VARIATIONS OF UNDERGROUND COSMIC RAY INTENSITY WITH TIME

A Thesis

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ABSTRACT

The experiment, to be described in this thesis, was conducted at an underground laboratory at a depth of 70 m.w.e. below the top of the atmosphere in order to investigate the cosmic ray intensity variations with time. Six semi-cubic Scintillation Telescopes with an overall area of $\sim 8.9\ m^2$ and a counting rate of about 150,000 per hour were employed for this purpose.

The investigation of the atmospheric effects on the day to day changes in the cosmic ray intensity by correlation analysis yielded the following coefficients: the barometric coefficient, -.037% per mb; the positive temperature coefficient, +.041% per $^{\circ}C$ for the air between 200 and 70 mbs. No significant μ-e decay effect was detected. The decay coefficient was estimated to be about -.72% per Km.

The underground intensity was found to have an annual variation with a maximum in the summer months and an amplitude $\sim$ .33%, when the barometric and decay effects were removed. This variation could be explained as being due to the upper air temperature changes, but the positive temperature coefficient obtained was about 1.7 times larger than that for the day to day variations. The cause for this discrepancy is discussed. An approximate correction with Dorman's method, however, showed that the annual variation can be attributed entirely to the atmospheric temperature changes.

After the corrections for the atmospheric structure changes, small variations of primary origin in the underground intensity remained. A solar daily variation of small amplitude ($\sim$ .018 $\pm$ .004%, averaged over 1961-64) was obtained which was found to be consistent with a rigidity independent diurnal anisotropy having the higher cut-off at about 50 Gv.

A significant sidereal daily variation with an amplitude of ($.027 \pm .006$)% and the time of maximum at 19.40 hrs. L.Sid.T. was obtained. This result is

discussed in the light of some of the existing theories of the origin of cosmic rays and it is found that the sidereal anisotropy at these rigidities ($\sim$ 100Gv) is consistent with the galactic origin together with diffusion along the spiral arm of the Galaxy.

Individual and average characteristics of Forbush decreases observed at Holborn have been studied. The rigidity dependence of the events is found to favour a spectrum of primary variation with a simple power law in rigidity without any other constraints.[5]

The 27-day variations over the three years were studied and the rigidity dependences of Forbush decreases and 27-day variations were compared. These two variations appear to show different forms of rigidity dependence. The amplitudes of the 27-day variations showed a gradual decline over the years from 1961 to 1964.

All these results from the present experiment have been discussed in relation with those obtained by others and the areas of agreement and disagreement have been pointed out.

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CHAPTER I

INTRODUCTION

1.1 General Introduction

Many investigations of the time variations of the cosmic ray intensity have been conducted during the past few decades and it has become clear from these investigations that the galactic cosmic radiation is subject to modulation processes within the solar system. The primary cosmic rays are charged particles and it is the general belief that the modulation is achieved through the medium of plasma clouds carrying magnetic and, possibly, electric fields which are ejected from the sun. Thus a study of the time variations can assist in building up a picture of the electro-magnetic state of the interplanetary medium, although the best that has been achieved so far has been to consider some rather simple models of the interplanetary fields and to predict the effects on the galactic cosmic rays with a view to selecting that model which is in best accord with experimental facts. The demands made on the models have become more stringent when direct measurements of the characteristics of the interplanetary medium were made by instruments borne by satellites and space probes. One of the aspects where a comparison between theoretical prediction and experiment can be made is the rigidity or energy dependence of the modulation process.

However, the comparison of the theoretical prediction of the rigidity dependence of a modulation process and the observation is not straight forward because of several complicating factors. The most reliable information about time variations is provided by ground based detectors which respond to the secondary radiation generated high up in the atmosphere. Thus the variations recorded by these instruments reflect notonly the changes in the primary radiation

but also the changes in the parameters in the overlying atmosphere. Appropriate correction has to be applied to the data for the atmospheric changes and these corrections may be uncertain due to lack of accurate information regarding the atmospheric variables, particularly the temperature. This difficulty can be overcome by selecting a secondary component, such as the nucleon flux, which is not sensitive to the changes in atmospheric temperature. After the application of the corrections for the effects of the barometric pressure changes, which does not present any undue difficulties, variations recorded by neutron monitors can be assumed to represent the variations in the primary cosmic ray intensity. However, the entire energy spectrum of the primary cosmic rays which has access through the geo-magnetic field contributes to the counting rate of a neutron monitor and it is the overall changes due to the changes in a broad energy band of the primary cosmic rays that is recorded by a single instrument. It is, therefore, necessary to study the changes recorded by a chain of such detectors responding to different portions of the primary spectrum in order to arrive at the rigidity dependence of the variation. The earth's magnetic field can be employed as a magnetic spectrometer for this purpose.

The development and installation of the nucleonic detectors - the neutron monitors - throughout the world during IGY and afterwards were thus a major achievement in the studies of the time variations of cosmic rays. With the help of neutron monitors located at different latitudes, the primary variation in different rigidity ranges can be studied by using the geo-magnetic effect on cosmic rays. From the comparison of the primary variations recorded at different neutron monitoring stations, the rigidity dependence of the variations can be determined. Unfortunately, however, the neutron monitors have much

greater response at lower rigidities and the information furnished by neutron monitors is limited to a maximum rigidity of $\sim$ 25 Gv above which the response of the neutron monitors falls off rapidly. Meson telescopes working at sea level have maximum response up to about 40-50 Gv (for inclined directions), but to extend the range to higher rigidities the detectors should be placed under different amount of absorbers. The best one can do is to use the earth as the absorber i.e., the experiments should be conducted at different depths underground. The response characteristics of such detectors will be different from those of neutron monitors - the maximum response being shifted to higher rigidities as the depth increases. A neutron monitor at sea level and a meson telescope at a certain depth underground will record different extent of the same primary variation, so that a comparison of the variations recorded by these two recorders will give an idea of the rigidity dependence of the modulation process causing the particular variation. Therefore, an experiment conducted underground is of great importance in order to study cosmic ray variations in different rigidity ranges and to determine the extent of the rigidities up to which the modulation processes are operative. An adequate understanding of this problem has undoubtedly been limited by the lack of sufficient experimental data at rigidities between those obtained by ground level monitors and air shower detectors.

The experiments conducted underground (or at higher rigidities) is also important from another point of view. The underground measurements of the cosmic ray intensity variations over a long period of time can be used to study the long-sought sidereal daily variations. The results of the studies of sidereal variations from sea level measurements have in the past been inconclusive and

inconsistent, because of the larger variations of solar and atmospheric origin recorded by a sea level detector. The separation of the true sidereal variation from the spurious sidereal variation arising from the seasonal changes of the solar daily variation becomes difficult in this case. However, the solar and the atmospheric effects decrease as the mean energy of the recorded particle increases and hence a useful search for the sidereal daily variation can be made by using an underground detector.

With these aims in mind, an underground experiment at a depth of 70 m.w.e. below the top of the atmosphere was started in November 1960 at the Holborn underground station in the central London area with two semicubical scintillation counter telescopes. A preliminary study of the variations of the cosmic ray intensity during 1961 by Mathews (1962) revealed a sidereal variation of amplitude $\sim .052 \pm .015\%$, which was barely significant and no conclusion could be drawn as to the origin of the cosmic rays. In order to examine this, it was thought necessary to increase the statistical accuracy of the data. The detection area was, therefore, increased three-fold by installing six more new telescopes essentially of the same design as before but with improved efficiency and instrumental stability.

These improvements made during 1963-64 as well as the available data from November 1960 from the two old telescopes, made it possible to study the time variations of cosmic rays reaching a depth of 60 m.w.e. underground with great confidence. For example, with the three years' data available from the underground experiment, it was found that the sidereal effect, if it exists at all, could be detected with an accuracy of $\pm .006\%$. Furthermore, the solar

modulation of the galactic cosmic rays decreases with the decreasing solar activity, and hence, the approach of the minimum of the solar activity also presented an ideal condition for the detection of the sidereal anisotropy, in principle, by terrestrial measurements.

This thesis will describe the improvements made in constructing the six new telescopes during 1962-63 in the next chapter and the results obtained with these telescopes about the time variations will be presented in the subsequent chapters. In the study of some of the time variations (such as, solar and sidereal daily variations, Forbush decreases and 27-day variations), the data from the two old telescopes during 1961-62 will be used in order to increase the statistical accuracy of the data as well as to make comparison of the variations observed during different years (such as, in the case of 27-day variations).

With the higher accuracy of the data attained, it is aimed to make some useful determination of the rigidity dependence of some of the time variations (such as, in the case of solar daily variations and 27-day variations as well as in the case of Forbush decreases), by comparing the variations observed at sea level with neutron monitors at different latitudes with those observed with the meson telescope at Holborn.

1.2 The Composition and Energy Distribution of Primary Cosmic Rays

The composition of the primary cosmic ray flux at the top of the atmosphere has been determined by large number of balloon or rocket flights and recently by satellites. The chemical composition of the primaries in balloon flights are generally made first of all at the observation level and then extrapolated to the top of the atmosphere. From these studies it has now been found

that the primary cosmic ray flux consists of atomic nuclei with the atomic number Z extending from 1 to about 26 and perhaps more. The bulk of the primary flux is composed of protons amounting to about 85-90% of the total flux. The second abundant nuclei are the He-nuclei which account for about 13-8% (Winckler et al 1950; Singer 1958 and Waddington 1960). The rest of the nuclei above Helium comprise less than about 2% of the total flux. The present knowledge of the primaries other than atomic nuclei is quite rudimentary. The presence of about .6% of cosmic electrons above 1 Gv has been suggested by Critchfield (1952) and recent observation by Earl (1961) and Vogt et al (1961) have confirmed the existence of primary electrons in very small number. The existence of cosmic gamma rays above 10^{14} ev has been reported by Suga et al (1961) from air shower experiment as well as above 200 MeV by Kraushaar et al (1962) from the gamma ray astronomy satellite Explorer XI.

The most remarkable feature of this primary cosmic radiation is the enormous amount of energy stored in each nucleon - the energies extending from about .1 GeV (Neher 1957) to about 10^{9-10} Gev. This radiation may come from the sun or the Galaxy. Sun is a source of radiation with energies from about 100 Kev to Mev region (Meinal 1951, Meredith and Van Allen 1955) and can, on occasions of large solar flares, emit high energy particles which overlap the lower part of the cosmic ray spectrum. The differential rigidity spectrum of protons can be represented by a power law of the form $\frac{d\,J(R)}{dR} = K\,R^{-\gamma}$, where $\frac{d\,J(R)}{dR}$ is the differential primary flux of particles of rigidity R incident per sq.cm. per unit solid angle per sec.; K and γ are the constants. For solar flare particles, γ ranges from 4 to 6. For primary particles of galactic origin, the value of the exponent γ has been found to be about 2.5 from

rigidities about 1 Gv to higher rigidities; but there is some evidence that the slope of the rigidity spectrum gets steeper at higher rigidities approaching a value of about 2.8. Peters (1958) and Webber (1958) found that the different charge components have the same rigidity spectra as that of protons, while Singer (1958) has found that the spectrum may get steeper with increasing Z.

1.3 The Differential Response Curves for Different Types of Detectors

The different instruments located deep within the atmosphere record the variations of the secondary particles generated by the primary particles at the top of the atmosphere. It is, therefore, necessary to find the relationship between the primary radiation and their secondary components in order to transform the variations of the secondaries into those of the primaries. Neher (1952) first attempted to do this by introducing the idea of 'overall multiplicity', m(E,h), that gives the number of secondaries produced at a certain atmospheric depth, h, due to a primary particle of energy E. Simpson et al (1953) extended the idea to calculate the 'specific yield functions' for the neutron monitors and Fonger (1953) used these calculations to find the relationship between the variations of the secondaries and primaries. These relationships have also been estimated by introducing the idea of 'coupling coefficients' (Dorman 1957) or 'differential response curves' (Webber and Quenby 1959). These curves give the ratios of the particles recorded by the detector, originating from primary particles of a given rigidity, to the total counting rate of the detector. Hence with the help of these curves one can study the time variations of primary cosmic radiation recorded by a detector at a certain place as well as study the rigidity dependence of a certain variation by comparing the variations measured by different detectors, responding to different portions of the primary rigidity

spectrum. These curves are functions of the 'overall multiplicity' and the primary spectrum and an accurate knowledge of both of them is essential to calculate the response curves. Theoretical calculations are, however, difficult to make because of the uncertainties in the knowledge of the secondary processes. A simpler way to calculate such curves is to use the geo-magnetic effects on cosmic rays. The latitude variations of cosmic ray intensity up to rigidity of 15 Gv are known quite accurately from latitude surveys of Rose et al (1956) and others but for higher rigidities, it is necessary to extrapolate. Dorman (1957) and others have estimated the response curves for different detectors at different depths using threshold rigidities calculated from dipole representation of the earth's magnetic field. However, this dipole approximation has been found to fail to account for all geomagnetic effects (Webber and Quenby 1959) and recently Webber (1962) has given some more occurate response curves using threshold rigidities that have been calculated taking into consideration of quadrupole and higher terms as well as the effects of the penumbra. These response curves for neutron monitors at sea level, at mountain altitude ($\sim$680 gm/cm^2) and for meson telescopes at sea level, together with the empirically derived response curve for the underground detector at Holborn are given in Appendix II. Methods of calculation of the response curves from the geomagnetic effects have also been described there.

1.4 The Geo-magnetic Effects on Cosmic Radiation

The problem of the effects of the earth's magnetic field on cosmic rays is two-fold - (i) the problem associated with the determination of the magnetic cut-off rigidity i.e., the minimum rigidity of the particles that is necessary to arrive at a point on the earth and (ii) the problem associated

with the determination of the asymptotic direction of the particles at larger distances from the earth. In the determination of the primary spectrum and the differential response curves, an accurate solution of the first problem is essential. Similarly, in the study of the anisotropies of primary radiations, a knowledge of the trajectories of the particles with different rigidities arriving at various points on the surface of the earth is particularly important. The solution of these two problems rests on the preciseness of the data on the character of the earth's magnetic field.

The theory of motion of the charged particles in a dipole field was first developed by Stormer (1930) and later these calculations were extended to cosmic ray studies by Lemaitre and Vallarta (1933), who computed a large number of trajectories of the particles in the geomagnetic field. Experimental confirmation of these calculations, however, faced certain difficulties. It was soon discovered that the observed distributions of minimum cosmic ray intensity were different from those expected from the theory. The results from the world-wide latitude surveys with ionisation chambers and counter telescopes by earlier workers (such as, Johnson and Donald 1937, Compton and Turner 1937 and others) were uncertain due to uncertainties involved in correcting for temperature effects and, in fact, Maeda (1956) attributed the discrepancy to the temperature effect. However, more accurate and recent surveys with neutron monitors by Rose et al (1956), Kodama and Miyazaki (1957), Katz et al (1958), Storey (1959) and others showed that the discrepancy is a real one and does not arise from the temperature effects. Measurements of the cut-off rigidities by photographic emulsion techniques and counters (Waddington 1956, McDonald 1957) also showed that the observed cut-off rigidities at a certain place on the surface of the

earth were in error by more than 50% from the cut-off rigidities expected from the dipole model of the earth's magnetic field. Simpson et al (1956), Maeda (1958), Marsden and Wilson (1958) tried to explain the discrepancy by introducing eccentric or rotating dipole fields.but, even then, it failed to explain the large disagreement between the theory and observation. Later on Rothwell and Quenby (1958) pointed out that the discrepancy arises because of the difference between the earth's real field and the eccentric dipole field approximations. Quenby and Webber (1959), Kellogg and Schwartz (1959) calculated new values of cut-off rigidities taking into account of the higher order harmonics. Recently, Quenby and Wenk (1961) introduced further correction for the effect of the penumbra into the calculations of Quenby and Webber. These new values of the cut-off rigidities have been found to be in reasonably better agreement with the observations than hitherto, though certain discrepancy still exists between the calculated and the observed values.

The asymptotic directions of approach of the charged particles arriving in a given direction at the surface of the earth have been determined by scale model experiments by Brunberg and Dattner (1953), Jory (1956) and others. These trajectories have also been calculated numerically from the integration of the equations of motion by several workers (Firor 1954, Lust 1957 and others). The diagrams, showing the trajectories as functions of the particle energy and zenith angle of incidence at any one latitude, enable one to study the anisotropies connected with solar daily variations and to determine the direction of the anisotropies in space. McCracken (1962) recently has pointed out the limitations of the earlier calculations that were made by assuming a dipole structure of

the earth's magnetic field. McCracken et al (1962) have calculated the asymptotic directions of approach of cosmic ray particles for large number of existing cosmic ray detectors, representing the earth's magnetic field by the first six spherical harmonics and introducing the corrections for the finite widths of the asymptotic cones of acceptance of the detectors. Rao et al (1963) have claimed that these calculations give consistent results about the diurnal anisotropies observed at the earth.

1.5 The Time Variations of Cosmic Ray Intensity

(i) Variations of atmospheric origin

The atmospheric effects on the cosmic radiations observed with detectors deep within the earth's atmosphere are now well understood. The development of this was closely related to the development of our knowledge of the secondary particles which are generated by the interactions of the primary particles with the air nuclei. The primary cosmic ray particles entering the atmosphere initiate nucleon-nucleon interactions with the air nuclei giving rise to nuclear cascade showers. The resultant particles of these interactions are: the energetic nucleons, $\pi^{\pm,0}$-mesons and other higher mesons (such as K-mesons which, however, decay to charged pions and muons within a very short time $\sim 10^{-11}$sec The neutral pions decay into two quanta of photons within about 10^{-16}sec. The charged pions have, however, a relatively longer life ($2.6.10^{-8}$sec) and they can either decay to charged muons and neutrinos or be captured in further nuclear interactions. The secondary nucleons cause further nuclear disintegrations until the end products attain such energies that they are no longer capable of initiating any more nuclear interactions. The charged muons have a life time of about $2.2.10^{-6}$sec and are nuclear inactive. They can either decay to electrons

and neutrinos or be stopped in passing through matter, losing energy mainly by ionisation. Therefore, the electron-photon (soft) and muon (hard) components (constituting the bulk of the cosmic radiation at sea level) as well as the nucleonic components (consisting of protons and neutrons) are the secondary particles that are recorded at the surface of the earth by different detectors.

The studies of the atmospheric effects by Duperier (1944, 1948, 1949), Dorman (1957), Maeda and Wada (1954) and others have established that the soft and nucleonic components are affected only by the changes in the sea level pressure. But for the hard component, there are two other atmospheric effects in addition to the barometric effect - the positive and negative temperature effects which have to be taken into account (Duperier). The negative temperature effect arises due to the increase in height of the layer of the production of muons due to the increase in temperature (μ-e decay effect) and the positive temperature effect arises due to the reduced probability of nuclear capture of pions and increased probability of $\pi - \mu$ decay with the increase in the atmospheric temperature.

These atmospheric effects will cause day to day changes as well as the seasonal changes in cosmic ray intensity.

(ii) Variations of cosmic ray intensity due to changes in the primary flux

The variations of cosmic ray intensity of primary origin may be conveniently divided into two groups:

(a) the variations of solar origin - which may be caused either by the modulation of the primary cosmic ray flux of galactic origin within the solar system or by the production of cosmic rays on the sun during large solar flares, and

(b) the variations of galactic origin - which manifests itself as the sidereal

diurnal anisotropy of the cosmic ray flux of galactic origin. As yet there is no reliable evidence available about any anisotropy of extra-galactic origin.

(a) Variations of solar origin - Of the different types of time variations in cosmic ray intensity caused by the modulation processes occurring within the solar system, the solar daily variations, the 27-day variations and the Forbush decreases have been discussed in great detail elsewhere in this thesis. The long term changes due to the 11-year cycle of solar activity as well as the short term changes due to the solar production of cosmic rays do not form part of the subject matter of this thesis, for the obvious reason that the experiment is in operation only for about three years and the solar flare effects do not produce particles with energies with which we are concerned here. Since the discussion of these variations may have some bearing on what may follow, we shall describe in short some of the important features of these two types of variations.

Variations of cosmic ray intensity with a period of 11 years in anti-correlation with the sunspot numbers of solar activity were first demonstrated by Forbush (1954) from the study of the long term records from the Carnegie Institution Stations. The annual mean intensity from these stations were found to change by about 4% from the sunspot maximum to the minimum. Evidence from the neutron monitor data for the last decade shows that the corresponding variation in neutron intensity for a high latitude station may amount to about 25% (Webber 1962). The 11-year variations of cosmic ray intensity at high altitudes have been measured by extensive series of balloon flights (McDonald and Webber 1959, Winckler 1960, Neher and Anderson 1962 and others) as well as by aircraft flights (Meyer and Simpson 1957). From these studies Forbush (1958), Neher and Anderson

(1962) found that the cosmic ray intensity changes lag a year or more from being anti-correlated with the sunspot numbers implying that the 11-year solar cycle variation is due to the solar plasma that extends to several astronomical units out into the solar system. It is also found that the high energy particles attain the maximum and minimum intensity a year or two earlier than the low energy particles, implying that while modulation processes cease for high energy particles, the low energy particles are still modulated and, in fact, probably the modulation process never ceases for the galactic particles of very low energy (Simpson 1963). The rigidity dependence of the 11-year variations and Forbush decreases have been compared by several workers in order to examine whether the same modulation mechanism is responsible for these two variations or not. Fenton et al (1958), McCracken (1960), Kuzmin et al (1963) found different rigidity dependence for the two variations, while Lockwood (1960), Webber (1962), Nerukar and Webber (1964) have found similar rigidity dependence for both variations. Recent study of the long term variation and its rigidity dependence has shown that the recovery and decrease phase of the 11-year cycle of the cosmic ray intensity have different rigidity dependence - the dependence being smaller during recovery phase (Simpson 1962). This has also been confirmed by Lockwood and Razdan (1963a), Hatton and Marsden (1963). Lockwood and Razdan also investigated the Forbush decreases to find whether this effect is observed during such events. They have found that some Forbush decreases may show different rigidity dependence during recovery and decrease phases but others show identical rigidity dependence.

As distinct from these modulation effects, the sharp increases in cosmic ray intensity (increasing many-fold above the normal level) following a large

visible solar flare have been observed several times in the past and studied in great detail recently, (Elliot 1952, Carmichael 1962, Webber 1962, Dorman 1963). A typical solar flare increase is characterised by rapid rise of intensity within a few minutes, followed by a slow exponential decay to the normal level over a period of several hours. Studies of the events show that protons are produced in the solar flares and extend in energies from few GeV to a fraction of one MeV. The particles have been found to arrive, on certain occasions, at the earth with a time nearly equal to that expected from the rectilinear transit from the sun to the earth. On other occasions, the particles are found to be delayed in transit, arriving later at the earth isotropically. Therefore, the transit time and the direction of arrival of such particles can furnish important information about the configurations of the interplanetary magnetic field, the acceleration and escape mechanisms in solar flares. The development of our knowledge of the interplanetary magnetic field will, in fact, depend on the proper understanding of the solar flare events.

(b) Variations of galactic origin - Since the variations of cosmic ray intensity with sidereal time is expected to give fundamental information about the origin of cosmic rays, many attempts have been made to find such a variation. The historical development and the present state of our knowledge of the sidereal daily variations will be discussed in Chapter VI, where the experimental results from the present experiment about the sidereal daily variation and the possible sources of cosmic rays with rigidities $\sim$100 Gv will also be discussed.

1.6 Modulation Theories of Galactic Cosmic Rays

Many models of modulation mechanisms in the past have been proposed to explain the variations of galactic cosmic rays as measured by detectors at the

earth. Webber (1962), Dorman (1963) and Quenby (1964) have given a comprehensive account of different models proposed so far and have critically examined them in the light of the recent observations. For example, there have been (i) energy modulation theories - the modulation being caused by the static geo- or helio-centric electric field (Nagashima 1951, Ehmert 1960), by the inverse Fermi mechanism of deceleration of galactic cosmic rays (Singer 1958) and by the solar corpuscular beam (Alfven 1954, Dorman 1957, 1963) as well as (ii) the magnetic field modulation theories - the modulations in this case being caused either by ordered magnetic field configurations (Davis 1955, Gold 1959 and Elliot 1960) or by disordered magnetic field configurations (Morrison 1956 and Parker 1958). Some of these models try to explain all the different types of variations observed, while others try to explain one or two types of variations. The energy modulation theories and the ordered magnetic field theories cannot be reconciled with the experimental evidence, now available from cosmic ray observations as well as from the direct measurements of the solar plasma and the magnetic field in the interplanetary space with space probes and satellites (Webber 1962, Quenby 1964).

It has now been found necessary to reconsider the models in the light of the advances made in our knowledge of the solar plasma and interplanetary magnetic field. Recent observations with these new devices have helped to find cosmic rays and their time variations deep in the interplanetary space. The first successful attempt to measure the solar plasma was made by the Russian workers with ion traps installed in the Lunik space probes (Gingauz et al 1960). Several American space vehicles such as Mariner II (Snyder et al 1963) and Explorer X (Bonetti et al 1963) also measured the ion flux in the interplanetary

space. A prevailing magnetic field of about 5-10 γ has been found in the interplanetary space by Pioneer V (Coleman et al 1961). From these studies it has now become clear that the solar plasma (or the solar wind, as it was called by Parker 1958) is found to flow continuously with a velocity of about 300-700 km per sec.

The modulation mechanisms affecting cosmic ray variations are, therefore, essentially dynamic and connected with the magnetic field movements in the interplanetary medium. Parker (1958) first predicted the existence of the solar wind originating from the continual expansion of the corona of the sun and proposed a model of modulation of cosmic rays by the solar wind into which various types of kinks are introduced. Since this model seems to be more realistic than the others we shall describe this model in some detail.

According to the picture envisioned by Parker the corona is almost stationary in the vicinity of the sun, but because of the high temperature of the corona ($\sim 10^{6^\circ}$ K) near the sun, when the distance increases the pressure within the corona overcomes the weight of the gas and rapid expansion takes place. The coronal gas is accelerated gradually and eventually becomes a high velocity plasma stream. This solar wind, as he called it, carries with it the general field of the sun (since the gas pressure exceeds the magnetic pressure of the general solar field) and essentially leads to a radial field in the inner solar system. Due to the rotation of the sun, however, the field, carried out by the solar wind, would take a spiral form. The density of the solar wind falls off in proportion to the sq. of the distance from the sun and eventually the wind becomes so tenuous that it is stopped by other thinly dispersed gases and the magnetic field of the interstellar space. From the density of the solar wind (as measured by space probes) and the resisting

magnetic field at a certain distance, Parker (1964) calculates that the solar wind may extend from 12 to 160 A.U. from the sun.

The wind becomes turbulent beyond a fraction of an A.U. due to the growth of instabilities of the outflowing solar wind and the consequent disordering of the frozen-in magnetic field. The outward motion of the disordered part of the solar wind presents a barrier to the incoming cosmic rays. Cosmic rays will be swept away ahead of such wind so that the intensity inside the barrier will be less than outside. This will give rise to the 11-year variation in cosmic ray intensity due to the change in the strength of the wind as well as the strength and thickness of the associated barrier with the 11-year cycle of the solar activity. This model of modulation of galactic cosmic rays by the solar wind appears to have consistent spatial and time scale characteristics to explain the 11-year variation but the rigidity dependence predicted by the model appear to be greater than the observed value (Dorman 1963). Dorman therefore, introduced certain modifications into this model by considering the different scales of the magnetic inhomogeneities (as compared to a fixed value of 2.10^{11}cm used by Parker) and different path length for the scattering of the particles by the inhomogeneities. He found that below a certain rigidity R_{max}, which will depend on the size and strength of the inhomogeneities in the modulating barrier, the spectrum of the primary variation may be written as,

$$f(R) \propto R^{-1}, \quad R < 60 \text{ Gv}$$
$$\propto R^{-2}, \quad R > 60 \text{ Gv} \qquad \ldots\ldots\ldots \qquad 1.1$$

With these modifications introduced, Dorman found a good agreement of the prediction of the solar wind theory with the observations in the entire range of experimental data. The different rigidity dependence of the recovery and decrease phase of the 11-year variation has also been found to be consistent with this theory, if the thickness of the barrier is assumed to be of the order of

20-50 A.U. (Hatton and Marsden 1963). The rigidity dependence of 11-year variation, according to this theory, is different for different charged particles. McDonald and Webber (1962) have found that this prediction of charge dependence of 11-year variation is not in agreement with the observations. Komori (1963) however, has found that the Light and Medium nuclei display different rigidity dependence in agreement with the prediction of the modulation mechanism by solar wind.

Parker (1961) has also put forward some explanation for the solar flare increases and the storm decreases of galactic cosmic rays on the basis of his solar wind model. He assumes that the solar flares eject solar material at velocities $\sim$ 1000 km/sec. and generate shock waves which propagate ahead of the solar material. The quasi-radial magnetic field which is embedded in the interplanetary plasma are sheared by the passage of this shock wave. This will generate an expanding shell of magnetic kinks. Parker has calculated that the particles are restricted in their passage through this kink so that when the shock fronts have passed the earth a reduction in cosmic ray intensity will occur.

Similarly, if a shock wave propagates through a plasma containing frozen-in magnetic field, still loaded with solar particles ejected from a solar flare, the solar particles will still be embedded in the magnetic field while it is being absorbed in the shock. There will, therefore, be an increase in the measured flux when the shock passes through the detector.

Ahluwalia and Dessler (1962) extended the idea of the solar wind modulation theory to explain the daily variation of cosmic ray intensity and attributed the diurnal anisotropy to the spiral magnetic field of the solar wind. Their calculations predicted that the diurnal amplitude should increase with the solar wind velocity. The direct measurements with Mariner II (Snyder et al

1963) are, however, in disagroement with this prodiction. But it is to be pointed out that Ahluwalia and Dessler assumed a very simple case of solar wind that is moving outward in a smooth manner. Since there is indication that the solar plasma does not have in general the ideal uniformity as assumed by Ahluwalia and Dessler, it is at present very difficult to verify the relationships predicted by a model of corotation of the spiral magnetic field of the solar wind. It is, therefore, clear that though the solar wind model seems to be realistic and can explain some of the time variations qualitatively, the quantitative aspects of the model are by no means in agreement with the observations (Quenby 1964) and have still to be investigated and tested before one can understand the modulation mechanism by the solar wind.

However, it must be admitted that the continuous outflow of solar plasma with variable velocity and inhomogeneous plasma density must be an integral part of the model of the interplanetary space and the modulation processes existing within that space. No model, capable of explaining all the facts about the time variations of cosmic ray intensity observed at the earth, has yet been proposed.

CHAPTER II

EXPERIMENTAL METHOD

2.1 Introduction:-

In a study of the time variations of cosmic ray intensity, a continuous and unbroken record of the intensity is essential. It is also necessary to extend this recording over a long period of time in order to smooth out the uncertainties arising from short-term intensity variations associated with atmospheric and geomagnetic effects. All these conditions introduce the extremely difficult problem of maintaining the efficiency of the instrument constant over long intervals of time. Considerable care should, therefore, be taken from the beginning in designing such a detector with a view to achieving long term stability.

The second important point one has to take into account, specially, in designing a detector intended for use at an underground laboratory is that the variations one wishes to study at these rather high energies are themselves very small, some being of the order of a few hundreths of a percent. In cosmic ray phenomena statistical considerations become very important and to study small short-and long-term effects we need a sufficiently large detector so that the errors of statistical origin are at least several times smaller than the actual effects. The vital importance of improving the statistical accuracy of the measurements has been demonstrated by the earlier works of MacAnuff (1951) and Mathews (1962).

In addition to these difficulties it is necessary to ensure that the periodic variations measured by the instrument, particularly those with the period of a solar day, are free from the influence of other factors which exhibit the same periodicity, such as, mains voltage variations and changes in environmental temperature. Steps have been taken to ensure that the mains voltage applied to the detectors was constant to a high degree of accuracy and tests carried out to make certain that the sensitivity of the instruments to changes of environmental temperature was not appreciable.

In the following sections, we shall first describe the advantages of using plastic scintillation detectors, their constructions and different precautions we have taken in order to obtain maximum efficiency and a high degree of long-term and short-term stability, followed by a critical evaluation of possible errors arising from different sources. This last consideration is vital in claiming the significance of any result.

2.2 Choice of the Detector

Any system, concerned with nuclear particle detection, depends on the effects of the collision processes initiated by the passage of a charged particle through matter enclosed in a specified sensitive volume so that with suitable counting or measuring systems, one can either count the passage of each particle or measure other physical charactoristics of the particles. The ideal state of affairs for an experiment concerned with the continuous counting of the integrated flux of the particles within a certain time interval will be to count each and every particle passing through that volume as efficiently as possible. Ionisation chambers, Geiger-Muller counters and Proportional counters have been successfully used in this kind of investigation of cosmic rays. In early work the ionisation chamber

served as an important instrument for the study of the time variations of cosmic ray intensity; but it is essentially an omnidirectional instrument and its maintenance and constructional difficulties, together with its comparatively long time-constant ($\sim$1 μsec.) make it unsuitable for our purpose. Geiger-Muller or Proportional counters are, however, easier to maintain and with the aid of coincidence circuits can be used in the form of a Telescope, so that the particles arriving from a restricted cone of directions are accepted by the detector system. Besides, the use of the coincidence circuit makes it possible to isolate successfully the background radioactivity from the cosmic ray flux.

These advantages of G. M. Counters are to some extent offset by the inherent defect that external quenching is required in order to extend the working life of the G. M. Counter to a sufficiently long period of time. Even then, the gas multiplication decomposes the quenching vapour molecules, so that the counter characteristics change with time, the threshold rises and eventually the counter becomes unserviceable.

The use of scintillation and Cerenkov detectors has recently become important in the study of nuclear physics and the continuous recording of cosmic rays, mainly because of their high efficiency, reliability and the extremely high resolution in time which is obtainable.

Scintillation radiation is generated when a charged particle passes through certain materials called 'fluors' or more generally 'scintillators'. The maximum emission of light occurs in the blue range of the visible spectrum and with suitable light guide to focus the light on a photomultiplier tube (having maximum sensitivity for this range of light) one can construct what is called a Scintillation detector. The P. M. tube

converts this light into electrons and multiply them inside the tubes, so that a high voltage output is obtained whenever a charged particle passes through the scintillator. The output scintillator emission depends on the degree of ionization and no such limitation as the velocity condition in Cerenkov detectors is imposed in this case.

Two scintillation counter telescopes of semi-cubical geometry have already been developed at Imperial College by Mathews (1963), and the reliability and satisfactory performance of, at least the Scintillator-P.M.-tube combination have been established, even though the associated electronic system exhibited long term drifts which made the data unsuitable for an analysis of the seasonal variation. Moreover, the stability of the detector against changes of environmental temperature had never been tested.

Under the circumstances, it was decided to construct the proposed six new telescopes incorporating some of the basic design adopted by Mathews but modifying the associated electronic system, testing its stability against temperature changes at all stages and incorporating safeguards to ensure the long term stability of the detector. In the meantime, P.M. tubes of improved design and scintillators of superior characteristics became available in the market and this opportunity of including these improved versions in the detector was exploited fully.

2.3 The Basic Principle and Design Considerations of a Scintillation Detector

The basic components in a scintillation detector. consist of the scintillator, a P.M. tube and a suitable light guide which would direct the photons from the scintillator on to the P.M. tube, all enclosed in a container box. This container box must be light-tight and should be free from moisture in the case of hygroscopic scintillators being used. The combined

characteristics of the P.M. tube, the scintillator, the container box and, of course, the electronic system, will determine the final build up of the output pulse and the overall efficiency of the system.

It has been shown by Swank (1954) that the pulse-height of the output voltage of such a system is given by,

$$V_{out} = \frac{N.f.S.E.G.}{C} \gamma^{\frac{1}{1-\gamma}}$$

$$= \frac{N.f.S.E.G.}{C} \text{ , if } \gamma \gg 1 \qquad \ldots\ldots\ldots 2.1$$

where, $\gamma = RC/\tau$, the circuit constant over the decay time of the fluorescence;

N = the total number of photons emitted by the scintillators per passage of a charged particle (depends on the scintillator characteristics)

f = the fraction of the emitted photons which is collected at the cathode of the P.M. tube (depends on the geometry of the container box and the light-guiding system inside it)

S = the average photo-sensitivity of the P.M. tubes (depends on the secondary emission characteristics of the photo-cathodes)

E = the collection efficiency of photo-electrons in the dynode system of the P.M. tube (depends on the design, magnetic shielding and focussing mechanism in the dynode chain of the P.M. tube)

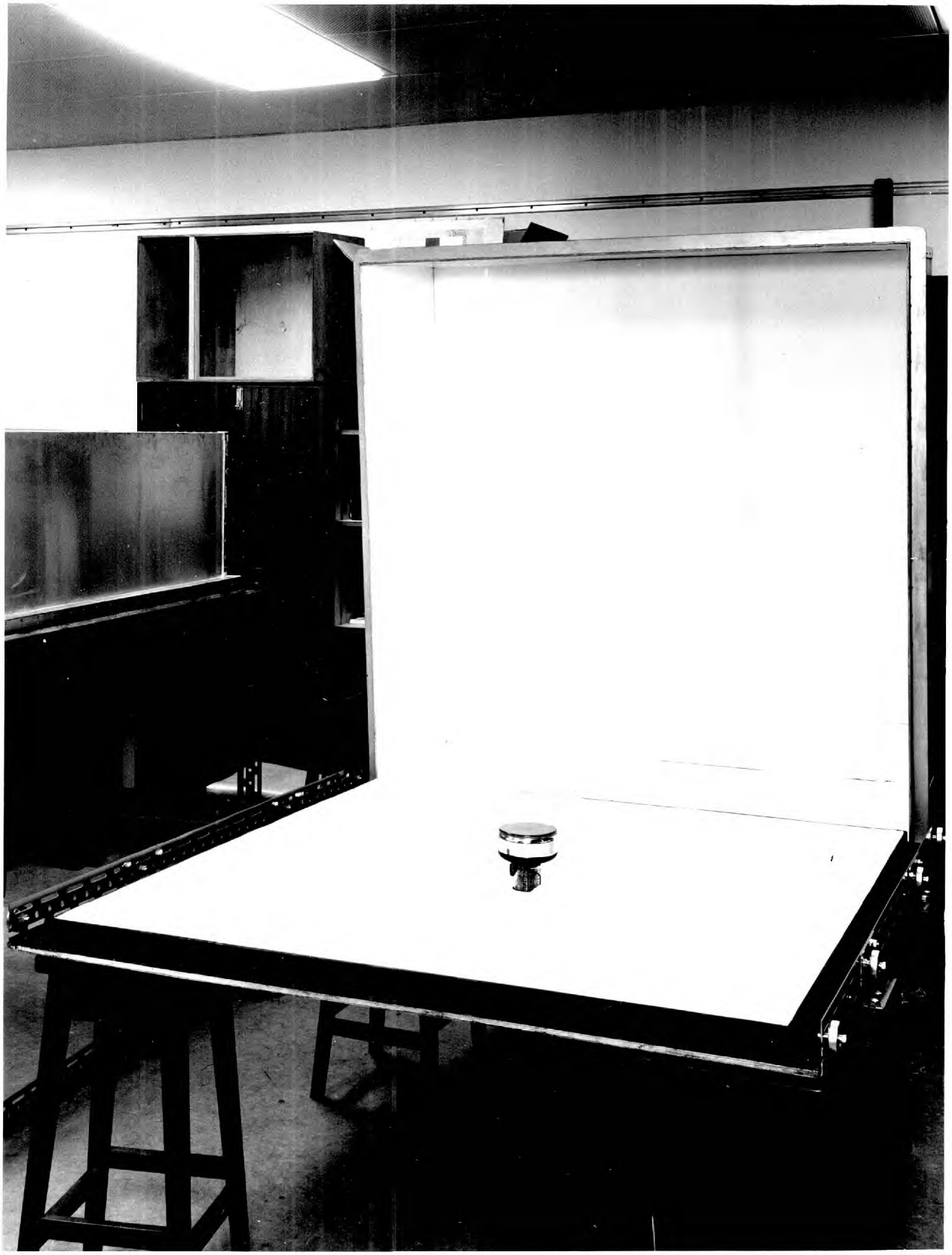
G = the overall gain of the P.M. tube at the operating voltage (depends on the number of dynodes and design of the P.M. tube)

It can be seen from eqn (2.1) that except the factor, f, all others are predetermined by the P.M. tube and scintillator characteristics. So, the best one can do is to select suitable P.M. tube and scintillators to ensure V_{out} as high as possible.

