phase is easily understood in terms of the deflection of the primary particles. The reduction in the amplitude is due to the fact that the geomagnetic bending of the primary particles is a function of energy. Any anisotropic flux extending over a finite energy range will be spread so that the time of maximum observed on the surface of the earth will occur at different times for different energies. The observed amplitude will therefore be reduced because of smoothing. A further reduction in the amplitude will be caused because of the scattering of the secondary particles in the atmosphere and their deflection in the earth's magnetic field. BRUNBERG (1954).

Many features of the dependence of the diurnal and semi-diurnal variations on the geomagnetic latitude can be accounted for in terms of the geomagnetic effects on the primary particles which contribute to the counting rate at different latitudes.

5) BRUNBERG and DATTNER (1954), DORMAN (1957), SANDSTROM et.al. (1962) have investigated the direction of the diurnal anisotropy in free space and the variation of its strength with the angle that the primary particles make with the ecliptic plane. A mean asymptotic direction was chosen to represent the asymptotic angle of viewing of the particles contributing to the counting rate of the detector. With such an assumption it was found that after correcting for geomagnetic and atmospheric effects that the direction of the anisotropy in free space makes an angle of approximately 90° with the earth sun line, the flow of the particles overtaking the earth from the 1800 direction.

SANDSTROM et.al. used directional telescopes located at KIRUNA, MURCHISON BAY and UPPSALA pointing towards different azimuths to scan a considerable range of latitudes off the ecliptic. (10°N to 80°N). As a result of this study it was found that the diurnal variation amplitudes fit a linear function of the cosine of the angle between the equatorial plane and the mean asymptotic direction.

The decrease in the amplitude of the diurnal variation at polar stations can be explained in terms of this falloff with asymptotic latitude, since these stations will sample particles at relatively large angles to the ecliptic plane.

The problem of evaluating the effect of the geomagnetic field is of fundamental importance for calculations of this type. McCRACKEN (1963) has improved on earlier methods adopted by BRUNBERG etc. to calculate the geomagnetic deflection on the primary particles recorded.

The chief improvements are:

*1) SPHERICAL HARMONICS up to the sixth order have been used to specify the geomagnetic field instead of the simple dipole approximation used by earlier workers.

*2) The workers have taken into account the fact that the asymptotic directions contributing to the counting rate of the detector are contained in a cone of finite width.

*3) A detailed study of the asymptotic cones of detectors located at various places have revealed that the width of the cone depends on the geographic location of the detector, being narrow in width at the high latitude stations and broad at low latitude stations.

*4) A discussion on the dependence of the response of a cosmic ray detector on the shape of its asymptotic cone of acceptance reveals that an appreciable latitude dependence of the amplitude of any anisotropy present will result even if the anisotropy is dependent neither on the rigidity nor on the asymptotic latitude. The calculations also point out that a difference of greater than five hours between the diurnal phases at two different places could arise purely from the different geomagnetic deflections at the two places.

Using the improved technique to isolate the effects due to the geomagnetic field McCRACKEN and RAO (1963, 65) have studied the diurnal variation as measured by neutron monitors located at different latitudes and longitudes. They find that the S.D.V. can, on average, be related to an anisotropy of the primary radiation 0.4% in amplitude in the direction 90° East of the earth - sun line. They also find a COS L dependence on the declination L.

6) The rigidity dependence of the diurnal variation can be established from neutron monitors and meson telescopes spread over the surface of the earth and meson telescopes located at various depths underground.

McCRACKEN and RAO (1963,65), MARSDEN (1965), SARABHAI (1964) have used neutron monitor data to study the rigidity dependence of the diurnal variation and find that the observed diurnal variation is consistent with an energy independent primary anisotropy which extends to about 100 Gev.

Owing to the shape of the primary spectrum and that of the diurnal variation, the low rigidity region plays the most important part as concerns the diurnal anisotropy and the apparent ratio between the isotropic and anisotropic parts decreases with increasing rigidity. This is the reason why the nucleon component usually displays a larger amplitude than the meson component at the same point of observation.

4.1.4. VARIABILITY OF THE DAILY VARIATION:

a) DAY TO DAY VARIABILITY:

The characteristic features of the daily variation outlined in the preceding paragraphs represent the average properties of the diurnal and semi-diurnal anisotropies. A considerable variability has however been observed in the daily variation on a day to day basis. Only a part of this variability can be attributed to statistical fluctuations. A detailed study of the diurnal variation on a day to day basis has in fact revealed an intimate correlation between the characteristics of the daily variation and the parameters characterising the level of geomagnetic and solar activity, e.g. ELLIOT and DOLBEAR (1951), SEKIDO (1950, 52), SANDSTROM (1956, 60).

The geomagnetic conditions are described by Kp, the sum of the three hour K indices, or by Ap the amplitude expressed in gamma, of the disturbance in the earth's magnetic field. A disturbance in the electromagnetic state of the interplanetary medium in the vicinity of the earth is reflected in the change of the Kp and Ap indices. As a result of grouping daily variation data on a day by day basis according to the Kp and Ap values it was found that the amplitude of the diurnal variation is found to increase and the phase to shift to earlier hours on days of high Kp and Ap.

Interesting changes were also observed in the diurnal variation on days after sudden geomagnetic disturbances. Enhanced daily variations with an earlier than normal phase were the chief characteristic of these changes.

SARABHAI et.al. report a tendency for the enhanced amplitude of the daily variation to occur after 27 day periods which points to a relationship with solar activity.

b) LONG TERM CHANGES IN THE DAILY VARIATION

In addition to the day to day variability exhibited by the daily variation which in effect reflects the day to day variability of the electromagnetic state of the interplanetary medium, a long term variability of the diurnal anisotropy has also been detected. Such a change in the daily variation reflects the slow long period changes of the large colume aspect of the interplanetary state.

THAMBYAHPILLAI and ELLIOT (1953) first pointed out that the time of maximum of the daily variation as measured by ionization chambers and counter telescopes located at widely separated stations shows strikingly similar variations over a period of several years. The time of maximum was found to increase systematically at all stations studied from 1933 to 1942 and then to become progressively earlier from 1942 to 1952. They noted that the phase had shown a tendency to go to earlier hours at alternate solar minima and therefore concluded that the phase of the diurnal variation shows a 22 year periodicity. Since this early discovery, the long term variability of the diurnal variation has been a subject of intensive study by several groups, e.g. STEINMAURER and GHERI (1955) have pointed out that the diurnal variation has a tendency to shift to earlier hours at the years of minimum activity 33, 44, 55, etc., however, the phase shift during the three minima is different, being more pronounced at the minimum of 1954 than those of 1933 or 1944. SARABHAI (1953, 55) have noted that the amplitude of the diurnal variation also exhibits a variability along with the phase.

VENKATESAN and DATTNER (1959), using ionization chanber data from the CARNEGIE INSTITUTE stations, CHRISTCHURCH, CHELTENHAM and HUANCAYO for the period 1937 to 1955 have shown that the long term changes of the amplitude of the diurnal variation follow the changes in geomagnetic activity more closely than they do the solar activity as given by the number of sunspots. This would indicate that the solar activity is only the indirect cause and the changes in the interplanetary state which is influenced by solar activity the direct cause of the phenomenon. The changes in the semi-diurnal variation do not reveal any common features among the stations studied, though a variability is observed at different stations. In view of the smaller amplitude of the semi-diurnal variation, corrections for atmospheric parameters is of greater importance and due care must be taken in this regard to ensure that an incorrect correction is not performed before attributing any variability to external causes.

FORBUSH (1960), extended earlier analyses by using ionization chamber data from the CARNEGIE INSTITUTE stations for a 23 year period from 1936 to 1959. He calculated the yearly mean diurnal and semi-diurnal vectors for the period and the 23 year mean for the entire period for the three stations. On calculating the vector differences of the daily variation as measured in each year from the 23 year mean he found that the mean departures from the three stations exhibit a quasi-systematic 22 year periodicity. The departures at the three stations were found to correlate to a very high degree. Forbush pointed out that this periodicity could not be of atmospheric origin since atmospheric effects would be expected to be the same for each year and the vector difference of the yearly means from the mean of the whole period should be free from atmospheric influences. More recently FORBUSH (1967) has analysed the data from the CARNEGIE INSTITUTE stations for a longer period, 1937 to 1965 and finds that the diurnal variation as measured at the C.I. stations can be resolved into two components.

1) A component at about 128° to the Earth - Sun line which exhibits a 22 year periodicity, and

2) A component at 90° to the Earth - Sun line which follows an 11 year cycle. The amplitude of the 22 year wave is found to be about 60% of the amplitude of the average diurnal anisotropy 90° East of the Earth - Sun line. Forbush points out that the direction of the 22 year component is approximately in the direction of the lines of the interplanetary magnetic field and this may give a clue as to the origin of the 22 year wave.

WADA et.al. (1966) have approached the problem from another point of view. They point out that the topological patterns made by the excursions of the diurnal vectors at the CARNEGIE INSTITUTE stations and those of the TOKYO ionization chamber closely resemble revolutions about an origin. The sense of the revolutions is found to change after every eleven years and the change is found to occur simultaneously at the three C.I. stations and at TOKYO. They point out that the revolution patterns can in analogy with lissagous figures be explained as a resultant of two waves of the same frequency but with a phase difference, or, two waves identical in phase butone having a frequency twice that of the other. In the paractical case, the problem is to find two phenomena with either of the sets of characteristics given above which can influence the daily variation. They suggest the combination of sunspot numbers and geomagnetic activity. The latter has been shown to have a period of 22 years. Though it was not possible to generate the corresponding revolutions with the help of the parameters chosen, the authors point out that the existence of revolutions in the variation of the diurnal variation points to the existence of two components in the diurnal variation. In addition to the well known component at 90° they suggest another component in the 1200 hour direction.

c) THE SOLAR DAILY VARIATION AT TIMES OF SOLAR MINIMUM

The systematic variation exhibited by the daily variation during the solar cycle has elicited wide attention in view of the information it can yield about the modulation of the galactic cosmic rays by the interplanetary magnetic fields. In particular, the behaviour of the solar daily variation during the solar minimum is of great importance in view of the pronounced variability exhibited by the S.D.V. during this period. Thus, POSSENER and VANHEERDEN (1956) found that the phase and amplitude of the diurnal variation as measured by two G-M counter telescopes inclined at 45° to the vertical and pointing in the N/S directions showed remarkable changes during the solar minimum of 1954. The amplitude of the diurnal variation was found to reduce to about a third of its normal value and the phase was found to go very early hours (0800 hours). A detailed study of the diurnal variation over the period 53-54 revealed that the phase had in fact gone to the morning midnight quadrant for several groups of months during this period Such large changes in the phase of the daily variation could not be explained in terms of the normal features of the diurnal anisotropy at 1800 hours, external to the geomagnetic field.

Since the measurements on the meson component would be affected by temperature changes POSSNER et.al. studied the diurnal variation as measured by neutron monitors over this period of anomalous behaviour and found that the amplitude of the neutron monitor daily variation went to zero over the period when the N/S telescopes had shown an abnormal time of max. In view of this, it appears that the diurnal anisotropy had reduced considerably in its normal amplitude and may in fact have gone to zero over short periods over the solar minimum. A comparison of data from other stations, e.g. ITABASHI, TOKYO reveals similar results.

Interest has continued in the variation of the S.D.V. during the course of the solar cycle and with a greater coverage of instruments and improved techniques now available it has become possible to obtain more reliable information on these changes. Several workers have looked at the S.D.V. in recent years with a view to comparing its characteristics at the last solar maximum (1957-58) and during the years of minimum solar activity, 1964,65. Thus, MARSDEN et.al, (1965) and McCRACKEN et.al. (1965) have used neutron monitor data from an extensive network of stations over the periods 1957 to 1963 and 1957 to 1965 respectively and find that the solar daily variation has shown no change in phase and amplitude over the respective periods of their studies. On the other hand DUGGAL et.al. (1967) have compared the S.D.V. at times of max and min activity,i.e. 58 and 65 respectively using neutron monitors at different latitudes and longitudes and find that the diurnal anisotropy reduced by about 30% during the year 1965 as compared to 1958. (It may be mentioned here that DUGGAL'S analysis extends over the whole of 1965 while that of McCRACKEN etc. only use a few stations for the first half of 1965.)

AHLUWALIA (1964) has operated E/W counter telescopes at an equatorial station at CHACALTAYA and has compared the S.D.V. during the years of maximum and min imum activity 58 and 1964. He finds that the amplitude of the diurnal variation has gone down substantially in 1964 as compared to 1958. Neutron monitor data for two equatorial stations, MT. NORIKURA and HUANCAYO show a similar reduction. PEACOCK et.al. (1967) have measured the daily variation at a depth of 60 m.w.e. during the period 1960 to 1966 at LONDON. They find that the diurnal variation shows a time maximum of about 0600 hours and an amplitude of about 0.02% during the period 1964 and 1965. The diurnal variation during the years1960 to 1963 had an amplitude of about 0.03% and a time of maximum of about 1400 hours L.S.T. PEACOCK (1967) explains the phase reversal during the period 1964 - 65 as being due to an abberation effect caused by the orbital motion of the earth and concludes that the solar diurnal variation had reduced to zero for the high energies recorded by their recorders. (Greater than about 80Gv). In view of these results it appears that the secular changes observed in the solar diurnal anisotropy are more important for the high energies.

There appears to be a difference in the behaviour of the solar daily variation at the last solar minimum and that during the preceding minimum of 1954, insofar as, during 1954, the diurnal anisotropy even as measured by neutron monitors had shown an appreciable reduction. The phase of the diurnal anisotropy had also shown systematic changes unlike the solar minimum of 1965.

As mentioned in Chapter 1 we have installed two sets of crossed telescopes, one each at medium and low latitude stations to study the modulation of medium energy cosmic rays during solar minimum conditions. The results obtained from these investigations will be presented in the next chapter. The London measurements are directly comparable to the earlier measurements of POSSENER and VANHEERDEN (1956) and will be used to compare the characteristics of the diurnal variation during the two successive minima.

4.2 THE DAILY VARIATION (THEORETICAL):

The diurnal variation is explained as the result of a net drift or streaming of cosmic rays relative to the rotating earth. The anisotropy resulting from a relative motion between the earth and an isotropic cosmic ray flux was first discussed by COMPTON and GETTING (1935). They showed that there should be an increase in the flux of cosmic rays in the direction of relative motion. There are two principal reasons for this increase in flux:

1) As seen from the earth the energy of each particle moving in the direction of the drift $\underline{U}$ is increased by a fractional amount;

$$\frac{\delta E}{E} = \frac{\underline{U}}{C}$$

Therefore an instrument with a fixed lower energy threshold E_{min} will see a greater flux of particles when looking upstream because the particle energies are effectively raised by the bulk streaming motion, giving more particles above the threshold of the instrument. A correspondingly fewer number of particles will be observed while looking downstream.

2) The flux f of the particles / sec / cm^2 / sr is increased by a fractional amount,

$$\frac{\delta F}{F} = 3 \frac{\underline{U}}{C}$$

because a) because of abberation a greater number of particles are concentrated into a smaller solid angle in the direction of motion.

b) The number of particles arriving at a given surface / unit time is increased due to the higher relative velocity of approach between the particles and the Earth. Therefore, if the differential energy spectrum of the isotropic cosmic rays is given by $D(E) = AE^{-\gamma}$ where $\gamma = 2.5$ then from the above the fractional increase of the flux of cosmic rays of energy E is

$$\delta = (3+\gamma) \frac{\underline{U}}{C}$$

The maximum anisotropy being observed in the direction of $\underline{U}$.

AHLUWALIA and DESSLER (1962) have considered the motion of the cosmic ray particles in a smooth interplanetary magnetic field of an Archimedian spiral configuration as suggested by Parker. They find that under the action of this field, the guiding centres of the cosmic ray particles will drift in a direction perpendicular to the interplanetary magnetic field lines at the same velocity as that of the lines of the magnetic field.

Thus, if $\underline{B}$ is the magnetic field associated with the archimedes spiral and $\underline{V}$ is the velocity of the solar plasma, then due to the radial streaming of the solar plasma and electric field $\underline{E}$ exists perpendicular to the plane of the ecliptic given by:

$$E = -\frac{\underline{V} \wedge \underline{B}}{c}$$

under the action of this field the guiding centres of the cosmic ray particle will drift at a velocity V_D given by:

$$V_D = \frac{c\underline{E} \wedge \underline{B}}{B^2}$$

or on substituting for E and expanding the crossproduct we obtain $V_D = V$.

Thus on this model the guiding centres of the cosmic ray particles drift in a direction perpendicular to the magnetic field lines. Further the drift velocity is seen to be independent of the energy of the particle. The diurnal variation amplitude will consequently be independent of the energy. This will, however, only be so up to some high energy limit of the order of 100 Gv or so. Beyond this the diurnal variation amplitude will be zero. This is so because particles higher than a certain energy will be only partially affected by the corotation of the solar magnetic field and very high energy particles will pass through the solar system without being affected by the interplanetary magnetic fields. In general particles with gyro radii less than about 1 A.U. will take part in corotation. The predicted time of maximum beyond the geomagnetic field is 1500 hours L.S.T.

Two fundamental objections are levelled against this model.

*1) The drift velocity has a radial component which implies that the sun is a source of cosmic ray particles, or else the cosmic ray number density in the solar system will be depleted because of radial convection.

*2) Stern pointed out that the mechanism proposed here for the diurnal variation in effect violates Liouvilles theorem. For, according to this theorem, if the cosmic ray intensity is isotropic at every point outside the solar system, then it must remain so at any accessible point inside the solar system, if the magnetic fields operative in it are constant in time i.e. $\frac{dB}{dt} = 0$. In practice the streaming V_D is cancelled exactly by an equal and opposite streaming caused by a density gradient. (This density gradient is generated by the electric field E which deflects cosmic rays coming into the solar system producing a gradient in the direction of E. Parker (1965) has shown that the density gradient will cause a streaming exactly equal and opposite to that given by V_d.)

PARKER (1965), AXFORD (1965) have shown that the only way by which a sustained streaming can be set up in the solar system is that there be a sufficient number of magnetic field irregularities in the basic spiral pattern which can obliterate the pressure gradient. The cosmic ray particles will random walk in the frame of reference moving with the wind. In this frame of reference there is no electric field and hence the random walk will lead to diffusion which progressively reduces the pressure gradient. If there is sufficient diffusion in the magnetic field irregularities the pressure gradient can be reduced to negligible values.

PARKER (1964) divides the solar wind cavity into two regions:

1) In the inner region of the cavity near to the orbit of the earth, the interplanetary magnetic field is assumed to have a regular archimedes spiral configuration and the motion of the cosmic ray particles is described in terms of the usual guiding centre approximation.

2) Beyond the orbit of the earth there are assumed to be a large number of magnetic field irregularities so that the motion of the cosmic ray particles is describable in terms of isotropic diffusion equations.

In region (2) the particle motion is a combination of two effects, a) an outward convection due to the radial outflow of the magnetic irregularities and b) inward diffusion through the magnetic irregularities. As a result of this diffusion all pressure gradients are assumed to be wiped out so that when the particles enter the inner region their motion will consist of just the electric field drift (which will now appear without impediment from the pressure gradient), and a velocity parallel to the magnetic field lines. The velocity $V_{\parallel}$ is determined from the boundary conditions that there is no net radial outflow from the solar system.

Under these boundary conditions, Parker shows that the net stream velocity is just $V = \Omega \wedge r$ the velocity of rigid rotation with the sun and is in the azimuthal direction.

In general, Parker's description of the solar system is rather artificial insofar as magnetic irregularities also occur within the orbit of the earth and the motion of the cosmic ray particles beyond the orbit of the earth, although one of diffusion is never quite isotropic. Though diffusion occurs it is usually highly anisotropic, with $k_{\parallel}$ greater than $k_{\perp}$. ($K_{\parallel}$ being the diffusion coefficient parallel to the field and $k_{\perp}$, perpendicular to the field).

Axford (1965) has considered the general case of anisotropic diffusion in which the diffusion coefficient is a tensor. He finds essentially the same result as Parker, i.e. rigidity independent co-rotation up to a high energy limit. (However, a density gradient in the plane of the ecliptic turns out to be a natural consequence of this treatment).

On both the AXFORD and the PARKER models then, the cosmic rays have an azimuthal velocity component which represents corotation with the sun. The streaming velocity is independent of rigidity up to a high energy limit of about 100 Gv. In view of this the predicted amplitude of the diurnal variation should be (as given by the Compton getting equation) 0.730% (outside the geomagnetic field) and the time of maximum should be 1800 hours L.s.t. Further the anisotropy should fall off with the asymptotic latitude off the ecliptic plane.

Extensive measurements of the solar daily variation during recent years have indicated that the chief characteristics of the solar daily variation are an energy independent anisotropy of amplitude 0.4% at 1800 hours (outside the geomagnetic field) l.s.t. Though there is agreement between the phase predicted by theory and that observed in practice, the actual observed amplitude of the diurnal variation is only about half the value given by theory.

McCRACKEN (1965) explains this discrepancy as being due to the fact that the pressure gradient is never quite completely wiped out by the interplanetary magnetic field irregularities so that part of the electric field drift is actually cancelled by streaming caused by the rsidual gradient and the diurnal variation amplitude only attains 60% of the theroetically possible value.

PARKER (1967) has pointed out that the observed average amplitude of the S.D.V. also gives some information about the nature of the diffusion in the interplanetary magnetic field. In particular, it fixes the ratio $K_\perp/K_\parallel$ of the diffusion coefficients perpendicular and parallel to the magnetic field lines beyond the orbit of the earth $K_\perp$ controls the diffusion across the field lines and is responsible for reducing the pressure gradient. $K_\parallel$ controls the inward diffusion along the field lines. If the ratio $K_\perp/K_\parallel$ is too small diffusion across the field lines is inhibited and the pressure gradient will balance out the electric drift. If $K_\perp/K_\parallel$ is too large then the particles will be able to diffuse across the field lines with great ease and the pressure gradient will be completely wiped out and the maximum possible amplitude of (.73%) should be observed. Parker has shown that the value $K_\perp/K_\parallel = 10^{-2}$ (beyond the orbit of the earth) will give the right order of magnitude of cosmic ray streaming to account for the observed amplitude of the diurnal variation. He has also pointed out that this value of $K_\perp$ compares very favourably with the value obtained [illegible] for this ratio from power spectra analysis of interplanetary magnetic field fluctuations observed by space probes, (JOKIPII 66, 67) for particles in the energy range 0.05 Gv–10Gv. However, more recently Jokipii and Parker (1968, b) seem to be of the opinion that the values of $K_\perp$ are considerably larger than their earlier estimate. They suggest that $K_\perp$ has two contributions, one due to resonance scattering by irregularities in the interplanetary field and the other due to a random walk of the magnetic field lines themselves. The latter effect is due presumably to fluctuations and perturbations in the solar photosphere where the magnetic field lines have their origin. For particles in the Mev region the second contribution is large with the result that $K_\perp$ may be approximately equal to $K_\parallel$. Values of $K_\perp \simeq K_\parallel$ are also required to explain the absence of large diurnal anisotropies in the Mev region. RAO and McCRACKEN (1967), JOKIPII and PARKER (1968a), JOKIPII et.al. also suggest that the observed solar diurnal anisotropy for particles up to a few Gv can also be explained in terms of a high value of $K_\perp / K_\parallel$ at the orbit of the earth, rather than postulating that $\frac{K_\perp}{K_\parallel} \simeq 10^{-2}$ beyond the orbit of the earth and part of the pressure gradient is present all the time as discussed above. It is interesting to note in this connection that if the amplitude of the diurnal anisotropy depends on $\frac{K_\perp}{K_\parallel}$ as discussed above, then at least in the low rigidity region, (up to a few Gv) the anisotropy will be dependent on rigidity insofar as $K_\perp$ and $K_\parallel$ are rigidity dependent. As mentioned earlier, the solar daily variation is found to exhibit considerable variability on a day to day basis and with the solar cycle. In particular, the observed amplitude of the diurnal variation is found to go down at times of solar minima. On the basis of the foregoing discussion, changes in the diurnal anisotropy can be explained in terms of changes in either $K_\perp / K_\parallel$ which will affect the free space amplitude or those in the upper limiting rigidity corotation. This is discussed more fully in chapter VI.

MARSDEN (1967) has considered the effect of an assymetric density gradient perpendicular to the plane of the ecliptic on the diurnal variation. Such a gradient has been predicted by SARABHAI and SUBRAMANIAN (1965, 66) from the fact that an assymetry is observed in the zonal activity on the surface of the sun as measured by the intensity of coronal emission (5303 A^{o}) from the northern and southern hemispheres of the sun. Thus during the period 1958-63 an excess of coronal emission was observed from the northern solar hemisphere as compared to the southern hemisphere. This can lead to a gradient of cosmic ray intensity across the plane of the ecliptic with a higher density occuring below the plane of the ecliptic than above it.

Particles from above and below the ecliptic can spiral round the magnetic field lines and enter the ecliptic plane. With an asymmetric gradient of the type described and for a magnetic field directed outwards there will be a nett flux of particles from the 1500 direction. However, when the field direction will reverse the direction of the flux will also reverse and become 0300 hours. Thus, on the average the effect can lead to no permanent change in the S.D.V. However, an additional component lasting over a few days may result from this mechanism. MARSDEN (1967) estimates this additional component to be about 0.3% for the case of mid latitude neutron monitors. He also points out that the effect will be energy dependent with the amplitude increasing with energy up to a high energy limit and suggests that this mechanism may well be the cause of the day to day variability of the rigidity dependence of the diurnal variation reported by Sarabhai etc. (1965).

On the other hand, QUENBY and LIETTI (1967, 68) suggest that a symmetric gradient will exist with respect to the ecliptic plane, with the cosmic ray density being minimum in the plane of the ecliptic and increasing with latitude on both sides of this plane. Such a gradient is a natural consequence of the fact that the interplanetary magnetic field is less tightly wound in the polar zones than in the solar equatorial plane. As a result, galactic cosmic ray particles entering the solar cavity at high helio latitudes will follow almost straight lines and suffer much less modulation than those arriving in the solar equatorial plane. The intensity of the cosmic ray particles will, as a result, be greater at higher latitudes off the ecliptic plane.

QUENBY (1968) has suggested that a radial streaming may be generated from the direction of the sun because of this gradient. Particles coming into the solar system via the solar polar zones will be pushed out into the plane of the ecliptic, thereby generating a streaming in the radial direction and therefore a radial component to the diurnal variation. (The magnitude of this radial streaming can be as high as about 20% of the velocity of the solar plasma QUENBY (1968)).

They have also suggested that this symmetric gradient will be directly responsible for a semi-diurnal variation. The mechanism by which this is generated is explained as follows. When looking at right angles to the spiral field lines a maximum intensity will be observed because the particles moving in this direction belong to a guiding centre density one gyro radius above or below the equatorial plane. Particles arriving along the field lines belong to the density in the equatorial plane. A maximum flux will therefore be observed when looking at right angle to the field direction and a minimum while looking along the field direction. A semi-diurnal variation will result in a time of maximum at 0300 hours and 1500 hours respectively. QUENBY et.al. (1968) predict a first power of rigidity dependence for the semi-diurnal variation so generated. The peak to peak amplitude is suggested to be:

$a_2 = 0.005 \ P \%$ where P is the particle rigidity.

In the following chapter we shall describe the experimental results obtained by means of the directional recorders at LONDON and MAKERERE and see how these results compare with the predictions of the current models of the solar anisotropy and the result obtained by other workers.

CHAPTER V

SOLAR DAILY VARIATION II

(EXPERIMENTAL RESULTS)

5.1 INTRODUCTION:-

The solar daily variation has been measured at,

1) A medium latitude station, LONDON (51.53 N, 0.09 W), by means of two inclined cubical telescopes pointing towards the NORTH and the SOUTH directions, during the period Aug 1965 to May 1968.

2) A low latitude station, MAKERERE in UGANDA (00.3 N, 32 E), by means of two inclined cubical telescopes pointing towards the EAST and WEST directions over the period JLY 1964 to APR 1967.

Results obtained from this study of the diurnal and semi-diurnal variations over the period of minimum solar activity and during the ascending phase of the solar cycle (No. 20) will be presented in the following sections.

5.2 ANALYTICAL PROCEDURE:

The bihourly counting rates (scaled by factors of 100 and 1000 respectively), from the MAKERERE and LONDON recorders were corrected for variations in atmospheric pressure using pressure coefficients of -0.21%/m.b. and -0.185%/m.b. respectively, obtained by correlation analysis procedures described in Chapter 3. No correction could be applied for variations in atmospheric temperature over the period of a day because of lack of temperature data.

Any effects associated with changes in upper air temperature will be accounted for separately. These pressure corrected bihourly counting rates were then summed over a period of a month to obtain 12 mean bihourly pressure corrected values/month/channel.

It is usually found adequate to describe the solar daily variation in terms of the first and second harmonics.

The first and second harmonics of the continuous curve corresponding to the 12 bihourly pressure corrected counting rates/ month have been calculated according to the scheme given by CHAPMAN and BARTELLS (1940). Harmonic analysis of the data in this manner yields the coefficients a1,b1 and a2,b2 for the first and second harmonics c1,c2 respectively. These are usually plotted on a harmonic dial in such a way that an,bn are the coordinates of the end point of the vector cn, which represents the nth harmonic in phase and amplitude.

Data from both the sets of telescopes located at LONDON and MAKERERE have been analysed in this manner on a month by month basis for the entire period of their operation. The average diurnal and semi-diurnal variations over a calender year can be easily obtained from the monthly values of a1,b1 and a2,b2. In the calculation of the mean pressure corrected bihourly counting rates for a month, care has been taken to include only those days in the summation when both the recorders used at a particular station were operative for at least 20 hours in a given day. The harmonic analysis has therefore been confined to identical days for both stations.

In the method of analysis described above no precautions had been taken to correct for non-cyclic variations in the cosmic ray intensity. Since such a variation, due either to a drift in the efficiency of the recorders or to a change in the general level of the cosmic ray intensity itself, can cause spurious components to the daily variation, the data obtained at both LONDON and MAKERERE has been reanalysed in a manner to take into account the "curvature" in the data and the changes in the mean level of the intensity. The method of "MOVING AVERAGES" has been adopted. For each bihourly value a 24 hour mean level has been calculated from six bihourly values on either side of it. Percent departures have then been calculated from each bihourly value and its corresponding mean. The harmonic analysis is then carried out on the 12 bihourly departures obtained for each day. Only those days have been used in which all the bihourly values are present. All days on which the cosmic ray intensity dropped by several percent as a result of Forbush decreases were excluded from the analysis.

The average value of the diurnal and semi-diurnal variations for periods of any length can be obtained from the values of the first and second harmonics for all days comprising the period. Mean values of the diurnal and semi-diurnal variation over yearly periods have been obtained for both stations by the two methods.

In practice it has been found that there was no significant difference between the results obtained by the two methods. This indicated that the effect of curvature and drift are negligible on the data presented in the following. The estimate of the daily variation on a day by day basis has however been used to calculate the error on the diurnal and semi-diurnal vectors as described in the following section.

5.3 ERRORS ON THE DAILY VARIATION:

The errors on the first and the second harmonics of the daily variation can be estimated from the statistical fluctuations of the counting rate. If N is the mean counting rate from a telescope the standard POISSONIAN FLUCTUATION on this value is SQRT(N). The error on the daily variation for a given period can be calculated from the mean bihourly counting rate for this period. From such a definition the error on the daily variation at MAKERERE and LONDON for an annual period will be 0.004% and 0.007% respectively. Such an estimate is founded on the assumption that the secondary particles recorded by the telescopes are randomly distributed and the only contribution to the error is from statistical fluctuations.

However, it is known that the daily variation as measured on a day by day basis exhibits considerable variability. In view of this we have used the daily values of the first and second harmonics calculated for MAKERERE and LONDON to estimate the errors on the mean diurnal and semi-diurnal variations, from a study of the scatter of the diurnal and semi-diurnal vectors by the method of the "CLOUD OF POINTS" e.g. DORMAN (1957), CHAPMAN and BARTELLS (1940).

The HARMONIC coefficients determined for each day can be plotted on a harmonic dial. If the period of observation contains a sufficient number of days we get a cloud of points. The dispersion of the points on the harmonic diagram is characterised by the ellipse of probable errors, within which lie half of all the points of measurement. The parameters characterising the ellipse, viz, the major and minor axes, can be calculated from the an and the bn values of the harmonic coefficients on a day to day basis. If the a's and the b's are correlated for the relevant period the error ellipse will have a high eccentricity; if the correlation is low the error ellipse will tend to a circle. In practice if the eccentricity of the ellipse is not great the dispersion of the cloud of points can be specified by a single parameter M which may be called the two dimensional standard deviation in so far as it is calculated from the standard deviations of the a's and the b's as follows;

$$M^2 = (\text{SIG A})^2 + (\text{SIG B})^2$$

We calculated the errors on the diurnal and semi-diurnal vectors obtained at LONDON and MAKERERE by this procedure. The parameters characterising the ellipse of probable error for the different periods of analysis are given in tabular form overleaf, for MAKERERE and LONDON. An examination of Table I shows that the ellipse of probable errors is never very eccentric and can be approximated by a circle. In view of this the two dimensional standard deviation is a fair approximation to the error on the diurnal and semidiurnal vectors.

TABLE I

PARAMETERS CHARACTERISING THE ELLIPSE OF PROBABLE ERRORS AT LONDON AND MAKERERE DURING SEVERAL PERIODS OF ANALYSIS.

CHANNEL	YEAR	SIGMA A %	SIGMA B %	MAJOR AXIS	MINOR AXIS	COR-COEFF	THETA deg	2-D-ERROR %
LONDON								
NORTH	AUG65-DEC65	0.148	0.118	0.177	0.137	-0.002	-0.26	0.019
	1966	0.199	0.184	0.246	0.203	+0.006	2.37	0.016
	1967	0.212	0.200	0.262	0.227	0.005	2.07	0.019
SOUTH	AUG65-DEC65	0.158	0.156	0.187	0.184	+0.003	0.76	0.023
	1966	0.187	0.216	0.255	0.220	0.0019	-0.4	0.016
	1967	0.192	0.225	0.265	0.227	0.001	-0.8	0.017
MAKERERE								
WEST	JLY64-JUN65	0.187	0.239	0.283	0.219	0.003	-0.37	0.017
EAST	JLY64-JUN65	0.216	0.306	0.366	0.248	0.011	-0.9	0.021
WEST	JLY65-JUN66	0.208	0.253	0.299	0.243	0.004	-0.6	0.018
EAST	" "	0.229	0.298	0.351	0.269	-0.002	+0.2	0.021
WEST	1966	0.207	0.235	0.287	0.231	0.008	-1.9	0.016
EAST	1966	0.220	0.225	0.276	0.248	-0.005	7.03	0.017

5.4 THE SOLAR DAILY VARIATION MEASURED AT MEDIUM LATITUDES: (LONDON).

The solar daily variation of the (pressure corrected) cosmic ray intensity as measured at LONDON has been obtained by methods described in the preceding section. The errors on the mean diurnal and semi-diurnal vectors for any particular period have been evaluated by the method of the cloud of points, from a study of the scatter of the diurnal and semi-diurnal vectors on each day comprising the period.

The London telescopes have been in continuous operation from Aug. 1965 and the data obtained up to May 1968 has been harmonically analysed for the diurnal and semi-diurnal components. The first and second harmonics of the daily variation have been grouped for annual periods as follows:-

I AUG 1965 to JLY 1966

II AUG 1966 to JLY 1967

III JUN 1967 to MAY 1968.

The results for these periods have been summarized in table II and fig. 1. It may be pointed out that during the period AUG 1967 to SEP 1967 both the telescopes were made to point towards the SOUTH direction (for purposes of a temperature test) and therefore data for the NORTH direction are missing for this period.

There are several advantages in grouping data in annual groups as above:

1) An average over an annual group reduces the statistical error

to a reasonable value.

2) Any seasonal modulation of the diurnal and semi-diurnal vectors due to imperfect meteorological corrections or due to a seasonal variation in the primary intensity will be averaged out.

3) Any SIDEREAL components due to a flow of excess particles in a fixed direction will be removed by averaging over the period of a year.

TABLE II

Daily Variation results obtained at London.

CHANNEL	Period	First Harmonic		Second Harmonic	
		Amplitude %	Phase hrs(L.S.T.)	Amplitude %	Phase hrs(L.S.T.)
North	Aug 65-Jly 66	0.122 ±0.0141	12.73	0.02 ±0.01	11.66
South	Aug 65-Jly 66	0.167 ±0.019	15.00	0.069 ±0.012	1.79
North	Aug 66-Jly 67	0.137 ± .019	13.33	0.023 ±0.011	10.00
South	Aug 66-Jly 67	0.130 ± .017	15.40	0.056 ±0.011	1.53
North	Jun 67-May 68	0.106 ± .017	13.13	0.023 ± .012	0.47
South	Jun 67- May 68	0.210 ± .017	16.2	0.062 ± .012	1.86

An examination of TABLE 2 and fig. 1 shows:

1) Within the errors of observation the amplitudes of the diurnal waves for the NORTH and the SOUTH telescopes are the same, for all the three periods considered.

2) The phase of the diurnal variation as measured by the NORTH pointing telescope is about two hours earlier than that for the SOUTH. As mentioned earlier in Chapter 4 this phase difference between the diurnal vectors is an indication of the anisotropy being of primary origin.

3) The semi-diurnal variation as recorded by the NORTH pointing telescope is about half the value measured by the SOUTH pointing telescope. The small amplitude of the North second harmonic causes a greater uncertainty in the phase; however, the nominal phase of the second harmonic variation recorded by the North telescope is earlier than that for the South telescope, as in the case of the first harmonic.

4) There appear to be no significant changes in the first or the second harmonics during the three years of data averaged in annual groups as above.

As has been mentioned in Chapter 4 the diurnal variation as measured by meson telescopes and ionization chambers had shown amplitude and phase changes during the solar minimum of 1954. DUGGAL et. al. (1967) have found a 30% reduction in the diurnal anisotropy in 1965 as compared to 1958. AHLUWALIA etc. also find a reduction as mentioned earlier. The maximum cosmic ray intensity (as measured by Neutron monitors), which corresponds to a minimum modulation by the interplanetary magnetic field, was recorded during the middle of 1965. The LONDON telescopes came into operation in August 1965 and therefore we have data covering the ascending phase of the new solar cycle. (No 20). We have looked at the data in greater detail so as to pin-point any changes in the solar daily variation as measured by the NORTH/SOUTH telescopes as the solar activity builds up.

Since the monthly values of the diurnal variation show a large scatter which prevents any significant conclusions to be drawn we have averaged the diurnal vectors for the North and South telescopes over three monthly batches to reduce the statistical fluctuations. These three monthly vectors starting from August 1965 have been plotted in Fig 2. It is seen from this figure that the diurnal vectors for both the North and South directions show time dependent changes during the period AUG 1965 to MAY 1968. In view of the rather large errors it is not possible to draw very significant conclusions; however, the diurnal variation as measured by both telescopes does show a tendency to increase during the periods of observation corresponding to 1966 as compared to those in 1965. Both channels however show a reduction during a group of three months in 1967. After this period, however, the vectors again tend to larger values. We have also analysed data from the

Table III

Daily variation results obtained at London

Channel	Period	First Harmonic		Second Harmonic	
		Amplitude %	Phase (hrs L.S.T.)	Amplitude %	Phase (hrs L.S.T.)
North	Aug 65 - Dec 65	0.09 ±0.019	12.27	0.013 ±0.016	11.33
South	Aug 65 - Dec 65	0.080 ±0.023	13.86	0.037 ±0.016	1.26
North	Jan 66 - Dec 66	0.142 ±0.016	13.33	0.020 ± .010	11.32
South	Jan 66 - Dec 66	0.171 ±0.016	15.46	0.071 ±0.011	1.86
North	Jan 67 - Dec 67	0.131 ± .019	12.53	0.014 ± .013	9.01
South	Jan 67 - Dec 67	0.148 ± .017	15.07	0.046 ± .011	1.66

Neutron monitor at DEEP-RIVER over a period AUG 1965 to JULY 1967. A similar tendency showing an increase of the diurnal variation during the year 1966 and a reduction during the middle of 1967 is detectable.

To avoid large statistical errors and make the results directly comparable with other stations we have averaged the diurnal and semi-diurnal vectors for the North/South telescopes over the following periods:-

I	AUG 1965 to DEC 1965
II	JAN 1966 to DEC 1966
III	JAN 1967 to DEC 1967.

Since results are usually presented over calendar years, this makes them directly comparable with those from other stations. The average for 1965 however only corresponds to five months data. The results grouped according to this scheme are presented in TABLE III and fig. 4. The errors on the vectors have been calculated from a study of the scatter of the vectors on individual days.

Figure 4 brings out the following points:-

1) The diurnal amplitudes corresponding to the periods August 1965 to December 1965 are considerably smaller than those for the periods 1966 and 1967 for both the North and the South directions. The increase in the South telescope is more pronounced than that in the North. No significant increase has occurred in 1967 as compared to 1966.

2) The phase difference between the NORTH and SOUTH first harmonics has increased considerably in going from 1965 to 1966. No significant change, however, is evident during 1967 as compared to 1966.

3) The second harmonic for the South direction has also shown a significant increase in going from 1965 to 1966. There has been a slight reduction in 1967. The second harmonic for the North direction has remained invariant within the limits of the errors, which are rather large compared to its amplitude.

In order to see whether the increase in the diurnal amplitude in 1966 as compared to 1965, observed at LONDON, is also seen in neutron monitor data we have averaged the DEEP RIVER neutron monitor data over directly comparable periods as follows:-

I AUG 1965 to DEC 1965

II JAN 1966 to DEC 1966.

The results are plotted in Fig. 5. The figure shows that the Deep River daily variation shows a significant increase in 1966 over its value in 1965. However, whereas the South telescope in

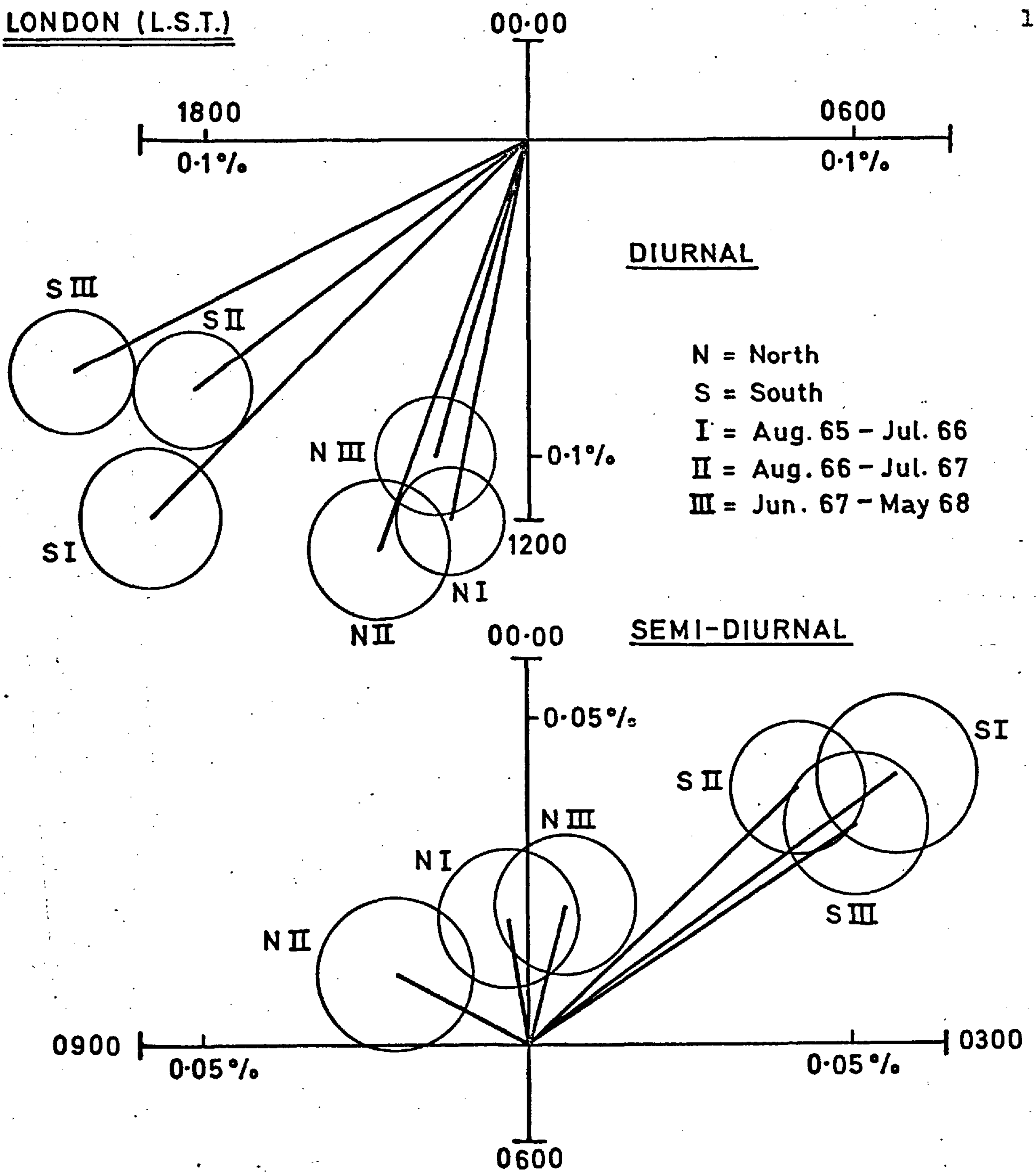


Fig. 1. Solar diurnal and semi-diurnal vectors as recorded by the London (North/South) telescopes over the period Aug 65 – May 68. (Grouped as indicated).

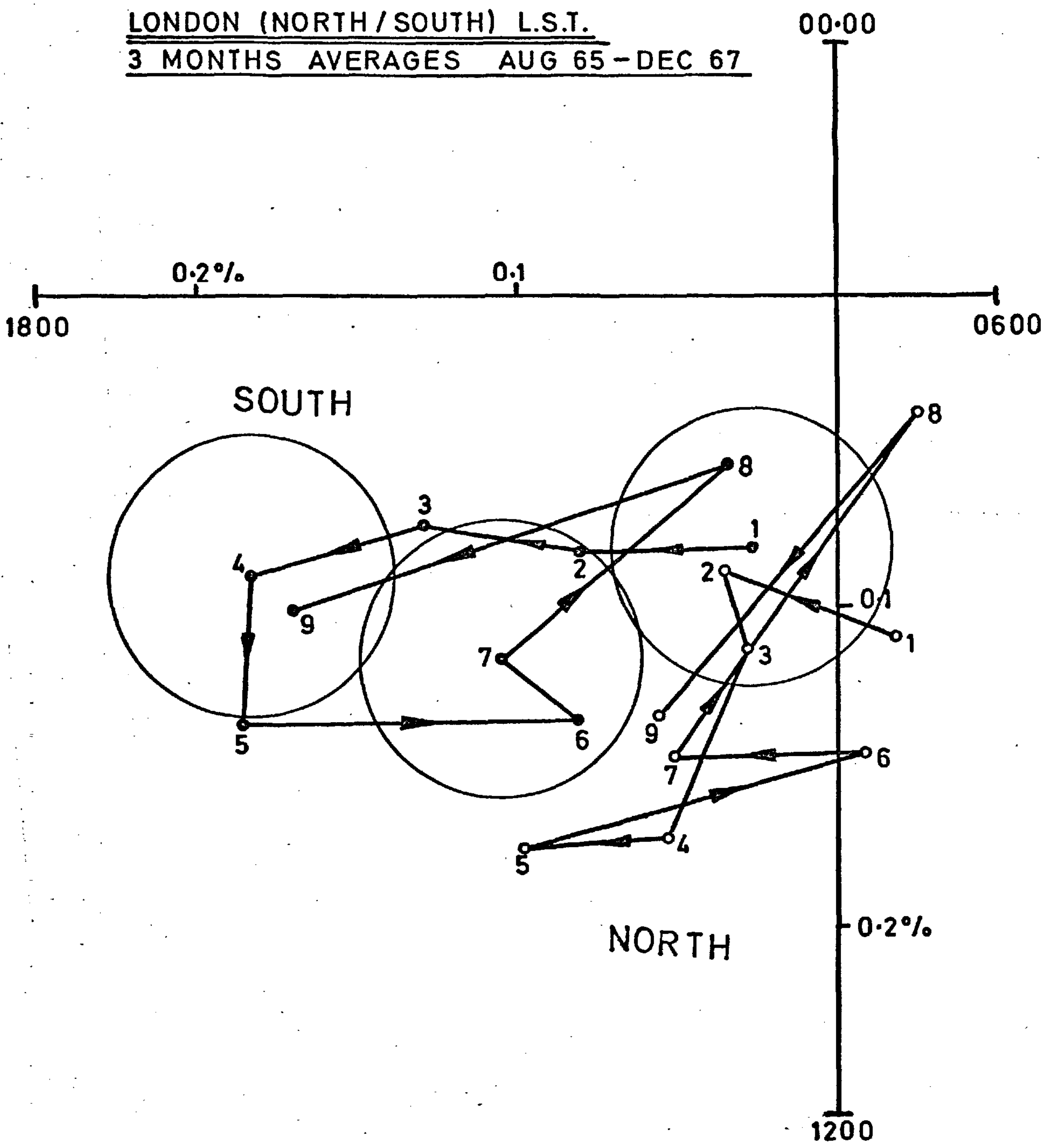


Fig. 2. End points of the solar diurnal vectors observed by the North/ South telescopes, averaged over three monthly batches over the period Aug 1965 - Dec 1967.

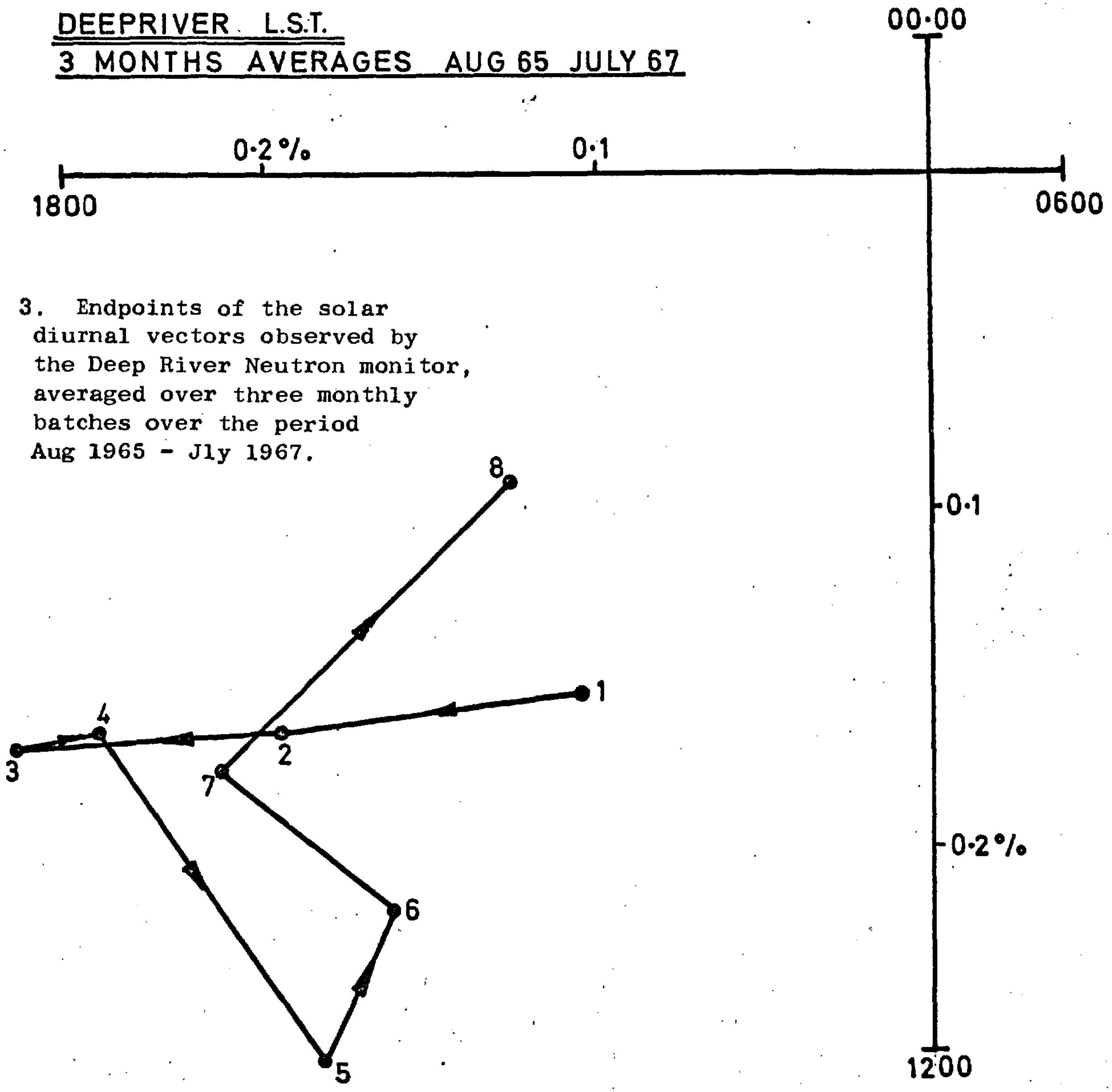


Fig. 3. Endpoints of the solar diurnal vectors observed by the Deep River Neutron monitor, averaged over three monthly batches over the period Aug 1965 - Jly 1967.

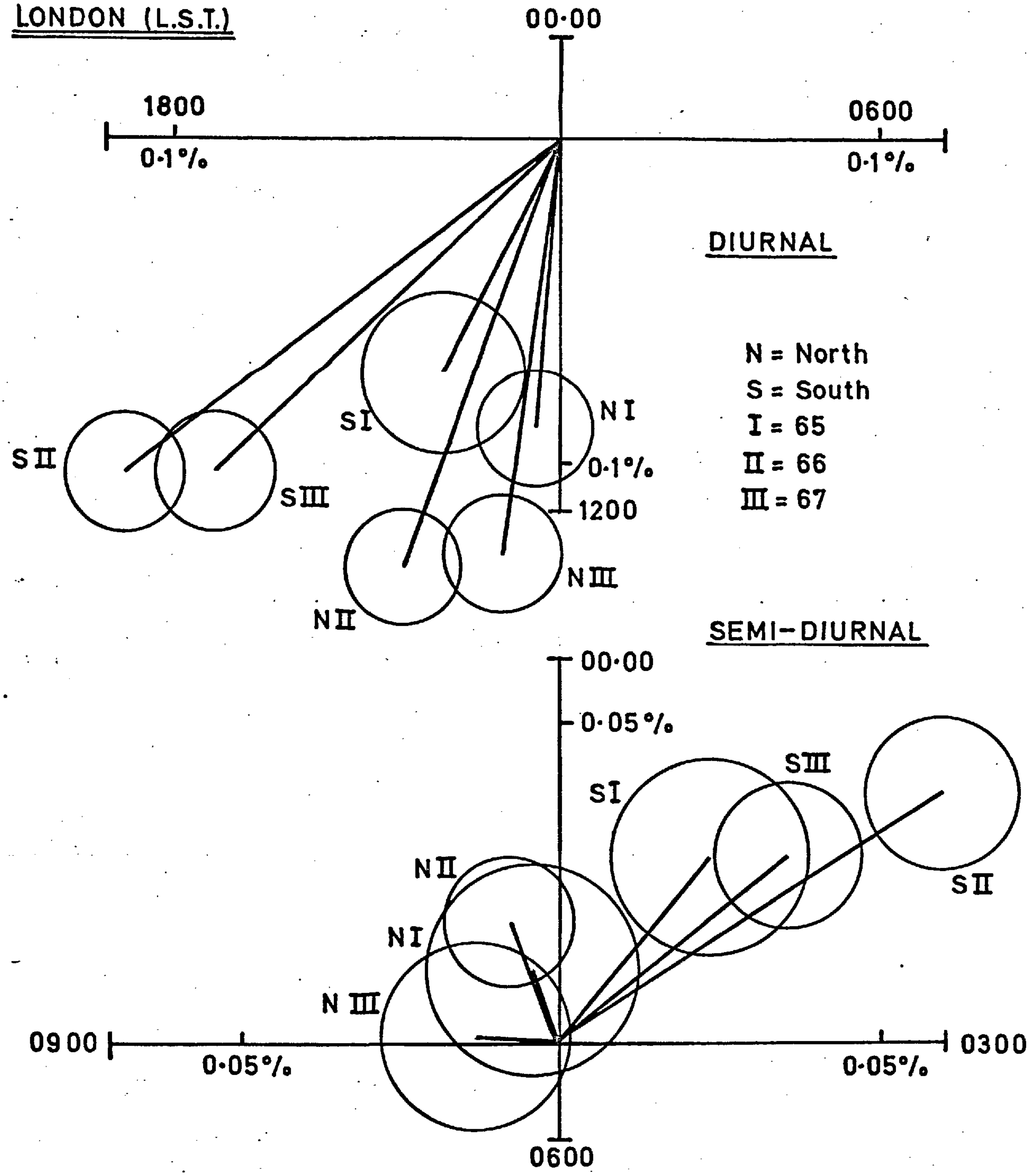


Fig. 4. Solar diurnal and semi-diurnal vectors observed by the London (North/South) telescopes averaged over calendar years 1965,66,67.

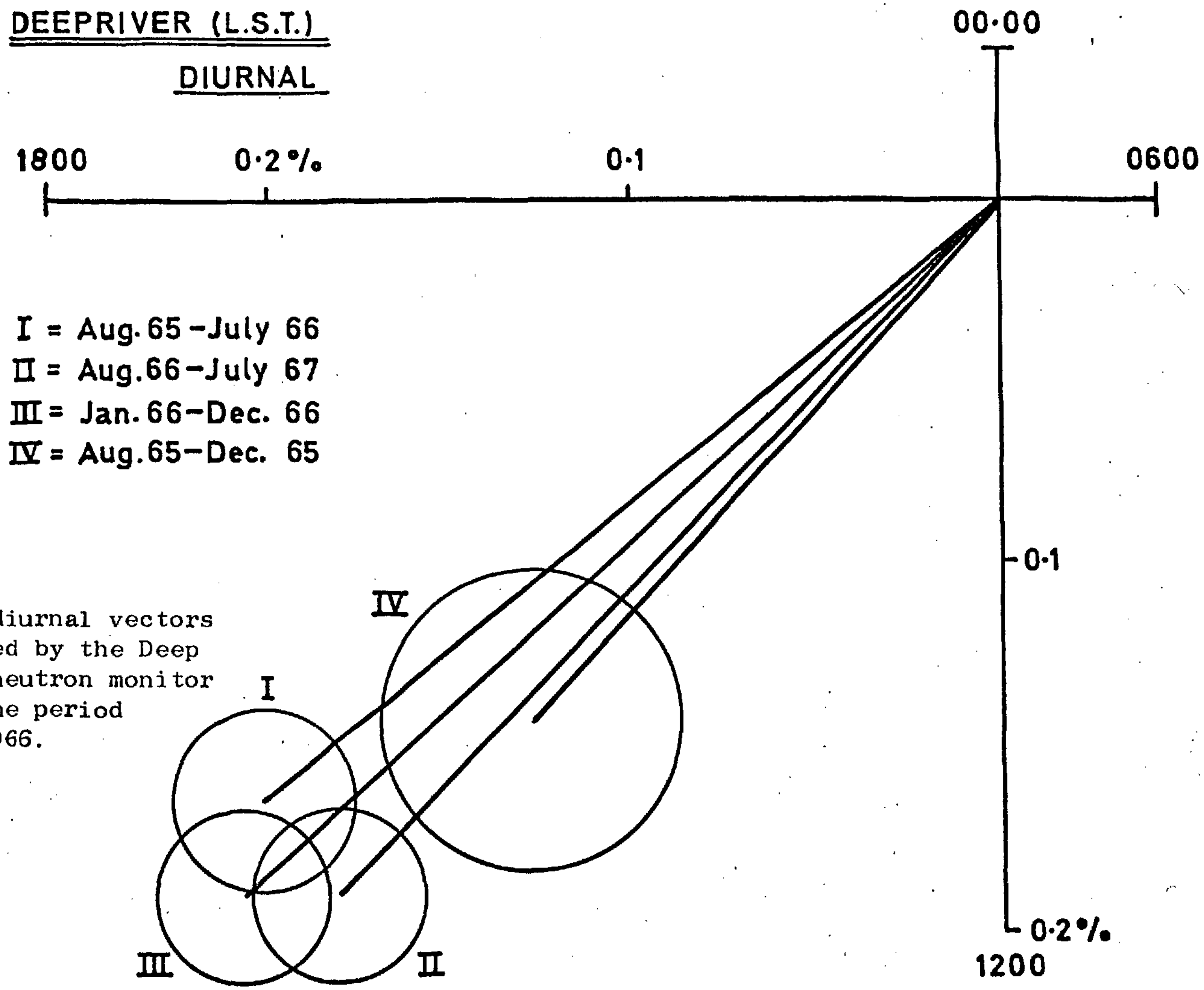
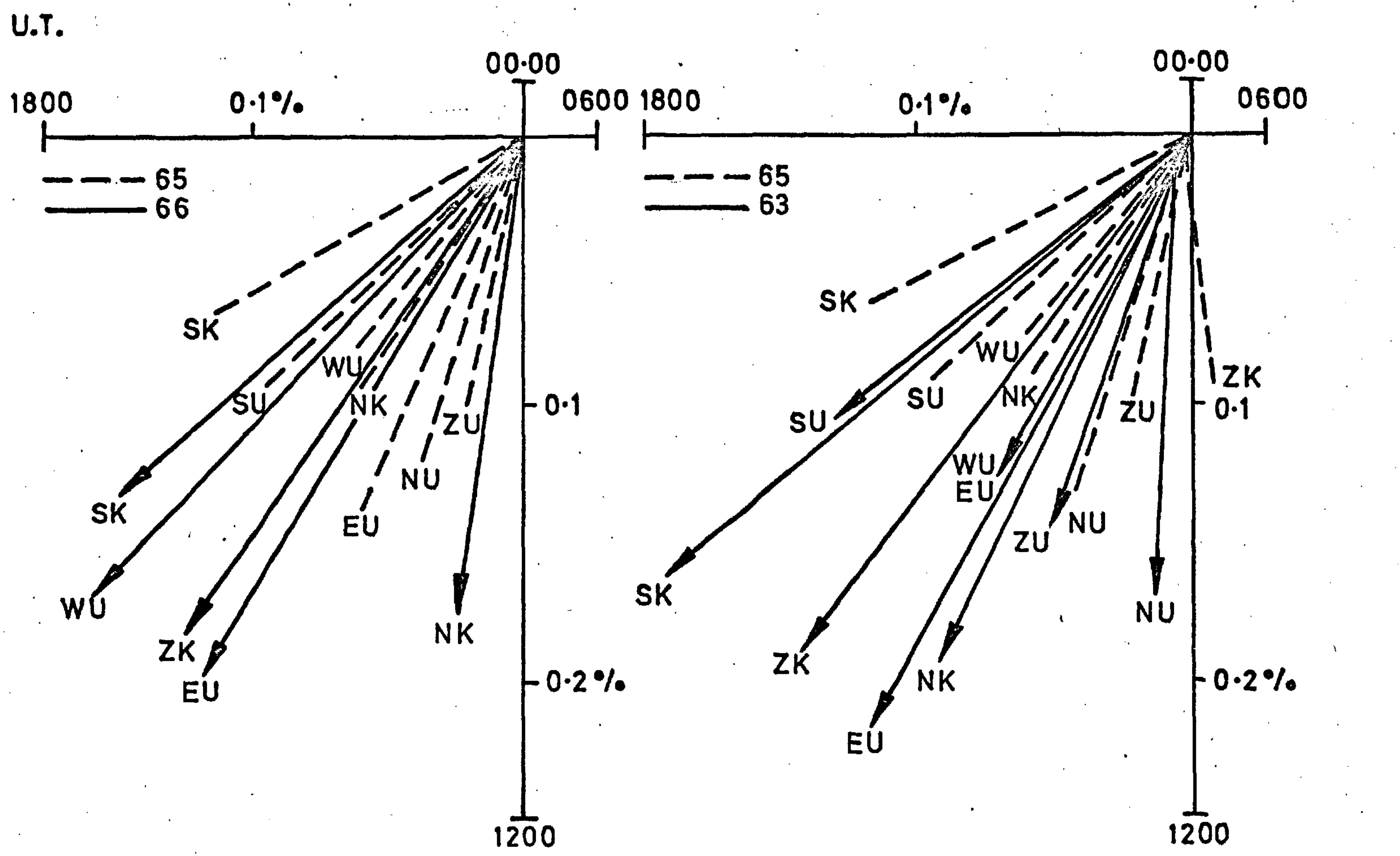


Fig. 5. Solar diurnal vectors observed by the Deep River neutron monitor over the period 1965-1966.

London showed almost double the amplitude in 1966,1967 as compared to 1965 the Deep River neutrons have shown a much smaller difference between the two years.

The daily variation has been studied extensively at UPPSALA (59.85 N, 17.92 E) and KIRUNA (67.83 N, 2093 E) in SWEDEN by SANDSTROM et. al. (65,66), using directional and vertical meson telescopes. Figures 6 and 7 show the diurnal variation as measured by the E/W, N/S and vertical telescopes at UPPSALA and KIRUNA, during the 1965, 1966 and 1963, 1966 respectively. It is obvious from this figure that the diurnal variation at these stations had shown a definite reduction during 1965 as compared to 1963 and that it had increased to its former value in 1966. These changes were shown by all the seven channels operating at these two stations. It may be mentioned here that the meson telescope data will be affected by temperature changes in the atmosphere. However, since the temperature correction will be the same for each yearly period, we are justified in comparing uncorrected values.

The results proposed in the foregoing sections point to the conclusion that the diurnal anisotropy had reduced during the year 1965, the year of maximum cosmic ray intensity, and has recovered since then. No large changes in the phase of the diurnal variation as observed during the last solar minimum in 1954 were evident.



K = Kiruna
U = Uppsala
S = South
W = West
N = North
E = East

Fig. 6,7. Solar diurnal vectors observed by the inclined and vertical meson telescopes at Kiruna and Uppsala for the years 1963, 1965, 1966.

Comparison of the changes observed at medium and low energies:

The daily variation observed by the neutron monitors situated at a high latitude station reflects the effect of the modulation of the cosmic ray primaries in a lower energy range as compared to a meson telescope situated at a medium latitude station. Since the intensity recorded by the neutron monitor is relatively independent of changes in atmospheric temperature, the characteristics exhibited by the diurnal and semi-diurnal anisotropies of the pressure corrected N.M. intensity reflect the changes in the Interplanetary or geomagnetic conditions, without any aberrations. As a result of a detailed study of the diurnal variation as measured by the neutron monitors (McCRACKEN et. al. 1965) it has been found that the amplitude of the diurnal anisotropy assumes values anywhere between 0.1% and 0.7% (after correction for geomagnetic effects) when studied on a day to day basis. The value of 0.4% quoted in the earlier chapter (IV) represents an average over a sufficiently long period of time.

We have investigated in detail the correlation between the diurnal anisotropy at medium energies as measured by the NORTH/SOUTH telescopes situated at LONDON and the lower energies monitored by a neutron monitor at a high latitude station (DEEP RIVER).

The pressure corrected cosmic ray data obtained from the Deep River neutron monitor, for the period August 1965 to July 1967, has been harmonically analysed on a day by day basis. The daily amplitudes thus obtained have been grouped into three classes according to the following scheme:

GROUP I The diurnal variation as measured by the Deep River neutron monitor is less than 0.2%.

GROUP II The diurnal variation measured by the Deep River neutron monitor lies between 0.2 and 0.4%.

GROUP III The diurnal variation measured by the Deep River neutron monitor is greater than 0.4%.

The first and second harmonics of the Deep River neutrons, grouped according to this scheme are shown in figure 8. The day to day harmonic coefficients obtained by the harmonic analysis of the North/South data on a daily basis have also been grouped according to the daily variation measured by the neutron monitor. (Thus the data on all those days over which the Deep River neutron monitor shows a large diurnal variation have been grouped together etc.) The results for the North/South telescopes are plotted in figure 9. The following points are evident from this figure:-

1) The first harmonics of the N/S telescopes follow closely the amplitude variations exhibited by the Deep River neutron monitor.

2) Within the limits of errors no systematic changes in phase can be discerned, along with the changes in amplitude, either for the neutrons or for the mesons.

3) There is a tendency for the second harmonics to be larger for days on which the first harmonics are the largest. This is

so for both the Deep River and the North/South data.

4) The ratios between the first harmonics for the Deep River and the N/S data for the three groups are as follows:-

RATIO	GROUP I	GROUP II	GROUP III
NORTH/DEEP RIVER	1.28 ± 0.63	0.535 ± 0.14	0.555 ± 0.168
SOUTH/DEEP RIVER	1.42 ± 0.61	0.696 ± 0.131	0.622 ± 0.173

While calculating these ratios the N/S data has been corrected for atmospheric temperature effects assuming a vector of 0.06% at 0600 hours. The justifications for assuming this temperature vector are discussed in chapter VI. Within the limits of errors the ratios are seen to be equal for the three groups of data. This can be taken to mean that within the limits of the errors the same energy dependence applies for the high medium and low diurnal amplitudes observed in the Deep River and N/S data. (In view of the large errors for the 'low' days, this cannot be established with certainty for this group of data.)

Correlation with geomagnetic activity

The Ap index has been used to characterise the level of geomagnetic activity. The daily variation has been studied as a function of the level of geomagnetic activity for the N/S telescopes and the Deep River Neutron Monitor. The day by day values of the first and second harmonics for the period August 1965 to July 1967 have been grouped according to the following scheme

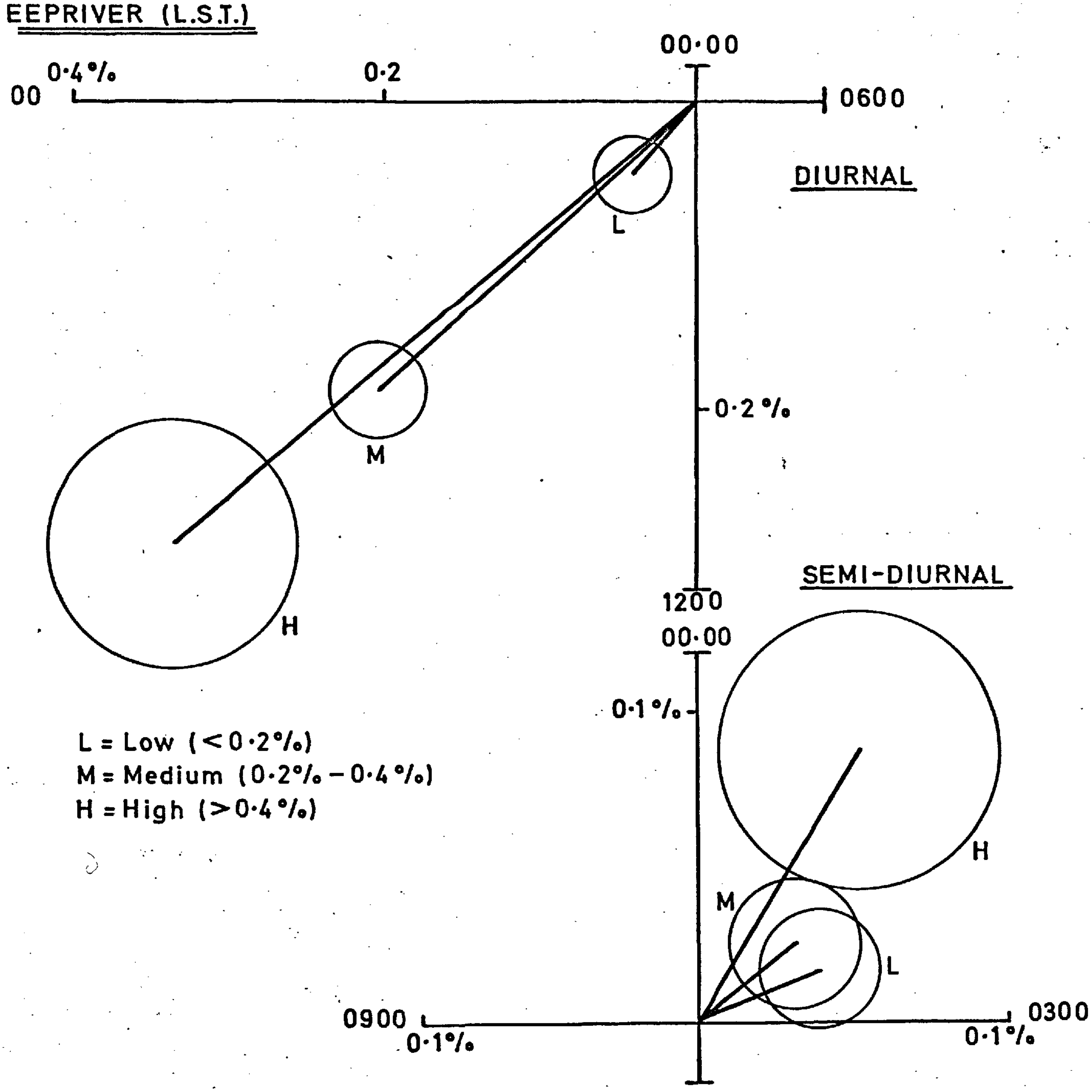


Fig. 8. Diurnal and semi-diurnal vectors at Deep River (Neutron monitors). Grouped into high, medium and low days, according to the diurnal amplitudes on individual days. Analysis carried out over the period Aug 65 - Jly 67.

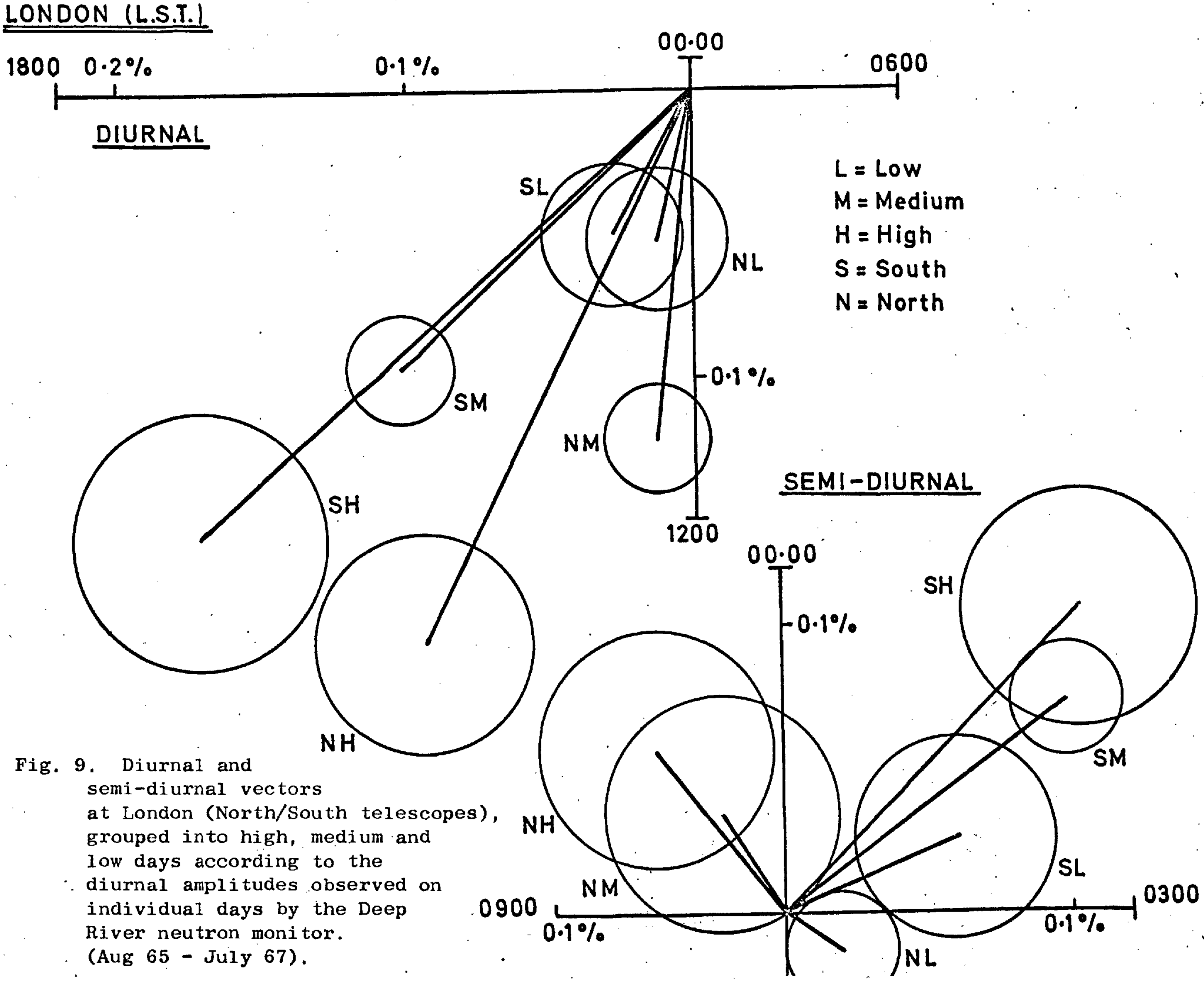


Fig. 9. Diurnal and semi-diurnal vectors at London (North/South telescopes), grouped into high, medium and low days according to the diurnal amplitudes observed on individual days by the Deep River neutron monitor. (Aug 65 - July 67).

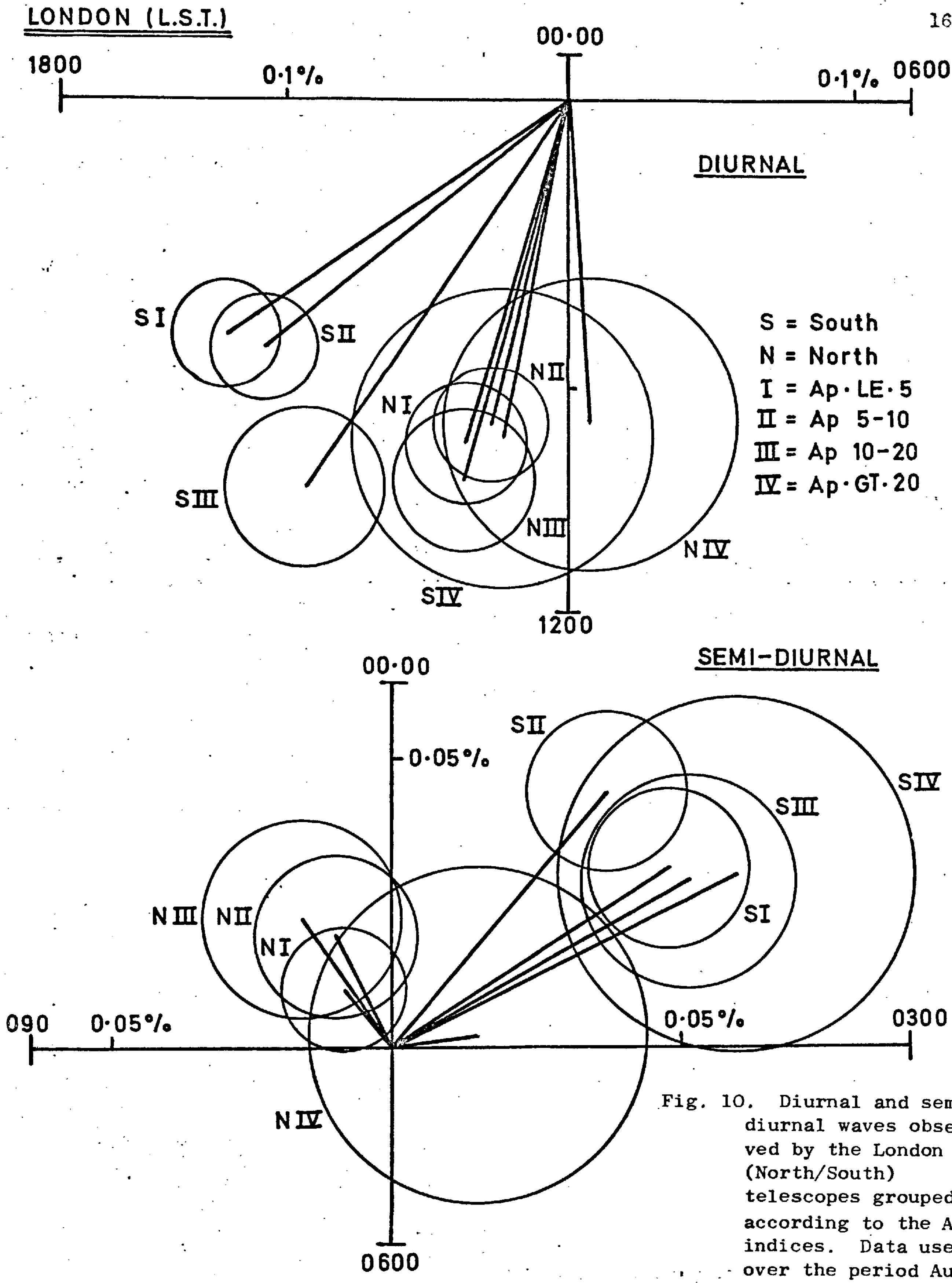


Fig. 10. Diurnal and semi-diurnal waves observed by the London (North/South) telescopes grouped according to the Ap indices. Data used over the period Aug 65 - Jly 67.

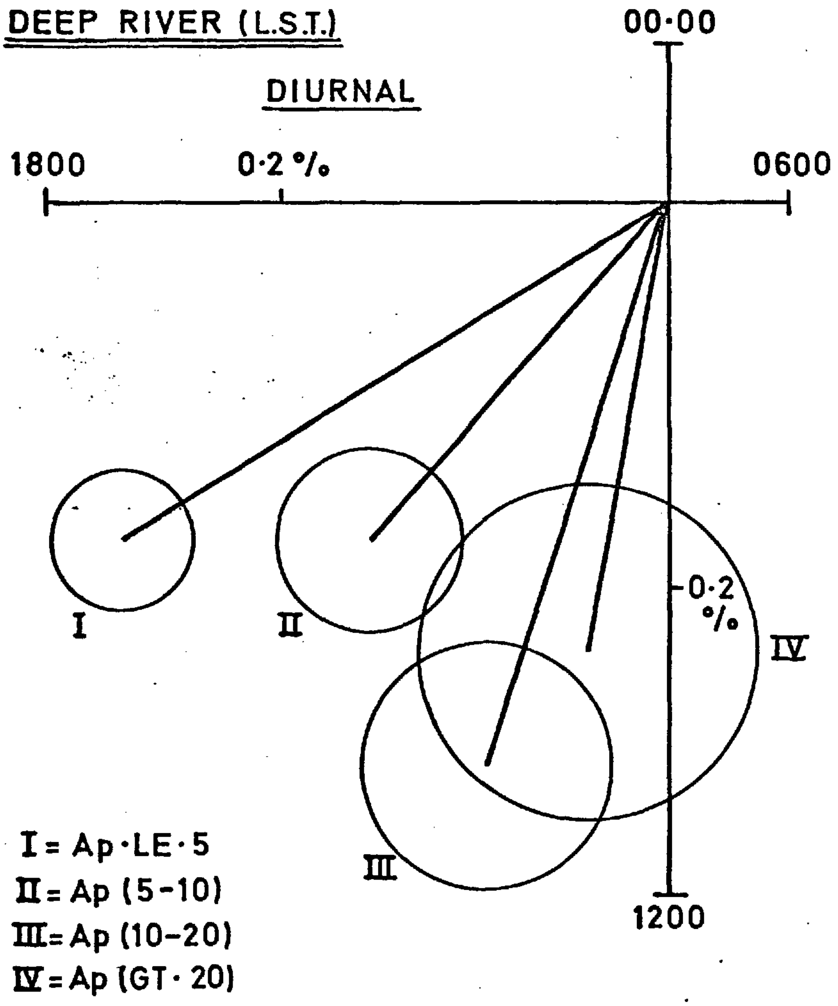


Fig. 11. Diurnal and semi-diurnal waves observed by the Deep River neutron monitor grouped according to the Ap indices, over the period Aug 65 - Jly 67.

for the N/S telescopes and the Deep River monitor:-

GROUP I Ap is $\leq$ 5

GROUP II Ap lies between 5 and 10

GROUP III Ap lies between 10 and 20

GROUP IV Ap is greater than 20

The results for the N/S telescopes and the Deep River neutrons are presented in figure 10 and 11 respectively. From this figure we observe 1) The first harmonics of the Deep River neutron monitor show a tendency to go to earlier hours as the Ap index increases. No change in amplitude can be detected within the limits of errors. 2) The first harmonics for the South telescope show a slight tendency similar to the Deep River monitor in so far as the phase of the last two groups is earlier than those of the first and second. However, no significant change can be noticed in the case of the North telescope.

3) The second harmonics show no systematic variations in either the Deep River or the N/S data.

5.5. THE SOLAR DAILY VARIATION MEASURED AT LOW LATITUDES

Data from two cubical meson telescopes inclined in the E/W directions has been obtained over the period of the solar minimum of 1964-1965 and during the ascending phase of the present solar cycle. The data has been corrected for variations in barometric pressure and harmonically analysed to give the first and second harmonics of the daily variation of the cosmic ray intensity with a view to elucidate the behaviour of the primary anisotropy during the sunspot minimum and its immediate vicinity. Continuous data are available from the recorders over the period JULY 1964 to APRIL 1967.

The data may be conveniently grouped into three annual batches as follows:-

I JULY 1964 to JUNE 1965.
II JULY 1965 to JUNE 1966.
III MAY 1966 to APRIL 1967.

Though the last annual group contains data for an overlapping period of two months which have already been considered in Group II, we have preferred this grouping because of the advantages that annual groups offer as stated earlier. Data in each of these batches have been analysed harmonically on a day to day basis and the errors for each group evaluated for the scatter of the diurnal and semi-diurnal vectors during each period. The results for these periods have been summarized in table IV and fig. 12.

From this figure the following facts are evident:-

1) During the first year of observation corresponding to the minimum period of solar activity, the solar daily variation as measured by both the EAST and the WEST recorders are identical in phase and amplitude, within the limits of errors.

2) During the second year of observation the amplitudes have

reduced slightly and the phase difference has increased to a significant value (about 1 hour).

3) The third batch of data shows that the amplitudes have increased considerably, though the phase difference remains essentially the same.

4) The second harmonics observed for both the EAST and the WEST recorders retain the same amplitude for all the three years of observation. However, the vectors corresponding to the second and third batches of data show a significant phase difference between the two recorders whereas those corresponding to the first year of observation show no significant phase difference between the two directions.

These results, and in particular the lack of any appreciable phase difference between the two recorders along with the rather large amplitudes of about 0.2% for the first year of observation, cannot be reconciled with the idea of a single primary anisotropy external to the geomagnetic field. For any such anisotropy would appear with a phase difference of about 3 to 4 hours for the two recorders, with the east recorder having an earlier phase. It may be mentioned here that any temperature corrections in accordance with current ideas of the temperature effect (e.g. THAMBYAHPILLAI and QUENBY, 1961) will have a time of maximum of about 1800 hours and will not be able to cause any appreciable separation between the diurnal vectors for the E/W directions.

Table IV

Daily variation results obtained at Makerere

Channel	Period	First Harmonic Amplitude %	First Harmonic Phase (hrs L.S.T.)	Second Harmonic Amplitude %	Second Harmonic Phase (hrs L.S.T.)
West	Jly 64 - Jun 65	0.167 ± .017	15.6	0.074 ± .014	2.46
East	Jly 64 - Jun 65	0.185 ± .021	14.4	0.066 ± .015	2.00
West	Jly 65 - Jun 66	0.154 ± .018	15.8	0.098 ± .013	1.83
East	Jly 65 - Jun 66	0.135 ± .021	13.73	0.092 ± .014	0.66
West	May 66 - Apr 67	0.252 ± .021	16.1	0.092 ± .014	2.16
East	May 66 - Apr 67	0.199 ± .021	13.2	0.071 ± .014	0.73

Table V

Daily variation observed at Makerere

Channel	Period	First Harmonic		Second Harmonic	
		Amplitude %	Phase (hrs L.S.T.)	Amplitude %	Phase (hrs L.S.T.)
West	Jly 64 - Dec 64	0.208 ± .025	14.8	0.090 ± .014	3.1
East	Jly 64 - Dec 64	0.273 ± .03	14.73	0.088 ± .014	2.00
West	Jan 65 - Dec 65	0.170 ± .020	14.8	0.098 ± .012	1.83
East	Jan 65 - Dec 67	0.159 ± .020	13.86	0.090 ± .013	1.1
West	Jan 66 - Dec 66	0.220 ± .017	15.33	0.113 ± .012	1.73
East	Jan 66 - Dec 66	0.186 ± .017	13.33	0.094 ± .014	0.90

The solar daily variation has been measured by EAST/WEST telescopes at another equatorial station, CHACALTAYA in BOLIVIA (AHLUWALIA et. al. 1965) during the years of maximum and minimum activity 1958 and 1964. For purposes of comparison we have plotted the first harmonics as observed at CHACALTAYA in Fig. 12 along with the MAKERERE results. Although the periods of observation at CHACALTAYA are slightly different we observe from this figure that even during sunspot minimum conditions the amplitudes at MAKERERE were bigger than those observed at CHACALTAYA and the times of maximum substantially earlier. Comparison with the CHACALTAYA results suggests that there is an additional component contributing to the diurnal variation at MAKERERE. (We shall consider the possible causes of this additional vector later).

As it is the usual procedure to group data according to calendar years we have also calculated the average daily variation observed at MAKERERE during the calendar years 1965 and 1966. The average vectors for the last six months of 1964 are also presented. The relevant information is presented in fig. 13 and table V. From this we observe;

1) The diurnal variation for the last six months of 1964 are abnormally large when compared with the subsequent periods. The two vectors are also identical in phase.

2) The diurnal vectors corresponding to 1965 have a slight phase difference.

3) There was an increase in diurnal amplitudes is 1966 as compared to 1965 and the phase difference has also increased.

4) The semi-diurnal variations for 1965 and 1966 do not exhibit any appreciable differences.

The gradual splitting apart of the vectors and the increase in amplitudes as is observed during the years 1965 and 1966 seems to suggest that the diurnal anisotropy had begun to reappear gradually over the ascending phase of the solar cycle. We have studied the data in greater detail in order to study any systematic changes in the diurnal variation over the period of the solar minimum and during the subsequent ascending phase.

Figure 14 shows three month averages of the diurnal vectors plotted for the period JULY 1964 to APRIL 1967 in eleven groups. We note the following points from this figure:-

1) During the first two groups of months the diurnal vectors for the EAST telescope are exceptionally large as compared to the other months.

2) During the period JAN 1965 to MARCH 1966 corresponding to Figs. 3 to 7 the diurnal vectors for both telescopes are of a value 0.15% and are very close together in phase.

3) During the period APRIL 1966 to APR 1967 the vectors have become progressively larger and the phase difference has also increased to about three hours between the two telescopes.

These interesting changes in the diurnal variation over the period JULY 1964 to APRIL 1967 seem to suggest 1) In view of the small phase difference between the E/W telescopes over the period 1965 to MARCH 1966 the diurnal anisotropy appears to have been absent or at least greatly reduced during this period in the medium energy range monitores by the MAKERERE telescopes. 2) During the period APRIL 1966 to APRIL 1967 the diurnal anisotropy had begun to reappear as is evidenced by a splitting of the vectors and an increase in the measured amplitudes.

These results are in qualitative agreement with

1) the results obtained at Chacaltaya in so far as they confirm a reduction in the primary anisotropy during the solar minimum.

2) The LONDON N/S measurements in so far as they show a reduction of primary anisotropy during 1965 and an increase in 1966.

3) Underground measurements of PEACOCK et. al. who have observed that the diurnal anisotropy had gone to zero at rigidities higher than about 70 GV during the period OCT 1964 to JUN 1966. We have seen in the foregoing sections that the E/W vectors have shown an identical phase difference implying an absence or at least a great reduction in primary anisotropy during the period over which Peacock et. al. report anomalous phase shifts which they take to mean an absence of the normal primary solar anisotropy 1800 hours. The MAKERERE results therefore seem to suggest that the reduction in the primary anisotropy recorded at higher energies by underground measurements also seems to extend to lower energies as recorded

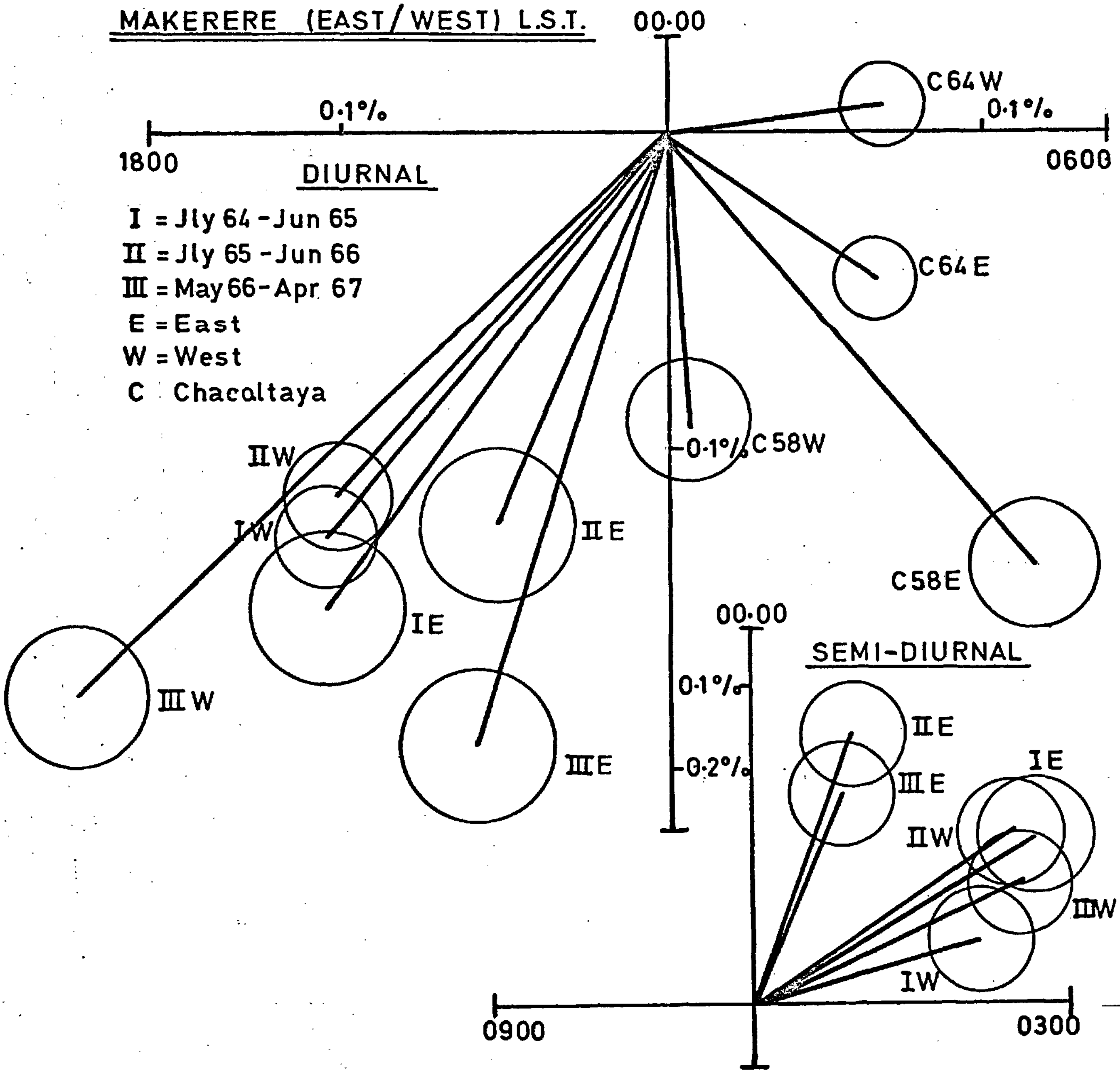


Fig. 12. Solar diurnal and semi-diurnal vectors as recorded by the Makerere (East/West) telescopes over the period July 1964 - April 1967. (Grouped as indicated).

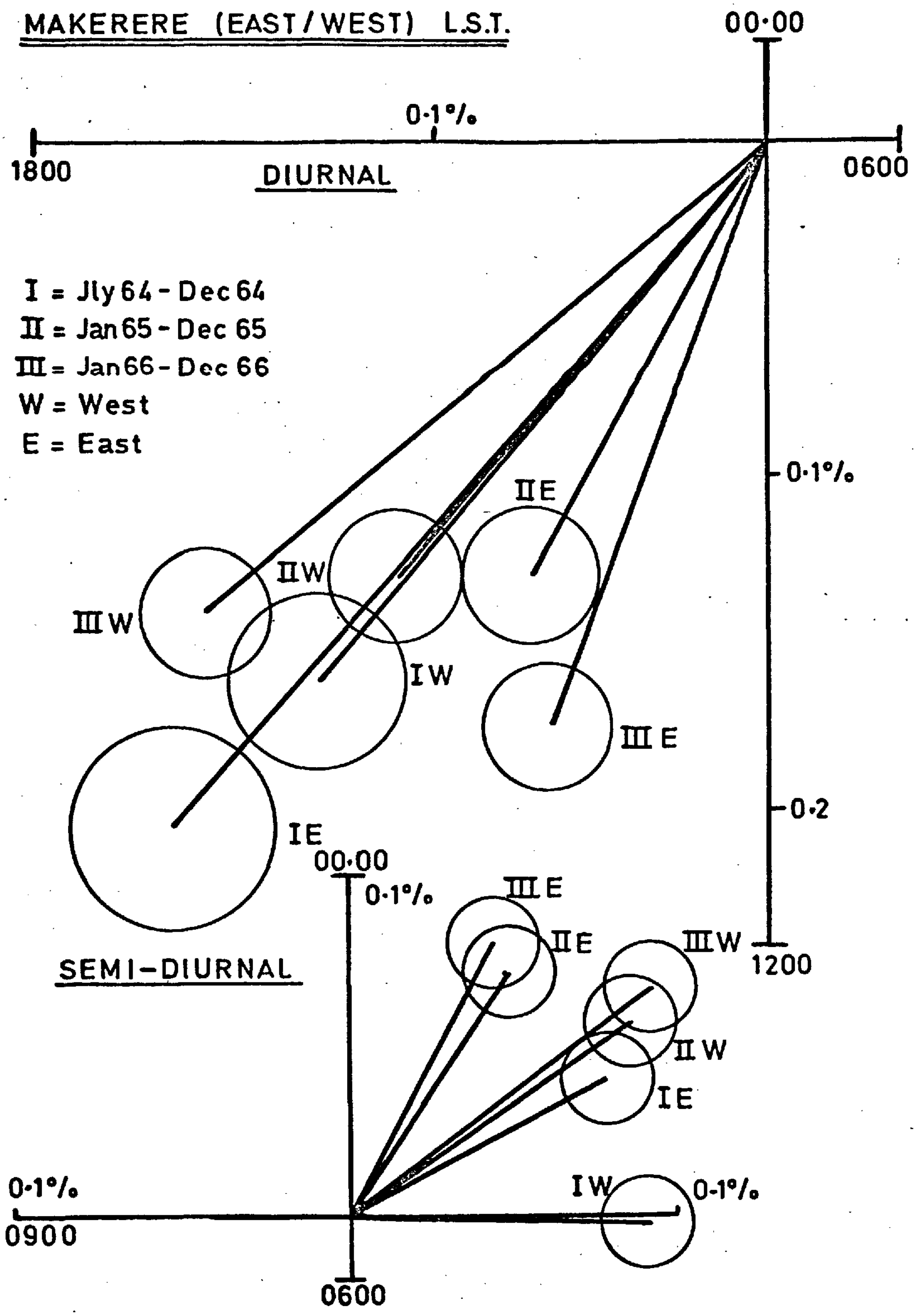


Fig. 13. Solar diurnal and semi-diurnal vectors as recorded by the Makerere (East/West) telescopes, grouped over calendar years 1964, 65, 66.

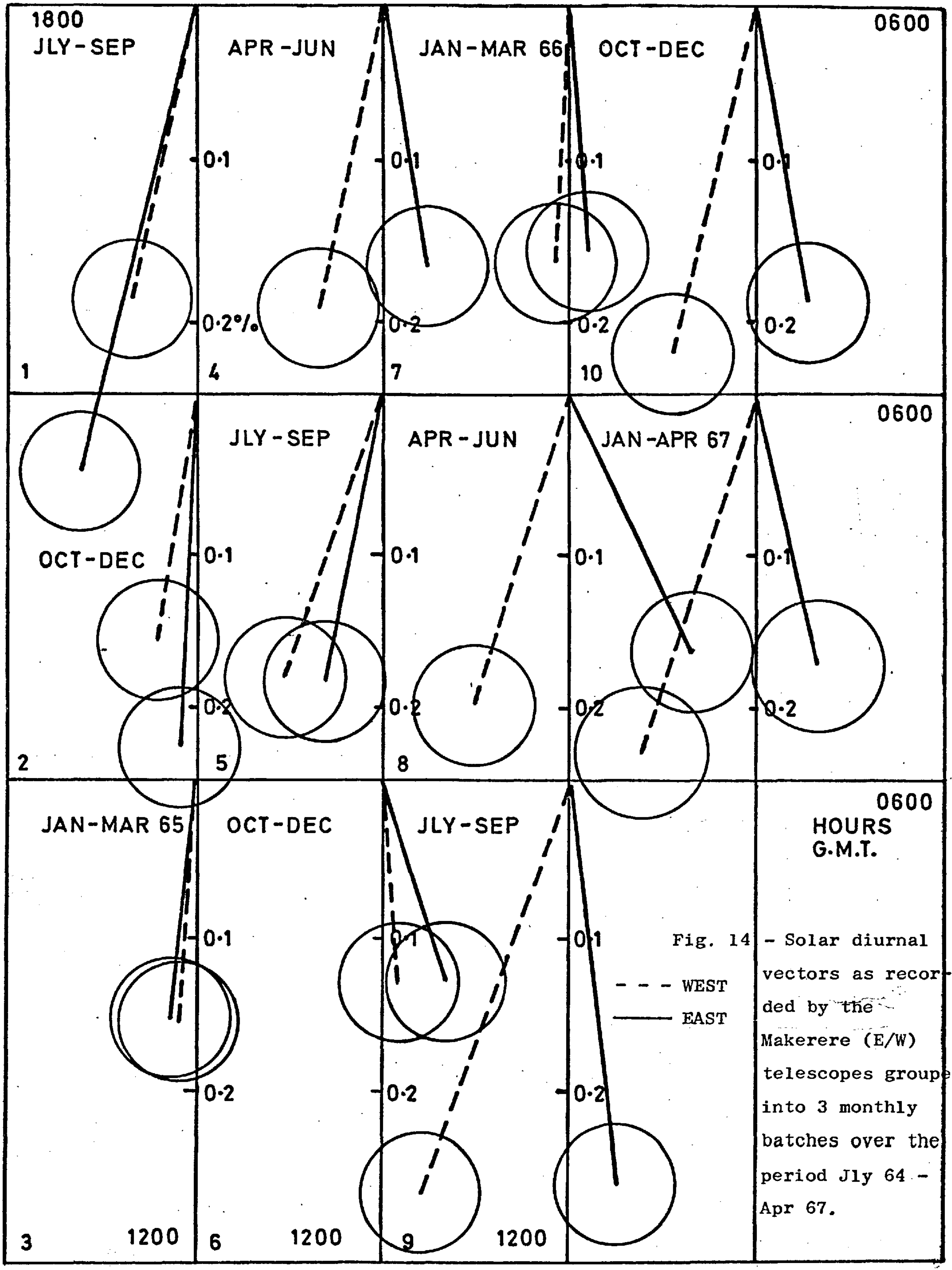


Fig. 14 - Solar diurnal vectors as recorded by the Makerere (E/W) telescopes grouped into 3 monthly batches over the period Jly 64 - Apr 67.

by the E/W telescopes. The Makerere telescopes however seem to suggest an earlier return in the primary anisotropy in about APRIL 1966 as compared to about JLY-AUG in the case of the underground recorders.

Day by day correlation with neutrons

We have investigated in detail the correlation between the daily variation measured by the E/W meson telescopes at MAKERERE with that observed by a neutron monitor at Deep River, for one year of data in 1966. The day by day coefficients of the daily variation measured at Deep River have been grouped into three classes according to the diurnal amplitude at Deep River. Group I contains days on which the diurnal variation is less than 0.15%, Group II those days on which the diurnal variation lies between 0.15% and 0.4%, and Group III those days on which it is G.T. 0.4%. Figure 15 shows the diurnal and semi-diurnal amplitudes at MAKERERE corresponding to these three groups of days. Because of the small number of days in each group the errors on any individual vector are rather large. However there does seem to be a tendency for the high neutron diurnal amplitudes to be accompanied by high meson amplitudes. The second harmonic amplitudes however show no great correlation. In view of the slight correlation observed with neutron amplitudes it appears that at least a part of the first harmonics observed at Makerere is of primary origin. However we observe from this figure that the diurnal amplitudes for the first group of days are about 0.14% for both the E/W telescopes. The corresponding values for the LONDON telescopes were about 0.06% and that for the Deep River neutron were 0.066%. Since the mean primary energy recorded by the MAKERERE telescopes is greater than both the N/S telescopes and considerably greater than that recorded by the Deep River neutron monitor one would normally expect that the diurnal variation recorded by the Makerere telescopes would be smaller than in either of these cases. In view of these results we have again to conclude that there is an additional component to the diurnal variation recorded by the Makerere telescopes.

Correlation with geomagnetic activity

The daily variation as determined on day by day basis has been grouped according to the level of geomagnetic activity using the Ap index as a criterion. The data have been grouped into three classes according to Ap values as follows:-

GROUP I Ap is $\leq$ 5
GROUP II Ap lies between 5 and 10
GROUP III Ap lies between 10 and 20
GROUP IV Ap is greater than 20.

Data extending over the period JULY 1964 to DEC 1966 has been used in this analysis. The results are presented in Fig. 16. In view of the rather large errors it is difficult to draw any definite

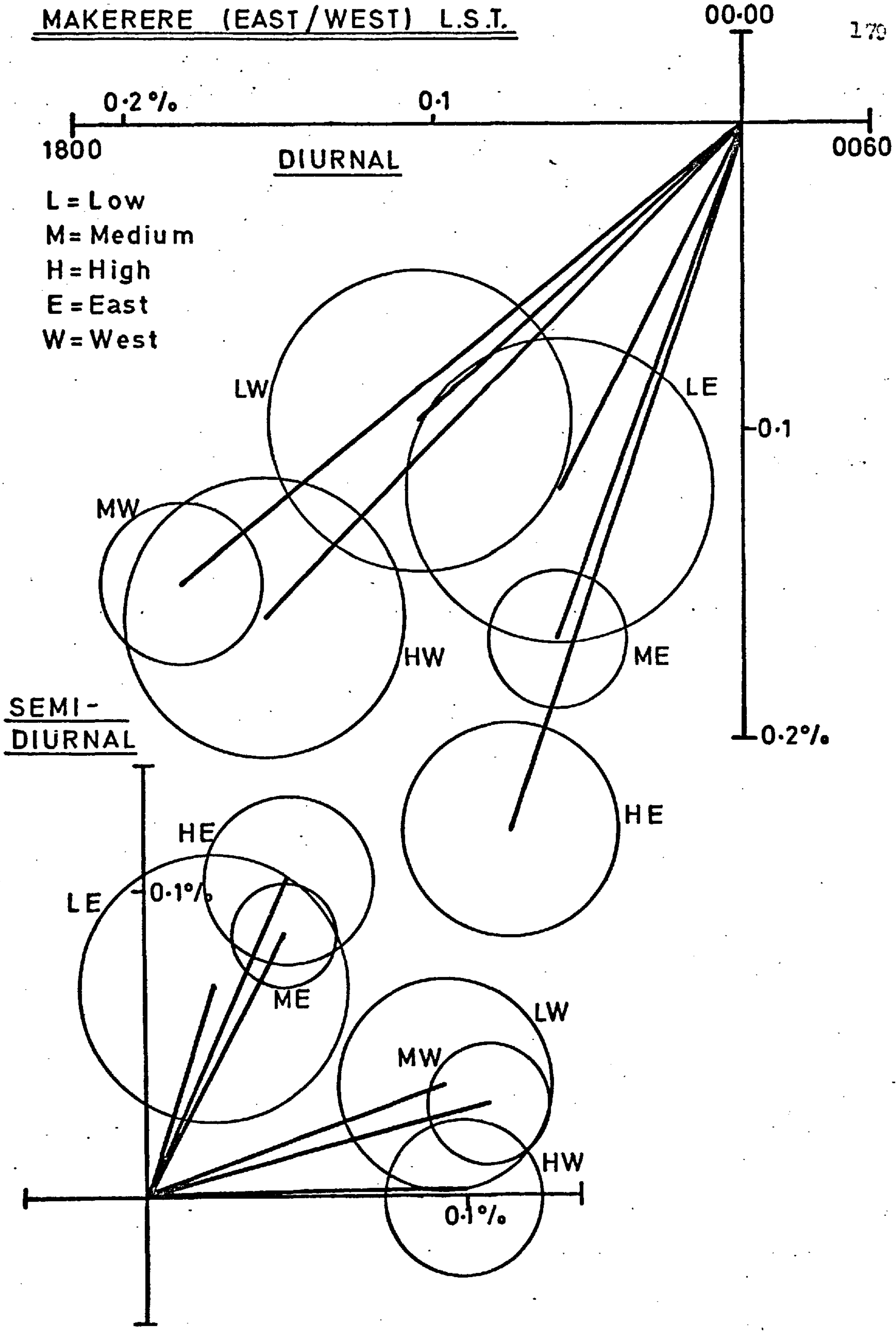


Fig. 15. Diurnal and semi-diurnal waves at Makerere (E/W telescopes) for 1966, grouped into high, medium, and low days according to the diurnal amplitudes observed by the Deep River Neutron monitor.

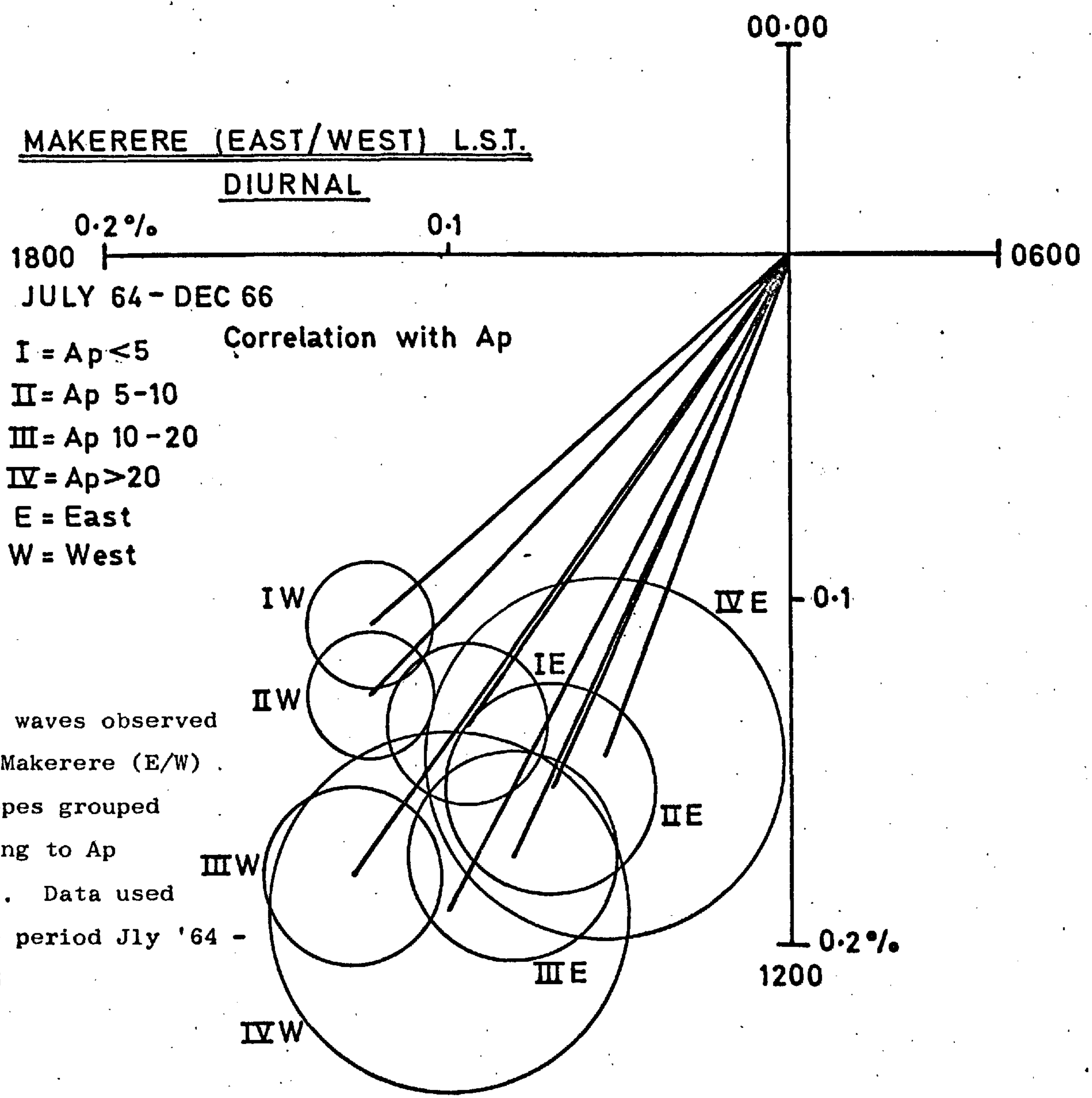


Fig. 16. Diurnal waves observed by the Makerere (E/W) telescopes grouped according to Ap indices. Data used for the period Jly '64 - Dec '66

conclusions about any systematic correlation of the phase or amplitude of the diurnal variation as measured by the East or the West telescope. However, a slight tendency does appear for the West telescope to have an earlier phase on days when the Ap index is high. No similar resolution is possible for the East telescope.

5.6 SUMMARY: a) LONDON RESULTS.

1) The solar daily variation has been observed at London by directional recorders pointing in the North and South directions, over the period August 1965 to May 1968. An examination of the first harmonics of the daily variation during these periods suggests that there has been an increase in the solar anisotropy in 1966 and 1967 as compared to the year of minimum activity, 1965. Only amplitude changes were evident; no significant changes in the phase of the diurnal variation were observed by either the North or the South pointing telescope in going from 1965 to 1967.

2) Comparison with the inclined telescope measurements of Sandstrom et. al. reveals that amplitude changes in the diurnal anisotropy were also observed by the directional recorders, situated at Uppsala and Kiruna, in Sweden, in going from 1963 to 1966.

3) Comparison of the day by day values of the diurnal anisotropy observed by the N/S telescopes with those of the S.D.V. observed at Deep River reveals that the diurnal amplitude observed at London (N/S telescopes) shows an intimate correlation with the diurnal wave observed at Deep River. The amplitude of the N/S telescopes increases progressively as the amplitude of the diurnal wave at Deep River increases. No significant changes in the phase are observed with an increase in amplitude. The second harmonics

observed at both London and Deep River are found to be larger on days on which the diurnal amplitudes are largest.

A comparison of the changes in the amplitude observed at Deep River and London was carried out by comparing the ratios of the amplitudes observed at Deep River and those observed by the N/S telescopes. This reveals that within the limits of the errors the ratios remain constant for the three groups of days. This suggests that the energy dependence of the diurnal anisotropy does not alter on days which exhibit high, low or medium diurnal variations.

4) The N/S diurnal amplitudes also show some correlation with the level of geomagnetic activity. The phase of the South telescope shows a tendency to become progressively earlier as the level of geomagnetic activity (characterised by the Ap index) increases. No significant changes in the phase of the diurnal wave from the North telescopes could be observed in view of the rather large errors. The Deep River diurnal amplitudes show a more pronounced tendency to go to earlier hours as the Ap index increases.

5) The semi-diurnal amplitude observed by the South telescope at London has shown a slight tendency to increase in going from 1965 to 1966. The North telescope shows no such tendency. No significant correlation is observed with the level of geomagnetic activity.

b) MAKERERE E/W RESULTS:

1) The solar daily variation has been observed at MAKERERE by directional recorders pointing in the E/W directions over the period JULY 1964 to APRIL 1967. The lack of any appreciable phase difference in the diurnal vectors for these telescopes during the first year of observation suggests that the diurnal anisotropy had reduced during the year of minimum solar activity. A gradually increasing phase difference in the data for the subsequent period implies that the diurnal anisotropy had begun to reappear over these years as the solar cycle progressed.

2) The lack of a phase difference in the Makerere vectors and the rather large amplitudes observed during the years of minimum activity cannot be reconciled with the idea of a primary anisotropy external to the geomagnetic field. This fact and a comparison of the diurnal variation observed at Makerere with that observed at another equatorial station, Chacaltaya, suggests that there is an additional component to the diurnal variation contributing to the observations at Makerere. The possible causes of this additional component are discussed in Chapter VI.

3) The Makerere results are in qualitative agreement with those obtained at London, Chacaltaya, etc. for the solar minimum, in so far as they imply a reduction in the primary anisotropy during the years of minimum activity.

4) A comparison of the day to day amplitudes observed at

Makerere during 1966 with those at Deep River (neutron monitor) reveals some correlation between the two. It appears therefore, that at least a part of the First Harmonic observed at Makerere is of Primary origin. However the fact that the diurnal amplitudes at Makerere are considerably larger than the amplitudes at Deep River during days on which the Deep River neutron monitor shows low amplitudes (implying a low primary anisotropy) again suggests that there is a spurious component to the diurnal variation observed at Makerere.

5) In view of the large errors no significant correlation could be established between the diurnal or the semi-diurnal amplitudes at Makerere and the level of geomagnetic activity.

CHAPTER VI

SOLAR DAILY VARIATION III (Discussion of Results):

In the following sections we shall investigate whether the results obtained concerning the solar daily variation by the North/South recorders located at London, and the East/West recorders situated at Makerere, can be reconciled with current ideas about the solar anisotropy based on the theoretical models of AXFORD (1965), PARKER (1964, 67), QUENBY (1968). Since results obtained by meson telescopes are complementary to those obtained by Neutron monitors, in so far as the latter exhibit the variations due to the modulation of somewhat lower primary energies, it will also be interesting to compare the behaviour of the primary anisotropy in the two energy ranges. In addition, the data obtained from the North/South telescopes, during the ascending phase of the present solar cycle is directly comparable with measurements carried out near the solar minimum of 1954 by DOLBEAR and ELLIOT (1951) THAMBYAH PILLAI and ELLIOT (1953), and POSSENER and VAN HEERDEN (1956). The North/South results can therefore be used to compare the chief characteristics of the solar anisotropy during the two periods.

6.1. THE DIURNAL VARIATION:

6.1.1. INTRODUCTION:

As discussed in Chapter IV, the current theoretical models of the solar diurnal anisotropy (PARKER (1964), AXFORD (1965), predict a solar diurnal variation with a free space amplitude of 0.7% in the solar equatorial plane with a time of maximum at 1800 hours L.S.T. (outside the geomagnetic field). The amplitude is expected to fall off as the cosine of the angle between the solar equatorial plane and the mean direction of viewing of the detector. (That is with the mean asymptotic latitude). On this model, the solar diurnal variation is expected to be independent of rigidity upto an upper limiting rigidity which may have typical values of a few tens of Gv (20-150Gv). Results obtained from a world wide network of neutron monitors (e.g. McCRACKEN and RAO (1965) have however indicated that the average free space amplitude of the diurnal variation, over the period 1958-65 was in fact 0.4%. McCracken and Rao conclude from these results that gradients due to the polarization electric field are not completely wiped out in practice and some of the streaming responsible for the diurnal variation is cancelled out. As discussed in Chapter IV Parker (1967) has demonstrated that the actual amplitude of the diurnal anisotropy will depend on the diffusion characteristics of the cosmic ray particles in the Interplanetary magnetic fields.