The factor 'f', which is within the experimentor's control, should be as high as possible. In practice, a satisfactorily high value of 'f' is not realisable in a large area detector where it is necessary to allow the photons to diffuse inside the detector volume before reaching the photo-tube. A complicated light-guiding system is likely to be costly, the reflectivity of the container wall cannot be perfect and there is the added problem of handling. Hence a compromise solution is generally reached where 'f' is allowed to have such a value that a large fraction of the V_{out} from other factors is sacrificed and still the electronic circuit is capable of detecting the signals without the necessity of amplifying them.

2.4 Design of the Scintillation detector

The basic details of the construction of the scintillation detector used in the present experiment can be seen from Plate 2.1 where the container box has been left open to show the interior. The base of the box is made of wood in the form of a tray, the internal measurement being 54" x 54". The lid of the box, which can be fitted tightly with the base and removed when necessary, is made of Aluminium and has the measurement 54" x 54" x 17". The upper face of the base and the inside of the lid are coated with a diffusive reflector called 'Darvic'. Four scintillator slabs are laid out along the edges of a square inside the tray and have their highly polished surfaces facing upwards. A P.M. tube which is placed at the centre of the box and is surrounded by the scintillator slabs, looks upwards with its 5" photo-sensitive cathode exposed to the lid. The diffusive reflector coating on the lid serves as the light-guide between the scintillator and the P.M. tube in the present case. A more detailed description of the various components will be given in the following sections.



2.4a Scintillators:-

Scintillators exist in several forms such as liquids, crystals, gases and plastic solids. The scintillation phenomenon in different substances has been discussed by Curran (1953) and others and may be stated briefly as follows:-

The kinetic energy of the radiation falling on the scintillation material is converted into energy of excitation and ionization of the atoms or molecules of the scintillators in a manner which depends on the rate of energy loss and the velocity of the particle. The de-excitation and de-ionization of the molecules occur within a very short time ($\sim 10^{-12}$ sec.) giving rise to the emission of fluorescent radiation.

In the past liquid scintillation detectors of large area have been successfully developed in the study of air showers (Brennan 1957), neutron detection (Reines et al 1954) and others. However, the liquid scintillators are inflammable and need special containers. They should be stored in an inert atmosphere to maintain the scintillation efficiency over long periods of time and need special quenching. On the other hand, plastic scintillators are now available in sizeable solid blocks so that large area detectors can be constructed with plastic scintillators, avoiding at the same time the dangers and difficulties associated with liquid scintillators (Clark et al 1957). As regards other physical properties of liquid and plastic scintillators, such as their photo-conversion efficiencies and transparencies to their own radiation, it is very difficult from available literature to make any worthwhile comparison.

For the present detectors we have used plastic scintillators type NE 102A made by the Nuclear Enterprises (G.B.) Ltd. and possessing the

following physical and chemical characterstics:-

The plastic scintillators are in the form of slabs with dimensions of 2' x 2' x 1". They consist of scintillation chemicals in polyvenyltoluene and have the density ~ 1.032 gm/c.c. and refractive index ~1.581. They contain 3.4×10^{23} electrons per c.c., soften at ~ 75°C and are soluble in aromatic solvents. The light output is ~ 65% of Anthracene and the transparency to their own radiation reaches about 70%. The scintillators are not hygroscopic. The scintillators also contain a wavelength-shifter which shifts the wavelength of the emitted radiation from about 3800 Å to 4250 Å, so that the spectral distribution of fluorescent emission is well matched to the spectral sensitivity of the photo-cathode of the P.M. tube used here (section 2.4b).

The number of photons emitted by such a scintillator slab can be estimated by using the formula given by Rossi (1952) for energy loss of a relativistic singly charged particle. It can be shown that for a minimum ionising particle, the energy loss per gm-cm^{-2} through a material of NZ/A (= the electron concentration per c.c.) = 3.4×10^{23}, is of the order of ~2.2 Mev. Hence a total loss of energy in passing through 2.54 cm thickness of the material is ~ 5.5 Mev. The manufacturers state that the light output is ~ 65% of that of Anthracene. Now, Anthracene has a photo-conversion efficiency of the order of 4-6% for a photon of wavelength 4200 Å or about 60 ev is dissipated in releasing one of these photons. Hence, the number of photons emitted in our case will be about 4.6×10^4 per vertical passage of a minimum ionising particle.

2.4b The P.M. Tubes

The P.M. tubes used here are EMI type 9618 and are of 5" diameter

flat-face end window with 11 venetian type dynodes, containing highly stable Ca-Sb secondary emission surfaces. The photo-cathode itself is of Sb-Cs-O(11) type with maximum efficiency at 4250 Å. They contain a focussing electrode to obtain maximum efficiency of collection of electrons (~60%) from the photo-cathode to the first dynode. The photo-cathode sensitivity is ~ 40-50 μA/l (i.e. about 10 electrons are released per 100 photons) and the dark current is ~ 0.2 μA at 1800 volt applied to the P.M. tube. The total gain, G, at the operating voltage is estimated to be about 15×10^6 and the interelectrode capacitance is ~20 pf.

This type of photo-multiplier tube was selected as the manufacturers recommended it as being eminently suitable for fast coincidence work and as possessing the added advantage of being free from after-pulsing or the occurrence of multiple pulses initiated by a single primary event. The tubes were selected for low noise characteristics, the dark current being used as a measure of the noise level. It was verified that the noise pulses of the selected tubes constituted less than 5% of the total counting rate at the operating voltage. The accidental pulses due to tube noise produced in the coincidence arrangement would be correspondingly low in the telescope.

2.4c The Container Box

Apart from the size and light-tightness, the light collection efficiency of the photo-tube from different parts of the container box is of the utmost importance in designing a large area detector. The light collection efficiency will depend on the geometry of the box and the reflecting coating of the container box. As far as the reflecting coating is concerned, a diffusive reflector called 'Darvic' has been found to be very satisfactory. It has a reflection coefficient r= .75 and retains its whiteness over a long

period of time. For simplicity and economy we have selected a container box which has rectangular shape with dimensions of 54" x 54" x 17" as described in the section 2.4.

The light-tightness of the box was tested first by measuring the anode current with the P.M. tube well covered with a piece of black cloth and then placing the open P.M. tube inside the box with the lid closed. No appreciable change of the current was detected. The uniformity of the light collection by the P.M. tube from the different parts of the box was tested by measuring the anode current of the P.M. tube when a small tungsten lamp was placed in different positions inside the box relative to the tube. It has been found that the current falls by about 30% when the lamp is removed to the extreme corner of the box. Reasonably uniform light collection can, therefore, be expected from this arrangement.

It is, however, very difficult to calculate the light collection efficiency of the present arrangement, but an approximate estimate was made in the following way. It is likely that the transmission of the photons from the scintillators to the photo-cathode of the tube is essentially through a diffussion phenomenon. On the basis of the diffusion and reflection phenomena, Clark et al (1957) gave an approximate formula for the light collection efficiency of such a system as ours, and can be written in the form,

$$\eta = \frac{\beta \sigma t}{1-rt\,(1-\sigma)} \qquad \ldots\ldots 2.2$$

where η is the fraction of the photons released which give rise to photo-electrons; t, is the average survival probability of a photon transmitted across the detector between successive reflections; r, is the reflection coefficient of the diffusing coating of the container walls; σ, is the ratio

of the photo-cathode area to that of the diffusive surface and β, is the probability that a photon striking the photo-cathode will eject a photo-electron.

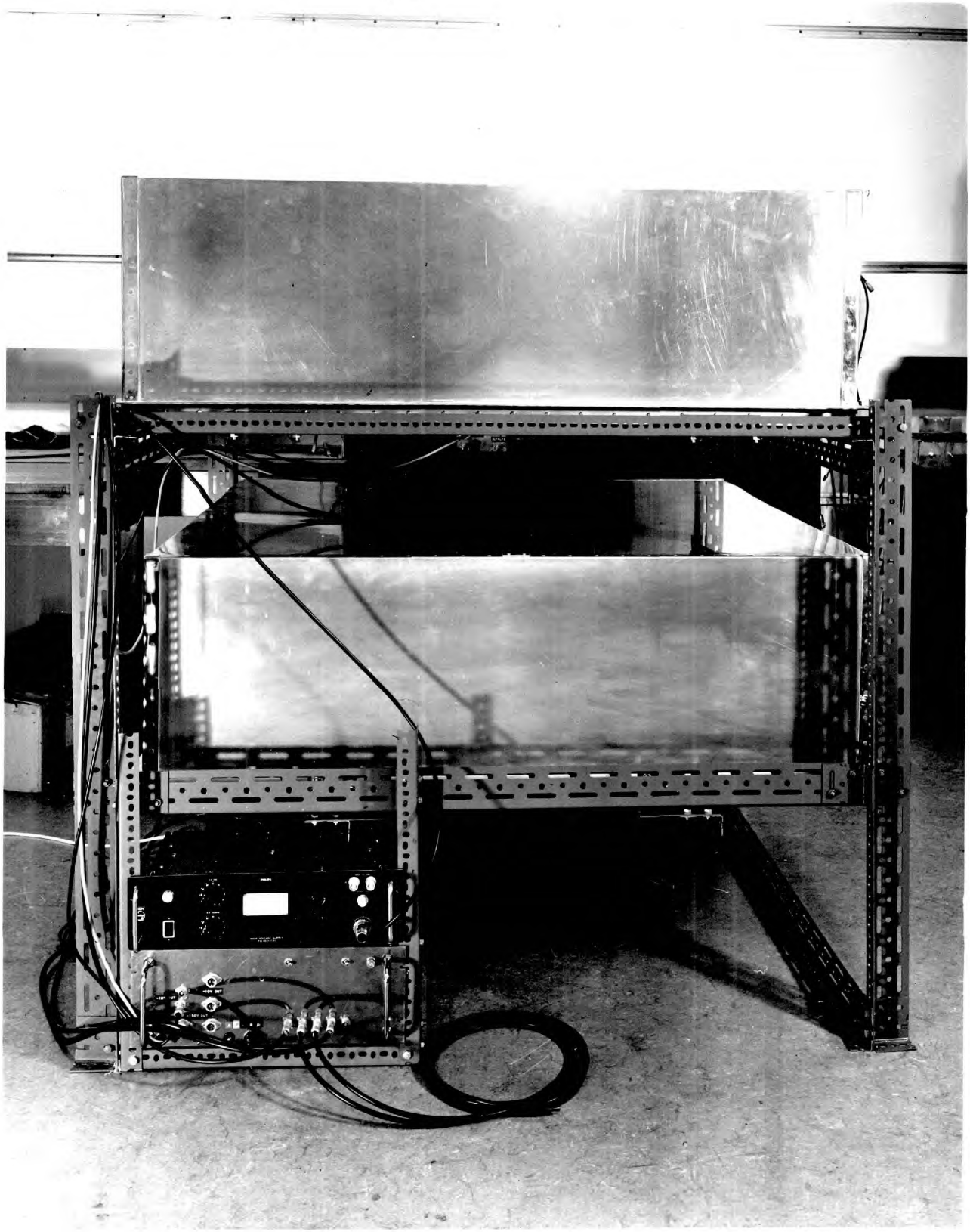
In estimating the value of the eqn. (2.2) we put $\beta \cong .05$, $\sigma \cong 6.8 \times 10^{-3}$, $r \cong .75$, $t \cong .8$. We thus obtain the expected value of $\eta \cong 6.8 \times 10^{-4}$. Therefore, putting this value of η, together with other factors in the eqn. (2.1), as given above (Viz., $N \cong 4.6 \times 10^{4}$, $S \cong .1$, $E \cong .6$, $G \cong 15 \times 10^{6}$, $C \cong 20 \times 10^{-12}$ F), we obtain an output voltage $\sim$200mv per passage of a minimum ionising particle through the box. Incidentally, our electronic system has been so designed as to accept any pulses above a minimum threshold of about $\sim$150mv. Hence, this pulse-height is quite sufficient for our present system.

2.4d. The Coincident Arrangement

Due to the high sensitivity of the scintillation counting system to the gamma-rays, it is very difficult to discriminate the cosmic rays from the background radio-activity, if only a single counter is used; so, two such counters are generally used to form a telescope. In the present system, two counters of identical design are placed one above the other in a Dexion frame with a separation of 27" to give approximately semicubical geometry for the telescope. Each pair of P.M. tubes used to form a telescope was specially chosen to have approximately identical gain at the same operating voltage so that a single E.H.T. supply could be used to drive both P.M. tubes in a telescope. The Plate 2.2 shows the complete arrangement of such a telescope.

2.4e. The Electronic System

Fig. 2.1 shows the block diagram of the arrangement of two such telescopes together with the associated detecting equipment. The output



pulses from the Head-units of the two counters forming a telescope are fed into a coicidence-discriminator circuit. The output pulses from two coicidence circuits (i.e. from two telescopes) are fed to a mixer circuit. The output from this mixer circuit is then connected to a scaler which drives an electromechanical printer. At the end of every hour the numbers recorded by the printer are automatically printed out on a paper tape, when the printer gets a signal from a clock.

In view of the extreme sensitivity of the P.M. gain with the voltage applied to it, great care has been taken to keep the voltage fluctuations as small as possible. The lower diagram in Fig.2.1 shows the voltage supply system to the different parts of the telescope. The mains voltage is stabilised in two stages. At first a Servomex A/C stabiliser is used to take into account larger fluctuations in the mains so that the 230V output is kept constant within $\pm$.25% for an input change from -17.5% to +8.75%. This output is then fed through a saturated core constant voltage transformer which takes into account the residual fluctuations in the form of transients, etc. The transformer stabilises the voltage continuously and instantaneously within $\pm$.1% for an input change of $\pm$15% and is self-protecting against short-circuits and transient overloads. This stabilised output is then supplied to the E.H.T. and L.T. units. The E.H.T. units are of the type PW 4024/01 made by the Philips and are themselves stabilised up to .05% for fluctuations in the input voltage up to 10%. The L.T. units are transistorised (type TS 20, made by the Venner Electronics Ltd.) and well stabilised against the mains fluctuations. The temperature coefficients of the E.H.T. units were measured and a coefficient of only about $\sim$.02%/^{oe} was found. The temperature of the underground laboratory changes only by less than a degree centigrade in the

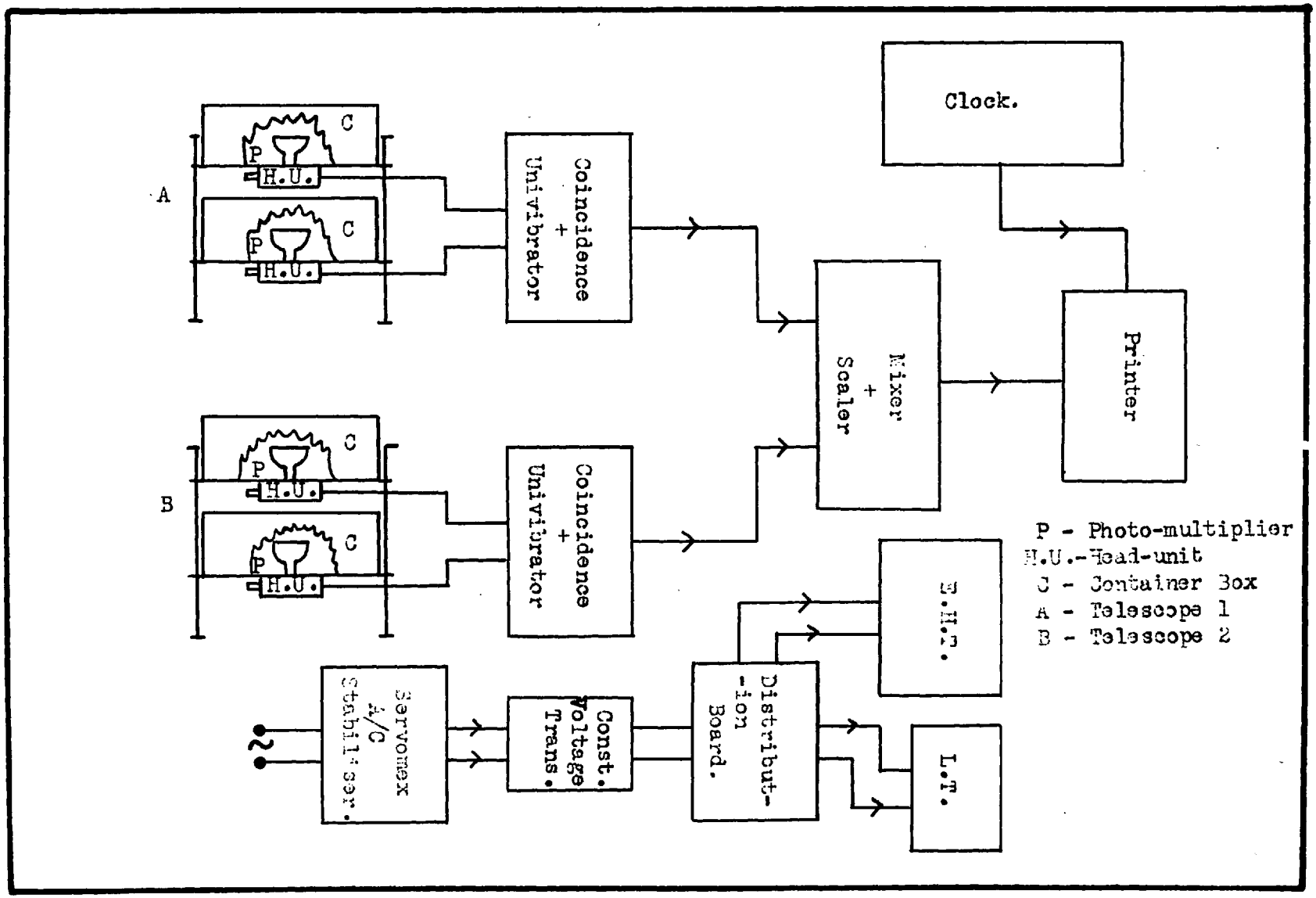


Figure 2.1 The block diagram of two Scintillation Counter Telescopes (A and B) and the recording system. The two telescopes A and B form what is referred to as 'Recorder' in the text. The lower diagram shows the voltage supply system to the telescopes and the associated recording equipments.

course of the whole year and hence cannot introduce any appreciable fluctuations in the voltage supplies.

We have used high frequency transistors in the electronic circuits instead of vacuum tubes, because of the long life, low voltage dissipation and the compactness of the former. Since it is necessary that the P.M. tube and the amplifier-discriminator circuits contained in the Head-unit should be placed close to each other to keep the stray capacitance to a minimum, the use of the transistors helps to keep the heat dissipation near the P.M. tube negligible; their long lives ensure reliable operation over a long period of time and their compactness is an added advantage. Nevertheless, the use of the transistors also introduces certain difficulties, viz., their characteristics are sensitive functions of temperature and voltage. However, with the suitable choice of the circuit parameters and transistors it is possible to keep the temperature dependence of the circuitry to a minimum; the voltage can be kept constant within certain tolerable limits and special voltage stabilising components incorporated in the circuit design whenever necessary.

(i) Head-unit

Figs. 2.2 and 2.3 show the complete sets of the electronic circuits contained in the Head-unit. Fig. 2.2 shows the resistor chain of the dynode system of the P.M. tubes. The high collection efficiency for the electrons by the first dynode of the P.M. tube is ensured by using 1.8M ohm resistor between the first dynode and the cathode. The output from the anode is taken through a capacitor (1000 pF, 2.5kvW) to the base of the first transistor (Mullard type OC 170) of the amplifier. The amplifier is of the negative feed-back type which makes its amplification independent of the L.T. voltage changes. Its gain ($\sim$ 2.5) was found to be stable against the temperature

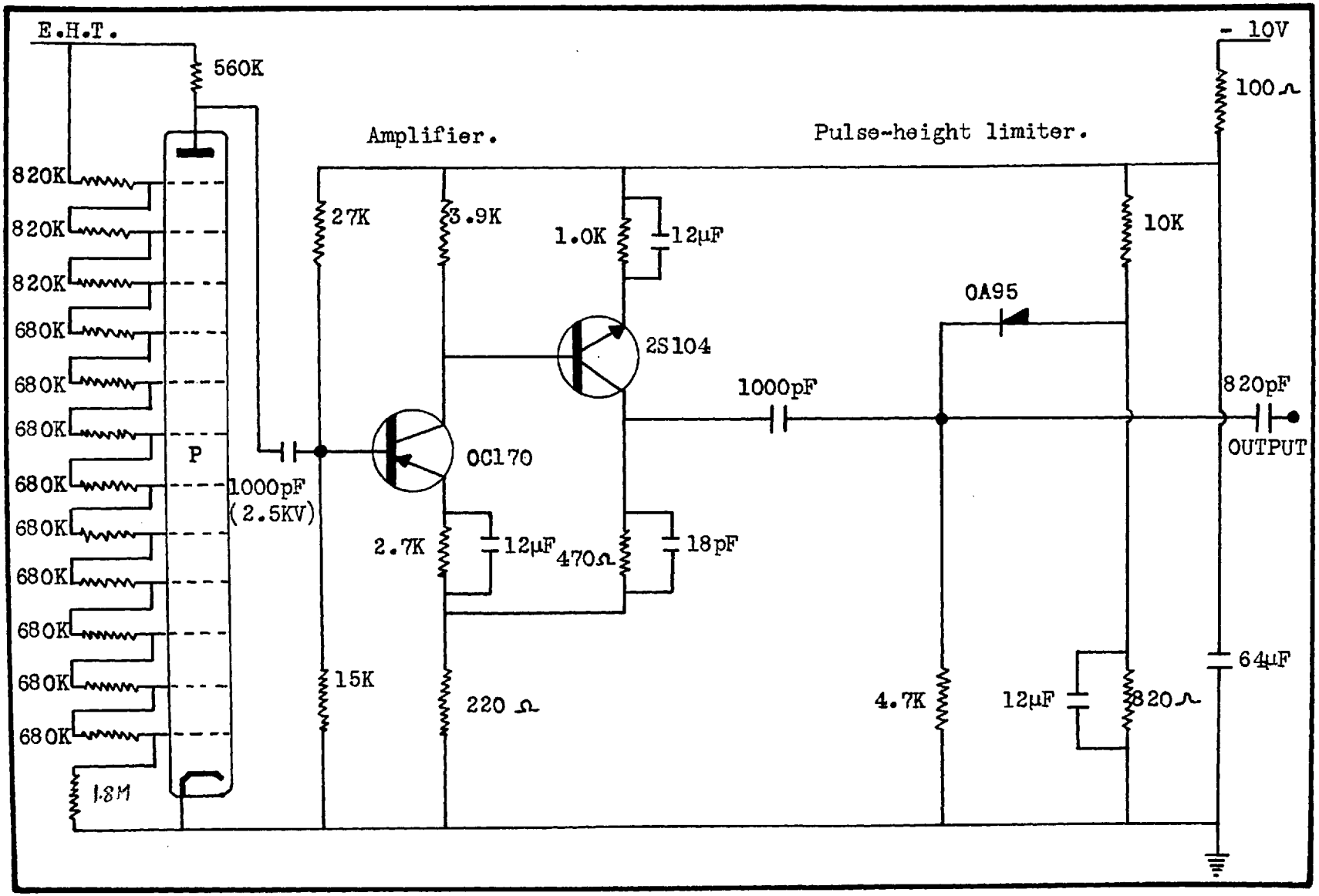


Figure 2.2 The circuit diagram of the Head-unit (section I). P - Photo-multiplier tube.

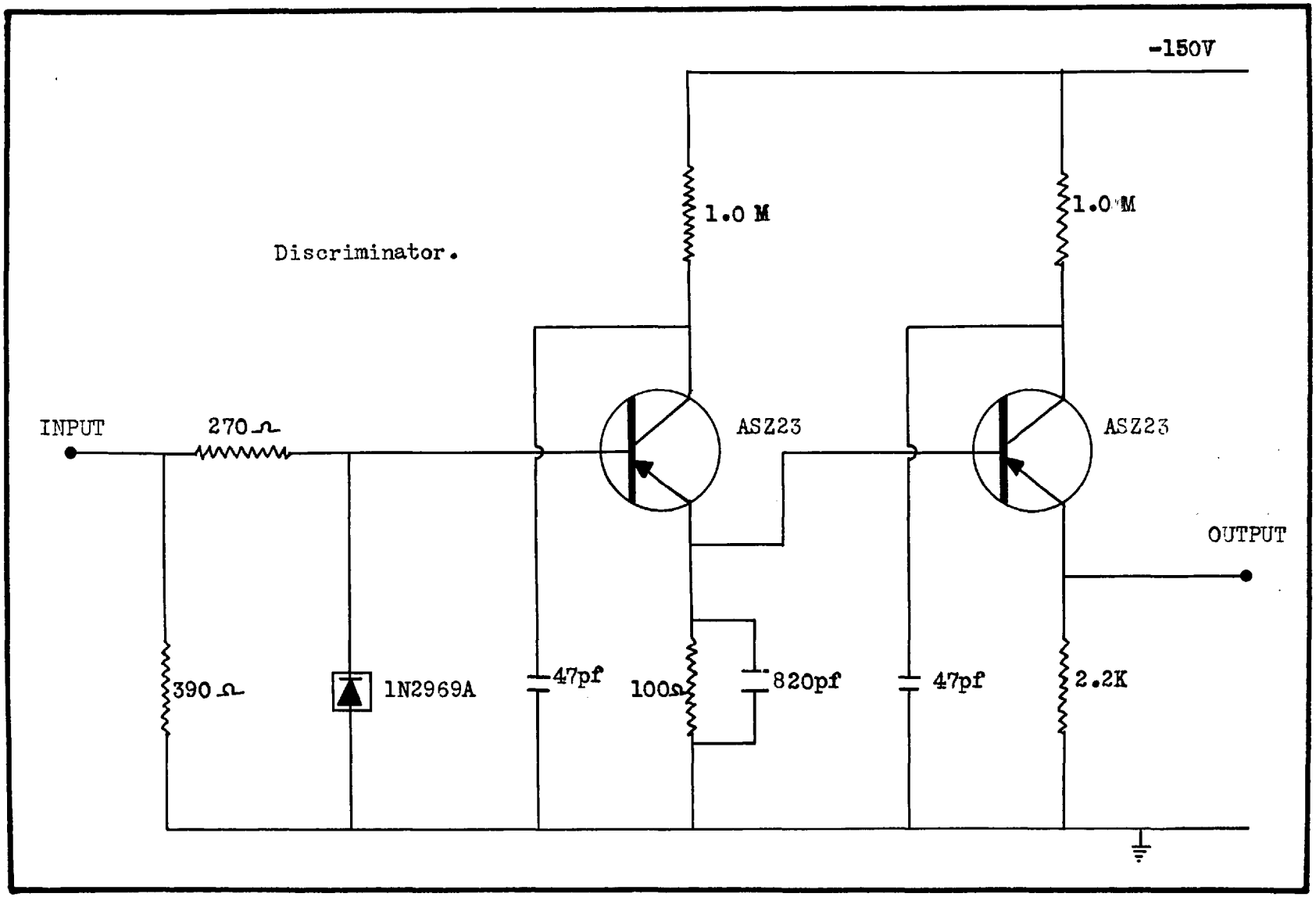


Figure 2.3 The circuit diagram of Head-unit (section II).

changes of the transistor. It also acts as an impedance matching device between the high impedance output of the P.M. tube and the low impedance input of the tunnel diode discriminator circuit (Fig.2.3)

The output of the amplifier is taken through a pulse-height limiter to the input of the discriminator, containing a tunnel diode (type 1N2969A, made by the General Electric Co.). The tunnel diode discriminator has been preferred here because of its temperature characteristics. For example, the peak point current of the tunnel diode, which determined the switching threshold has a temperature coefficient of only $\sim 60\mu v/^{o}C$ and the forward voltage, which determines the amplitude of the output voltage has a temperature coefficient of ~ 1.0 mv/^{o}C. These values have been quoted by the manufacturers. The tunnel diode is placed at the base of an Avalanche transistor (type Mullard ASZ23) so that whenever the discriminator operates an output is obtained from the Avalanche transistor. With this arrangement the threshold of the discriminator was found stable within $\sim 0.1\%$ per ^{o}C. The emitter circuit of the Avalanche transistor can drive pulses without attenuation through a long length of coaxial cable. The output pulses from the Avalanche transistor were equalised at an amplitude of about ~ 1.0 volt and were very narrow with an average width of about ~ 20 nanosec.

(ii) The Coincidence-Univibrator Circuit

The output pulses from the Head-unit are taken through a coaxial cable to a diode (type OA95, Mullard) coincidence circuit (Fig.2.4). The coincidence output is then fed into an emitter coupled univibrator circuit which gives out square pulses of amplitude ~ 1.0 volt and width greater than 6 micro-sec., suitable to drive the vernier decade units (type TS 10/5). There is an emitter follower at the output end of the univibrator so that

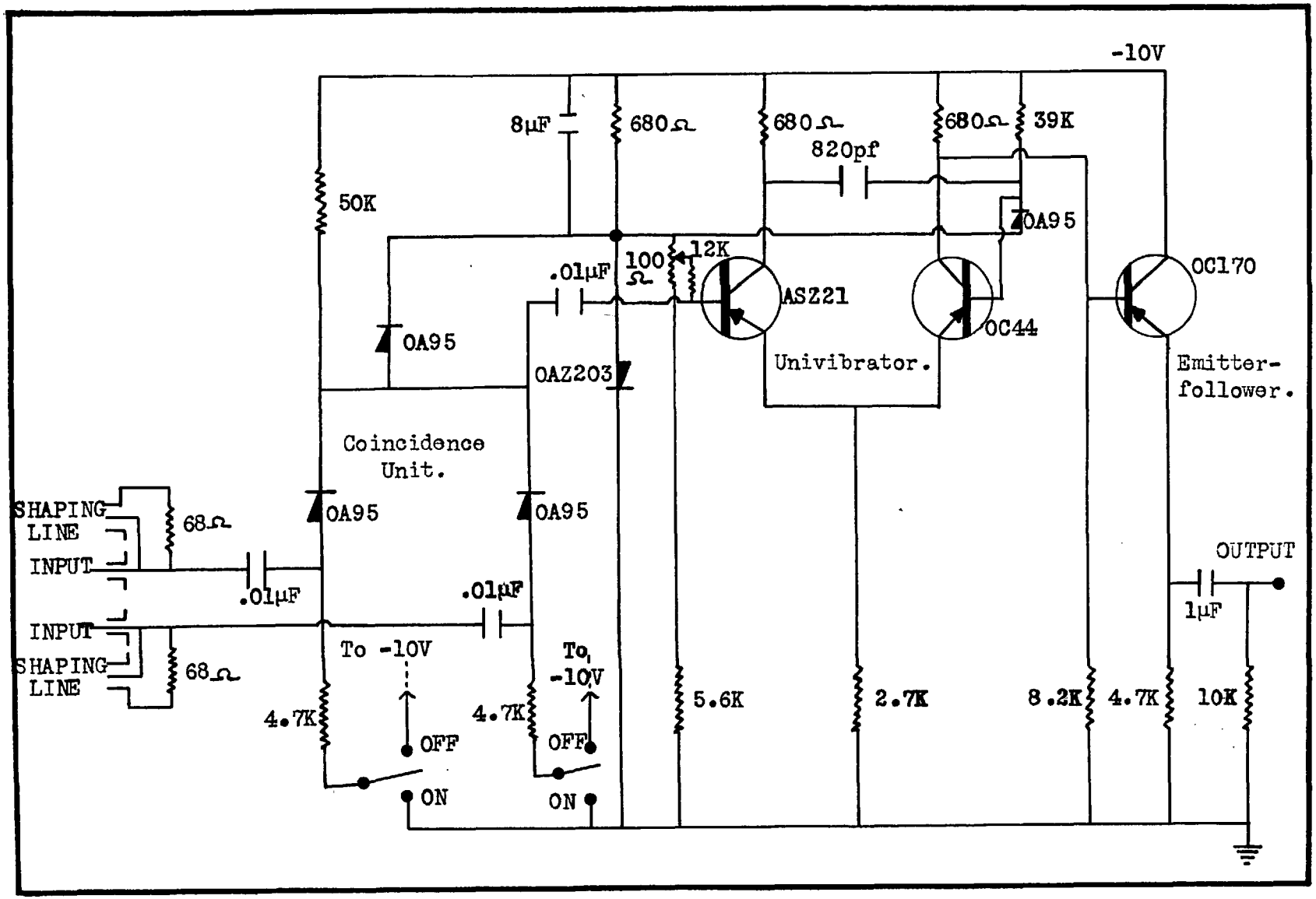


Figure 2.4 The circuit diagram of the Coincidence Unit, the Univibrator and the Emitter-follower.

this circuit can be separated from the disturbing effects of the scaler-printer systems by means of a matched coaxial cable.

(iii) The Mixer-Scaler Unit

In order to reduce the number of printers and scalers from six each, corresponding to the six telescopes developed here, to three each, the pulses from two telescopes were first added up by means of a mixer circuit and then fed into the scaler unit. The circuit diagram of the mixer unit is shown in Fig.2.5. The scaler contains two vernier decade units followed by a relay unit (type TS 13) which closes a relay contact after every 100 pulses have been counted. The six telescopes run in this way will yield three sets of data corresponding to the three pairs of telescopes, henceforth called Recorders I, II, and III.

(iv) The Printer-Clock Systems

The relay unit of the scaler is connected to an electro-mechanical printer. At the end of every hour, a clock closes a pair of contacts in the printer which causes the printer to print out the number recorded during that interval. Thus the data were recorded and printed automatically on paper tapes which could be collected at convenient times and tabulated for further analysis.

2.5 Operation and Performance of the Telescopes

(a) At Sea Level:

First of all, the telescopes were set up at sea-level as described above (Viz. Fig.2.1) and tests were carried out to determine the voltage characteristics of the telescopes and to ascertain the reliability of their performance as well as their dependence on the environmental temperature.

Voltage characteristics of each counter were determined by finding

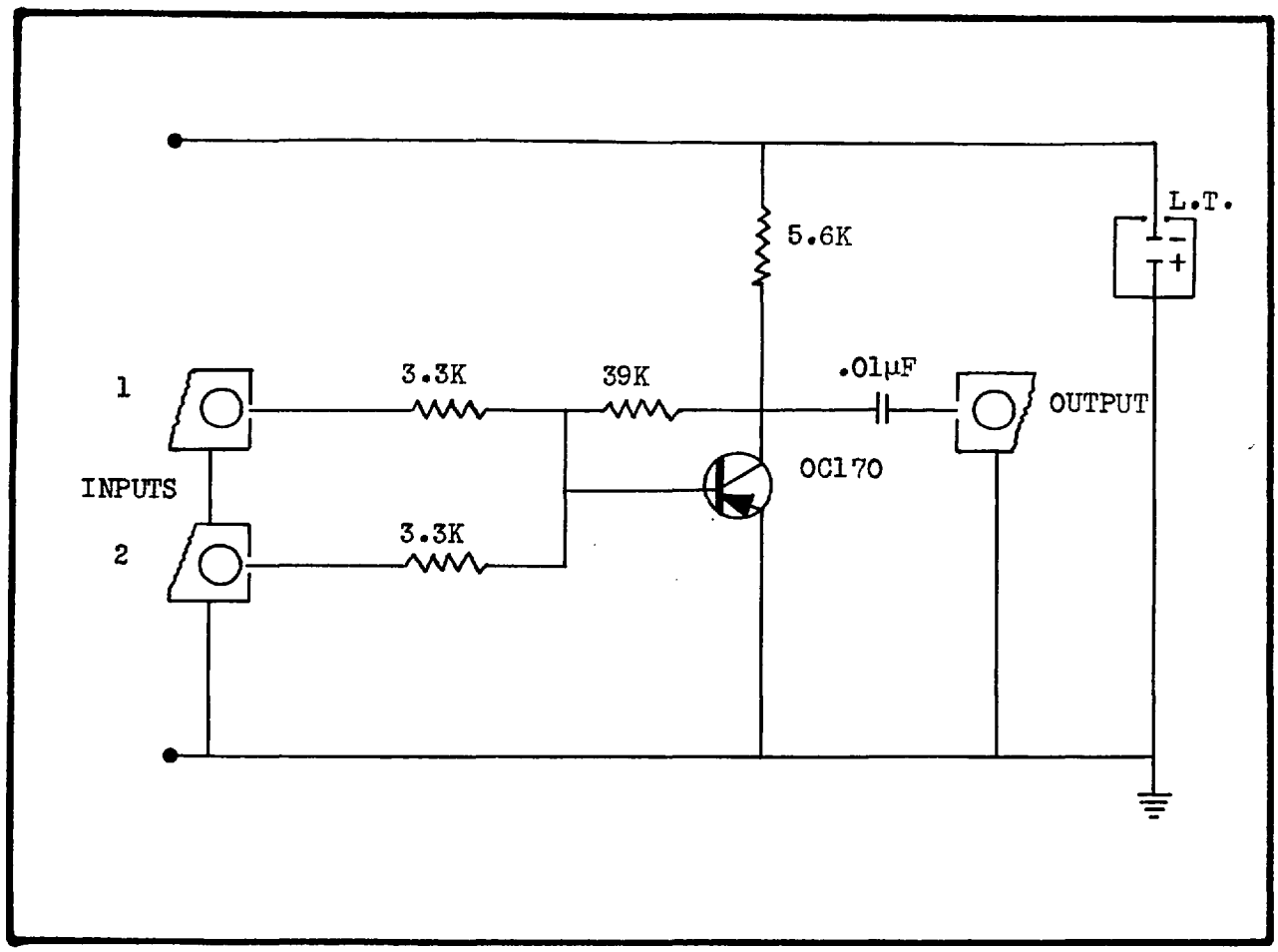


Figure 2.5 The circuit diagram of the Mixer Unit.

the change of counting rates against the voltage applied to the P.M. tube. At a fixed amplification of the amplifier and at a fixed level of discriminator voltage at the base of the univibrator, changes in the counting rates can only occur due to the change of E.H.T. voltage if the radiation level remains constant during the measurement. The measurements from one typical telescope are shown in Fig.2.6. The curves (a) and (b) show the single counting rates from the two counters. These curves show that there is a continuous distribution of the pulses and no plateau region is evident. However, when the counters were run as telescope, so that the pulses from the two counters were fed to the two channels of the coincidence circuit, a distinct plateau region was obtained as shown in the Fig.2.6 (Curve c), indicating that the discrimination between the cosmic rays and the background radiation is possible in this arrangement. In this plateau region, all cosmic ray particles should be counted and it is the usual practice to set the operating voltage in the centre of the plateau region. The plateau region extends over about 100 volts with a slope of about 0.1% for an increase of 10 volts in the E.H.T.