In the following we shall adopt the experimental point of view and assume that the free space diurnal anisotropy can be described by,

$$\begin{aligned} A\,(R)\,\% &= 0.4 \times \mathrm{Cos}\,\lambda \quad (R < R_{max}) \\ A\,(R) &= 0 \qquad\qquad\quad (R > R_{max}) \qquad ------ \quad (7) \\ T_{max} &= 1800 \text{ Hours L.S.T.} \end{aligned}$$

at least during the recent years. In the above equations, λ is the angle between the solar equatorial plane and the particle trajectory beyond the influence of the geomagnetic field, and R max is the upper limiting rigidity beyond which the diurnal anisotropy reduces to zero.

As mentioned earlier (Chapter IV) the diurnal variation actually observed on the surface of the earth will differ both in phase and amplitude from the values given above due to the deflection of the primary particles in the geomagnetic field. The diurnal variation observed in the secondary flux will also have to be corrected for any atmospheric effects that may be present.

In order to make a meaningful comparison between observed and predicted values for the diurnal waves it is necessary to correct for these effects; we shall accordingly, discuss these corrections first.

6.1.2. EFFECT OF THE GEOMAGNETIC BENDING OF THE PARTICLES:

The effect of the geomagnetic field will be to bend the trajectories of the primary particles passing through it, and the time of maximum of the anisotropy will shift from its free space value of 1800 hours. In general the deflection in the geomagnetic field will make the time of maximum earlier than its value outside the geomagnetic field. For a particular direction of arrival the magnitude of the deflection in the geomagnetic field will be a function of the rigidity of the primary particles. Since the amount of bending will be quite different for the different rigidities the time of maximum observed for the anisotropy in each rigidity range will vary and the actual amplitude observed will be the resultant of a vector addition of the elementary amplitudes in a number of small rigidity intervals. (Over which the deflection may be thought to be constant). Because of this the observed amplitude will be considerably less than the free space value outside the geomagnetic field.

For a particular direction of arrival, the amplitude and phase to be expected at the earth, may be calculated with a knowledge of,

a) The asymptotic directions of approach Λ_E , Ψ_E of the particles contributing to the counting rate of the detector.

b) The differential response functions W (R) corresponding to the secondary particles being recorded.

c) The free space amplitude, angular dependence and the rigidity spectrum of the anisotropy. (e.g. as given by eqtn. (i)).

The calculation consists of a process of vector addition of the amplitudes expected in the differnet rigidity ranges, the summation being carried out over the rigidity range over which the anisotropy is expected to be present. For a particular direction of incidence the normalized amplitude integrated over the relevant rigidity range may be written as:

$$A_{obs} = \frac{\left\{ \left[\int_{Ro}^{Rmax} A(R) \cdot \cos\lambda \cdot \sin\psi \cdot W(R) \cdot dR \right]^{2} + \left[\int_{Ro}^{Rmax} A(R) \cdot \cos\lambda \cdot \cos\psi \cdot W(R) \cdot dR \right]^{2} \right\}^{\frac{1}{2}}}{\int_{R_o}^{\infty} W(R) \cdot dR}$$

and the net phase advance in degrees of longitude as:

$$\psi_E = \tan^{-1} \left[\frac{\int_{Ro}^{R\,max} A(R) \cdot \cos\lambda \cdot \sin\psi\, W(R) \cdot dR}{\int_{Ro}^{Rmax} A(R) \cdot \cos\lambda \cdot \cos\psi \cdot W(R) \cdot dR} \right]$$

Where R_o is the geomagnetic threshold corresponding to the direction of observation and R max is the upper limiting rigidity beyond which the diurnal anisotropy is expected to vanish.

In the practical case of a telescope of finite dimensions, particles arriving at different zeniths and azimuths will contribute to the counting rate of the detector. Since the geomagnetic effect for the different directions of arrival will be different the amplitude will be further reduced due to smoothing in the finite acceptance cone of the detector. McCRACKEN et. al. (1963) have shown that the amount of smoothing in the acceptance cone of the detector is a function of the geomagnetic latitude of the location in addition to the actual aperture of the instrument. In general the asymptotic directions contributing to the counting rate of a telescope will be contained in a cone of finite width, called the cone of asymptotic directions. The amount of smoothing will depend on the width of this cone and will accordingly be greater for equatorial stations where the asymptotic cones have a greater width as compared to high latitude stations.

Because of the collimating properties of directional telescopes, (as illustrated by the directional sensitivity patterns given in Chapter II), the major contribution to their counting rate comes from a comparitively narrow cone of directions near the direction of maximum sensitivity (about 30° to 35° to the vertical for the case of the cubical geometry employed in the present experiment). Therefore, as a first approximation the actual detectors may be approximated by a narrow angle telescope inclined at about 32° to the zenith and pointing in the appropriate azimuth. (North and South in the case of the London telescopes and East/West in the case of the Makerere recorders).

Under this assumption we can calculate the solar diurnal variation to be expected for the directional recorders at London and Makerere for a given primary anisotropy (e.g. Described by eqtn. 2 above), using the expressions 2 and 3 of this section.

We have accordingly calculated the diurnal amplitudes and phases to be expected in the NORTH/SOUTH TELESCOPES AT LONDON and the EAST/WEST telescopes at MAKERERE if there was a primary anisotropy with a free space amplitude of 0.4% which is independent of rigidity upto an upper limiting rigidity beyond which the amplitude falls to zero as given by eqtn. (i) of this chapter. This value of the upper limiting rigidity can quite concievably vary over the solar cycle and will in general depend on the scale size of the interplanetary magnetic field. In order to investigate whether a part of the variability exhibited by the solar diurnal variation can be attributed to a variation in R max, we have used the upper limiting rigidity as a variable parameter and have calculated the expected S.D.V. for different values of R max from 20 Gv to about 150 Gv. The loci of the expected positions for the endpoints of the diurnal vectors for the different values of the parameter R max are shown in figure I and figure II for the London and Makerere recorders respectively. In figure I the locus with the earlier time of maximum corresponds to the North telescope and that with the later time of maximum to the South telescope. In figure II, the locus with the earlier time of maximum represents the expected range for the East telescope and the other curve gives the expected positions for the West telescope. The number against the points on the curves give the corresponding values of the upper limiting rigidity. In these calculations we have used the differential response functions of KRIMSKY et. al. (1965) for directions inclined at 32° to the zenith. The asymptotic directions corresponding to a zenith angle of 32° have been calculated by McCRACKEN et. al. (1962) for London and Kampala. The calculations for the latter station which is nearby Makerere have been used here.

An examination of the figures I and II shows that:-

a) The amplitude expected for the North telescope do not increase with the higher values of the upper limiting rigidity quite so rapidly as that for the South telescope. This is due to the fact that the diurnal anisotropy is assumed to fall off as the cosine of the angle that the particles make with the ecliptic and the higher energy particles recorded by the North telescope make large angles with the ecliptic.

b) In the case of the E/W curves corresponding to the Makerere recorders, no such saturation with rigidity is observed since both the telescope sample particles coming from or near the ecliptic plane.

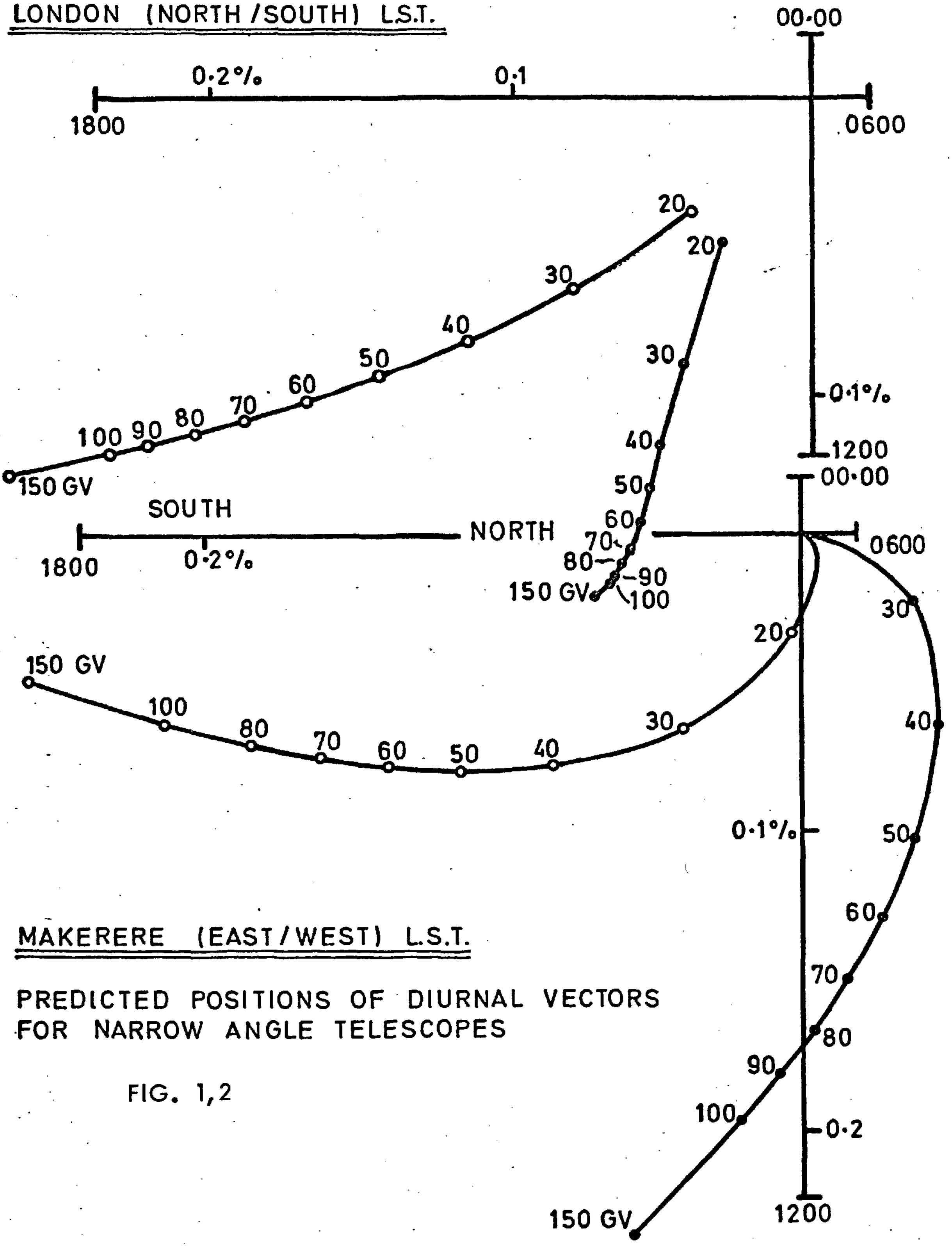
We have also investigated the amount of smoothing to be expected in the case of the London and Makerere recorders because of the finite opening angle of the telescope.

An examination of the directional sensitivity patterns of cubical recorders inclined at 45° to the vertical (Chapter II) shows that in the meridional plane of the recorder the sensitivity is a maximum at about

30° to the zenith and falls off fairly rapidly on either side, so that it is only half its maximum value at a zenith of 48°, while it reduces by about 30% at a zenith angle of 16°. Thus we may estimate the amount of smoothing to be expected by examining the differences in the geomagnetic effects at these zenith angles from those at 32°. Since the bulk of the particles recorded by the instrument will be contained within these zenith angles i.e. 48° and 16° this will give an idea of the magnitude of the smoothing to be expected.

Since the smoothing for the case of the Makerere recorders is expected to be relatively more important we have investigated the problem in greater detail for this case. We have calculated the S.D.V. to be expected (with a primary anisotropy described by (i)) for 5 different zenith angles of arrival at 16°, 24°, 32°, 40°, and 48° to the vertical in the E/W plane. The corresponding curves are shown in figure III. The net resultant amplitude for the E/W telescopes will be obtained by a vector addition of the amplitudes expected for a particular value of the upper cut-off for the different zenith angles. In this process of vector addition values for a particular zenith have been weighted by an appropriate factor obtained from the directional sensitivity patterns which determines the fractional contribution of the particular zenith angle to the total counting rate of the instrument. This summation has been carried out for values of the upper cut-off from 20 to about 150 Gv and the resulting curves representing the mean loci are shown in the figure III b. The resultant curves are very similar to the curves for 32° and the smoothing due to the different zenith angle contributions in the meredional plane of the instrument is seen to be small.

It should be noted that this proceedure only estimates the smoothing in the meredional plane of the detectors. In practice particles arriving at



PREDICTED POSITIONS OF DIURNAL VECTORS FOR NARROW ANGLE TELESCOPES

FIG. 1,2

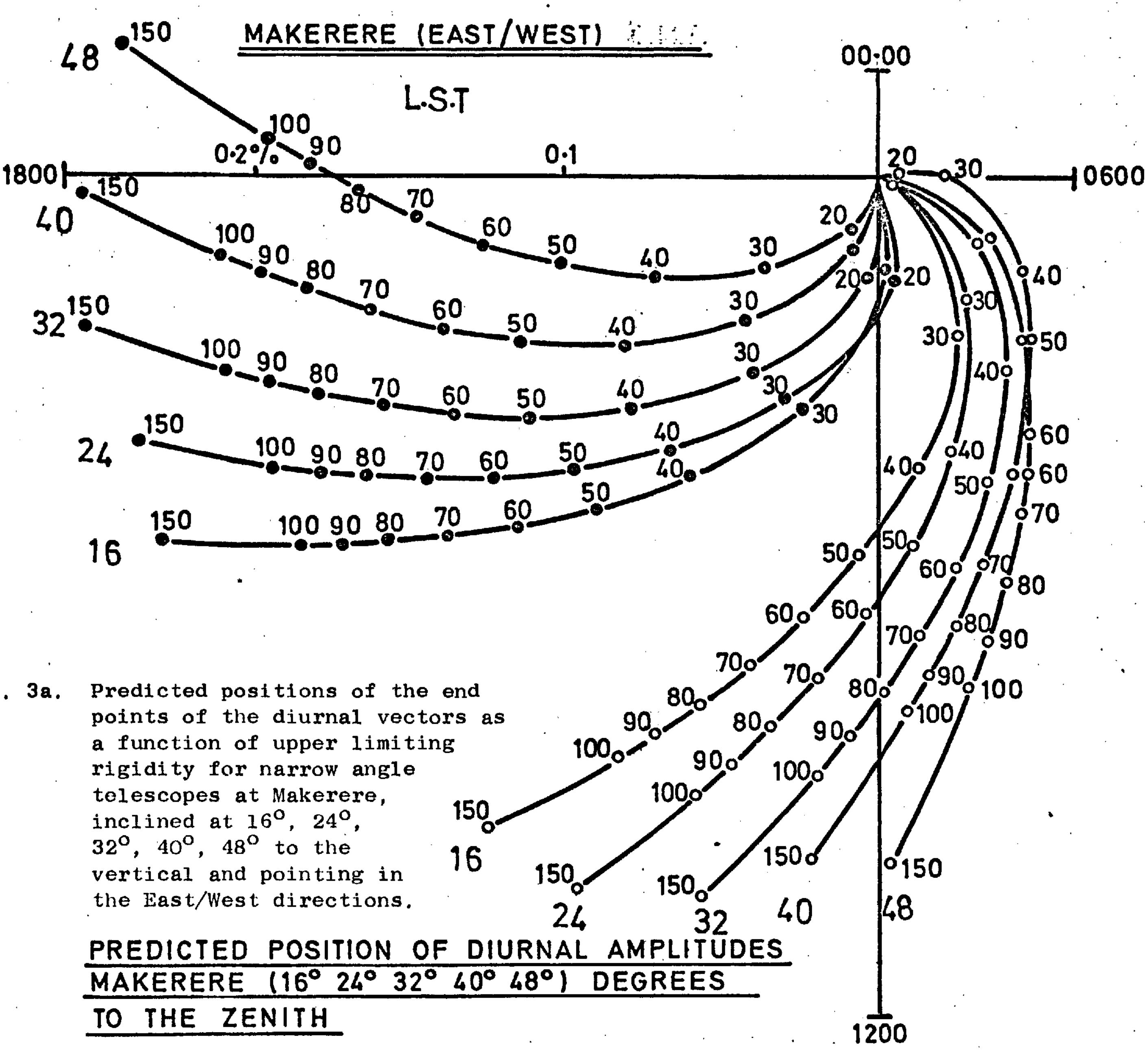


Fig. 3a. Predicted positions of the end points of the diurnal vectors as a function of upper limiting rigidity for narrow angle telescopes at Makerere, inclined at 16°, 24°, 32°, 40°, 48° to the vertical and pointing in the East/West directions.

PREDICTED POSITION OF DIURNAL AMPLITUDES MAKERERE (16° 24° 32° 40° 48°) DEGREES TO THE ZENITH

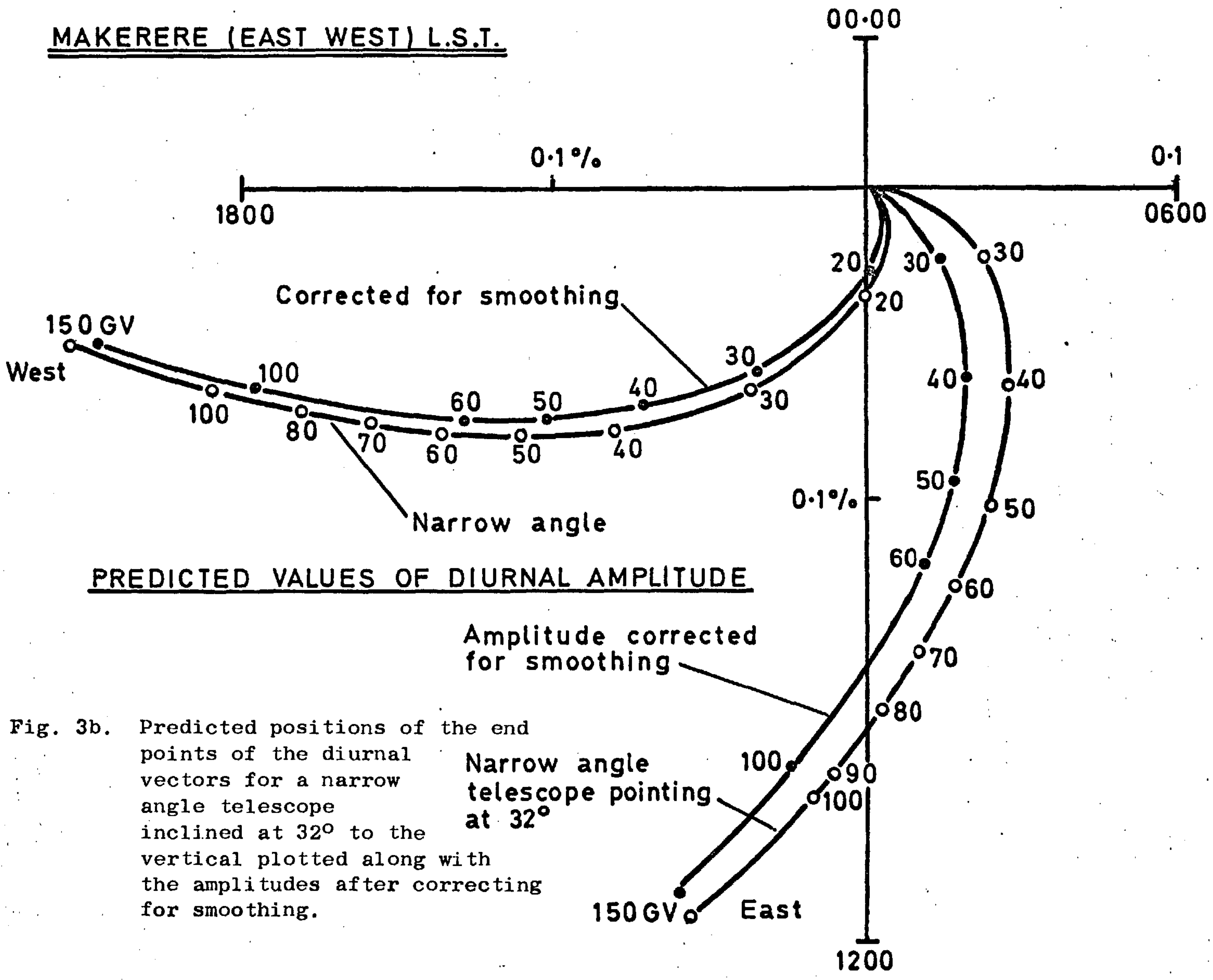


Fig. 3b. Predicted positions of the end points of the diurnal vectors for a narrow angle telescope inclined at 32° to the vertical plotted along with the amplitudes after correcting for smoothing.

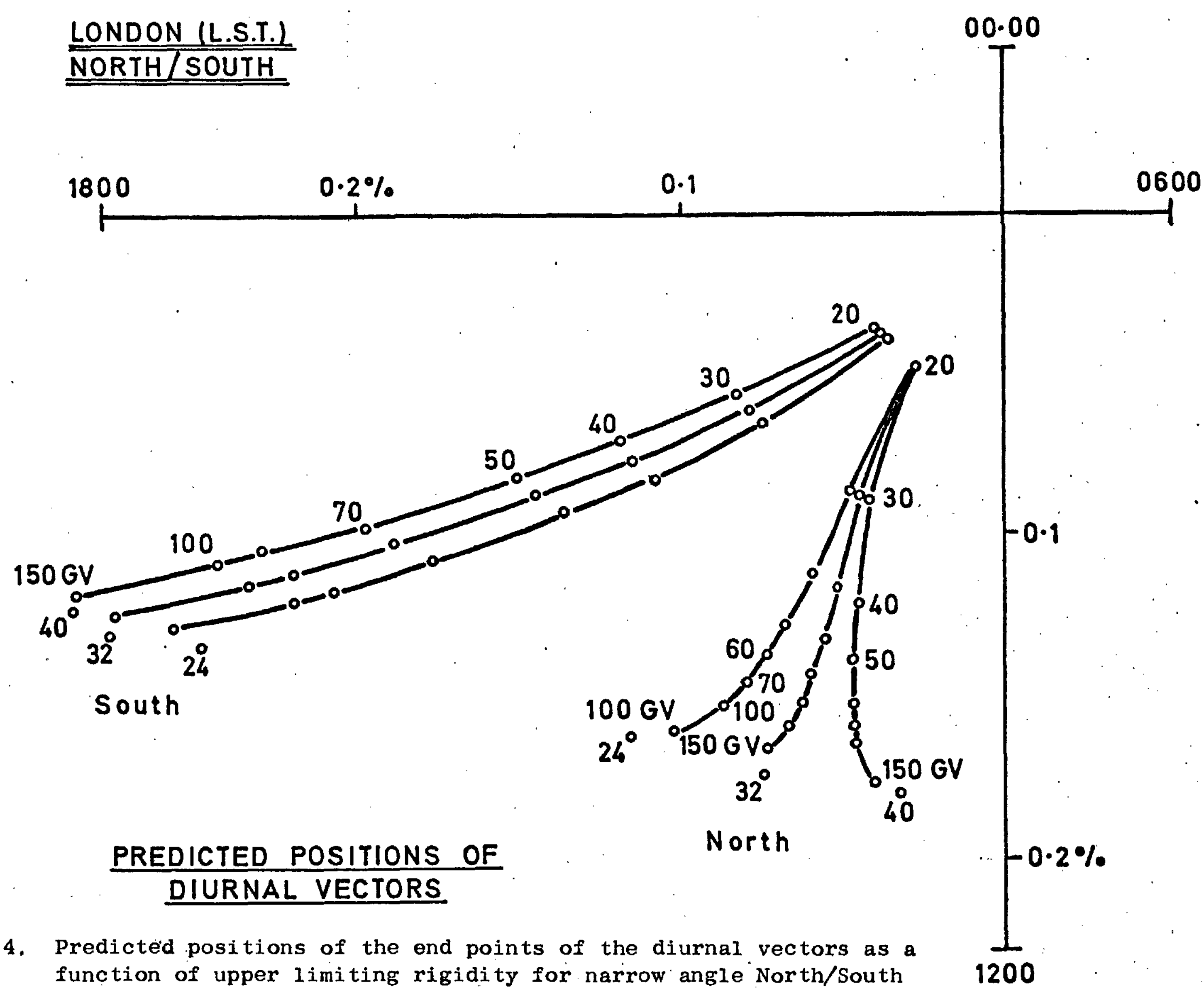


Fig. 4. Predicted positions of the end points of the diurnal vectors as a function of upper limiting rigidity for narrow angle North/South telescopes at London inclined at 24°, 31° and 40° to the vertical.

different azimuths will contribute to the counting rate of the detectors and will cause a further smoothing. However the directional sensitivity of the cubical telescope arrangement falls off fairly rapidly with azimuth on either side of the mean value and the smoothing effect will be correspondingly small. We have, therefore, not considered the transverse case in detail.

For the case of the London recorders we have calculated the expected amplitudes and phases of the S.D.V. for three zenith angles, 24° 32° and 40° for the North and South recorders. The curves are shown in figure IV. It is obvious from this figure that in the case of the London recorders the smoothing will be very small since the different curves lie very close to each other.

These calculations will be used to compare the observed values of the diurnal variations with those expected from theory in the following sections.

6.1.3. ATMOSPHERIC EFFECTS:

The Atmospheric effects on the meson component of the cosmic radiation which constitutes the major part of the flux recorded by the NORTH/SOUTH and the EAST/WEST recorders have been discussed in Chapter III. From there it is clear that the main effects are,

a) A barometer effect, and

b) A negative temperature effect.

In view of the dependence of the secondary cosmic ray intensity on the atmospheric temperature and pressure any diurnal or semi-diurnal variations in these atmospheric variables will also be reflected in the cosmic ray intensity and will accordingly generate diurnal and semi diurnal variations due to changes in the state of the atmosphere.

Variations introduced in the secondary intensity due to variations in the barometric pressure may be easily accounted for by using the barometer coefficients derived in Chapter III and the data analysed for the daily variation has in fact already been corrected for pressure changes.

In the case of the temperature effects on the other hand a similar correction is not possible because of the lack of data on the variation of the temperature of the atmosphere (from the S/L to the upper atmospheric layers (100 m.b. or so)), over the period of a day. Radiosonde data normally used for assessing the temperatures of the atmospheric layers are available only twice per day on average. Further moredata obtained by this proceedure, has in fact been found to be contaminated by radiation errors especially in the upper atmospheric layers. In addition to the uncertainty in the quality of the radiosonde data there is also some uncertainty in the values of the density of temperature coefficients calculated theoretically by Dorman and others., especially as regards their variability over the year. (seasonal variability).

In view of these uncertainties indirect methods are adopted for determining the magnitude of the temperature induced diurnal wave in the hard component data. e.g. THAMBYAHPILLAI and QUENBY (1961), BERCOWITCH (1965), MORI et. al (1965).

The proceedure consists essentially of a comparison of the diurnal waves in the hard component data obtained from say, ionization chambers and those observed in Neutron monitor data. Since the secondary particles recorded by the neutron monitor are affected only very slightly be temperature changes in the atmosphere, the diurnal variations observed in neutron monitor data may be assumed to be free of atmospheric effects (after a proper correction has been made for pressure variations). Thus if the neutron monitor diurnal wave reduced to zero over any particular period (as e.g. during a year of low solar activity) then the diurnal waves observed in the hard component by an ionization chamber may be taken to represent the temperature effects, under certain assumptions. (In such a comparison equatorial stations are usually to be preferred since the response of a neutron monitor and an ionization chamber at an equatorial station are very similar.) This proceedure has been employed by Quenby et. al. to derive the temperature effects in the hard component data obtained from a mountain altitude equatorial station, Huancayo. Variations of the basic process of comparing the diurnal waves in the neutron monitors and meson counters, have been used by several workers to establish the temperature effects on the hard component. The results of the more recent attempts in this direction are listed in TABLE I and the corresponding diurnal temperature effects are plotted in figure 5. The figure shows that there is considerable discrepancy in the results of the different workers. In particular the temperature effects obtained by Bercovitch for Deep river, a high latitude station, are observed to be about half those obtained for Huancayo by Quenby et. al. The temperature effects deduced by Mori et. al are the average over several stations and the individual effects from which this average is derived exhibit considerable variability.

In view of these facts it appears that a considerable uncertainty is still associated with the temperature corrections. In general, though the temperature effects are the result of processes occuring over the whole depth of the atmosphere, and as such local influences would tend to be smoothed, a possibility of a local dependence in the temperature effects cannot be ruled out. In particular there may well be a variation of the temperature effect with latitude as is in fact illustrated by the results of BERCOWITCH et. al. (1965) and QUENBY and THAMBYAHPILLAI (1961).

Fig. 5.

OBSERVATIONS OF THE HARD COMPONENT TEMPERATURE EFFECTS

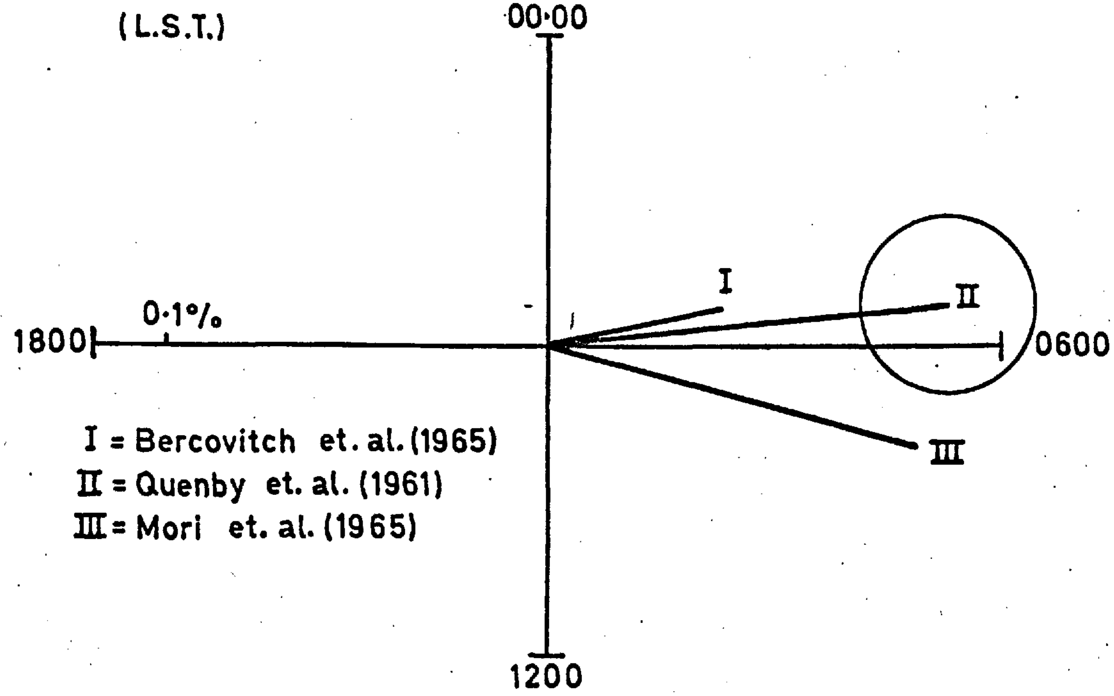


TABLE I.

DIURNAL TEMPERATURE CORRECTIONS FOR THE HARD COMPONENT:

WORKER.	AMPLITUDE. %	PHASE. Hours (L.S.T.)
QUENBY & THAMBYAHPILLAI (1961)	0·11 ± ·01	05·40
BERCOVITCH et. al. (1965)	0·050± ·01	05·30
MORI et. al. (1965)	0·095 ± ·015	7·10

6.1.4. DIURNAL VARIATION OBSERVED AT LONDON:

a) PERIOD MEANS:

In order to compare the results on the solar diurnal variation, obtained by the North/South telescopes at London, with values predicted on the basis of a rigidity independent anisotropy of amplitude). 0.4% at 1800 hours (l.s.t.), (these being the chief characteristics of the solar diurnal anisotropy during recent years as indicated by McCRACKEN and RAO (1965), we have plotted the observed diurnal vectors for the North/South directions along with the loci of the endpoints of the expected vectors for different values of the upper-limiting rigidity, Rmax. (Figure 6). The characteristics assumed here for the diurnal anisotropy also lie within the framework of the corotation model of Axford and Parker.

The experimentally obtained vectors for both the North and the South telescopes are seen to be considerably earlier in phase than the loci of the predicted positions for the two telescopes. However, it is found that if the diurnal temperature correction is assumed to have an amplitude of 0.06% and a time of maximum at 0600 hours (a value obtained for Deep River by BERCOWITCH et. al. (1965)), then the phases of the corrected diurnal vectors agree with the values predicted on the basis of the model we have assumed. In figure 7, the theoretical curves have been redrawn with their origin shifted by 0.06% along the 0600 hour direction, in order to take into account the temperature effects. It is observed that within the limits of errors the end-points of the observed vectors now fall on the theoretical curves.

As has been mentioned in Chapter V, the data from the N/S telescopes, for the second half of 1965 indicate that the diurnal anisotropy had reduced considerably over this period. If we assume that the amplitude of the free space anisotropy was 0.4% in the range of the primary energies monitored by the North South recorders, then a comparison of the observed data for 1965 with the theoretical curves suggests that these low amplitudes may be explained by a reduction in the parameter Rmax to a value of about 30-40 Gv, as compared to values of about 60-80 Gv for the subsequent periods. (1966-67).

On the corotation model Rmax characterises the upperlimiting rigidity upto which corotation is possible. A reduction may be caused, e.g. by a reduction in the scale size of the interplanetary magnetic field at times of solar minima.

It may be mentioned here that it is not possible to distinguish, with certainty, between the reductions in the observed amplitudes caused by a reduction in the free space amplitude and those caused because of reduction in the upperlimiting rigidity on the basis of the North/South data alone. (A comparison of the changes observed in the North and the South telescopes affords a certain amount of discrimination between these two types of changes, however, as we shall see in the following section, this method is more sensitive to detect large increases in amplitudes).

However, with a given external amplitude, a reduction in upper limiting rigidity will cause a much greater reduction in the amplitudes observed at higher rigidities (e.g. those monitored by surface or underground telescopes), than at lower rigidities. (Those monitored by neutron monitors). On the other hand a change in the amplitude alone will cause proportionate changes in all cases. We may therefore obtain some information on the true cause of the reductions in the observed amplitude by comparing the character of the changes recorded in different energy ranges.

As mentioned in Chapter V, several workers working with surface and underground meson telescopes have observed that the diurnal anisotropy had reduced considerably during 1964-65.

Thus AHLUWALIA et. al. (1965), have operated E/W pointing directional recorders at Chacaltaya, and found the diurnal wave to reduce considerably during 1964 as compared to 1958 (the time of the solar maximum). PEACOCK et. al. (1967) have operated directional telescopes at an underground station (60 m.w.e.) in London and find that the diurnal anisotropy reduced to zero during the second half of 1964 and the whole of 1965 (The period over which a maximum cosmic ray intensity was recorded). The anisotropy began to reappear at about the middle of 1966. Results obtained during the course of the present investigation by directional recorders at Makerere also indicate that the diurnal anisotropy had reduced in 1964-65 and had begun to build up in 1966. (HASHIM et. al. 1967).

On the other hand McCracken et. al. find that the diurnal anisotropy retained its phase and amplitude over the period 1958-65 (first half). (A smaller reduction (25%) was however recorded during the second half of 1965 as reported by DUGGAL et. al.) It appears therefore that the reductions observed in the higher rigidity range were more pronounced than those in lower rigidities. Such a behaviour as we have seen, can only be explained in terms of a reduction in the upper-limiting rigidity of corotation. PEACOCK et. al. (1967) and HASHIM et. al. have in fact interpreted the changes observed at Holborn (underground) and Makerere in terms of a reduction in the upperlimiting rigidity. The values obtained for this parameter from the underground results were less than 70 Gv. With the help of the directional recorders at London and Makerere it is possible to lower this limit further, and as has been indicated in the foregoing, the London results indicate that the upperlimiting rigidity had reduced to about 30-40 Gv during the second half of 1965. The low diurnal amplitudes at London had in fact persisted until March 66 and the resultant vectors for the period Aug. 1965, Mar. 66, are in fact found to be the same as the vectors during the period Aug. 65 - Dec. 65, for both the North/South telescopes. This would indicate that the upperlimiting rigidity had remained low during this period. Peacock on the other hand finds that the diurnal anisotropy began to reappear at higher energies somewhat later (Jun 66) indicating a gradual increase in the upperlimiting rigidity from 40 Gv to greater than about 70 Gv during 1966. It may perhaps be mentioned here that both the surface recorders at London and the underground telescopes at London (Holborn) showed a reduction in the diurnal anisotropy during about the middle of 1967. The diurnal amplitudes have however recovered since then.

In view of the foregoing discussion we can say:

1). The chief characteristics of the diurnal anisotropy observed by the N/S recorders over the period 1965-67, can be reconciled to the idea of a rigidity independent anisotropy of amplitude 0.4% at 1800 hours (L.S.T.).

2). In view of the energy dependent characteristics of the secular changes observed in the diurnal waves at the time of the recent solar minimum (1964–65) it is possible to attribute these variations to a reduction in the upperlimiting rigidity.

3). From the North/South results it is possible to estimate the following values for the upperlimiting rigidity during the period of operation of the telescopes.

YEAR	Rmax.
1965	30–40 Gv
1966	60–80 Gv
1967	60–80 Gv.

b) DAY BY DAY VARIABILITY:

As discussed in Chapter V, we have also investigated the day to day variability of the diurnal variation measured by the North/South recorders situated at London, and its correlation with the diurnal variation measured by a Neutron monitor at Deep River. In the following we shall atempt to establish whether the diurnal amplitudes obtained for High, Medium, and Low days (grouped according to the diurnal amplitudes observed at Deep River) for the North/South recorders can be reconciled with the predictions of a rigidity independent anisotropy as seems to be the case for annual averages as discussed in the foregoing section.

In figure 8, we have plotted the diurnal vectors observed by the North/South recorders grouped according to the diurnal variation observed in the Deep River neutron monitor, along with the loci of the expected positions of the diurnal vectors predicted on the basis of a 0.4% rigidity independent anisotropy 1800 hours. The theoretical curves have been shifted along the 0600 hour direction by 0.06% to account for temperature effects, as discussed in the foregoing paragraphs. An examination of this figure shows that a variation in just the upperlimiting rigidity is not able to explain all the observed data. The vector corresponding to the high amplitudes for the North telescopes exhibits the largest discrepancy.

However, the value of 0.4% obtained for the amplitude of the diurnal anisotropy is only an average which appears to obtain over a long period of time. In general the diurnal amplitudes have a range of values, e.g. McCRACKEN et. al. (1965). On the corotation model also, the free space amplitude may have values up to 0.7%. It is likely therefore, that the largest amplitudes observed in the data are the result of the external anisotropy having values greater than 0.4%. To investigate this further we have calculated the diurnal variations to be expected in the N/S recorders if the external amplitude was 0.7% instead of 0.4%. The corresponding curves giving the expected positions of the observed vectors for several upper cutoff rigidities are also shown in the figure. It is seen from this figure that the largest amplitudes can, within the limits of error, be reconciled with external amplitudes greater than 0.4%.

As has been mentioned in the foregoing section it is not possible to establish whether all the increase in the amplitude exhibited by the "High" vectors is due to an increase in the free space amplitude, or due to a combination of an increase in free space amplitude and upperlimiting rigidity. Nevertheless, the fact that the "High" vectors for the north telescope are considerably larger than the predicted values for very high values of the upperlimiting rigidity, suggests that at least a part of the increase is due to a larger free space amplitude on "High" days. (This brings out a rather interesting feature of the N/S telescope arrangement. The North telescope will be more sensitive to changes in the free space amplitude of the anisotropy than to changes in the upperlimiting rigidity. While the South telescope will respond to both equally readily.)

From figure 8 it is observed that the vectors corresponding to the medium (M) group are consistent with an amplitude of 0.4% and a upper cut-off of about 70 Gv, which appears to have been the average value of this parameter over the period of this analysis. (AUG 65 - JULY 67). The smallest amplitudes, on the other hand, could be attributed to lower

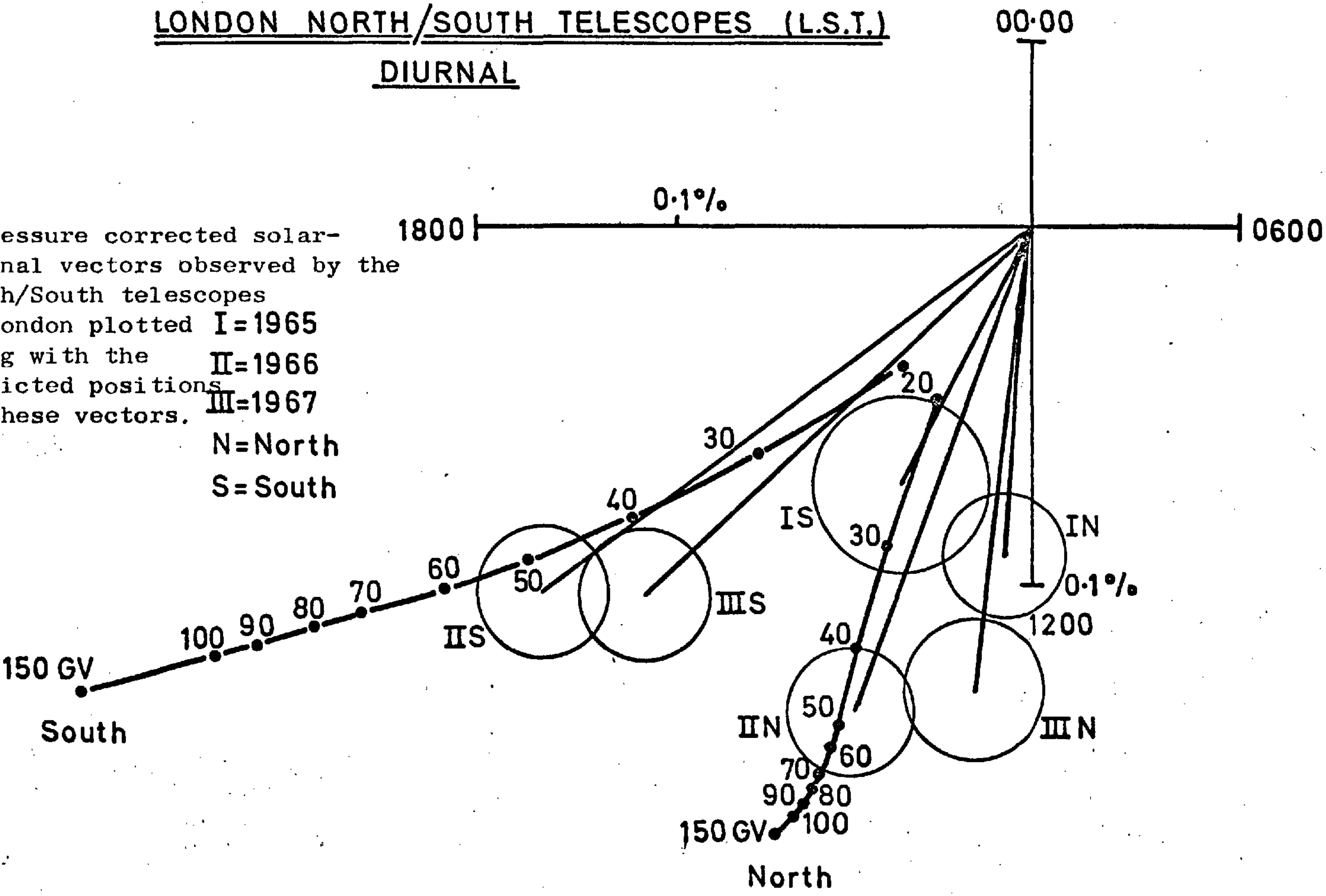


Fig. 6. Pressure corrected solar-diurnal vectors observed by the North/South telescopes at London plotted along with the predicted positions of these vectors.

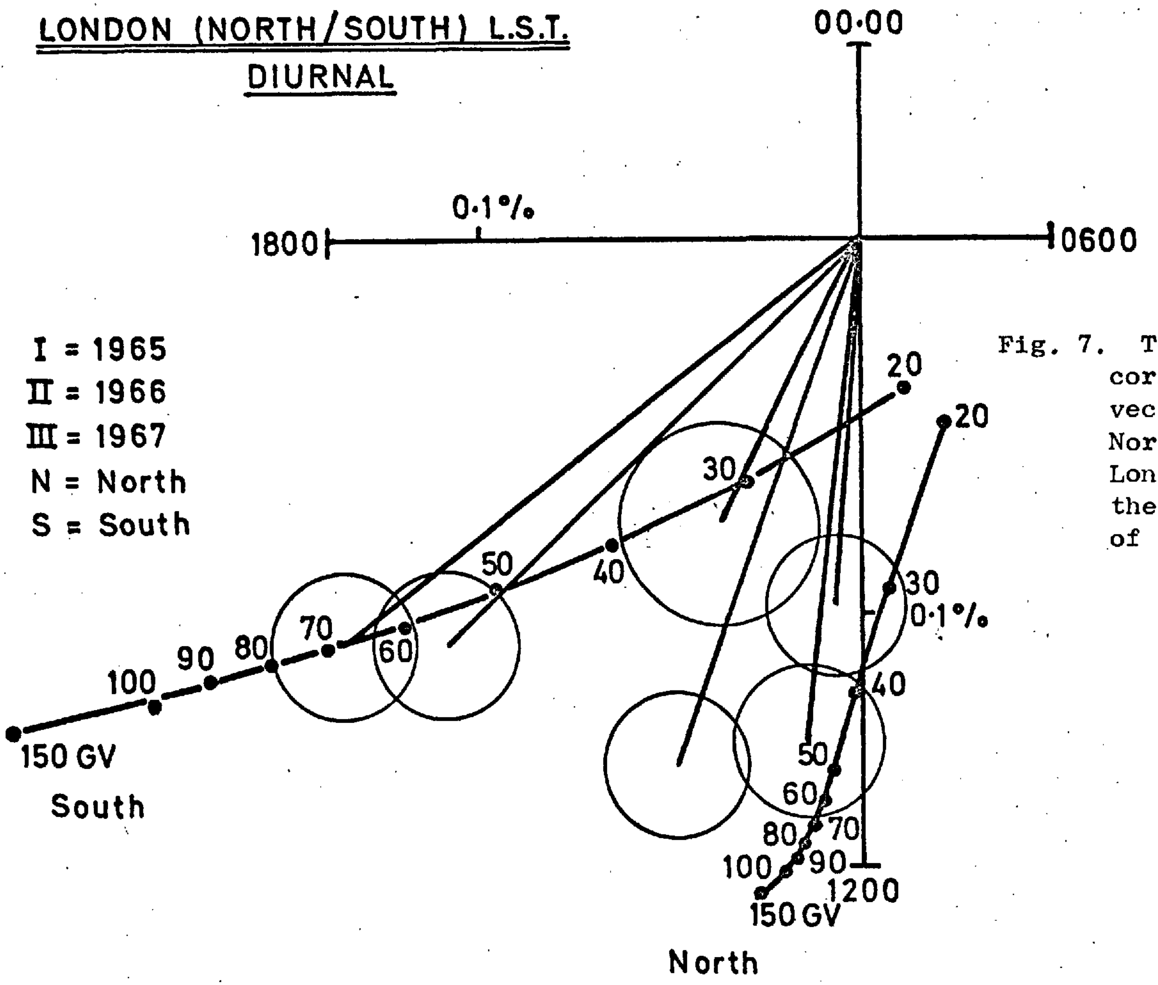


Fig. 7. Temperature and pressure corrected solar-diurnal vectors observed by the North/South telescopes at London plotted along with the predicted positions of these vectors.

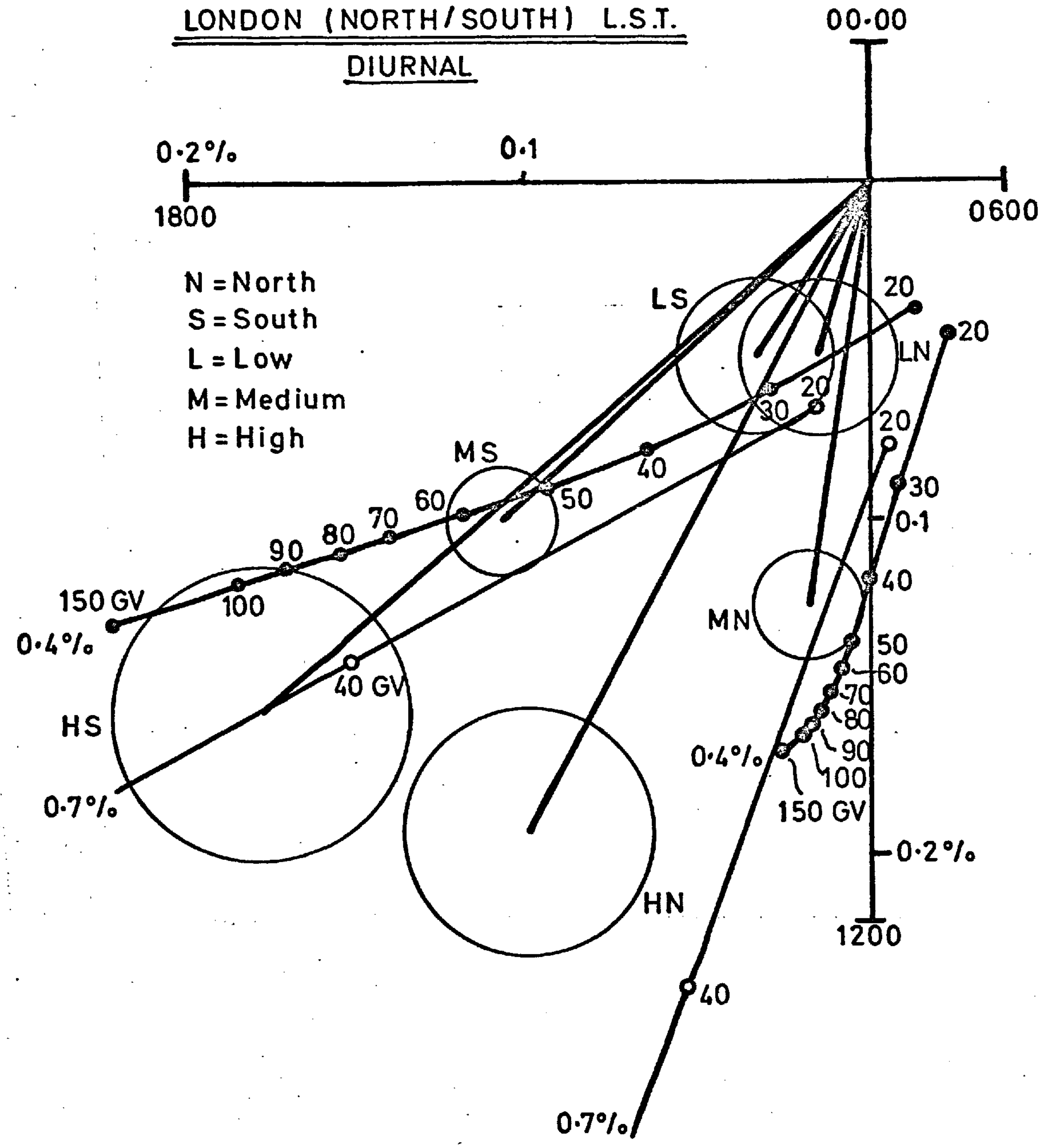


Fig. 8 - THE CURVES SHOW THE EXPECTED DIURNAL VECTORS FOR VARIOUS VALUES OF THE R MAX. AND FOR TWO VALUES (0.4% AND 0.7%) OF THE FREE SPACE - AMPLITUDE. THE VECTORS REPRESENT THE OBSERVED DIURNAL VARIATIONS ON HIGH MEDIUM AND LOW DAYS.

values (less than 0.4%) of the free space amplitude and/or upperlimiting rigidity. It is perhaps interesting in this connection, to recall from section 5.4, that the amplitudes corresponding to the "Low" days, for the Deep River neutron monitor, showed a tendency to be smaller than the amplitudes observed by the N/S telescopes. The ratios of the Deep River to North/South amplitudes are given in section 5.4. From there it is observed that while the ratios are about 0.6 for the "High" and the "Med" days, those for the "Low" days are about 1.25. However, in view of the errors, these differences are only marginally significant and it was not possible to establish with certainty whether they are real. Nevertheless, these features would seem to indicate that a possibility of a change in the energy dependence cannot be ruled out for the lowest amplitudes.

6.1.5. DIURNAL VARIATION OBSERVED AT MAKERERE:

As in the case of the London results we have plotted the diurnal vectors observed at Makerere by the E/W recorders along with the theoretically expected values on the basis of a 0.4% anisotropy at 1800 hours L.S.T. outside the geomagnetic field, for several values of the upper cut-off from 20 Gv to about 150 Gv. (figure 9). It is evident from this figure that the phases of the diurnal waves observed for the East/West recorders do not agree with those expected on the basis of an external anisotropy described above. The theoretical curves show that phase difference expected between the E/W recorders is a function of the upper cutoff rigidity and for low values of the upper cutoff the phase difference can be small. However, the amplitudes expected for these low values of the upper cutoff are also correspondingly smaller and the large amplitudes observed in the E/W telescopes cannot be explained by a lowering of the upper cut-off.

In fact, (as has been discussed in Chapter V), in order to enhance the phase difference between the residual vectors to the values expected on the basis of a rigidity independent anisotropy descirbed, it is necessary to subtract from the observed vectors for the E/W directions a constant vector of amplitude about 0.15% at about 1500 hours.

It is possible to estimate the value of this residual vector by comparing the results obtained at Makerere with those obtained at London during the same period and using the predictions of the rigidity independent anisotropy model. We have already seen that the London results indicate that the solar diurnal anisotropy during the period 1965-1967 can be described in terms of this model if it is assumed that the upperlimiting rigidity reduced to about 40 to 50 Gv during 1965 and has since recovered to about 80 Gv during 1966 and 1967. This average picture of the diurnal anisotropy (during the period under consideration), was also indicated by the results of PEACOCK et. al. In fact the low phase difference observed between the MAKERERE E/W telescopes during 1965 and a gradually increasing phase difference observed during subsequent periods, itself indicates a reduction in the primary anisotropy during 1965 and a gradual recovery during the subsequent periods. Thus, it appears plausible to assume that the average features of the external anisotropy described above also obtained at Makerere during 1965-67. In view of this we may use the values suggested for the upper cutoff by the London measurements at S/L and underground to estimate approximately the magnitude and direction of the spurious vector, by subtracting the vectors corresponding to 40-50 Gv predicted for the East/West Telescopes from those actually observed during 1965. Such a process indicates that the spurious vector has an amplitude of 0.15% and a time of max of around 1400-1600 hours L.S.T. If the same vector is again subtracted from the vectors for 1966 the corrected vectors appear to be consistent with the model and suggest that the upperlimiting rigidity has increased somewhat during 1966. This conclusion which we have also obtained from the London recorders gives some confidence in our estimate of the spurious vector.

The only way to justify the subtraction of a constant vector as above from the observed diurnal vectors is to postulate the existence of a local source of diurnal variation which contributes to the E/W telescopes.

It is possible to envisage a number of ways in which a local source of this kind can be generated. These are detailed below:-

a) Possible effects associated with the geomagnetic field

b) Atmospheric temperature effects associated with the mesons

c) Instrumental temperature effects

In the following we shall investigate these possibilities in greater detail.

a) EFFECTS ASSOCIATED WITH THE GEOMAGNETIC FIELDS:

It appears to be extremely difficult to find any effects connected with the geomagnetic field to explain the common diurnal variation in the E/W telescopes. Dirunal changes in the threshold due to ionospheric currents are too small to account for the spurious vectors of 0.15%. Effects associated with the deformation of the geomagnetic field cavity are likewise too small to account for these large vectors.

b) ATMOSPHERIC TEMPERATURE EFFECTS:

These are expected to be negative in character and would be of the wrong phase (QUENBY and THAMBYAHPILLAI 1960, BERCOWITCH 1965 etc) to explain the time of maximum of about 1500 hours, that the spurious vector seems to have.

c) INSTRUMENTAL TEMPERATURE EFFECTS:

In view of the fact that the atmospheric temperature effects and effects associated with the geomagnetic field, could not provide an explanation for the spurious diurnal variation we have considered the possibility that this spurious vector is generated by instrumental temperature effects, associated with the diurnal variation in the temperature of the laboratory.

Over the period Jly 1964 to Apr 1967 the E/W telescopes were operated in a laboratory without any temperature stabilization and the diurnal temperature wave in the ground level temperature at Makerere is about 4 °C with a time of maximum at 1430 L.S.T. Therefore, if the temperature coefficient of the apparatus is about + 0.04%°C, a temperature wave induced by an instrumental effect may well be the cause of the spurious vector.

As discussed in the Chapter II, we have carried out an extensive temperature on the telescopes stationed at London which are very similar in design to the Makerere telescopes and have found the temperature effect to be less than 0.006%°C ± 0.003. In view of these results the temperature coefficient required to explain the spurious vector at Makerere appears to be excessive. However, it may be mentioned that the temperature coefficient found for the London telescopes, was critically dependent on the plateau slope of the Counting-rate /voltage characteristic. Though, with the values of about 2%/100 volts for the plateau slopes no significant coefficient could be detected, a large positive temperature coefficient appeared if the plateau slope was worsened. (e.g. by placing a gamma source beneath the telescopes). Therefore the possibility of a temperature coefficient in the apparatus is quite concievable and the magnitude of the coefficient would depend on the plateau slope.

In Aug 1967, the telescopes at Makerere were taken apart and restarted in a temperature controlled laboratory. Data is available from this new set up for a period of 8 months for Aug 1967 to Mar 1968. In order to establish whether the temperature stabilization has caused any differences in the diurnal vectors we have analysed this latest data from the E/W recorders, for the diurnal waves, and the results are shown in the figure 10. It is immediately apparent from this figure that the first harmonics obtained for the latest group of data are significantly smaller for both the East and West

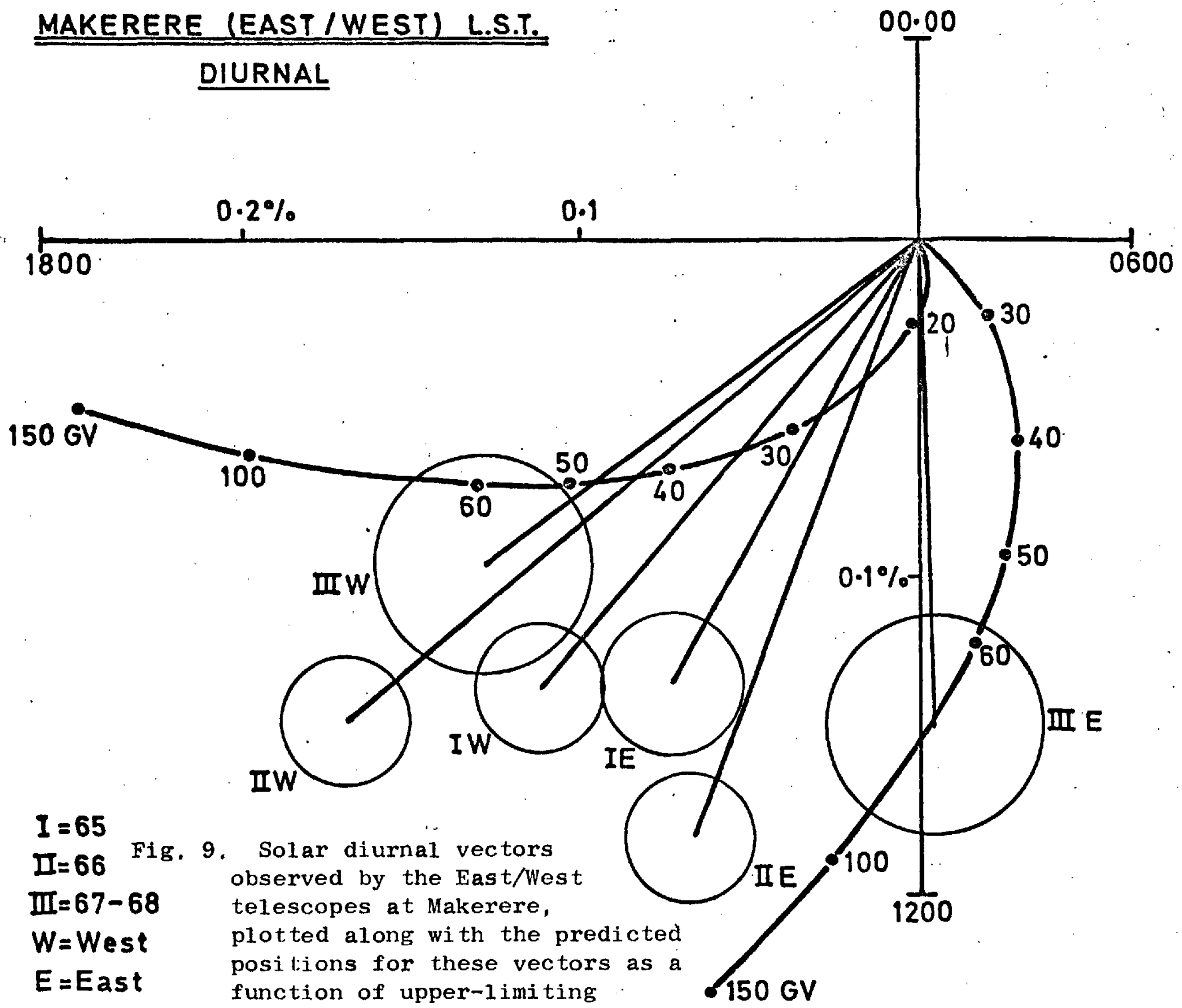


Fig. 9. Solar diurnal vectors observed by the East/West telescopes at Makerere, plotted along with the predicted positions for these vectors as a function of upper-limiting rigidity.