When the telescope was operating with a fixed E.H.T. voltage corresponding to the middle of the plateau, any change in the counting rates of the telescope should reflect, in practice, the change in the cosmic ray flux passing through the telescope. However, this ability of the scintillation counter telescope to record the cosmic ray intensity variations can only be judged in comparison with those recorded by a standard geiger counter telescope. The scintillation counter telescope was run for several weeks at sea level under two floors of concrete. A cubical geiger counter telescope of sensitive area ~3600 sq.cms. with 10 cms. of lead between the trays was

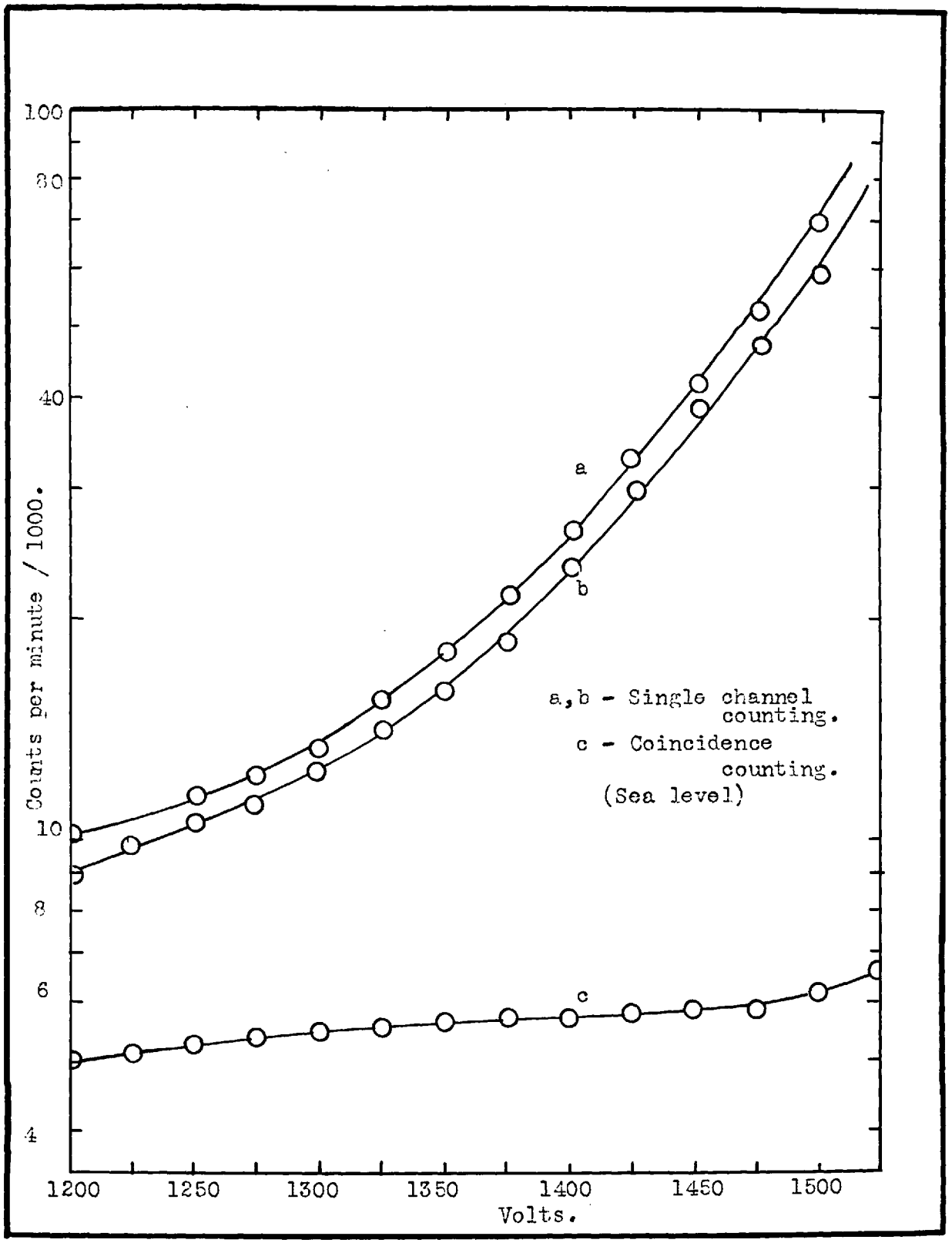


Fig. 2.6 The counting rates of two single scintillation counters and the telescope formed by them as functions of E.H.T.

also in operation at the top floor of the laboratory. The scintillation counter telescope should in this case be recording the hard components mainly, together with a small amount of soft component. Hence under identical conditions of operation, both the scintillation and the geiger counter telescopes should only be affected by the atmospheric changes, provided the scintillation counter telescope is assumed to be as efficient in detecting the cosmic ray intensity variations as the geiger counter telescope. Consequently, the intensity record over the same period obtained by them should show parallel variations when the records are plotted against time. Simultaneous records for six days from two such scintillation counter telescopes as well as from the geiger counter telescope during September, 1963 are shown in Fig.2.7 (curves a,b,c,). Parallellism of the curves shows that identical variations have been recorded by the scintillation and the geiger counter telescopes. The correlation between the bi-hourly rates of the two detecting systems was found by drawing a scatter diagram, where the best fit line showed a slope of $\sim .99$. This leaves no doubt about the efficiency of the scintillation counter telescope in detecting the cosmic ray intensity variations at sea level.

The assessment of the dependence of scintillation counter telescopes on the environmental temperature was made by comparing the simultaneous records from the scintillation and the geiger counter telescopes, when only the temperature of the room, in which the scintillation counter telescopes were running, was changed at random from $40^{\circ}F$ to $90^{\circ}F$. The electronic equipment of the geiger counter telescope consists of vacuum tubes and, in fact, the whole detecting system has negligible dependence on the environmental temperature. Furthermore, the temperature of the room, in which the geiger

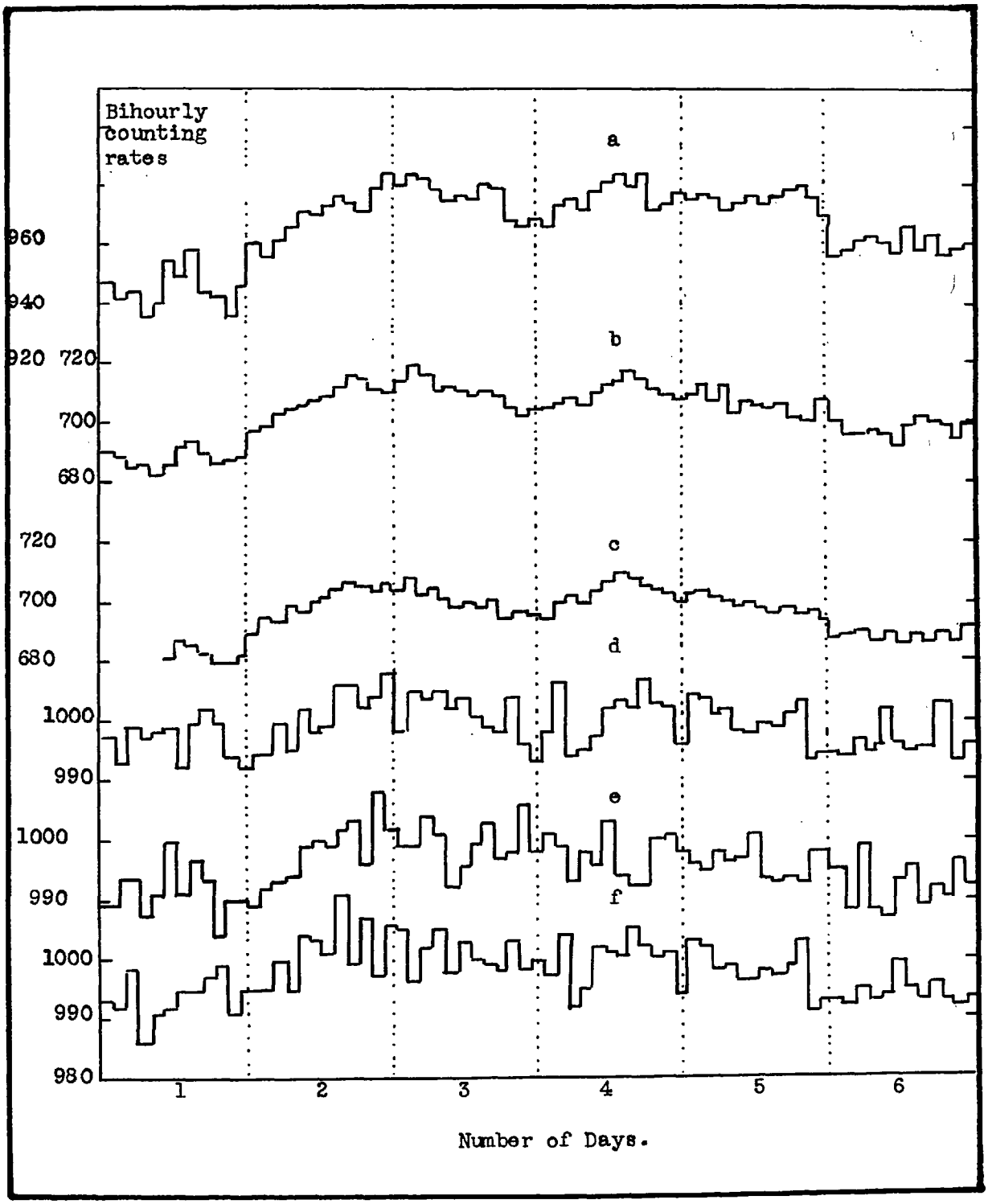


Figure 2.7 Cosmic ray intensity variations recorded by a sea-level Geiger Counter Telescope (a), two sea-level Scintillation Counter Telescopes (b,c) and three underground Scintillation Recorders (d,e,f).

counter telescope was running, remained reasonably constant during the test period. Hence, under these experimental conditions, the records over the same period from these two detecting systems should still show parallel variations, provided the scintillation counter telescopes are reasonably independent of the environmental temperature. Accordingly, simultaneous records for 8 days from these two detecting systems are shown in Fig.2.8, together with the temperature records of the scintillation counter room. It can be seen from the Fig.2.8 that the parallellism between the records of the standard geiger counter telescope and the scintillation counter telescope has not been broken, even when the temperature of the scintillation counter room was changed over such a wide range. For further quantitative assessment, we grouped the bi-hourly counting rates of the geiger and the scintillation counter telescopes according to high and low values of the temperature of the scintillation counter room as indicated in the Fig.2.9. A scatter diagram of the geiger rates against scintillation rates was drawn and the 'best fit' straight line showed a slope of $\sim .97$ (Fig.2.9). It can be seen from this figure that all the groups are evenly distributed along the straight line, which indicates that the low or high counting rates of the scintillation counter telescope do not depend on the environmental temperature. We thus conclude that the temperature coefficient of the scintillation counter telescope is negligibly small and could not be detected.

(b) Underground:

The telescopes were dismantled and taken down to a disused part of the Holborn underground station of London Transport deep under the city. There the telescopes were set up in an arrangement of semi-cubical geometry to record the cosmic ray flux in the vertical direction. The depth of the

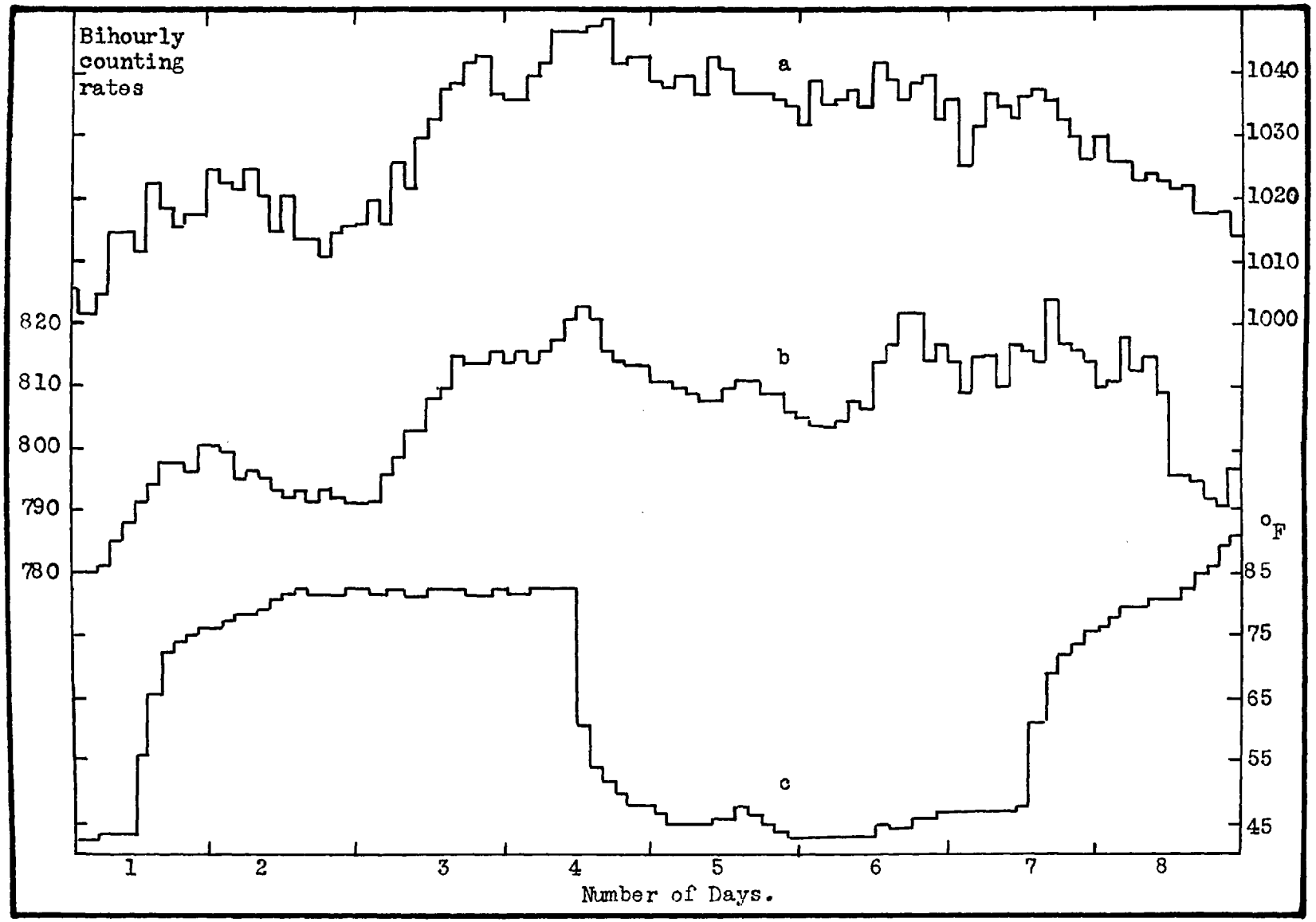


Figure 2.8 Cosmic ray intensity variations recorded by a sea-level Geiger Counter Telescope (a) and a sea-level Scintillation Counter Telescope (b) when the temperature of the Scintillation counter room was changed as shown by the curve c.

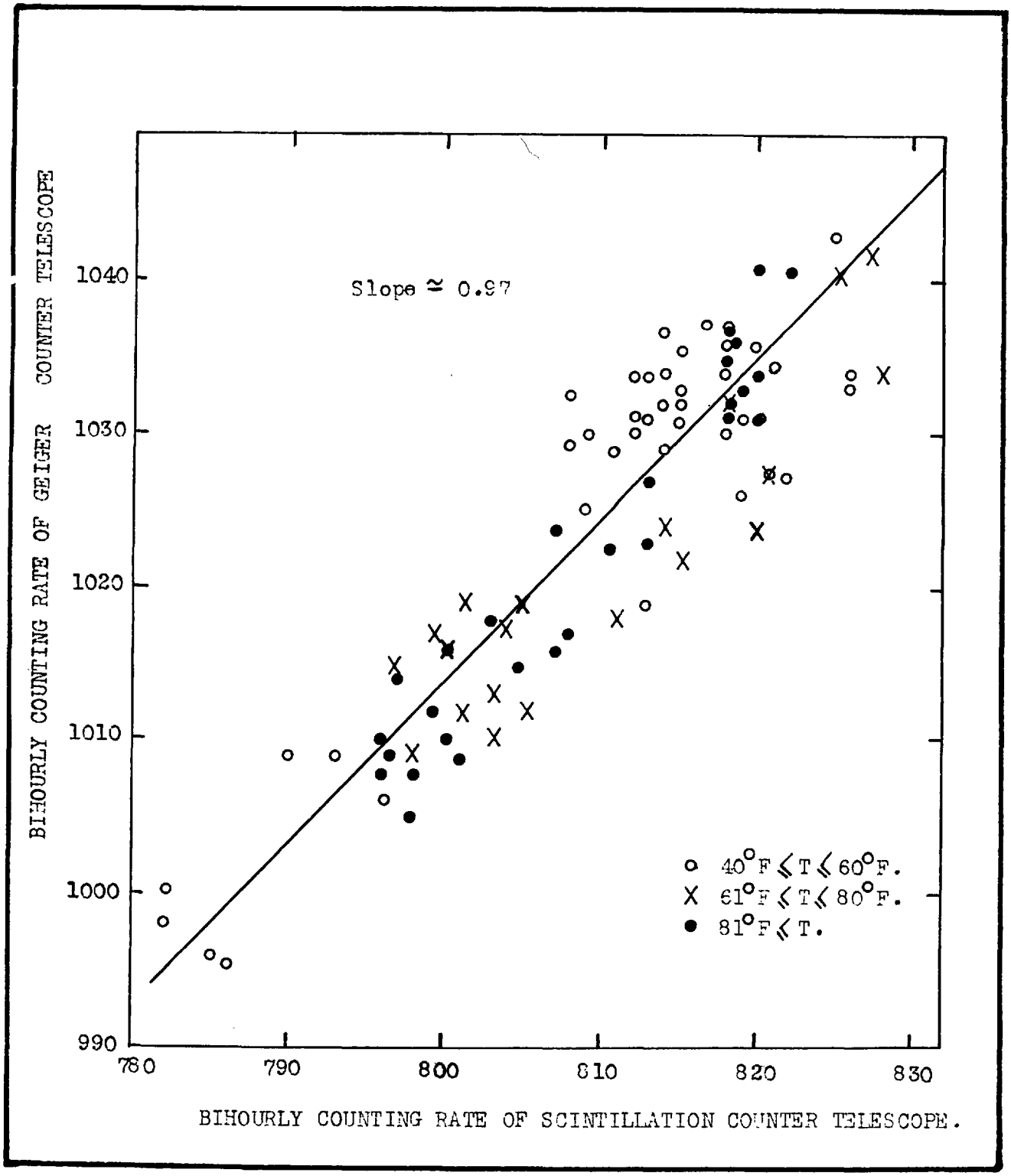


Figure 2.9 The scatter diagram showing the regression line of the bi-hourly rates of Geiger Counter Telescope on those of Scintillation Counter Telescope. T - the temperature of Scintillation Counter room. The values refer to those shown in Fig. 2.8.

laboratory is about 60 m.w.e. below sea level. The site has been specially chosen because, some investigations of the time variations of the cosmic ray intensity have already been made in the past (McAnuff, 1951, Mathews, 1963) so that a comparison can be made between these investigations; the scintillation telescopes can run in the complete darkness and the location is ideal for long term investigations because of the small change of the temperature of the laboratory.

New sets of voltage characteristics, i e. the coincidence counting rates against E.H.T., were found for each telescope underground. Typical examples from one of the telescopes are shown in Fig.2.10. Now the plateau region extends over about 200 volts with a slope of about .25%for an increase of 10 volts in the E.H.T. (curve c). No further temperature test was conducted here. However, to show the reliability of the operation of the telescopes in recording the cosmic ray intensity variations underground, we have also plotted in Fig.2.7 the simultaneous records during September, 1963, from the three underground Recorders (curves d, e, f). The time variations recorded by the scintillation and geiger counter telescopes show excellent agreement with each other, indicating the satisfactory performance of the scintillation detectors at sea level as well as underground.

2.6 Methods of Recording the Data

The bi-hourly records from the three Recorders were plotted against time and a visual inspection of the records was made day by day as the data was coming in. No mutual disagreement of the intensity variations recorded by them could be detected in this way. We have accumulated almost unbroken records for the last 12 months starting from August, 1963 to July, 1964. No breakdown in the electronic system ever occurred, except that one or two

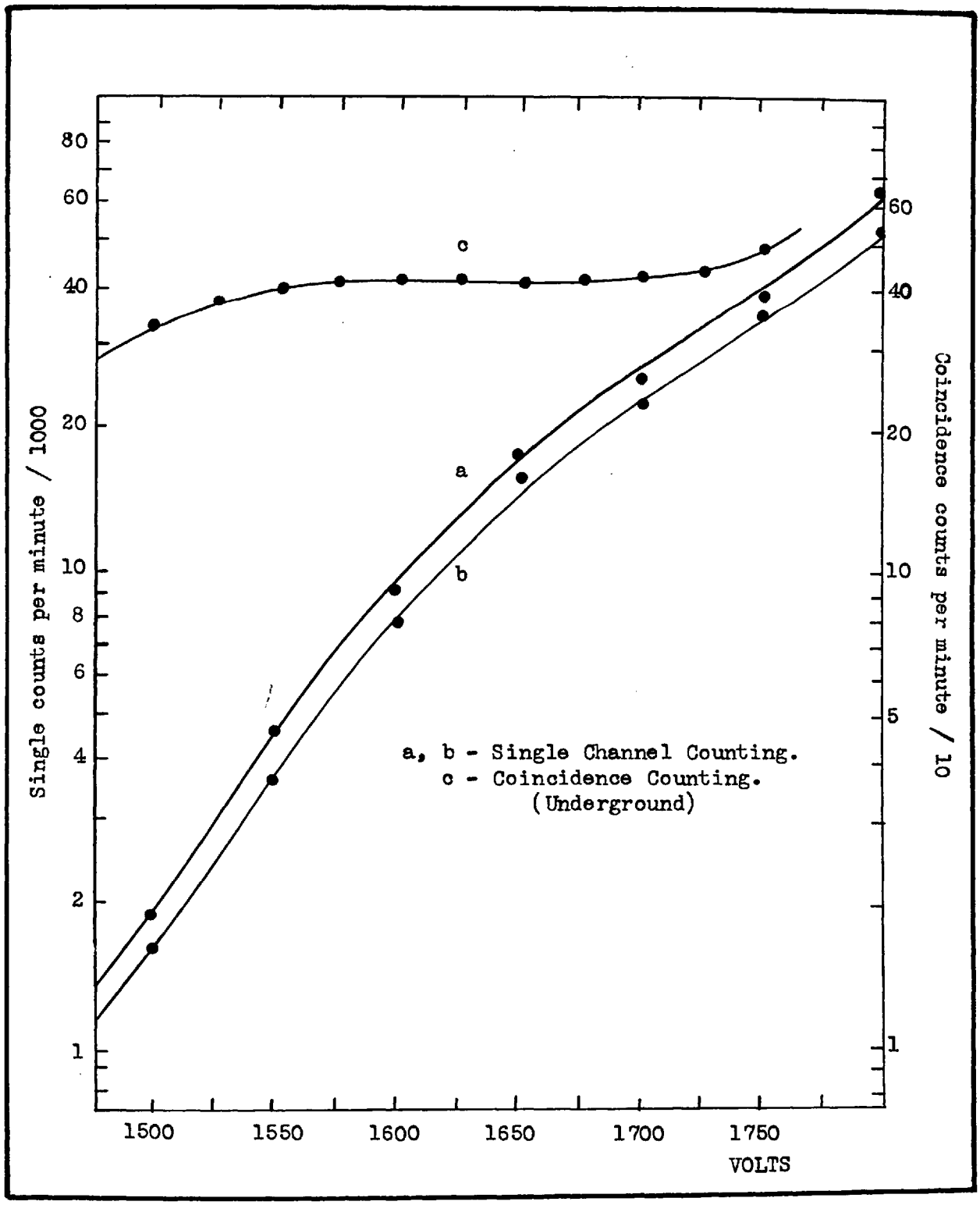


Figure 2.10 The counting rates of two Scintillation Counters (a,b) and the Telescope formed by them (c) as functions of E.H.T..

decade units in the scaler caused the loss of data for several days in one Recorder or the other, but complete records from at least two Recorders were always available.

2.7 The Statistical Tests of Mutual Agreement

Apart from this visual inspection of the parallellism of the records, two more quantitative tests, based on the statistical theory of errors, were carried out to assess the mutual agreement between the records.

In the first method a 'Chi-square' test was carried out to show that there is no significant difference in their long-term or short-term tendencies and that the records from each Recorder are equally influenced by outside factors e.g. of atmospheric or of primary origin. For the calculation of the quantity χ^2, we have used 10-day means of the daily intensity from each Recorder so that altogether 26 such values were obtained from August, 1963 to April, 1964. Since there were three Recorders, two sets of χ^2 - values were obtained between the Recorders I & II, as well as, between the Recorders III & II, as given below:-

$$\chi^2_{12} = 29.41 \qquad \text{(between the Recorders I and II)}$$

$$\chi^2_{32} = 25.01 \qquad \text{(between the Recorders II and III)}$$

Entering these values in Fisher's table of χ^2 with 25 degrees of freedom, we find that the corresponding probabilities, P, are $0.20 < P < 0.30$ and $0.30 < P < 0.50$, i.e. such values would arise on the basis of sampling. Hence it can be concluded with a fair degree of confidence that, if one of the Recorders is unbiased, the other two are just proportional.

In the second method the distribution of the differences in the daily counting rates between any two of the Recorders were plotted out in the

form of histograms, as shown in Fig.2.11 and Fig.2.12.

In Fig.2.11 we show the histogram of the differences of the daily counting rates (altogether 335 days of unbroken records were used) between the Recorders I & II. In Fig 2.12 we show the same between the Recorders II and III (in this case altogether 303 days of unbroken records were used).

Now assuming that the daily counting rates from each Recorder is normally distributed (which is approximately the case for counting rates extended over long periods), their differences should also be normally distributed. On the other hand, while the individual distributions may be affected by the irregular atmospheric changes, the differences will be free from these effects since each Recorder has been found to be equally influenced by the outside factors. Hence the differences in the counting rates were used to see how they approximate to the normal distribution.

We have calculated the normal frequency distributions for these two pairs and have plotted them as a continuous curve in Fig.2.11 and Fig. 2.12. The two observed distributions can be seen to agree fairly well with the expected distributions. However, a quantitative test of 'goodness of fit' was carried out by finding χ^2 as a sum of the differences between the expected and the observed frequencies divided by the expected frequencies. The values so obtained came out to be in the two cases as, 11.8 and 12.4. Since the distributions were estimated from the population means and the standard deviations, the degrees of freedom were 20 in each case. The probabilities of obtaining such values by chance are between 5 & 10 in every 100 random values. We conclude, therefore, with a fair degree of confidence that the three Recorders agree with each other within statistical accuracy.

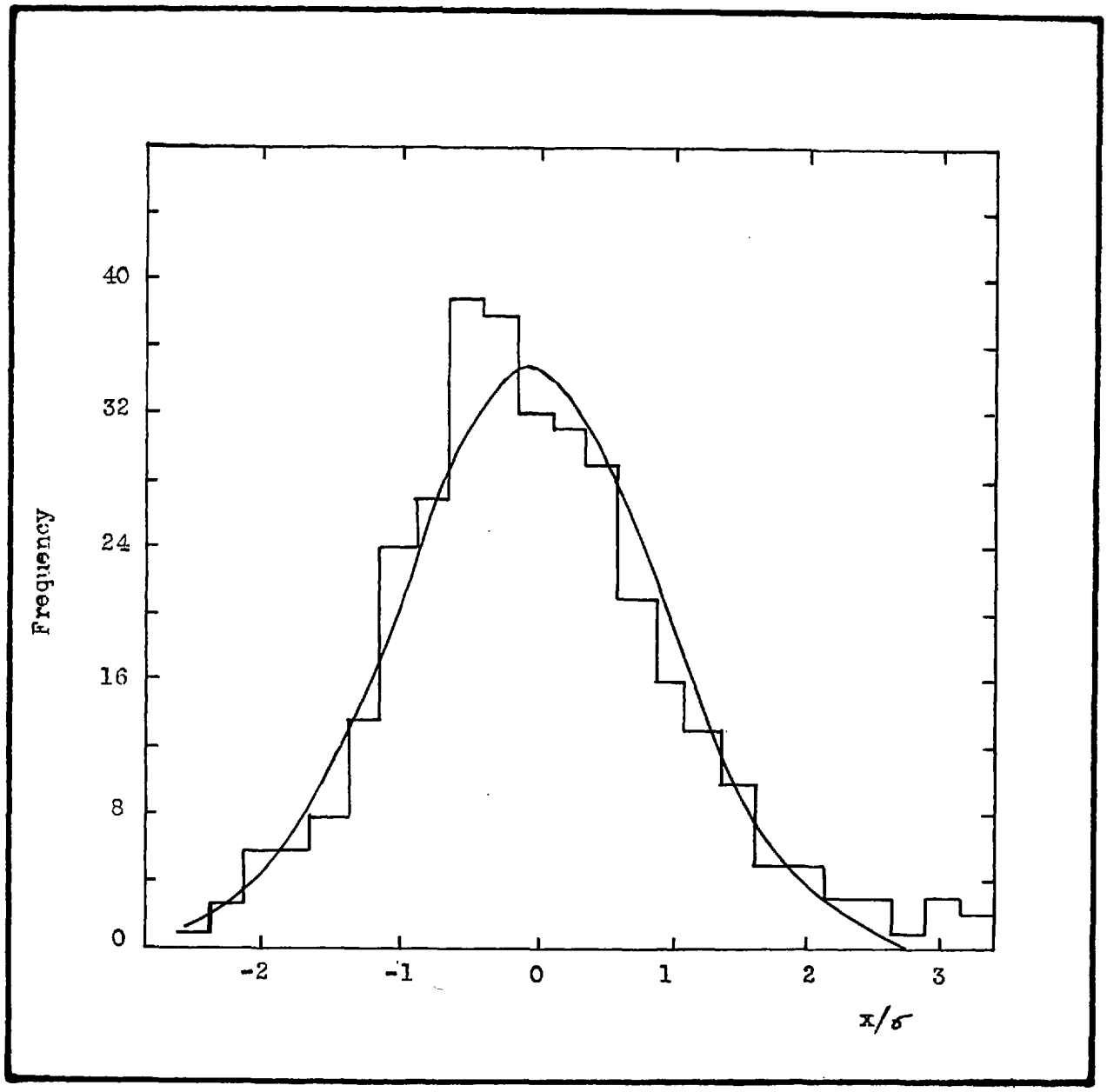


Figure 2.11 The frequency distribution of the difference in daily counting rates of Recorders I and II for 335 days. The observed frquency distribution is shown by means of the histogram and the expected normal distribution is shown by means of the continuous curve.

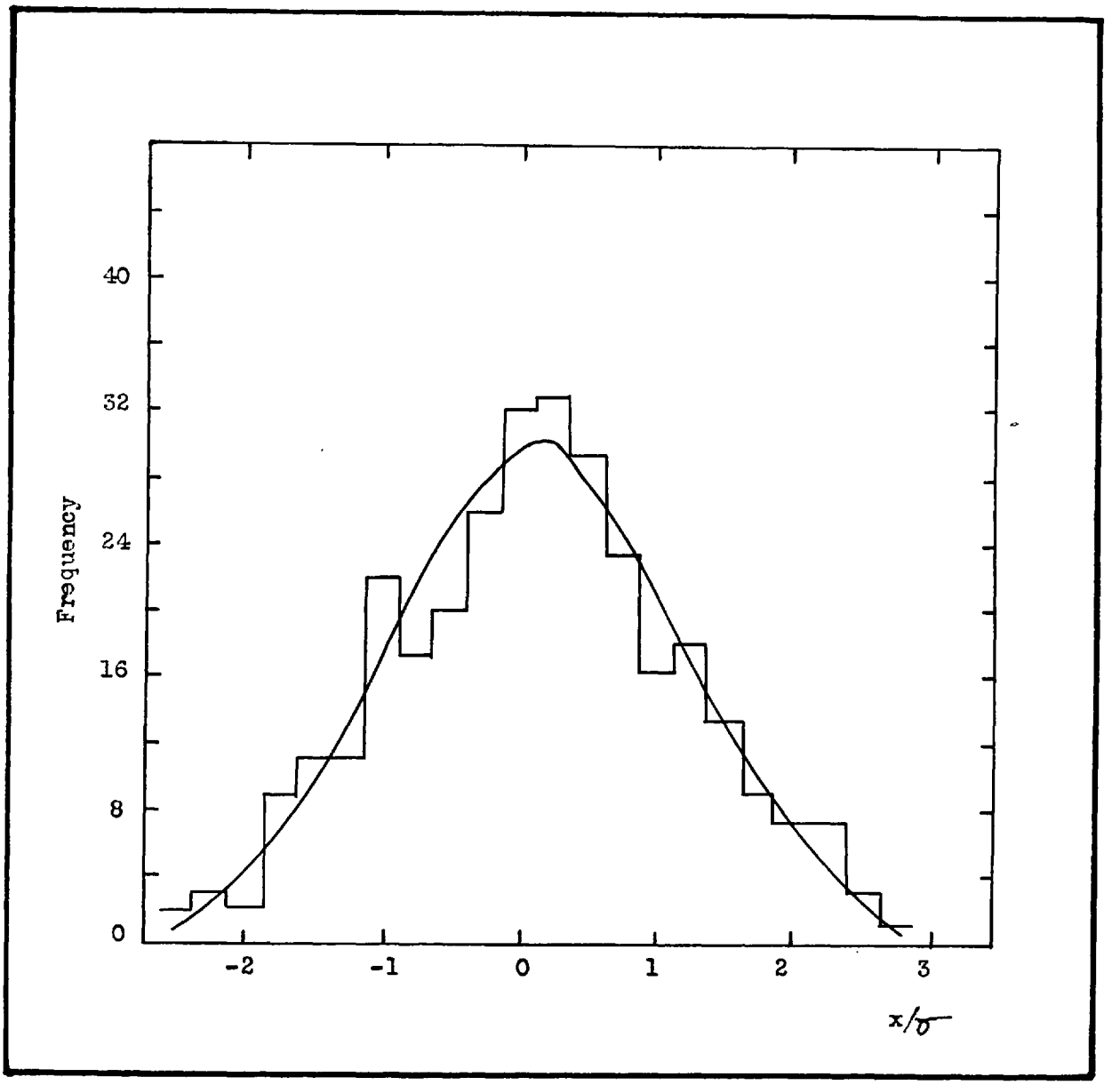


Figure 2.12 The frequency distribution of the difference in daily counting rates of Recorders II and III for 303 days. The observed frequency distribution is shown by means of the histogram and the expected normal distribution is shown by means of the continuous curve.

2.8 The different errors involved in the Measurement

It has been shown above that both the visual and statistical tests failed to reveal any disagreement between the three Recorders. But the instrumental errors not detected in these tests may, however, be present in the form of systematic errors arising from the fluctuations of the mains voltage and the environmental temperature which will affect each Recorder equally and hence will not be detected by the above tests. With the adequate voltage stabilisation and temperature compensation as discussed above, the systematic errors are, however, likely to be negligible.

Apart from that, some other sources of errors will still be present e.g. (i) the errors due to the scaling factor and the registration time; (ii) the errors for using the coincidence and the mixer circuitsand (iii) the errors due to statistical fluctuations of the counting rates.

The grouping of the data in units of 100 will, according to Sheppard, introduce an error $\sim 100^2/12$ in the variance. Hence the increase of error in the daily counting rate ($\sim 36 \times 10^5$) will amount to about 64 in 36×10^5 and will, therefore, be negligible. The registration time of each printer is only a fraction of a second and since only ~ 0.14 counts/sec. on the average are recorded underground, it involves also negligible loss of counting rates.

The use of the coincidence circuit with the resolving time τ, will introduce an error in terms of chance coincidence, C, given by,

$$C = m.C_1 \ldots C_m \tau^{m-1}, \text{ for m-fold coincidences} \quad \ldots\ldots 2.3$$

where C_1 and C_m are the counting rates of the 1st and m-th counter. In the present case, m=2, $C_1 \cong C_2 \cong 12 \times 10^3$ per minute, $\tau = 50 \times 10^{-9}$ sec. Hence this introduces an error of only $\sim 0.01\%$ of the true counting rate. The errors for

using the mixer circuit will also be negligible, because the counting rate from each telescope is only about 4 counts/sec.

The errors due to the statistical fluctuations of the counting rates are inherent in the cosmic ray investigation. It is well-known that the counting rates of the cosmic ray detectors have Poissonian distributions. Hence for the total counting rate, N, a standard deviation, $\sigma=\sqrt{N}$, will always occur. The bi-hourly counting rate for each Recordor is $\sim 1\times10^5$. So the σ, for the combined bi-hourly values from these three Recordors will be $\sim .18\%$; for the combined daily intensity σ will be $\sim .059\%$; the mean monthly bi-hourly values have $\sigma\sim .036\%$ and the bi-hourly values averaged over a year will have $\sigma\sim .007\%$ This error for the mean bi-hourly values over a year is thus sufficiently small compared with the expected solar daily variation $\sim .05\%$ (MacAnuff, 1951) or the sidereal daily variation $\sim .05\%$ (Mathews, 1962), if they at all exist.

2.9 Summary

(i) The relative ease and the flexibility of the construction and maintenance of the scintillation counter telescopes using Plastic scintillators have been described in the beginning of the chapter.

(ii) Both the long-term and the short-term instrumental instabilities have been fully taken into account. Both the visual and the statistical tests revealed no significant disagreement between the different Recorders during last 12 months of running.

(iii) The different sources of errors have been discussed and the magnitudes of the errors estimated to show that allowing for all these errors, a significant and useful investigation of the anisotropies produced by the solar or the galactic modulation of the primary cosmic rays is possible.

CHAPTER III

DAY TO DAY VARIATIONS OF ATMOSPHERIC ORIGIN

3.1 Introduction

A cosmic ray detector located at sea-level or underground for the continuous recording of the cosmic ray flux will monitor the secondary particles produced by the interactions of the primary particles with air nuclei near the top of the atmosphere. Consequently, the number of the particles falling on the detectors is strictly controlled by the state of the atmosphere particularly, its pressure and temperature. This means that before the time-variations of these cosmic ray intensities can be related to those of the primary cosmic rays adequate corrections have to be applied for the variations in the atmospheric parameters which control the cosmic ray intensities.

Investigation of the atmospheric effects on cosmic ray variation began as early as 1928, when Myssowsky and Tuwim (1928) first discovered the barometric effect, or the negative correlation of the cosmic ray intensity with sea-level pressure. Later on the works of Compton and Turner (1937) and others showed that the sea level cosmic ray intensity was related to atmospheric temperature variations. There were, however, many difficulties in finding a consistent temperature effect for example, Hess (1939) found that the temperature coefficient varied with the season. There were also severe difficulties in finding a reasonable explanation for the seasonal variations of the cosmic ray intensity (Chapter IV).

In the meantime more and more properties of the secondary cosmic rays became known and it was realised that the hard component of the cosmic ray flux consists mainly of unstable μ-mesons. Therefore an explanation of the cosmic

ray variations of atmospheric origin consistent with the known absorption and decay properties of mesons was sought. For instance, it became clear that since most of the sea-level muons are produced at a height $\sim$ 16 km, the mean temperature upto that height is likely to control the cosmic ray flux observed at sea level, rather than the ground temperature.

Duperier (1944) using an unshielded three-fold coincidence counter telescope, found that the cosmic ray intensity, I, correlates with the sea-level pressure, B as well as with the height of the meson production layer, H. The first factor gives the absorption effect while the second factor determines the decay effect of the muons. This decay effect arises from the fact that when H increases, the path length of the muons reaching the detectors at sea-level increases, but since the muons have a short life time ($\sim$2.1 μ-sec), a decrease of the cosmic ray flux will occur thus giving rise to a negative correlation with H. In order to separate these two effects for day-to-day cosmic ray variations, he used a regression eqn. of the type,

$$\frac{\delta I}{I} = \beta_{1B.H}\,\delta B + \beta_{1H.B}\,\delta H \qquad (3.1)$$

where, $\delta\xi$, denote the deviations of the parameters from their means during the period of the analysis; $\beta_{1B.H}$ and $\beta_{I\,H.B}$ are the partial regression coefficients representing the barometric and the decay effects; B, H, and I have the same meanings as above. Duperier found that the height of the 100 mb level appeared to be the dominant production layer for the sea-level muons.

However, in subsequent experiments with shielded counter telescopes Duperier (1949) discovered what is now known as the positive temperature effect - the effect of the changes in the density of the air near the production level. The density of the air is inversely proportional to the air-temperature in this

region and consequently he modified the eqn.(3.1) to include the effect of the variable mean temperature, T of the 200-100 mb level so that,

$$\frac{\delta I}{I} = \beta_{1B.TH}\,\delta B + \beta_{1H.BT}\,\delta H + \beta_{IT.BH}\,\delta T \qquad \ldots\ldots(3.2)$$

where, $\beta_{IT.BH}$ now is the partial regression coefficient representing the positive temperature effect while the other regression coefficients have the same meanings as above.