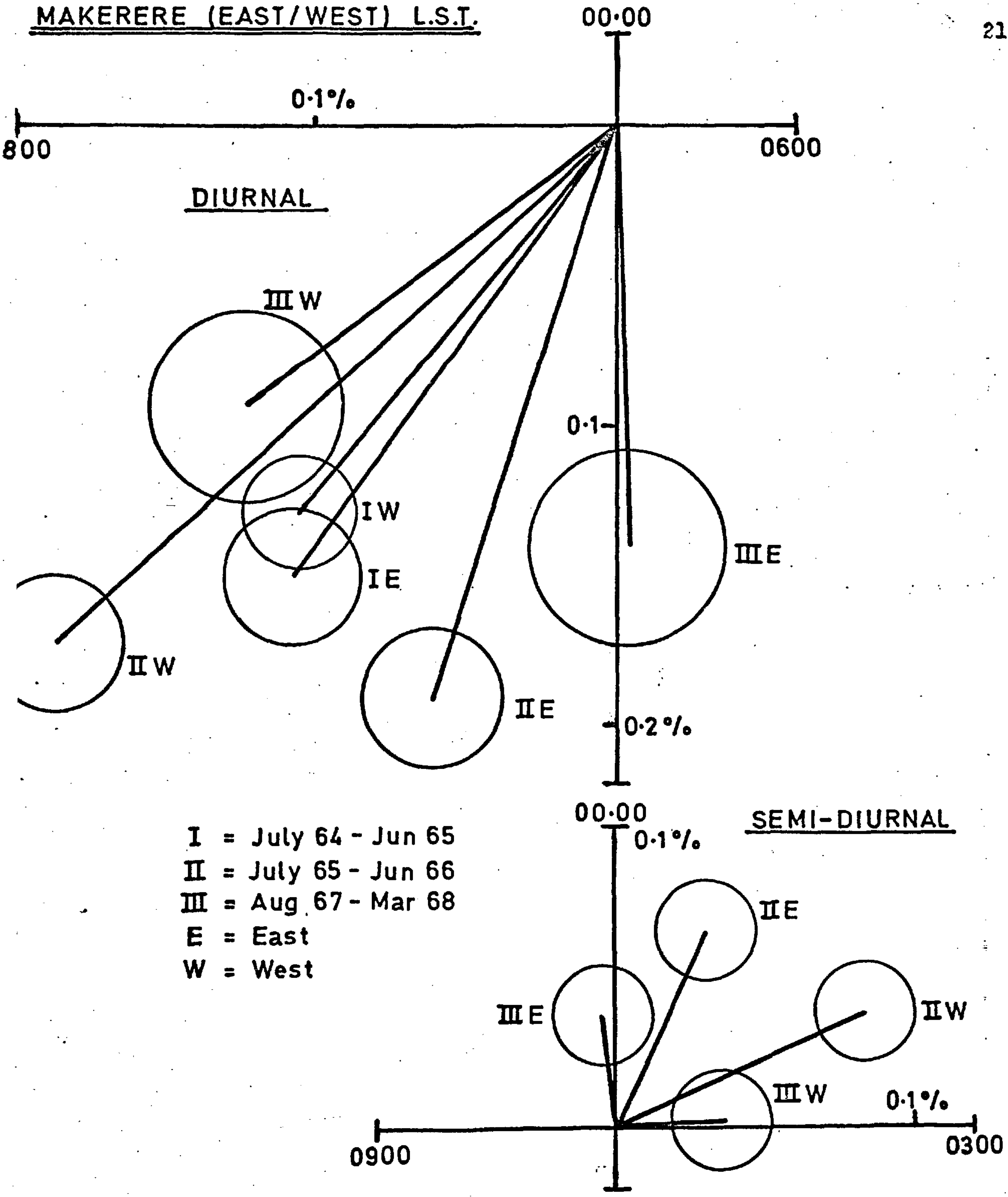


Fig 10. Solar diurnal and semi-diurnal vectors observed by the East/West telescopes, before and after temperature stabilization of the laboratory.

telescopes than the vectors obtained for either 1965 or 1966. The phase difference between the E/W vectors has also increased to about three hours.

Now a comparison of the diurnal vectors obtained at London during 1966 and for the period August 1967 to March 1968 shows that the diurnal vectors remained essentially constant for the two groups of data and therefore one would expect this to be so also for the MAKERERE recorders. In view of this the decrease in the amplitude and the splitting apart of the diurnal vectors for the latest group of data obtained from a temperature stabilised laboratory indicates that the effect has been caused by a removal of at least a part of the spurious vector which now appears to be due to the temperature wave in the laboratory. A comparison of the diurnal vectors obtained for the latest group of data with those for 1966 shows that the possibility of a temperature induced (instrumental) vector of about 0.12% is concievable. The phase of the difference vector for the two groups appears to be around 1500 hours.

In conclusion therefore, it appears that the Makerere telescopes have associated with them an instrumental temperature effect of about 0.15% at 1500 hours L.S.T. After this vector is subtracted from the data for 1964-66 the results agree with the corotation model and can be reconciled with the results obtained at London by the N/S recorders.

6.1.6. COMPARISON OF THE LONDON DATA WITH RESULTS OF DIRECTIONAL MEASUREMENTS NEAR THE SUNSPOT MINIMUM OF 1954.

The solar daily variation has been measured at Manchester by means of unshielded counter telescopes pointing in the North and the South directions at a zenith angle of 45° to the vertical during the declining phase of the solar cycle (No: 18) over the period 1948-54. (POSSENER and VAN HEERDEN (1956). Several interesting results were obtained from these measurements. In particular the phase of the diurnal variation measured by both the North and the South telescopes, was seen to go progressively to earlier hours from 1948 to 1954 and the amplitude was found to reduce considerably in the years of minimum solar activity 1953-54, as compared to the values during the period 1948-1952.

It will be interesting to compare the results obtained at Manchester with those obtained with the NORTH/SOUTH telescopes at London during the ascending phase of the present solar cycle (No: 20) over the period 1965-67.

We shall also investigate whether the average features of the solar daily variation, which seem to obtain in recent years, (namely a rigidity independent anisotropy cutting off at an upperlimiting rigidity, with a phase at 1800 hours (L.S.T.) outside the geomagnetic field), as indicated by neutron monitor and meson telescope measurements and lies within the framework of the Axford-Parker model, can also explain the main features of the earlier data.

The NORTH/SOUTH telescopes at London, are similar to the directional apparatus of POSSENER and VANHEERDEN (1956), with only slight differences in geometry and response. Thus, both the sets of apparatus record the total ionizing component of the cosmic radiation. While the direction of maximum sensitivity for the Manchester recorder is about 24° to the vertical (falling off fairly rapidly on either side), the corresponding direction for the North/South telescopes at London is about 32°. However, in view of the discussion in section 6.1.2. such differences in inclination do not cause any significant differences in the amplitude or phase of the diurnal variation to be expected in the two cases. In view of the small difference in the geomagnetic latitude (about 3°), the geomagnetic effects on the particles recorded at the two stations may be considered to be the same. In view of these facts we are justified in making a direct comparison between the two sets of data.

The results obtained at Manchester (1948-54) have been plotted along with those obtained at London during 1965-67 in figure 11. In this figure we have also plotted the loci of the endpoints of the solar diurnal vectors expected on the basis of a 0.4% rigidity independent anisotropy at 1800 hours, for different values of the upperlimiting rigidity. To take into account the slight differences in the geometry of the two sets of the recorders, we have constructed two curves for each of the North and the South recorders, one for a zenith angle of 32° and the other for a zenith angle of 24°, which will be applicable for the case of London and Manchester respectively. The theoretical curves have been drawn from a point shifted along the 0600 hour direction by 0.06% in order to take into account the temperature effects. (Since both the telescopes record the total ionizing component of the cosmic radiation the temperature effects can be taken to be the same for the two sets of data).

An examination of this figure brings out the following points:

a) The S.D.V. vectors for Manchester corresponding to 1948 are similar in phase and amplitude to the corresponding vectors observed at London during 1966-67. Further within the limits of the errors the S.D.V. vectors at Manchester also agree with values predicted on the basis of a rigidity independent anisotropy of 0.4% at 1800 hours, with values of the upper-limiting rigidity being about 100 Gv. Perhaps the agreement will be somewhat better for slightly larger external amplitudes. The actual vectors are also somewhat larger than the London vectors for 1966-67. In particular the vector corresponding to the North direction for 1948 is larger than the predicted values for reasonably high values of upperlimiting rigidity (100-200 Gv) and would seem to indicate that the larger observed amplitudes are in fact due to a larger free space amplitude. As discussed in section 6.1.4.

b) For both the North and South telescopes, the vectors corresponding to 1949-52 show a progressive shift to earlier hours as compared to the values obtained during 1948, and the predicted positions corresponding to the theoretical curves. This tendency is more pronounced for the South telescope.

It is interesting to note the changes in the phase difference between the North South vectors as the vectors progress to earlier hours over this period. The phase difference between the vectors during the four years of observation 1948-52 are as detailed below. They are expressed in degrees for convenience.

YEAR	PHASE DIFFERENCE. (as observed in the pressure corrected data)
1948	28°
1949	35°
1951	20°
1952	3°

The uncertainty in these values are typically about 10°. In view of this it would appear that the phase difference during the last year is smaller than that for the first two years listed above. For the year 1952 the maximum possible phase difference between the N/S telescopes can be about $12-15^\circ$ which is considerably smaller than the values obtained in the earlier years, 1948-49. A reduction in the phase difference can be the result of the fact that the mean energy of the particles taking part in the diurnal variation goes down. This is so because an examination of the Asymptotic directions for the N/S telescopes (Chapter IV) shows that if the mean energy of the particles taking part in corotation, (or what ever mechanism is responsible for the diurnal variation), goes down to about 15 Gv then the phase difference between the North/South recorders would vanish. This is also illustrated by the theoretical curves for the N/S directions plotted in figure 11. Thus for low values of the upperlimiting rigidity (Rmax below 20 Gv) a very small phase difference is expected between the North/South recorders. On the other hand it is seen from this figure that the amplitudes corresponding to such low values of the upperlimiting low values of the upperlimiting rigidity are also correspondingly small. The rather large amplitudes actually observed indicate that this cannot be the mechanism resulting in a small phase difference between the North/South telescope.

The pregressive shift towards earlier hours observed during 1949-52, cannot, in fact, be reconciled with a rigidity independent anisotropy at 1800 hours, even if the amplitude and upperlimiting rigidity are allowed to vary. This is so since the variations exhibited by the North/South recorders over this period seem to be at right angles to the theoretical curves in figure 11, whereas any variations which are associated with changes in upper cutoff will be along the theoretical curves. An examination of figure 8 shows that at London, or Manchester, variations in the free space amplitude will also result in the vectors increasing along the theoretical curves. The progressive shift at right angle seems to indicate that the phase of the diurnal anisotropy has decreased from the value of 1800 hours (L.S.T.). This would imply that an additional vector with a time of maximum earlier than 1800 hours seems to be contributing to the diurnal variation observed by these telescopes. This would also explain the gradual reduction in phase difference in the North/South vectors observed, since the effect of any additional vector will be different for the North and the South telescopes. This is illustrated by the fact that even for a rigidity independent anisotropy at 1800 hours the vectors predicted for the North and the South telescopes differ in their amplitudes, with the South telescope having the larger amplitudes, for the same value of the upperlimiting rigidity. In view of this a different response to any additional vector depending on its energy characteristics is plausible and can be the cause of the reduction in the phases observed between the N/S recorders.

At this point it may be mentioned that the conclusions obtained above will not be affected to any appreciable extent by any erroneous assumptions that we may have made as regards the temperature effects. Thus, e.g. if we assume that the temperature correction is 0.1% at 0600 hours instead of the value of 0.06% at 0600 hours assumed above then, though the vectors for the North telescope will agree with the predictions of the theoretical curve more closely than before, those for the South telescope will be shifted even further away from the predicted values. In fact it is not possible to obtain a fit with the predicted value by merely making a temperature correction by means of a common vector for both the North and the South telescopes.

c). The vectors for 1953-54 are very much smaller than the corresponding vectors for the earlier periods. Though the nominal phases for both the North and the South recorders are in fact earlier than those obtained in earlier years the vectors for 53-54 are in fact quite close to the theoretical curves and the data corresponding to this period can, in fact, be reconciled with a 0.4% rigidity independent anisotropy, if it is assumed that the upper limiting rigidity had in fact reduced to below 20 Gv during this period. Such an assumption seems to be justified in view of the fact that these years represent the years of minimum solar activity corresponding to the solar cycle No. 18., and reduction in upperlimiting rigidity have already been observed to occur at the recent solar cycle minimum.

It is observed, however, that the values of the upperlimiting rigidity required to explain the data corresponding to the period 1953-54, are considerably smaller than the values suggested by cosmic ray data for the recent solar minimum of 1964-65. The actual amplitudes of the North/South vectors for the period 1953-54 are also seen to be somewhat smaller than the corresponding vectors for the period 1965. This difference in behaviour during the two minima may be attributed to the fact that the solar minimum of 1954 was deeper (in terms of sunspot activity, number of quiet days etc), than the minimum of 1965.

In conclusion therefore it appears that the behaviour of the solar diurnal anisotropy during the two periods of 1965-67 and 1948-54 were different in

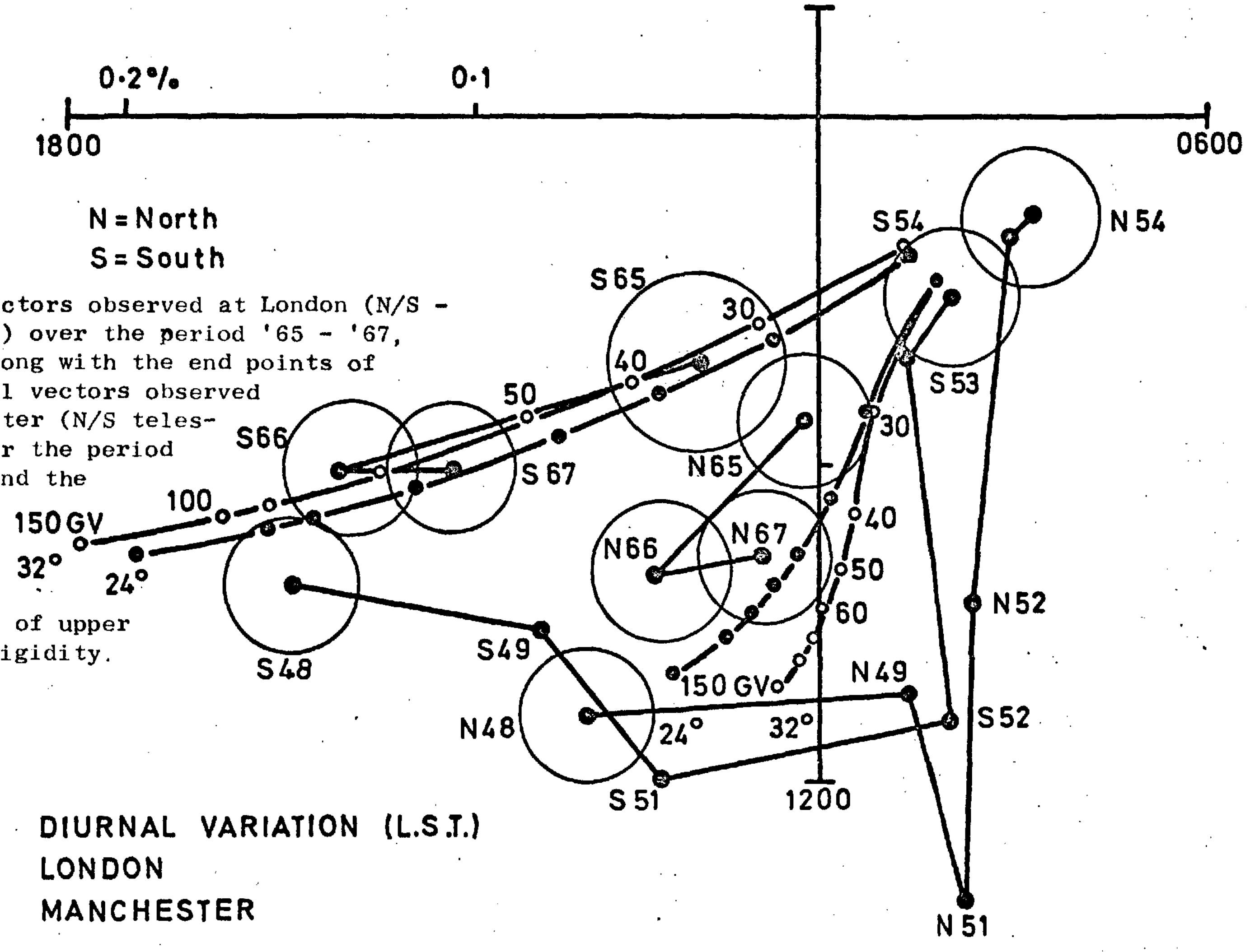


Fig. 11. Diurnal vectors observed at London (N/S - telescopes) over the period '65 - '67, plotted along with the end points of the diurnal vectors observed at Manchester (N/S telescopes) over the period 1948-54, and the predicted positions for these vectors as a function of upper limiting rigidity.

so far as all the data for the second period cannot be reconciled with a 0.4% anisotropy at 1800 hours. Though the results obtained during 1948 and during 1953-54 can be reconciled with these characteristics of the diurnal anisotropy, the data obtained during 1949-52 seem to indicate the presence of an additional vector with a time of maximum earlier than 1800 hours, which seems to be contributing to the diurnal variation observed by the N/S telescopes during these years.

A comparison with the predictions of a rigidity independent anisotropy at 1800 hours, suggests that the upper limiting rigidity had reduced to 20 Gv, during the years of minimum solar activity, 1953-54, corresponding to the solar cycle No. 18.

6.1.7. COMPARISON OF THE COROTATION MODEL WITH IONIZATION CHAMBER DATA ACQUIRED OVER THREE SOLAR CYCLES:

As discussed in the foregoing section, we have noted that the phase changes observed in the diurnal variation by the directional recorders in Manchester, during the period 1948-52, cannot be reconciled with the idea of a rigidity independent anisotropy at 1800 hours L.S.T. as predicted by the corotation model. The primary characteristics of the data for this period was seen to be a progressive shift in the diurnal vectors almost at right angles to the variations expected from a change in the upperlimiting rigidity, or the free space amplitude, the two parameters that can vary according to the ideas of the corotation theory.

We have accordingly pursued this point further and have examined data on the diurnal variation, acquired over some thirty years from ionization chambers run at Cheltenham, Christchurch and Huancayo, under the auspices of the Carnegie Institution of Washington, D.C. It is our purpose to establish whether or not all the data on the S.D.V. accumulated over about three solar cycles can be explained in terms of the average features of the diurnal anisotropy which seem to obtain in recent years (McCRACKEN et. al. (1965) etc. and are within the framework of the corotation model), or by reasonable variations of the upperlimiting rigidity and free space amplitude which are permitted by the corotation theory. In particular we wish to investigate the phase and amplitude changes observed at these stations near times of solar minima and reported by several workers, and to establish whether these features of the data are explicable in terms of upperlimiting rigidity reductions or free space amplitude changes in a similar manner to the amplitude reductions observed at London during the recent solar minimum.

The chief particulars of the three Carnegie Institute stations are given in Table I below. At each station a shielded ionization chamber has been operated and the data obtained has been analysed by Forbush for the diurnal and the semi-diurnal waves. FORBUSH (1968).

We have calculculated the solar daily variation to be expected at the three stations on the basis of a rigidity independent anisotropy with an amplitude of 0.4% at 1800 hours L.S.T. for several values of the upper-limiting rigidity from 10 to 150 Gv. Methods detailed in the foregoing sections have been used for these calculations. Asymptotic directions required for these calculations have been obtained from the I.Q.S.Y. manual No. 10. (McCRACKEN et. al. 1962). In the case of Cheltenham and Christchurch, we have used the asymptotic directions calculated for Swarthmore and Invercargill respectively, since the trajectory calculations from Cheltenham and Christchurch are not available. The difference in the geographic co-ordinates between the two groups of stations are sufficiently small to justify this choice. Differential response functions calculated by Webber for the hard component at S/L, have been used for the calculations. In the case of the low latitude station Huancayo the effects of smoothing in the finite asymptotic cones of the detector are expected to be the most important and we have therefore considered the effects of this smoothing and have corrected the amplitudes accordingly for this station. We have also investigated whether smoothing will be an important factor for the other two medium latitude stations employed, by studying in detail the effects of contributions from inclined directions to the amplitude and phase of the S.D.V. at Cheltenham. It was found that these effects will be only very small and accordingly we have only considered vertically arriving particles for the case of Cheltenham and Christchurch. Since, Huancayo is a mountain altitude station there will be some errors in the calculations for this station since we have used S/L response functions. The effect of this will be to slightly reduce the amplitudes expected for low rigidities and give greater weight to the higher rigidities. However, since Huancayo is an equatorial station, the geomagnetic field will exclude particles below about 15 Gv anyway, and the net effect will be small.

However, before we can make any meaningful comparison with the predictions of the corotation model it is necessary to establish the temperature effects at these stations reasonably accurately. In effect we wish to find out the origin from which we should plot the theoretical curves, we have calculated.

We have endeavoured to fix the temperature effects at each of these stations by employing the data obtained from these stations for 1958-66, over which corresponding measurements are also available from other types of apparatus, e.g. neutron-monitors and meson telescopes located underground (at depths of 40 m.w.e. and 60 m.w.e.). Results obtained from neutron monitors will be free of atmospheric temperature effects and results arrived at using these instruments will be free of uncertainties associated with these effects. For underground telescopes it is possible to determine the temperature effects reasonably accurately by using the crossed telescope technique discussed in Chapter IV, since at the rigidities monitored by telescopes located at about 50 m.w.e. the paths of the cosmic ray primaries are affected very slightly by the geomagnetic field. Underground measurements have been carried out by PEACOCK et. al. (1967) and JACKLYN et. al. (1965) (using directional meson counters) at depths of 60 m.w.e. and 40 m.w.e. respectively. From results obtained (by directional telescopes) at both these stations it was concluded that the contribution from a temperature induced diurnal effect to the actual diurnal waves observed at these two stations was insignificantly different from zero. (an examination of the Dorman density of temperature coefficients, DORMAN (1957), corresponding to these depths, also shows that the negative temperature effects at these depths will be very small).

In view of these facts, it is reasonable to expect that the conclusions regarding the diurnal anisotropy reached from an analysis of data from these stations will also be uncontaminated by temperature effects. In addition to this advantage the measurements by neutron monitors and U-G telescopes have over S/L measurements using meson telescopes or ionization chambers, these instruments will in effect provide information on the behaviour of the solar anisotropy in energy ranges on either side of those monitored by surface level ionization chambers and meson telescopes. This is so because the neutron monitors will on average respond to a lower mean primary energy than that recorded by ionization chambers located at the same place, (this is so especially for a high or medium latitude station), while underground telescopes situated at 40 m.w.e. or 60 m.w.e. record secondary particles generated due to the interaction of higher energy particles than those contributing to the counting rate of ionization chambers, located on the surface of the Earth. Therefore, using information on the S.D.V. from U-G telescopes and neutron monitors, we can infer the possible characteristics of the Solar diurnal anisotropy in the intermediate energy range also.

Now, as already mentioned, analysis of data from a world wide network of neutron monitor stations (e.g. McCRACKEN et. al. (1965)) has shown that over the period 1958–65 the main characteristics of the solar diurnal anisotropy were a rigidity independent amplitude of 0.4% and a time of maximum at 1800 hours L.S.T. Though, more recent analysis has shown that the amplitude of the S.D.V. as observed by S/L neutron monitors had reduction during 1965, as compared to 1958 (DUGGAL et. al. 1967), we know that such a reduction in amplitude can in fact be explained by a reduction in the upperlimiting rigidity, without any change in the free space amplitude. These features, as we have seen, are consistent with the idea of corotation of the cosmic ray particles, with the interplanetary magnetic field.

On the other hand, measurements carried out over the period 1960–66, at the underground station at London (60 m.w.e.) by DUTT (1965) and PEACOCK (1967) using vertical and inclined meson telescopes, found that the data acquired over this period were also consistent with the idea of an external anisotropy at 1800 hours with an amplitude of 0.4%. Though, neutron monitors do not provide a sensitive measure of the upper-limiting rigidity, (since a major part of their response comes from energies in the range 1 Gv to 60 Gv.), this parameter can in fact be determined more accurately from underground results. PEACOCK (1967) finds that the data acquired during the period 1960–64 indicate that the upperlimiting rigidity had a value of about 100–130 Gv during this period. They also find from an analysis of data acquired over the period of the solar minimum that the upperlimiting rigidity had reduced to below 60 Gv during this period. Data for 1966 indicates that R max has again increased to about 60–80 Gv during this period. Underground measurements have also been carried out by JACKLYN (1965) over the period 1959–65. Data obtained from this experiment are also consistent with a rigidity independent anisotropy of amplitude 0.4% at 1800 hours. Values of the upperlimiting rigidity suggested from these measurements are about 100 Gv. These measurements also indicate that the upper cutoff had reduced to 50 Gv during 1961 and 1965.

In view of these results which appear to be consistent among themselves and are also consistent with the predictions of the corotation model it appears that the idea of corotation of the cosmic ray particles seems to account for the major features of the diurnal anisotropy observed during 1958-66.

Now since the Neutron monitor and underground telescope data seem to indicate that the main features of the diurnal anisotropy during the period 1958-66 were a rigidity independent anisotropy of amplitude 0.4% at 1800 hours (L.S.T.) (outside the geomagnetic field), it is reasonable to expect that the data from the ionization chambers at Cheltenham, Christchurch and Huancayo should also lie on the curve giving the predicted positions of the diurnal vectors for various values of the upper-limiting rigidity with a free space amplitude and phase of 0.4% and 1800 hours respectively. Now we can use these facts to fix the temperature effects at the three ion-chamber stations, Cheltenham, Christchurch and Huancayo. (i.e. to fix the origin from which the theoretical curves corresponding to the loci of the endpoints of the expected position of the diurnal vectors, should be plotted in order to take into account the temperature effects).

We find that if we assume the temperature vectors at Huancayo to be about 0.13% at approximately 0530 hours L.S.T. and those for Cheltenham and Christchurch to be about 0.07 to 0.08% at 0530 hours (similar to the North/South telescopes at London) and take the origin of the theoretical curves above to be at these points respectively on a Harmonic dial, then the endpoints of the observed diurnal vectors at each of the three stations, for the period 1958-66 fall reasonably near to the predicted values. Further, the values of the upperlimiting rigidity required to explain the data for this period (1958-66), are about 100 Gv for years of high solar activity and about 40 Gv for 1961 and 1965 during which the Solar daily variation measured at London (Underground) and Hobart, also showed a similar reduction to low values. Data for Christchurch is available only for 1958-61 and therefore there can be some uncertainty in positioning the theoretical curve for this case.

It may be mentioned here that the temperature vectors assumed here, (in order that the data for 1958-66 are consistent with a rigidity independent anisotropy at 1800 hours), compare favourably with the actual measurements of these vectors at medium and low latitude stations. (e.g. BERCOVITCH et. al. (1965) and QUENBY and THAMBYAHPILLAI (1961)). The temperature vectors that we have assumed here for the three ion-chamber stations are also suggested from another reasoning. It was found that during 1954 the neutron monitor at Huancayo showed a zero diurnal variation. Since at equatorial latitudes the response of a neutron monitor and an ionchamber are very similar, it was assumed that the diurnal variation observed by the ionchamber at Huancayo represented the atmospheric temperature effects. It we assuem that the diurnal waves observed at Cheltenham and Christchurch (ionchambers), during 1954 are also largely due to the atmospheric temperature effects, then we would expect the temperature wave for these stations to be near about the actual observed diurnal vectors for 1954. An examination of figure 12 shows that the values of the temperature vectors we have assumed at the three ionchamber stations in order to bring the results for 1958-65 in line with those obtained for underground telescopes and neutron monitors, are in fact within the limits of the errors equal to the values of the diurnal vectors actually observed at the three stations during 1954.

These facts give additional support to our choice of the temperature vectors at the ionchamber stations.

Now, in figure 13 (a, b, c), we have plotted the endpoints of the diurnal vectors observed during the period 1938-46 for the three ionization chambers, along with the loci of the predicted values corresponding to a 0.4% rigidity independent anisotropy as above. The temperature effects assumed at the three stations are the same as above. We observe from this figure that data for all three stations corresponds fairly closely with values predicted be the curve. The agreement is seen to be especially good for Cheltenham, An examination of the figure also shows that values of the upper cutoff obtained from a comparison of the observed points for this period also agree with values similarly obtained from a comparison of the observed vectors with the predicted values.

In particular, the data corresponding to the years of minimum solar acitivity (1944), give values for the upper cutoff which are in reasonable agreement at the three stations and also agree with values of this parameter obtained for 1965 from figure 12. (About 30-40 Gv). Values for years of high solar acitivity are about 100 Gv for both groups of data. In view of these facts it appears that the data obtained over the two groups of years (1939-46 and 1958-66) are consistant with the idea of a rigidity independent anisotropy at 1800 hours, as is predicted by the corotation theory. The observed data are consistent with free space amplitudes of about 0.4% Perhaps during the years of minimum activity the free space amplitude reduces somewhat as is indicated by the fact that the vectors for 1965 and 1944 tend to shift slightly away from the curves. During the years of maximum activity the amplitude may have a somewhat greater value than 0.4% However, the data seems to indicate that large variations in free space amplitudes do not occur and the amplitude reductions during the years of minimum solar activity are primarily the result of reductions of upperlimiting rigidity.

Now in figure 14 we have plotted the data for the intervening period (1947-57) and also for the periods (37-46) and (57-66), for the three stations along with the predicted values of the end points of the vectors according to the corotation theory. From this figure the following points are obvious.

a) The vectors for 1947-53 show a progressive shift away for all the three stations as was in fact observed at Manchester by the North/South recorders. As mentioned in section 6.1.6. this motion of the diurnal vectors at Manchester could not be reconciled with the predictions of the corotation model, in so far as they cannot be explained in terms of reductions in upper cutoff and/or changes in free space amplitudes. In this figure we have also plotted the predicted values of the diurnal vectors corresponding to a free space amplitude of 0.7%, (the maximum limit on the idea of corotation), other features of the anisotropy remaining the same. The figure shows that all the data cannot be explained in terms of a simple increase in free space amplitude. In view of these features it would appear that these data also seem to indicate the presence of another vector at a time of maximum earlier than 1800 hours, that seems to be contributing to the observations. (If we are to retain the idea of a rigidity independent anisotropy)

b) In the data corresponding to the declining phase of the solar cycle (1950-54), we observe a reduction in amplitude, superposed on the gradual shift away from the theoretical curves. The data for 1954, in fact, seems to suggest that the diurnal variation had reduced to zero. It appears, therefore, that the 1800 hour component normally attributed to corotation had gradually diminished over the years of declining activity, while at the same time an additional component with a somewhat smaller amplitude was

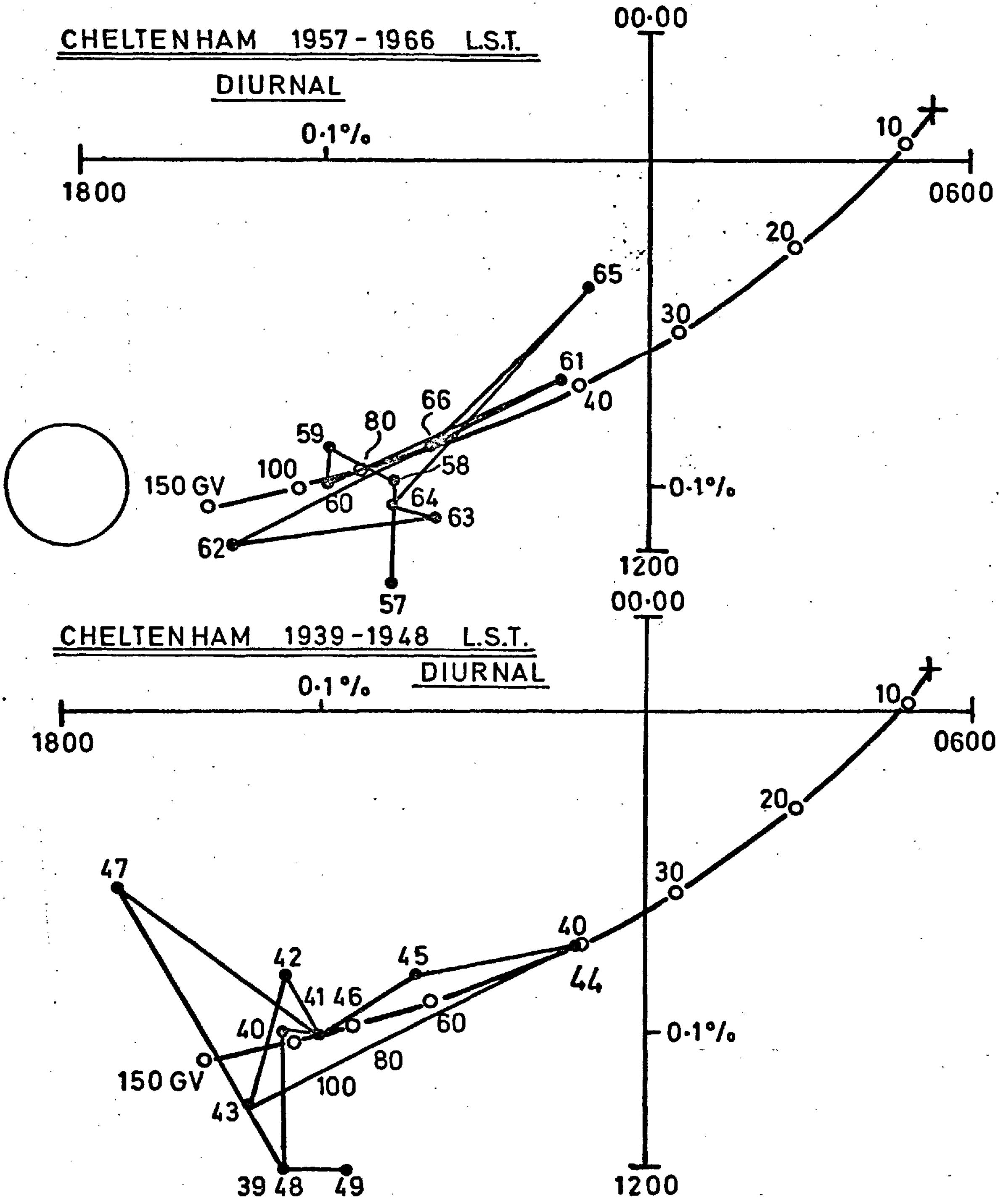
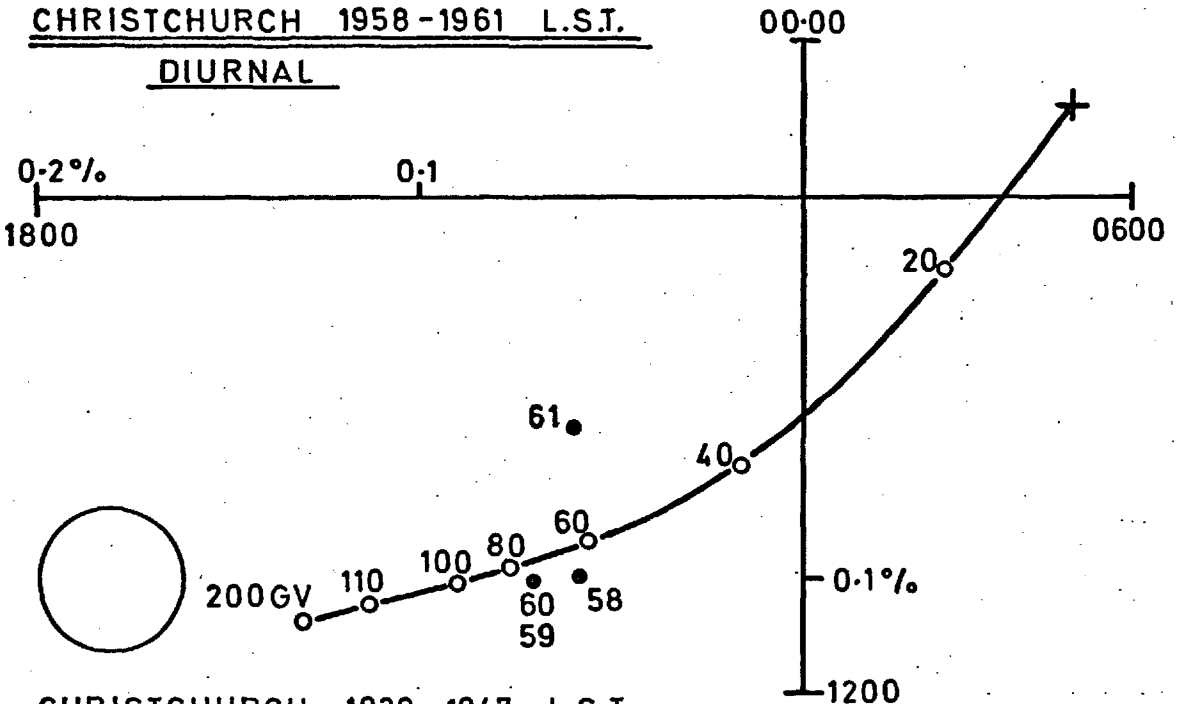


Fig. 12a, End points of the diurnal vectors observed at CHELTENHAM
Fig. 13a, over the period 1957-66 (top) and over the period 1939-48 (bottom) along with the predicted positions for these vectors.



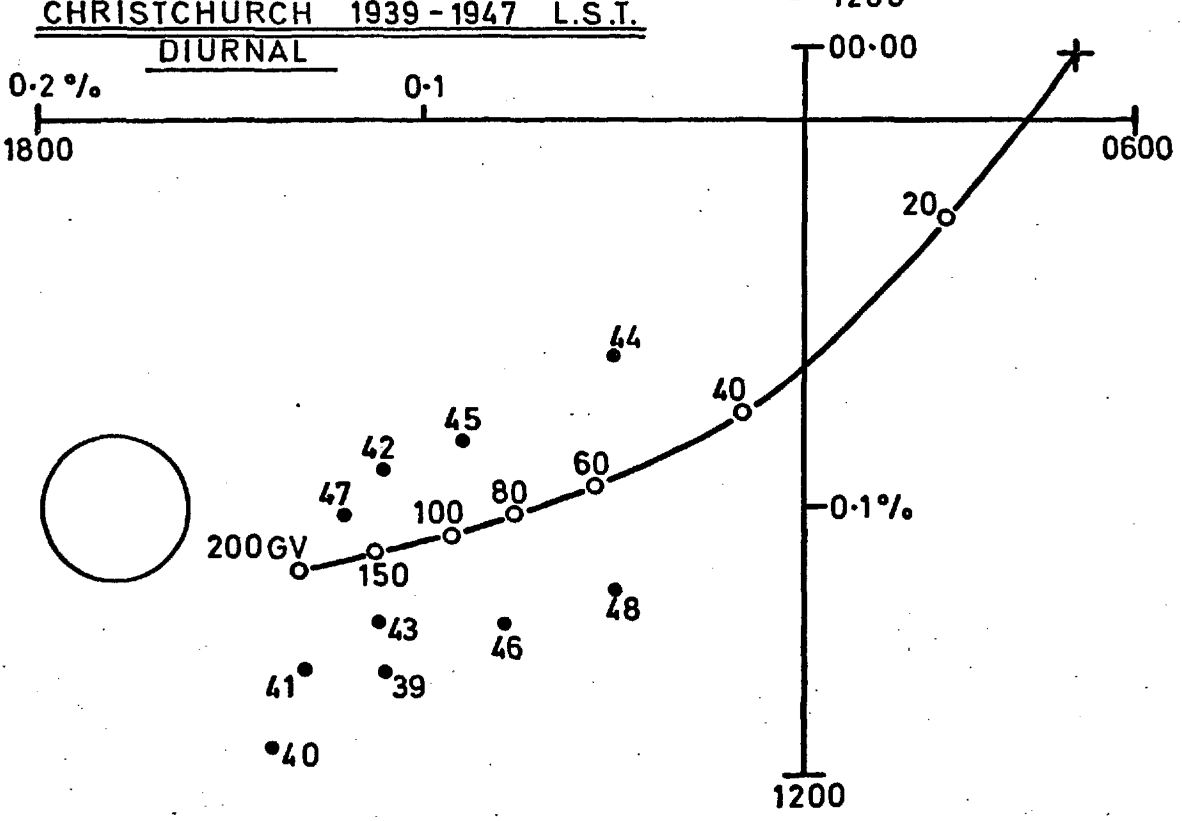


Fig 12b, End points of the diurnal vectors observed at CHRISTCHURCH
Fig 13b, over the period 1957-66 (top) and over the period 1939-48 (bottom) along with the predicted positions for these vectors.

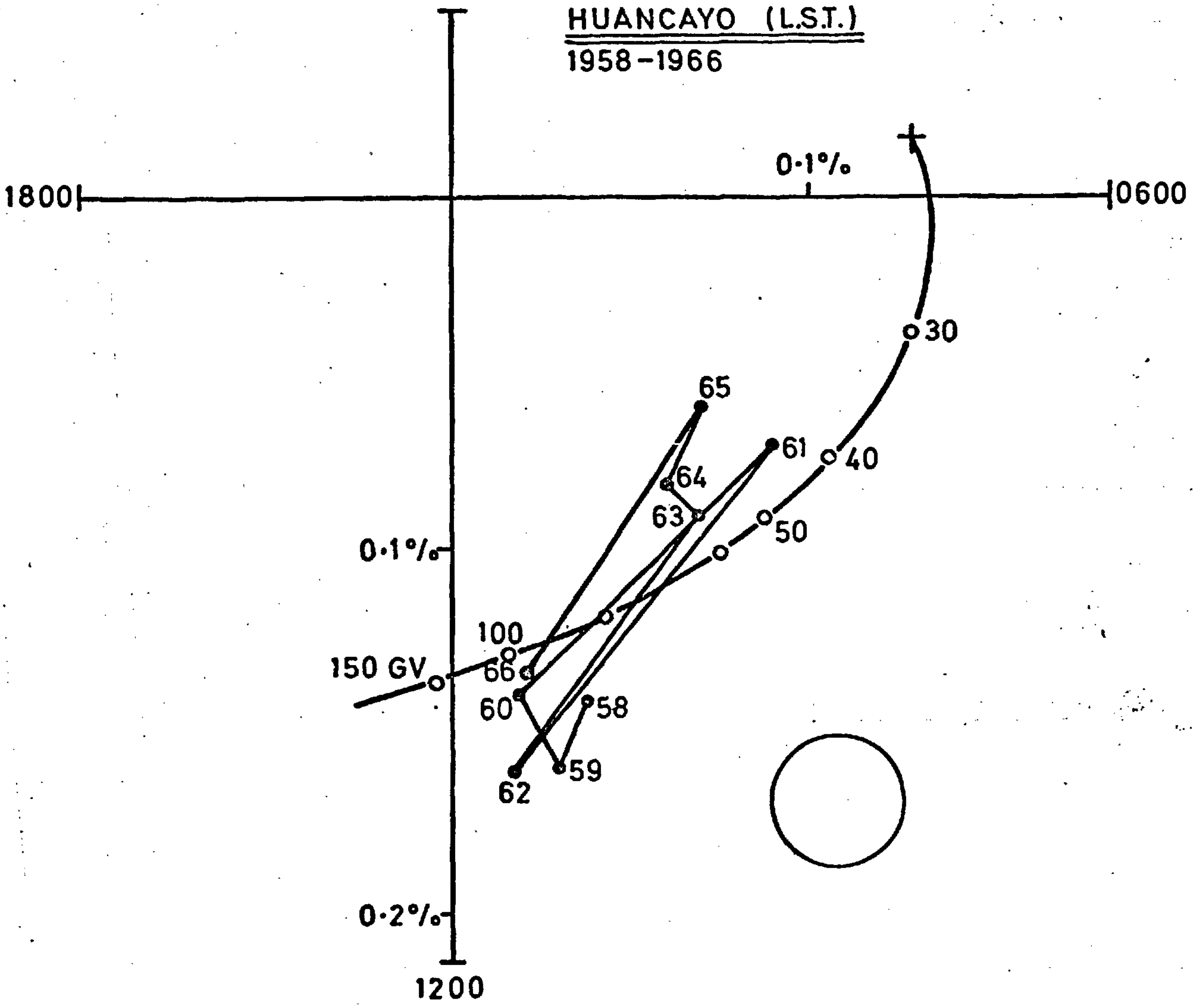


Fig. 12c. End points of the diurnal vectors observed at HUANCAYO over the period 1957-66 along with the predicted positions for these vectors.

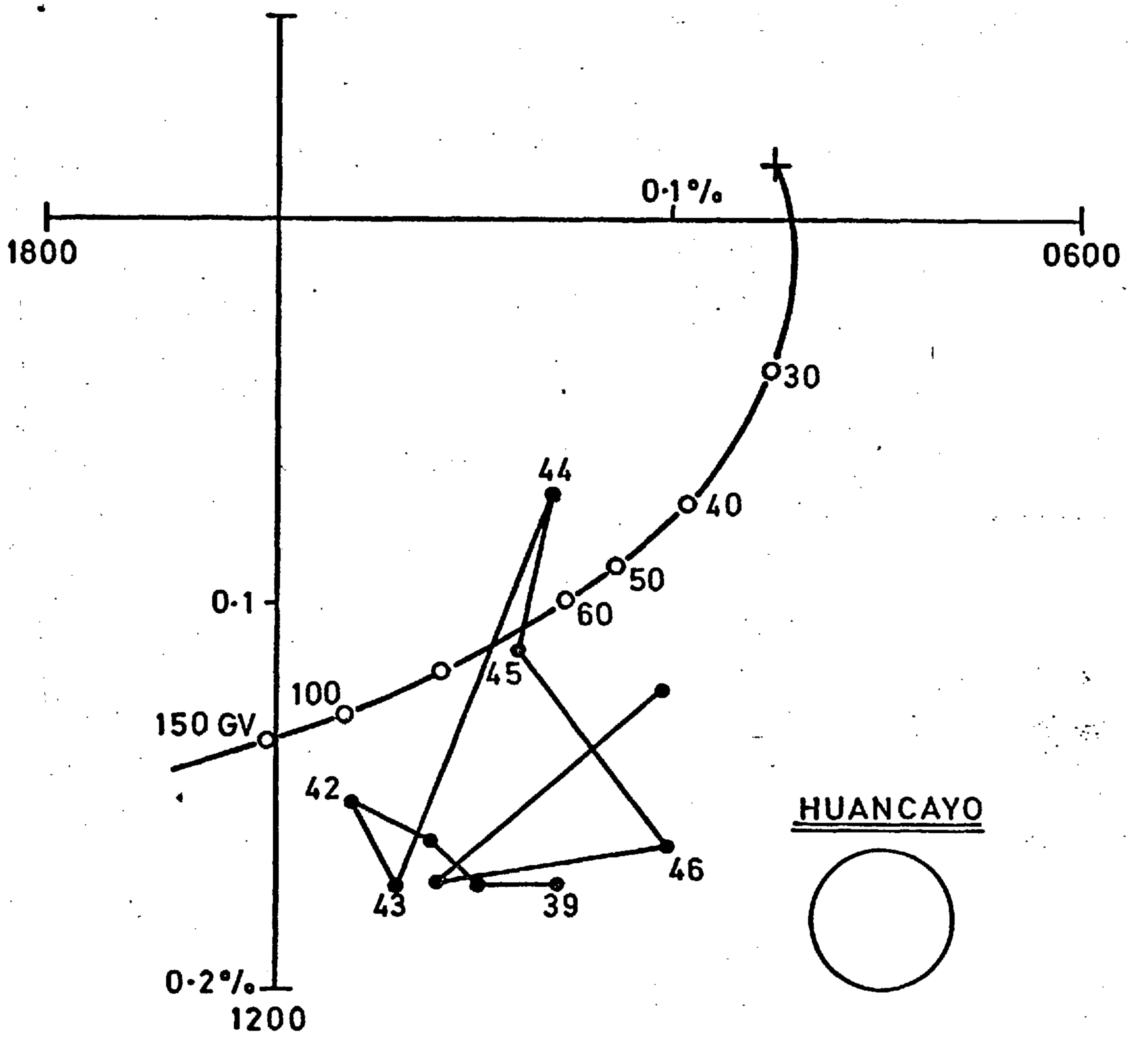


Fig. 13c. End points of the diurnal vectors observed at HUANCAYO over the period 1939-1948 along with the predicted positions for these vectors.

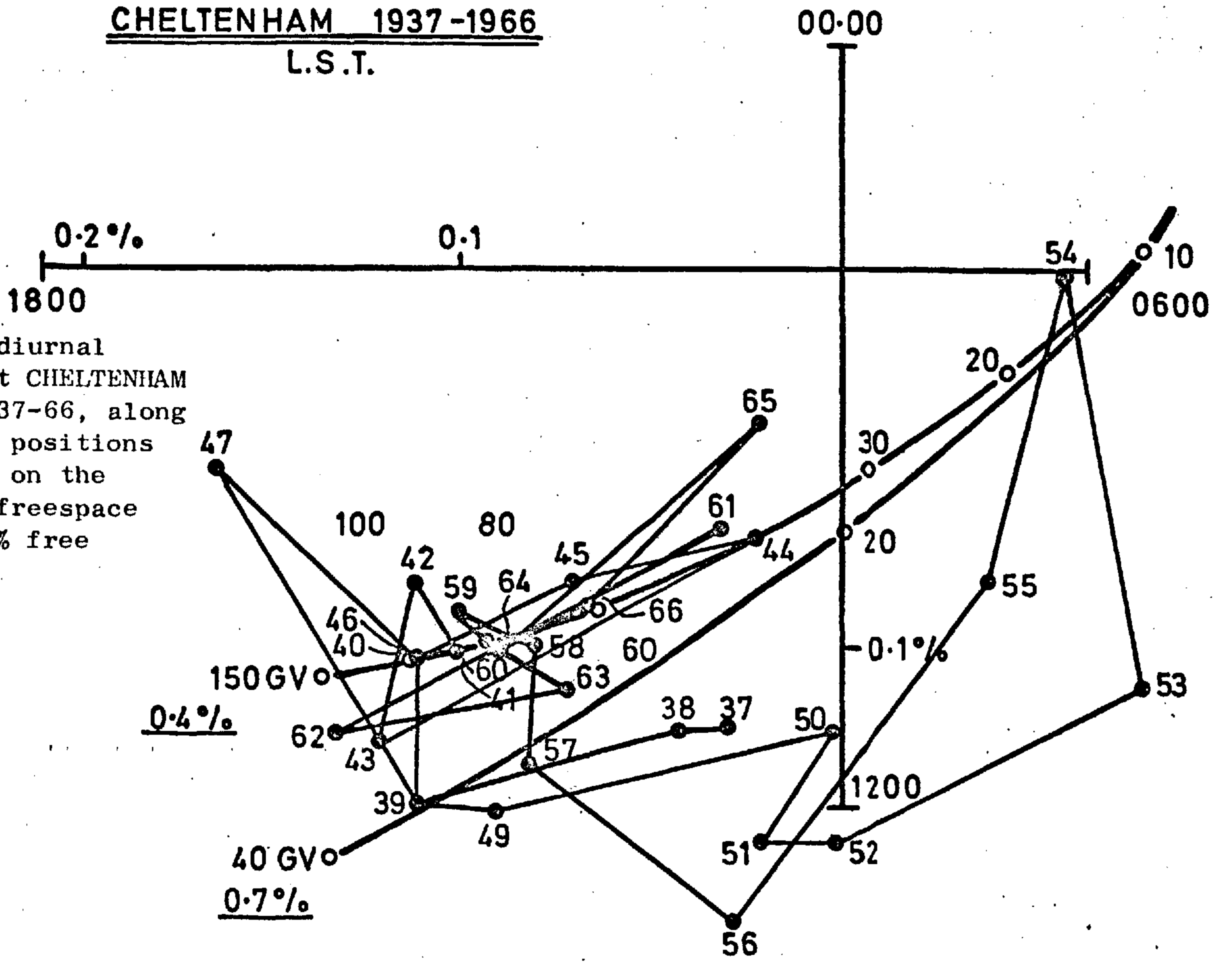


Fig. 14a. End points of the diurnal vectors observed at CHELTENHAM over the period 1937-66, along with the predicted positions for these vectors, on the basis of a) 0.4% freespace amplitude, b) 0.7% free space amplitude.

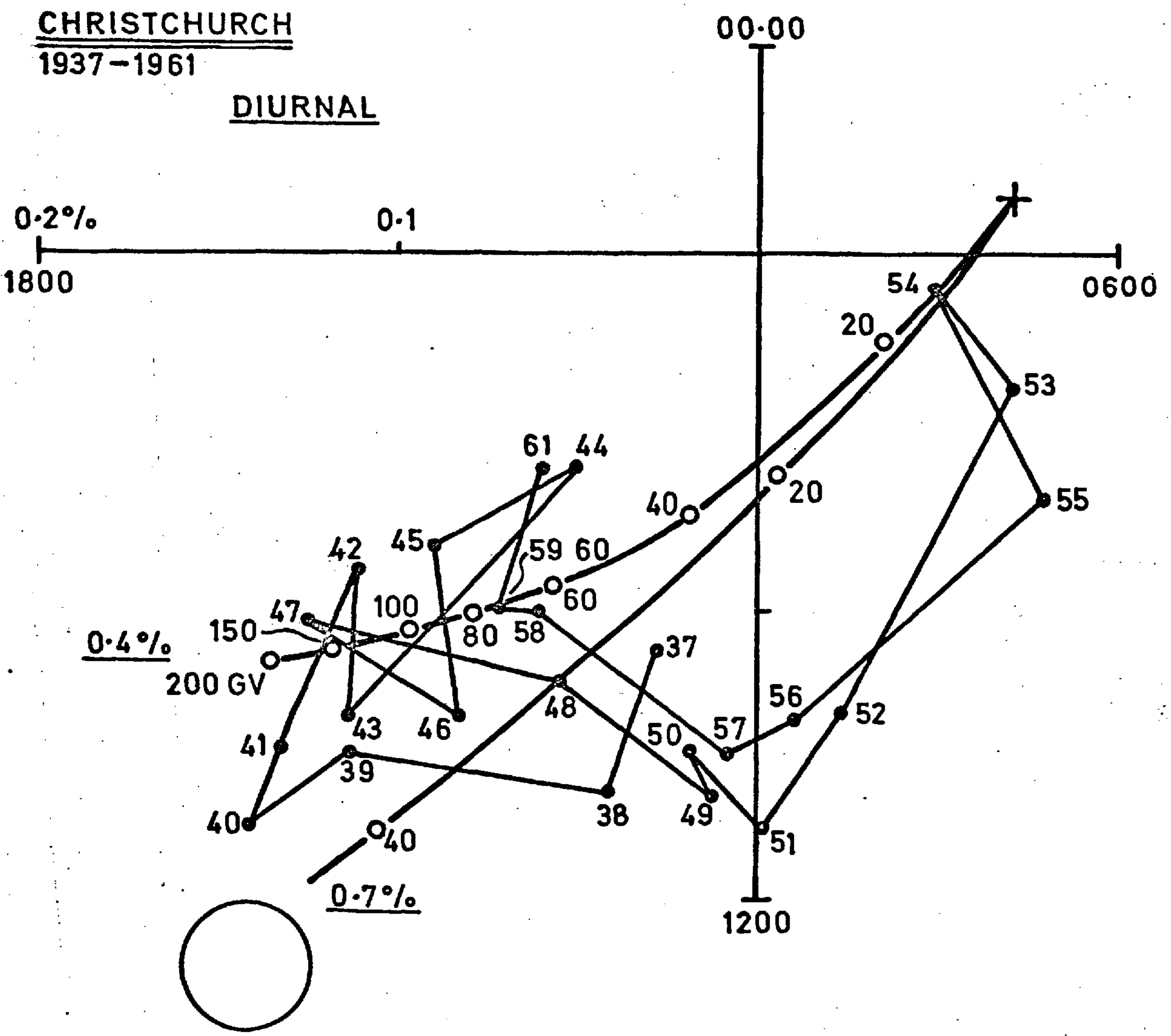


Fig. 14b. End points of the diurnal vectors observed at CHRISTCHURCH for 1937-66 along with the predicted positions for these vectors.

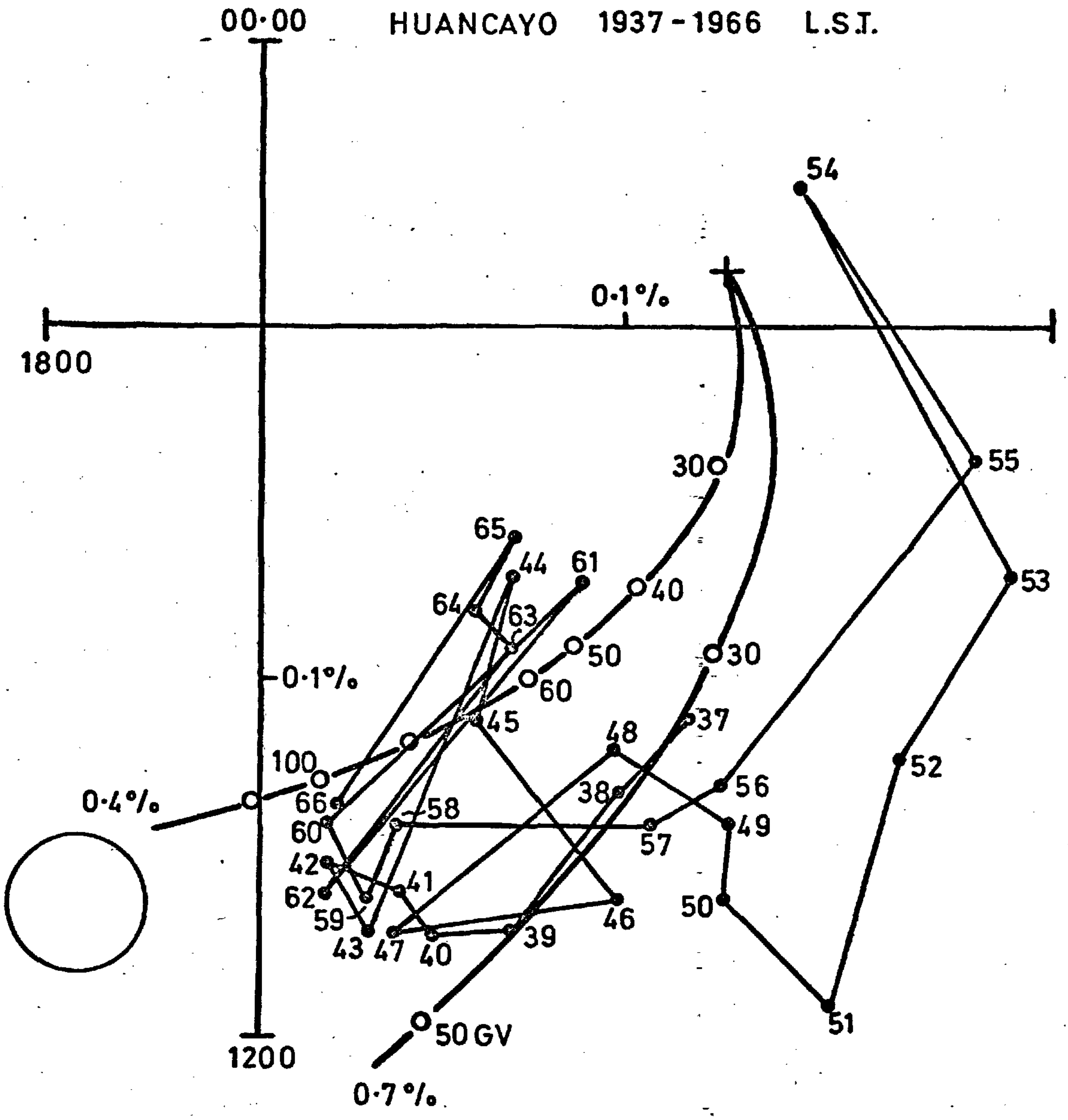


Fig. 14c. End points of the diurnal vectors observed at HUANCAYO for 1937-66 along with the predicted positions for these vectors.

also contributing to the diurnal variation observed. The data for 1954 suggests that both components had reduced to zero. A decrease in the contribution of the corotation component during the years in the neighbourhood of the solar minimum is, as we have already seen, explicable in terms of a lowering of the upperlimiting rigidity. However, in order to explain the reduction observed during the period 1949-52, which represent years of fairly high activity, it appears that we will have to invoke a reduction in the free space amplitude.

c) In going from 1954-57 we observe that at all the three stations the end points of the diurnal vectors fall considerably to the right of the curves, giving the predicted amplitudes on the corotation theory, thereby indicating the presence of an additional component during these years also. The contribution from corotation seems to be building up from 1954-58 while the endpoints of the vectors gradually shift towards the corotation curves.

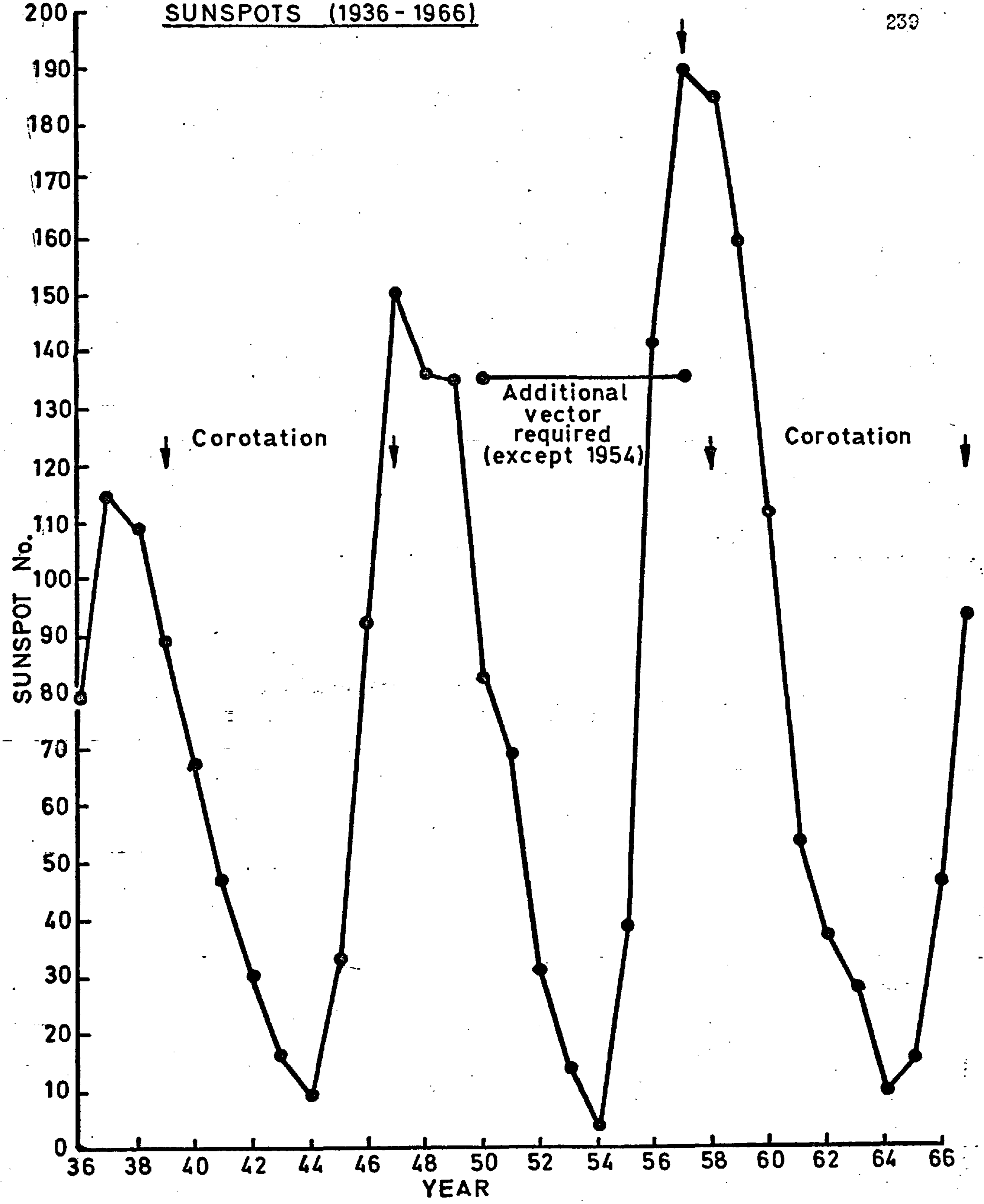
d) Over the period 1958-66 the data are consistent with a single anisotropy at 1800 hours (Rigidity independent and with an amplitude of about 0.4%), as we have already seen.

In view of the foregoing observations it appears that all the data obtained at the ionization chamber stations from 1939-66 is not explicable in terms of a single rigidity independent anisotropy at 1800 hours, as is predicted by corotation theory. In the figure (15) we have plotted the sunspot numbers which can be used to characterise the cycle of solar activity. In this figure we have also indicated the periods over which corotation seems to provide the basic mechanism responsible for the diurnal variation and the periods over which a single rigidity independent anisotropy at 1800 hours is not able to explain the observed features of the data. Data for these years seems to indicate the presence of an additional vector with a time of maximum earlier than 1800 hours.

It must be mentioned here that the choice of the temperature vectors

Fig. 15.

SUNSPOTS (1936-1966)



at the three ionization chamber stations will affect our conclusions regarding the direction and magnitude of the additional component (required to explain the diurnal variation at these stations over the period 1949-57), considerably. Thus e.g. if the temperature effects are taken to be somewhat larger, (about 0.1% for Christchurch and Cheltenham and 0.17% at Huancayo) with a later time of maximum (about 0700 to 0900 hours L.S.T.) then the loci of the expected positions of the diurnal vectors will be shifted so that the data for 1958-66 lies on one side of these curves while the data for 1949-57 on the other side. Though this will not affect our basic conclusion that only one vector at 1800 hours, (as predicted by the corotation theory), is inadequate for explaining all the observed data, it will mean that this additional vector that we have to invoke to explain the data reverses direction over a period of ten years. In one case it tends to drag the observed vectors to later times of maximum than those predicted by corotation theory, and in the other case intends to drag the diurnal vectors to the opposite side and tends to make the time of maximum earlier than that predicted by corotation.

This picture will correspond to the idea suggested by FORBUSH (1967) that the secular variations exhibited by the diurnal vectors are the result of a 20 year wave, superimposed on the corotation effect. The average vector in the 1800 hour direction is shown to have an amplitude of 0.12% and the 20 year wave, an amplitude of about 0.08%. According to Forbush, the time of maximum of the 20 year wave reverses from the 2100 hour direction to the 0900 hour direction over a period of 10 years. The maximum effect in the 0900 hour direction should occur at about 1953-54, the wave should gradually reduce to zero by 1958 and then gradually increase to its maximum value in the 2100 hour direction by about 1963-64. Further the 20 year wave is shown to be independent of magnetic activity, while the

1800 hour component shows a correlation with magnetic activity and increases to about 0.16% during years of high activity.

However, the neutron monitor data and underground telescope data over the period 1958-65 seems to indicate that the observed data can be explained in terms of a vector at 1800 hour direction quite adequately. The neutron monitor data in fact, show that the time of maximum of the diurnal waves during 1958-65 is 1800 hours L.S.T. to within a few degrees. Whereas, if there was a 2100 hour vector contributing to the variations and of the relative size (60% of the 1800 hour vector), as suggested by Forbush then one would expect that the phase of the diurnal wave shifts to later hours from 1958-65 as the 2100 hour effect builds up. This phase shift should be most pronounced for the case of 1964-65 when the corotation effect is expected to be small so that the relative importance of any other component increases. Thus unless the additional vector has a peculiar energy dependence whereby it does not contribute to the neutron monitors and underground telescopes, while it has a large contribute to the ion-chamber data, were justified in assuming that the data from 1958-65, are free of any other major component besides that due to corotation. This, as we have discussed in the foregoing sections, has been used to fix the temperature effects, for the ionization chamber data.

It is also interesting to note that the temperature vectors that Forbush derives from his analysis after subtracting his 20 year wave, as above, are in fact larger than the values we have assumed. It is perhaps relevant to note here that the average 1800 hour vector (over a period 37-66), as obtained by Forbush is 0.12%. This vector is applicable for Cheltenham. (The other two stations, Huancayo and Christchurch have been normalized to Cheltenham). Now, if we assume that this 1800 hour component is in fact due to a free space anisotropy of 0.4%, and is produced by the corotation of the cosmic ray particles, then by a comparison with the curve giving the expected amplitudes at Cheltenham we find that, observed amplitudes of 0.12% will correspond to an upperlimiting rigidity of only 25-30 Gv. However, as mentioned the 1800 hour component will be larger during the years of high activity and will be 0.16%. (FORBUSH, 1967.) This amplitude is found to correspond to upperlimiting rigidities of 50-60 Gv. These values of the upperlimiting rigidity are very low to account for the amplitudes of the diurnal vectors actually observed by underground telescopes. (at e.g. Hobart and London). The inconsistency is more apparent during years of maximum activity (e.g. 57-60), since, during these years the 20 year wave will only be very small (FORBUSH, 1967), and if the upperlimiting rigidity is only 60 Gv, as above, then the large amplitudes actually observed at Hobart (0.1%) (JACKLYN, 1965), during these years cannot be explained. (In our argument here we have assumed that the free space amplitude was 0.4%. However, if we assume that the free space amplitude was lower (0.2%) then we can increase our estimate of the upperlimiting rigidity to around 100 Gv. However, it is still not possible to explain the large observed amplitudes at Hobart on the basis of a 0.2% free space amplitude). In view of this discrepancy it appears that the estimate of the 1800 vector given by Forbush is low. This low value of the 1800 vector can, in our opinion be attributed to the fact that the 1800 vector will have a component along 2100 hours and the critial resolution along the 0900-2100 hour direction will reduce the value of the 1800 vector. (Note, that Forbush in fact constructs the 1800 vector from the departures of the 20 year wave (in the 09-21 hour direction), and the component perpendicular to this direction).

6.1.8. CONCLUSIONS AND DISCUSSION:

As a result of the foregoing comparison of the LONDON (North/South), MANCHESTER (North/South) and ionization chamber data (from

Cheltenham, Christchurch and Huancayo), with the predictions of the corotation model and other data on the diurnal variation obtained from neutron monitors and underground telescopes we find:

a) Amplitude changes observed in the solar diurnal anisotropy during the years of minimum solar activity can be explained in terms of the corotation model, by assuming that the upperlimiting rigidity reduces at these times. The data obtained near the solar minima of 1965 and 1944 seems to suggest that the free space amplitude for an annual average shows a fairly constant value in the neighbourhood of 0.4% (0.3% - 0.5%) over the years 1939-46 and 1958-66 which correspond to the years of declining and increasing solar activity in the neighbourhood of the two minima. (1944, 65). The data corresponding to these years do not exhibit any large changes in phase that cannot be reconciled with reductions in upperlimiting rigidity, and small changes in the free space amplitude.

In general the behaviour of the solar diurnal anisotropy during the two groups of periods above, seems to be very similar, in so far as the data for both groups is consistent with a free space rigidity independent anisotropy of 0.3-0.5% at 1800 hours L.S.T. In addition, the data for the years of minimum solar activity 1944 and 1965 indicate that the upperlimiting rigidity had reduced to about 40 Gv during these years. Values of this parameter for years of high solar activity, as indicated by the data are about 100 Gv.

b) The large phase changes observed in the diurnal variation during 1948-57 at the three Carnegie institution stations. HUANCAYO, CHELTENHAM, and CHRISTCHURCH and those observed by the North/South telescopes at Manchester cannot be reconciled with the corotation model. These data indicate that an additional vector with a time of maximum earlier than 1800 hours is required to explain the phase changes observed in the diurnal variation in this period. In addition it appears that the upperlimiting rigidity had reduced to below about 20 Gv during the solar minimum of 1954. This, as we notice, is considerably smaller than the values for the minima for 1944, 65.

On the AXFORD-PARKER model which we have discussed in some detail in Chapter IV, cosmic rays below a certain upperlimiting rigidity will exhibit azimuthal streaming which corresponds to rigid rotation with the sun. Two conditions as given below determine this upperlimiting rigidity.

i) The gyro radii of the cosmic ray particles are smaller than a certain value which depends on the scale size of the interplanetary magnetic field. For particles with rigidity less than this value the guiding centre approximation will be valid.

As mentioned, observations on the interplanetary magnetic fields by sattelites e.g. MARINER I and IV, IMP I and III have shown that there exists a regular longitudinal sector structure in the interplanetary magnetic field. The sectors corotate with the sun and for several consequtive days corresponding to a particular sector the field polarity remains unidirectional. These observations also suggest that each sector is a coherent entity in terms of plasma velocity and field magnitude. As a first approximation, one would expect corotation to be possible for particles with Gyro radii less than the half width of a sector. Earlier observations of IMP I and MARINER II suggested the presence of four quasistable sectors with a half width of about 0.75 A.U. Since the gyro radius of a 150 Gv proton in a field of 5γ is approximately equal to 0.75 A.U., we would expect the upperlimiting rigidity to have a value in the neighbourhood of this figure. (150 Gv). More recent observations pertaining to 1965 (MARINER IV and IMP III) have indicated a breaking up of this quasi-stable sector structure described above

The sector pattern was found to be evolutionary during this period, with new sectors appearing and others disappearing. A decrease in R max during 1965 would accordingly seem to be a natural consequence of this reduction in the scale size of the interplanetary magnetic field.

ii) There are enough scattering centres present (beyond the orbit of the earth), with dimensions corresponding to the gyro radii of the particles corotating with the interplanetary magnetic field, so that any gradients in the cosmic ray intensity caused by the polarization electric field may be cancelled out by diffusion across the magnetic field lines. If scattering centres corresponding to a particular Gyro frequency are absent, the drift motion for these particles will be cancelled out by an opposite streaming generated because of gradient set up in the cosmic ray intensity. Thus even though the motion of the particles of particular gyro radii can be described in terms of the guiding center approximation, an absence of scattering centres of the corresponding dimensions will prevent an azimuthal streaming to be set up. In general the scattering centres corresponding to a particular rigidity range will determine the diffusion characteristics of the cosmic ray particles in that range and may cause the free space amplitude of the diurnal anisotropy to vary.

(As mentioned in Chapter IV, the ratio, $\frac{k_{\perp}}{k_{11}}$, of the diffusion coefficients perpendicular and parallel to the interplanetary magnetic field will determine the free space value of the diurnal anisotropy. It would be expected that the "power" contained in magnetic irregularities imbedded in the interplanetary magnetic field will be a determining factor for the diffusion characteristics and perhaps $\frac{k_{\perp}}{k_{11}}$.

Power spectra of interplanetary magnetic field fluctuations have been obtained by several workers e.g. COLEMAN et. al. (1964, 1966). HOLZER (1966), NESS. et. al. (1966) and more recently SISCOE et. al. (1968).

The last group of workers report that a comparison of the power densities for days of widely varying activity reveals that power levels (in the frequency range $0.5 - 3 \times 10^{-4}$ c.p.s.) were typically a factor of 10 higher for disturbed than for quiet days. Further, there appears to be the greatest discrepancy in the power levels for the transverse, radial and normal directions, for the most disturbed days. Such a variation and asymmetry may cause a variation in the ratio $\frac{k_{\perp}}{k_{11}}$ therefore the free space amplitude of the diurnal anisotropy. With the increasing amount of information becoming available from space probes and sattelites it will perhaps become possible to establish in detail the variation of $\frac{k_{\perp}}{k_{11}}$ with heliocentric distance as an average and on a day to day basis).

In view of these facts it appears that observed amplitude of the diurnal anisotropy will show variations which can be explained as being results of a reduction in the upperlimiting rigidity of the free space amplitude. In general the magnitude of the effects at times of solar minimum will be a function of the quality of the minimum (i.e. whether it is more or less active), and the behaviour of the diurnal anisotropy may vary from minima to minima. In the present investigation it has been observed that the diurnal wave showed a much greater reduction during the years of minimum activity 1954, as compared to the minima of 1964 and 1944. It was noted that the behaviour of the diurnal waves at the two minima of 1944 and 1965 was very similar. It is perhaps, interesting to note in this connection that the solar minimum of 1964 resembled the solar minimum of 1944 very closely in terms of the level of solar activity recorded during these two years. (PRINCE and HEDEMAN (1967)). During both minima the level of residual activity was unusually high and the 1964 minimum resembled the 1944 minimum more closely than any other during the 20th century in this respect. The 1954 minimum, on the other hand was observed to be very quiet in terms of solar activity. A greater reduction in the upperlimiting rigidity for the 1954 minimum than for the 1944 or 1964 minima does not appear to be unreasonable in the light of these facts.

The mechanism which may be responsible for the additional component of the diurnal variation which seems to be present during a certain phase of the data is not know. However, as discussed in Chapter IV QUENBY (1968) has suggested that a 1200 hour component can be generated as the result of a symmetric gradient perpendicular to the ecliptic plane. This may have some bearing on the foregoing observations. We have accordingly resolved the diurnal vectors observed at Cheltenham, Christchurch and Huancayo (ionization chambers), and the North/South telescopes at Manchester and London (for periods over which data is available,) into an azimuthal (1800 hour) and a radial component in order to investigate whether any systematic relationship exists between the two. If such a relationship is established it can be tested against any theoretical predictions regarding the radial component. (Temperature effects have been taken to be the same as discussed in the foregoing pages).

In order to determine the geomagnetic deflection we have assumed as a first approximation that both components have a similar rigidity dependence. (i.e. a flat spectrum up to an upperlimiting rigidity). We have further assumed that the upperlimiting rigidity has a value of 100 Gv during years of high solar activity and reduced to about 40 Gv during the periods of the solar minimum.

The magnitude of the Average, Azimuthal and radial components for the three ionization chambers at Cheltenham, Christchurch and Huancayo and the North/South telescopes at London and Manchester, obtained under the above assumptions are plotted in figure (16).

It can be seen from this figure that large and sudden variations occur in the observed amplitude of the azimuthal component at times of solar minimum and for one or two years in its immediate vicinity. However, in addition to these relatively sudden variations at times of solar minimum, we observe, that the observed azimuthal component also shows a gradual change in amplitudes over the periods 37-39, 47-52, 56-59. These periods represent years of farily high solar activity. An examination of the figure also shows, that it is -in fact over these periods (over which the azimuthal component shows gradual variations spread over a few years), that the radial component is present. Over these periods there appears to be an inverse relationship between the two components. Over periods of solar minima e.g. (54), however, both components tend to go down.

In general, variations in the observed amplitude of the azimuthal component (if we interpret it as being due to corotation), can be caused by either a change in the free space amplitude, or that in the upperlimiting rigidity, or both. Changes observed at the solar minima of 1944, and 1965 can, as we have seen, be interpreted in terms of a change in R max, with the free space amplitude remaining fairly constant. The foregoing discussion has also indicated that R max changes at the solar minima of 1944, and 1965 were in fact confined to one or two years in the vicinity of the minimum and R max recovered to 100 Gv fairly quickly after this.
On the other hand, in order to explain the gradual changes observed in the azimuthal component we can either say that these changes were caused by a slow variation in R max spread over these periods, or on the other hand postulate that these changes are caused by a reduction in the free space amplitude of the azimuthal component. In order to distinguish definitely between these two possibilities one requires data from underground telescopes (at say 70 m.w.e.) and high latitude neutron monitors, over these periods. (The former afford a sensitive method of measuring R max while the latter

can give more accurate values of the free space amplitude, since they are relatively insensitive to R max changes). Unfortunately these data are not available over the periods in which we are most interested. i.e. 37-39, 47-52, 55-57. Nevertheless, we notice that since the observed amplitudes of the azimuthal component for the years 37, 38, 49, 50, 52, 56, are not much above the corresponding amplitudes for 44, 65, it appears that if we are to attribute all variations in the azimuthal component to R max changes, then the R max values for these years are 40-50 Gv. Since these years represent periods of fairly high activity these values seem to be rather low, as compared to 100 Gv, during the period 1958-63. In view of this it appears that at least a part of these changes are caused by free space amplitude changes in the azimuthal component.

Now if we make a tentative assumption that R max remains fairly constant at 100 ± 20 Gv during years of high solar activity and upperlimiting rigidity changes take place over one or two years, in the immediate vicinity of the solar minimum, then we can fix the free space amplitude of the azimuthal component for different years over the period 37-66. (By comparing the predicted values of the azimuthal component for different free space amplitudes with the observed values corresponding to these upperlimiting rigidities of 100 Gv). This is shown in figure (17). Here we have considered three year running averages of both the azimuthal and radial components, (averaged for the stations mentioned). Furthermore, we have left out data corresponding to years of minimum activity and years in its immediate vicinity, since these data, as we have seen, are definitely contaminated by R max changes. (As mentioned earlier, we cannot be sure whether all the other variations are due to pure free space amplitude changes but are adopting this as our tentative position). The diagram brings out the inverse relationship between the two components very clearly. In figure (18) we have plotted the azimuthal component - VS - the radial component for the three ionization chamber stations. (Each point is a 3 - year running average). The inverse relationship is evident here also.

According to QUENBY (1968), the radial and azimuthal components are both functions of $\frac{k_\perp}{k_{\parallel}}$, the ratio of the diffusion coefficients perpendicular and parallel to the interplanetary magnetic field. The exact form of the relationship between the two components will depend upon several assumptions regarding the conditions in the interplanetary medium. However, for a typical situation, an inverse relationship is predicted between the free space amplitudes of the two components for values of the radial component, above about 0.02 - 0.04%. It appears therefore, that an inverse relationship, between the radial and azimuthal components, as suggested by the foregoing analysis, also seems to be in accord with present theoretical predictions about the relative magnitudes of the two components. Further, since the theory predicts such a relationship between the free space amplitudes of the two components, this also lends support to our tentative assumptions, whereby we assumed that the slow variations in the observed amplitude of the diurnal variation, are in fact, due to free space amplitude changes with a relatively constant value for R max over these periods.

The foregoing analysis, represents only a very approximate attempt to investigate any systematic changes between the radial and azimuthal components. Perhaps with increased coverage available by neutron monitors and underground telescopes, it will be possible to make a more accurate assessment of the amplitudes and relationship between the azimuthal and radial components.

In this connection it is perhaps also relevant to point out, that the time of maximum of the diurnal variation as measured by both neutron monitors

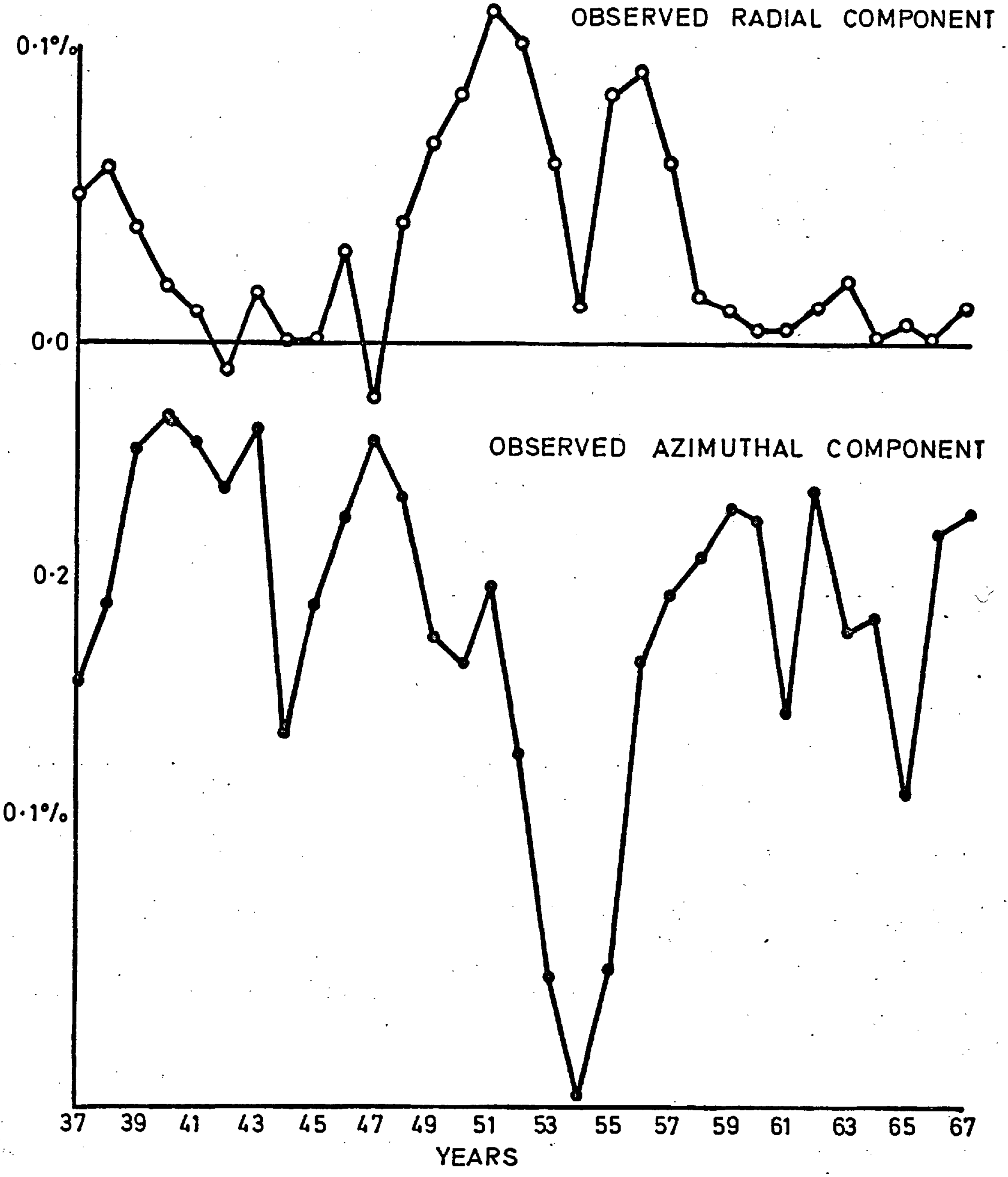


Fig.16 - AVERAGE AZIMUTHAL AND RADIAL COMPONENTS (FOR CHELTENHAM, CHRISTCHURCH AND HUANCAYO AND THE N/S TELESCOPES.)

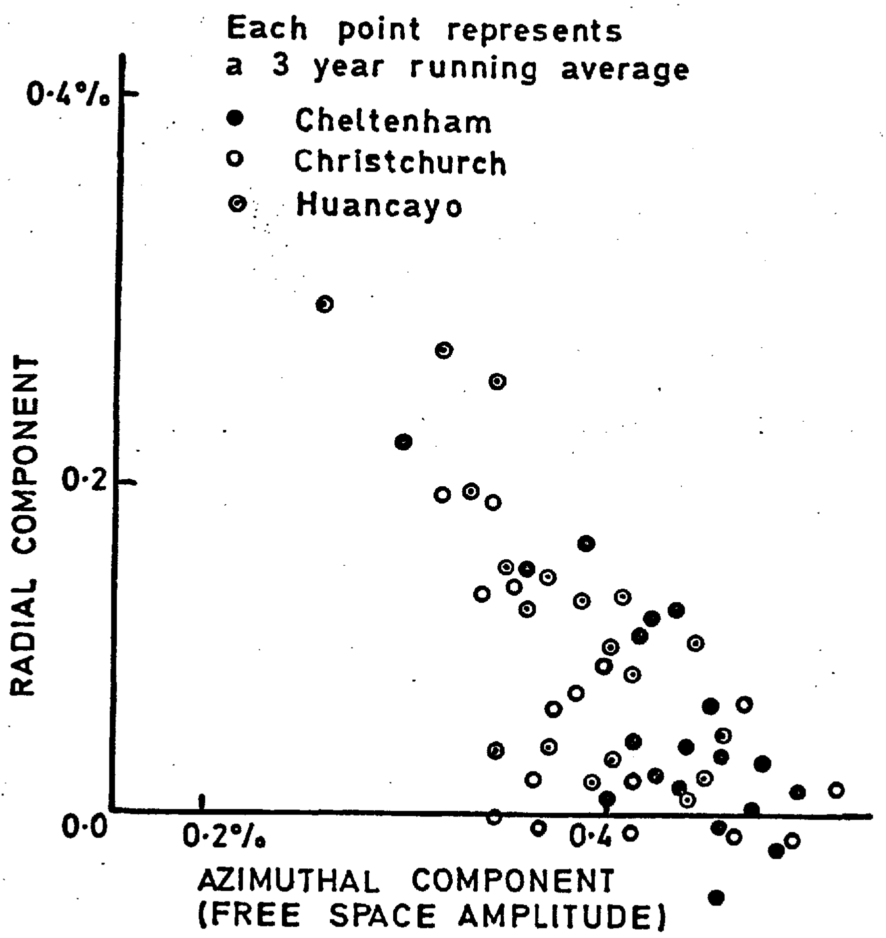


Fig. 17 - AZIMUTHAL COMPONENT PLOTTED -VS- THE RADIAL COMPONENT (FOR HUANCAYO, CHELTENHAM AND CHRISTCHURCH.)

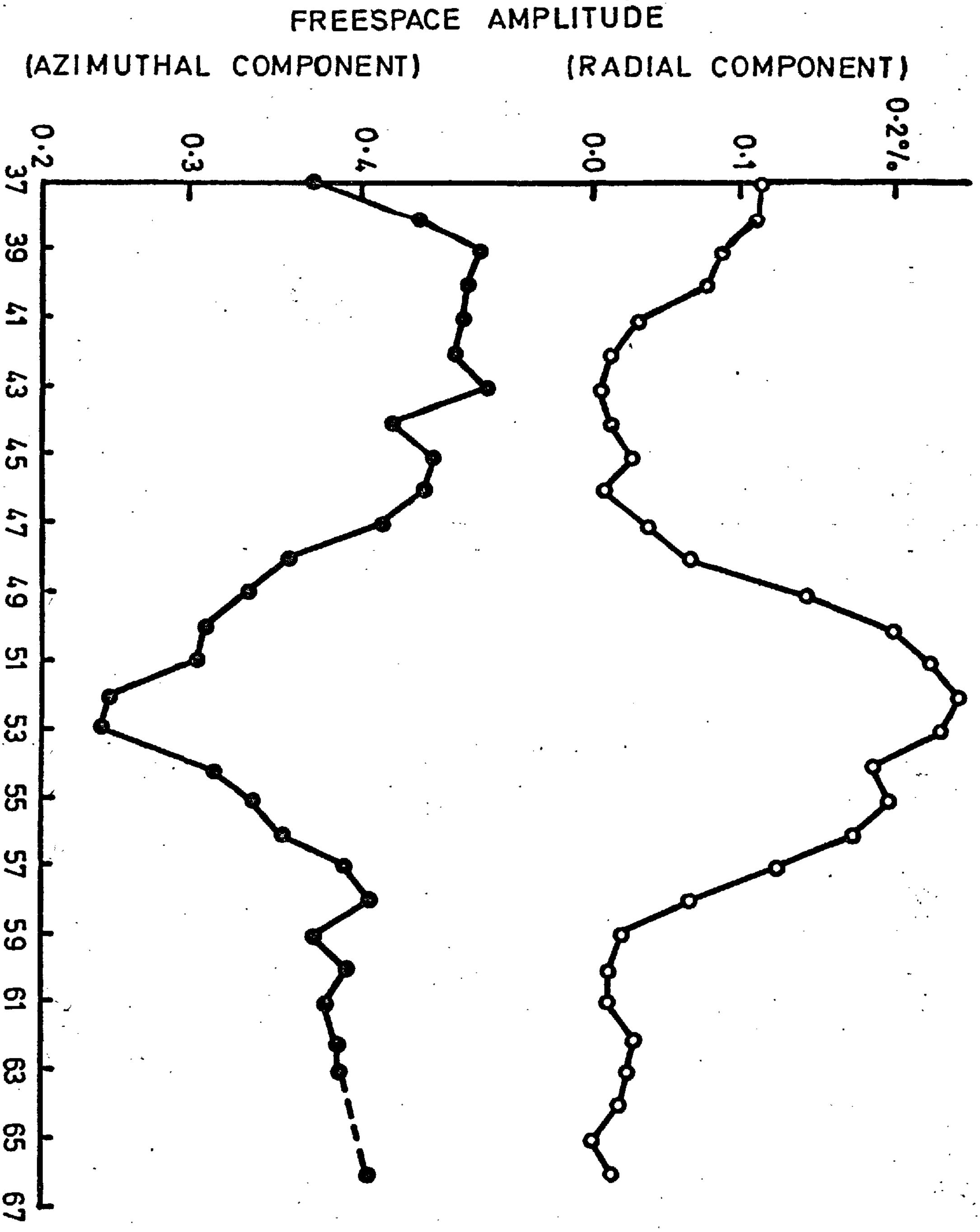


Fig. 18 – THREE YEAR RUNNING AVERAGES FOR THE AZIMUTHAL AND RADIAL COMPONENTS.

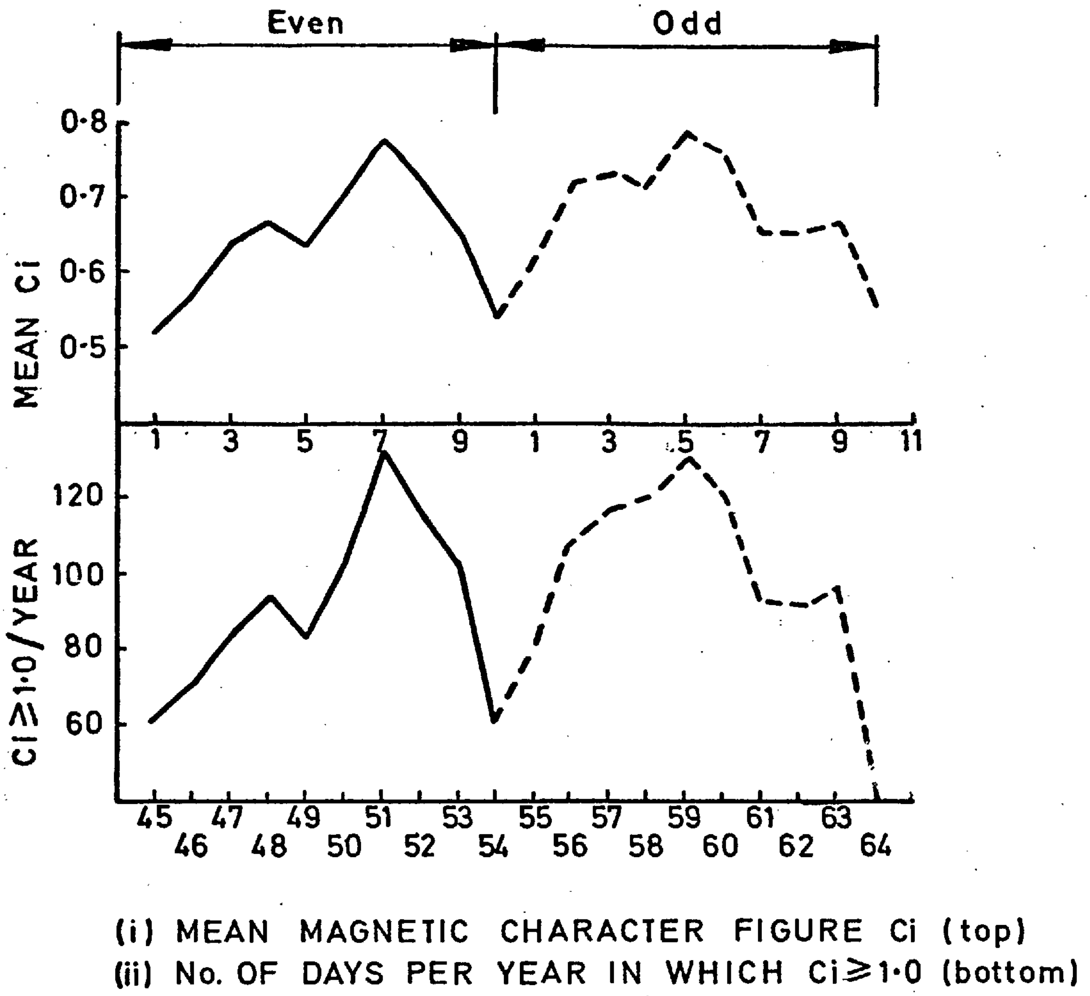


Fig. 19. Double sunspot cycle variation in geomagnetic activity CHERNOSKY (1966).

and meson chambers shows a tendency to go to earlier hours in days of high geomagnetic activity. Such a movement can also be taken to mean the existence of an additional component to the diurnal variation with a time of maximum earlier than 1800 hours. (e.g. a radial component as above).

In view of this it could be suggested that the conditions characterising the interplanetary medium during some periods may have similar average characteristics as those on days of high geomagnetic activity. (i.e. a highly disturbed state, with the interplanetary magnetic field more disturbed than usual and $\frac{k_{\perp}}{k_{\parallel}}$ larger than usual and the two phenomenon, may have a common cause.

It is interesting to note in this connection, that a double sunspot cycle variation has been observed in geomagnetic activity. CHERNOSKY (1966). In the Zurich even numbered cycles, the last half of the cycle is found to be more active than the first half and the reverse is true for the odd numbered cycles. The years on either side of the sunspot minimum of 1954 correspond to periods when the geomagnetic activity will be high according to this scheme. (i.e. the maximum in the geomagnetic activity will be observed during the second half of the sunspot cycle No. 18., and in the first half of the sunspot cycle No. 19). These are also the approximate periods in which we have observed an abnormal diurnal effect as discussed above. (figure 19).

CHAPTER VII

FORBUSH DECREASES AND ASSOCIATED ANISOTROPIES:

7.1. Introduction:

A world wide, rapid decrease in cosmic ray intensity, occuring in association with a strong geomagnetic storm was first pointed out by FORBUSH (1937), and is known after him as the FORBUSH DECREASE. Since its discovery some thirty years ago, considerable effort has gone into a study of the main characteristics of the event, (e.g. rigidity dependence, onset and recovery characteristics, anisotropic variations during the onset and recovery phases of the Forbush decrease etc.) and into the causes of its occurrence. As has been mentioned in chapter I, it is now recognized that the Forbush decrease represents the modulation of the galactic cosmic ray intensity by violent disturbances in the interplanetary medium. Several interesting associations have been noted between the characteristics of the Forbush event and helio-physical and geophysical phenomena which lend support to this idea. The general features of the Forbush decreases have already been outlined in Chapter I. We shall detail below some of the observed characteristics, regarding the correlation with geophysical and heliophysical phenomena, as noted by several workers.

Large Forbush decreases are found to occur in close correlation with solar flares accompanied with particularly strong and long lasting continuom radio emissions (type IV outbursts). e.g. KAMIYA and WADA (1959), BACHELET et. al. (1960), WEBBER (1962). No direct association between the amplitude of the Forbush decrease and the position of the parent flare is evident. However, there is some evidence that the delay from the flare to the onset of the Forbush decrease is greatest for flare's near the east limb of the sun WEBBER (1962). FEDCHENKO (1965), finds that the further to the west of the sun's central meridian the chromospheric flare responsible for the decrease is situated, the longer is the duration of the decrease. Several workers e.g. (BACHELET, BALATA, CONFORTO, and MARINI (1960), FENTON, McCRACKEN, ROSE and WILSON (1959)), have studied the association of onset times of Forbush decreases and sudden commencement magnetic storms. They find that a close correlation exists and that the Forbush decrease is generally delayed a very short time after the ssc magnetic storm (about 2 hours). On the other hand several workers have reported anisotropic decreases in the cosmic ray intensity before the ssc e.g. McCRACKEN and PARSONS (1958), MATHEWS et. al. (1967), SANDSTROM et. al. (1965), have analysed cosmic ray data from high latitude, high counting rate neutron and meson monitors and find that most ssc type storms are accompanied by universal time intensity variations, though quite often these variations are rather inconspicuous and can be resolved only by high counting rate monitors. However, there does not seem to be a one to one correspondence between the magnitude of the magnetic storm and the amplitude of the Forbush decrease e.g. TRUMPY (1959). SANDSTROM et.al. (1965b), also report that several prominent Forbush decreases are accompanied by only small magnetic events which are not classed as sudden commencements.

It is accepted now, that there is no casual relationship between the geomagnetic storms and Forbush decreases. It is more plausible that both have a common origin in the corpuscular plasma streams emitted from the sun. Thus YOSHIDA and AKASUFU (1966) are of the opinion that the sudden commencement is due to a sudden compression of the magnetrosphere by an enhanced solar plasma flow; and the Forbush decrease, the result of the arrival of turbulent regions of plasma which act as a barrier and reduces the cosmic ray intensity as the region envelopes the earth.

In the course of the present investigation we have studied the onset and recovery characteristics, rigidity dependence, and anisotropic morphology of several Forbush decreases occuring during 1966 and 1967. We shall present the results of these investigations, along with a short review of the present state of knowledge, regarding each of these properties, separately, in the following sections.

7.2. ANISOTROPIES DURING THE ONSET AND RECOVERY PHASES OF THE FORBUSH DECREASE.

7.2.1. Techniques of analysis and review of previous results.

A striking feature of large Forbush decreases is their rapid onset time ranging from one hour to about a day. The recovery on the other hand is considerably slower and may have a time constant of a week or even more. Several groups of workers have studied the onset and recovery characteristics of Forbush decreases. As a result of these investigations it has been established that anisotropic intensity variations (restricted to a relatively small cone of directions in space), are a characteristic of many Forbush decreases. These anisotropies often manifest themselves many hours before the onset of the actual Forbush decrease and are found to continue for several days, through and after the onset. They are probably related to the spatial characteristics of the modulating mechanism responsible for their occurence. Accordingly a systematic study of intensity - time changes of the cosmic radiation in space, prior to, and during a Forbush decrease is important for an explanation of the space time behaviour of the agency responsible for these events.

The particles detected by an instrument at a particular station are due to primaries arriving from a cone of acceptance (ASYMPTOTIC CONE) of rather small solid angle compared to 4π . Thus as the earth rotates the recorder effectively scans a limited region in space. The size and position of this region is determined by the location of the cosmic ray recorder and several geophysical factors. A given station records particles coming from a particular direction in space, only once in 24 hours. Therefore, in order to obtain a simultaneous survey of the cosmic ray intensity corresponding to different directions in space, one requires data from stations situated at different geographic locations, such that the acceptance cones of the different stations provide a simultaneous scan of different regions in space.

In view of these requirements, it appears, that for a systematic study of the space time behaviour of the anisotropies it is imperative to have an accurate knowledge of the asymptotic cones of acceptance corresponding to recorders situated at different geographic locations.

It is possible to calculate the asymptotic cones of a particular detector with a knowledge of:

1) The differential response function W(R) corresponding to the particular component being recorded.
2) The asymptotic directions of arrival of the particles contributing to the counting of the detector.
3) The geometrical sensitivity pattern of the detector.

Previous investigations in this regard, e.g. DORMAN (1957), were restricted to the determination of the mean asymptotic directions of viewing corresponding to a particular station and detector. LAPOINTE and ROSE (1961), proceeded a step further and also assigned a certain source width to the asymptotic cone corresponding to a particular station. These calculations were, however, based on the asymptotic directions given by BRUNBERG and DATTNER (1954) and calculated on the basis of the dipole model of the geomagnetic field. Response functions used were those given by DORMAN (1957).

More recently, with the advent of high speed digital computers, it has become possible to determine the asymptotic directions corresponding to more accurate simulations of the geomagnetic field (employing higher harminics upto the sixth degree, FINCH and LEATON (1956)) e.g. McCRACKEN et. al. (1962) SHEA et. al. (1965, 68) RAO et. al. (1963) have used these data on the asymptotic directions, along with more recent response functions given by WEBBER (1962) to investigate the asymptotic cones corresponding to the different geographic locations. As a result of these investigations it was established that:

1) Asymptotic cones corresponding to medium and low latitude stations (L less than about 40°) are broad in width and look along the solar equatorial plane.
2) Asymptotic cones of stations in the latitude range 55° to about 65° are found to be narrow in width (30° in longitude) and in spite of their high geographic latitudes also look along the equatorial plane.
3) The asymptotic cones of polar or near polar stations, (65° or above) scan latitudes significantly away from the ecliptic.

The widths of the asymptotic cones(in longitude), are narrow for these stations also. RAO et. al. have also pointed out that the observed shape of a particular anisotropy will vary from station to station according to shapes of the corresponding asymptotic cones. In particular, stations with wide asmptotic cones will see the given anisotropy with the amplitude considerably smoothed out. (if the anisotropy is narrow in width this effect will be even more prominent). Stations with narrow asymptotic cones will provide the most faithful reproduction of the anisotropy and should therefore be preferred for investigations of shortlived narrow anisotropies.

In practice, high latitude stations, which have narrow asymptotic cones, which look along the ecliptic plane are found most suitable to investigate the morphology of the Forbush decreases. Further more, in order that data obtained from the different stations used in the investigation are directly comparable, it is necessary that all stations used have a similar:

a) Asymptotic response,

b) Geomagnetic threshold,

c) Geographic location e.g. altitude etc.

Data from neutron monitors is to be preferred in view of the comparative ease of correction for the atmospheric affects associated with the nucleonic component. Further, with the advent of super-neutron monitors with very high counting rates it is now possible to achieve statistical accuracies of about 0.1% / hour. MERCER and WILSON (1967), have employed the methods developed by RAO and McCRACKEN (1963) to calculate the asymptotic cones of acceptance for several high and medium latitude neutron monitors which are found to be most suitable for a study of the morphology of the Forbush decreases and other short term anisotropies. Their results are presented in figure 1. In this figure the width of the cone in azimuth represents the extent of the cone which is responsible for 70% of the counting rate of the detector. The contribution corresponding to a particular longitude is represented by the height of the histogram corresponding to that longitude. The base latitude represents the median latitude, with 50% of the counting rate coming from above that latitude and 50% below it.

With an accurate knowledge of the asymptotic cones of the recorders, and with the availability of data from high counting rate super-neutron monitors, it has now become possible to study the intensity-time behaviour, or "morphology" of the Forbush decreases in considerable detail. We have, accordingly, selected four events, occuring during 1966-67, where the onset and recovery phases showed evidence of considerable anisotropy (on an examination of the intensity records of several high-latitude neutron monitors) and have studied the characteristics of these anisotropies in detail. However, before we describe out results we shall detail below the main findings of several earlier efforts in this direction.

FENTON, McCRACKEN, ROSE, and WILSON (1959), have investigated the onset characteristics of several Forbush decreases observed at Hobart, Mawson, Ottawa and Sulphur Mountain. They found that if the onset times at different stations were plotted as a function of the direction of maximum sensitivity of the recorders relative to the earth-sun line, then the depression in intensity was first found to occur for asymptotic directions between 30° and 120° west of the earth sun line. The intensity was found to be depressed last from directions between 0° and 90° east of the earth sun line. The maximum depression was found to occur at about 90° West of the earth sun line. Furthermore, they found that on some occasions the cosmic ray intensity was found to be depressed from asymptotic directions west of the earth sun line several hours before the ssc occured. The detection of cosmic ray changes for particles arriving from the west of the earth sun line, several hours before the ssc suggested that the agency responsible for the decrease is able to influence the intensity at a considerable distance from the earth.

LOCKWOOD and RAZDAN (1963), have analysed data corresponding to several large Forbush decreases which occured during 1957-61. They have used data from a large number of neutron monitor stations to determine the chief onset characteristics of the events. They found that the onset of the Forbush decrease was always earlier from the west of the earth-sun line regardless of the location of the solar-flare which was the source of the plasma cloud responsible for the decrease. The onset times recorded from west and east of the earth sun line varied from the order of minutes to a few hours. Stations which registered an onset earlier than the s.s.c., were in general found to be sampling particles from the west of the earth sun line, at the time of the decrease. Furthermore, the solar plasma cloud associated with the decrease, was found to originate from the western hemisphere of the solar disc. LOCKWOOD and RAZDAN state that the observed time delays between the onset from the east and west of the earth sun line can be explained in terms of the time required for the earth to penetrate in the plasma cloud to about two gyro-radii for particles of the mean rigidity recorded by a neutron monitor. They find that values of the field of about 3×10^{-4} Gauss (within the cloud) and values of the plasma velocity of about 300-700 km/sec are able to explain the observed differences in onset times. FEDCHENKO (1965) has analysed the onset times of several Forbush decreases occuring during 1957-61. In general his results support the conclusions of FENTON et. al. and LOCKWOOD et. al. stated above.

More recently MERCER and WILSON (1967) have used data from a series of super neutron monitors and the data on the asymptotic cones corresponding to these recorders calculated by them, to carry out a detailed study of the morphology of a Forbush decrease which occured on the 23rd March, 1966. They found that both the predecrease and the onset occured from the east of the earth sun line (90° East), contrary to what has been said above. These results are not explicable on the ideas of the interplanetary magnetic field configuration suggested by Parker. However, it may be relevant to point out that NAGASHIMA et. al. (1968) have found, on analysis of the recovery phase of this event, that a pronounced North/South asymmetry had developed during the recovery phase of the event. In order to explain these features, they find that they have to postulate that the configuration of the magnetic fields enveloping the earth at this time were not symmetrical about the solar equatorial plane. In view of these features, it seems that the interplanetary field conditions during the course and perhaps at the onset of the event were rather peculiar and the early onset from the east may be an exception rather than the rule. Nevertheless, this study clearly brings out the relevance that a study of the anisotropies has on the configuration of the interplanetary magnetic field.

In addition to the anisotropic onset of the Forbush decrease, anisotropies are also frequently found to exist during the recovery phases of the event. If the anisotropy is relatively longlived and persists over a few days the result appears as an enhanced diurnal variation, with an abnormal time of maximum. Quite often however, they are only short lived and last for a few hours. LOCKWOOD and RAZDAN (1963, b), have analysed the intensity variations superimposed on the recovery phases of several Forbush decreases, and have related them to directions in space, from which they appear to occur. They found that the anisotropies occuring during the recovery phases could either be a short lived increase or a decrease. Anisotropies recorded as decreased intensities, occured from the west and those recorded as increases, from the east of the earth sun line. The time scales of the anisotropies were found to vary from a few hours to a few days. The long lived anisotropies were found to shift westwards as time progressed.

Short lived increases in the cosmic ray intensity during the recovery phase of the F.D. have been observed by several workers e.g. ROSE and LAPOINTE (1961), TRONCOSO (1964), AHLUWALIA (1965, 68). ROSE and LAPOINTE (1961) and LOCKWOOD et. al. explain these short lived increases as being due to a 'hole' in the modulating mechanism responsible for the decrease. They find that the directions in which the holes first appear seem to be at right angles to the direction found by several workers in which the greatest depressions are recorded, and conclude that the recovery in the Forbush decrease mechanism, seems to be preferential in

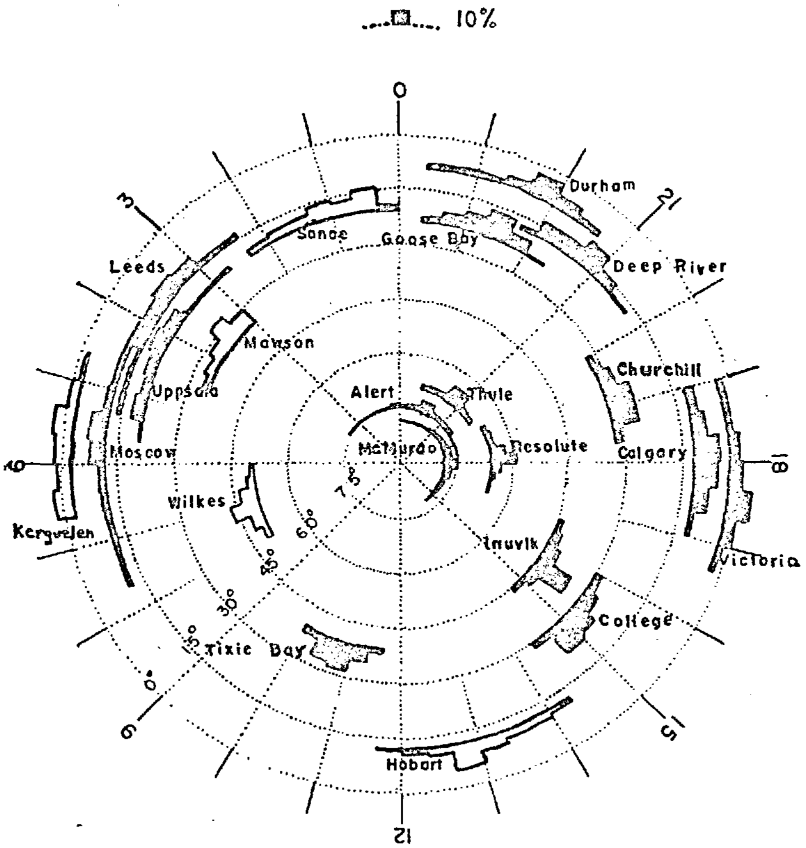


FIG. 1. Directional response functions for various high-latitude neutron monitors.

the directions 15°E and 165°W of the earth sun line. Furthermore, an analysis of the rigidity spectrum corresponding to the event showed that the spectrum was rather flat, which supports the view that galactic particles were taking part in the process.

7.2.2. EXPERIMENTAL RESULTS OBTAINED DURING 1966-67.

We have studied the space-time development, or Morphology, of four moderately strong Forbush decreases, which occured during 1966-67. In the case of each event a high latitude neutron monitor showed a maximum depression of 5% We have used data from a series of high latitude neutron monitors. The location of the stations and other relevant data pertaining to the stations are presented in Table 1.

TABLE 1.

List of stations used for determining the onset and recovery characteristics of Forbush decreases:

Station:	Geographic coordinates		Altitude	Threshold Rigidity
	Lat.	Long.	meters	(Gv)
Wilkes	-66.25	110.52	s.l.	0.05
Kergeulen	-49.35	70.22	s.l.	1.19
Leeds	53.82	-1.55	100	2.20
Goosebay	53.27	-60.40	46	0.52
Deep River	46.10	-77.50	145	1.02
Churchill	58.75	-94.09	s.l.	-
Calgary	51.05	-114.08	1128	1.09
Inuvik	68.35	-133.72	21	0.18
Wellington	-41.28	174.77		3.5

Most of the stations operate high counting rate super-neutron monitors. However, in order to get adequate coverage of different azimuths relative to the earth sun line, we have used data from some I.G.Y. type neutron monitors also. The standard deviations (2-sigma) at the various stations, based on the bihourly counting rates are:

a) Super monitor stations.	Less than	0.08%
b) HOBART	" "	0.25%
c) WILKES	" "	0.35%

The asymptotic cones corresponding to neutron monitors situated at these stations have been calculated by MERCER and WILSON (1967), and are shown in figure 1. An examination of this figure shows that by using data from these stations it is possible to get a simultaneous scan of different azimuths (relative to the earth-sun line). The Asymptotic cones of these recorders are of comparable width in longitude. Further, the cones of most recorders actually look along the solar equatorial plane. Those for INUVIK and WILKES, however, have a moderate inclination with this plane (45°). We have used data from these stations because of absence of data from other suitably situated neutron monitors which could provide a scan of these longitude belts. Since the asymptotic cones of these stations look at a considerable angle to the ecliptic plane it was found that the behaviour of the intensity as recorded by these stations was sometimes different as compared to stations which scan the ecliptic plane. In most cases however, the stations (INUVIK and WILKES) follow the general pattern of the intensity as recorded by the other stations reasonably closely. We have kept this feature in mind while using data from these stations. The geomagnetic thresholds at all the stations are less than or reasonably near the atmospheric cutoff, and the altitude of the observatory reasonably near S/L. The data from the different stations is therefore directly comparable.

The main phases of the events under study occured on the following dates.

1. 9 JULY 1966
2. 23 SEPT 1966
3. 13 DEC 1966
4. 13 JAN 1967

In each case we have taken the intensity obtaining at a station, for 24 hours before the epoch day as the mean pre-decrease level. Data for the subsequent periods have been normalized by taking this mean level as 100%. The percent change in the intensity as recorded by a particular neutron monitor are then plotted as a function of time and asymptotic direction for several days over the period of each event. We have restricted our analysis to bihourly values in order to achieve reasonable statistical accuracy.

In a bihour the asymptotic cone of any station will move through 30° . Furthermore, since the width of the asymptotic cone is 30° for most cases, the intensity observed during any bihour will represent the average effect over about 60° in space. As we shall see in the following, in spite of the averaging effect over this relatively large cone, by the use of data from several stations which have overlapping asymptotic cones, it is possible to get a fair idea of the progress of the Forbush decrease with respect to directions in space.

We shall consider each of the events studied, separately, below. (All directions are given with respect to the Earth-Sun line).

1) <u>Event occuring on 9 July 1966.</u>

a) <u>Associated geophysical and heliophysical phenomenon.</u>

Solar flares:

Date: 7 July 1966: Time: 0022 hours (U.T.)

Location: N36, W48

Importance: 2B

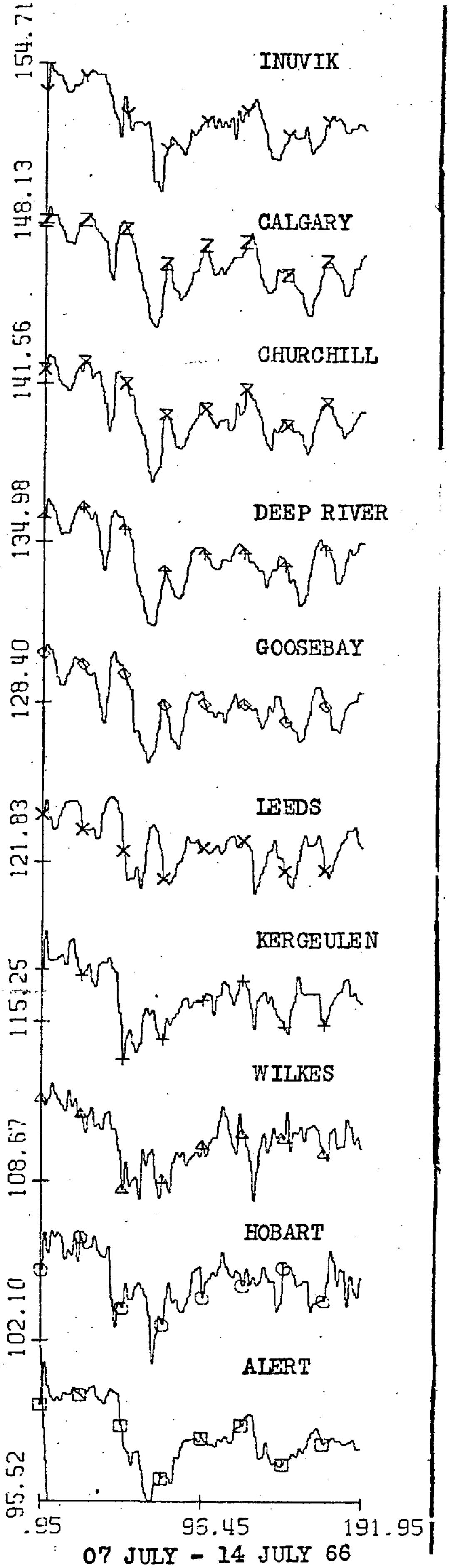
Intense type IV emission was observed at meter wave-lengths. The sudden commencement for the flare of 7 July occured at 2102 U.T. (8 July). Before this a pair of sudden impulses occured at 0529 and 0731 on the same day. Kp indices for the period 6th July to 10th July are: 10^{o}, 7^{-}, 27^{-}, 33^{-}, 28^{+}. (No major flare occured after the 2B flare at the beginning of 7th July till about 1200 U.T. on the 8th July when another 2B flare was observed. The source of the plasma cloud responsible for the Forbush decrease was therefore most probably the flare mentioned above).

b) <u>Morphology of the event.</u>

The figure 2, shows the intensity profile corresponding to this event as recorded by a series of neutron monitors from which we have used data. The intensity direction diagrams corresponding to the period 8 July 1966 - 10 July 1966 are plotted in figure 3. From this figure the following points are evident.