This positive temperature effect has been explained by Duperier as being the consequence of the competition between the processes of nuclear interaction and decay of π-mesons. π-mesons are produced by the nucleon-nucleon interaction of the primary cosmic ray particles with the air nuclei near the top of the atmosphere (the mean production layer being 100 mb) and then can either decay to μ-mesons or interact with the air nuclei. The probability of interaction of π-mesons of a certain energy will be directly proportional to the density of the air along its path. When the temperature increases, the density decreases; this reduces the probability of interaction and consequently increases the μ-meson intensity at sea-level as more π-mesons can decay to μ-mesons in this case. A positive regression coefficient is, therefore, a direct consequence of the known properties of π-mesons. With this interpretat the positive temperature coefficient β_T can be written as,

$$\beta_T = -\frac{L}{R}\,\frac{d\rho}{dT} \qquad \ldots\ldots(3.3)$$

where L = the range in cm. before decay

R = the m.f.p. in gm/cm^2

ρ = the density of the air.

This explanation, though successful in eliminating certain difficulties of the seasonal variations in sea-level cosmic ray intensity (Dolbear and Elliot,19[1])

it proved to be insufficient when Duperier (1951) himself found that the observed coefficient is about 3 times greater than the value calculated according to eqn. (3.3). Trefall (1955a,b,c) attempted to explain the temperature effects found by the correlation analysis in terms of theoretical expressions. He succeeded in obtaining theoretical values for the barometric coefficient and the positive temperature coefficient by taking into account the known properties of the atmosphere and the contributions made by the second order effects of the μ-e decay on these coefficients. Trefall finds good agreement between the theory and the experiment, if, and only if, the spurious contributions from the μ-e decay are included.

A completely new approach was made by Dorman (1957) and Maeda (1960) to find the atmospheric effects on the cosmic ray intensity variations. Dorman has shown that the discrepancies observed, when the correlation method is used to find the temperature coefficient, are due to the fact that the correlation method does not take account of the distribution of air masses in the essentially non-equillibrium atmosphere and spreading of the muon production throughout the atmosphere. The first factor can reduce the effect of the lower layers in producing the temperature effect, while the second factor can increase the importance of the higher layers in producing the temperature effect. Hence, different temperature coefficients will result from the correlation analysis depending on the correlations existing between the temperature variations of the air in the upper and lower layers of the atmosphere

In order to avoid the difficulties of the correlation method, Dorman deduced a theoretical expression representing the cosmic ray variations due to the atmospheric effects, as given by,

$$\frac{\delta I}{I} = \beta dB + \int_0^{B_0} W(B)\,\delta T(B)\,dB \qquad \ldots\ldots(3.4)$$

where, β is the barometric coefficient; $\delta T(B)$ is the variations of the temperature at various isobaric levels ranging from the observation level with pressure, $B=B_0$ to $B=0$; dB is the variations in B and $W(B)$ is the 'density of temperature coefficient'. $W(B)$ is a definite function and is calculated taking into account of the energy spectrum of the primary cosmic rays, energy loss and production of μ-mesons in the atmosphere, etc. It also includes the effects of the decay properties of the π-meson and the μ-meson.

In calculating the temperature effect in this case (eqn. 3.4), it is necessary to divide the whole atmosphere into several layers, starting at ground level and reaching beyond the 100 mb level and determine the mean values of $\delta T(B)$ for those layers from the radio-sonde data. Then by multiplying these values with the corresponding values of $W(B)$ appropriate for the place of observations and the detectors used (as calculated by Dorman), one can easily correct the cosmic ray variations due to the second term in eqn.(3.4).

Nonetheless, both of these methods suffer from several sources of errors and disadvantages. The theoretical models depend on the exact knowledge of the composition of primary cosmic rays as well as their energies, charges and directions of arrivals; they will also depend on the nature of the interactions of the primary and secondary particles with matter at different energies. The inadequacies in our knowledge of these factors are bound to introduce errors in these theoretical estimates. In correlation methods, it is necessary that I is dependent on the selected atmospheric variables which should be independent of each other. Furthermore, there should be a linear

relationship between I and the other variables. While the linear relationship is generally assumed to be the correct one and the normal distributions of the variables are approximated by using long periods in the analysis, the condition of independence of the variables is not usually realised in practice (Weatherburn, 1952; Dyring and Lindgren, 1962).

We have, however, preferred the use of the correlation method in evaluating the atmospheric effects in our present analysis for the reasons stated below. An examination of the function W(B) calculated by Dorman (1957) for a semicubica telescope located at ~ 55 m.w.e. underground shows that W(B) is very small and negative from ground level to 250 mb level but changes sign and tends to large values in the region of the 40 mb. isobar. However, the average meteorological sounding balloon rarely goes higher than the 100 mb. level and consequently the necessary temperature information for the satisfactory application of Dorman's method is not available on a day-to-day basis. Besides, the computational labour involved in the use of this method is formidable. On the other hand, the correlation method recommends itself for its relative simplicity. In addition, Trefall (1955) has pointed out that the spurious effects introduced by the second order effects of μ-e decay tend to negligibly small values at the high energies involved in underground measurements so that a simple interpretation of the regression coefficients obtained from correlation analysis is possible in our special case.

3.2 Analysis of the Underground Data

We shall present the results of the correlation analysis carried out on the basis of Duperier's correlation method in two groups. The first group relates

to the period from May, 1961 to April, 1963 and uses data from the two original telescopes built by Mathews (1962). The whole period has been subdivided into 11 smaller periods of roughly 30 to 35 days duration (total of 330 days) for purposes of our analysis. The combined daily counting rates from these two telescopes are 12×10^5, their standard deviations being $\sim .09\%$.

The second group relates to the period from July, 1963 to July, 1964 when six more new telescopes were operating with improved instrumental efficiency and stability as discussed in the previous chapter.

Daily mean values of the variables appearing in the eqn.(3.2) were computed for those days during which all the telescopes were running satisfactorily and during which the corresponding aerological data were available. The pressure data were taken from the values supplied by the Kew Observatory, London and the upper air data were taken from meteorological charts supplied by the British Meteorological Office. The upper air data at Crawley, about 25 miles due south-west of London have been used in the present analysis. Since there are only two radio-sonde flights per day - one at mid-day and another at mid-night - the weighted averages of the mid-day values and the preceding and following mid-night values were calculated to use as daily upper air temperature parameters.

3.2a. Results Obtained During 1961-63

First of all to take into account of all the possible atmospheric effects, we have carried out a four-fold correlation analysis on the basis of eqn.(3.2) where the barometric effect, the positive temperature effect and the decay effect are represented by separate terms. The temperature inside the atmospheric

layers of varying thickness and position in the range 200mb-70mb (the upper end being limited by the availability of the aerological data on a sufficiently large number of days) were used as the temperature parameters in the above analysis. The differences in the heights of 200 mb, 150 mb, 100 mb and 70 mb levels from that of 1000 mb level were used as the height variables. The values of the partial correlation coefficients obtained from this analysis are given below in Tables I(a,b,c).

Table I(a)

Period	Temperature between	Ref. levels H	$r_{1B,TH}$	$r_{1T,HB}$	$r_{1H,BT}$
I	200 mb - 100 mb	200 mb	-.696	+.459	-.307
		150 mb	-.683	+.459	-.335
		100 mb	-.718	+.545	-.246
		70 mb	-.734	+.605	-.193
II	200 mb - 100 mb	200 mb	-.986	+.820	+.189
		150 mb	-.988	+.793	+.375
		100 mb	-.986	+.754	+.114
		70 mb	-.986	+.731	+.014
III	200 mb - 100 mb	200 mb	-.876	+.583	-.245
		100 mb	-.869	+.635	-.168
		70 mb	-.865	+.578	-.061

Table I(b)

Period	Temperature between	Ref. levels H	$\gamma_{1B.TH}$	$\gamma_{1T.BH}$	$\gamma_{1H.BT}$
II	200mb-70mb	200mb	-.984	+.757	+.121
		100mb	-.983	+.667	-.022
		70mb	-.984	+.683	-.079
IX	200mb-70mb	200mb	-.872	+.714	-.335
		100mb	-.852	+.690	-.188
		70mb	-.849	+.700	-.067

Table I(c)

Period	Temperature between	Ref. levels H	$\gamma_{1B.TH}$	$\gamma_{1T.BH}$	$\gamma_{1H.BT}$
II	100mb-70mb	200mb	-.969	+.415	+.025
		100mb	-.960	+.411	+.261
		70mb	-.961	+.111	+.357
IX	100mb-70mb	200mb	-.894	+.345	+.080
		100mb	-.897	+.356	-.464
		70mb	-.890	+.384	-.022

It can be seen from the above tables that while the partial correlation coefficients between the cosmic ray intensity and the ground pressure as well as those between the cosmic ray intensity and the mean temperatures are significant and consistent, this was not the case for the correlation coefficients between the cosmic ray intensity and the height of an isobaric pressure level irrespective of whether 200 mb, 150 mb, 100 mb or 70 mb level was assumed to be the dominant production level of the observed muons. The reason for this poor correlation between the cosmic ray intensity and the heights of these isobaric levels, however, becomes clear if we note that the day-to-day fluctuations in the heights from the mean values seldom exceed .10 Km. Since the theoretical estimate of the decay ocefficient is of the order of $\sim$.72% per km (section 3.4b below), such a decay effect will be too small to be detected by the correlation method in the face of larger statistical fluctuations and variations of primary origin in the cosmic ray intensity (specially the 27-day type variations).

Therefore, further analysis on the basis of eqn.(3.2) was discontinued and the equation was modified into the form,

$$\frac{\delta I}{I} = \beta_{IB.T}\,\delta B + \beta_{IT.B}\,\delta T \qquad \ldots\ldots (3.5)$$

where we now neglect the decay term and include only those variables showing significant correlations with the cosmic ray intensity. The regression coefficients obtained on the basis of eqn.(3.5) for different temperature variables are shown in the Tables I(a,b,c) in the Appendix I. The errors shown there are in 95% fiducial limits.

The weighted mean values of the regression coefficients of this analysis with their errors in 95% fiducial limits are shown below in Table II.

Table II

limits of air layer	$\beta_{IB.T}$ %/mb	$\beta_{IT.B}$ %/°C
200mb-100mb	-0.0363 ± 0.0023	$+0.0415 \pm 0.0052$
200mb-70mb	-0.0369 ± 0.0024	$+0.0413 \pm 0.0061$
100mb-70mb	-0.0364 ± 0.0040	$+0.0500 \pm 0.0083$

The mean values in the Table II were obtained by weighting each value by $\frac{1}{\sigma^2}$, where, σ, is its standard deviation. It can be seen from the above table that neither the pressure nor the positive temperature coefficients differ significantly whatever the thickness or position of the air layer that is used. Since from the theoretical point of view it appears preferable to use the mean temperature of an even thicker layer of air extending from 200 mb to 10 mb level (Dorman, 1957), we have decided to use the mean temperature between 200 mb to 70 mb isobaric levels as the appropriate temperature parameter for correcting the data. It is also to be noted that the pressure or the positive temperature coefficients (as shown in the Table I(a,b,c) in Appendix I) obtained during the 11 periods analysed did not show any significant fluctuations nor did they show any seasonal dependence, even for all the three cases where three different temperature variables were used. This can be seen in Fig. 3.1 where we have plotted the regression coefficients obtained during different periods for a particular case of the mean temperature between 200mb - 70mb level.

3.2b. Results Obtained During 1963-64

During this period the combined data from the six telescopes improved the statistical accuracy by $\sqrt{3}$ times over the previous period (Section 3.2a) and no instrumental bias was expected in the results of the analysis. The

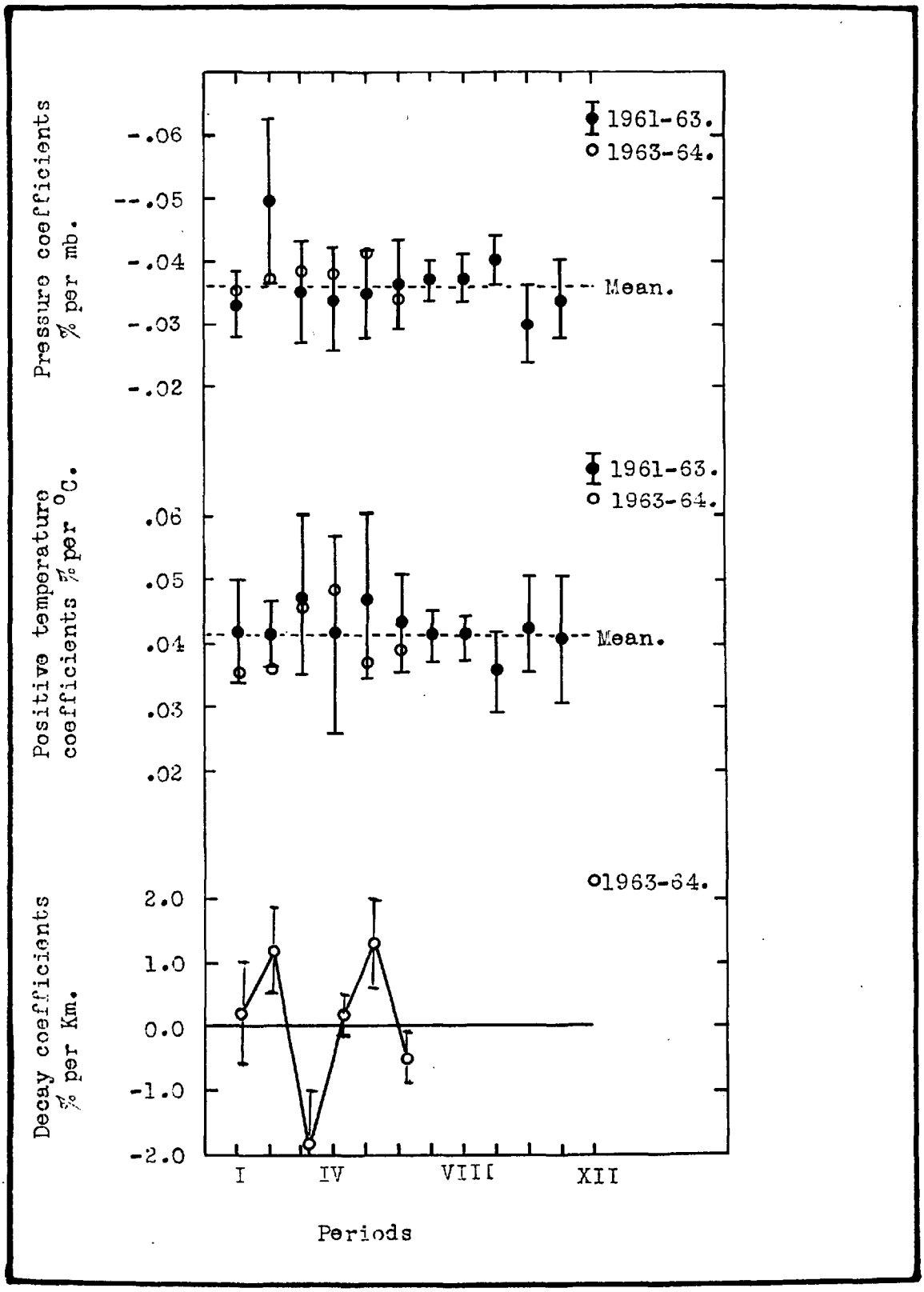


Figure 3.1 The regression coefficients as obtained from the correlation analysis.

period concerned was near the solar minimum epoch, so that the variations of primary origin in the cosmic ray intensity (as shown by 27-day variations and Forbush-decreases discussed in later chapters) were negligible. Hence conditions at the present time are most favourable to finding the atmospheric effects more accurately, than hitherto. Accordingly a four-fold correlation analysis (eqn.3.2) was carried out for six months using the more recent cosmic ray data. For upper air parameters we have used the difference of heights of the atmosphere between 100 and 1000 mb levels and the mean temperature of the air layer extending from 200 mb to 70 mb level. The results of the day-to-day analysis of each monthly periods are shown in Fig. 3.1 for comparison with those obtained during 1961-63. It can be seen that though the present analysis confirms the earlier results about the pressure and positive temperature effects, the decay coefficients were both positive and negative as well as significant and insignificant. Our attempt to find any meaningful decay coefficient was again fruitless. As a result further analysis on a monthly basis was postponed. However, to reduce the computational labour we calculated 5-day means of the variables appearing in the eqn. 3.2 for the 12 months in 1963-64. The results of the four-fold analysis carried out in this way are shown below in Table III. In this table we show the weighted mean values of the atmospheric coefficients obtained during 1961-63 (using the eqn. 3.5) and from 5-day means during 1963-64 (using the eqn. 3.2) together with their errors in 95% fiducial limits.

These results show that the correlation analysis yields consistent and significant pressure and temperature coefficients but still cannot detect the small decay effect although the indications are that an approximately consistent

Table III

Mode of analysis	Press.coeff.%/mb	Positive temp. coeff.%/°C	Decay coeff. %/Km.
Day-to-day (1961-63)	-0.0369±0.0024	+0.0413±0.0061	———
5-day mean (1963-64)	-0.0355±0.0015	+0.0520±0.0050	-0.5820±0.4290

value of the decay coefficient may be obtained by using longer periods in the analysis.

3.3 Discussions of the Results

The results obtained from the present analysis about the atmospheric effects on cosmic ray intensity variations at moderate depth underground will be compared with those expected from theoretical calculations, mainly following Trefall (1955,a,b,c) who developed theoretical expressions in an attempt to explain the regression coefficients yielded by the correlation methods. We shall then compare these theoretical estimates with those observed in the present analysis as well as those made by others.

In this connection it is interesting to compare the atmospheric coefficients obtained by two other workers, who also conducted experiments at the same place as the present one. MacAnuff (1951) worked with three geiger counter telescopes and Mathews (1963) worked with two scintillation counter telescopes. Their results from day-to-day correlation analysis (with the errors in 95% fiducial limits) are shown below in Table IV for comparison

Table IV

Investigators	Press. Coeff.%/mb	Positive temp. coeff.%/°C	Decay Coeff. %/Km
MacAnuff (1951)	-.0338±.0044	+.0550±.0100	———
Mathews (1963)	-.0424±.0086	+.0365±.0240	———

It can be seen from the tables III and IV that though MacAnuff used the mean temperature between the 300 mb and 100 mb levels and Mathews used that between the 200 mb and 100 mb levels (as compared to that between the 200 mb and 70 mb levels in the present case), the results from these three sets of measurements agree within the limits of statistical accuracy. We shall compare these values again with the expected values in the next sections.

3.3a The Barometric Effect

Trefall (1955c) has shown that the correlation analysis according to the eqn. (3.2), where μ-e decay effect is taken into account by a separate term, yields a 'partial' barometric coefficient. This partial barometric coefficient at these high energies represents simply the mass absorption effect. On the other hand, the correlation analysis on the basis of the eqn. (3.5) where the μ-e decay term is omitted, or the analytical methods outlined by Dorman (1957) and others, yield a 'total' barometric coefficient which includes the combined effects of mass absorption and μ-e decay effect operating simultaneously during changes of barometric pressure.

Trefall showed that the mass absorption effect of vertically travelling muons of momenta, P_s , at sea-level can be calculated only from an exact knowledge of their differential and integral intensities, n(P) and N(P) respectively, together with the cut-off momenta P_c of the recorders, as given by the expression,

$$\beta_m = \frac{n(P_c)}{N(P_c)} \quad \frac{dP_c}{dB} \qquad \ldots\ldots(3.6)$$

where, β_m is the mass absorption effect of the muons and $\frac{dP_c}{dB}$ is the rate of loss of momenta of the muons per unit change of pressure, B.

In calculating the mass absorption coefficient for our detectors we shall

assume that due to the special weighting properties of the counter telescopes, β_m for such recorders (semicubical telescopes) will be approximately the same as calculated for vertically incident muons. The reasons for such assumptions are as follows:

The intensity depth curve for the vertical intensity I(h) at a depth h(m.w.e.) is written as,

$$I(h) = Ah^{-m(h)} \qquad \ldots.(3.7)$$

where, m(h) is a positive number and A is some constant. Hence differentiating eqn.(3.7) and dividing each side by dB, a simple rearrangement yields,

$$\beta_m = \frac{m(h)}{h} \frac{dh}{dB} \qquad \ldots.(3.8)$$

where, $\frac{dh}{dB}$ is the effective change in depth per unit change of pressure, B. Now for particles arriving at a zenith angle θ, not only is the effective depth increased to hsec θ, but also the coefficient $\frac{dh}{dB}$ is increased by the same factor if the scattering in the solid absorber is neglected. This means that so long as m(h) remains constant, β_m would be same for particles arriving from the vertical as from inclined directions. m(h) is a slowly varying function but it is only at large zenith angles and at large energies that this variation becomes significant (Sheldon, *et al* 1962). Consequently, at this moderate depth and for the angle of acceptance subtended by the present telescopes we can expect that the calculated mass absorption coefficient according to the equation (3.6) will be correct to within a few percent.

Measurements of the muon spectra up to 1000 Gev/c have been made recently by groups at Cornell, Manchester, Sydney, and Durham using cosmic ray spectrographs of greatly improved resolution and statistical accuracy. Since there is good agreement amongst the different measurements up to ~100 Gev/c

and the values of differential and integral spectra from Durham cosmic ray spectrograph measurements were available from a paper published by Hayman and Wolfendale (1962), we have used Durham values of N(P) and n(P) for our present calculation. Similarly, the factor $\frac{dPc}{dB}$ was calculated by using formula developed by Rossi (1952) (in the range 5-10 Gev/c) and by Rossi and Greisen (1941)(in the range 10-100 Gev/c). The curve B in Fig. 3.2 gives the expected mass absorption coefficients for vertical mesons at different cut-off momenta of the recorders.

In calculating the contribution to the barometric coefficient, from the μ-e decay, we have again used the formula developed by Trefall, but using the Hayman and Wolfendale differential spectrum in order to get the integrated effect. The results of this calculation are shown in Fig. 3.2 (curve c). The combined effects of mass absorption and decay effect, i.e., the total barometric coefficients expected at different cut-off momenta P_c are shown as curve A in the same figure.

The comparison of curve A with that given by Trefall shows that it agrees well with Trefall's calculated values in the low momentum region. Similar agreement is found with the calculations of Wada (1962) except in the high mementum region (above 50 Gev/c) where our calculated values seem to be a little higher than those of Wada. This disparity at higher momentum region may be due to the differences in the momentum spectra selected as well as the factor $\frac{dPc}{dB}$ which is rather uncertain at high momenta.

The experimental values of barometric coefficients obtained by MacAnuff (1951), Mathews (1963) and the present author at London, by Fenton et al (1961) at Hobart (42 m.w.e.) as well as by Sandor et al (1962) at

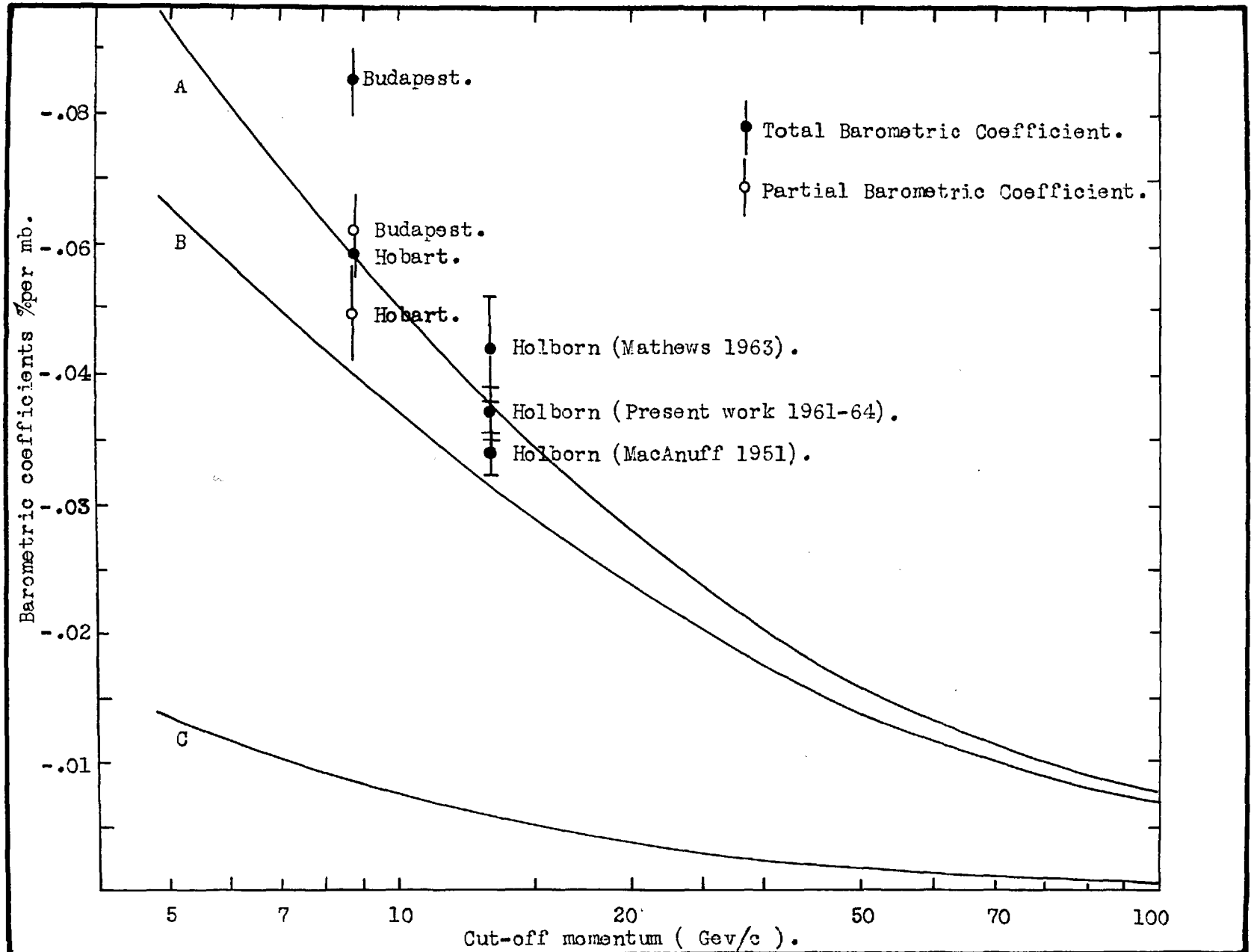


Figure 3.2 The barometric coefficients as a function of cut-off momenta.

Budapest (40 m.w.e.) are also shown in Fig. 3.2 for comparison with our estimates. The errors are given as 95% fiducial limits. The agreement between the calculated and the observed values at London is excellent. There is also good agreement at Hobart, though Fenton et al found some discrepancy between theory and observation. The Budapest point, however, appears slightly higher than our calculation but a part of this discrepancy can surely be ascribed to the increased elevation of the Budapest station.

3.3b The μ-eDecay Effect

It has been shown earlier in this chapter that even with the higher accuracy of the cosmic ray data used here, only an approximate value of the negative temperature effect could be detected by the correlation analysis. A theoretical estimate of the decay effect has therefore been made, and the method of doing so is outlined below.

At a depth of 60 m.w.e. the momentum lost by a muon in traversing the atmosphere is not negligible in comparison with the average momentum of the recorded mesons. In the calculation it is assumed that the muons are produced in the vicinity of the 100 mb level through π-μ decay. The decay coefficients were calculated for vertically incident mesons with the momenta corresponding to mesons (i) at sea-level, (ii) at 550 mb level and (iii) at production from the formula,

$$\beta_{decay} = - \frac{m_\mu}{\rho_x \, P_x \, t_\mu \, C} \qquad \ldots.(3.9)$$

where, C, is the velocity of light; m_μ and t_μ are the mass and life-time of muons at rest; ρ_x is the density of the air, and P_x is the momentum of the muon, at a depth x-gm/cm^2. The average of these values was calculated as the decay coefficient for the mesons at sea-level with the momentum, P_s. The decay

coefficients of vertically incident mesons at a recorder with the cut-off momentum, P_c were calculated as the integrated effect over the recorded part of the momentum spectrum by using differential intensity at sea-level as a weighting factor. The results are given as a continuous curve in Fig. 3.3, together with the observed values at London, Budapest and Hobart. Wide variations of the values and their large statistical errors, however, make any conclusion difficult.

The estimated value of decay coefficient for London is found to be about 0.72% per km. Considering the day-to-day variations in H (about 100 meters), we find that the corresponding change in the daily intensity caused by the decay effect is only about .07%. This change compared to the statistical error of the combined daily records during 1963-64 (about 0.05%) is not expected to be detected by the correlation method and is more likely to be masked by the statistical errors of the parameters used in the correlation analysis and also by the dominant pressure and temperature effects. However, this correction becomes important for periods of large atmospheric disturbances and in the seasonal analysis of the data. An approximate value of the decay coefficient obtained by using 5-day means during 1963-64 might have been accidental. No significance can, however, be attached to this value because of the error involved.

3.3c The Positive Temperature Effect

Even though the temperature inside the atmospheric layers of varying thickness and position in the range 300mb - 70mb was used in the correlation analysis, none of the positive temperature coefficient measurements obtained at London differ significantly from each other, (viz, Tables III and IV).

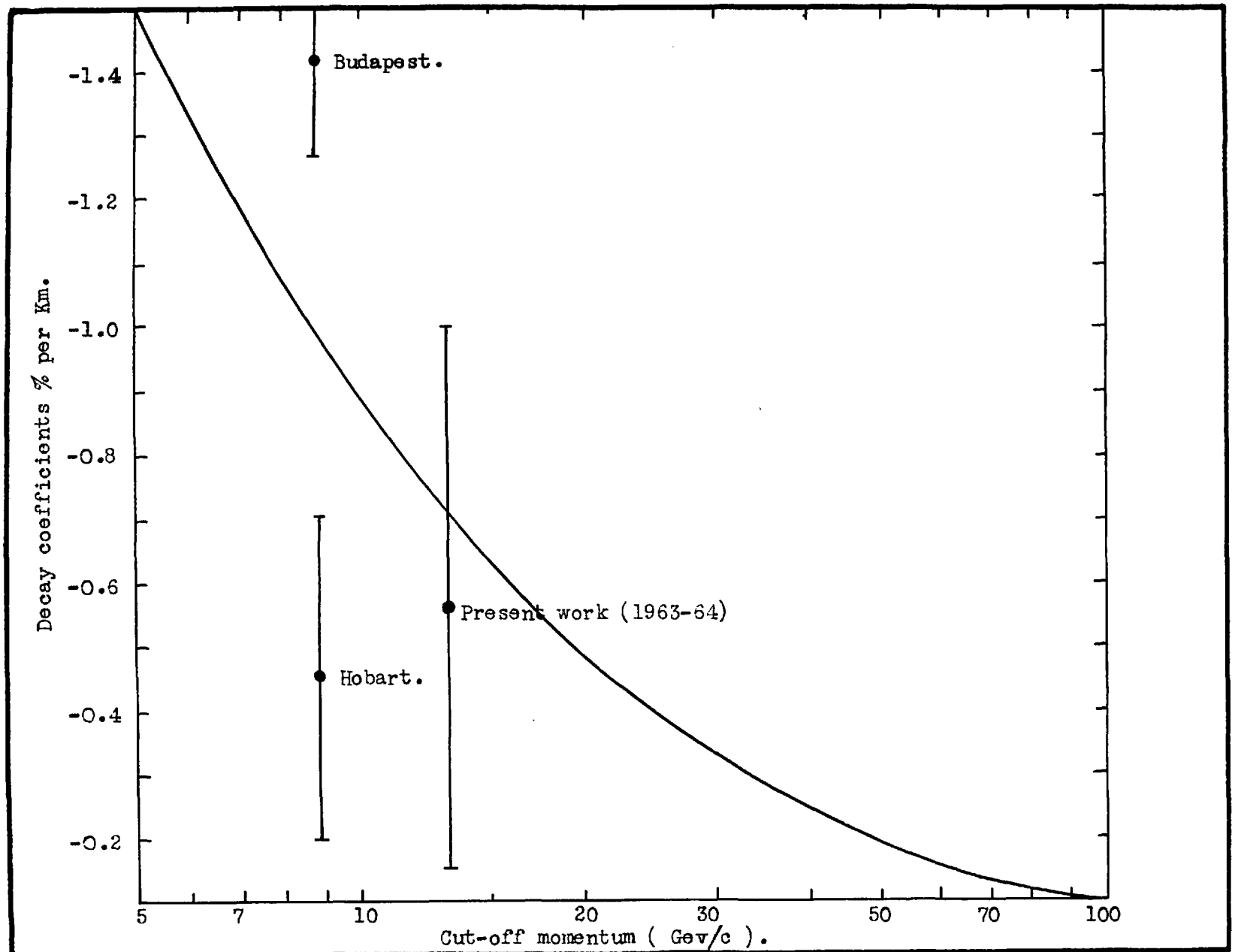


Figure 3.3 The decay coefficients as a function of cut-off momenta.

However, we note that all these values are consistently lower than the theoretical estimate ($\sim$.1% per ^{o}C) of Trefall (1958) where he calculated the positive temperature coefficients by assuming temperature variations in the atmosphere independent of depth and taking the attenuation length of pions to be as high as $\sim$250 gm/cm^2.

It is, therefore, interesting to look into the overall significance of these results and examine the possible reasons of this lowering of the observed positive temperature coefficient.

First of all, the inclusion of the negative effect from μ-e decay may partially cancel the positive effect from π-μ decay (Trefall, 1955a; Barrett et al, 1952). Theoretical calculations were carried out assuming an atmosphere with strongly correlated temperature changes at all levels of the atmosphere. Since in our correlation analysis with the eqn.(3.5) μ-e decay term was omitted, the above factor might have played an important part in our measurements during 1961-63. However, the negative effect arising from the temperature changes in the portion of the atmosphere below the 100 mb level could not be incorporated into our measurements due to the fact that the average correlation between the movement of the 100 mb level and the changes of the temperature in the portion of the atmosphere between 200mb and 70mb levels was found to be negligibly small over the entire periods considered. A similar conclusion can be drawn from the measurements of Fenton et al (1961) at 42 m.w.e. In both the measurements it is found that the positive temperature coefficients obtained from a four-fold correlation analysis (where the μ-e decay is included) and also from a three-fold correlation analysis (where the μ-e decay term is omitted) do not differ significantly from each other.

It thus can be concluded that the negative effect produced by the temperature variation below the selected reference level is not the cause of the low value of the observed positive temperature effect. However, if the meson beam above the reference level contains also muons, as is likely to be the case, a negative temperature effect would be incorporated into our measurements due to the changes in stratospheric temperature, so that the final value of the positive temperature coefficient would be determined from the relative proportions of pions and muons.

Diminution of the observed positive temperature effect may also result if a considerable fraction of the mesons observed underground originate from the decay of mesons heavier than pions. Judge and Nash (1963) have, indeed, pointed out that about 30% of the muons with production momenta above 40 Gev/c could come from Kaon-decay. The positive temperature effect will in this case be smaller because of the shorter mean life of K-mesons. There is also some indication (Trefall, 1955a) that due to further pion production in pion-nucleon interaction, the absorption length of the pions may be few times longer than their interaction mean free path.

Finally, it is to be noted that our selection of the portion of the atmosphere to be used in the correlation analysis was made according to the availability of the aerological data. This portion of the atmosphere, as pointed out by Dutt and Thambyahpillai (1964), may not be a sufficiently representative sample of the entire region of the stratosphere whose temperature controls the cosmic ray intensity observed underground. It was found from the available upper air data that the temperature changes above and below 100mb level (e.g., 50mb and 200mb levels) are in general poorly correlated

and the amplitudes of the temperature variations above 100 mb level seem to be smaller than those below by a factor of two or more. Now, it has been pointed out by Barrett et al (1952) and Dorman (1957) that the upper most layers of the atmosphere should be given increased weighting in determining the atmospheric temperature coefficient. Under these circumstances, the observed value of the positive temperature coefficient could well be smaller by a factor of 2 or more than is to be expected from the theoretical estimates. A further discussion of this temperature coefficient will be given in the next chapter dealing with the seasonal variation of intensity.

3.4 Summary

1) The barometric coefficient (-.037% per mb) has been measured from correlation analysis and the measured value agrees very well with the theoretical estimates.

2) No decay effect was detectable even with higher accuracy in our cosmic ray data and even in the absence of any variations of primary origin in the cosmic ray intensity. A theoretical estimate of the decay effect (-.72% per Km) was made for correcting our data, especially during seasonal analysis.

3) The experimental positive temperature coefficient, (+.04% per ^{o}C), though it agrees within statistical errors with those obtained by MacAnuff and Mathews, is lower than the estimated value. The possible causes for this discrepancy are discussed and it is found that the omission of the influence of the upper-most layers of atmosphere might be the chief cause for this uncertainty.

CHAPTER IV

ANNUAL VARIATION

4.1 Introduction

A seasonal wave of the hard component of cosmic rays corrected for ground pressure was detected as early as the 1930's, but these early results were not mutually consistent and they had not been properly corrected for the atmospheric effects. A seasonal wave with maximum during the summer months was reported by Clay (1930), Steinke (1930), Hess (1940) and others, while a pronounced maximum during the winter months was reported by Compton and Turner (1937), Hess (1936) and others. Working with the Compton-Bennett meters at Cheltenham, Toloyucan, Christchurch and Huancayo, Forbush (1938) also found a maximum during the winter months. He found a negative correlation with the ground temperature which differed from station to station. He, however, thought that this apparent seasonal wave was due to the distribution of air density with height in the atmosphere. Gill (1939), on the other hand, found poor correlation with the ground temperature and could explain the winter maximum on the basis of Blackett's (Blackett, 1938) meson decay theory. Vallarta (1939a) showed that the seasonal wave cannot be explained by the solar magnetic moment model which he proposed earlier (1939b).

Duperier (1941, 1948) in the mean time made detailed studies of the annual variations in cosmic ray intensity at sea-level and showed that the theory of meson decay can adequately explain the annual variations and can also account for the discrepancies observed by the earlier workers. He showed that it is necessary to take into account the movement of the meson production layer, which is more closely related to the mean temperature of the atmosphere than to the ground temperature.

This theory was successfully applied by Dolbear and Elliot (1951) in their analysis of the seasonal wave obtained with two inclined counter telescopes at Manchester. They found a pronounced maximum during the winter months when the cosmic ray intensity was corrected only for pressure, but when due allowance also was made for the decay effect a seasonal wave with the maximum during the summer months was obtained. They concluded that this variation can be explained with the help of Duperier's positive temperature effect, because the upper air temperature was found to be in phase with the seasonal variation of the cosmic ray intensity. Since then their finding about the meteorological modulation of the seasonal wave has been confirmed by others. A small extra-atmospheric modulation of the seasonal wave was reported by the Russian workers (Dorman and Feinberg, 1958).

However, all these results refer to the sea-level observations and very few results have been reported from underground measurements. Rau (1939) reported a seasonal wave of ~2% at 40 m.w.e.; his records, however, were not corrected for any atmospheric effects. MacAnuff (1951) working at the same place as the present experiment reported a seasonal wave of ~ 0.5% with the maximum during summer months. This could be explained on the basis of Duperier's theory of competitive decay and nuclear absorption of π-mesons. Kuzmin (1960) working with recorders situated at 7, 20 and 60 m.w.e. underground, showed that when corrected for pressure the seasonal variations diminished with the depth and the correction of the wave with Dorman's 'density of temperature coefficients' completely eliminated the seasonal variations in each case.

We intend to present below the results of the study of annual variation in cosmic ray intensity observed at 60 m.w.e. underground and see to what extent

the observations can be explained in terms of meteorological factors.

4.2 The Seasonal Variation Observed Underground

For the study of the annual variation in the cosmic ray intensity it is necessary that the recorders should yield reliable and continuous data for at least 12 complete months; these data should also be free from large irregular variations, often associated with the Forbush-decrease type phenomenon. It has already been stated elsewhere, that from August 1963 to July 1964, we have accumulated almost unbroken cosmic ray data from the six new telescopes. There were no electronic faults breakdown nor any other detectable instrumental defects during this period. Furthermore, no Forbush decrease, which could modulate the cosmic ray intensity at Holborn, occurred during this period, except in September, 1963, when a barely significant decrease occurred in the cosmic ray intensity. All these conditions, together with the higher accuracy of the cosmic ray data, made it possible to study the annual variation underground during 1963-64 with a fair degree of confidence.