1) The diagrams corresponding to the period 00.00 U.T. to 12.00 U.T. on the 8th July 1966 show that stations sampling radiation from the approximate region 45°E to 135°W record a somewhat lower intensity than those in the other hemisphere. Over the period 0800 U.T. - 1200 U.T., there appears a definite anisotropy in a cone of from about 45°E to about 45°W. The intensity from these directions is about 1-1.5% lower than from other directions.

2) The diagrams for the period 1200 U.T. to 24 U.T. clearly bring out the anisotropic character of the onset of the Forbush decrease. Very approximately it can be said that stations recording particles from the hemisphere of directions 45°E to 135°W show a pronounced depression in the intensity while stations from the other hemisphere show 100% intensity. The maximum depression (about 3% below the predecrease level) appears to occur from a wide cone of directions centered at about 45°W. Directions between 90°E



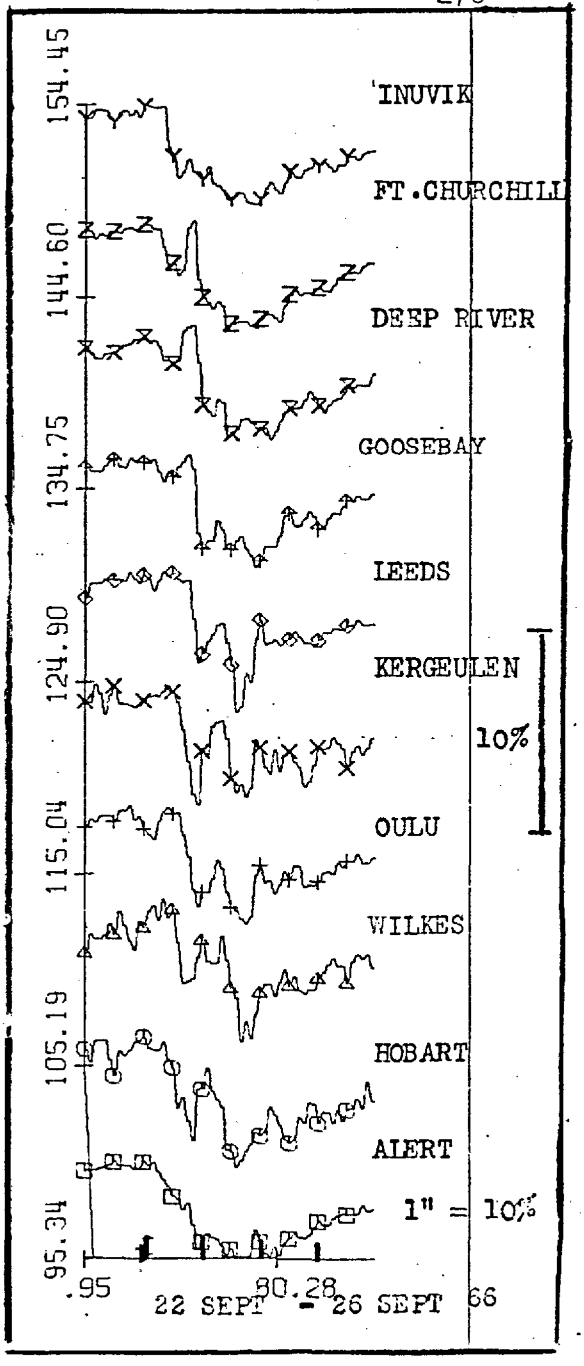


Fig 2,4. Intensity-time profiles corresponding to the Forbush decreases of 09 July and 22 Sept 66. The symbols indicate 12 hour periods.

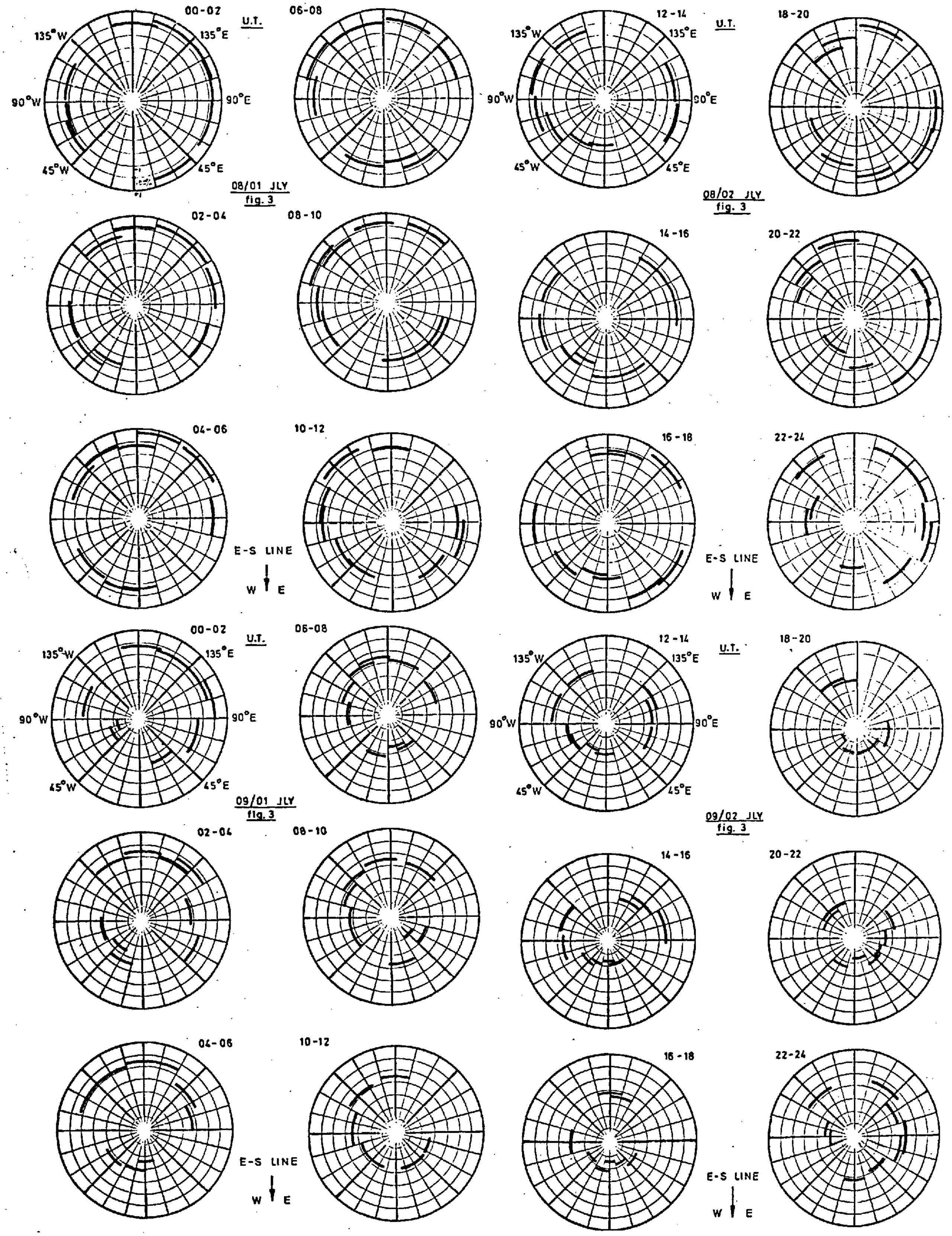


Fig. 3: Intensity direction diagrams corresponding to the event of 08 July 1966.

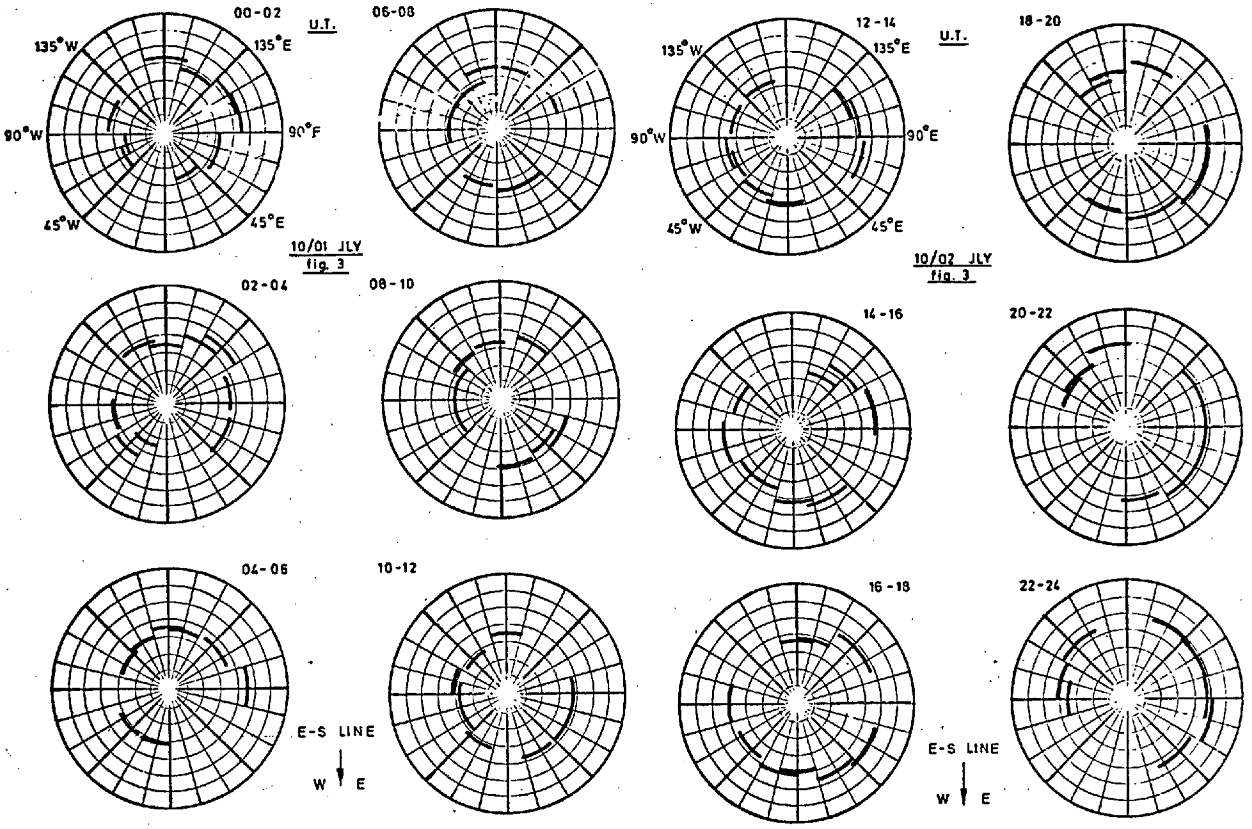


Fig. 3 continued.

to 180°E show no depression whatever. It should be noted that the s.s.c. recorded in conjunction with this event did not occur until about 2100 hours, while the cosmic ray intensity from some directions had started showing significant depressions from about 0800-0900 U.T.

3) Over the period 00.00 U.T. to 1200 U.T. on the 9th July, the intensity depression gradually spread to other directions in space. At about 0400 U.T. - 0600 U.T. stations looking at the directions 90°E to 180°E first started showing a depression. Thus it appears that the depressed intensity was observed from this direction about 18-20 hours after that from directions at about 45°W. However, even by 1200 U.T. the depression was not uniform. Stations looking towards the sun were showing a more depressed intensity, than those in the anti-sun direction.

4) By about 22 U.T. on the 9th an approximate isoptropy is achieved in so far as stations looking in all directions show approximately the same intensity. Between 22 U.T. and 24 U.T. a recovery begins. This is first observed by stations looking in the rather wide cone from about 90°E to 135°W. Over the period 00 U.T. to 24 U.T. on the 10th July the intensity gradually recovers. The diagrams corresponding to this period show that there is a slight preference in this recovery for directions 45°E to 135°E.

2). EVENT OCCURING ON 23 SEPT 1966.

a) Associated geophysical and heliophysical phenomenon.

Solar flares:

Date: 20 Sept 1966 Time: 1738

Location: N04, W15.

Importance: 2B. Plage 8505.

S.S.C. occured on the 23rd Sept at 08-56 U.T.

Kp indices for the period 22 Sept - 25 Sept are, 13^-, 24, 20^+, 18.

b) Morphology of the event:

Figure 4 shows the intensity records from the high latitude neutron monitors used for the study of the Morphology of the event. The intensity as recorded by the polar station ALERT is also given in this diagram. The intensity direction diagrams are plotted in figure 5. We observe the following interesting features during the development of the Forbush decrease.

1) Over the period 00.00 U.T. to 0400 U.T. on the 23rd Sept, there appears to be an approximate isotropy from all directions, in so far as the intensity recorded by all the stations is about equal. Between 0400-0600 U.T. there was some indication of a depression from about 45°W of the earth-sun line. When the depression first started, Leeds was looking along the direction 45°W. Kergeulen, which had just passed this sector showed no indication of any depression; Goosebay which at this time looking at about 120°W also did not record a depressed intensity. It appears therefore that the preliminary depression was confined to a fairly narrow cone about 45°W. Notice that the S.S.C. recorded in conjunction with this event did not occur until about 3 hours after this preliminary depression had been recorded.

2) Over the period 0600 U.T. to 2200 U.T. (23 Sept), the depression gradually became more intense. The diagrams corresponding to this period show that stations recording intensity from the West of the earth-sun line show a much greater reduction than stations from the East of this line. The greatest depression appears to have been recorded from 90°W and the stations looking at 90°E are the last to record the depression. These diagrams also show that it took about 1600 hours for the decreased intensity to envelope the whole earth, (starting from 0600 hours, when a slight depression had been seen from about 45°W of the Earth-sun line,

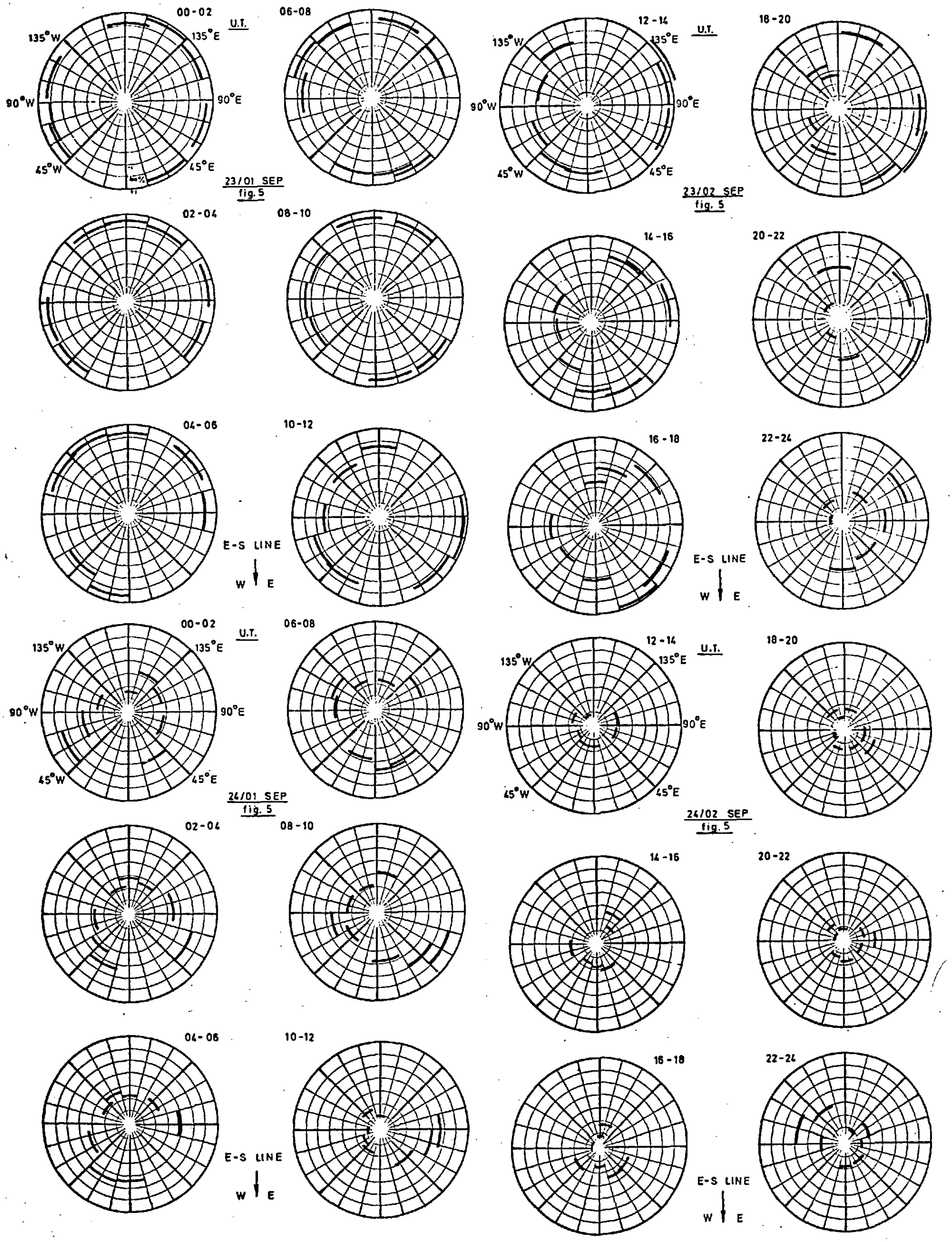


Fig. 5: Intensity direction diagrams corresponding to the event of 23 Sept. 1966.

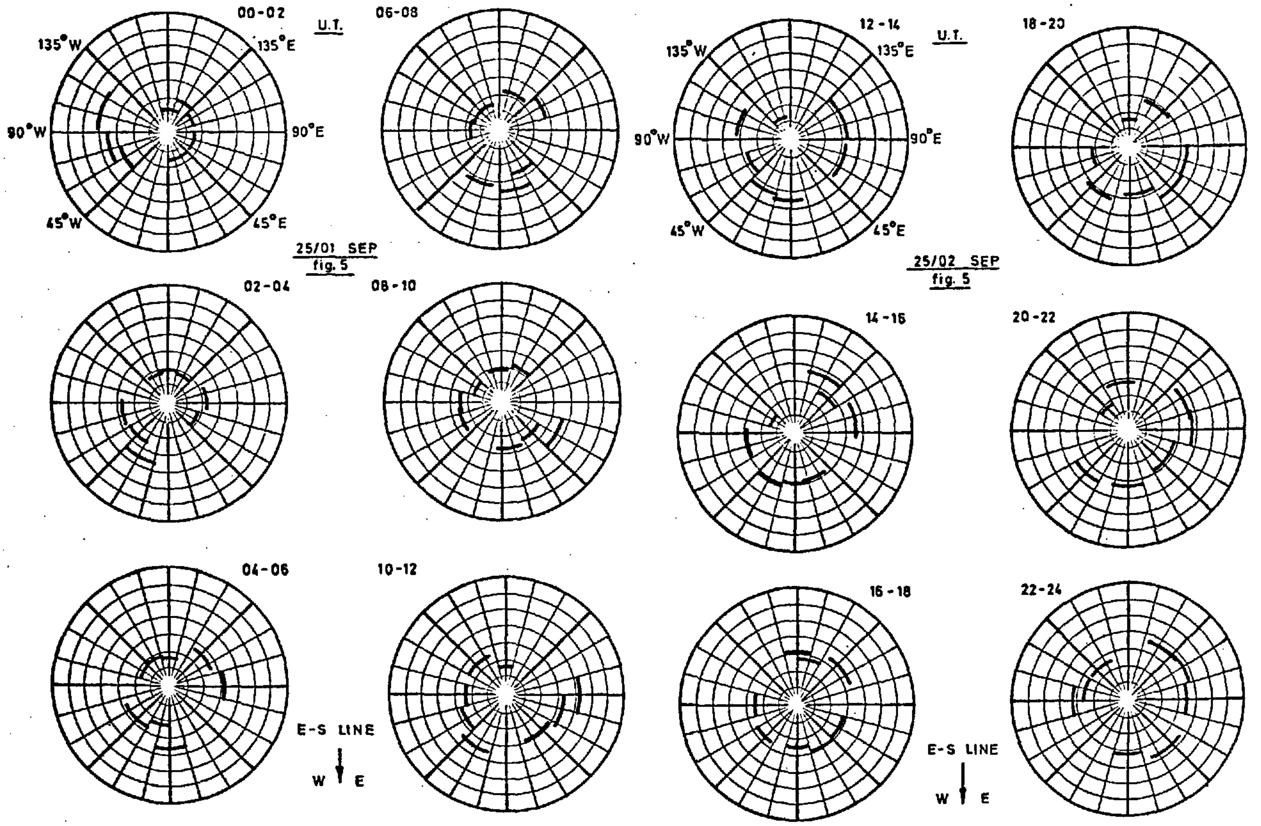


Fig. 5 continued.

to about 22-24 U.T. when all the stations showed a depression below the normal level.

3) Over the period 00 U.T. to 1200 U.T. on the 24th Sept, the intensity showed a short lived recovery from a cone of direction about 45°W to about 90°E. This is clearly seen in figure 4 where Leeds, Kergeulen and Hobart showed a rather broad peak during the first half of the 24th. However, stations in the American sector, did not see this increase when they came round to look in this direction. As a matter of fact the intensity direction diagrams corresponding to the period 1200 U.T. to 2400 U.T. on 24th Sept, show that the increase was short lived and had disappeared. The intensity depression is seen to be the greatest during the whole event. The Forbush decrease appears to have a two-step nature in the onset phase.

4) Diagrams corresponding to 00 U.T. to 2400 U.T. on 25 Sept, show that the intensity started recovering from about 90°W of the earth sun line. Gradually the increased intensity spread to other directions and by 2400 U.T. the intensity from all directions had recovered by about 2-3%. The remainder of the recovery was essentially uniform from all directions as is shown by the gradual increase in the intensity records corresponding to the periods 25-26 Sept in figure 4.

3) EVENT OCCURING ON 13 DEC 1966.

a) Associated geophysical and heliophysical phenomenon.

Solar flares:

Several solar flares of importance 1^+ or less were observed.

No s.s.c. was recorded in conjunction with this event.

Kp indices for the period 12 DEC to 15 DEC: 3^-, 26, 35, 25^-.

b) Morphology of the event.

Figure 6 shows the intensity records from the high latitude neutron

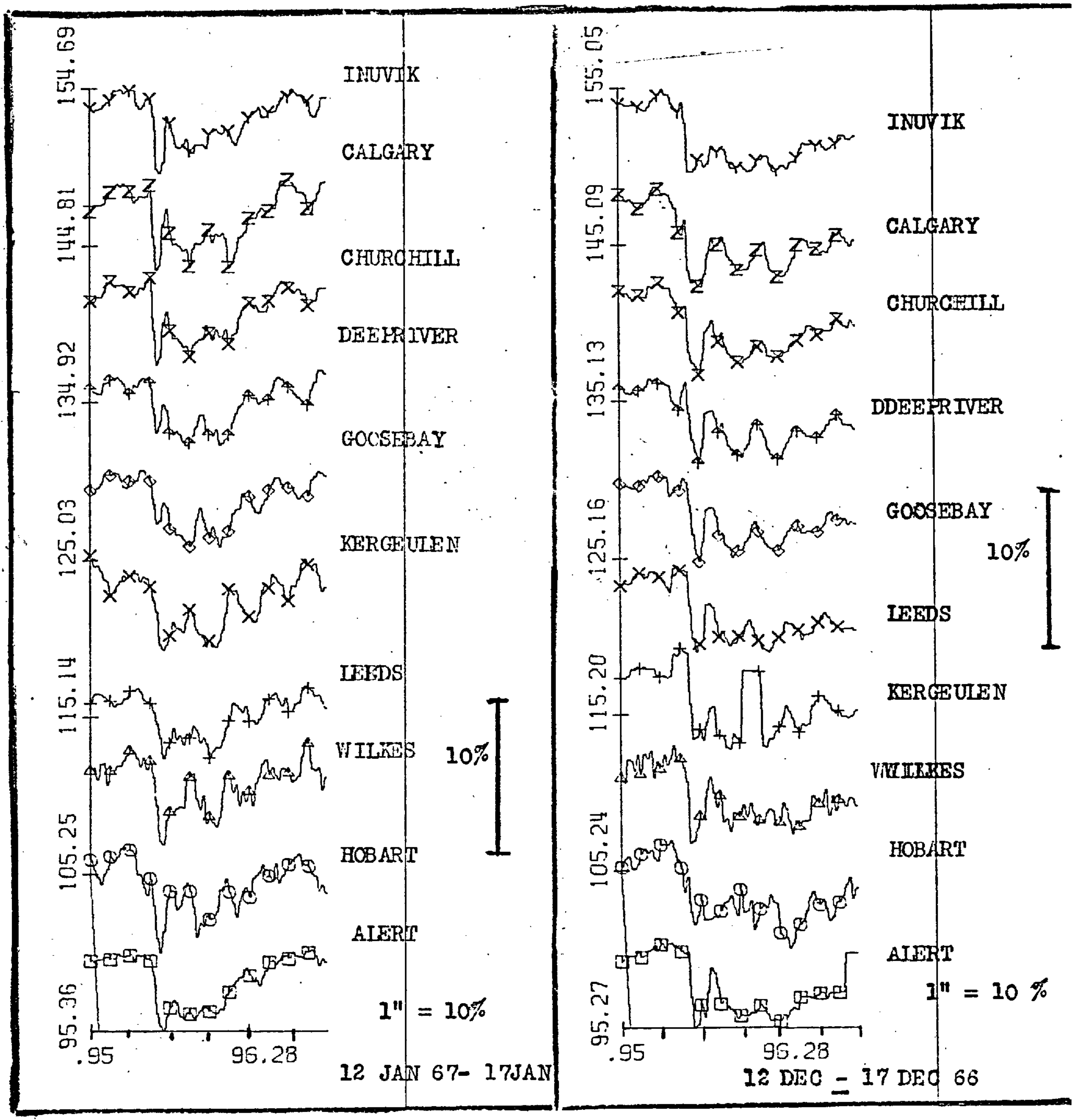


Fig 6,8. Intensity- Time profiles corresponding to the Forbush decreases of 12 Dec 66 and 12 Jan 67. The symbols indicate 12 hour periods.

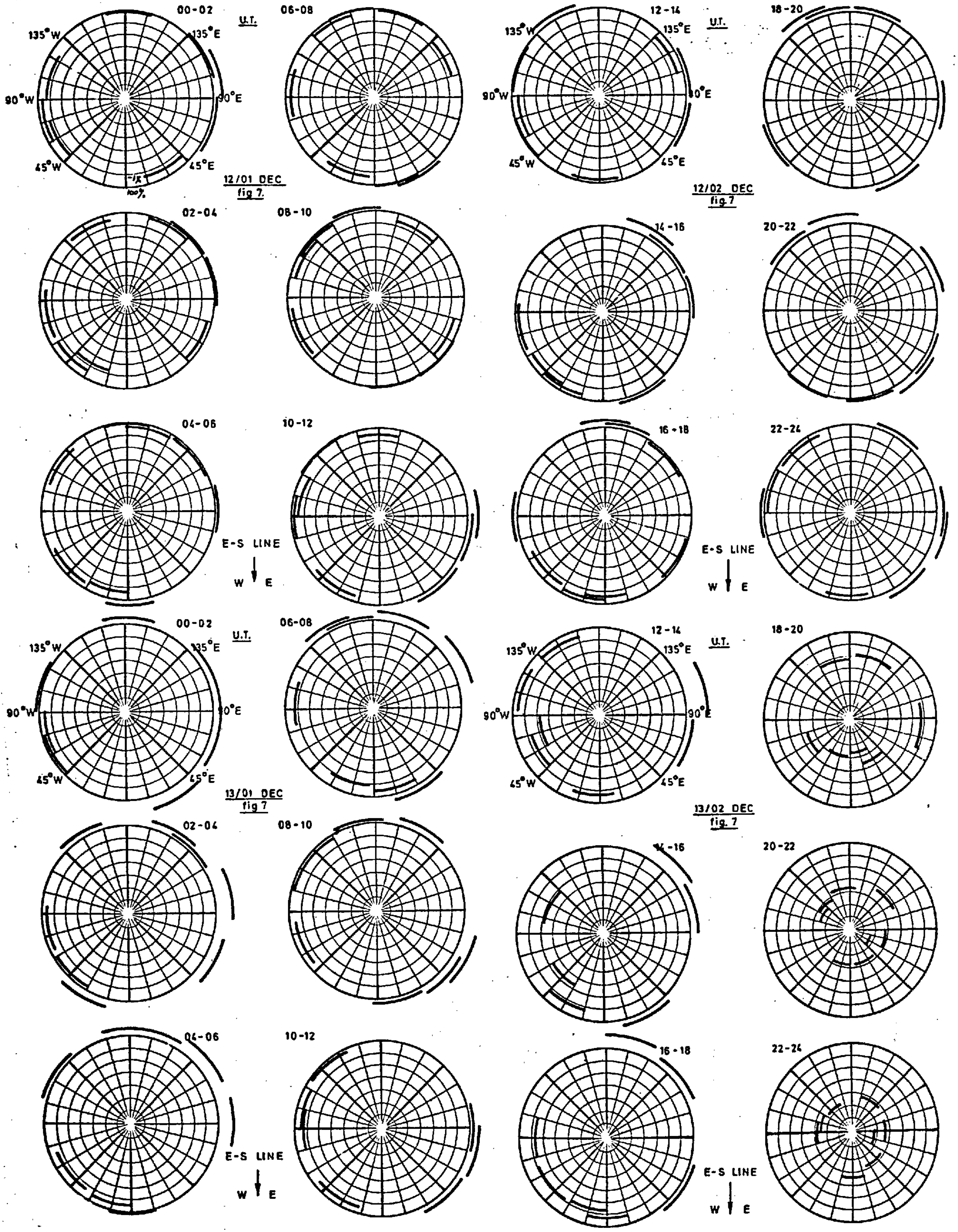
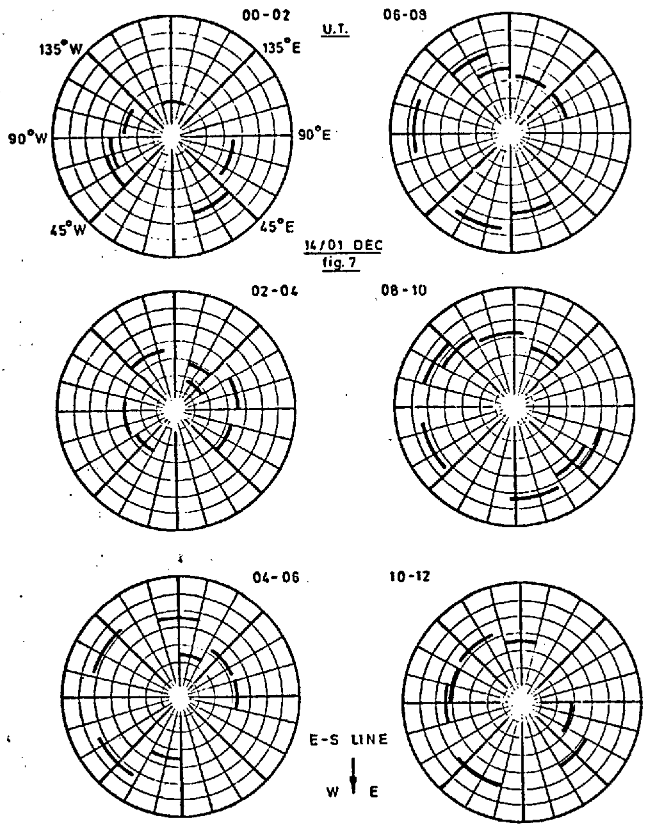
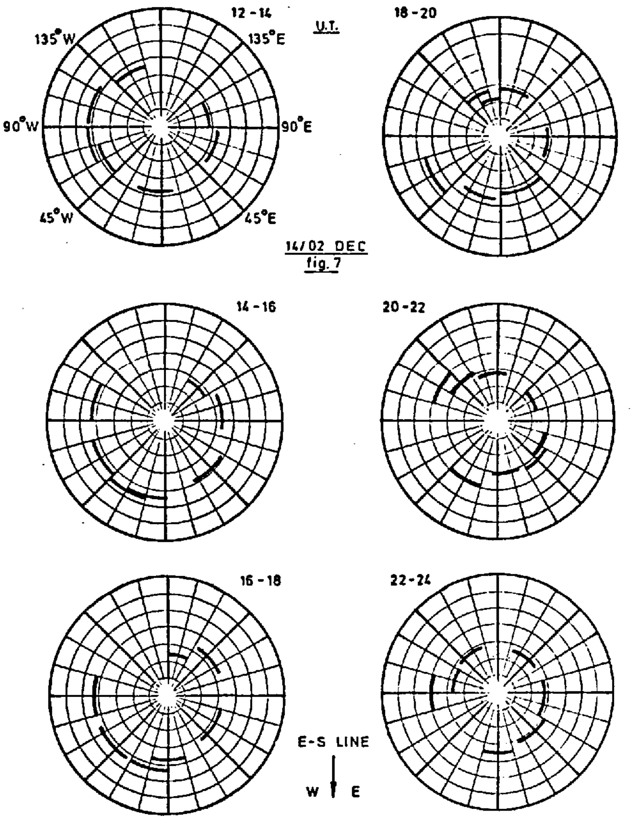
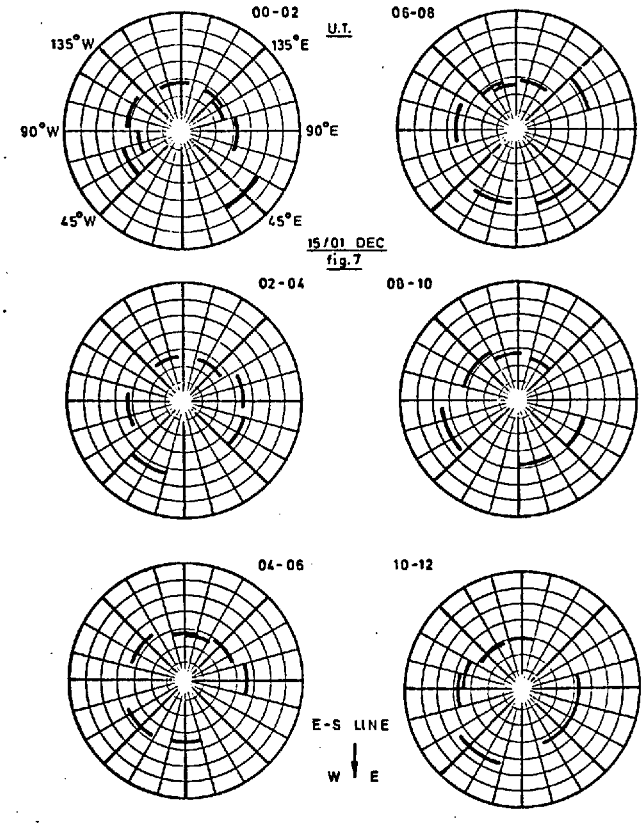


Fig. 7: Intensity direction diagrams corresponding to the event of 12 Dec. 1966.







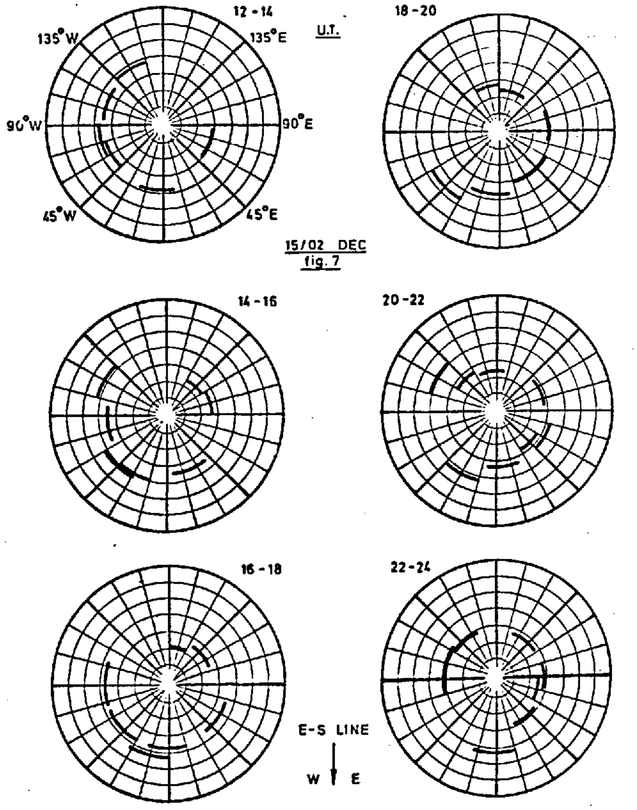


Fig. 7 continued.

monitors from which we have used data. The intensity records from Alert are also given for purposes of comparison of the behaviour of the onset and recovery phases in the solar equatorial plane and at large angles to this plane. The intensity direction diagrams are plotted in figure 7. The salient features of the progress of this event are enumerated below.

1) The diagrams corresponding to the period 00 U.T. to 16 U.T. on the 13th Dec, show that the onset of the Forbush decrease was highly anisotropic, with directions west of the earth sun line recording the decrease before those recording particles from the east of this line. These features were also noted in the previous two events studied. However, it is observed that the time taken for the depression to be recorded from all directions is only about 8 hours.

2) By about 20.00 U.T. on 13 Dec, all directions with respect to the Earth sun line were showing a depression of about 3-4% below the pre-decrease level. The intensity direction diagrams corresponding to the 14 and 15 Dec, show that a relatively long lived increase was recorded from a broad cone of directions about 45°E to 135°W. The intensity from these directions remained above that from other directions for most of these two days. The intensity records from the neutron monitors clearly show the peaks corresponding to this anisotropic increase. The increase appears to have reduced slowly from the 14th Dec onwards.

4) EVENT OCCURING ON 13 JAN 1967.

a) Associated heliophysical and geophysical phenomenon.

Solar flares: Date: 1) 10 JAN 1967 Time: 2053 U.T.
2) 11 JAN 1967 " 0131 U.T.

Location: 1) N22, W58
2) S26, W47

Importance: 1) 2^-
2) 3

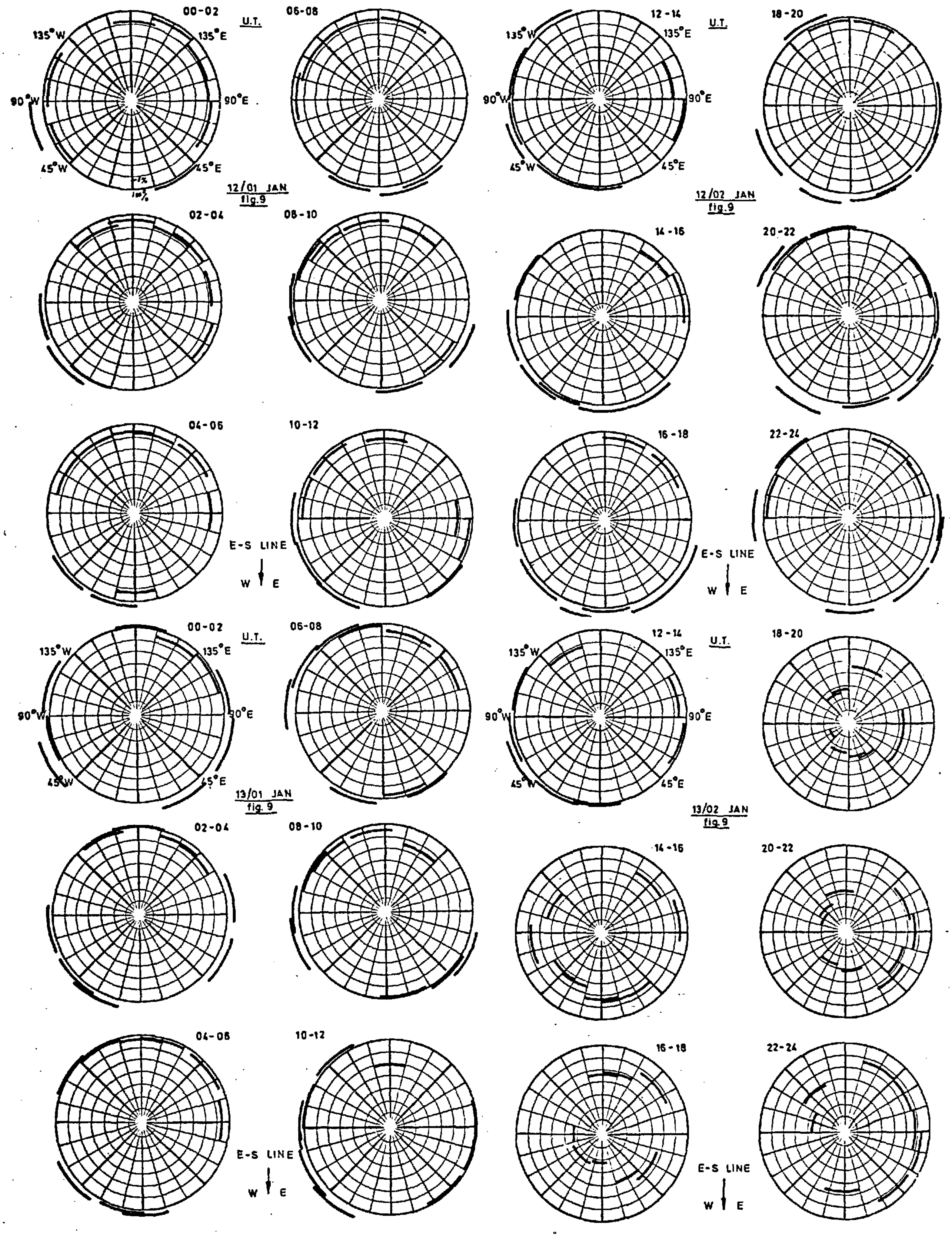
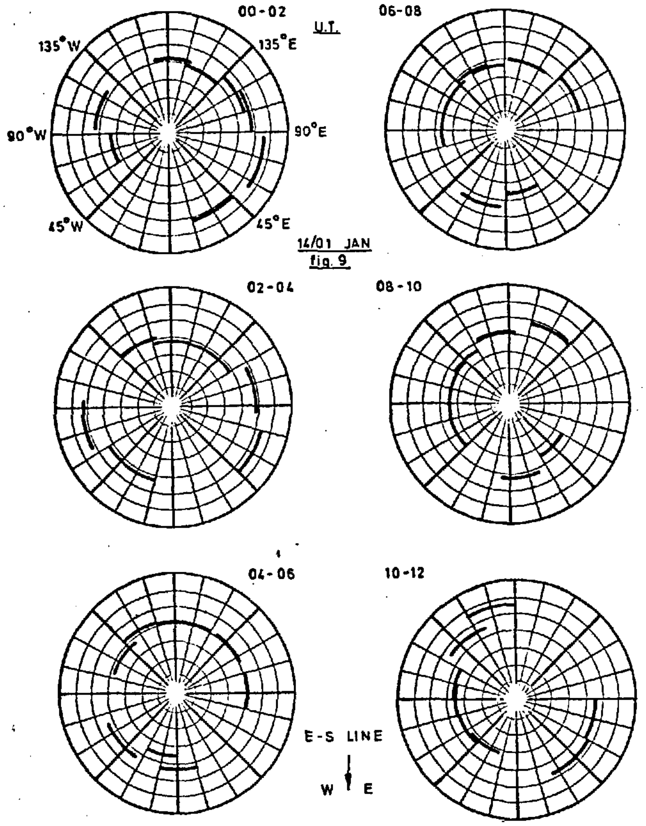
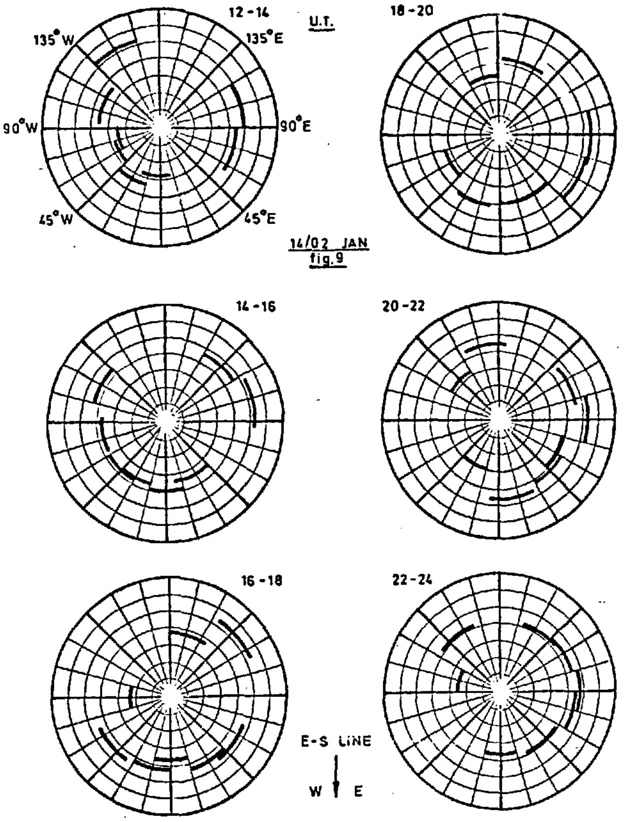


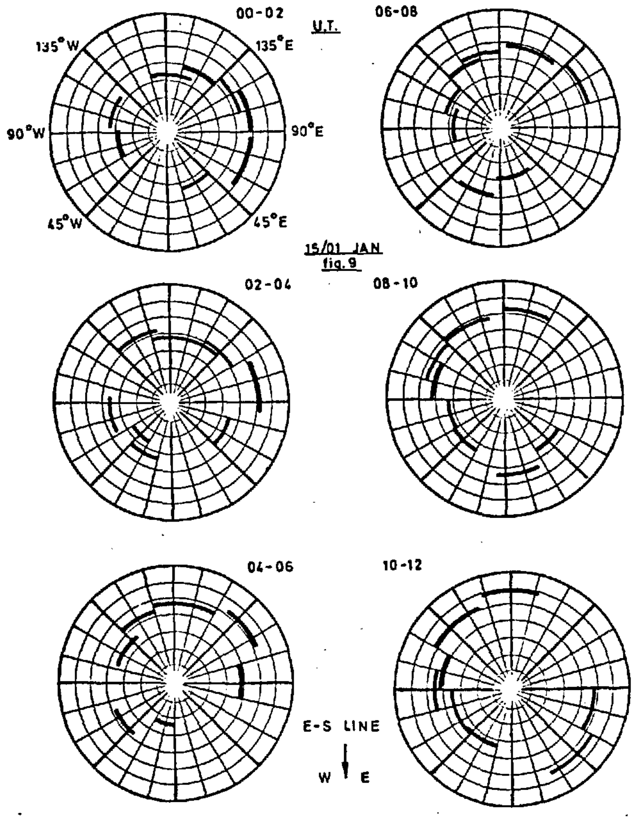
Fig. 9: Intensity direction diagrams corresponding to the event of 12 Jan 1967.



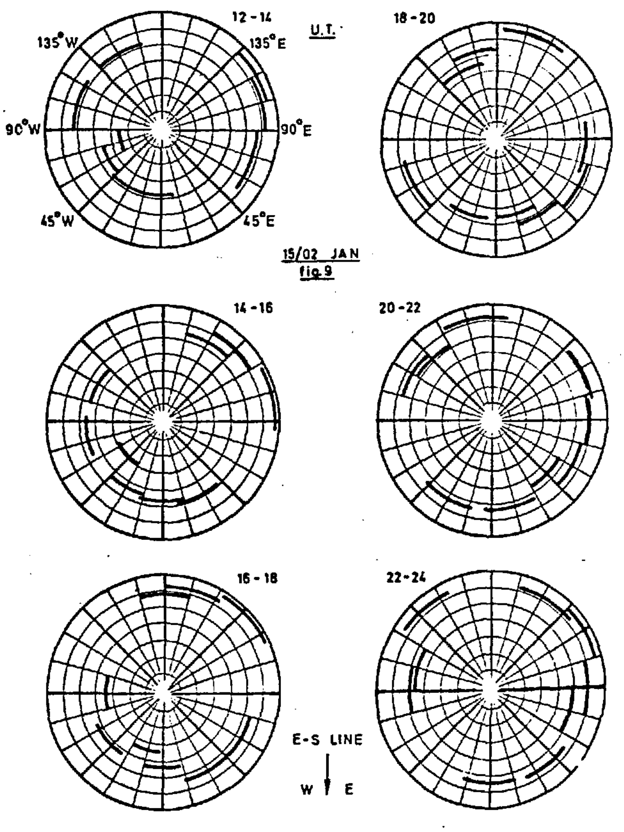
14/01 JAN
fig. 9



14/02 JAN
fig. 9



15/01 JAN
fig. 9



15/02 JAN
fig. 9

Fig. 9 continued.

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S.S.C. occured on the 13th Jan 1967 at 1202 U.T.

Kp indices for the period 11 Jan to 15 Jan 1967: 24^+, 3, 26^+, 31^+, 16^+.

b) Morphology of the event:

The intensity records from several high latitude neutron monitors, corresponding to the period 12 Jan 1967 - 16 Jan 1967, clearly bring out the anisotropic aspects of the event. (Figure 8). The intensity-direction diagrams for this period are presented in figure 9. The chief features of the development of this event are detailed below.

1) The diagrams corresponding to 00. U.T. on the 12th Jan to about 1200 U.T. on the 13th Jan, show that there was some evidence of a depression in intensity from the directions 90°E to about 180°E, over this period.

2) The onset of the Forbush decrease began at about 1400 U.T. on the 13th. It is seen to be highly anisotropic, with the stations looking at West of the earth sun line showing a much greater depression than those recording particles from the east of this line. The maximum depression appears to be recorded from about 90°W. The intensity is depressed last from 90°E. However, it only takes about 4-6 hours before all directions record significant reductions in the intensity.

3) The diagrams corresponding to 00 U.T. to 1200 U.T. on the 14th show that approximate isotropy is established over the course of this period. The diagrams for 1000 U.T.-12 U.T., however, indicate that the intensity had begun to increase from a limited cone of directions about 90°E to about 165°W. The anisotropic nature of this increase persisted for the most of the period from 1200 U.T. on the 14th, to about the end of the 15th. The intensity records for this period (figure 8), show this anisotropic recovery as an enhanced diurnal variation. It appears from this figure that the

preferential recovery from the above diagrams persisted over the 16th also.

7.2.3. SUMMARY AND DISCUSSION:

The following features characterised the morphology (space-time development), of four moderately strong Forbush decreases observed during 1966-67.

1. The onset of the Forbush decrease was observed as an anisotropic depressed flux from a rather broad cone of direction within the hemisphere (45°E - 135°W). The initial phase of the onset was found to occur from a cone about 45°W of the earth-sun line. (There is some indication that in the case of the 13th Jan event the initial depression may have occured from the quadrant 90°E to 180°E. However, the onset of the main phase of the event was found to occur as an anisotropic depression from a cone about 90°W of the Earth-sun line, quite similar to the other events).

2. The anisotropic nature of the onset of the Forbush decrease persisted for several hours. The time difference between the onset to be recorded from directions west and east of the earth-sun line varied from about 20 hours in the case of the 8th July event to 4-6 hours in the case of the 13th Jan, 1967 event. For the events occuring on the 23rd Sept and 13th Dec, these time differences were about 16 hours and 8 hours respectively.

3. In two cases (8 July and 23 Sept), the onset of the Forbush decrease was found to precede the s.s.c. recorded in conjunction with these events. No s.s.c. was recorded in conjunction with the Forbush decrease of 13 Dec. In the case of the 13th Jan event the onset of the main phase was recorded about 2-4 hours after the s.s.c.

4. A short lived increase (duration about 12 hours), was observed during the onset phase of the 23rd Sept event which made the intensity profiles of some stations appear to have a 'two-step' nature. This increase was recorded from a rather broad cone looking towards the Sun.

5. The recovery from the Forbush decrease was often observed to start from a limited cone of directions, and subsequently spread to other directions. In the case of the events recorded on the 8 July and 13 Jan, 1967, stations looking in the hemisphere of directions 45°E – 180° – 135°W, had in general shown a greater intensity than the other hemisphere, more or less through out the onset phase. During the recovery phase of these events it was observed that these directions first recorded a gradual recovery which spread to other directions. In the case of the 23 Sept event, as mentioned, a short lived increase had been recorded from the sunward hemisphere during the onset phase of the event. During the recovery phase also, an anisotropic increase was observed from these directions, which gradually spread to other directions. In the case of the 13 Dec event, a pronounced preference was observed for recovery from a rather broad cone of directions about 45°W of the earth-sun line, i.e. approximately the same directions from which the Forbush decrease was first recorded.

The characteristics of the onset and the recovery phases of the Forbush decreases is explained in terms of the relative position (with respect to the earth) and the geometry of the modulating region (plasma cloud or blast wave) responsible for the Forbush decrease. (e.g. LOCKWOOD and RAZDAN (1963), MATHEWS et. al. (1967)). Thus Lockwood and Razdan have explained the time difference for the onset to be recorded from the West and the East of the earth sun line in terms of the time taken for the earth to penetrate about 2 Gyro radii, (corresponding to the mean energies of the particles recorded) into the plasma cloud. In the case of the large Forbush decreases studied by Lockwood and Razdan, the observed time differences were rather short ranging from a few minutes to about 10 hours.

The smaller of these differences can be explained in terms of the above reasoning if we assume that the magnetic field in the plasma cloud is 20-30 gamma and that the velocity of the cloud is 500-700 Km/sec. However, if we attempt to explain the rather large time differences (15-20 hours), observed in some of the events we have investigated, in terms of this reasoning, then we have to assume either, a very low value of the magnetic field in the cloud (5 gamma or less) or to postulate that the velocity of the cloud is about 100 Km/sec, or less.

(The gyro radii of 10 Gv protons, (which may be taken as the mean rigidity recorded by high latitude neutron monitors) in a field of about 30 gamma is about 1.1×10^6 Km. Therefore, if we assume that the plasma cloud travels with a velocity of about 750 Km/sec, which is a reasonable estimate of the plasma velocity in times of flare activity, as confirmed by satellite measurement, (e.g. NESS 67), then the time taken to travel two gyro radii is about one hour. With the value of 30 gamma for the magnetic field in the cloud, we will in fact have to use a very low value of the plasma velocity (50 Km/sec or less), in order to explain time differences of 15-20 hours. On the other hand, we will have to lower the value of the field in the cloud to 3 gamma or less, if we retain the velocity of 750 Km/sec for the plasma cloud.)

As mentioned in Chapter I plasma velocities of 700-900 Km/sec have actually been observed by space probes in the case of enhanced plasma flow from solar flares etc. Values of the magnetic field at such times is also not much below 20-30 gamma. In fact the magnetic field associated with the modulation region will have to be several times the average (5 gamma) interplanetary magnetic field in order to explain the lowering of the galactic cosmic ray intensity associated with this region.

In view of the foregoing discussion it appears that the long time delays observed between the West and the East of the Earth-sun line, cannot be explained only in terms of the time taken for the earth to penetrate a reasonable distance in the plasma cloud. In fact it appears difficult to avoid the interpretation suggested by McCRACKEN (1962), that stations looking towards the West of the earth-sun line are sampling the depressed intensity associated with the modulating region before the region has actually reached the earth. According to McCracken, the anisotropic onset of the Forbush decrease from the West of the earth-sun line well in advance of that from the east of this line, is a consequence of the fact that at the orbit of the earth the interplanetary magnetic field lines are inclined at about 45°W to the Earth-sun line. Particles moving along the field lines or at small angles to the field lines will experience minimum scattering in the magnetic field regime associated with modulating region. The proportion of the trajectories connecting with the inside of the modulating region will therefore, be greatest for small pitch angles and the cosmic ray intensity in this direction will therefore be the least. This preferential sampling, well in advance of the main decrease, will be possible only for plasma clouds emitted on the western hemisphere of the sun. For plasma clouds emitted on the eastern hemisphere of the sun, this connection with the inside of the modulating region will only be possible when the cloud comes very close to the earth and therefore the time differences observed at onset will not be so great.

From the investigation of the recovery phases of four strong Forbush decreases, which we have studied here, we observe that direction from which recovery first commences varies considerably. In the four events we have studied, we have noted preferential recovery from two broad cones,

1) about 45°W of the earth sun line (for the events occuring on 23 Sept and 13 Dec) and

2) About 135°E to the earth sun line (for the events on 8 July and 13 Jan). This is at variance with the findings of LOCKWOOD et. al. (1963) that anisotropic increases during the recovery phases of the Forbush decreases always occur from the East of the earth sun line, while anisotropic depressions are recorded from the West of this line. It appears that the nature of the anisotropies during the recovery phases are strongly dependent on the characteristics of the modulating region and vary widely from event to event. Several workers have attempted an explanation of the short lived anisotropies during the recovery phases of the Forbush decrease (e.g. ROSE and LAPOINTE 1961). AHLUWALIA (1967), on the other hand invokes a rather special mechanism in terms of scattering of the particles by irregularities in the interplanetary magnetic field and reflections from the blast waves associated with the plasma cloud. In general, the relatively long lived anisotropies probably represent anisotropic diffusion of the cosmic ray particles into the region emptied of the galactic particles by the blast wave. These anisotropic increases appear in the intensity records as greatly enhanced diurnal variations with times of maxima and amplitudes greatly different from the quiet time diurnal variation, attributed to corotation. Enhanced diurnal waves of this sort were observed during the recovery phases of two events studied here. The amplitudes and phases of these diurnal waves vary greatly from event to event depending on the amplitude and position of the anisotropy producing these waves. (Times of maximum from the morning directions have sometimes been observed e.g. LINDGREN (1967)). This clearly brings out the necessity of excluding these days while looking for the characteristics of the quiet time daily variation.

In this connection it is also important to realise that if a plasma cloud located at some distance from the earth is able to affect the cosmic ray intensity at the Earth, as the foregoing discussion seems to suggest, then such distantly situated plasma clouds may well cause transient anisotropies in the intensity and thereby contribute to the variability of the diurnal variation. (MATHEWS et. al. 1967). Such a situation would be most likely when the lines of the interplanetary magnetic field connect the turbulent region to the earth as in the case of the anisotropic onset of the Forbush decrease. One would expect the maxima and minima of the intensity in such cases to be orientated along 135°E (The anti-gardenhose direction) and 45°W (the garden hose direction) respectively.

Sequences of enhanced diurnal waves are sometimes observed on their own, in so far as they are not accompanied by a large Forbush decrease. Two such periods when the daily variation was obviously enhanced (as observed by the intensity records from neutron monitors) though the cosmic ray intensity remained fairly constant, were 2 Jan to 4 Jan 1966 and 1 Feb to 6 Feb 1967. In both cases the peak to peak variations were about 4% and could not be caused by the corotation effect alone. We have looked at the intensity direction profiles for these cases by the same method employed to investigate the morphology of the Forbush decreases. The large amplitudes of the variations made them amenable to study by this method.

The intensity direction diagrams for the first sequence of days from 2 Jan to 4 Jan are presented in the figure 10. The intensity records for several high latitude neutron monitors from which we have used data are presented in figure 11.

The intensity direction diagrams for 2 Jan show transient changes in intensity over the first half of the day. However, by 20 U.T., a pronounced anisotropy can easily be seen to be developing from a rather broad cone of directions about 45°W of the Earth-Sun line. The intensity from this cone is about 1-2% below that shown by the detectors looking along

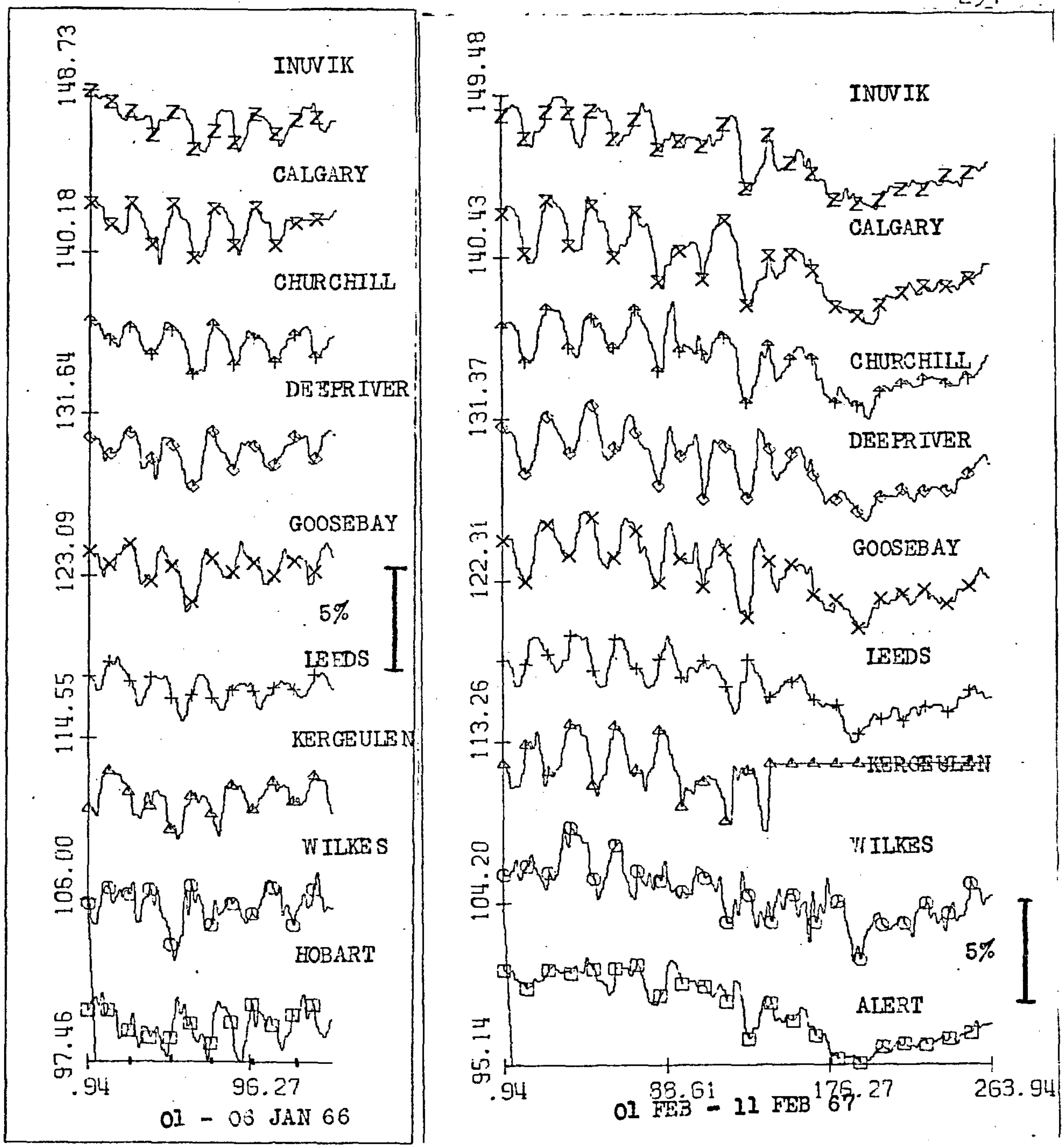


Fig 11,12. Intensity - time profiles corresponding to the periods of enhanced diurnal variations occuring on 01 Jan 66 and 01 Feb 67. The symbols indicate 12 hour periods.

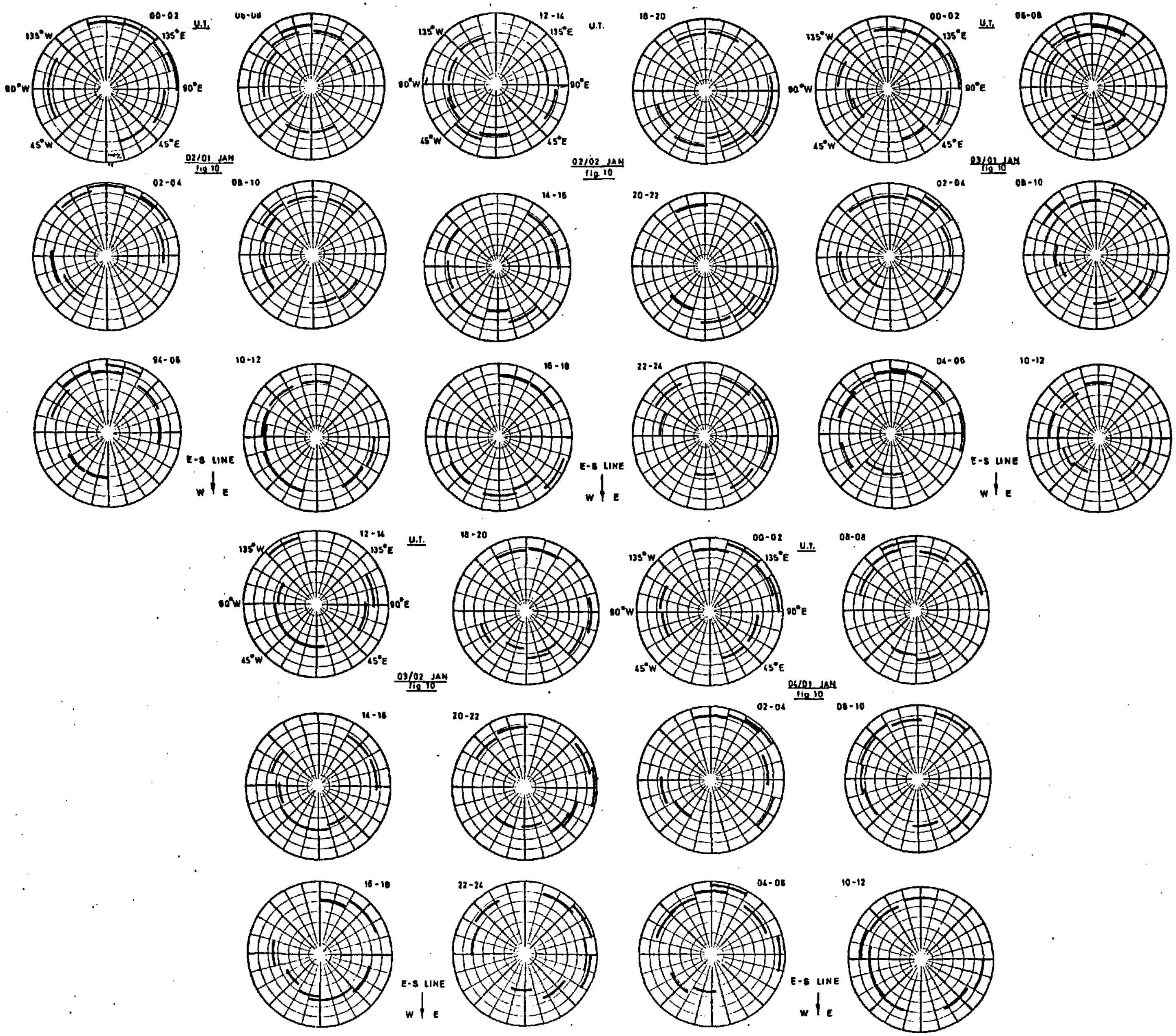


Fig. 10: Intensity direction diagrams corresponding to the event of 02 Jan 1966.

the quadrant 90°E to 180°E. (i.e. From the opposite directions from which the depression has been recorded). The anisotropy persists over 3 Jan and perhaps intensifies somewhat. The diagrams for 00 U.T. to 12 U.T. on 4 Jan show that the anisotropy had reduced as compared to 3 Jan.

Over the period of the event no sudden commencement geomagnetic storm had been recorded, although an M-region recurrence event was evident over the period 27 Dec - 1 Jan. The daily sum of the Kp index for the period 1 Jan to 5 Jan is: 4^-, 16^o, 11^-, 16^o, 7^o. The Kp indices seem to show some increase over the period over which the anisotropy was the most pronounced.

The intensity direction diagrams for the period 2 Jan - 4 Jan described above, seem to suggest that the pattern of enhanced diurnal variation recorded by the S/L neutron monitors over this period were a result of a transient anisotropy from 45°W of the earth-sun line which caused a decrease in intensity from these directions.

It is perhaps relevant to mention here, some results, obtained over this period, by - BARTLEY et. al. (1966), RAO et.al. (1967) and McCRACKEN et. al. (1967) by means of the PIONEER VI space probe, which may have some bearing on the phenomenon responsible for these transient depressions.

BARTLEY et. al. conclude from a study of the anistropic propagation characteristics of 13 Mev protons that the interplanetary magnetic field exhibited a filamentary structure over this period. They suggest that spatial irregularities exist in this filamentary structure in which the neighbouring filaments are intertwined and twisted with their immediate neighbours. These irregularities move radially outwards from the sun. The interplanetary magnetic filaments have a scale size of about 10^6 km. Since the gyroradius of a 1 Gv proton at the orbit of the earth is 1.8×10^6 Km, such a particle would sample cosmic rays from more than one filament in one gyro rotation and would experience scattering. BARTLEY et. al. and McCRACKEN and NESS (1966) suggest that this filamentary structure is a quasi-stable, regular feature of the interplanetary medium. On the other hand, RAO et. al. have observed that one of their channels, which records the galactic counting rate (as opposed to cosmic rays of solar origin) due to particles of energy greater than 7.5 Mev, recorded a Forbush decrease. The onset of the event started on 14 U.T. on 2 Jan and the intensity had reached a minimum on 3 Jan. The intensity remained considerably low on the 4th Jan and recovered slowly afterwards. McCRACKEN et. al. (1966) have presented evidence which suggests that the Forbush decrease observed by PIONEER VI on 2 Jan was one of a series of recurrent modulation phenomena, - Co-Rotating Forbush decreases - which are caused by shock fronts corotating with the sun. They suggest that the origin of each recurrent series lies in the contineous emission of fast plasma by a restricted area on the sun. McCRACKEN et. al. identify this area with the active and long lived M-regions on the sun. The fast plasma from this hot region is supposed to create a standing shock wave at its interface with the slower moving plasma . Theenhanced magnetic field in the shock will inhibit the passage of cosmic rays and will cause a reduction in intensity as the shock passes. The enhanced plasma density associated with the shock will give rise to enhanced geomagnetic activity which will appear as an M-type storm, at the earth. (Recently more conclusive evidence has been obtained, which confirms the co-rotating shock hypothesis. (RAO et. al. 1967). A single shock front was observed by two space craft situated at a distance from each other. The predicted and observed time differences for observation by the two space craft agreed very closely).

It is interesting to note that the main phase of the corotating Forbush decrease occured on the same days on which the enhanced diurnal variation was observed, at the earth. We have examined the data from several high latitude neutron monitors corresponding to the periods over which the other co-rotating Forbush decreases reported by McCracken et. al. during Jan, Feb and March 1966, were observed and find that the intensity observed by the neutron monitors shows evidence of considerable anisotropy on these days. In view of this it appears that there is some correlation between the intensity of the cosmic radiation at mean particles energies of 10^7 and 10^{10} Gv. This suggests that the mechanism causing a depression in the intensity at the lower energies may also be responsible for the anisotropy at higher energies which appear as a depression in the cosmic ray intensity from the direction of the field lines. The regions of depressed intensity created by the passage of the shock will lie along the field lines and will therefore be observed preferentially by a detector looking along the field lines. Such an origin for the enhanced diurnal waves will also explain any 27 day recurrence tendencies in the diurnal variation, since the shock will rotate with a period of 27 days.

Alternatively, the enhanced diurnal variation may represent the average effect of the interplanetary magnetic field which has been re-arranged after a solar flare, such that interplanetary field lines have a larger number of kinks, or spatial inhomogenieties (of the type sampled by Bartley et. al.), than usual.

We have also examined the space time characteristics of another event, in which the diurnal variation exhibited abnormally large amplitudes, in order to establish whether there are any common features in the two events. Figures 12 and 13 present the intensity time profiles observed by several high-latitude neutron monitors, and the intensity-direction diagrams corresponding to the second event. (1 Feb - 7 Feb, 1967).

A study of the daily mean intensities at the various stations showed that

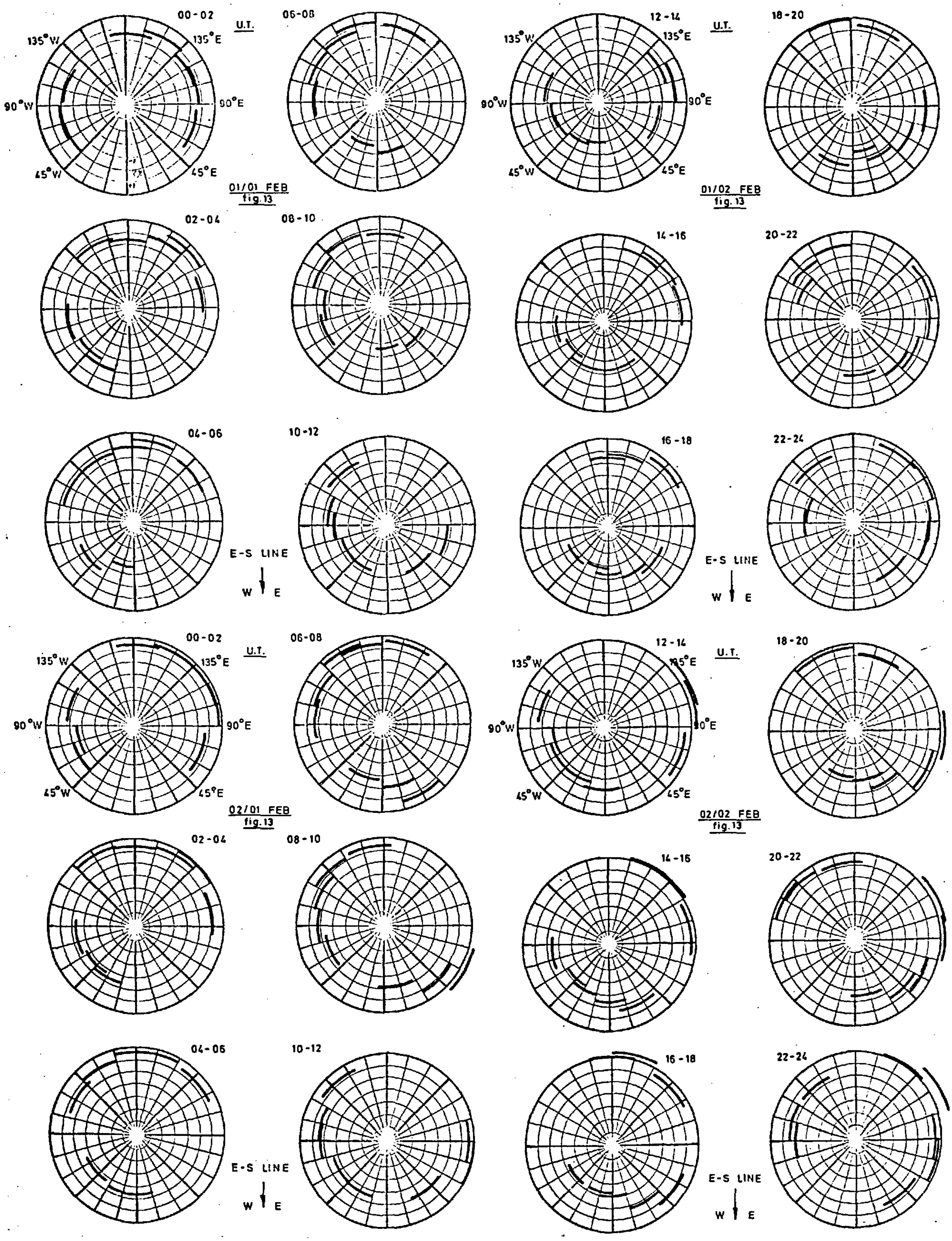
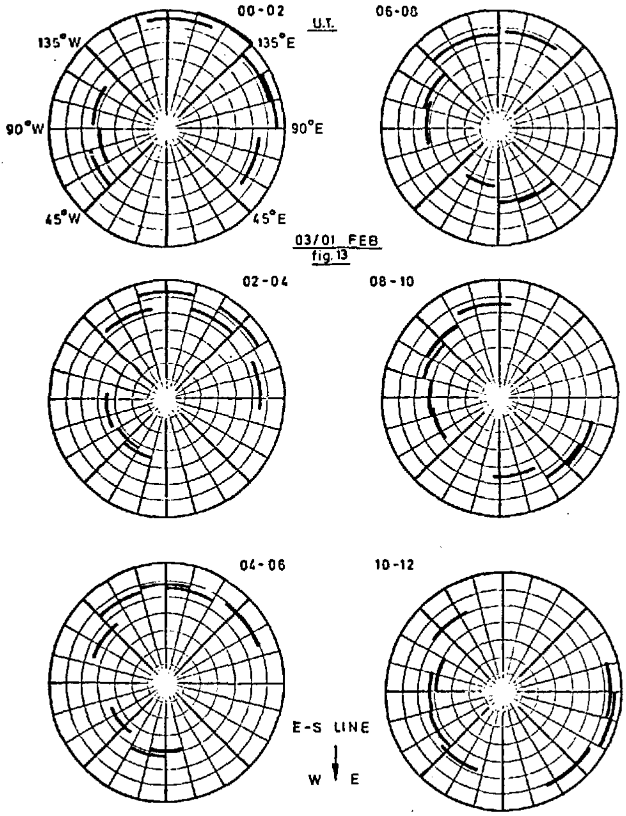
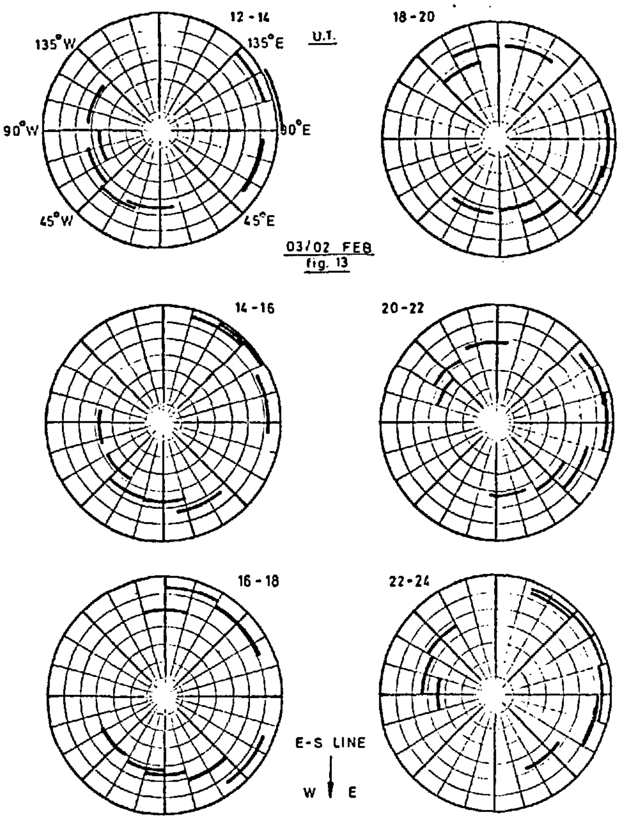
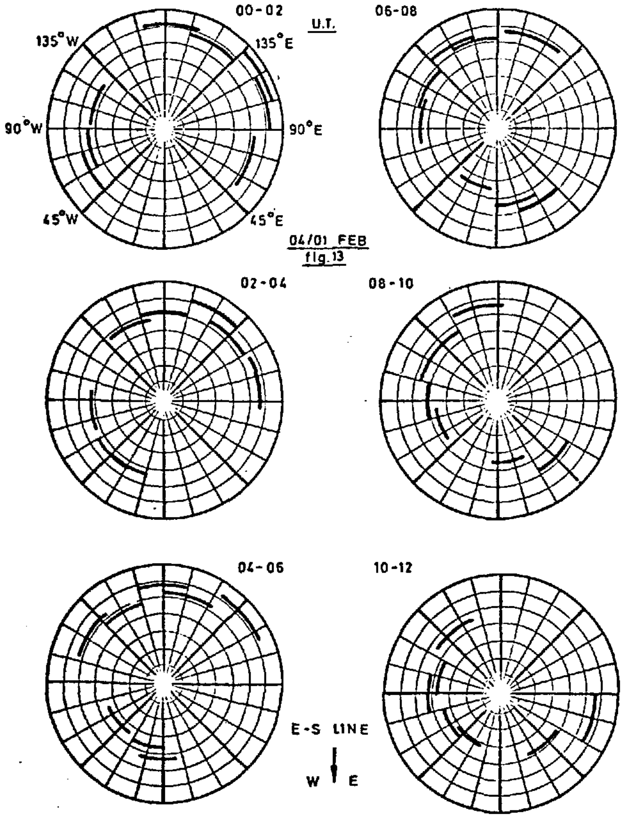


Fig. 13: Intensity direction diagram corresponding to 01 Feb 1967.







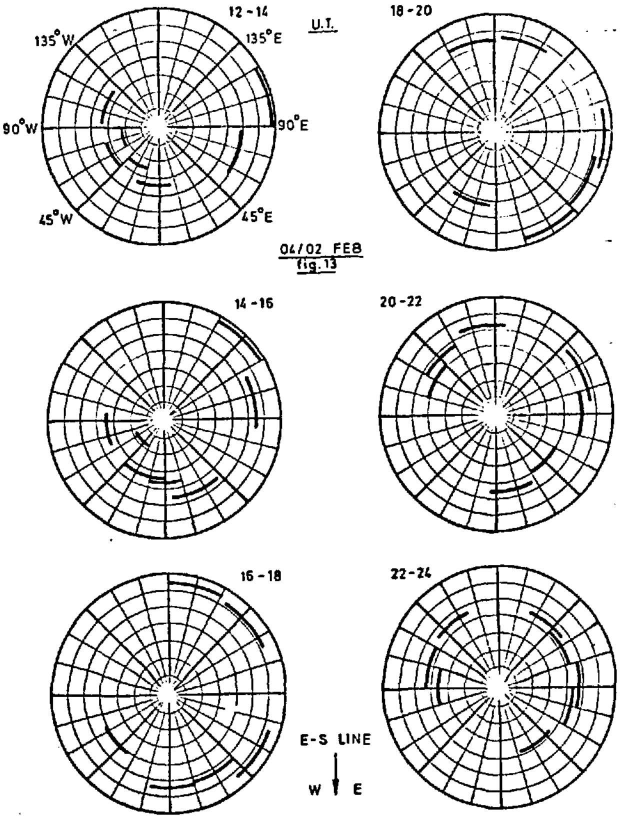
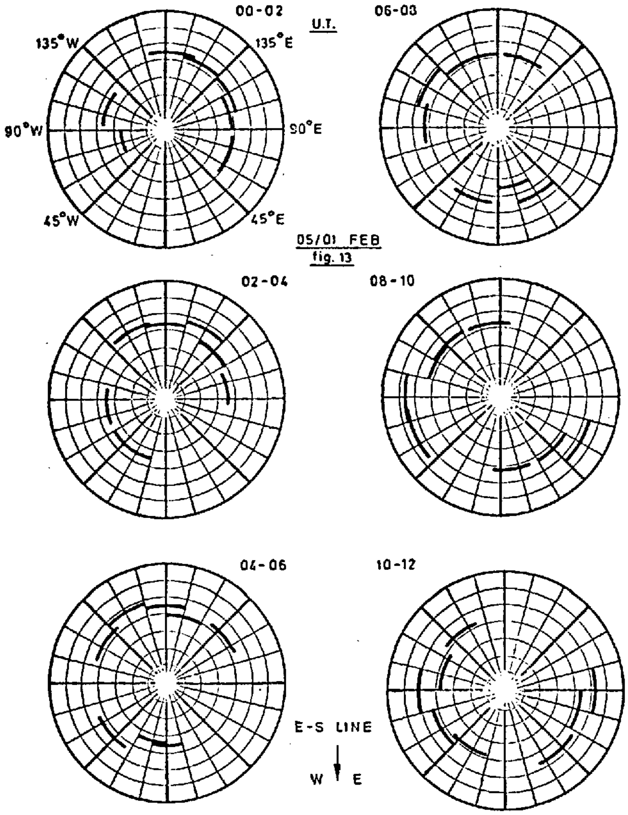
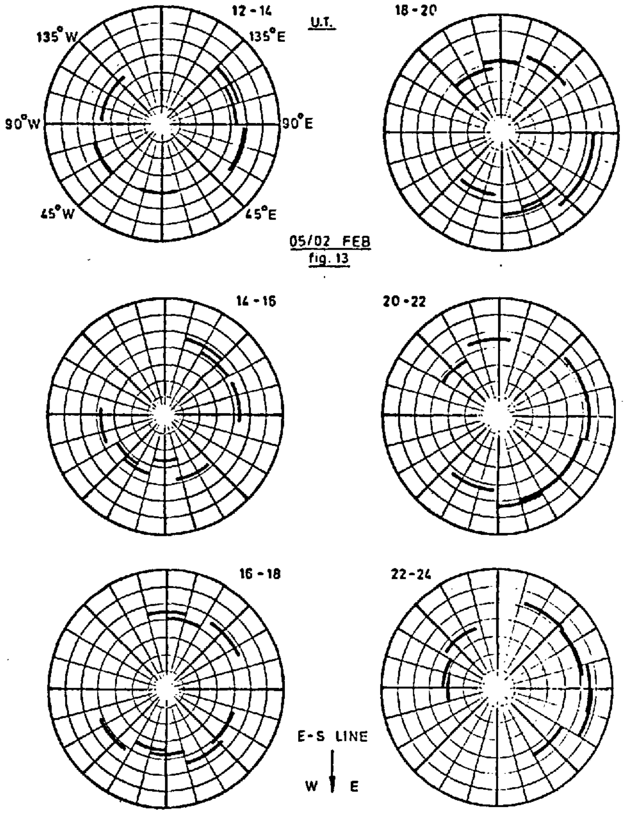
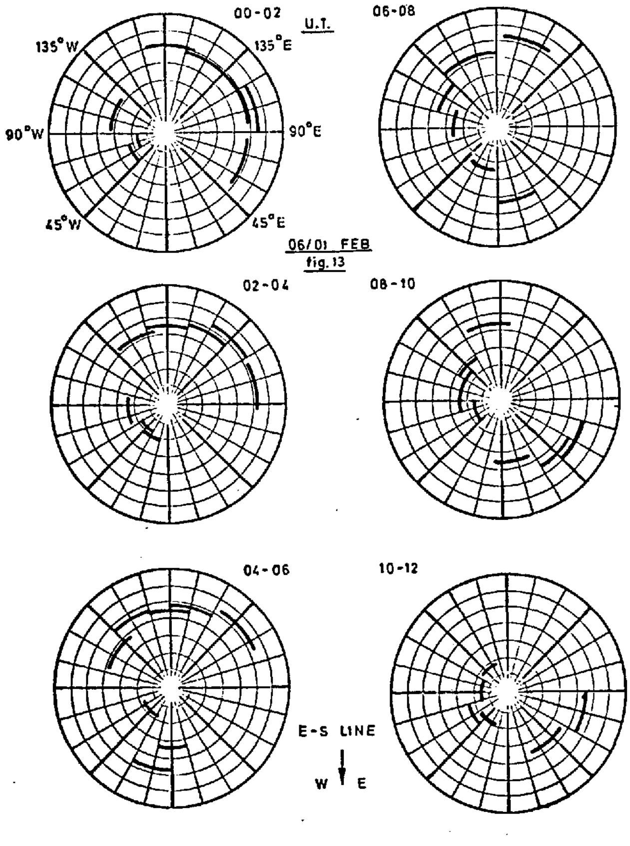


Fig. 13 continued.







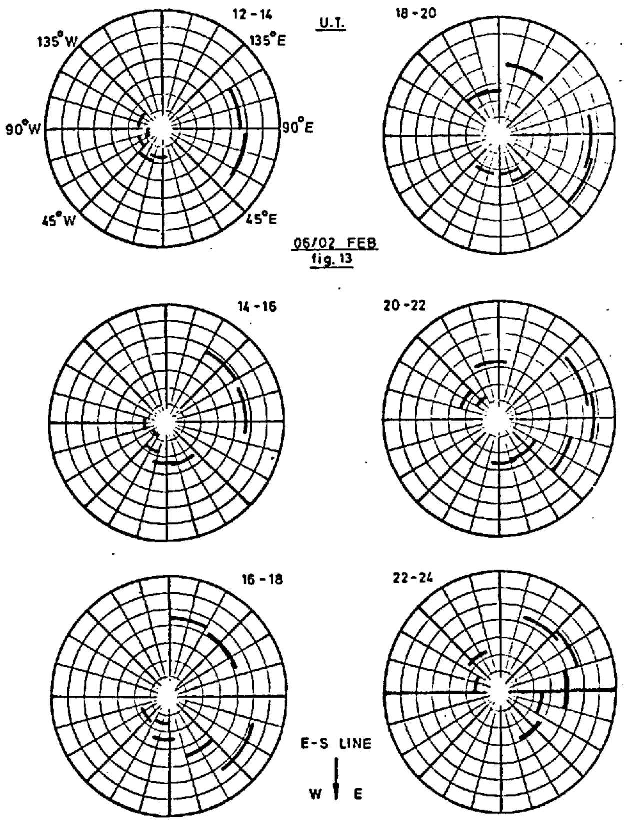


Fig. 13 continued.

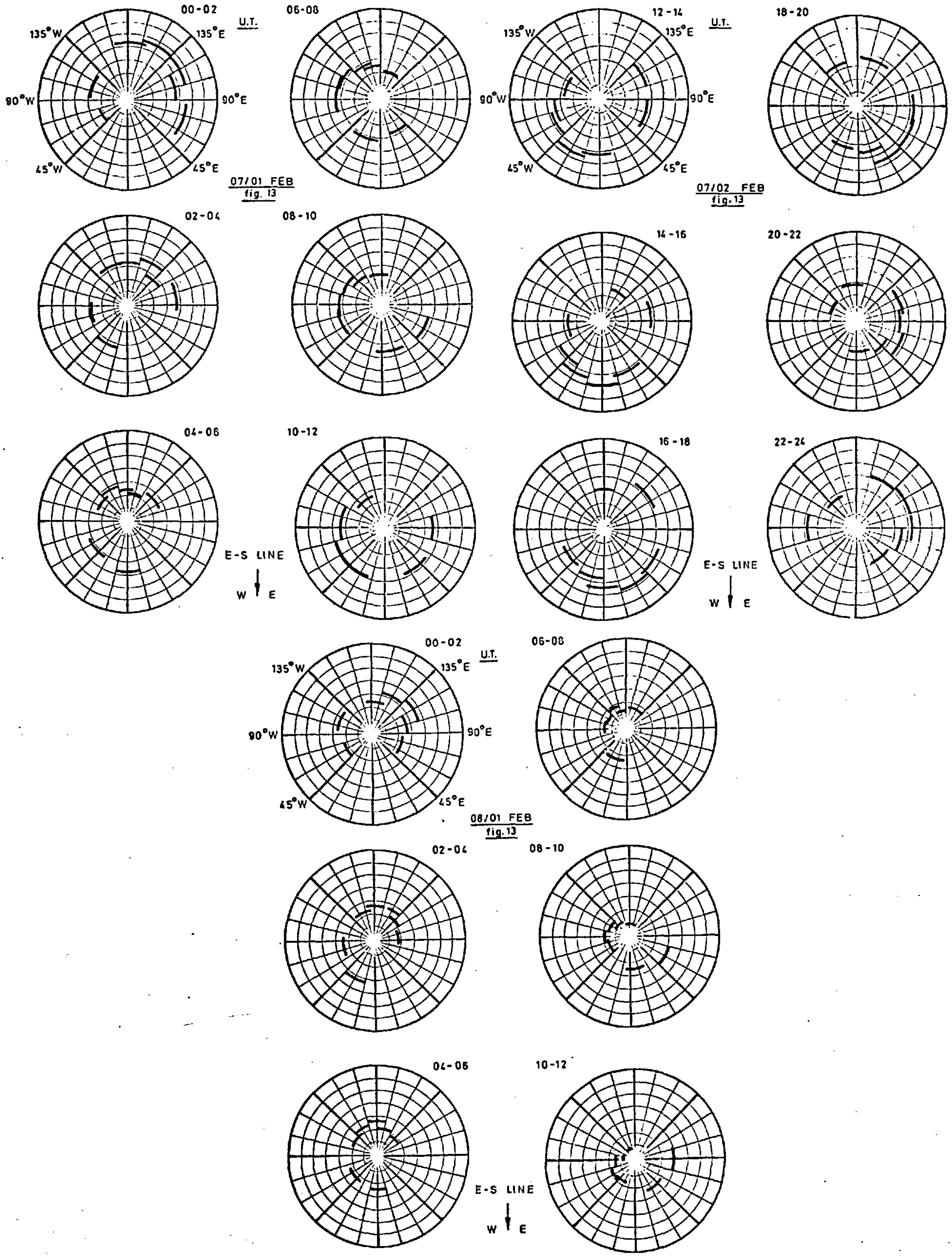


Fig. 13 continued.

the mean level of intensity was approximately constant over the period 1 to 4 Feb, and had then gradually reduced till 9 Feb 1967, when it was about 3% below the mean level on 1 Feb. Superimposed on this gradual variation in intensity were a series of enhanced diurnal waves which reached peak to peak amplitudes of 4-5% on some days. The intensity profiles of the polar and the near polar stations (Alert and Wilkes) show that the diurnal waves observed at these stations were considerably damped as compared to stations whose asymptotic cones sample particles from the ecliptic plane. It appears therefore, that the anisotropy causing the large superimposed variations was largely confined to the ecliptic plane.

The Kp index (daily sums), for the period 1 Feb - 8 Feb are: 9^-, 4, 4, 19, 22^-, 14^-, 24, 38^+. A sudden commencement geomagnetic storm was observed at 16.36 on the 7th Feb.

The intensity direction diagrams in figure 13 show the development of the event. From these diagrams we note the following features.

1) The diagrams corresponding to 1 Feb show, clearly the anisotropic distribution of the galactic flux as recorded by stations over the globe. The intensity from a broad cone of directions about 45°W of the earth-sun line is seen to be about 1-2% less than that from the other directions. Essentially the same pattern continues over 02, 03, 04 Feb, however, there are transient changes.

2) The diagrams for the period 22 U.T. on the 4th to about 18 U.T. on the 5th Feb show that the intensity had become approximately isotropic over this period. Moreover, the intensity appears to have decreased by about 1-2% by this time as compared to the level obtaining on 1 Feb. It appears in fact, that by this time the depression which was originally confined to a broad cone about 45°W had spread to other directions as well, thereby lowering the general level of the intensity and also causing the anisotropy

to disappear.

3) By the end of 5 Feb and over 6 Feb there again appeared a pronounced anisotropy from a broad cone about 45°W of the earth-sun line, as observed earlier. The diagrams corresponding to the second half of 6 Feb clearly shows that while the intensity from the hemisphere 45°E to 135°W showed a pronounced depression of amplitude 4% that from the quadrant 90°E to 180°E showed a much smaller depression. (w.r.t. the 100% mark).

4) During the first few hours of 7 Feb, the depression seems to have spread to the quadrant which had been up to now showing an enhanced intensity and the diagram for 04 U.T. on 7 Feb shows that approximate isotropy had been achieved by now. This situation persists for a few hours, however, a recovery commences from the directions about a broad cone about 45°W. (The very directions from which the intensity had shown a depression earlier). The recovery persisted for about 8-10 hours and over this period there seems to be some indication that the direction of maximum flux shifted towards the Earth-sun line. During the first half of 8 Feb the intensity appears to have reduced considerably from that on the 7th.

From the foregoing description it appears that the intensity had fallen from 1 Feb to 8 Feb in two steps. In each of these two steps the stations sampling particles from the West of the Earth-sun line from a direction of about 45°W (the quiet time spiral field directions) had shown a depression earlier than that from other directions. The time difference for the depression to be observed from all directions was about 2-3 days. In view of this large differnece it appears that the intensity changes observed by the neutron monitors are perhaps related to the general conditions of the interplanetary medium and the interplanetary magnetic field in the Earth-sun region, and the gradual outward propagation of these features of the interplanetary medium over a period of a few days rather than a single outward travelling or co-rotating shock wave.

Further, the characteristics of the anisotropy observed in both cases (2 Jan 1966 and 1 Feb 1967) i.e. a pronounced depression recorded first by detectors sampling particles from 45°W of the Earth-sun line is seen to be very similar to the onset characteristics of some Forbush decreases which show a depressed intensity from these directions several hours before the cloud responsible for the decrease reaches the earth. In view of our earlier discussion it appears therefore, that this earlier depression from 45°W of the Earth-sun line could be due to a similar cause as the anisotropic onset of the Forbush decrease. i.e. the ability of stations looking along the spiral field to be able to detect any modulation of the cosmic rays before the modulating mechanism reaches the earth.

Unfortunately, we do not have any data from space probes for this period. However, it will be interesting to see whether any co-rotating shock waves or spatial inhomogenieties of the type sampled by Bartley et. al. were observed over this period.

Nevertheless, this study clearly brings out the fact that short term anisotropies may be introduced in the cosmic ray intensity which will affect the amplitudes and phases of the quiet time daily variation.

7.3. Intensity Increases during magnetic storms.

7.3.1. INTRODUCTION:

Besides primary anisotropies is cosmic radiation which can be recognised by a strong local time dependence (of the type discussed in section 7.2.), increases in cosmic ray intensity are sometimes observed at the same universal time, at stations distributed over the globe. These increases are usually found to occur during and after the onset phase of a large Forbush decrease and coincident with the main phase of a magnetic storm (Dst variation of H) of large magnitude. (G.t. 200 gamma). This effect manifests itself as a sharp increase lasting for 6-12 hours and reaching amplitudes of 5% or more at middle latitude stations. The increase effect shows a pronounced latitude effect, with the maximum increase being observed at middle latitude stations with cut-off rigidities in the range 4-6 Gv. The increase effect observed in the low latitude stations is somewhat smaller, while that in the high latitude stations is considerably smaller. The increase tends to be larger at mountain altitudes. Neutron monitors show a larger increase than meson monitors situated at the same latitude. In view of the latter observation it appears that low energy particles are taking part in the effect. This effect called the "storm time increase", was first reported by YOSHIDA and WADA (1959) and has since then been studied by several workers, e.g. KONDO (1961), KONDO et. al. (1960), DORMAN (1963), LINDGREN and PAK (1967), YOSHIDA, AKASOFU and KENDALL (1968). It has been found that in addition to the features enumerated above the storm time increase also exhibits a considerable longitude effect. Thus YOSHIDA et. al. (1968), report that at the maximum epoch of the main phase of the geomagnetic storm the largest increase occurs at stations located in the 1000-1200 hour local time sector. Yoshida et. al. also show that the magnitude of the storm time increase is strongly correlated with the Dst (H), which is an approximate measure of the ring current field. For storms with a weak Dst the increase is small or absent regardless of the magnitude of the Forbush decrease.

The earlier workers e.g. YOSHIDA et. al. (1959), KONDO et. al. (1961), explained the storm time increase as a consequence of lowered threshold rigidities during megnetic storms. The agency responsible for the reduction being the same as that for the large reduction in H at the equator. Kondo et. al. have suggested that the decrease is caused by the application of a temporary uniform external field oriented anti-parallel to the earths dipole axis and carried by the plasma cloud causing the magnetic storm. It is possible to evaluate the change in cutt-off rigidity on the basis of this reasoning. It was found that the computed decrease in thresholds is directly proportional to dH (the decrease in H) for values of dH between about 0-500 gamma, and is dependent on the pre-storm value of the cut-off rigidity for the case of the two components.

On the analysis of data for the storm time icnreases occuring on Sept 13th 1957 and Feb 11th 1958, Kondo et. al. (1960) found that the observed effects are quite consistent with the modification of the threshold rigidities by large external fields, during these events. On the other hand DORMAN (1963), points out that the longitude effect observed for some of the events cannot be explained in terms of an axially symmetric mechanism of the type invoked by KONDO et. al. He also observes that the latitude effect exhibited by the storm time increase as observed in the hard component cannot be entirely due to a change in geomagnetic threshold and a substantial part is played by the enhanced diurnal variations often observed during geomagnetic storms.

It has been suggested that the increase effects can also be explained in terms of an equatorial ring current system. CHAPMAN (1937), first attempted to explain the Forbush decrease in terms of such a system. The reasoning was that the ring current provides an additional magetic moment dM to that of the earth. According to Chapman, this should lead to an increase in the geomagnetic threshold and to a corresponding decrease in the cosmic ray intensity at the earth. However, it was later found that the ring current system tends in general to increase the cosmic ray flux on the ground, rather than to reduce it. This is becuase the reduction of the earth's magnetic field inside the ring current tends to be more important for in-coming cosmic rays than the increase outside. The ring current will have to be unreasonably close to the earth if it depressed the cosmic ray intensity at the earth. Since the field changes induced by a ring current will depend on the parameters characterising the size and position of the ring current, a longitudinal asymetry in the field changes and therefore the threshold changes are quite conceivable. YOSHIDA et. al. (1968) have in fact shown that the asymetric component of the storm-time increase can be related to the asymetry in the ring current.

7.3.2. STORM-TIME INCREASE DURING THE MAGNETIC STORM OF 25-26 MAY 1967.

During the course of the present investigation a large magnetic storm was recorded on the 25th May 1967. The horizontal component of the geomagnetic field as recorded at two near equatorial stations HONOLULU and KAKIOKA showed a decrease of about 500 gamma during the main phase of the storm. High latitude neutron monitors recorded a large Forbush decrease of about 8% over this period. Since storm-time increases have been observed in the past in association with magnetic storms of this magnitude, we have looked at the cosmic ray data from a series of high, medium and low latitude neutron monitors and the NORTH/SOUTH directional meson recorders at London corresponding to this period, to study the characteristics of any storm time effects that may have been associated with this event.

A major problem in the study of the storm time increase is that this effect is normally superimposed on the main phase of the Forbush decrease that invariably accompanies magnetic storms of this magnitude. Furthermore, the Forbush decrease frequently exhibits considerable anisotropies, both during the onset and recovery phases. In the case of large Forbush decreases the anisotropic effects during onset are usually confined to the few hours during the onset which is fairly rapid. However, the amplitudes of the anisotropies during the recovery phase are often considerable and may last for a few days appearing as enhanced diurnal variations during the recovery phase of the Forbush decrease. Therefore, before we can make a study of the storm time effect on its own it is necessary to,

1) Separate out the Forbush decrease effect and

2) make an estimate of any anisotropies during the recovery phase and make allowance for these effects.

In practice, the isotropic part of the Forbush decrease, may be supressed from the records of the middle and low latitude stations by using the cosmic ray data from polar stations. Since the geomagnetic threshold at such high latitudes is very much less than the atmospheric cut-off, the cosmic ray intensity at these stations will not be affected by any reductions in the geomagnetic threshold. Furthermore, since the acceptance cones of a Neutron monitor located at polar stations looks almost at right angles to the ecliptic, the effect of any longitudinal anisotropies confined primarily to the ecliptic, will also be suppressed. In view of these facts we are justified in expecting that the data from polar stations will represent the isotropic part of the Forbush decrease. A better approximation may however be achieved by using data from several near polar stations, distributed in longitude and belonging both to the Northern and Southern hemispheres so as to smooth out any anisotropies during onset and also any North/South asymmetries of the type observed by NAGASHIMA et. al. (1968). However, because of the lack of such data, in the following study we shall only use data from the polar station, Alert.

Since, the magnitude of the Forbush decrease is observed to be largest at Polar stations and is found to diminish with decreasing latitude, it is also necessary to have a knowledge of the latitude effect of the isotropic part of the Forbush-decrease, before a subtraction can be effected.

In the following section (7.4) we shall show that the rigidity spectra of several Forbush decreases, occuring over the period 1966-67 may be expressed by a power law of the form

$$\frac{d\,D(R)}{D(R)} = AR^{-\gamma}$$

where R is the rigidity and γ is a constant with a value between 0.7 - 1.1. These results are also in agreement with results of earlier investigations of the rigidity dependence of Forbush decreases. With a knowledge of the rigidity spectrum and that of the diffrential response function corresponding to a particular situation it is possible to evaluate the variation expected at a particular station, or in a particular component relative to a given variation at Alert. We have carried out such a calculation, using the differential response functions of LOCKWOOD et. al. (1965), and WEBBER (1962) and the proportionality factors F thus obtained will be used to subtract the isotropic part of the Forbush decrease. In order to determine the main features of anisotropies during the recovery phase, unrelated to threshold changes, we have used data from a series of high latitide neutron monitors. These stations have their geomagnetic thresholds reasonably near to, or less than the atmospheric cut-off and will therefore not be affected in any appreciable way by threshold changes. However, since the asymptotic cones of these recorders are all of comparable width and look along the ecliptic plane, they shall be able to record faithfully any anisotropies during the recovery phase of the Forbush decrease. We have also used data from the directional (North/South) recorders, at London, to determine the characteristics of the anisotropies at medium energies, higher than those recorded by Neutron monitors. Since the atmospheric cut-off for mesons is $\simeq 3.5$ Gv., while the geomagnetic threshold is $\simeq 2.5$ Gv, these data are also unlikely to be contaminated by threshold changes.

Before we describe the cosmic ray effects observed, we shall detail below the main features of associated Geophysical and Heliophysical phenomena observed in conjunction with these effects.

a) Associated geophysical and heliophysical phenomena:

Several large solar flares were observed over the period 20-30 May 1968 associated with the McMath Plage region 8818. The region first appeared on the 17th May, 1967 and was observed to be very active from this time to 31st December when it disappeared from the visible solar disc. Over this period it produced about 15 solar flares of importance 2 or above. The relevant data corresponding to these flares is listed in the table below.

TABLE 2.

Solar flares observed over the period 20th May to 25th May 1967.

DATE:	IMPORTANCE:	LOCATION:
20	2B	N23. E51.
21	2B	N24. E39.
22	3B	N24. E54.
23	2B	N30. E25.
	3B	N27. E25.
	2B	N27. E28.
25	2B	N28. E12.
	2B	N23. W02.

26	3N	N15. E19.
	2B	N30. W05.
	2B	N31. W04.
28	4B	N28. W33
	3B	N28. W34
	2B	N25. W42
	2B	N23. W47

Many of the flares were associated with intense type II or type IV radio-bursts. Several storm sudden commencements were observed over this period and are listed below.

TABLE 3.

S.S.C. observed over the period 24th May 1967- 30th May, 1967.

DATE.	TIME:
24	1726
25	1021
"	1235
28	1303
30	1426

The magnetic storm starting on 1235 on 25th May was severe and the equatorial observatories recorded variations in the horizontal component of about 500 gamma during the main phase of the storm. The hourly values of the Horizontal component of the geomagnetic fields as observed at Kakioka and Honolulu are plotted in figure 14. As both stations are reasonably near the equator, most of the variations may be regarded as the Dst Variation in the geomagnetic field.

The daily mean values of the Kp indices for the period 23 May to 28 May 1967 are 15^-, 19^-, 42^+, 51^-, 26^+, 39.

b) Cosmic ray effects:

In figure 15 we have plotted the data from several high latitude neutron monitors corresponding to the period 24th May - 31st May 1967. (The relevant data for these stations are listed in the table below). (The symbols on the records correspond to OO U. T. of the beginning of each day).

TABLE 4.

List of High latitude stations.

Station:	Geographic coordinates (degrees).		Altitude (meters)	Threshold Rigidity (Gv)
	Lat	Long.		
Alert	82.50	-62.33	66	0.05
Wilkes	-66.25	110.52	S.L.	0.05
Inuvik	68.35	-133.72	21	0.18
Goosebay	53.27	-60.40	46	0.52
Deep River	46.10	-77.50	145	1.02
Kergeulen	-49.35	70.22	S.L.	1.19
Swarthmore	39.90	-75.35	80	1.92
Leeds	53.82	-1.55	100	2.20
Sulphur mtn	51.20	-115.61	2283	1.14
Mt. Washington	44.28	-71.30	1909	1.24

In this figure we have also plotted the data from the directional (North/South) recorders at London. Since the geomagnetic thresholds at most stations are close to the atmospheric cut off, these records will not be contaminated by threshold changes. An examination of this figure brings out the following points:

1. The intensity time profiles of most of the high latitude neutron monitors show that considerable anisotropies were associated with the recovery phase of this event.. These anisotropies appeared as enhanced diurnal variations, during the recovery phase. (A detailed discussion of the space-time features of these anisotropies will be given shortly).

2. The intensity time profiles corresponding to the North/South telescopes show that the anisotropies extended to even the medium ranges of energies

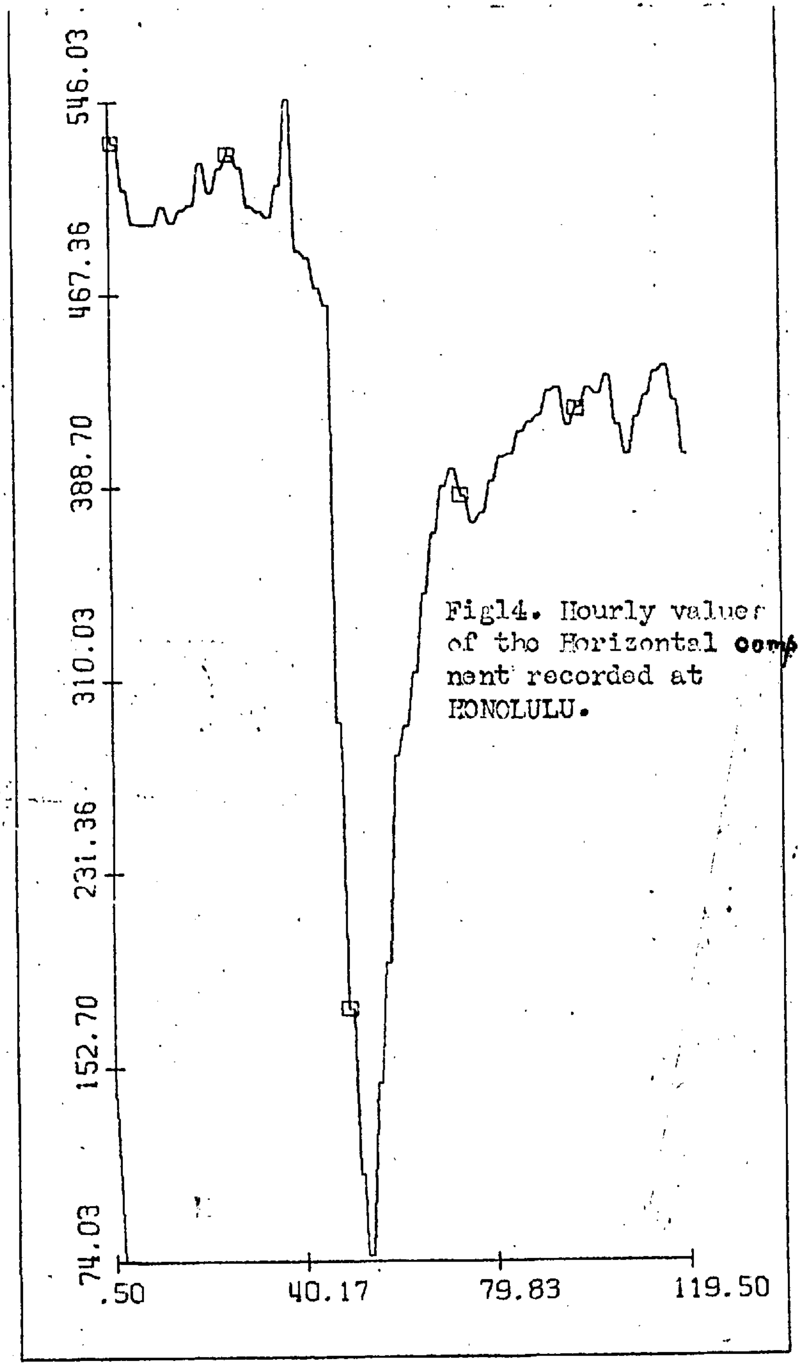


Fig14. Hourly values of the Horizontal component recorded at HONOLULU.

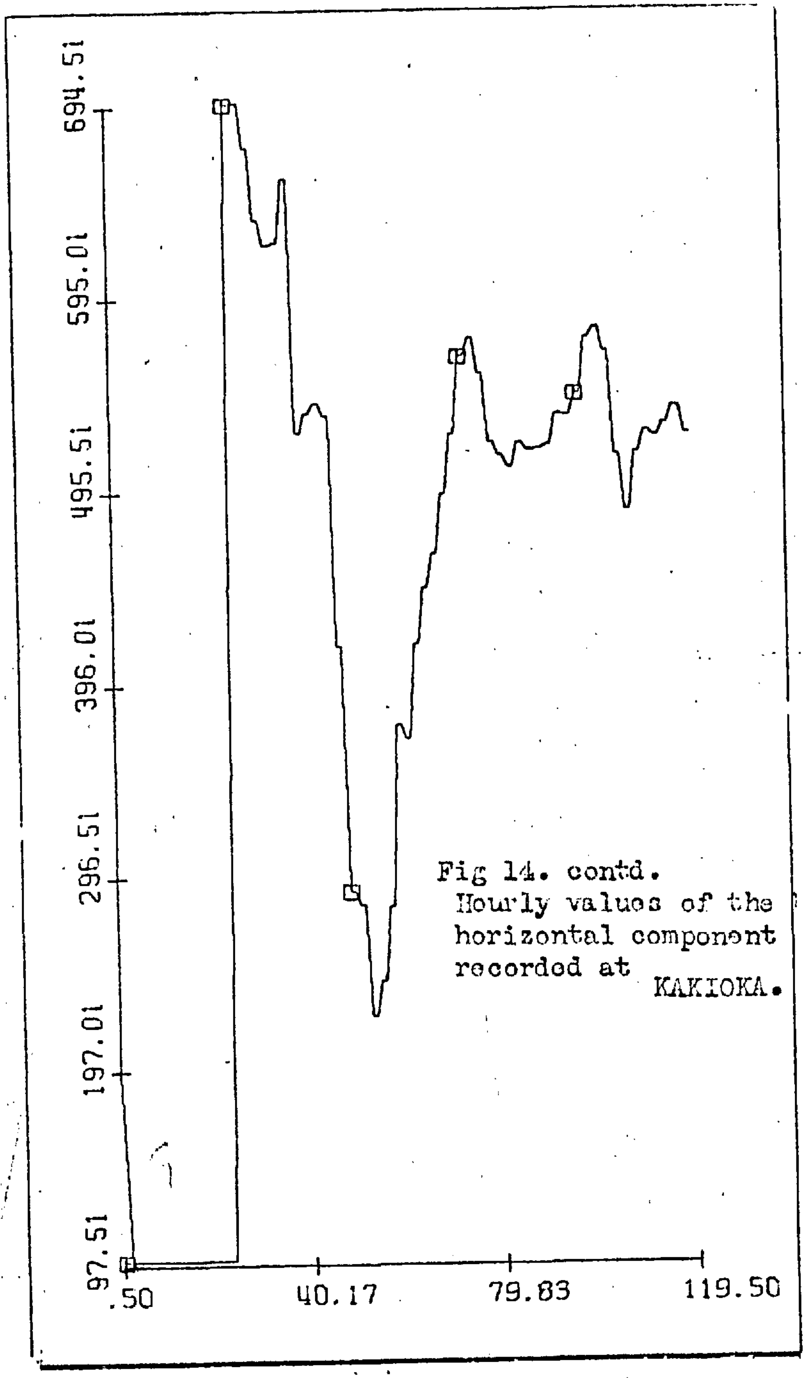


Fig 14. contd.
Hourly values of the horizontal component recorded at KAKIOKA.

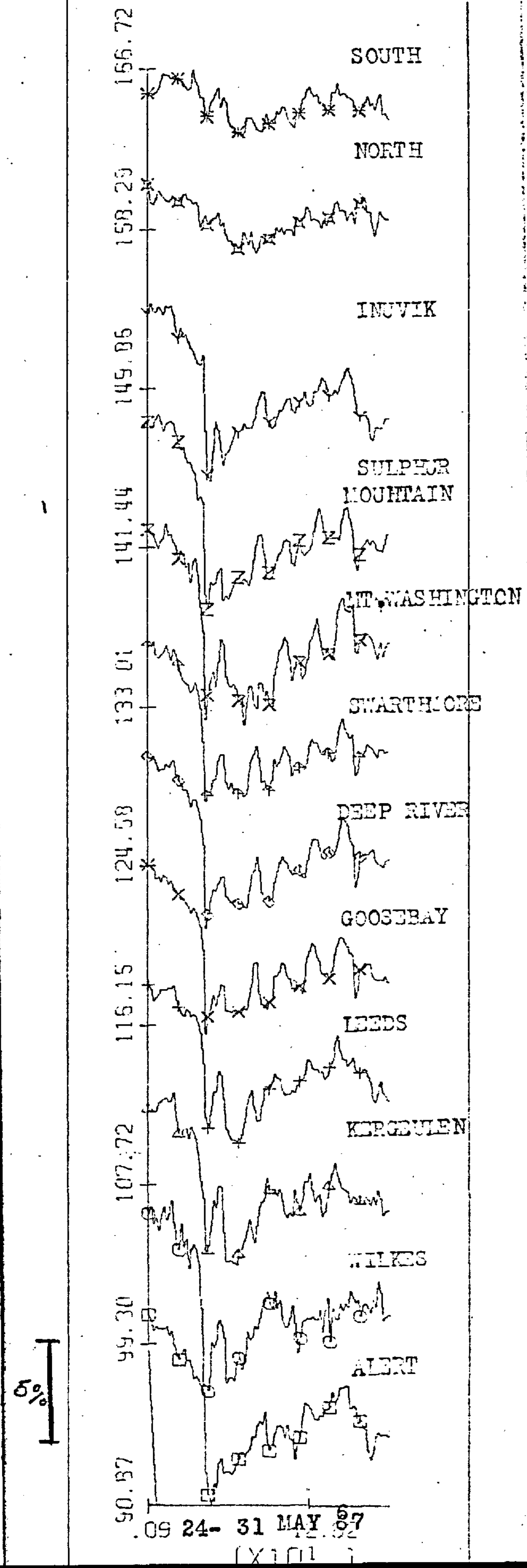


Fig15.

Intensity - Time profil from severa high Latit- tude stati- ons.24-31 May 67. (Symbols correspond to 24-hour periods.)