We shall also present the results of the study of annual variation in the cosmic ray intensity underground using cosmic ray data from one of the two old telescopes. The data from December 1960 to November 1961 have been selected for presentation as during this period, at least one of the two telescopes appeared to function in a completely stable fashion.

Uncorrected monthly mean intensities and the corresponding values of the sea-level pressure during 1960-61 are shown in Fig. 4.1a. The curves are drawn from August to August in order to facilitate the comparison of these results with those obtained during 1963-64. The monthly mean intensities during 1963-64, corresponding to the three Recorders I, II and III have been plotted

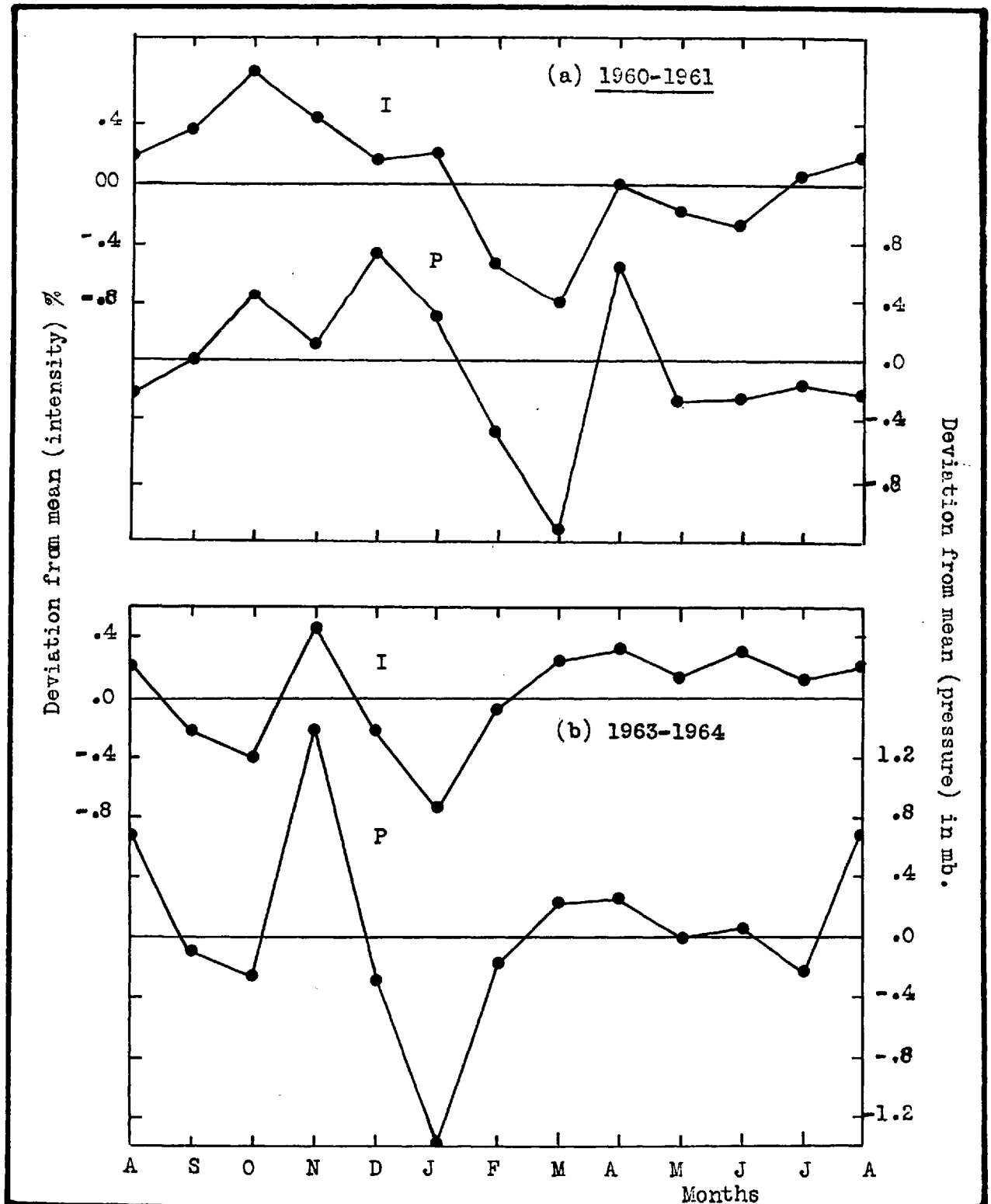


Fig. 4.1 The mean monthly intensity variations underground for periods (a) 1960-61 and (b) 1963-64. The intensities have not been corrected for any atmospheric effects. I - intensity; P - pressure.

in Fig. 4.2. The Recorder III, however, showed a small drift (~.2%) during the period January to April, 1964 and the points corresponding to these months have been plotted after correcting for this drift. It can be seen that all three intensity curves show fairly good agreement with each other. However, in order to avoid introducing any bias in the analysis we have used the cosmic ray data from the Recorders I and II only in the following analysis. The mean monthly intensities from these two Recorders together with the corresponding sea-level pressure over the period August 1963-July 1964 are shown in Fig. 4.1b. The curves showing sea-level pressures have been plotted in the reverse scale in order to show the marked negative correlation with the cosmic ray intensity. The cosmic ray intensities, therefore, have been corrected for the sea-level pressure, using a barometric coefficient of -0.037% per mb. as obtained from the day to day analysis and the resultant curves for these two years are shown in Figs. 4.3a and 4.3b.

It has been shown in the previous chapter that the muon decay effect was small enough to be negligible for day to day variations in the cosmic ray intensity, but would be appreciable during seasonal analysis. To see that this is so, we have plotted the mean monthly values of the differences of the heights between the 100 mb. and 1000 mb levels in these figures, corresponding to these two years concerned. It can be seen that the annual range in the height of this pressure level is of the order of 500 to 600 meters which, according to our estimate of the decay coefficient (-0.72% per Km), would cause an annual change in the cosmic ray intensity of the order of ~.4%. This variation, compared to the observed annual range of the cosmic ray intensity, is not negligible. Hence, the observations were then corrected for the movement of the

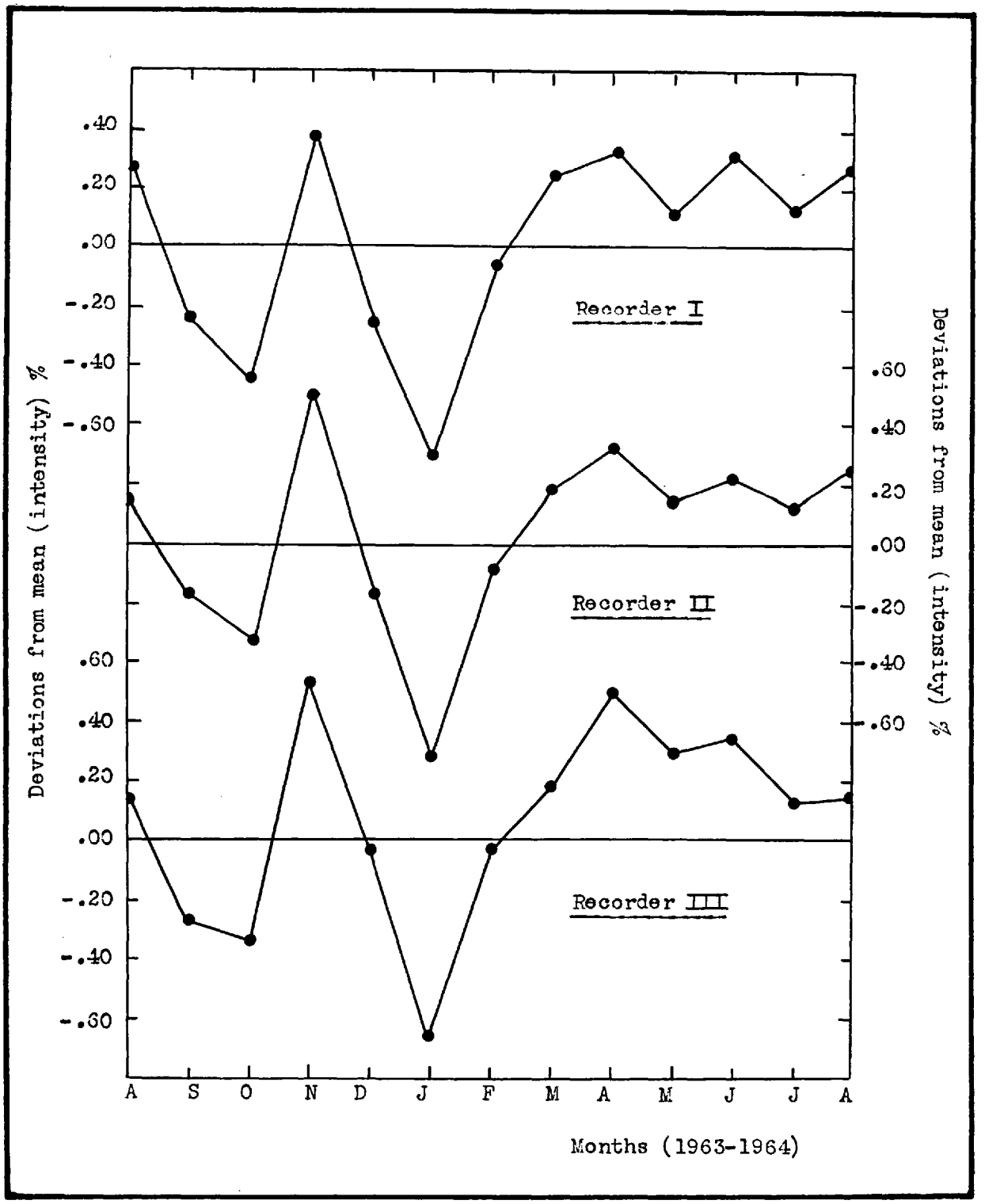


Figure 4.2 The mean monthly intensities underground for 1963-1964 measured by the three recorders. Intensities have not been corrected for any atmospheric effects.

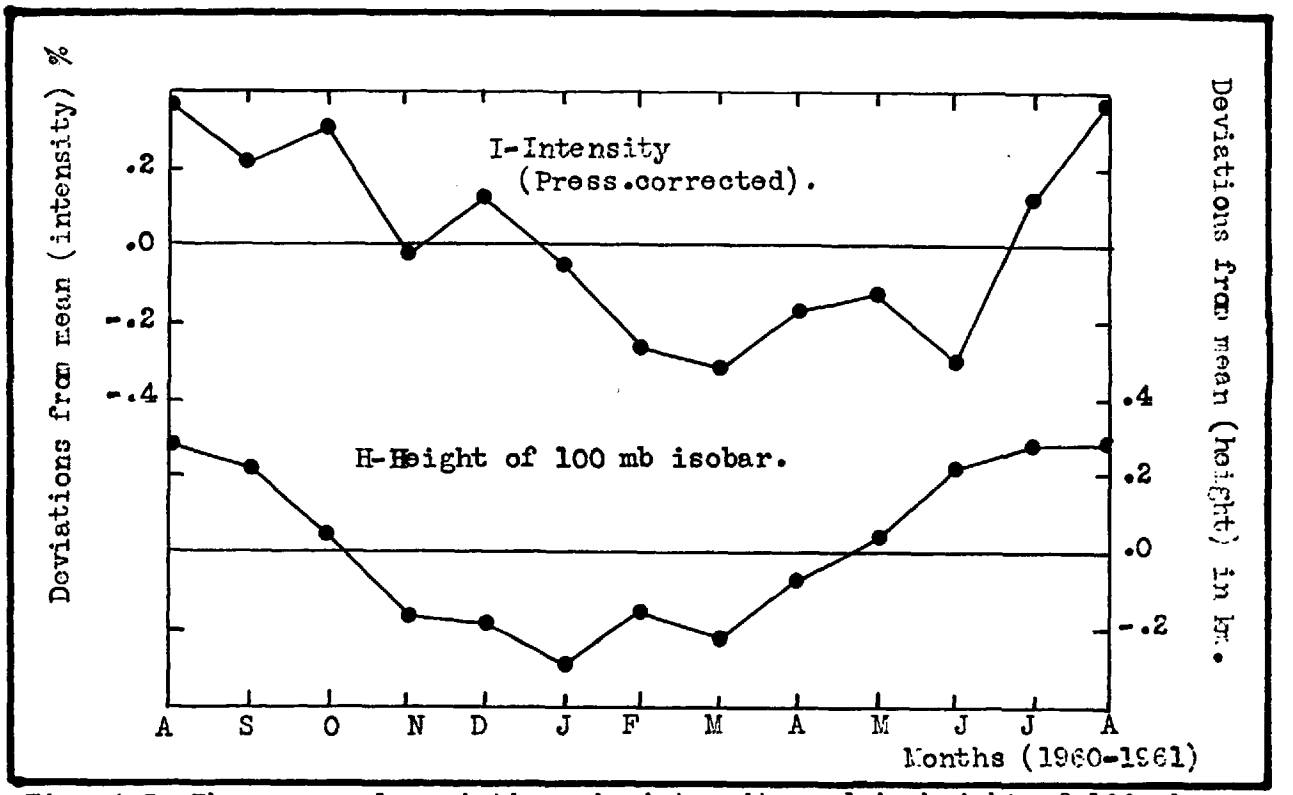


Fig. 4.3a The seasonal variations in intensity and in height of 100 mb.

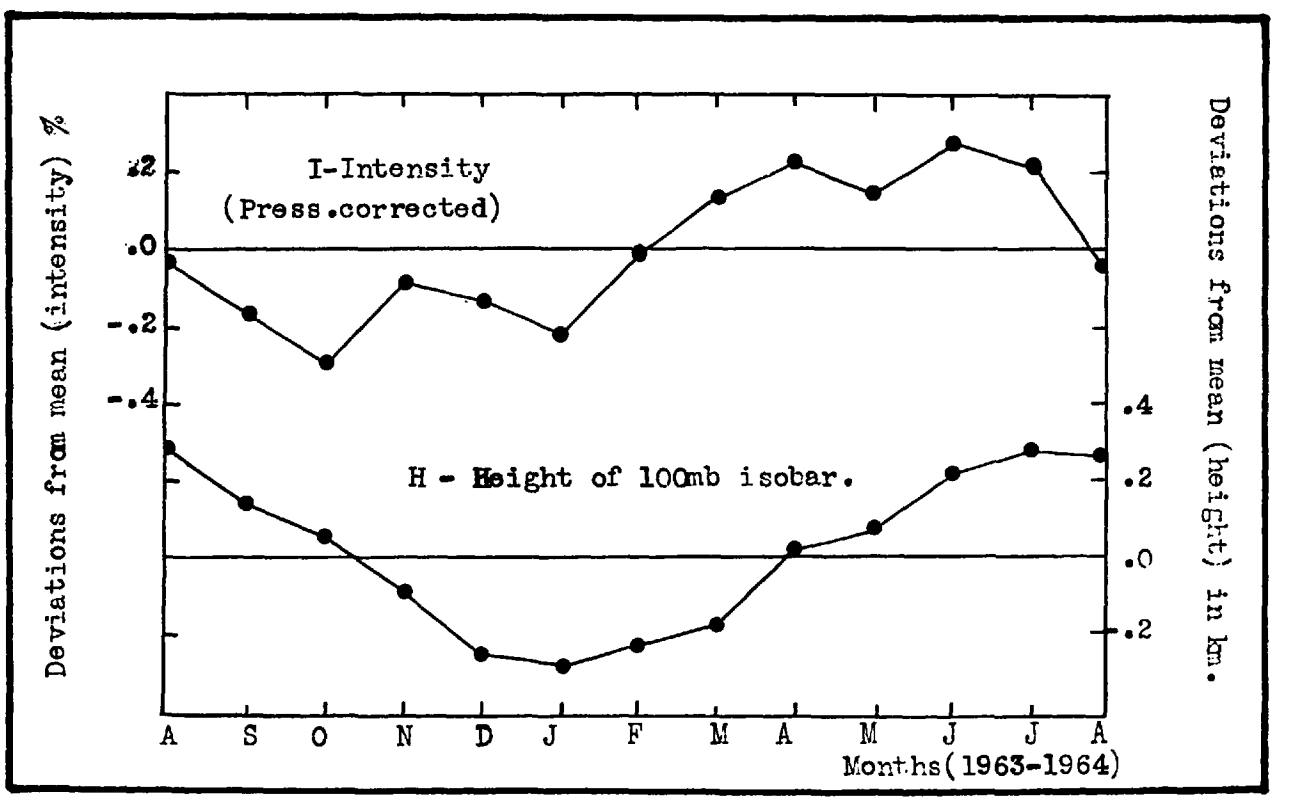


Fig. 4.3b The seasonal variations in intensity and in height of 100 mb.

height of the 100 mb isobaric pressure level and the corrected curves are shown in Figs. 4.4a and 4.4b corresponding to these two years. The difference in height between the 100 and 1000 mb levels has been chosen as the appropriate variable for the decay correction because a total barometric coefficient has been used to correct for the effect of pressure changes.

In Figs. 4.4a and 4.4b, are shown the corresponding mean monthly values of the average temperature of atmospheric layer lying between the 200 mb and 70 mb pressure levels. The positive correlations of the cosmic ray intensities with these temperature waves are clearly evident in both the years.

This parallelism between the cosmic ray intensity and the lower stratospheric temperature has been investigated further by the methods of correlation and harmonic analyses. The harmonic analysis was carried out for the two years using the 12-monthly values of the cosmic ray intensity (corrected and uncorrected for barometric and decay effects) and those of the temperature waves. In Figs. 4.5a and 4.5b, we have plotted the first harmonics of different vectors for the two years and the results are shown below in Table I. We have also given in this table the amplitudes of 2nd-harmonics to show that they are negligibly small.

It can be seen from Table I that in both the years there were small phase differences between the cosmic ray intensity and the temperature vectors. The phase difference is reduced when a height correction is introduced but the height correction enhances the amplitude to such an extent that this amplitude cannot be accounted for by a temperature coefficient of +.04% per ^{o}C which was obtained by the day to day correlation analysis.

It will, therefore, be interesting to examine the results of the correlation

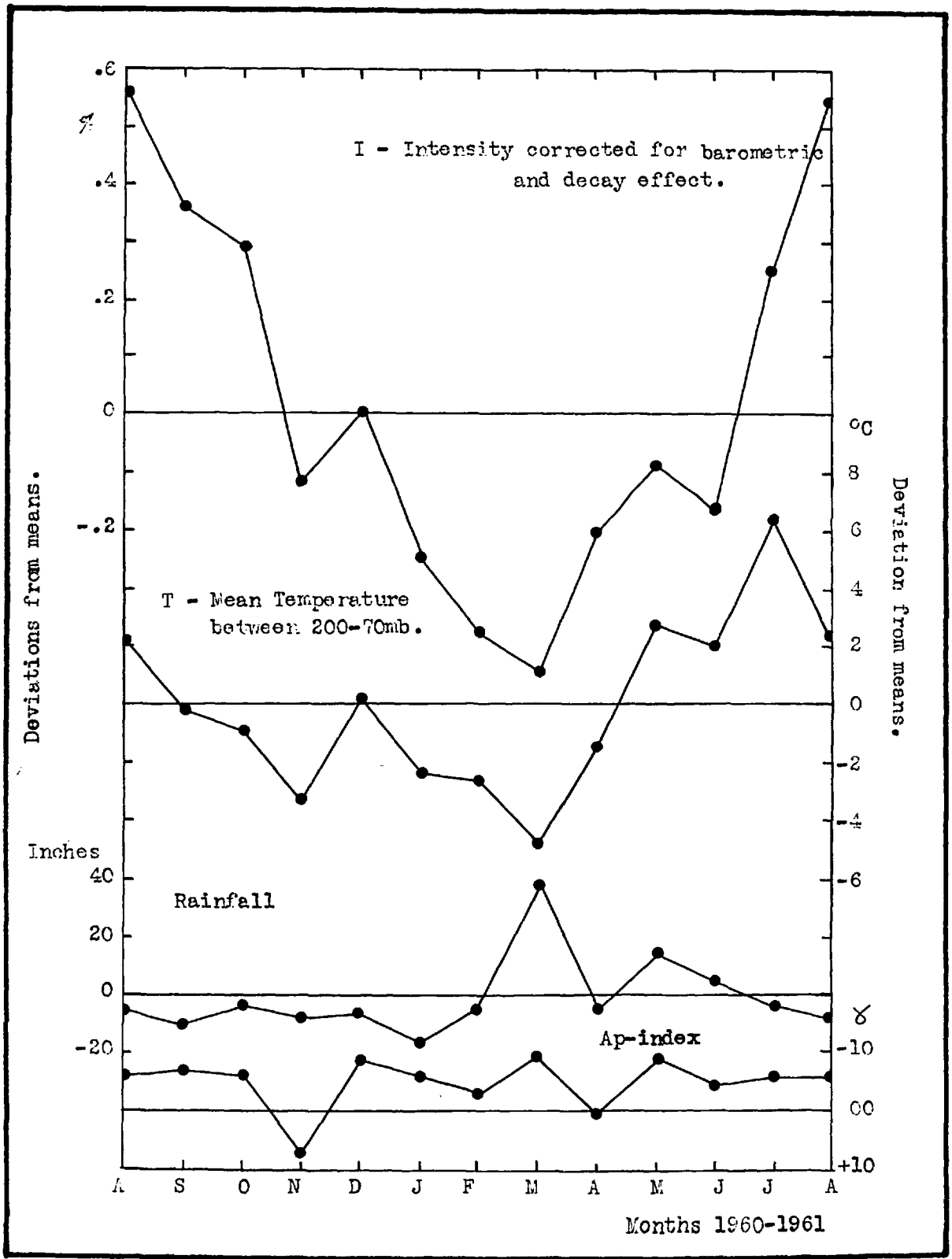


Fig. 4.4a The seasonal variations in Intensity, Temperature, Rainfall and Ap-indices for 1960-61.

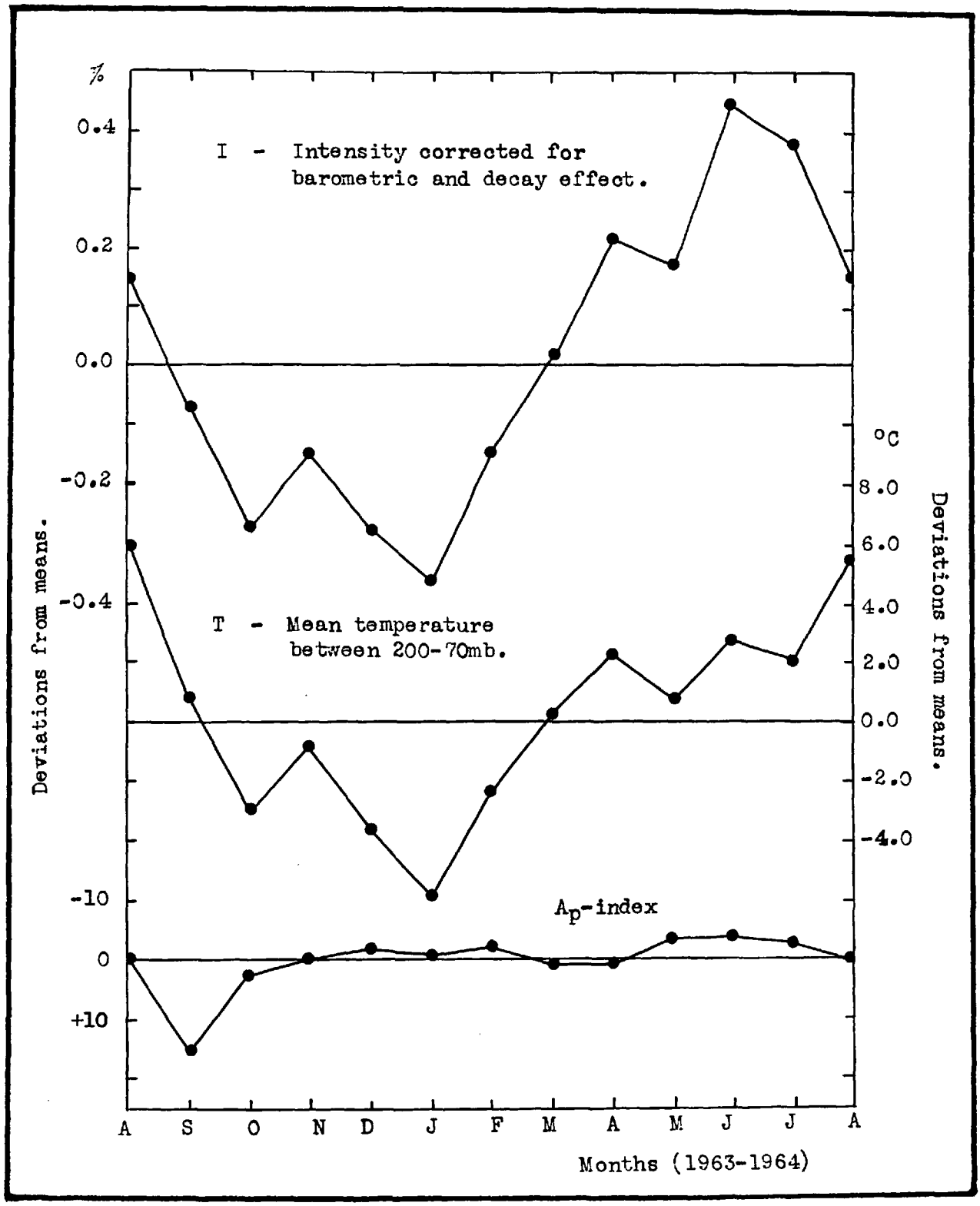


Figure 4.4b The seasonal variations in Intensity, Temperature and Ap-indices for 1963-1964.

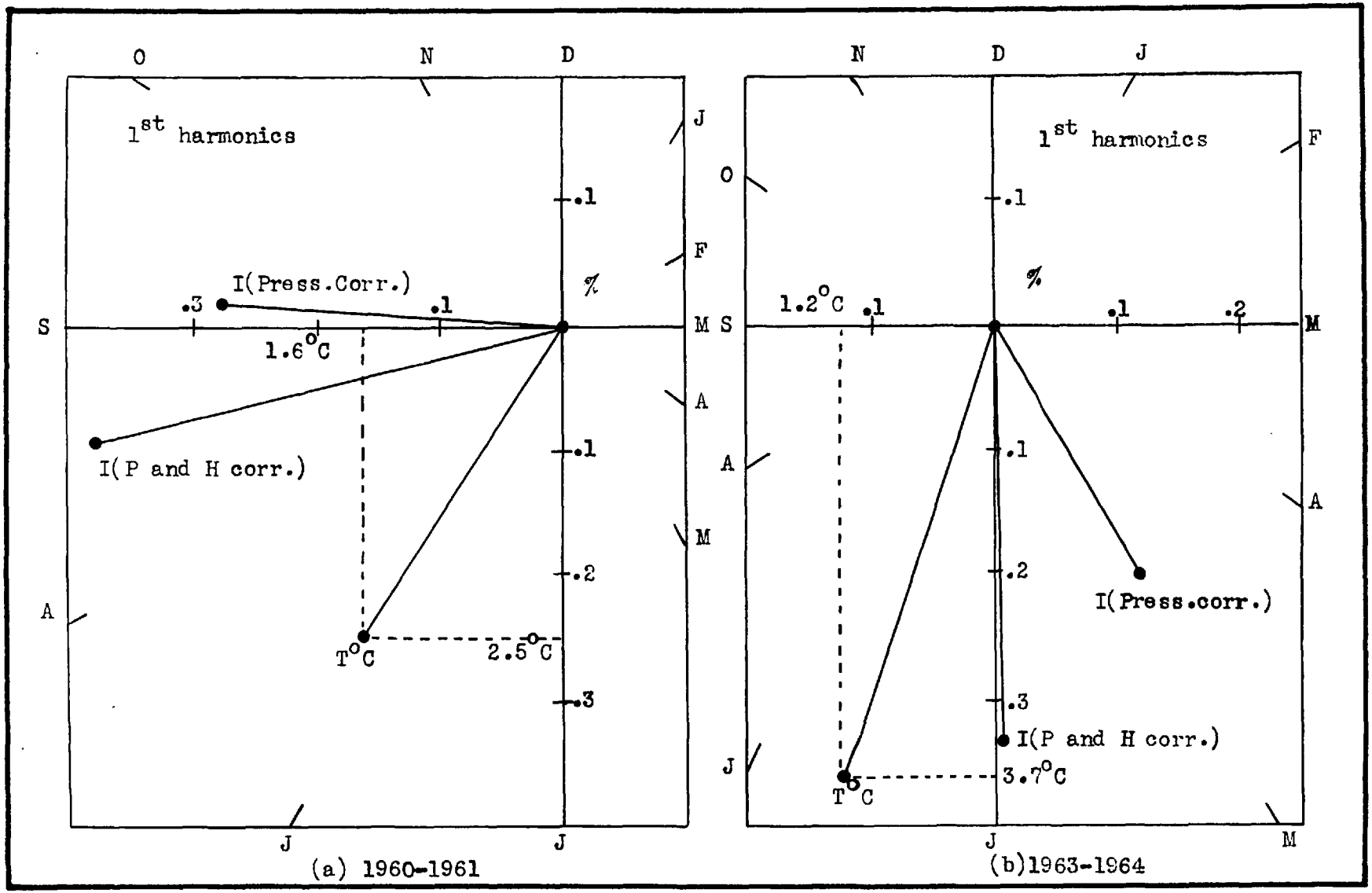


Fig. 4.5 The first harmonics of the annual variations in intensity and temperature for the periods (a) 1960-61 and (b) 1963-64.

Table I

Year	Component	Amplitude of the 1st harmonics	Time of maximum	Amplitude of the 2nd harmonics
1960-61	Intensity corrected for pressure only	A = .28%	Sept.-Oct.	A = .09%
	Intensity corrected for pressure and height	A = .39%	Aug.-Sept.	A = .02%
	Temperature	T = 3.0°C	July-Aug.	----
1963-64	Intensity corrected for pressure only	A = .20%	May-June	A = .04%
	Intensity corrected for pressure and height	A = .33%	May-June	A = .03%
	Temperature	T = 3.9°C	July-Aug.	----

Table II

Year	Component	r_{1T}	$\beta_{T\%}$ per °C
1960-61	Intensity corrected for pressure only	+.39	+.035 ± .023
	Intensity corrected for pressure and height	+.60	+.074 ± .034
1963-64	Intensity corrected for pressure only	+.60	+.035 ± .014
	Intensity corrected for pressure and height	+.85	+.067 ± .015

analysis carried out using the mean monthly values. The correlation and the regression coefficients obtained in this way are given in Table II. (Errors are in 95% fiducial limits).

Examination of the Table II reveals some interesting features. It is seen that similar results are obtained in both the years and that when the pressure and the height variations are taken into account in the seasonal analysis, a positive temperature coefficient is obtained which is greater by a factor of $\sim$ 1.7 than that obtained from the day to day analysis. Similarly, if effect of the height variations in the seasonal analysis is neglected the positive temperature coefficient assumes a value which is approximately equal to that measured from the day to day analysis.

Similar results were, it is to be noted, obtained by MacAnuff (1951) and we reproduce below in Table III the values calculated by him, for the purpose of comparison. (Errors are also in 95% fiducial limits).

Table III

Year	Component	r_{1T}	$\beta_{T\%}$ per ^{o}C
1949-50	Intensity corrected for pressure only	+.76	+.054± .015
	Intensity corrected for pressure and height	+.79	+.096± .024

Nonetheless, it must be admitted that the decay effect over the year has to be taken into account and, therefore, it would appear that there is a disagreement between the positive temperature coefficients derived from the day

to day correlation analysis and from the seasonal variation. It remains to be seen whether this apparent discrepancy can be explained in terms of experimental limitations, particularly the ignoring of the temperature variations above 70 mb.

4.3 Discussion of the Results

The results presented above show that the explanation of the annual wave in cosmic ray intensity underground in the light of known atmospheric effects meets with several difficulties. For example, the observed amplitude of the annual wave is too large to be explained by the positive temperature coefficient obtained from the day to day correlation analysis and there exists a difference between the observed positive temperature coefficients obtained from day to day and from month to month analyses.

However, we can now examine the different possibilities which might account for this disagreement;

(i) There may be other agents of terrestrial and extra-terrestrial origin which can control the annual variation in the cosmic ray intensity and which have not been considered so far.

Regarding this possibility, the only other conceivable agents appeared to us to be the geomagnetic activity and the amount of the absorber over the recorders during different months due to the amount of rainfall at Holborn. The amount of the rainfall per month falling at Holborn was extracted from the records supplied by the Meteorological Office, Holborn. The mean monthly rainfall at Holborn during 1960-61 is plotted in Fig. 4.4a; the poor correlation with the cosmic ray intensity is obvious ($r = -.09$). Similarly, the poor correlation between the cosmic ray intensity and the A_p -index can be seen

in the Figs. 4.4a and 4.4b. The correlation coefficients obtained during these years are $r_{1960/61} = -.04$ and $r_{1963/64} = -.09$. It can thus be concluded that the annual variation in the cosmic ray intensity is not influenced by these agents at all.

(ii) The disagreement is a consequence of experimental limitations resulting from the fact that the temperature in large portions of the stratosphere where the positive effect can be expected to occur has been neglected in the analysis.

Concerning this possibility of (ii), we might refer back to the discussions of the positive temperature effect given in the previous chapter. There the different possible causes for lowering of the observed positive temperature effect have been examined and it was concluded that the correlation existing between the temperature changes above and below 100 mb level may lower the observed positive temperature coefficient obtained from the day to day analysis by a factor of 2 or more.

While the day to day changes of temperature in the stratosphere appear to have smaller amplitudes than those prevailing near the 100 mb level, just the reverse applies for the seasonal variation, i.e.; the seasonal temperature changes in the stratosphere are known to have larger amplitudes than those occurring in the lower levels (Newell, 1964). If, as pointed out by Dorman (1957) and others, the region where the positive effect occurs extends well into the stratosphere, the larger stratospheric changes will produce corresponding intensity changes which will be correlated with the 200 mb - 70 mb layer to the extent that the stratospheric temperature is correlated with the temperature of the lower layer. It is clear, however, that the effect of ignoring the

temperature of the uppermost layers of the atmosphere will be to produce an apparent lowering of the day to day positive coefficient and an apparent increase in the seasonal coefficient as is found to be the case. While it is thus possible to account qualitatively for the discrepancy encountered earlier, a quantitative check is not possible for the lack of the necessary upper air data. However, a rough confirmation of this explanation will be attempted by working out theoretically expected seasonal variation from Dorman's values of the 'densities of the temperature coefficient', as described below.

It has been shown by Dorman that the expected annual variation in cosmic ray intensity is given by,

$$\frac{dN}{N} = \int_{0}^{B_o} W(B)\ \delta T(B) dB \qquad 4.1$$

where, $\delta T(B)$, is the change of the temperature at various isobaric pressure levels, dB, is the variation in the pressure B; W(B) is the 'density of temperature coefficient' and dN is the expected change of the pressure corrected intensity N, at the place of observation with pressure B_o.

The expected annual variation at Holborn using the eqn. (4.1) has been calculated in the following way:

The values of the function W(B) at different pressure levels have been taken from the curve given by Dorman corresponding to a semi-cubical telescope at 55 m.w.e. underground and those of the temperature fluctuations $\delta T(B)$ have been extracted from the radio-sonde records. In replacing the integration in eqn. (4.1) by summation, we have divided the whole atmosphere up to 10 mb into 12 layers of 100, 50 or 20 mb thickness i.e., from B_o to 950 mb, 950 to 850 mb, and so on. In the region of the atmosphere from B_o to 40 mb, we have used the mean monthly values of the temperatures at Crawley averaged over

5 years from 1951 to 1955 as supplied by the Meteorological Office, London. Since the temperatures of the isobaric levels higher than 40 mb were not available here, the temperature values of the rest of the atmosphere up to 10 mb level were extracted from the 1960-61 radio-sonde data supplied by the Berlin Meteorological Office. The inclusion of these values measured over Berlin is not expected to introduce any appreciable errors, because the upper air temperature cannot be very much different at the same latitude stations; and Berlin and London are situated roughly at the same geographic latitude.

Under these circumstances, the expected annual variation at Holborn, calculated in this way, should correspond more closely to an average variation rather than to any individual year, as there is some indication that the temperature of the upper air atmosphere may have different fluctuations during different years over London (compare Table I).

The comparison of the theoretical variations with the observed variations can still be made to see how close is the agreement between them. Accordingly, we have plotted the same Dorman's predicted annual variation in Figs. 4.6a and 4.6b (the dotted curves), together with the measured annual variations during 1963-64 and 1960-61 respectively (the solid curves). The agreement does not seem to be good during 1960-61; however, this may not be surprising if we note that during this period the data from only one of the telescopes were used. The data is liable to be less accurate and more likely to be biased. But there seems to exist fairly good agreement between the Dorman's prediction and the observed annual variation during 1963-64. Considering the fact we could not use the exact values of δ T(B) corresponding to this period, it seems reasonable to conclude that Dorman's method of atmospheric

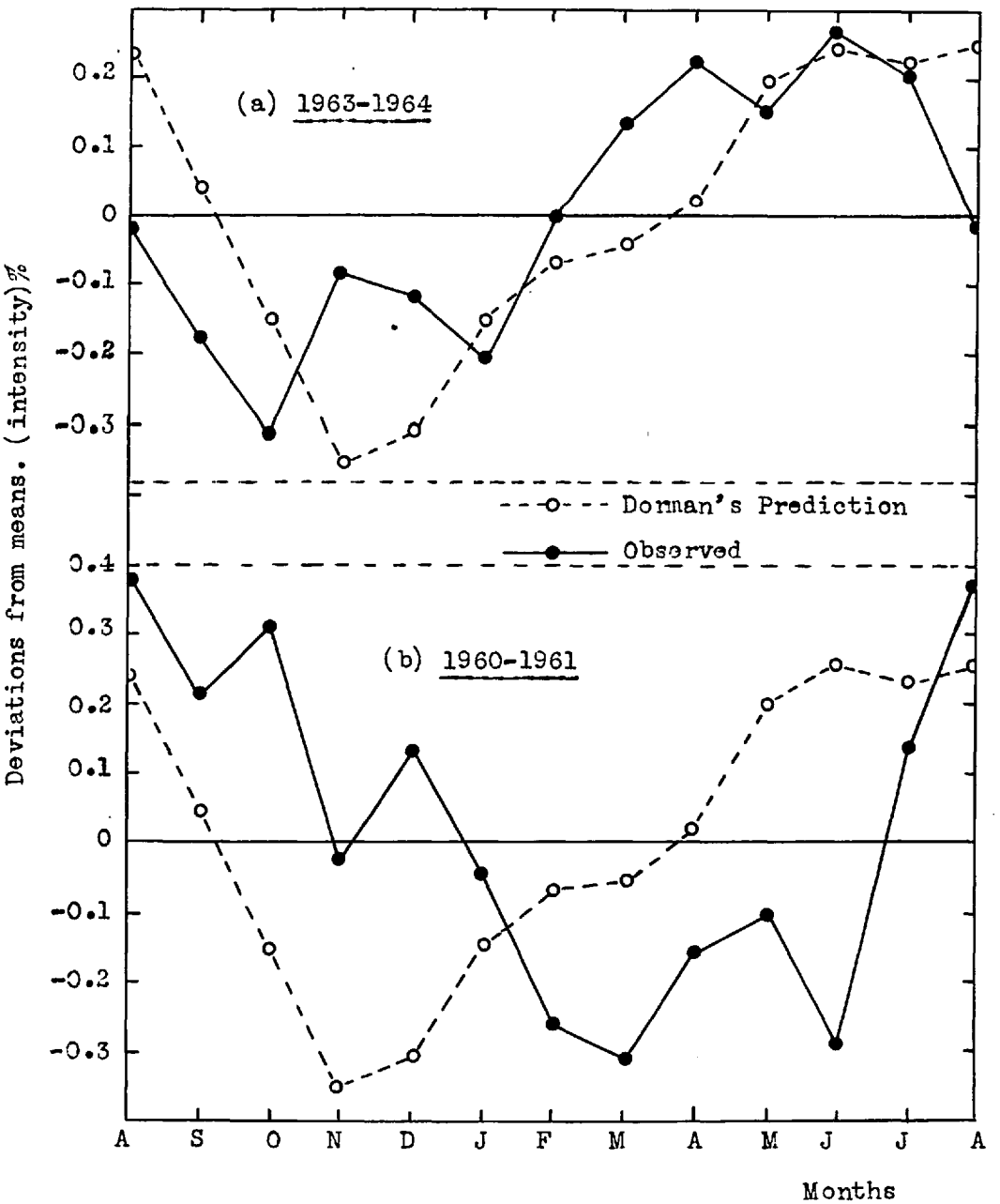


Figure 4.6 The seasonal variations in cosmic ray intensity underground observed at Holborn (60 m.w.e. underground) and those predicted by Dorman and Feinberg (1958).

corrections for the cosmic ray intensity can fully account for the annual variation observed underground i.e., the seasonal variation observed at Holborn is exclusively of meteorological origin.

4.4 Summary

To sum up, it can be said that the underground cosmic ray intensity demonstrates a 12-month wave when proper corrections are applied to take into account of the barometric and decay effects. No semi-annual wave of importance was observed. The annual wave has an amplitude of $\sim$ .33% and shows a maximum during summer months and a minimum during winter months. It is found that other terrestrial and extra-terrestrial agents have little control over this variation.

The positive temperature coefficient found from the seasonal analysis was significantly higher than that obtained from day to day correlation analysis and the explanation of this apparent discrepancy could be that the analysis did not include the temperature changes in the uppermost levels of the atmosphere. A comparison of the theoretically predicted and experimental curves for the seasonal variation appears to indicate that the origin of the seasonal wave of the cosmic ray intensity may be entirely atmospheric.

CHAPTER V

SOLAR DAILY VARIATION

5.1 Introduction

As early as in 1928, Lindholm (1928) observed that the pressure corrected cosmic ray intensity exhibited a solar daily wave whose amplitude appeared to be less than ~.5% of the mean. Similar observations by Compton et al (1932), Hess and Graziadei (1936), Schonland et al (1937), Forbush (1937) and others showed that the daily variation had an amplitude of about .2%, though no unique time of maximum could be ascertained from these observations; the published values showed the time of maximum anywhere between the morning and the late afternoon. Forbush (1937b) also reported a 12-hour wave whose amplitude (~.04%) differed little from that (~.05%) reported by Hess et al (1936). But all these early measurements were made by ionisation chambers and could have been contaminated by the fluctuations in the radioactive contents of the atmosphere (Forbush 1937a). Moreover, some of the results were corrected for pressure only (e.g. Forbush 1937b) while others were corrected for pressure and ground temperature (e.g. Hess et al 1936). These results thus were not very reliable and the existence of an anisotropy in the primary radiation could not be established.

However, the subsequent development of Geiger counter telescopes made it possible to study the daily variations unaffected by the background radioactivity. Such studies have been made by Duperier (1945, 1946), Malmfors (1949), and recently by Sandstrom et al (1962) and others. Duperier applied corrections to his data to allow for the pressure and μ-e decay effects and obtained a solar daily wave with an amplitude of ~.4% and a maximum at about 1600 hrs. In addition to these corrections, it is necessary to correct the data for the positive

temperature effect as stated in the previous chapters. Unfortunately, this positive temperature effect is largely uncertain for measurements of ionising components and the results, therefore, could not give any positive evidence about the degree of anisotropy in the primary flux.

To avoid these difficulties, measurements were made with directional counter arrays pointing in the North-South and East-West directions. In this kind of investigation a daily variation is sought as the difference between daily variations observed by the North and South pointing counter telescopes or those observed by the East and West pointing telescopes. This difference wave should be free from atmospheric effects and hence, if present, should be interpreted in terms of non-isotropic distribution of the primary cosmic ray flux. Kolhorster (1941), Alfven (1943), Elliot and Dalbear (1950) and Sarabhai and Gottlieb (1962) have investigated daily variations with their counter telescopes inclined to the South and North at different angles to the vertical. Similar measurements with counter telescopes inclined to the East and West at 45° angles to the vertical have been made by Elliot and Dolbear (1951), Rao and Sarabhai (1961) and others. The results of these directional measurements have proved conclusively that the difference curves, indeed, show variations over a solar day and hence, it represents the variation in the primary cosmic ray intensity.

More recently, conclusive evidence of an anisotropy in the primary cosmic radiation has come from neutron monitors which detect the low energy nucleonic components of the cosmic ray flux. It has been found that the neutron intensity needs correction for only sea-level pressure changes and is negligibly influenced by the atmospheric temperature changes (Simpson et al 1953, Dorman 1957). This

freedom from the influence of atmospheric temperature removed one of the main sources of error of the results of those earlier workers who used vertical intensities of the ionising components to measure the daily variation. The neutron intensity corrected for pressure changes shows a daily variation which can be interpreted with great confidence as arising from an anisotropy in primary radiation ([redacted] Katzman and Venkatesan 1960).

5.2 The Relation between the Daily Variation and the Geo-magnetic and Solar-activity

Many studies of the dependence of daily variation on the geo-magnetic and solar activity have been made recently by using the data from both the ionising and nucleonic detectors. Elliot and Dolbear (1951), Sekido et al (1950, 52), Sandstrom (1956) and others have observed anomalous diurnal variations of the ionising cosmic ray intensity during geo-magnetic storms. The characteristic features of these anomalous variations are that the amplitude increases and the time of maximum shifts to earlier hours during geo-magnetically disturbed days. Kane (1955) and Sandstrom (1962) reported the enhancement of the daily variation during the days with high K_p -index. It has also been found that there is a tendency of the high amplitudes of diurnal variations to recur at an interval of 27-days (Sittkus 1955, Sarabhai and Bhavsar 1958, Firor et al 1954).

Thambyahpillai and Elliot (1953) analysed the ionisation data from Cheltenham, Huancayo and Christchurch over the period 1932-1957 and found that the time of maximum of the diurnal wave showed a tendency to follow a 22-year cycle. Further studies of the long term changes of daily variations, measured at these stations, have been made by Steinmaurer and Gheri (1955), Sarabhai et al (1955) and recently by Forbush et al (1960). They made an exhaustive study of

these data from 1937 to 1959 covering a total period of 23 years. They averaged the data from the three stations and calculated annual mean daily variations for different years. Then they plotted the departures of the first harmonic vectors of the annual mean daily variations from the overall average for 1937-59 in a harmonic dial. These deviations of the yearly mean vectors from the 23-year average vector clearly displayed a large secular variation indicative of a quasi-systematic 22-year variation. It has been pointed out that though they analysed the pressure corrected data, the analysis would be free from other meteorological effects as the deviations of the yearly means from the 23-year average were used and as the atmospheric effects would be expected to be about the same in different years. However, it still needs more data for a definite indication of this secular variation because, this analysis covers only one such period.

The evidence for short term changes of the daily variations in the nucleonic component has been reported recently by Lockwood and Razdan (1963). They analysed several Forbush-decreases observed by a large number of neutron monitors scattered all over the world during 1957-60 and found significant enhancement of the daily variations during the main phase of Forbush-decreases; the time of maximum also appeared to shift to earlier hours as observed by others in the case of ionising component. Since the neutron monitors have been developed recently the information about long term changes of the daily variations as measured by neutron monitors is not yet available.

5.3 The Rigidity Spectrum of Diurnal Anisotropy of the Primary Cosmic Radiation

In order to study the dependence of the daily variations on the rigidity of the detected particles, it is necessary to carry out measurements with

different detectors which will respond to the primary radiation of different energies. The cosmic ray detectors located at different longitude, lattitude and altitude on the surface of the earth can give information of rigidity dependence up to about 100 Gv; the underground detectors can extend this rigidity range to higher values. However, the neutron monitors at sea-level are better suited for such studies than the meson detectors because the neutron data needs only pressure correction and the response curves for neutron monitors are more accurately known than those for the meson detectors at sea-level. In the case of meson detectors underground the response curves have to be calculated by empirical methods (hence likely to be more inaccurate) from those of the sea-level meson detectors. Besides, the atmospheric corrections for meson detectors at sea-level or underground are not known with great certainty.

So the data from neutron monitors have been widely used for this kind of investigation. It is now clear from the studies made in the last decade by workers like Katzman and Venkatesan (1960), Kane and Thakore (1960), Pomerantz et al (1962) and others that the amplitude of the daily variation remains nearly constant from the equator up to about 60° latitude and then decreases sharply towards the pole. The hour of maximum appears to increase from about 1000-1200 hrs. at the equator to about 1500 hrs. at high latitudes. The amplitude does not show any marked dependence on the longitude or altitude of the detectors. The phase of the diurnal variation, however, shows significant longitudinal dependence which is due to the differences in geomagnetic deflections suffered by the primary particles (Murakami 1961).

The above results of the daily variations have been utilized in theoretical

investigations of the diurnal anisotropy of the primary radiation δf by different workers who generally assume a power law spectrum, in rigidity R of the particles, of the form,

$$\delta f = A R^{\pm m} \qquad \ldots\ldots (5.1)$$

where, A = Cos λ (= the source strength) mainly confined to the ecliptic plane; m, is a constant; λ is the asymptotic latitude.

For this study of the diurnal anisotropy the time of maximum and the amplitude of the daily variations are the two fundamental quantities. Now, it is known that neutron monitors respond to the lower energy part of the primary cosmic ray spectrum, so that the particles reaching the detectors will suffer considerable deflections by the geomagnetic field. The daily variations measured by neutron monitors will, therefore, depend on the amount of deflection suffered by the particles of different rigidities. An exact evaluation of these two quantities - the time of maximum and the amplitude of the daily variation-is essential before ascribing them to primary radiation entering the geomagnetic field.

This problem has been tackled by Brunberg and Dattner (1953, 54), Dorman and Feinberg (1958) and others who used the concept of 'the asymptotic direction of viewing' of the primaries outside geomagnetic field in order to correct for geomagnetic deflections. In all these calculations, however, the geomagnetic field was represented by that of a dipole whose axis coincided with the rotational axis of the earth.

Nagashima et al (1961) and Murakami (1961) later on introduced an important correction to these calculations. They pointed out that the geomagnetic axis is, in reality, inclined 11.5° with respect to the earth's rotational axis,

so that the above calculations will have to be modified accordingly. With the introduction of this modification, they found that the longitudinal effect on the time of maximum expected from inclined dipole axis agrees very well with observations.

Recently, McCracken (1962) introduced two other refinements into the calculations of Nagashima et al (1961). Firstly, he represented the geomagnetic field by using higher spherical harmonics up to the sixth order according to Finch and Leaton (Finch and Leaton 1957) sixth degree approximation. This was justified because the magnetic data and other cosmic ray data from the ground based or satellite observations amply show that the geomagnetic field is rather complicated and approximates more to a field containing higher degree spherical harmonics than to a dipole field. Secondly, he introduced the effect of the finite width of the asymptotic cones of acceptance of different detectors. This effect of the finite width has been carefully examined by Rao et al (1963) and it has been shown that the earlier concept of the 'mean asymptotic cone of viewing' is only an approximation of the actual cone of acceptance. This difference will give rise to large errors, if the angular extent of the cone of acceptance is comparable to that of the anisotropy of primary cosmic radiation. They instead introduced the concept of 'the asymptotic cone of acceptance of the detector' which was defined as the solid angle containing the asymptotic direction of approach that significantly contributes to the counting rate of the detector.

This method of studying the anisotropy thus appears to be more accurate and sophisticated than the earlier approaches using the concept of 'asymptotic direction of viewing'. On the basis of these modifications, Rao et al (1963)

made theoretical calculations to predict the daily variations that would be measured by different detectors at different places on the surface of the earth. From the analysis of the daily variations observed by a large number of neutron monitors during IGY, they came to the conclusion that the observed diurnal variations are consistent with an anisotropy which is independent of rigidity in the range 1-100 Gv. Kane (1964) used the data from a larger number of stations than was used by Rao et al and came to the same conclusion. It is to be noted that Rao et al have compared their results with the observed daily variation at Hobart (42 m.w.e.) and have found that the upper limit of the rigidity to which modulation extends has to be placed at about 200 Gv. This rigidity independent anisotropy will be examined later on in this chapter in the light of the experimental measurements of the daily variations at Holborn.

5.4 Experimental Results of the Daily Variation Observed at Holborn during 1961 to 1964

The solar daily variations measured underground have been studied over the period of three complete years as follows: (i) from November, 1960 to October, 1961 (ii) from November, 1961 to October, 1962 and (iii) from August, 1963 to July, 1964. During the first two periods (henceforth referred to as the periods 1961 and 1962), we have used the meson data from the two old telescopes, while during the third period (henceforth referred to as the period 1963-64) the data from the six new telescopes were used.

The data for the intermediate period between November, 1962 to July, 1963 has not been used, since the period does not cover 12 months and also during this period there had been many gaps in the records as the laboratory was being re-arranged to make room for the new telescopes.

It is also to be noted that the data for the period 1961 has been analysed by Mathews (1962). But as he used in his analysis a pressure coefficient of -.042% per mb for correcting the data and as there is some indication that this value is slightly higher than the expected value, the data has been reanalysed by using a pressure coefficient of -.037% per mb which has been found to be in good agreement with the expected value (viz. , Chapter III).

For the study of the daily variations underground, the records from different telescopes were arranged into bi-hourly values according to local solar time and the annual means for the three periods were obtained by using only those days during which the records from all the telescopes were available. These bi-hourly values were corrected for pressure changes by using a pressure coefficient of -.037% per mb. The numbers of days used for the analysis during the three periods are as follows: (i) 350 days during 1961 (ii) 303 days during 1962 and (iii) 360 days during 1963-64.

The pressure corrected daily variations during these periods are shown in Fig. 5.1 (curves a,b,c,). The daily variations during 1949-50 observed by MacAnuff (1951) is also shown in the same figure (curve d) for comparison. It can be seen from the figure that within limits of statistical accuracy the daily variations observed during different periods agree very well with each other.

The daily variations for the three periods were harmonically analysed and their first and 2nd harmonics are shown in Figs. 5.2a and 5.2b (dotted lines). The close agreement between amplitudes and phases of the daily variations observed during different periods is evident.

To increase the statistical accuracy, the data from the three periods were

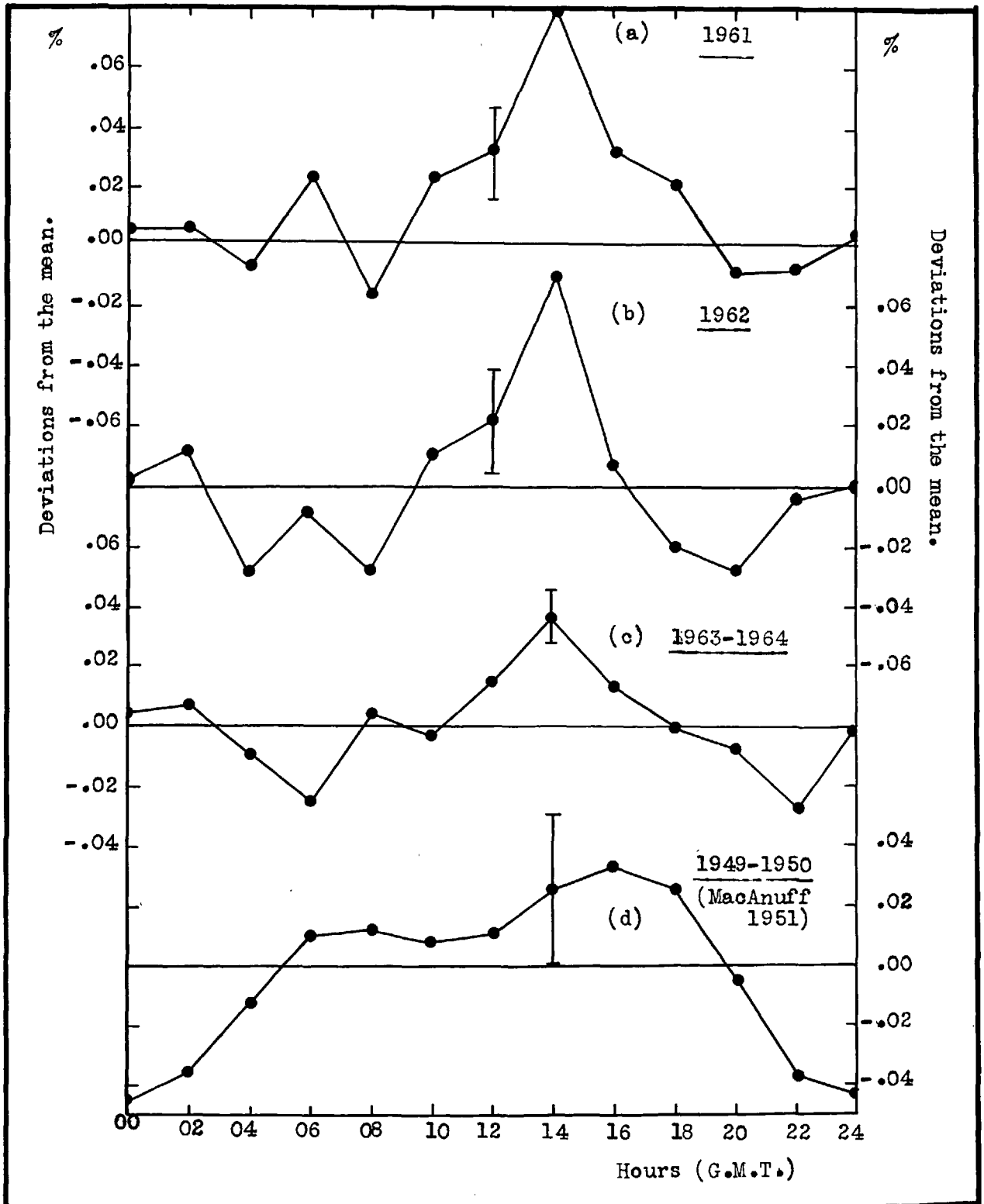


Fig. 5.1 The solar daily variations at Holborn (60 m.w.e.) for different years after correcting for pressure changes. ⊕- Standard deviations for mean bi-hourly counting rates.

added up and the average daily variation over the period 1961 to 1964 is shown in the Fig. 5.2c. (dotted curve). In averaging the data for the three periods we have given 3 times greater weight to the period 1963-64 (because of the higher statistical accuracy of the data) than that given to the periods 1961 or 1962. The solid curve in Fig. 5.2c has been obtained as the fitted daily variation by taking into account of the first two harmonics only. The amplitudes of the third and higher harmonics appeared to be negligible and have not been used in the analysis. The average vectors for first and second harmonics are shown as solid lines in Figs. 5.2a and 5.2b. The error circles shown in these figures correspond to these average vectors and have been calculated from the standard deviations of bi-hourly counting rates. The amplitudes A's and the times of maximum T_{max} of the first three harmonics are given below in Table I.

Table I

	Amplitude A_1%	T_{max}	Amplitude A_2%	T_{max}	Amplitude A_3%
Solar daily variation (1961 to 1964)	$.018 \pm .004$	$13.58 \pm .82$	$.014 \pm .004$	$1.81 \pm .82$	.002

It will be seen from the above table that the solar daily variation of the underground cosmic ray intensity (corrected for pressure only) contains a significant 24 hour and a 12 hour component and the higher harmonics have negligible amplitudes.

Experimental measurements of the daily variations underground have been made at Hobart and Budapest. From the analysis of Budapest data during 1961-62, a semi-diurnal wave of amplitude of about $(.028 \pm .004)$% compared to $(.045 \pm .004)$%

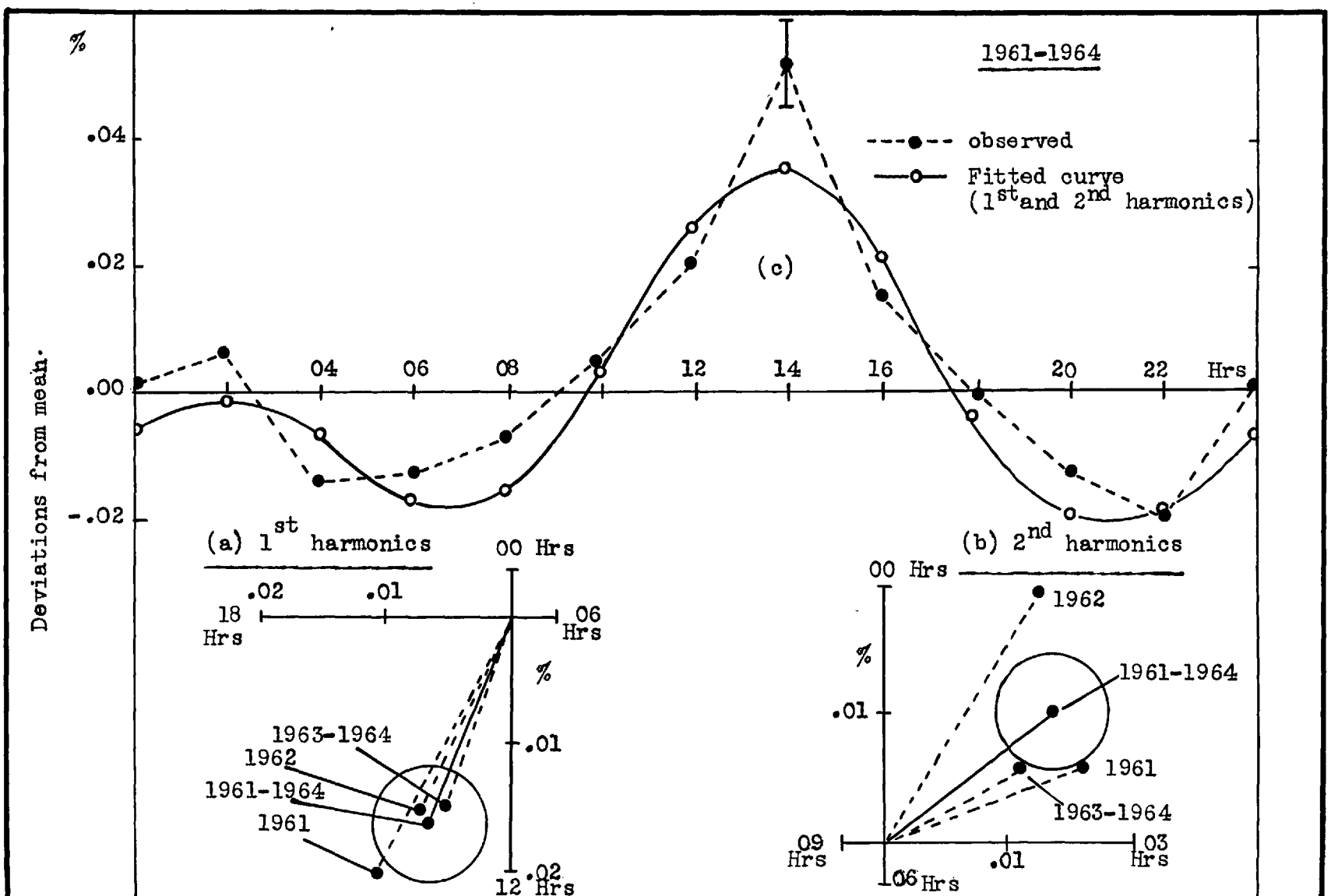


Fig. 5.2(a,b,c) The solar daily variation at Holborn averaged over 1961-64(c) and the first and second harmonic vectors of the daily variation (a and b). The times shown are the Greenwich Mean Time.

for the diurnal amplitude was obtained. From the paper published by Jacklyn (1963), a semidiurnal amplitude of about (.027±.01)% compared to (.126±.01)% for the diurnal amplitude was obtained for the year 1958 at Hobart. In the present case, the existence of the semidiurnal wave cannot be doubted and it will therefore be necessary to consider both the diurnal and semi-diurnal waves in the study of the solar daily variation underground.

5.5 Discussion of the Results

The observed daily variations underground have been corrected for the effects of pressure changes but not for the effects arising from the changes in the upper atmospheric temperature. So, before attributing the daily variation to the anisotropy in the primary radiation it will be necessary to correct for changes of the temperature in the upper atmosphere (Chapter III).

It is at this stage that we encounter serious difficulties in making allowance for the atmospheric effects because of our lack of adequate knowledge of diurnal variations of temperature in the upper atmosphere. Primarily the number of atmospheric soundings made per day is two and it is not possible to make an accurate assessment of the diurnal and semidiurnal variations on the basis of such a small number of flights. Even if this situation could be remedied, the insolation and the lag errors near the ceiling altitudes of the balloons are large and the corrections for these effects are also correspondingly large and, unfortunately, rather uncertain.

Consequently, there are very few published results about the measurements of daily variations of the temperatures and heights of different pressure levels, especially near the region of the atmosphere of greatest importance

to us (i.e. near the lower half of the stratosphere).

Dorman (1957) reported that the maximum deviation from the mean daily temperature of the atmosphere above 300 mb over Russian stations was about $1^{\circ}C$ with the time of maximum at about 1300 hrs local solar time. Harris (1962) found a mean annual amplitude of the diurnal wave of stratospheric temperature of about $.77^{\circ}C$ with the time of maximum near about 1400 hrs. Wada and Kudo (1962) calculated the diurnal wave of upper air temperature over Japan as having an amplitude of $\sim .66^{\circ}C$ and the time of maximum at 1300 hrs. Scrase (1956) found that the temperature near 50 mb level showed a daily variation with an amplitude of about $1.5^{\circ}C$ over Britain; Kay (1951) also reported an amplitude of about $.5^{\circ}C$ to $1^{\circ}C$ near about 150-80 mb level over Britain. Dolbear and Elliot (1951) analysed the radiosonde data supplied by the British meteorological stations and estimated annual mean amplitude of the daily variation of the height of 100 mb level to be of the order of ~ 42.6 meters with the time of maximum at about 1300 hrs. Similarly, they obtained the annual mean daily variation of temperature between 100-80 mb level of the order of about $1.5^{\circ}C$ with the same time of maximum. During the period selected by Dolbear and Elliot (1951) for analysis the British meteorological stations conducted four flights per day; nowadays, only two flights per day are made. However, an examination of the present-day aerological data reveals that the estimates made by Dolbear et al are still largely valid, except that the amplitude of the temperature wave estimated by them appears to be rather high. We can, however, use these estimates for an approximate correction for the underground diurnal wave observed in the present case.

Let us first consider the diurnal component of the daily variation of

cosmic ray intensity. It has been shown in Chapter III that both μ-e decay effect and positive temperature effect will have to be taken into account in correcting the underground intensity. In order to make allowance for the μ-e decay effect it should be recalled that we estimated the decay coefficient for the underground radiation to be about .72% per Km. So, if we use the above estimate of the daily variation of the height of 100 mb level (Dolbear et al 1951) we find that the diurnal variation of cosmic ray intensity will retain its phase but increase to an amplitude of about .048%, when corrected for the μ-e decay effect.

Considering first the possibility that the observed solar daily variation is entirely of atmospheric origin, the amplitude of the diurnal temperature variation in the upper atmosphere can be estimated. Using the day to day positive temperature coefficient of .041% per ^{o}C, the diurnal amplitude of the atmospheric temperature in the range 200-70 mb levels will have to be about $1.2^{o}C$. Meteorological observations indicate that this estimate may not be excessive and therefore we cannot entirely eliminate the possibility that the observed solar daily variation is totally of atmospheric origin. However, because of the uncertainty in the meteorological observations the possibility that an appreciable part of the observed solar daily variation is due to primary anisotropy cannot be eliminated. Under these circumstances, it is intended to examine the data more closely to see whether a part of the solar daily variation originates in a primary anisotropy.

A measure of the primary anisotropy in the low energy band is obtained by the daily variations observed by neutron monitors and it is possible to select days on which this anisotropy is larger than the average. If the

enhancement in amplitude of the primary anisotropy extends to energies corresponding to the underground measurements, then the same increase can be expected in the observation of the underground daily variations. The pressure corrected neutron and underground intensities at London for the period 1963-64 were arranged into two groups of days/- (i) days showing large daily variations (Group I) and (ii) days with no clear daily variations (Group II), selection being made on the basis of the neutron data. The mean daily variations corresponding to these two groups of days for meson and neutron intensities were calculated and are shown in Figs. 5.3a and 5.3b. We also show in these figures the first harmonics of daily variations corresponding to these two groups of days (Figs. 5.3c and 5.3d). It will be seen from these figures that in the case of neturon intensities the amplitude of the mean daily variation for group I days is nearly 1.5 times larger than that for group II days. But in the case of meson intensities it is not possible to decide whether there is any increase in the diurnal amplitude for Group I days because of the rather large statistical uncertainty in the underground data.

Secondly, it is known that there occurs an enhancement of the diurnal amplitudes of solar daily variations during geomagnetically disturbed days (section 5.2). So, if a part of the observed solar daily variation originates in a primary anisotropy, then larger diurnal amplitudes would be observed underground for days with high geomagnetic activity than for days with low geomagnetic activity. As a measure of the geomagnetic activity, Ap - indices were used. The pressure corrected underground data for 1963-64 were divided into two groups of days according to high and low values of A_p - (i) days

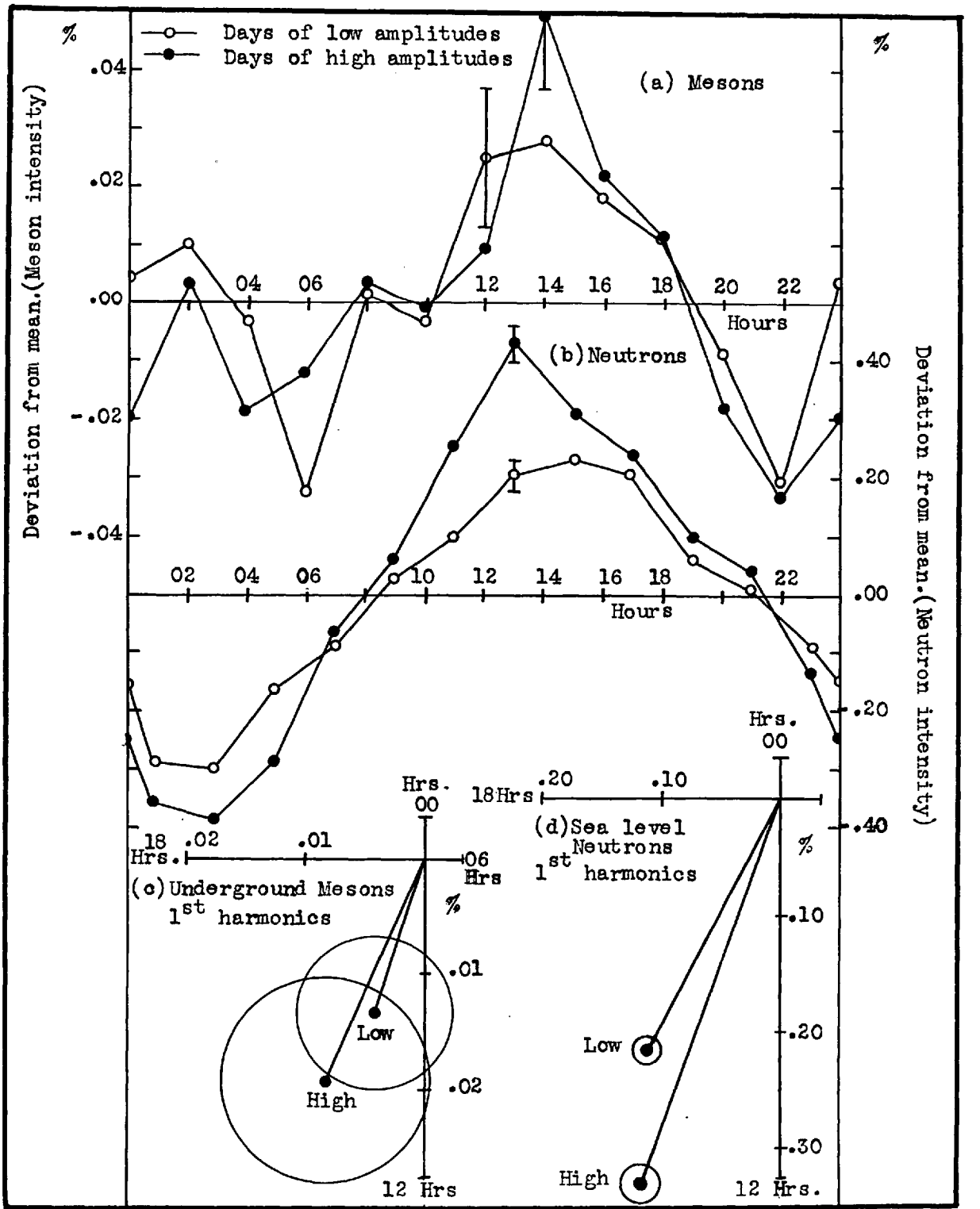


Fig. 5.3(a,b,c,d) The average solar daily variations in meson intensity at Holborn (a), in neutron intensity at London (b) and their first harmonics on selected days (c,d). Hours are in G.M.T.

with $0 \leq A_p \leq 10$ (Group I) and (ii) days with $A_p \geq 11$ (Group II). No further subdivision of the days was possible because during this period days with $A_p > 11$ were not numerous enough to justify the analysis. The mean daily variations corresponding to these two groups of days together with their first harmonic vectors are shown in Figs. 5.4a and 5,4b. It can be seen from the figures that though there is some indication that the higher amplitudes of solar daily variations underground may be associated with high geomagnetic activity, the statistical errors involved are such that no definite conclusion can be drawn.

We shall now consider the semi-diurnal wave. On the basis of the evidence produced by Harris (1959) for a semi-diurnal wave in the stratospheric temperature, a part of the semi-diurnal wave in cosmic ray intensity can be accounted for. Furthermore, if we examine the observed waves for solar daily variations (Figs. 5.1 and 5.2) we find that there is some sudden and sharp decrease of the intensity at about 0600 - 0800 hrs. in the morning and at about 1600 - 1800 hrs. in the evening, suggestive of a semi-diurnal effect. As suggested by MacAnuff (1951) this effect may arise due to the sudden influx of people and motor vehicles near Holborn during these hours of the day. MacAnuff estimated this 'population effect' to be of the order of $\sim$.025% by assuming 200,000 people per sq. mile packed close together. This estimate, however, seems to be rather high because of the following reason. The underground laboratory is situated at a place which is surrounded by big office buildings at the surface and the concentration of the people cannot be as much over the recorders as in the central London area. It could be, however,

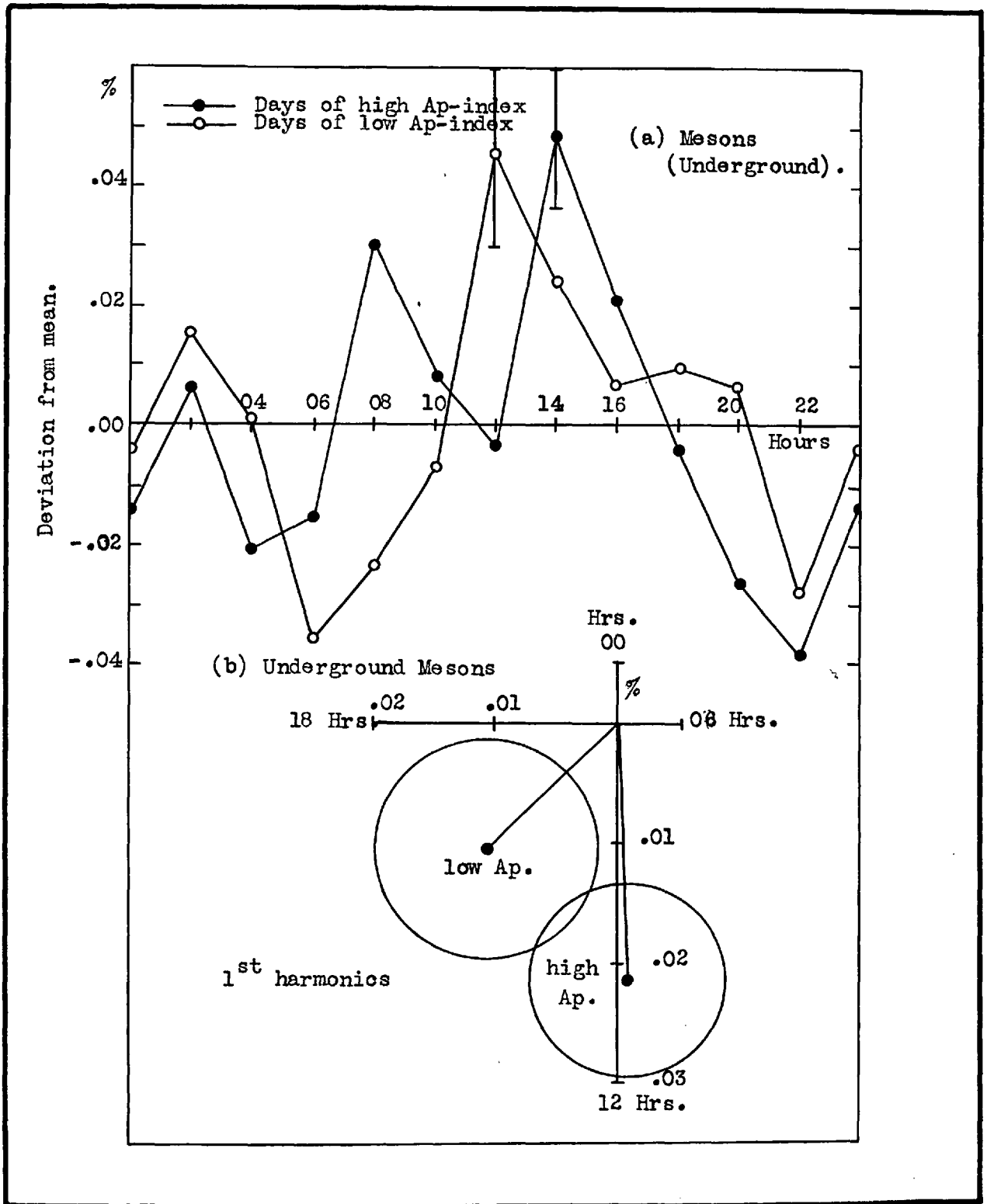


Fig. 5.4(a,b) The average solar daily variations in meson intensity at Holborn (a) and the first harmonic vectors on selected days (b). Hours are in G.M.T.

determined experimentally by finding the daily variation during weekends and holidays, when this population effect would be absent. Unfortunately, this could not be tested with the necessary degree of accuracy because of the small variation to be expected. For example, even by using the three years' data the mean daily variation during weekends and holidays will still be uncertain by a standard deviation of $\sim \pm .009\%$ and in the presence of such an error, we cannot achieve 95% confidence. In spite of this difficulty it must be admitted that a part of the semi-diurnal wave can obviously be caused by the population effect. Under these circumstances, we can reasonably conclude that the semidiurnal wave may well be caused by the temperature and population effects.

5.6 The Rigidity Spectrum of the Daily Variation as determined from the Underground Measurement

It has been stated above that Rao et al (1963) compared the daily variation measured at Hobart with the calculated anisotropy and found that the anisotropy was independent of rigidity in the range of 1-200 Gv. The upper limit of the rigidity range, however, could not be determined accurately from the neutron data since neutron monitors are not sensitive enough at this range, nor could it be determined accurately from the Hobart data because the response curve for such a detector is largely uncertain. Besides, the Hobart data was not corrected for changes of the atmospheric temperature.

As the amplitude of the diurnal variation observed at Holborn is much smaller than that observed at Hobart in 1958 (section 5.4), it would be interesting to see what extent the conclusion about the upper limit of the anisotropy has to be modified in order to conform to our experimental value.

In order to examine this, the expected amplitudes of the daily variations underground were calculated with the following assumptions: the anisotropy is along 90°E of the Earth-Sun line, is maximum in the ecliptic plane and falls off as $\cos\lambda_R$ (λ_R is the angle between the asymptotic direction of a particle of rigidity R, arriving vertically at a place with geomagnetic latitude Λ, and the ecliptic plane); the primaries incident on the detector other than from the vertical have negligible contributions to the total counting rate of the detector.