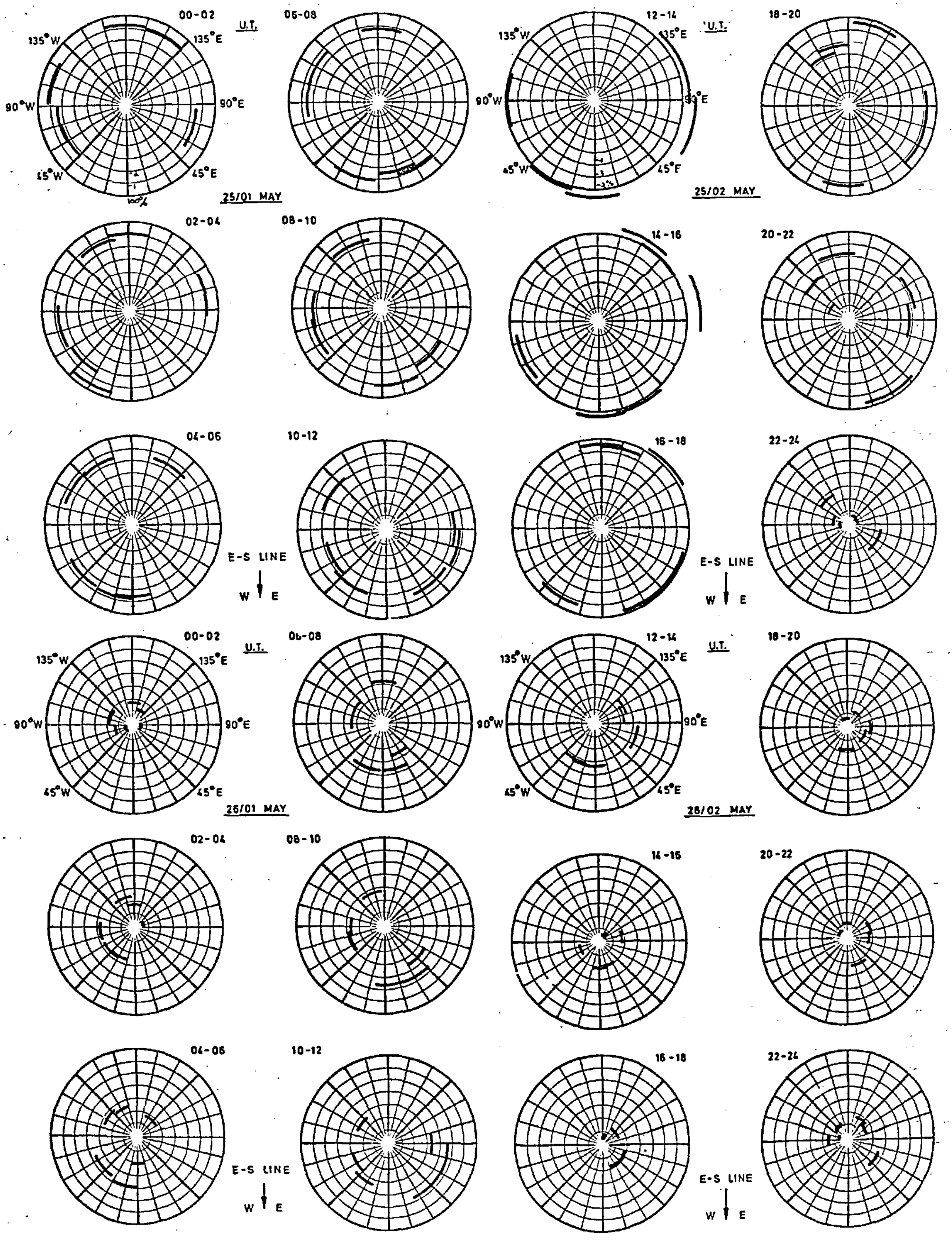


Fig. 16: Intensity direction diagrams corresponding to 25 May 1967.

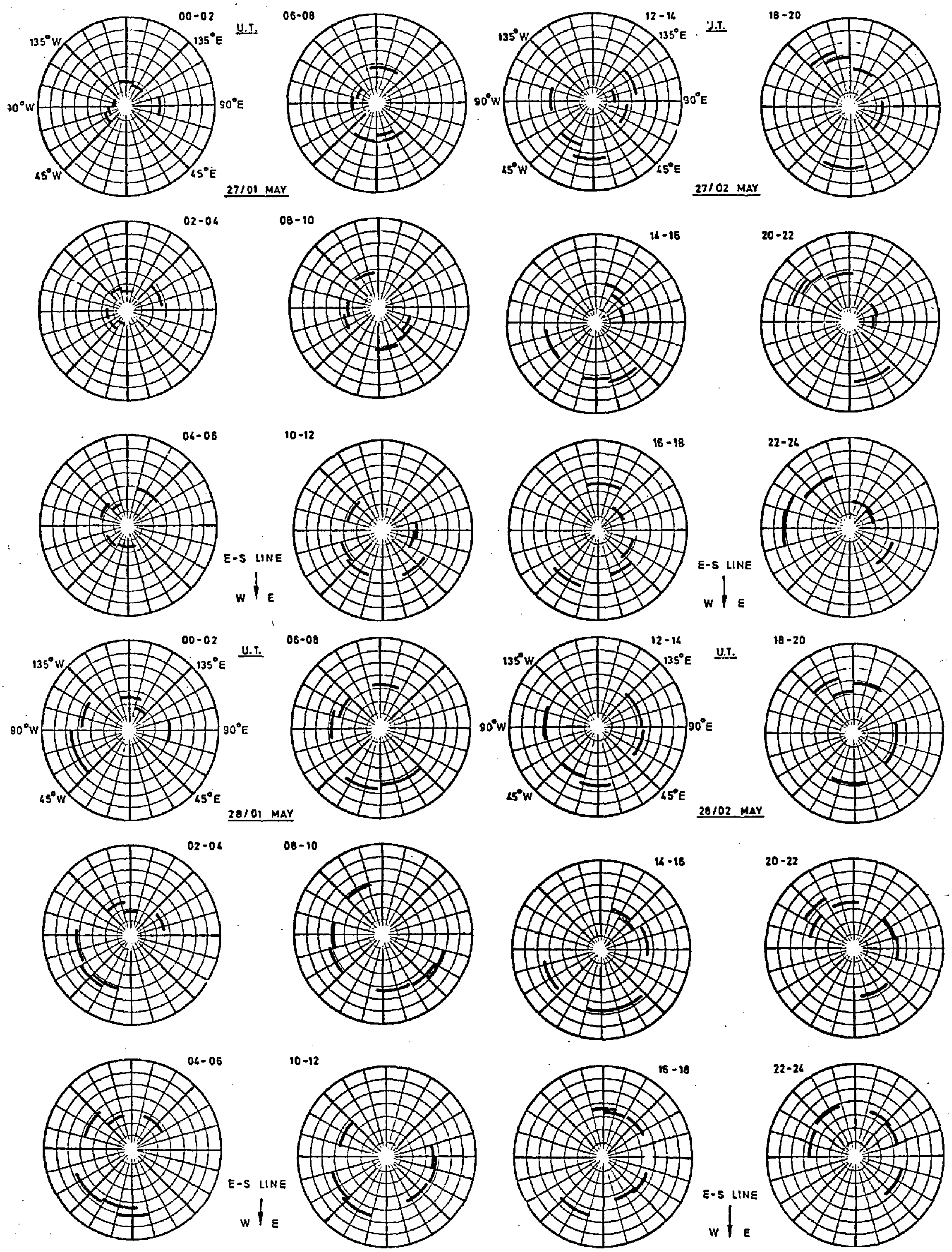


Fig. 16 continued.

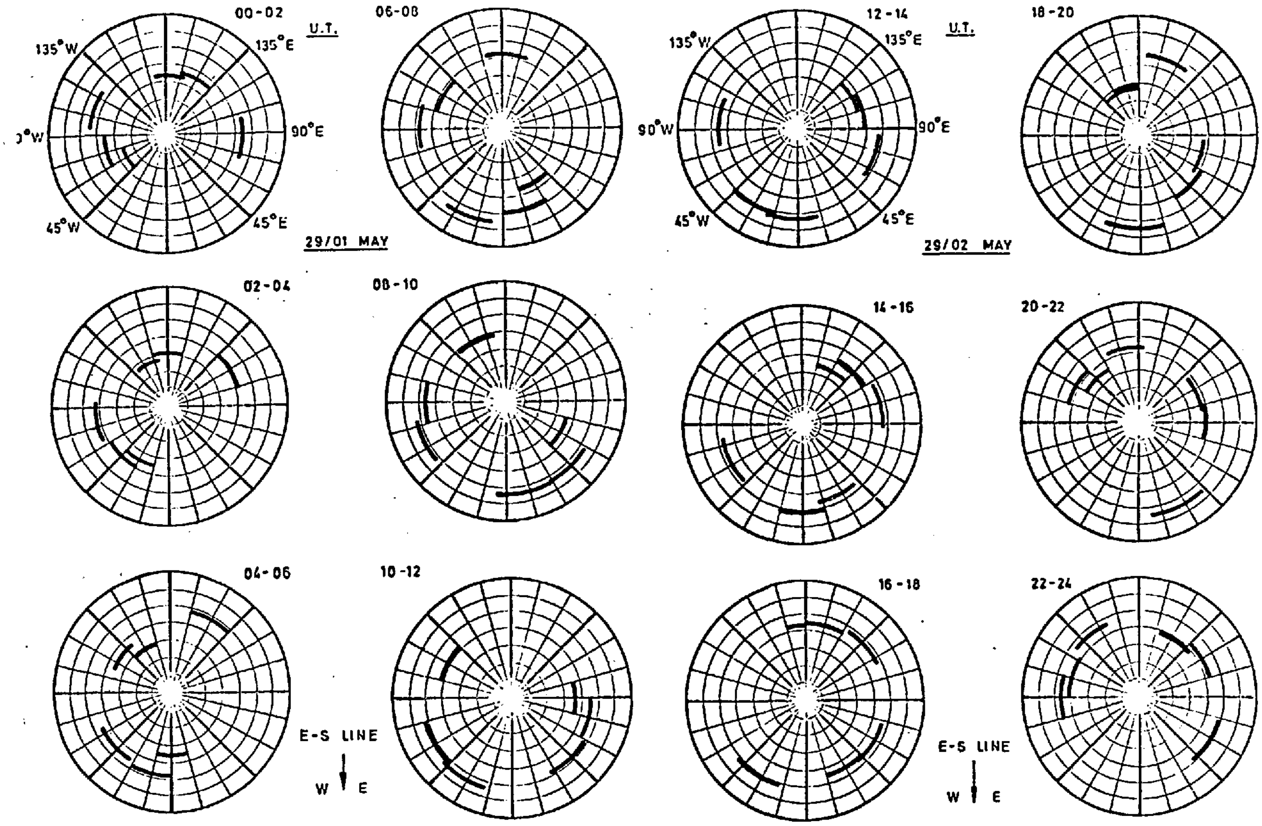


Fig 16 continued.

(20 GV or so) as recorded by these telescopes. The anisotropy is most clearly visible on 26th May.

3. On 26th May the amplitudes of the anisotropies appear to be somewhat larger, as observed by the European sector stations, Wilkes, Kergeulen and Leeds, than that recorded by the S/L American-sector stations.

4. The intensity records corresponding to the polar station, Alert, shows that the affect of the anisotropies is considerably reduced at near polar latitudes as expected.

The figure 16, shows the onset and recovery characteristics of the intensity corresponding to the period 25–28 May, 1967. For this analysis we have used data from the following high latitude stations, whose asymptotic cones of acceptance have comparable widths of about 30°.

1. Wilkes,
2. Kergeulen
3. Leeds
4. Goosebay
5. Deep River
6. Inuvik.

An examination of this figure brings out the following points.

1. The cosmic ray flux began to decrease early on the 24th May, and by 00 U.T. on the 25th the intensity from all directions had fallen by about 1.5%. Over the period 00 U.T. – 1800 U.T. on the 24th the intensity remained approximately uniform from all directions and about 2% below the pre-decrease level.

At about 18 U.T. the intensity showed an anisotropic depression from the West of the Earth-sun line, and by 24 U.T. the intensity had reduced by about 5% from all directions.

2. Over the period 02 U.T. on the 26 to about 14 U.T. there was a temporary recovery from all directions. The amplitude of this recovery was

however much larger in stations looking towards the Sun-ward hemisphere. Kergeulen, Leeds, and Wilkes were recording particles from this direction and consequently saw a much larger recovery. This is also evident from the intensity time profiles for these stations. By about 14 U.T. on the 26th the intensity had fallen to about the same level as that on 00 U.T. on the same day. The intensity remained low over the period 14 U.T. on the 26th to about 06 U.T. on the 27th.

3. The diagrams for the period 0800 U.T. on the 27th to 24 U.T. on the 28th, show evidence for an anisotropic recovery from abroad cone of directions about 45°W of the earth-sun line. This recovery appears as an enhanced diurnal variation in the intensity-time profiles of the high latitude monitors.

It is obvious from this discussion that considerable anisotropies were associated with the recovery phase of the event. The anisotropies at onset were however confined to about 4-6 hours only. In figure 17 we have plotted the data from several medium and low latitude neutron monitors corresponding to the period 24 May 1967 - 31 May 1967. (The symbols in the diagrams mark 12 hour periods). Considerable anisotropies are observed both in the onset and recovery phases of the Forbush decrease. However, it is observed that there are very prominent peaks in the cosmic ray intensity recorded by these stations, on the 26th May, 1967. These peaks are much larger than the peaks observed in the high latitude stations. Furthermore, the maxima in these increases in intensity occur about 6-8 hours earlier than the maxima in the anisotropies observed in high latitude neutron monitors. The data for the next two or three days shows that though enhanced diurnal variations are evident on these days, amplitudes are smaller than those of the increases observed on the 26th May. In view of these features it appears that the increases observed at

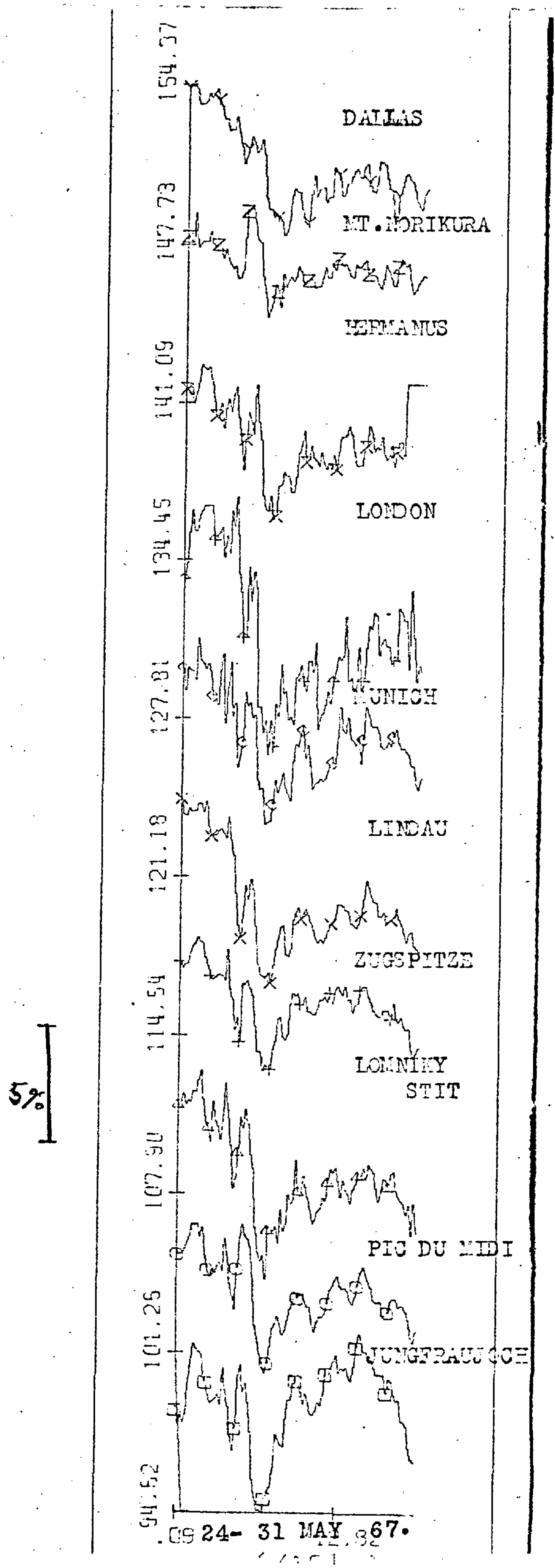


Fig 17. Intensity - Time profiles corresponding to several medium and and low latitude Neutron monitor stations, for the Forbush decrease of 25 May 67. The symbols indicate 24- hour periods.

the middle latitude stations have mainly a different origin from that which give rise to the anisotropies in the high latitude neutron monitors. However, a part of the large increase observed on the 26th May may have been caused by the anisotropic variations which persisted for several days and were observed both by the high latitude neutron monitors and meson telescopes. The main part of the increase on the 26th however, appears to be a storm time effect of the type discussed by Yoshida et al.

In the following we have attempted to separate out the storm time effects from the Forbush-decrease and the anosotropic variations unrelated to threshold changes, as discussed earlier.

In order to subtract the isotropic part of the Forbush decrease we have used data from Alert. The Forbush decrease observed at Alert was multiplied by a proportionality factor to take into account the latitude effect of the variation. The resulting data were then subtracted from the low latitude and medium latitude neutron monitors to suppress the isotropic part of the Forbush decrease of these stations. (We have assumed that the exponent in the power law expressing the rigidity dependence of the events is 0.9. Implicit in this method is the assumption that the exponent remains constant over the periods of the onset and the main phase of the Forbush decrease). The relevant data for the stations is given in the table below.

TABLE 5.

List of medium and low latitude stations.

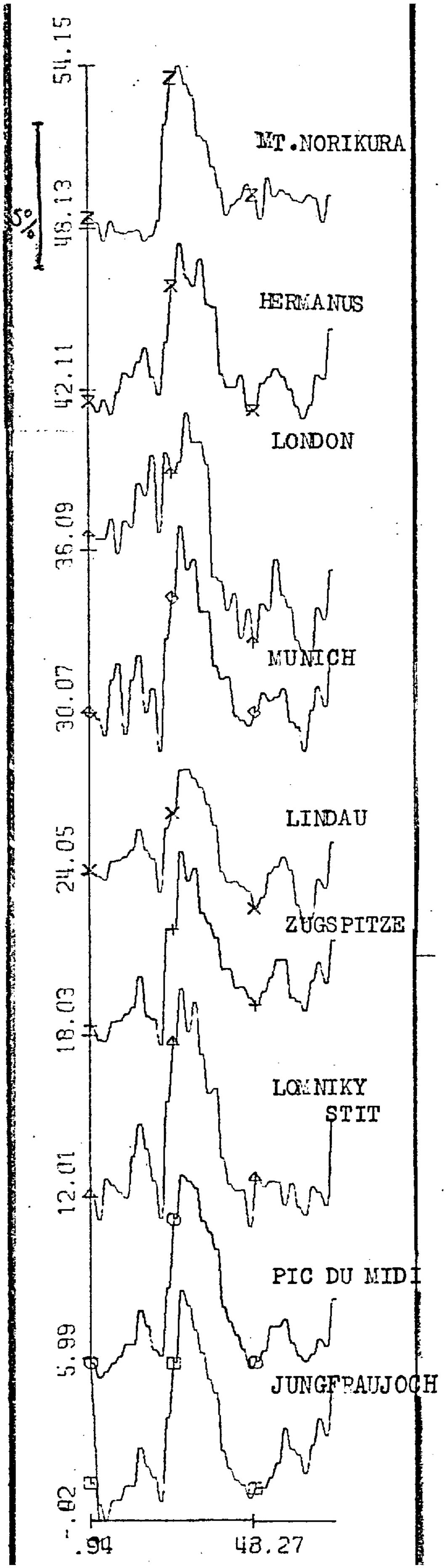
Station	Geographic coordinates Lat.	long.	Altitude meters	Threshold Rigidity Gv.
London	51.53	-0.10	45	2.73
Lindaü	51.60	10.10	140	3.00
Munich	48.20	11.60	500	4.14
Dallas	32.78	-96.80	208	4.35
Hermanus	-39.42	19.22	26	4.90
Lomniky stit.	49.20	20.22	2634	4.00
Zugspitze	47.42	10.98	2960	4.24

Jungfraujoch	46.55	7.98	3550	4.56
Picdumidi	42.93	0.25	2860	5.36
Mt. Norikura	36.12	137.56	2770	11.39

The figure 18 shows a plot of the cosmic ray intensity after subtraction of the isotropic part of the Forbush decrease as observed at Alert. This figure clearly brings out the relative importance of the increase observed on the 26th as compared to the anisotropies unrelated to threshold changes as given by the much smaller peak on the 27th May, 1967. Furthermore the time of maximum of this peak and its shape is very much different from the variations recorded by the high latitude neutron monitors clearly indicating that two effects were operative. The maximum of the increase observed above appears to coincide with the main phase of the geomagnetic storm, indicating that a major portion of the increase represents the effect of reduced threshold rigidities as discussed by Yoshida et. al.

Since the records of high latitide neutron monitors seem to indicate that in addition to the storm time effect, anisotropies were also present in the cosmic radiation it is necessary to subtract the effect of these anisotropies. As a first approximation we have assumed that the anisotropy has an energy independent spectrum for the range of energies involved. The magnitude of the anisotropy were then determined by comparing the records of the high latitude stations, Deep River and Kergeulen, with those of Alert over the period 26 May – 30 May 1967. (We have used the two high latitude stations Deep River and Kergeulen to obtain the amplitudes of the anisotropy in the case of the American-sector and the European Sector stations respectively, in order to take into account the fact that the anisotropic increase observed by high latitude stations was much larger in the European sector than in the American sector).

The figure 19 shows the resultant variations in the middle latitude stations over the period 25-27 May, 1967, after subtracting the anisotropy as



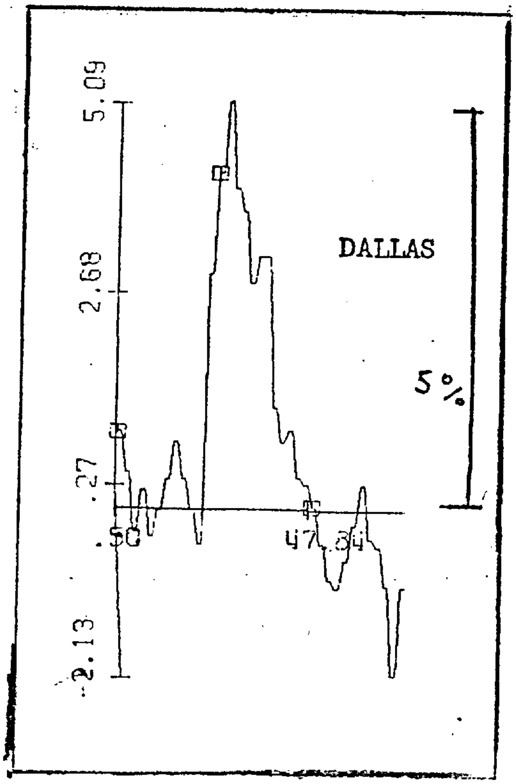


Fig 18. Intensity - Time profiles correspondin to several medium an low latitude neutron monitors after the isotropic part of the Forbush decrease(as recorded at Alert) has been substracted. Data presented for 25-27 May 67. The symbols indicate 24-hour periods.(Notice different scale for Dallas.)

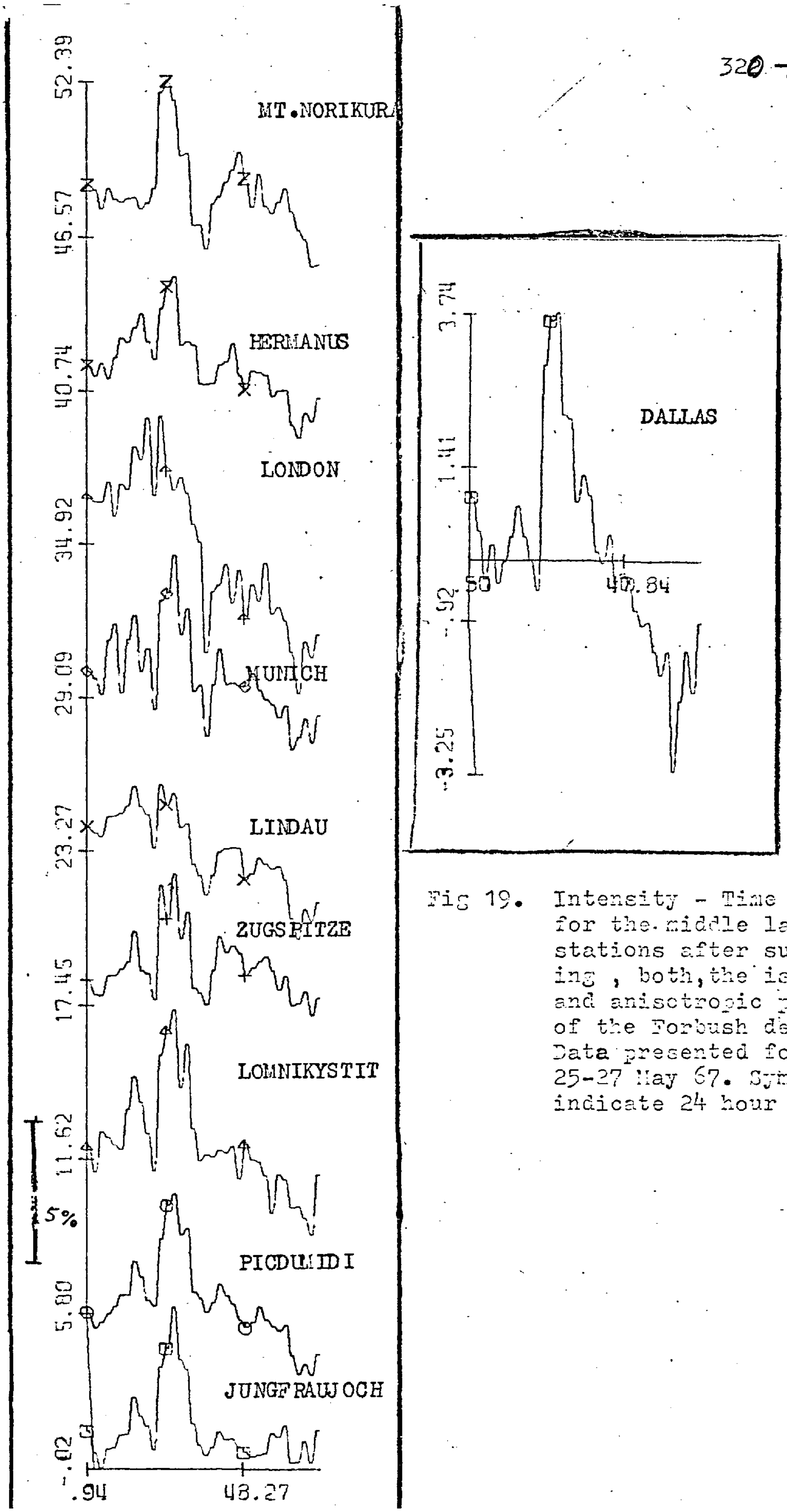


Fig 19. Intensity - Time profil for the middle latitude stations after subtracting , both, the isotropi and anisotropic parts of the Forbush decrease Data presented for 25-27 May 67. Symbols indicate 24 hour period

determined above. The Average increase(as summed over all the stations) reaches an amplitude of about 4.5% at the main phase of the storm. The maximum depression in the horizontal component during the main phase of the storm as measured at Honolulu and Guam was about 450 gamma.

7.4 RIGIDITY DEPENDENCE OF FORBUSH DECREASES.

7.4.1 Review of experimental results.

The rigidity dependence of Forbush decreases has been a subject of investigation for several years. The chief interest in such an investigation lies in the fact that it helps in determining a model for the modulation mechanism responsible for these events.

It in a quantitative representation of the rigidity dependence it is usual to attempt to fit the observed relative variations to analytical expressions of the form

a) $f(R) = AR^{-\gamma}$ model I (1)

b) $f(R) = -A \quad (R \quad Rmax)$ model II (2)
$\qquad\qquad\;\; 0 \quad (R \quad Rmax)$

where, R is the rigidity, f(R) the variational spectrum and A and γ are constants. Rmax in model II, is the upperlimiting rigidity up to which the modulation is operative.

In order to determine the rigidity dependence of the Forbush decrease one can rely on the latitude effect of the events, (the so called differential method).

However, this method will be able to provide information only for the rigidity range (0 – 20 Gv) below the equatorial geomagnetic cut-off. In practice, the method is most suitable for determining the rigidity dependence of events recorded by S/L and mountain altitude neutron monitors.

Alternatively, it is possible to calculate the decrease expected at a particular station for a given component with a knowledge of,

a) The differential response functions W(R), corresponding to the particular component being recorded.

b) The variational spectrum of the event, f(R).

c) The geomagnetic threshold at the station, R_o.

The relative variation $\delta I/I$ may then be written as,

$$\frac{dI}{I} = \frac{\int_{R_o}^{\infty} W(R)\ f(R)\ dR}{\int_{R_o}^{\infty} W(R)\ dR} \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

In practice the expected variations are calculated for stations at different latitudes and for different secondary components, using a particular form of the modulation function f(R). Since the ratios of the expected variations at any two stations will be independent of the arbitrary constant A, it is then possible, by comparing the observed ratios with the predicted values to fix, either, the exponent γ in the modulation function I, or the upperlimiting rigidity Rmax in the case of the modulation function II.

The application of this method, however, assumes that Ro remains constant during the perturbation and that the variation of the primary spectrum is isotropic. These requirements are however, a' priori not fulfilled for reasons detailed below.

1) As we have already seen in an earlier section, if the Forbush decrease is accompanied by a strong geomagnetic storm then a variation in the geomagnetic cut-off may occur. Therefore, one should be careful to use this method for geomagnetically clean events, in the case of stations for which the geomagnetic cut-off is greater than the atmospheric cut-off. This point has been pointed out by BACHELET et. al. (1963). On studying the spectral variations during Forbush decreases grouped into two classes according to the level of geomagnetic field fluctuations, they find systematic differences between the two groups of events. Furthermore, they find that the differences

vanish when tests independent of variations of the geomagnetic field are applied. KONDO et. al. (1959) have also suggested that the latitude dependence of the amplitude of the Forbush decrease arises from a superposition of two effects.
a) Spectral variations of primary cosmic rays impinging on the atmosphere and
b) decrease of the geomagnetic field occuring during strong geomagnetic storms associated with the Forbush decrease.

2) The discussion in section (i) of this chapter has clearly illustrated that anisotropies are frequently present during the recovery phase of the Forbush decrease, thereby invalidating the second assumption. Often these anisotropies last over a day or more and appear as enhanced diurnal variations. If this is the case an analysis using daily means (for determining the amplitude of the depression) will average out any contributions due to these anisotropies. On the other hand we have also noticed that sometimes these anisotropic variations last only for periods shorter than a day. In view of this it is important to normalize data from stations at different longitudes to a particular asymptotic direction, or cone of asymptotic directions, while evaluating the amplitude of the Forbush decrease.

Several workers have applied the methods detailed above to determine the law governing the rigidity dependence of the Forbush decrease. We give below some efforts in this direction.

McCRACKEN et. al. (1959, 1960) have analysed data for several Forbush decreases over the period 1956–58 and find that the rigidity dependence can be expressed by a power law of the form of equation I above, with the exponent $\gamma = 0.9$.

WEBBER (1962), has analysed eight large Forbush decreases occuring over the period 1956–1960. He finds that the rigidity dependence of the events occuring during times of solar maximum can be expressed by a power law with $\gamma = 0.5$. For events recorded during years near the solar minimum, however, the rigidity dependence obtained was much softer, with $\gamma = 1.0$. Webber has pointed out that such a change in the rigidity dependence can occur due to the following reasons.

a) As the 11 year modulation intensifies at times of solar maximum, more and more low rigidity particles are removed and therefore for a given rigidity dependence a smaller latitude effect will be observed, in the Forbush decrease amplitudes.

b) On the other hand the modulation due to the Forbush decrease mechanism itself appears to be less rigidity dependent at times of high solar activity.

FILIPOV and SHAFER (1963) on the other hand find that the rigidity dependence for 15 events during the I.G.Y. could be expressed by a power law of the form L with $\gamma = 0.8$. KUZMIN and KRIMSKY (1963) have analysed meson data collected by S/L and underground meson telescopes and find that their results follow a power law with $\gamma = 0.8$. On the other hand, DORMAN (1957) and SARABHAI et. al. (1961), interpret their results in terms of the modulation function II and suggest that Rmax has a value of about 40 Gv. DUTT (1965), has analysed data from underground meson telescopes at London along with data from S/L neutron monitors located at different latitudes and finds that for the period 1961-1963 the power law (with $\gamma = 1.0$) is able to explain the observations. On the other hand if an attempt is made to fit the data to the modulation function II then the Rmax values suggested by the observations are not consistent for the different groups of data.

7.4.2. EXPERIMENTAL RESULTS OBTAINED DURING 1966-67.

In the course of the present investigation we have studied the rigidity characteristics of several Forbush decreases recorded over the ascending phase of the present solar cycle during the years 1966-67. We have used pressure corrected data from a network of high, medium and low latitudes, high counting rate neutron monitors, along with data obtained from the NORTH/SOUTH telescopes at London and the EAST/WEST telescopes at MAKERERE, in this investigation. It is realized that the meson telescope data may be contaminated by temperature effects. However, since aerological data were not available for a correction of the bihourly values of the meson telescope data we have had to use data corrected only for pressure. However, by comparing pressure corrected and temperature corrected daily means it was found that no sudden changes associated with atmospheric temperature occured over the periods for which meson data has been used.

We have looked at the rigidity dependence of 5 events occuring during the 1966-1967 period. The main phase of the decrease corresponding to these events commenced on the following dates.

1) 23 Mar 1966.
2) 30 Aug 1966.
3) 23 Sep 1966.
4) 13 Dec 1966.
5) 13 Jan 1967.

All these events were in the class of moderately strong Forbush decreases during which a high latitude neutron monitor (DEEP RIVER) showed depressions of approximately 5% or more below the pre-decrease level. We have taken the mean intensity at each station for 24 hours before the epoch day as the pre-decrease level of the cosmic ray intensity. Data for the subsequent periods were normalized by taking this mean level as 100%. The intensity profiles for the events, observed by the different stations for which data is available are plotted in figure 20. From this figure it is obvious that the maximum depression has been registered by the high latitude station which has the lowest cut-off rigidity. The amplitudes of the depression are considerably lower for the low latitude neutron monitors and meson telescopes.

In order to determine quantitatively, the rigidity dependence during the events, we have calculated the ratios of the amplitudes expected in

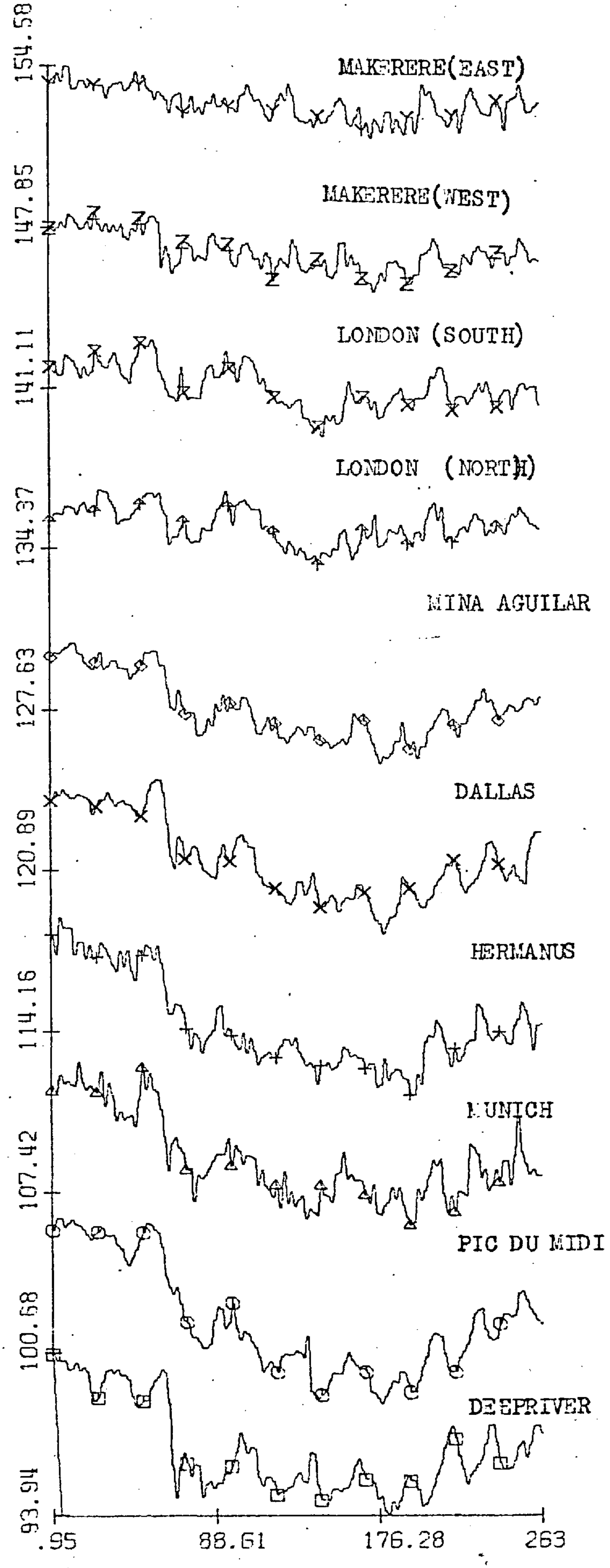
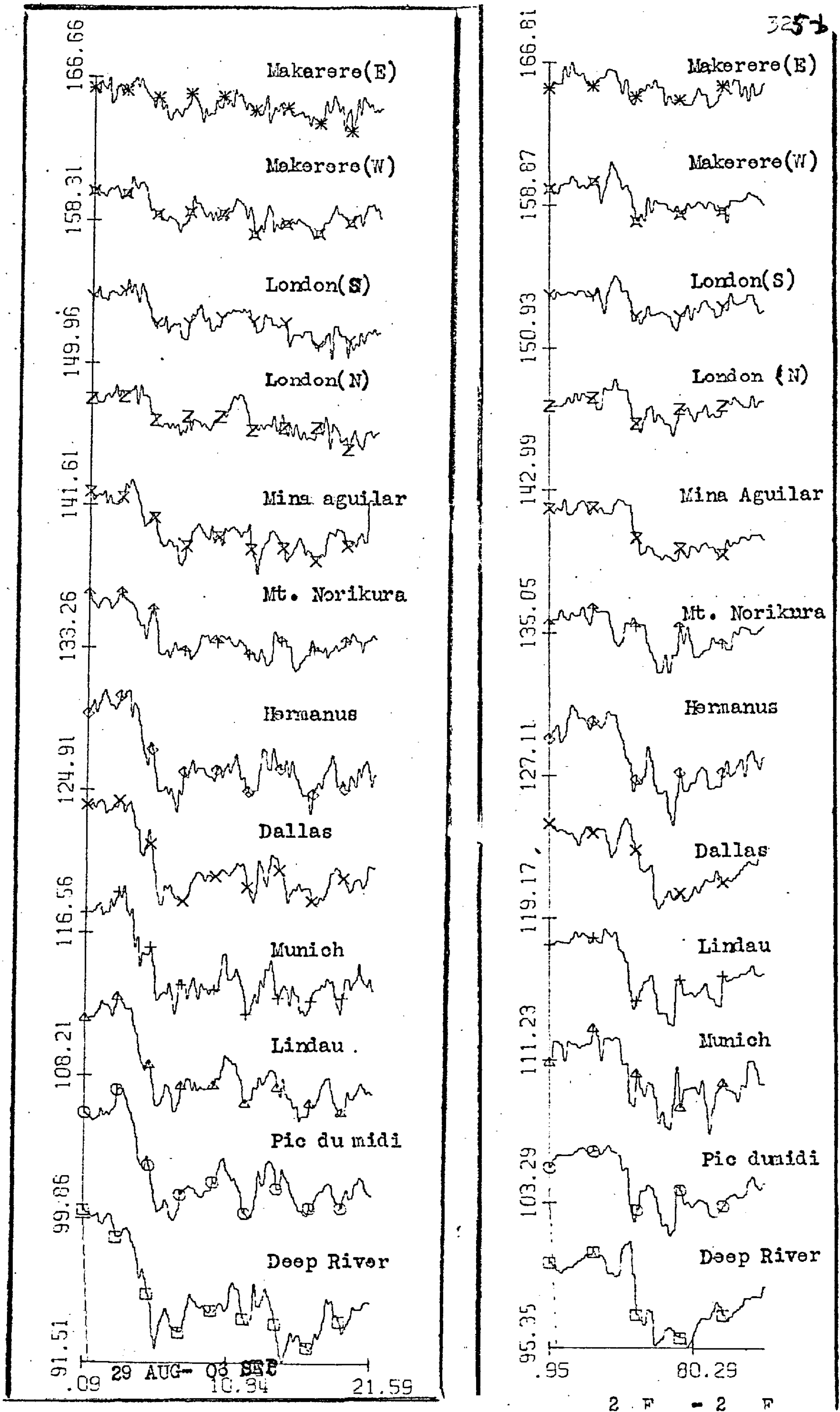


Fig 20.
Forbush decrease of 23Mar66.

Fig 20.
contd.


166.66
Makerere(E)
158.31
Makerere(W)
149.96
London(S)
London(N)
141.61
Mina aguilar
133.26
Mt. Norikura
124.91
Hermanus
Dallas
116.56
Munich
108.21
Lindau
Pic du midi
99.86
Deep River
91.51
.09
29 AUG- 03 SEP
10.34
21.59
166.81
Makerere(E)
158.87
Makerere(W)
150.93
London(S)
London (N)
142.99
Mina Aguilar
135.05
Mt. Norikura
Hermanus
127.11
Dallas
119.17
Lindau
111.23
Munich
103.29
Pic dumidi
Deep River
95.35
.95
80.29
2 F - 2 F

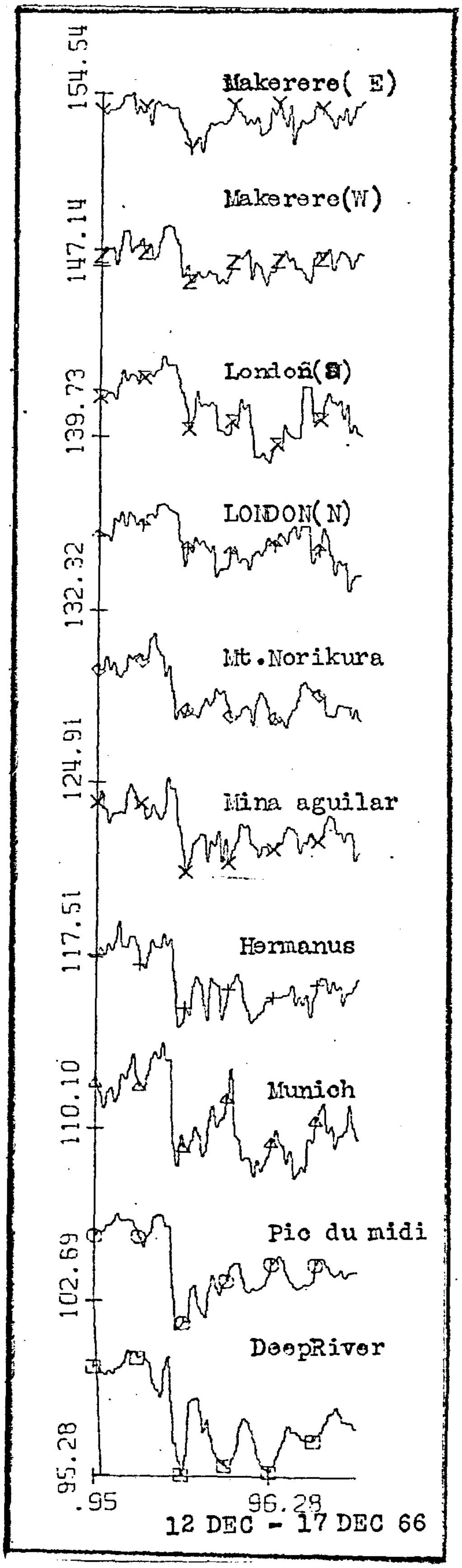


Fig 20.contd

Symbols correspond t
24-hour periods.

medium and low latitude neutron monitors and those expected in the meson telescopes at London and Makerere, relative to the amplitudes observed at Deep River (or KERGEULEN). We have used the modulation functions described by equations 1 and 2 of the previous section. In the first case we have calculated the expected ratios corresponding to several values of the exponent γ from 0.1 to 1.2. In the case of model II, we have used the upperlimiting rigidity Rmax as a variable parameter and have calculated the expected ratios, corresponding to several values of Rmax. In these calculations we have used the differential response functions given by LOCKWOOD and WEBBER (1966) for S/L neutron monitors and WEBBER (1963) for mountain altitude neutron monitors. For the case of meson telescopes we have used the differential response functions of KRIMSKY et. al. (1965). For the thresholds at these stations we have used the trajectory derived values of SHEA et. al. (1965, 68). We have considered vertically arriving particles only.

The results of these calculations have been plotted in figure 21 and 22 for models I and II respectively. By comparing the observed ratios with those predicted on the basis of either of these models we can attempt to fix the variable parameters namely, γ and Rmax.

As we have already noted, considerable anisotropies have been associated with some of the events for which we have carried out this analysis. Accordingly, care has to be taken by normalizing data to a particular cone of asymptotic directions while calculating the amplitude of the depression below the predecrease level. We have used the data from a series of high latitude neutron monitors to identify the cone of asymptotic directions which recorded the maximum depression. (As discussed in section 7.4.1.). We have then, used data corresponding to the same asymptotic directions for the other neutron and meson monitors as well. Normally while calculating the amplitude of the depressions we have averaged data for about 12 hours (corresponding to a hemisphere of asymptotic directions) over which the intensity was most depressed. (In most of the events the dimensions of the anisotropies were of about this magnitude). Furthermore, while calculating the ratios of the observed amplitudes we have used data from Deep River as the high latitude reference station, for stations in the American sector (e.g. MINA-AGUILAR, DALLAS, etc.), and data from KERGEULEN for stations in the European sector. This is so because the asymptotic cones in the two sectors are separated by about eight hours in longitude and the cosmic ray intensity may not be the same in directions corresponding to the asymptotic cones of detectors located in the two sectors. This is in fact the case for events in which considerable anisotropies were observed. (Since KERGEULEN and DEEP RIVER, both have a geomagnetic cut-off of about 1.1 Gv, the ratio of the expected decrease at the two stations will be 1 and we are justified in replacing one by the other for the purposes of our analysis. We feel that this proceedure is advisable for moderately strong Forbush decreases with which considerable anisotropies are associated. We have, in fact, found that if we use daily means in our analysis and use Deep River as the reference station for both the European sectors the observed ratios corresponding to a particular pair of stations vary widely from event to event. On the other hand, the choice of the proceedure detailed above results in a considerable reduction in the scatter of the observed ratios, for a pair of stations, for the five different events we have considered).

By following the proceedure detailed above we have calculated the ratios of the amplitudes observed at several medium and low latitude neutron monitor stations and meson telescopes (LONDON and MAKERERE) with respect to the amplitudes observed at Deep River (or Kergeulen). The pairs of stations and the corresponding ratio for the five different events are listed in the table 6. In view of the low scatter of the observed ratios for the different events listed we have calculated a mean ratio for all five events, (for a pair of stations) and compared this mean with the calculated values.

TABLE 6.

Ratios of Depressions observed at Various stations with respect to a high latitude station.

Stations	Event 23 Mar	30 Aug	22 Sept	12 Dec	12 Jan	Mean	Exponent
$\frac{\text{Picdumidi}}{\text{Kergeulen}}$	0.816	0.838	0.880	1.033	0.681	0.849	0.75 ± .06 1.15 ± .11
$\frac{\text{Munich}}{\text{Kergeulen}}$	0.700	0.797	0.861	0.670	-	0.757	
$\frac{\text{Lindao}}{\text{Kergeulen}}$	-	0.797	0.975	-	0.686	0.819	1.15 ± .11
$\frac{\text{Hermanus}}{\text{Kergeulen}}$	0.741	0.796	-	0.759	0.692	0.747	0.93 ± .05
$\frac{\text{Dallas}}{\text{Deep River}}$	0.638	0.640	0.865	-	-	0.714	1.14 ± .10
$\frac{\text{Mina Aguilar}}{\text{Deep River}}$	0.615	0.397	0.580	0.567	-	0.539	0.68 ± .04 0.68 ± .09
$\frac{\text{Mt Norikura}}{\text{Kergeulen}}$	-	0.477	0.631	0.504	0.734	0.586	
$\frac{\text{London (North)}}{\text{Kergeulen}}$	-	0.261	0.306	0.342	-	0.303	1.08 ± .10
$\frac{\text{London (South)}}{\text{Kergeulen}}$	-	0.275	0.338	0.269	-	0.294	1.10 ± .10
$\frac{\text{Makerere (W)}}{\text{Kergeulen}}$	0.195	0.244	0.282	0.297	-	0.259	1.05 ± .15
$\frac{\text{Makerere (E)}}{\text{Kergeulen}}$	0.214	0.216	0.255	0.330	-	0.253	0.88 ± .18

We have plotted the observed ratios at different stations (and for different components) in figure 21 along with the values expected on the basis of model I. (The errors are calculated on the basis of the counting rate). It is clear from this figure that the predicted values of the exponent χ for all the stations are in fair agreement. The figure indicates that the value of the exponent γ appears to be in the region of 0.7 to 1.1.

By a comparison with figure 22 which gives the values of the predicted ratios for the case of model II it appears that the predicted values of Rmax are less than about 30 Gv.

On the basis of the data presented above it is not possible to distinguish between the two models I and II. However, as mentioned in section 7.4.1. DUTT (1965) noticed an inconsistency in the values of Rmax predicted on the basis of neutron monitors. The values of Rmax for neutron monitors were found to be about 20 Gv while those for underground telescopes were about 100 Gv.

We have therefore examined records from underground meson telescopes operating at London (60 m.w.e.) corresponding to the period of these events. However, no depression could be observed within the limits of the errors, for any of these events. As mentioned in section 7.3 a large Forbush decrease was observed on the 25th May 1967 and the neutron monitor at Deep River recorded a depression of about 8% for this event. We have, accordingly, examined the data from underground telescopes for this period. It was observed that a depression of about 0.69% was registered in the temperature and pressure corrected daily mean intensity recorded by vertical meson telescopes underground on the 27th May, as compared to values of 2.35% and 2.19% for the meson telescopes (NORTH and SOUTH) at S/L and 6.89% at Deep River. (In each case the depressions have been calculated with respect to the intensity for five days before the epoch day). Since data from neither of these sources will be contaminated by geomagnetic field variations which also occured during these days, (since, in each case the geomagnetic cut-off is less than the atmospheric cut-off), we can use them to determine the rigidity dependence of the Forbush decrease, by comparing the ratios of the amplitudes observed by the S/L and underground meson with the predicted values of these ratios on the basis of model I and model II. The observed amplitudes are listed in the Table below, along with the parameters suggested by this data.

TABLE 7.

Station	Channel	Amplitude of depression.	Exponent predicted.	Rmax predicted.
London S/L	North	2.35% ± 0.02	1.0 ± 0.15	30 Gv ± 10
London S/L	South	2.19% ± 0.02	1.0 ± 0.15	30 Gv ± 10
Deep River	-	6.89% ± 0.01	-	-
London Underground	Vertical	0.69% ± 0.1	0.9 ± 0.2	100 Gv ± 20

(The values of the predicted ratios on model I and II, for the case of the Underground telescopes have been calculated by THAMBYAHPILLAI and DUTT (1965)).

In the case of model I we find on comparing the observed ratios with figure L that the exponent γ is about 1.0 for the S/L telescopes and underground telescopes as in fact we have found for the earlier period. In the case of model II however, the values of the parameter Rmax are about 30 Gv for the case of the S/L telescopes at London, while the values predicted by the underground telescopes are about 100 Gv. Thus it appears that the model II gives inconsistent results in so far as the values of Rmax seem to differ for the case of underground telescopes and S/L meson and neutron recorders. The model I, on the other hand gives consistent values of the exponent γ for all cases.

7.4.3. CONCLUSIONS.

The rigidity dependence of several Forbush decreases occuring over the years 1966–67 have been studied using data from a network of high medium

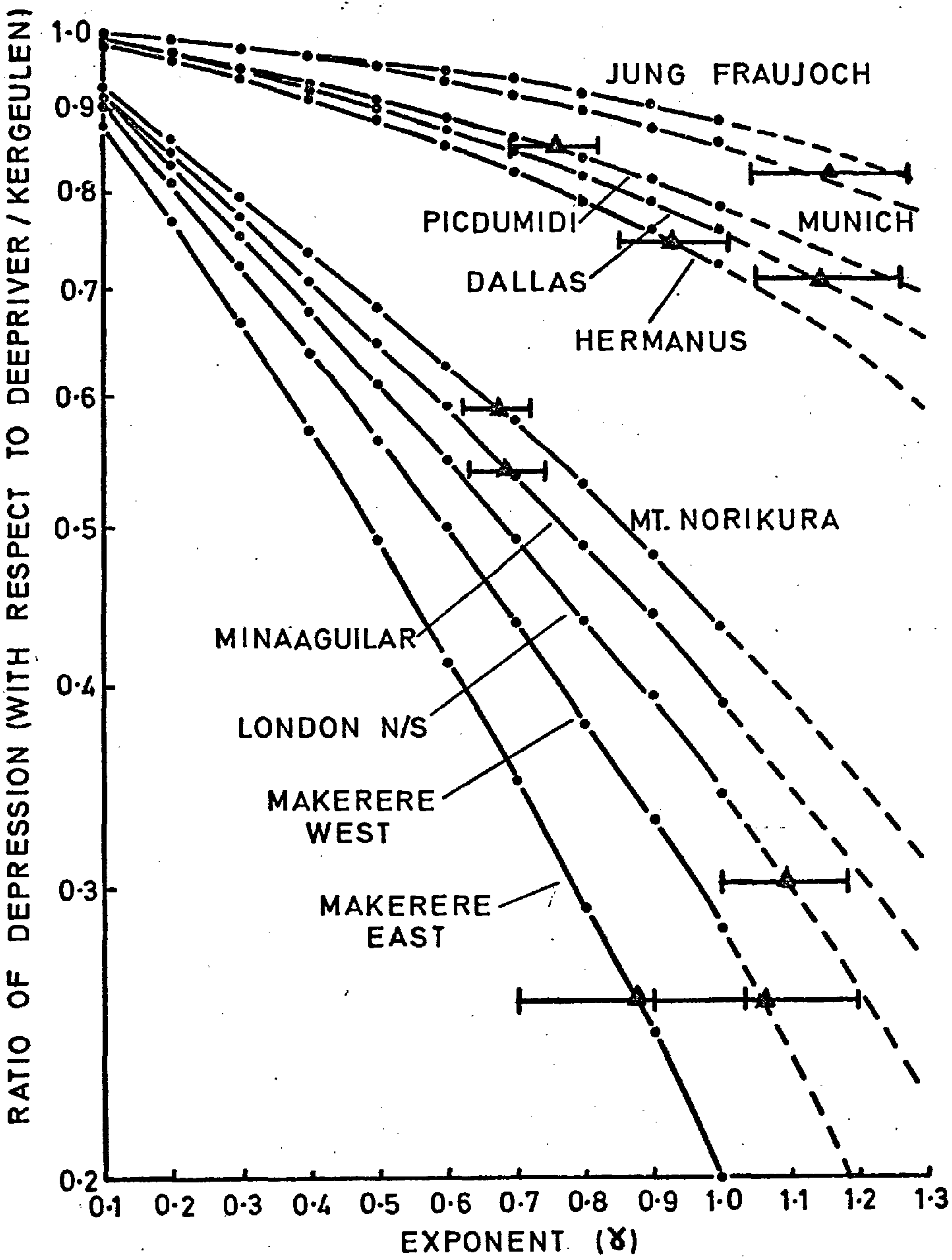


Fig. 29 - CURVES SHOWING THE EXPECTED VARIATION OF THE RATIOS BETWEEN INTENSITY VARIATIONS AT DIFFERENT STATIONS (AS INDICATED) WITH THE EXPONENT OF THE MODULATION FUNCTION. THE OBSERVED POINTS ARE ALSO PLOTTED.

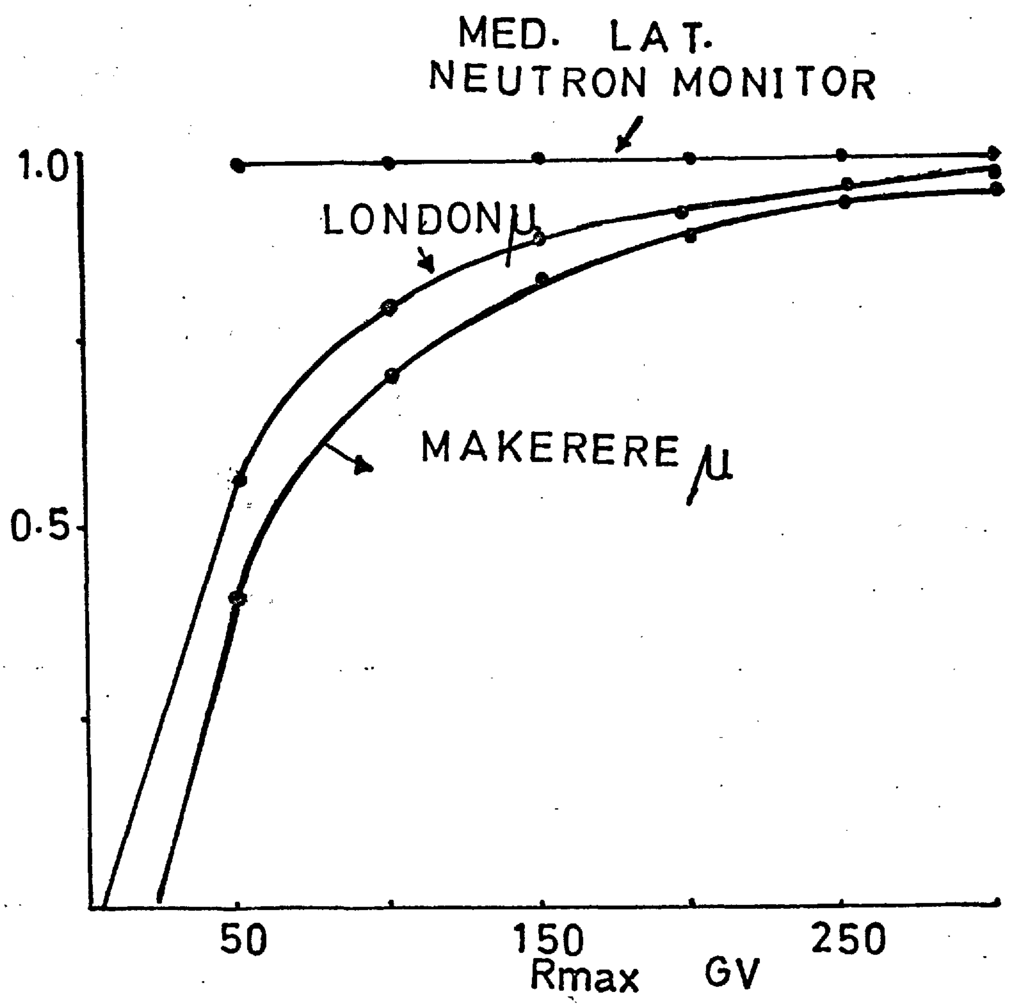


Fig 22 CURVES SHOWING THE EXPECTED VARIATION OF THE RATIOS BETWEEN INTENSITY VARIATIONS OBSERVED AT LONDON (μ), MAKERERE (μ) a MEDIUM LATITUDE NEUTRON MONITOR AND THOSE RECORDED AT DEEP-RIVER.

and low latitude neutron monitors and from the directional recorders operating at LONDON and MAKERERE. The proceedure adopted has been to compare the values of the observed ratios of the amplitudes of the event recorded by a particular recorded and a high latitude neutron monitor (after adequate care is taken to exclude effects due to anisotropic variations) with those expected on the basis of the modulation functions below:

$f(R) = AR^{-\gamma}$ model I

$f(R) = -A$ R less than or = Rmax
R greater than Rmax. model II

An examination of the rigidity dependence of five moderate events, during 1966-67 showed that the rigidity dependence can be expressed by model I with the exponent γ at about 0.70 - 1.1. These events could also be described in terms of model II with Rmax at about 30 Gv.

An analysis of the rigidity dependence of the large Forbush decrease observed on 25 May 1967, by means of data obtained from S/L and underground meson telescopes at London along with the data from a high latitude neutron monitor at Deep River showed that the rigidity dependence of this event could also be expressed in terms of model I with $\gamma = 1.0$ as in the case of the other decreases. In the case of model II it was found that the value of the parameter Rmax suggested by the underground data are about 100 Gv as compared to the value of 30 Gv suggested by the S/L meson telescope data. In view of this it appears that the modulation function II gives inconsistent results.

Values of the exponent (corresponding to model I) suggested by these results are in fair agreement with those obtained by other workers as discussed in section 7.4.1.

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