With these assumptions, it is possible to evaluate the amplitude A' of the daily variation measured by a detector at the latitude Λ from the formula,

$$A' = \frac{\left[\left\{\int_{R_\Lambda}^{\infty} W(R)f(R)\cos\lambda_R \cos\psi_{E,R}\, dR\right\}^2 + \left\{\int_{R_\Lambda}^{\infty} W(R)f(R)\cos\lambda_R \sin\psi_{E,R}\, dR\right\}^2\right]^{\frac{1}{2}}}{\int_{R_\Lambda}^{\infty} W(R)dR} \qquad \ldots.(5.2)$$

where, $\int_{R_\Lambda}^{\infty} W(R)dR$ = the counting rate of the detector having the differential response, $W(R)$, at R.

$f(R)$ = the fractional anisotropy in the primary cosmic radiation and assumed to be constant up to an upper limit in rigidity (Rao et al 1963).

$\psi_{E,R}$ = the angle between the asymptotic direction of a primary particle of rigidity R, arriving vertically at the latitude Λ, and the meridional plane measured eastward from this plane.

R_Λ = the cut-off rigidity of the detector at latitude Λ.

and λ_R has the same meaning as above. The anisotropy is defined by λ_R and $\psi_{E,R}$, the so-called asymptotic latitude and longitude.

In calculating A', the factors appearing in eqn. (5.2) were evaluated in the following way. The function W(R) has been extracted from the response curve as given in the Appendix II, corresponding to a meson detector at a depth of 60 m.w.e. below ground. The method of calculating such a response curve has been outlined in the Appendix. The angles $\psi_{E,R}$ have been evaluated from the Brunberg-Dattner (1953) diagram corresponding to $\wedge \sim 60^{\circ}$ for the vertical direction of approach. The angle λ_R was taken approximately equal to the geomagnetic latitude of the detector. The value of the factor f(R) has been taken to be equal to 4.10^{-3} (as given by Rao et al 1963).

The calculated values of the amplitudes are shown in Fig. 5.5 as a continuous curve plotted against R_{max}, the assumed value of the upper limit of rigidity up to which the anisotropy is present.

Now to compare the predicted amplitude with that observed and to deduce an approximate value for R_{max}, it is necessary to know the observed magnitude of the daily variation of primary origin when all other causes of variations have been adequately allowed for.

At this point, it should be noted that orbital motion of the earth around the Sun with the speed of about 30 km/sec, could give rise to a diurnal variation, the effect of which would be to lower the amplitude of the true solar variation and shift the time of maximum to earlier hours. This effect - the so-called aberration effect - has been calculated according to the theory of Compton-Getting and comes out to be of the order of $\sim .02\%$. This will, therefore, have a considerable effect on the observed solar variation and has to be taken into account.

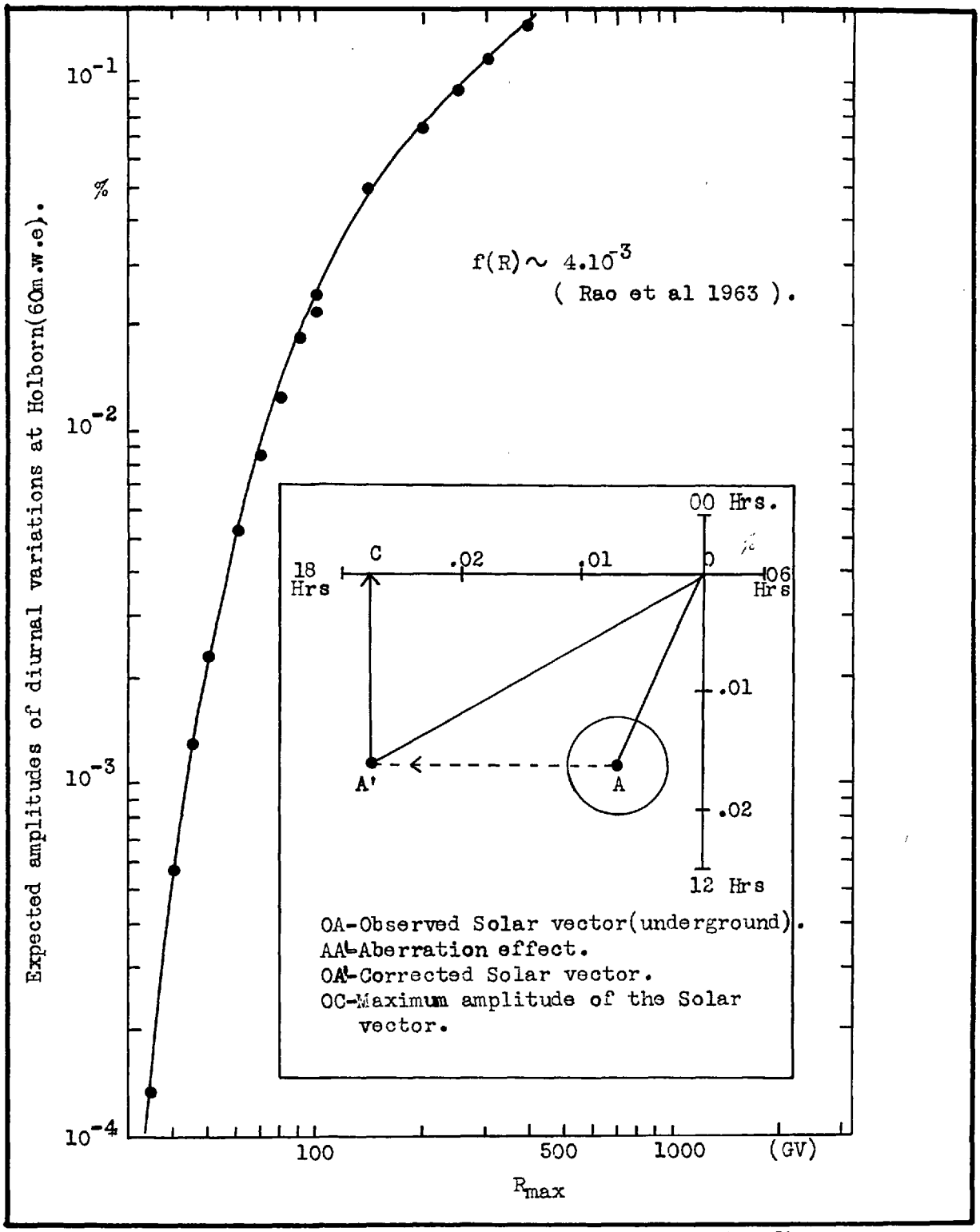


Fig. 5.5 The expected amplitudes of diurnal variation at Holborn as a function of R_{max}. The calculation is based on the rigidity independent diurnal anisotropy upto R_{max}.

The inset of Fig. 5.5 illustrates the method used to correct the solar variation for this aberration effect. The vector OA is the pressure corrected solar vector (amplitude ~.018%). The aberration effect is represented by the vector AA' so that OA' now represents the true solar vector (amplitude ~.031%). Assuming that the primary anisotropy is along the 1800 hr. direction the maximum amplitude of the solar vector is likely to be represented by OC (amplitude ~.028%).

Comparing the approximate value of the solar vector OC with the calculated value (as given by the continuous curve in Figure 5.5), we find that the upper limit R_{max} is to be set at about 100-125 Gv. On the other hand, if it is assumed that whole of this solar vector is accountable on the basis of known atmospheric effects, it is found that the limit is to be set at about 50 Gv.

This value of R_{max} seems to be much lower than the value quoted by Rao et al (1963). However, since their observations refer to the period of high solar activity (1957-58) this lowering of the value of R_{max} may well indicate that now in the solar minimum period the solar modulation of the primary cosmic rays does not extend beyond about 100 Gv or it is also possible that the amplitude of the anisotropy has decreased since the last sun-spot maximum.

To see whether this lowering of R_{max} can be confirmed, the annual daily variation measured by the neutron monitor at Makerer (an equatorial station having a high rigidity cut-off) during 1962 was calculated. The amplitude and phase of the daily variation during 1962 were then compared with those measured during 1957-58. In both cases the amplitudes and phases came out to be the same (ampl. ~ .42%; phase at about 1100 hrs.). So, the apparent lowering

of R_{max} could not be confirmed from neutron monitor data. This, however, does not exclude the possibility of its existence since neutron monitors operating at sea-level are not sensitive enough at this rigidity range to see this lowering of the value of R_{max}.

5.7 Summary

(i) The pressure corrected solar daily variation at Holborn appears to have an amplitude of $.018 \pm .004\%$ with the time of maximum at $13.58 \pm .82$ hrs. for the first harmonic vector, while the second harmonic vector shows an amplitude of $.014 \pm .004\%$ with the time of maximum at $01.80 \pm .82$ hrs.

(ii) When approximate corrections are applied to allow for changes in the stratospheric temperature, it is found that the observed daily variation underground may be largely of atmospheric origin, but the possibility that a part of the solar daily variation originates in a primary anisotropy cannot be ruled out.

(iii) The observation at Holborn seems to be consistent with an anisotropy which is independent of rigidity up to the limit of about 100 Gv, if the corrections for the changes in stratospheric structure are neglected and the aberration effect is included. But when the corrections for stratospheric structure changes are taken into account the range of rigidity up to which this anisotropy is consistent appears to come down to about 50 Gv. There is thus an indication that the value of R_{max} may have changed since IGY.

CHAPTER VI

THE SIDEREAL DAILY VARIATION

6.1 Introduction

Several questions of cosmic ray physics associated with the origin of cosmic rays and their propagation to the solar system from their sources are intimately related to the study of the sidereal daily variation i.e., the variation with the period of a sidereal day. But the studies of the sidereal variation over the last 40 years or so have shown that the effect is not definitely established and that, if it exists, this does not exceed a few tenths of a percent for primary particles of energy $E \sim 10^{13}$-10^{14} ev.

This means that the cosmic rays in the Galaxy are, to a first approximation, isotropic and nearly constant in time. But even if they are isotropic inside and outside the Galaxy, the rotation of the Galaxy itself will produce a small sidereal variation. This effect of the relative motion of the solar system with respect to the distant Galaxies has been considered by Compton and Getting (1935). They have shown that for isotropic distribution of cosmic radiation of extra-galactic origin a sidereal variation will be observed by a detector on earth with the maximum intensity $\sim .3\%$ on the side facing the direction of motion. Vallarta et al (1939) introduced the effect of the geo-magnetic field on the trajectories of cosmic ray particles into the Compton-Getting theory and showed that maximum of the sidereal variation should occur at 1320 hrs. local sidereal time (L.Sid.T.) with an amplitude of about $\sim .17\%$ at an equatorial station.

Verification of this theory, however, encounters several difficulties due to the fact that the effect is very small and there is usually a superimposed

solar daily variation. The first problem encountered involves statistical accuracy of the data and this should be improved so that the statistical uncertainty is very much smaller than the small sidereal effect which it is desired to establish. The second problem requires that the true sidereal variation should be separated from the spurious sidereal variation which arises whenever the superimposed solar daily variation changes with the season. The latter problem has been fully discussed by Elliot (1952) and can be summarised in the following way:

Consider a solar daily variation which remains constant over the year. If it is now assumed that there is a sidereal daily variation which also remains constant throughout the year, then the end-points of the monthly mean vectors of solar daily variations plotted on a solar harmonic dial would lie on a circle. The end-points of the monthly vectors will be shifted by 2 hours per month in an anti-clockwise progression as the sidereal clock gains about 2 hours per month over the solar clock. The centre of the circle would represent the tip of the average solar daily variation and the radius would represent the amplitude of the sidereal daily variation.

The situation will be different if there is a seasonal change in the amplitude or phase of the solar daily variation; a spurious sidereal variation will be generated in this case and the separation of the sidereal variation from the spurious sidereal variation becomes more difficult. This problem has been considered by Thompson (1939) and he has suggested a method of separating the true sidereal variation from the spurious variation in the simple case of the solar daily variation which undergoes seasonal change only in amplitude

but retains its phase constant throughout the year. In this case the end-points of the solar vectors will move along a straight line when plotted on a solar time dial and the presence of a superimposed constant sidereal variation will have the effect of elongating the circle of the previous example into an ellipse. The progression of the tips of the mean monthly vectors will be clock-wise or anti-clockwise depending on the relative amplitudes of the seasonal variation of the solar vector and the true sidereal vector.

Many results have been analysed on the basis of this method and have been reported so far. Thompson (1939) himself analysed the ionisation chamber data of Compton and Turner (1937) but could not find any statistically significant sidereal variation. Forbush (1937) analysed the ionisation data from Cheltenham and Huancayo but failed to establish sidereal variation greater than the statistical error. He also found that the phases of the sidereal variations differed by about 5 hours from one station to the other.

Duperier (1946) analysed the data from vertical coincidence counter telescope at London and found a true sidereal variation of amplitude about ~.21% with the time of maximum at about 2100 hrs. L.Sid.T. Hogg (1950) analysed the data from stations in the northern and southern hemispheres and compared the results with that obtained by Duperier. He found true sidereal variations of amplitudes of about $(.05 \pm .02)\%$ at every station but found that the times of maximum at stations in the northern and southern hemispheres differed by about 12 hours. Hogg suggested that these results did not represent the true sidereal variations but might be due to some solar cause.

Thompson's method is, however, applicable only for the case of the solar daily variation which changes in amplitude but not in phase over the year. It

will be inapplicable if the solar daily variation also changes in phase, which can happen if an amplitude modulated solar variation of atmospheric origin is superposed on a solar daily variation arising from primary anisotropy.

Dolbear and Elliot (1951) avoided this difficulty by an ingenious method based on the following facts. Since the meteorological changes in the northern and southern hemispheres are 6 months out of phase, the spurious sidereal effects introduced will also be 6 months out of phase at two stations in the northern and southern hemispheres. They, therefore, combined the data from two stations, one located in the northern hemisphere and the other in the southern hemisphere - thereby cancelling the seasonal variation in the solar vector. They also analysed the data from one equatorial station (where the seasonal changes in the atmosphere are likely to be small) as well as the data from two crossed telescopes at Manchester - one pointing North and the other South. They subtracted the daily variation in the northern direction from that in the southern direction. So the data used by them were least likely to be affected by the atmospheric changes. From the analysis of these data they found a true sidereal variation of amplitude of about ~.02% with the times of maximum at about 03-0600 hrs. L.Sid.T. at all stations. However, the phase of the sidereal variation at Huancayo (~ 0300 hrs.) was opposite to that calculated by Vallarta et al (1939) so that considerable doubt was cast by them on the theory of the extra-galactic origin of cosmic rays.

Though the above results might have been contaminated by the presence of spurious sidereal effects due to improper atmospheric corrections, this difficulty does not arise in the analysis of the neutron monitor data. This has been done recently by Conforto and Simpson (1957) who analysed the neutron data from Huancayo and Climax, the ionisation data from Freiberg and the meson data from Rome for the period 1953-55. They found that the phases of the first harmonics of mean

monthly diurnal variations were nearly constant when plotted on the solar time dial during 1953 and 1955. Whereas in 1954, the phases of the vectors were drifting in anti-clockwise progression with respect to the solar dial but were nearly constant ($\sim$ 0800-1000 hrsl) in sidereal time on a sidereal dial irrespective of the detectors used. They concluded that the variation of phase which produced a dependence on sidereal time occurred in 1954 and that the observed sidereal effect was not caused by any terrestrial phenomena but might have been due to anisotropy in the primary radiation. They suggested that a genuine sidereal anisotropy would have been observed if the solar system was remarkably free from the disturbed magnetic field during 1954. But the question of whether the effect was genuine or spurious was left open.

These results have been critically examined by Baliga and Thambyahpillai (1959) using the data from Huancayo, Cheltenham, Christchurch, Colombo, Hobart and Tokyo. No sidereal variation was observed at Colombo but the other stations showed sidereal variations of amplitudes of about .06% with rather consistent time of maximum at about 1900 hrs. at the equator and about 2200 hrs. at the higher latitude stations. From the study of the character of solar daily variations and the relation between seasonal changes in the solar and sidereal daily variations, they came to the conclusion that at least a part of the sidereal variation was due to spurious atmospheric effects.

Therefore, the results at low energies ($E \sim 10^{10}$-10^{11} ev) are still uncertain about the existence of sidereal daily variation. We will now look into the results of the measurements of sidereal daily variations at higher energies which have been made by finding the time variations of the frequency of extensive air showers, or the time-variations of meson intensities observed underground.

From a study of the extensive air shower experiment ($E \sim 10^{15}$ ev) at Wellington during 1955-56, Chapman and Ryder (1957) found a sidereal daily variation of amplitude of about $(.88 \pm .65)\%$ with the maximum at about 1700 hrs. L.Sid.T.

Farley and Storey (1957) analysed the extensive air shower data from Auckland during 1955 and found that the sidereal daily variation was not significant beyond statistical errors for particles of $E \sim 10^{14}$ ev (e.g., ampl. $\sim .14 \pm .15\%$ and the hour of maximum $\sim$ 2000 hrs. L.Sid.T.). This result was in direct contradiction with that obtained during 1954 by the same workers (Farley and Storey 1954) using less accurate data (e.g., ampl. $\sim 1.4 \pm .38\%$). The amplitudes of the sidereal variations were found to increase with energy of the particles detected, e.g., at $E \sim 10^{15}$ ev the amplitude was $\sim (1.17 \pm .44\%)$ and at $E \sim 3.10^{15}$ ev the amplitude was $\sim (2.3 \pm 1.0)\%$ (Farley and Storey 1957).

Escobar et al (1960) analysed the data from Chacaltaya and could not find any statistically significant sidereal variation for particles of energy $E \sim 10^{14}$ ev. However, they found for particles of $E \sim 2.10^{15}$ ev a sidereal variation of amplitude of about $(.76 \pm .20)\%$ with the time of maximum at about 1900 hrs. L.Sid.T.

Measurements by Citron and Stiller (1958) over the period 1953-56 and by Krasilnikov (1960) during 1958 of the extensive air shower experiments also failed to establish statistically significant sidereal daily variation up to $E \sim 2.10^{15}$ ev particles (ampl. being $\sim .2 \pm .1\%$ and phases differing widely between $E \sim 10^{14}$ ev to $E \sim 10^{15}$ ev).

Crawshaw and Elliot (1956) found a sidereal variation of amplitude $\sim 2.5\%$ at $E \sim 2.10^{16}$ ev. and about 6% at $E \sim 10^{17}$ ev; but the results were uncertain by large statistical errors.

At energies $E \sim 10^{18}$ ev, the investigations of the sidereal variation by Delvaille et al (1960) during 1957-58 also failed to show sidereal variation beyond statistical errors. For example, a sidereal variation of amplitude of about $(11 \pm 7)\%$ was observed for 800 showers with 1.5×10^7 to 10^8 particles and about $(35 \pm 29)\%$ was observed for 49 showers with 10^8 particles.

These results with extensive air showers at higher energies ($E \sim 10^{14}$-10^{18} ev) also show that one cannot be sure about the existence of a true sidereal variation with any certainty.

Investigations in the intermediate range of energies ($E \sim 10^{11}$ to 10^{13} ev) have been made by underground experiments. Sherman (1953) conducted an experiment at a depth of 846 m.w.e. ($E \sim 10^{12}$-10^{13} ev) and Barrett et al (1954) as well as Cocconi (1951) at a depth of about 1600 m.w.e. ($E \sim 10^{13}$-10^{14} ev); but all these experiments failed to establish a sidereal variation within an accuracy of $\sim$ .5%. Working at Holborn at a depth of 60 m.w.e., MacAnuff (1951) could not confirm a sidereal variation more than $\sim (.05 \pm .02)\%$ in amplitude. Mathews (1962) made observations at the same place during the period 1961 and found the true sidereal variation of amplitude of $\sim (.052 \pm .015)\%$ with the time of maximum at about 2030 hrs. L.Sid.T.

Jacklyn (1963) recently studied in great detail the existence of sidereal daily variation at Hobart using the data for 1958 from two counter telescopes located at a depth of 42 m.w.e. He considered the different possibilities which might give rise to annual mean daily variations in sidereal

and anti-sidereal time. He found a sidereal variation of amplitude of $\sim(.09\pm.10)\%$ with the time of maximum at about 0700 hrs. He has shown that this observation is in agreement with the hypothesis that a solar daily variation of constant amplitude and phase is superimposed on a sidereal daily variation which is modulated in amplitude and phase on a six-monthly basis.

It is, therefore, clear from the foregoing discussions that the main difficulty in establishing the sidereal effect was the large statistical errors which generally made the conclusions uncertain. Hence for any profitable analysis of the sidereal variation the first requirement would appear to be adequate statistics. The available underground data from Holborn for the last three years was found largely to meet this requirement. For example, it has been shown that the statistical error for the first harmonics of the annual daily variation (averaged over three years) is only about .004% so that sidereal variation as large as $\sim$.05% will easily be detected in the present case.

6.2 Results from the Underground Experiment

It has been suggested in the previous chapter that the observed daily variations at Holborn is largely due to atmospheric temperature effect and the solar variation of primary origin is quite small in comparison. Since the underground data could not be corrected for changes in the stratospheric temperature, pressure corrected data will be used in the following analysis. This will, therefore, mean that seasonal changes of the diurnal variations of stratospheric temperature will introduce corresponding changes in the solar daily variation underground and the spurious sidereal variation, generated in this way, will have to be taken into account in evaluating sidereal variation.

The calculation of the sidereal variation has been made following the method, developed by Farley and Storey (1954) in separating the true sidereal variation from the spurious effect which arises due to seasonal changes in amplitude of the solar daily wave. In this calculation it will be assumed that there is a true sidereal daily variation of constant amplitude and phase together with the solar daily variation which undergoes annual change in amplitude but keeps its phase constant over the year.

Farley and Storey introduced the technique of analysing the data in anti-sidereal time based on the analogous case of amplitude modulation of carrier wave in the radio-theory. The solar daily variation is considered as the carrier wave of frequency 365 cycles/year. If this is modulated to give an annual variation of amplitude, the modulating frequency will be 1 cycle/year. Hence this modulated carrier wave may be resolved into three components - the original carrier wave of frequency 365 cycles/year and the two side-bands with frequencies 364 cycles/year and 366 cycles/year - respectively called the anti-sidereal and sidereal waves. These are so called as the sidereal day is about four minutes shorter than the solar day (i.e. , there are 366 sidereal days in a year) and the anti-sidereal day is about four minutes longer (i.e., there are 364 anti-sidereal days in a year).

With these assumptions the daily variation in percentage can be expressed by a formula,

$$\frac{dI}{I} \times 100 = \left[A_{sol.} + B \cos 2\pi (t-\phi_{seas.})\right] \cos 2\pi (Nt-\phi_{sol.}) + C_{sid.} \cos 2\pi \left\{(N+1)t - \phi_{sid.}\right\} \quad \ldots\ldots\ldots 6.1$$

where, dI denotes the deviation from the mean intensity I; $A_{sol.}$ is the amplitude of the mean solar diurnal variation; the seasonal variation of the

amplitude is specified by B and $\phi_{seas.}$ i.e., B is the amplitude of the varying part of the solar daily variation. The third term represents the true sidereal variation of amplitude $C_{sid.}$ with the phase $\phi_{sid.}$; t has the unit of time in one year (00.00 hr. being on 22 September, the day on which coincidence occurs between the solar and sidereal times). N is the number of solar days and (N+1) is the number of sidereal days in a year.

Now, if the modulated solar wave of frequency N is decomposed into three components, as stated above, with frequencies N, (N+1) and (N-1) then the side-band with frequency (N+1) will be the fictitious sidereal wave and will modify the value of $C_{sid.}$ and $\phi_{sid.}$. The side-band with frequency (N-1) will be the anti-sidereal component. Therefore, the first term in eqn. (6.1) can be written as,

$$= A_{sol.} \text{ Cos } 2\pi(Nt-\phi_{sol.}) + \frac{B}{2} \text{ Cos } 2\pi \left\{(N-1)t-\phi_{sol.}+\phi_{seas.}\right\}$$

$$+ \frac{B}{2} \text{ Cos } 2\pi \left\{(N+1)t-\phi_{sol.}-\phi_{seas.}\right\} \qquad \ldots\ldots\ldots 6.2$$

Hence the apparent sidereal component D is obtained from eqns. (6.1) and (6.2) as given by,

$$D = \frac{B}{2} \text{ Cos } 2\pi \left\{(N+1)t-\phi_{sol.}-\phi_{seas.}\right\} + C_{sid.} \text{Cos. } 2\pi \left\{(N+1)t-\phi_{sid.}\right\} \ldots. 6.3$$

It can be seen from eqn. (6.2) that the second and the third term represent respectively the anti-sidereal and the fictitious sidereal waves whose amplitudes are equal and that the phase of the latter in sidereal time can be obtained from the former when reflected in the solar vector.

This method is unique in the sense that we can now analyse the data separately for the solar, apparent sidereal and anti-sidereal variations as though the other two are absent, when the analysis is carried over a complete year. For instance, if the amplitude modulated solar daily variation is now

arranged in sidereal time and averaged over the year the apparent sidereal variation will be obtained, the other two components having vanished.

Hence, if the cosmic ray data is arranged in anti-sidereal time and a significant anti-sidereal variation is obtained, it is generally assumed that this is entirely due to seasonal change of amplitude of the solar daily wave. The corresponding fictitious sidereal variation is calculated as outlined above and then subtracted from the apparent sidereal variation. Any significant variation is then taken to be a genuine sidereal effect (eqn. 6.3).

In order to see whether there is any indication of true sidereal variation underground, the mean monthly daily variations were subjected to harmonic analysis and the Fourier coefficients of the first harmonics of solar daily variations were calculated month by month. These have been plotted in solar time dial and are shown in Fig. 6.1a. It will be seen from the figure that the monthly vectors appear to have progressed in regular sequence over the year. Any divergence from the regular sequence can be attributed to the statistical errors; for example, the standard deviations for the tips of the monthly vectors are ~.012% and, therefore, the divergences cannot be considered statistically significant.

The annual mean amplitudes and phases of the solar, apparent sidereal and anti-sidereal variations were calculated and used in evaluating the 'ellipse of best fit'. The 'ellipse of best fit' calculated in this way is shown in Fig. 6.1b, together with the observed tips of the monthly solar vectors redrawn from Fig. 6.1a. The closed circles are the observed monthly vectors and the open circles are those expected on the 'ellipse of best fit'. The expected and the observed tips of the monthly vectors have been joined by straight lines

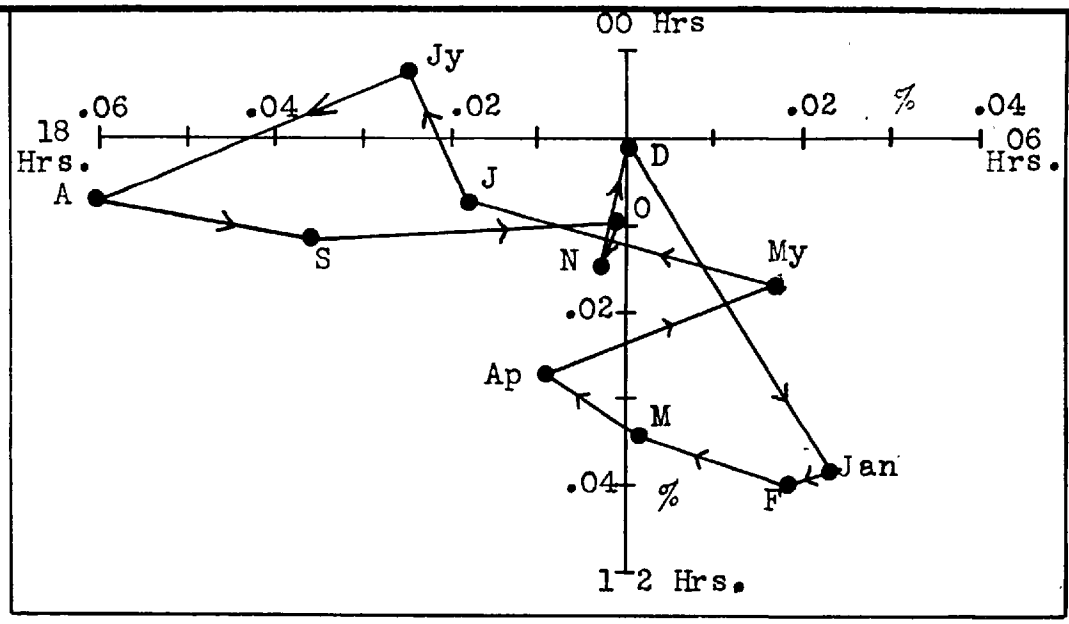


Fig.6.1a The first harmonics of mean monthly solar daily variations in cosmic ray intensity at Holborn from November 1960 to July 1964 plotted on a solar harmonic dial.

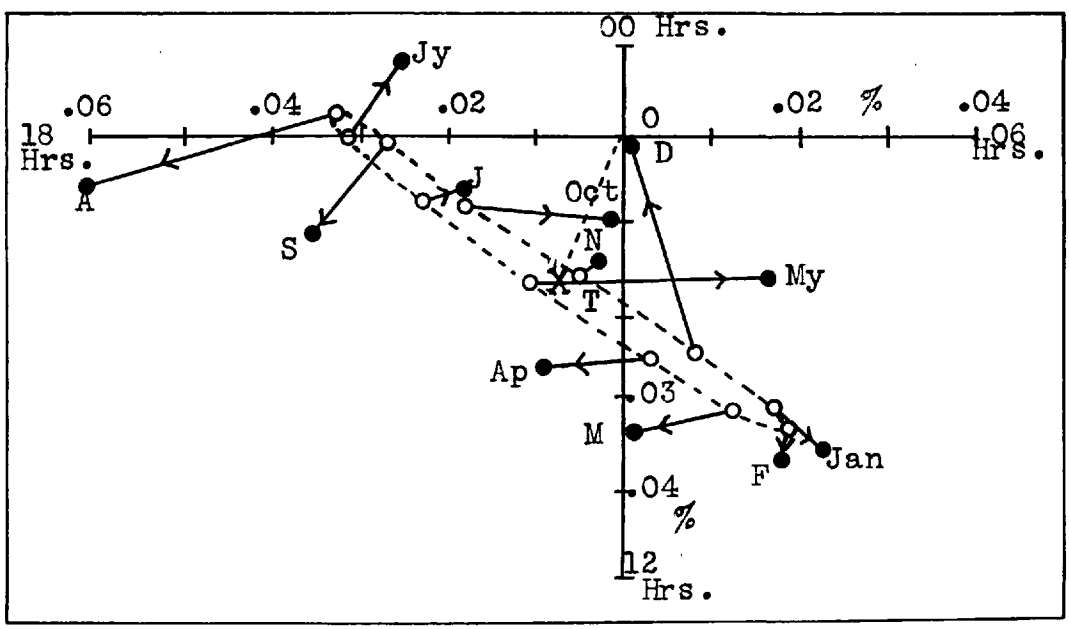


Fig. 6.1b The same as in Fig. 6.1a with the 'ellipse of best fit' drawn as ---O--- . OT is the average annual solar vector. Closed circles are the observed tips of the mean monthly vectors redrawn from Fig. 6.1a.

month by month in order to indicate the deviations of the observed tips from the 'ellipse of best fit'. It can be seen from Fig. 6.1b that there is very good agreement between the observed and the expected first harmonics within the limits of statistical errors. In evaluating the 'ellipse of best fit', second harmonics have not been taken into account because of the insignificant amplitudes of the anti-sidereal and apparent sidereal variations concerned.

The amplitudes and phases of the first harmonics of solar, apparent sidereal and anti-sidereal variations, which have been used to calculate the 'ellipse of best fit', are shown below in Table I. The amplitudes of the second harmonics are also shown in the table.

Table I

	Amplitude in % First	Amplitude in % Second	Phase, in hrs., of the First harmonics
Solar variation	0.018 ± 0.004	0.014 ± 0.004	13.58 ± 00.82
Anti-sidereal variation	0.016 ± 0.004	0.002 ± 0.004	22.15 ± 00.82
Apparent sidereal variation	0.015 ± 0.004	0.009 ± 0.004	18.00 ± 00.82

If we examine the above table, we find that the anti-sidereal vector is nearly as large as the solar vector. This anti-sidereal vector is too large to have originated from amplitude modulation of the observed solar vector, because the amplitude term B/2 in eqn. (6.2) should be smaller than the term A. Otherwise the depth of the modulation is so large that phase reversal of the solar vector will occur during parts of the year.

At this point it may be mentioned that in order to take into account of

the orbital motion of the earth around the sun, the aberration correction was introduced into the observed solar variation, so that on allowing for this effect the solar vector shifted to about 1600 hrs. and increased in amplitude to a value of about .03%(see the inset in Fig. 5.5, Chapter V). It will be seen that the correction for the aberration effect increases the average solar vector to about twice the amplitude of the anti-sidereal vector and consequently, if the anti-sidereal vector is generated by the amplitude modulation of the larger solar vector, no phase reversal of the solar vector can occur. The aberration correction thus removes this difficulty and yields a solar vector which compares more closely to the state of affairs as demanded by the eqn. (6.2).

The calculation of the true sidereal variation has been made following Farley and Storey as outlined above. The method of eliminating the spurious sidereal variation by means of the anti-sidereal variation is illustrated in Fig. 6.2. The observed solar vector OA has been corrected for the aberration effect (as discussed in the previous Chapter; inset in Fig. 5.5) and the corrected solar vector is represented by OA'. The vector OC' (dotted line) is the reflection of the anti-sidereal vector OC on OA'. Then CB' gives the magnitude of the corrected sidereal vector. The vector OD (dotted line) then represents the true sidereal vector which has been obtained by subtracting the vector OC' from the apparent sidereal vector OB. The error circles for the vectors OA, OB, or OC have been calculated from the bi-hourly counting rates. The error circle for OD is $\sqrt{2}$ times the error circles for OB, or OC, as the vector OD was obtained from the vectors OB and OC.

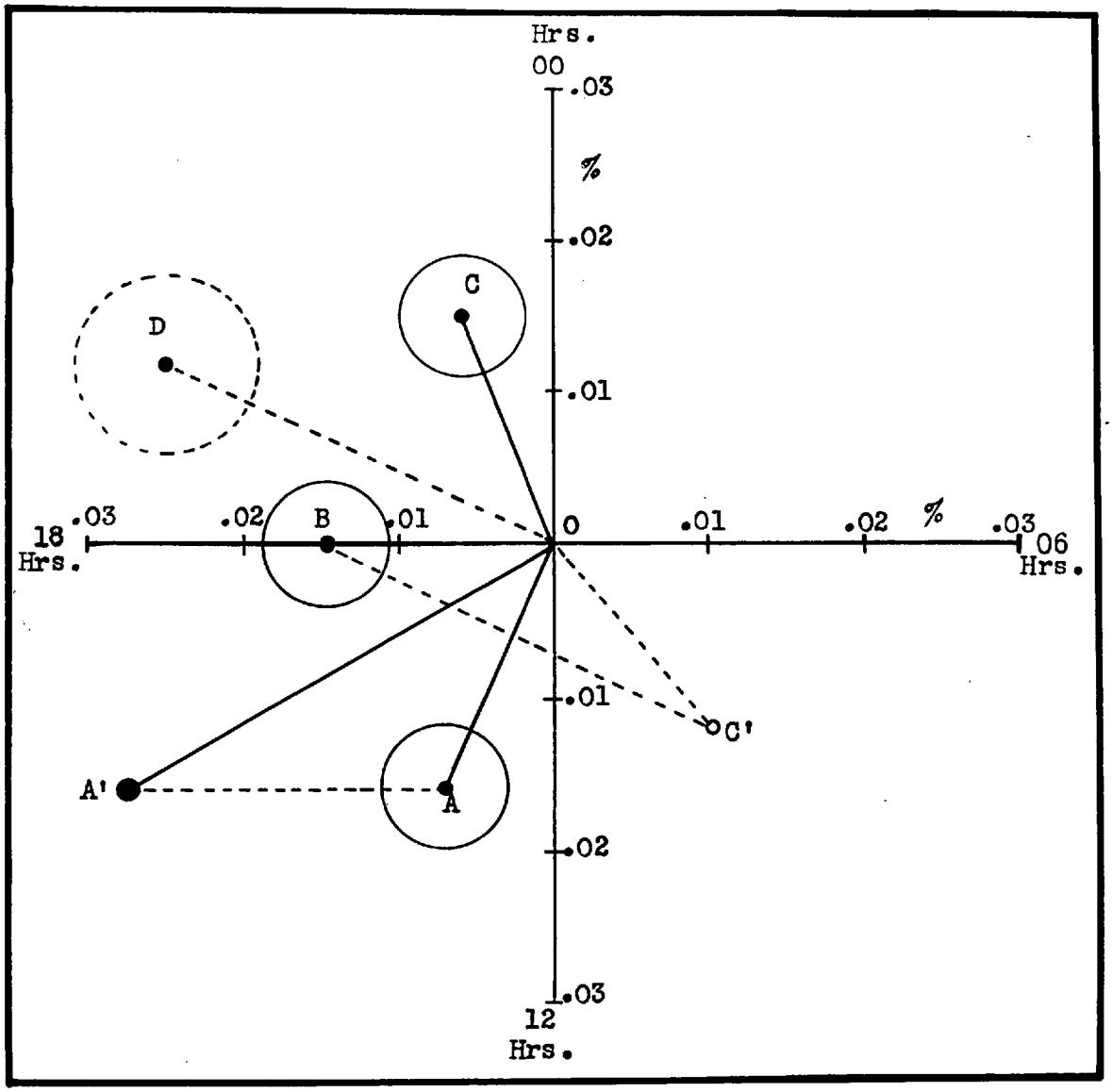


Figure 6.2 The first harmonic vectors of mean Solar, apparent sidereal, anti-sidereal and true sidereal variations observed at Holborn for the period 1961-1964. OA - observed Solar vector; OA' - Solar vector corrected for aberration effect; OC - anti-sidereal vector; OB - apparent sidereal vector; OD - true sidereal vector.

In table II are given the phases and amplitudes of the corrected solar and true sidereal variations as calculated from Fig. 6.2.

Table II

	Amplitude in %	Phase in Hrs.
Solar variation (corrected for aberration effect)	0.031 ± 0.004	16.00 ± 00.82 hrs.L.Sol.T.
True sidereal variation (after correcting for aberration effect)	0.027 ± 0.006	19.40 ± 1.00 hrs.L.Sid.T.

The amplitudes of the true sidereal variations as shown in Table II are several times the statistical errors and should, therefore, be considered as genuine and significant. We can thus conclude that there is a true sidereal anisotropy in the primary radiation (of energy $E \sim 10^{11}$ ev) measured at Holborn (60 m.w.e. underground) of an amplitude of $\sim (.027 \pm .006)\%$, the direction of anisotropy being in the direction of 19.40 ± 1.00 hrs. L.Sid.T.

6.3 Discussion of the Results

Apart from the sidereal variation observed at Holborn, two more experimental results of sidereal daily variations at this moderate energy range ($E \sim 10^{11}$ ev) from Hobart (42 m.w.e.) in the southern hemisphere and Budapest (40 m.w.e.) in the northern hemisphere will be examined here. The Budapest data has been supplied by Dr. A. Somogyi and the results analysed by Dr. T. Thambyahpillai (private communication). Table III below shows the results obtained at these stations.

Table III

Station, depth and location	Period of analysis	Sidereal Daily Variation	
		Amplitude %	Phase in Hrs.(L.Sid.T.)
Holborn (60 m.w.e.) 50°N	1961-64	0.027±0.006	19.40±01.00
Budapest (40 m.w.e.) 47.5°N	1961-62	0.030±0.006	20.00±01.00
Hobart (42 m.w.e.) 35°S	1958	0.094±0.010	07.00±0050

It will be seen from the above table that in all three cases significant and genuine sidereal daily variations were observed. This gives confidence in the internal consistency of the result obtained in the present analysis. But it is also worthy of note that the amplitude of the sidereal variation observed at Hobart is much larger than the amplitudes observed at Holborn and Budapest. There also appears to exist a phase difference of about 12 hrs. between the northern and southern hemisphere. It will, therefore, be of interest to examine the direction of maximum intensity of the anisotropy and see what light it can throw on the origin of the cosmic rays.

It will be recalled that for extra-galactic origin of cosmic rays the Compton-Getting theory (section 6.1) predicts an amplitude for the anisotropy in the primary radiation with sidereal times which is about .3%, with the time of maximum at about 2040 hrs. L.Sid.T. Now, if the above Table III is examined, it will be found that this predicted amplitude is about an order of magnitude larger than those observed in the northern hemisphere; and although the amplitude is somewhat larger in the southern hemisphere the time of maximum there is about 12 hrs. out of phase with that to be expected from the Compton-Getting theory. Therefore, we can conclude with a fair degree of confidence that at this moderate

energy range the cosmic rays cannot come from extra-galactic sources and hence must be of galactic origin.

However, before examining how well the galactic origin of cosmic rays will account for the above results, the following points may be forwarded against the extra-galactic origin of cosmic rays. For example, it is possible to contain the particles of energy even as high as $E \sim 10^{18}$-10^{19} ev within a space of radius $\sim 3.10^{20} - 3.10^{21}$ cm which is very much smaller than the assumed radius of the Galaxy $\sim 3\text{-}5.10^{22}$ cm. The radio-astronomical data indicate that the inter-galactic space has a lower concentration of soft cosmic rays than within the Galaxy. Besides, since there is a reduction of the magnetic field in passing from the Galaxy into the inter-galactic space, the particles coming from outside will be moving into a region of increasing field strength so that a mechanism of reflection will be operative. Finally, it is possible to account for the energy balance in the Galaxy when novae or supernovae inside the Galaxy are assumed to be sources of cosmic rays (Ginzburg 1958).

Now, considering the motion of the solar system with respect to the nearby stars ($\sim$ 20 km/sec.), we find that this will give rise to a sidereal variation with the amplitude less than about .02% and the time of maximum at about 1800 hrs. L.Sid.T. This expected effect is in very good agreement with the observations at Holborn and Budapest (the two northern hemispheric stations) but differs from that observed by Hobart (the southern hemispheric station) both in amplitude and in phase. Regarding the amplitude of the sidereal daily variation at Hobart, it might be pointed out that this value was obtained during the period of high solar activity (1958) when the solar daily variation itself was as large as

$\sim$.13%. On the other hand, the results obtained at Holborn and Budapest correspond to a period near the solar minimum epoch where the respective amplitudes of the solar daily variations were both $\sim$.03%.

In order to see how the above results (Table III) can be used to determine the possible direction of anisotropy, we shall consider here some of the theoretical models proposed so far in connection with the galactic origin of cosmic rays and examine the above results in the light of these models.

Cocconi (1951) found an isotropic distribution of cosmic rays for particles of energy $E \sim 10^{13}$-10^{14} ev and proposed that this isotropic distribution may be due to the curling effects of irregular magnetic fields which extend over regions larger by some order of magnitude than the radius of curvature, ρ, of the path of the particles, where,

$\rho \sim \frac{E}{300H}$, E, is the energy of the particles in ev and H is the magnetic field strength in gauss.

So, for $E \sim 10^{13}$-10^{14} ev and $H \sim 10^{-5}$ gauss (Spitzer and Tukey, 1951; Davis, 1951), ρ is $\sim 10^{16}$-10^{17} cm which is the average distance between the stars in the region of the Galaxy where our solar system is located. He showed that the low energy particles ($E \sim 10^{9}$-10^{10} ev) possibly come from the sun but at the higher energy end ($E \sim 10^{13}$-10^{14} ev) they can come from the whole of Galaxy. The radiation consists of particles which have leaked out from the trapping fields of the producing stars and have possibly undergone further acceleration in the interstellar space in their passage to the earth. These particles will disappear partly by collision with the interstellar matter or just by diffusing away from the Galaxy.

Fermi (1949) proposed that the particles diffuse randomly through the

interstellar space, gain energy by collision against the moving magnetic clouds and eventually loose their accumulated energy by collision with the hydrogen nuclei. This acceleration mechanism and model of the interstellar space can explain the isotropy of cosmic rays and energy spectrum of protons but fails to account for the heavier particles in the primary cosmic radiation - it needs exceedingly high energy to initiate acceleration process for heavier particles and it predicts an energy spectrum for them which falls off sharply with energy contrary to the observations (Morrison et al, 1954).

Morrison et al (1954) extended this model and proposed that the cosmic ray particles diffuse around the Galaxy for a time ($\sim 10^6$ years), long compared with the average time of escape from the Galaxy along straight line path, but short compared with the mean life before nuclear collision with the interstellar matter. They assumed the Galaxy to be a disk-shaped volume whose radius is $\sim 5.10^{22}$ cm and the thickness $\sim 2.10^{21}$ cm. The sun sits about 3.10^{19} cm away from the meridian plane. The galactic volume is assumed to be filled with masses of turbulent ionised and magnetic hydrogen plasma moving randomly in a rather unionised substratum. In this model the cosmic rays travel along nearly straight lines between the magnetic clouds of streaming gases. The particles enter into such masses, begin to follow complicated trajectories along the lines of force and eventually drift out of the clouds. The m.f.p. will depend on the spacing of the gas clouds whose cores may be of different sizes and different magnetic field strengths.

Recently, Davis (1954) suggested that the galactic magnetic field extends throughout spiral arms with quite regular structure which determines the character of the anisotropy observed at the surface of the earth. The field

strength was taken to be $\sim 10^{-5}$ gauss. The main consequence of this structure is that the particle is constrained to spiral around a particular line of force, so that it follows the line of force wherever the line of force may go. There may be occasional reversal of the direction of motion along the lines of force and there may be slow transverse diffusion due to inhomogeneities in the field. The assumed structure of the spiral arm is such that the magnetic lines of force lie in a parallel bundle which starts from one end of a spiral arm at the rim of the Galaxy, makes several turns around following the arm and eventually connecting another arm near the centre of the Galaxy. Then it spirals out again to the rim of the Galaxy along this arm and spreads out in the inter-galactic space with very much reduced magnetic field strength which can be represented by a dipole field like structure. Since the distribution of stars and the gas clouds along a spiral arm is far from uniform, there will be regions where the mass density and hence the gravitational force will drop a bit. The lateral pressure of the field will expand this region laterally forming a bulge through which cosmic ray particles will escape into the inter-galactic space.

Davis has considered different sources of sidereal anisotropy which might arise under this assumed structure of the Galaxy. Fermi mechanism and betatron collision (i.e., due to time varying magnetic field) can give rise to an anisotropy with more cosmic rays along the field lines than along directions at right angles to them. If the probabilities of escape from the system of the particles depend on the steepness of the spirals in a different way than does the probability of acceleration, then the acceleration processes will give rise to an anisotropy with more cosmic rays in the direction normal to the field than parallel to it.

Due to slow diffusion of particles out of the Galaxy, an anisotropy in the cosmic radiation will be observed. For example, if the particles diffuse along the lines of force out of the Galaxy either at the end of a spiral arm or at a region of low mass density, there will be net flux of particles towards the nearest point of escape. Scattering and collision processes will dominate this region and contribute to the flux in opposite direction. As a result, there will be less number of cosmic ray particles along the lines of force leading to the point of escape and more in the opposite direction. Finally, he considered the source of anisotropy which may arise due to the decrease of cosmic ray density and the magnetic field strength from the axis to the edge of the spiral arm.

Davis assumed that the spiral arm, in which the sun is situated, is roughly elliptical in cross-section with major axis extending $\sim 3.10^{21}$ cm in the galactic plane and minor axis to $\sim 1.10^{21}$ cm normal to the galactic plane. The sun is about 5.10^{19} cm north of the galactic plane and about 1.10^{21} cm away from the axis of the spiral arm. In the neighbourhood of the solar system this spiral arm runs in a direction whose galactic co-ordinates are $l = 40$, $b = 0$ and whose right ascension and declination are respectively 2000 hrs. and 35°N. This means that following this spiral arm in this direction leads towards the centre of the Galaxy.

We shall now consider the results given in Table III in the light of this model. Davis has calculated the sidereal anisotropy in the primary radiation which would be observed by detectors located in the northern and southern hemispheres of the earth, based on the different sources of anisotropy as discussed above i.e., the anisotropy which is due to (i) the effects of acceleration processes (ii) the effects of the diffusion process and (iii) the effects of the

inhomogeneities. The times of maximum expected for the northern hemispheric stations were found to be at 0800, 2000 and 1200 hrs. L.Sid.T. respectively for the three mechanisms to be operative; for the southern hemispheric stations corresponding times of maximum were 2000, 2000 and 1200 hrs. L.Sid.T.

So, comparing the times of maximum of the sidereal daily variations at Holborn, Budapest and Hobart, we find that the times of maximum observed in the northern hemispheric stations correspond to the inward direction of the spiral arm and the time of maximum observed in the southern hemispheric station corresponds to the outward direction of the spiral arm. The results from the northern hemisphere seem to favour the diffusion theories which would predict more diffusion parallel to the magnetic lines of force in the galactic arm than in the direction normal to it. However, the time of maximum at Hobart would suggest that there is a flow of cosmic radiation in the reverse direction due possibly to reflection at the irregularities in the magnetic field and that this reverse flow gives a larger number of particles than are observed in a direction at right angles to the field.

In this connection, it is of interest to mention the theory of cosmic radiation as suggested by Ginzburg (1958). Based on the evidences from radio-astronomy and the considerations of the energy balance, Ginzburg has proposed that certain specific objects, the expanding envelopes of supernovae and possibly of novae are the sources of cosmic radiation. These stars are significantly concentrated near the galactic plane mainly around $\sim 2.10^{21}$ cm about this plane. The cosmic rays produced in such stars can be accelerated to required energy range - the initial energy being supplied by the eruption of the stars which occurs once in about 30 years.

The above results showing the approximate direction of anisotropy in the primary radiation with the sidereal time along the galactic plane will not thus contradict the existence of these possible sources of cosmic radiation in the Galaxy.

6.4 Summary

(i) The pressure corrected cosmic ray intensity observed at Holborn (60 m.w.e.) exhibits a true sidereal daily variation of amplitude $\sim (.027 \pm .006)\%$ with the time of maximum at 1924 ± 0100 hrs. L.Sid.T.

(ii) This result has been compared with those obtained at Hobart (42 m.w.e.) and Budapest (40 m.w.e.) both of which stations observed significant daily variations in sidereal time.

(iii) The results are consistent with the galactic origin of cosmic rays at this energy range ($E \sim 10^{11}$ ev).

(iv) The direction of anisotropy as determined by the time of maximum of the sidereal daily variation suggests the sources of the sidereal anisotropy to be along the spiral arm of the Galaxy. The observations at these three stations seem to favour the diffusion theories which predict particles to diffuse more easily along magnetic lines of force than at right angles to them.

CHAPTER VII

FORBUSH DECREASES

7.1 Introduction

The sudden and transient decrease of cosmic ray intensity occurring during the time of geomagnetic storms was observed by many workers like Messerschmidt (1933), Forbush (1937) and others but the world-wide nature of these decreases was first pointed out by Forbush (1938a). During a large geomagnetic storm on 24th April 1937, Forbush observed that the decrease in cosmic ray intensity occurred simultaneously at stations located far apart (such as, Cheltenham 39°N and Huancayo 12°S). This proved the world-wide character of the decrease and also ruled out the possibility that its origin lies in atmospheric variations. Since then these short-term and non-periodic decreases have come to be known as Forbush decreases - so named after Forbush. The non-meteorological nature of these decreases was definitely established in 1954 when Simpson (1954) first observed that a neutron monitor and an ionisation chamber simultaneously recorded the Forbush decrease which occurred during a magnetic storm on 12 June 1951. The maximum decrease in the neutron monitor was about 4 times larger than the decrease in the ionisation chamber. Since, after correction for changes in atmospheric pressure, the neutron intensity variations reflect the changes in the primary cosmic radiation, Simpson's observations established that Forbush decreases represent depressions in the intensity of primary radiation.

Simpson (1954) also made two flights with an Aircraft carrying a neutron monitor during the period of the Forbush decrease of 12 June 1951 which reached its minimum value on about 18-19th and recovered to the normal value on about 26-27th. The first flight was made on 18th and the second one on 26th.

It was found that the neutron intensities above and below the knee of the intensity-vs-latitude curves were lower on the 18th and higher on the 26th. This conclusively showed that Forbush decreases are not caused by variations in the geomagnetic field. Recently the space satellite Pioneer V observed two Forbush decreases - one on 31 March and the other on 30 April 1960 at distances of ~.03 A.U. and .01 A.U. away from the earth. These decreases were also observed concurrently by sea level neutron monitors. These observations conclusively proved that the mechanism producing Forbush decreases is independent of the geomagnetic field.

It is indeed known that there is no one-to-one correspondence between Forbush decreases and geomagnetic storms - geomagnetic storms are found to occur without any Forbush decrease being observed, while large Forbush decreases are often associated with very small geomagnetic storms. It is generally believed, therefore, that there is no casual relationship between the two phenomena but both of them may have a common origin, particularly in the effects of the emission of corpuscular streams from the sun.

An interesting statistical study has been made by Sekido et al (1955) on the association of geomagnetic storms with Forbush decreases. They have found that it is necessary to classify the geomagnetic storms into S-types and M-types - the former being closely related to sunspot groups and being accompanied by Forbush decreases, while the latters are not related to the sunspot groups nor are they correlated with Forbush decreases. They have suggested that the S-type storms are caused by magnetic corpuscular clouds ejected by the solar flares; M-type storms are, on the other hand, caused by the non-magnetic corpuscular beams continuously emitted by the so-called M-regions. There was thus some evidence that Forbush decreases are related to solar flares.

Kamiya and Wada (1959) studied the association of solar flares with Forbush decreases and type IV outbursts (i.e., the broad band continuum of intense outbursts of radio emission from the sun). They have found that closely associated with many solar flares there occur these outstanding radio outbursts; they have also found that Forbush decreases are most likely to be observed following a major solar flares of importance 3 and 3^+ when it is accompanied by a type IV outburst.

Bell (1963) has studied statistically the relationship of the type IV outbursts and solar flares with the geomagnetic effects (such as geomagnetic storms, Polar Cap Absorption etc.). She has found that type IV outbursts are most strongly associated with major solar flares of importance 2 or greater and have a significant probability of being followed by geomagnetic storms, Polar Cap Absorption phenomena etc.

Webber (1962) has studied the relationship between Forbush decreases and the different associated solar and geophysical phenomena observed over the period 1955-60. A close relation of large Forbush decreases with preceding major solar flares accompanying type IV outbursts was confirmed. He also found that there was no association between the durations of Forbush decreases and geomagnetic storms nor was there any association between the time scales of these two variations. The recovery of Forbush decreases generally follows an exponential law with the time constant showing large variability from event to event; the recovery may take place over a period of days to weeks or months and may not even be complete. The recovery of Forbush decreases does not depend on the amplitude of the decrease nor on the strengths of the associated solar or geophysical phenomena.

It is, however, clear from the above discussions that Forbush decreases and other geophysical phenomena are closely related to the events occurring

on the surface of the sun and almost all theoretical models proposed so far to explain these sudden decreases in cosmic radiations are, therefore, based on the facts presented above. One of these models has been described in Chapter I.

7.2 The Rigidity Dependence of Forbush Decreases

Another feature of Forbush decreases is their rigidity dependence - the modulation is found to be greatest at low rigidities and extending over the range 1-100 Gv (Webber 1962, Mathews 1963). The conclusive evidence of the rigidity dependence of Forbush decreases came from the observations of Simpson (1954) in 1951. During the Forbush decrease event of June 1951 Simpson observed that the decrease in nucleonic component was about 4 times larger than in ionising component. Since the neutron monitors respond to the lower rigidity portion of the primary spectrum this observation has shown that the variation is indeed dependent on the rigidity of the primary particles. Recently Sandstrom and Forbush (1958) have studied about 8 Forbush decreases during 1956-57 and found that decreases in neutron monitors are about 2.5 to 4.5 times larger than in ionisation chambers.

The rigidity dependence of Forbush decreases evident from above has been studied by several workers using records from sea level neutron monitors, meson telescopes and ionisation chambers. Theoretically the rigidity dependence of Forbush decreases can be determined from a knowledge of the differential response curves W(R) and the fractional change in the differential rigidity spectrum of primary cosmic radiation, f(R) - the so-called modulation function or rigidity spectrum of the variation. Generally two types of modulation functions have been proposed and found to be consistent with observations, e.g.,

$$\text{(I)} \quad f(R) = AR^{-\gamma} \qquad 7.1$$

$$\text{(II)} \quad f(R) = -A, \text{ for } R < R_{max}$$
$$= 0, \text{ for } R \geq R_{max} \qquad 7.2$$

where, A and γ are constants; R is the rigidity of the particles. R_{max} ~ 30-40 Gv and differs from event to event. The modulation functions (I) and (II) given above will be henceforth referred to as type I and type II modulation functions respectively.

Observations favouring the first type of modulation function (eqn. 7.1) for Forbush decreases have been reported by Roederer et al (1959), McCracken (1960), Webber (1962) and others. The value of the exponent γ has been found to differ from one observation to the other; e.g., Roederer et al found γ=.5, McCracken found γ=.9, while Webber found γ= .5 for sunspot maximum and γ=1.0 for sunspot minimum. Lockwood (1960) has studied about 20 Forbush decreases during 1954-59 and found that the rigidity dependence of Forbush decreases which gives best fit is $f(R) = aR^{-1} + b$, where a and b are constants and can vary from event to event.

On the other hand, Dorman (1957, 63) and others have favoured the second type of modulation function (eqn.7.2) so that in their case γ =0, A = .08 to .20 appear to explain the rigidity dependence of Forbush decreases. They have suggested that the values of A and R_{max} will depend on the characteristics of the solar plasma stream causing the Forbush decreases and on the position of the earth with respect to the stream.

The study of rigidity dependence of the modulation at higher rigidities (R ~100 Gv) has recently been made by Mathews (1963). He analysed the large Forbush decreases of November 1960 and July 1961 recorded by sea level neutron and meson monitors and by underground detectors at Holborn (60 m.w.e.), Yakutsk (60 m.w.e.) and Budapest (40 m.w.e.). From the comparison of the ratios of the decreases at sea level to those underground, he has found that $f(R) \propto R^{-1}$ does not fit the observations.

In the following sections of this chapter several Forbush decreases observed at Holborn (60 m.w.e. underground) during 1961 to 1964 will be studied and an attempt will be made to decide which form of the modulation function can explain the observations.

7.3 Experimental Observations of Forbush Decreases at Holborn

The data available from November 1960 to July 1964 at Holborn was used to study Forbush decreases observed underground. Since bihourly values could not be corrected for atmospheric temperature effects due to lack of corresponding aerological data, the daily intensities will be used in the following analysis. In this case the necessary aerological data were available for day to day intensity corrections and consequently the data have been corrected for all atmospheric effects (such as, barometric, decay and positive temperature effects) using the appropriate coefficients as found in Chapter III.

The daily plots of underground intensity were then compared with those of pressure corrected neutron intensities at London and Deep River. From comparison of these daily plots, six Forbush decreases were selected during 1961-62 according to the following criterion - the maximum decreases observed in neutron monitors at London or Deep River were $\sim$ 3-4% (or greater). All the six decreases were preceded by moderate solar flares of strengths 2^+ to 1^+ and four of them were associated with sudden commencement type magnetic storms. The Forbush decreases of November 1960 and July 1961 have been studied by Mathews (1963) and have not been included in the present analysis.

During the period 1963-64 two Forbush decreases occurred - one in September and the other in October, 1963. These decreases were observed by the world-wide network of neutron monitors at sea level. At Holborn only a small Forbush decrease was observed in September but not in October. It may be pointed

out that during the September decrease cosmic ray intensity in the neutron monitor at London was depressed by about 8% as compared to about 2-3% in October. This small decrease in October which could be observed by neutron monitors at sea level could not be detected by the underground detector. On the other hand the month of September 1963 was characterised by intense solar and geomagnetic disturbances unusual for the period of minimum solar activity. Hence this Forbush decrease event in September 1963 will be studied in great detail in a separate section (section 7.3b).

7.3a Forbush Decreases during 1961-62.

The six Forbush decreases selected during the periods 1961 and 1962 have been analysed by using the method of superposition of epochs. This was done firstly to increase the statistical accuracy in underground intensity and secondly to study only the average feature of Forbush decreases. The data from sea level neutron monitors at Mina Aguilar, Buenos Aires, London and Deep River and those from the underground telescopes at Holborn were used for this analysis. No data from sea level meson detectors were used because of the uncertainty in correcting the data for atmospheric effects. No attempt has been made to study the relationship between Forbush decreases and geomagnetic storms.

The zero-days were selected as epoch-days when the daily intensity records from neutron monitors at London and Deep River started to decrease suddenly and simultaneously reaching within the next one or two days to a minimum level of about 3-4% (or greater) below the pre-decrease level. As these decreases were not directly observable in the underground data because of the rather large statistical fluctuations, the underground data were grouped using the same zero-days as were selected from the neutron data.

The results from the analysis of superposed epochs are shown in Fig. 7.1. The mean intensity for consecutive five days before the epoch-day was taken as the mean level of cosmic ray intensity and the percentage deviations of the daily intensities from this mean level have been plotted in the figure. The mean intensity during the first two days following the epoch-day was taken as a measure of maximum amplitude of the decrease.

From the Fig. 7.1 it can be seen that the maximum decrease has been observed at Deep River which has the lowest cut-off rigidity, the amplitudes of Forbush decreases being smaller at stations with higher cut-off rigidities.

Ratios of the decreases in neutron intensities at sea level to that in meson intensities underground as well as the ratios of the decreases in neutron intensities at different latitude stations to that at Buenos Aires (a low latitude station) have been calculated in order to study the rigidity dependence of Forbush decreases (section 7.4 below).

7.3b Forbush Decrease of 21-22 September 1963

During 13-27 September 1963 a very large and intensely active solar region associated with large sunspot groups was visible and was the cause for numerous solar and geophysical disturbances. The Central Meridian Passage occurred on September 20 at about 1500 hrs. More than 50 solar flares of all importances were recorded, eight of them being major solar flares of importance 3 and 3^+. Intense geophysical disturbances such as, short wave fade-out, magnetic storms etc. also occurred during this period. Three solar flares of importances 3^+, 3 and 3^- occurred on the 15th in succession at 0015 hrs., 0459 hrs. and 1858 hrs; three solar flares of importance 3 also occurred on the 16th. A moderate magnetic storm which started on the 13th subsided on the 17th. A solar flare of importance 3 started at 2351 hrs. on the 20th and it was followed by a severe magnetic

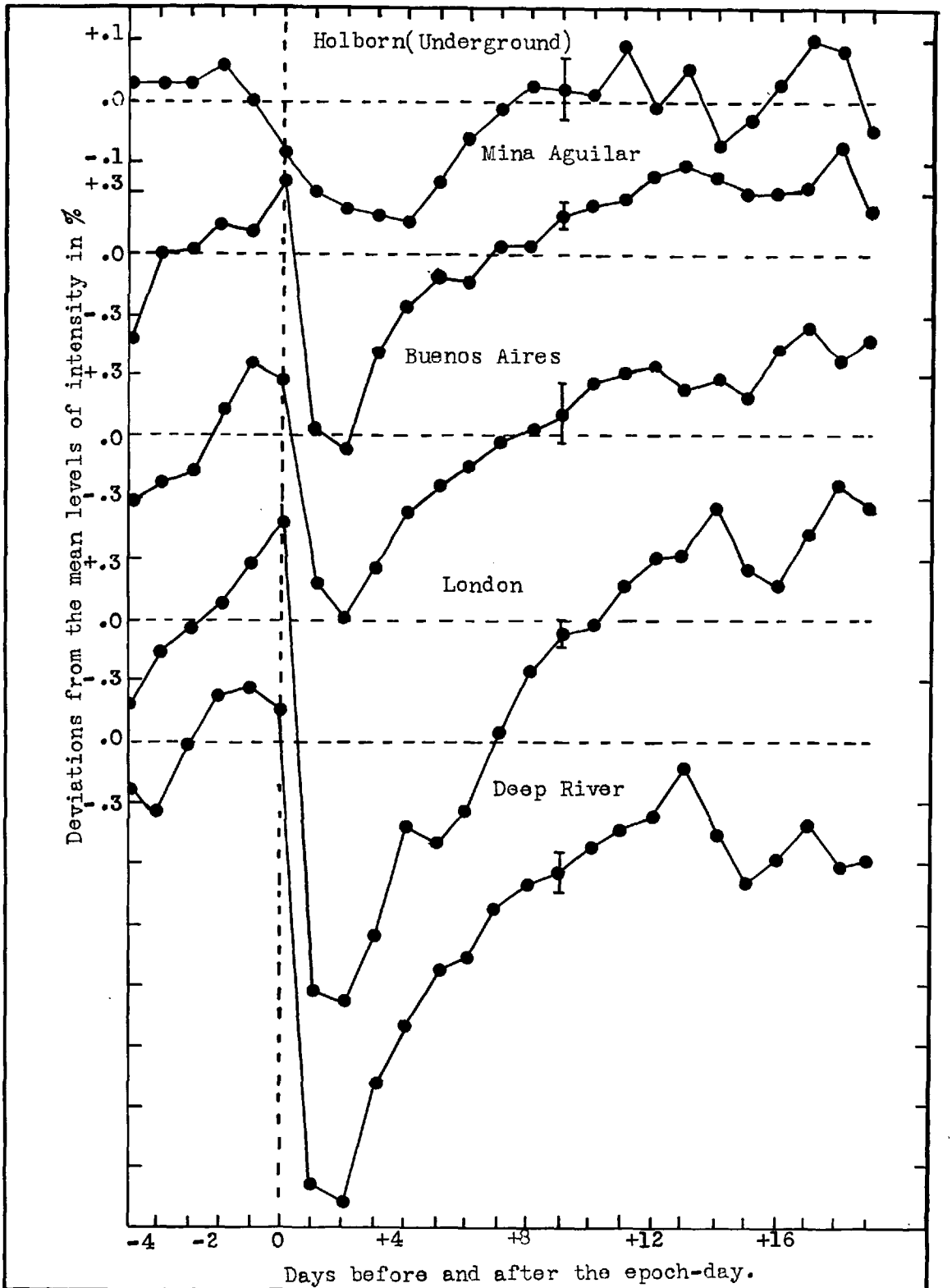


Fig. 7.1 The results of Chree analysis of the changes in neutron intensities at different sea level stations and in meson intensity at Holborn for the Forbush decreases during 1961-62 studied together. The mean levels---,correspond to the averages of 5 days before the epoch-day.

storm starting at about 1415 hrs. on the 21st. The cosmic ray intensity (based on neutron monitors at London and Deep River) at sea level started to decrease at about 22-2400 hrs. on the 21st and continued to drop until it reached the minimum level on the 23rd, when the magnetic storm subsided. There occurred one more solar flare of importance 3 on the 26th followed by a magnetic storm of moderate strength on the 27th. The recovery of the Forbush decrease from the minimum level took place over a long time of 9-10 days.

The cosmic ray intensities recorded by sea level neutron monitors at stations with different cut-off rigidities and by the underground Recorders at Holborn are shown in Fig. 7.2. The underground intensities from the three Recorders were added up and the mean intensities have been plotted. As an indication of geomagnetic activity the daily mean values of A_p-indices have also been plotted in the same figure in reverse scale for comparison.

It can be seen that a small decrease of about $(.30 \pm .05)\%$ was observed underground as compared to about 8-9% in neutron monitors at high latitude stations and about 2-3% at low latitude stations. The geomagnetic storm as measured by A_p -indices on the 13th was of moderate strength (A_p -indices increased to about 150γ) and this heralded the arrival of plasma cloud from the sun which caused a decrease in cosmic ray intensity that could be seen in high latitude neutron monitors. This Forbush decrease started to recover to normal values when a severe magnetic storm (A_p -indices increasing to about 250 γ) started on the 21st. This caused the cosmic ray intensity to decrease further and this Forbush decrease was observed by recorders at sea level as well as by Recorders underground. This decrease in cosmic ray intensity started a few hours after the severe magnetic storm of the 21st and was probably caused by the plasma clouds ejected by the major solar flare of importance 3 on the 20th. The

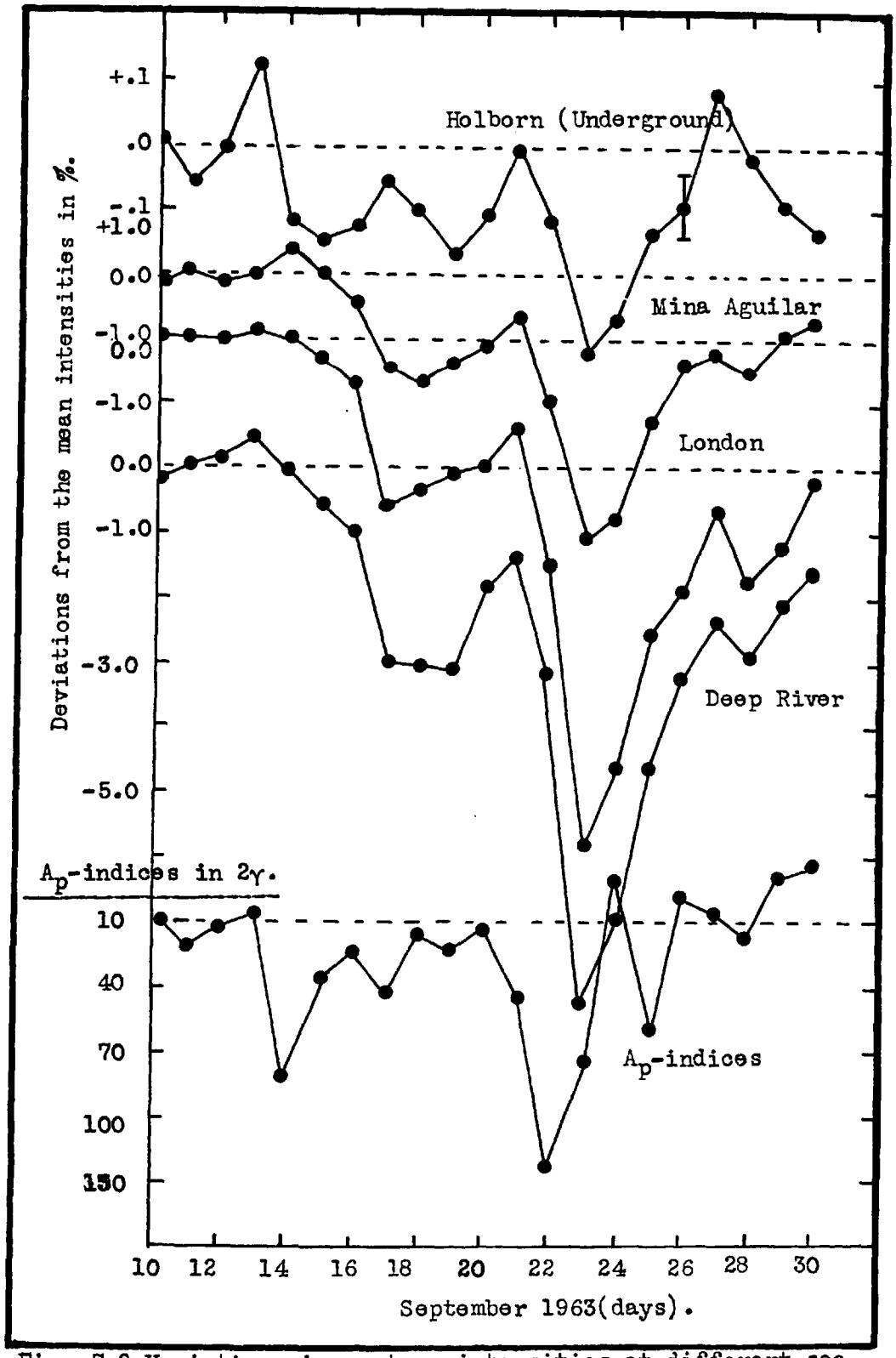


Fig. 7.2 Variations in neutron intensities at different sea level stations and in meson intensity at Holborn during the Forbush decrease event of 21-22 September 1963. The bottom curve shows the corresponding variations in A_p-indices.

maximum decrease resulting from the two Forbush decreases has been quoted above.

7.4 Discussions of the Results and the Observed Rigidity Dependence of Forbush Decreases

The events described in sections 7.3a and 7.3b have shown that in both cases significant Forbush decreases have been observed underground. These Forbush decreases have also been recorded by sea level neutron monitors, as can be seen by an examination of Figs. 7.1 and 7.2. It can also be seen that the amplitudes of the decreases were the highest at Deep River (the lowest cut-off rigidity station) and lowest at Holborn (having the highest cut-off). These experimental values of the decreases observed at different stations have been used to study the rigidity dependence of Forbush decreases. This study is of particular importance because the use of the underground data enables the study of the rigidity dependence of Forbush decreases to be extended to higher rigidities, perhaps as high as R~100 Gv.

Theoretically the expected decrease for any component of the cosmic ray flux can be calculated from the formula,

$$\frac{dI}{I} = \frac{\int_{R_\wedge}^{\infty} W(R)f(R)dR}{\int_{R_\wedge}^{\infty} W(R)dR} \qquad 7.3$$

where, $R_\wedge$ is the vertical threshold rigidity; $W(R)$ is the differential response function of the detector responding to the particular component of the cosmic ray flux; $\int_{R_\wedge}^{\infty} W(R)dR$ is the counting rate, I, of the detector and $f(R)$ is the modulation function specifying the rigidity dependence of the decreases.

So, knowing the response curves $W(R)$ for different detectors and using the different assumed modulation function $f(R)$ the expected decreases can be calculated. The expected decreases can then be compared with those observed and the form of the modulation function giving the best fit to the observations can then be taken as a measure of the rigidity dependence of the decreases.

It has been stated earlier that two types of modulation function have been extensively used by different workers and have been found to give consistent results about the rigidity dependence of Forbush decrease events. These modulation functions have been given in section 7.1 (eqns. 7.1 and 7.2). An attempt will now be made to examine which form of modulation function can give the best fit to the present experimental observations.

In order to study the rigidity dependence the following procedure has been adopted. It will be seen that both types of modulation function (eqns. 7.1 and 7.2) need an arbitrary constant 'A' to be evaluated. But instead of finding the expected decreases themselves at different stations, ratios of the decreases at two stations have been calculated thereby eliminating the arbitrary constant (eqn. 7.3). The response curves for different detectors at sea level, at mountain altitude and at Holborn underground are given in Appendix II and the values of W(R) have been taken from these curves for the present calculations.

The expected ratios of Forbush decreases in neutron intensities at sea level to the meson intensity underground have been calculated first of all using the modulation function of the type $f(R) \sim R^{-\gamma}$ (type I), with γ =.1,.2,... 1.0. The results of the calculation are shown in Fig. 7.3, where the expected ratios of Forbush decreases in neutron intensities at high latitude stations to that at a low latitude station (Buenos Aires $\Lambda \sim 35^{\circ}S$) are also shown in Fig. 7.3.

Secondly, using the modulation function of the type $f(R) \sim -A$ or 0, for $R < \text{or} \geq R_{max}$ (type II), the expected ratios of Forbush decreases in neutron intensities at sea level to that in meson intensity underground have been calculated with different assumed R_{max}. The results of the calculation are

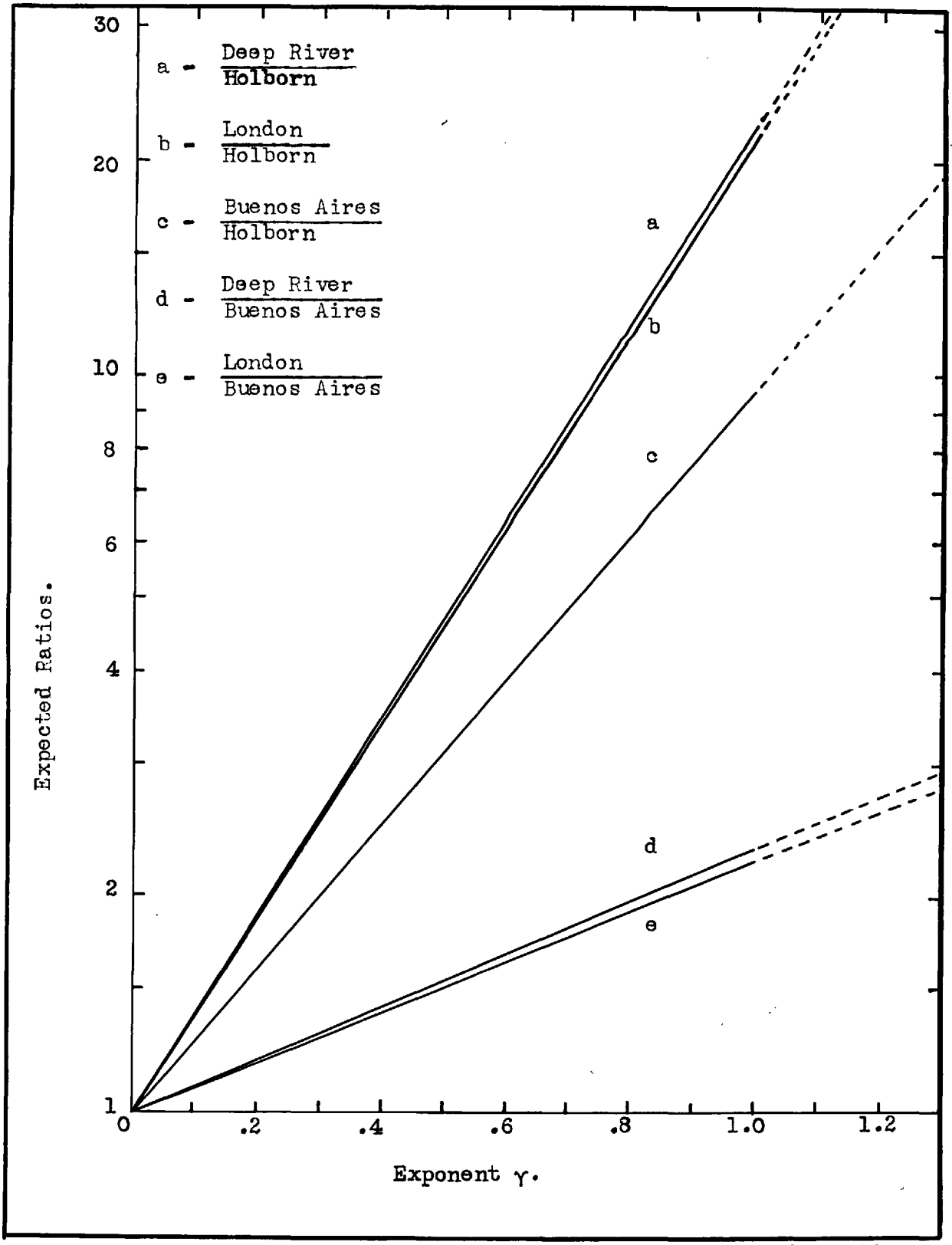


Fig. 7.3 The curves showing the predicted manner in which the ratios between intensity variations at different stations (as indicated in the figure) depend on the exponent of the modulation function $f(R) \sim R^{-\gamma}$.

shown in Fig. 7.4a, where the expected ratios have been plotted against R_{max}. The expected ratios of Forbush decreases in neutron intensities at high latitude stations to that at Buenos Aires are shown in Fig. 7.4b.

The results are summarised in Table I. The observed ratios for 1961-62 are those for the Forbush decreases described in section 7.3a and for 1963 are those for the September 1963 Forbush decrease event described in section 7.3b. During the September 1963 event no neutron data from a low latitude sea level station was available. Therefore, only the ratios of Forbush decreases in neutron intensities at high latitude sea level stations to that in meson intensity underground are shown in the table.

The values of R_{max} (according to type II modulation function) have been extracted from the Figs. 7.4a and 7.4b by comparing the observed ratios with the corresponding expected values. Similarly the values of the exponent γ (according to type I modulation function) which gave the best fit to observations were obtained from the Fig. 7.3. The expected ratios at $\gamma = .8$ during 1961-62 and $\gamma = 1.1$ during 1963 are also shown in the table (columns 6 and 7).

It can be seen from the table that the type I modulation function can account fairly well for the relative decreases in neutron intensities at sea level as well as for the ratios of the decreases in neutron intensities at sea level to that in meson intensity underground (columns 2, 3, 6 and 7). But the type II modulation function seems to give inconsistent results. For example, if the column 4 is examined it is seen that the type II modulation function can predict the relative decreases in neutron intensities at sea level if R_{max} is less than about 20 Gv; but to predict the ratios for the decrease in neutron intensities at sea level to that in meson intensity underground, it is necessary that R_{max} should be raised to about 100-125 Gv. However, it

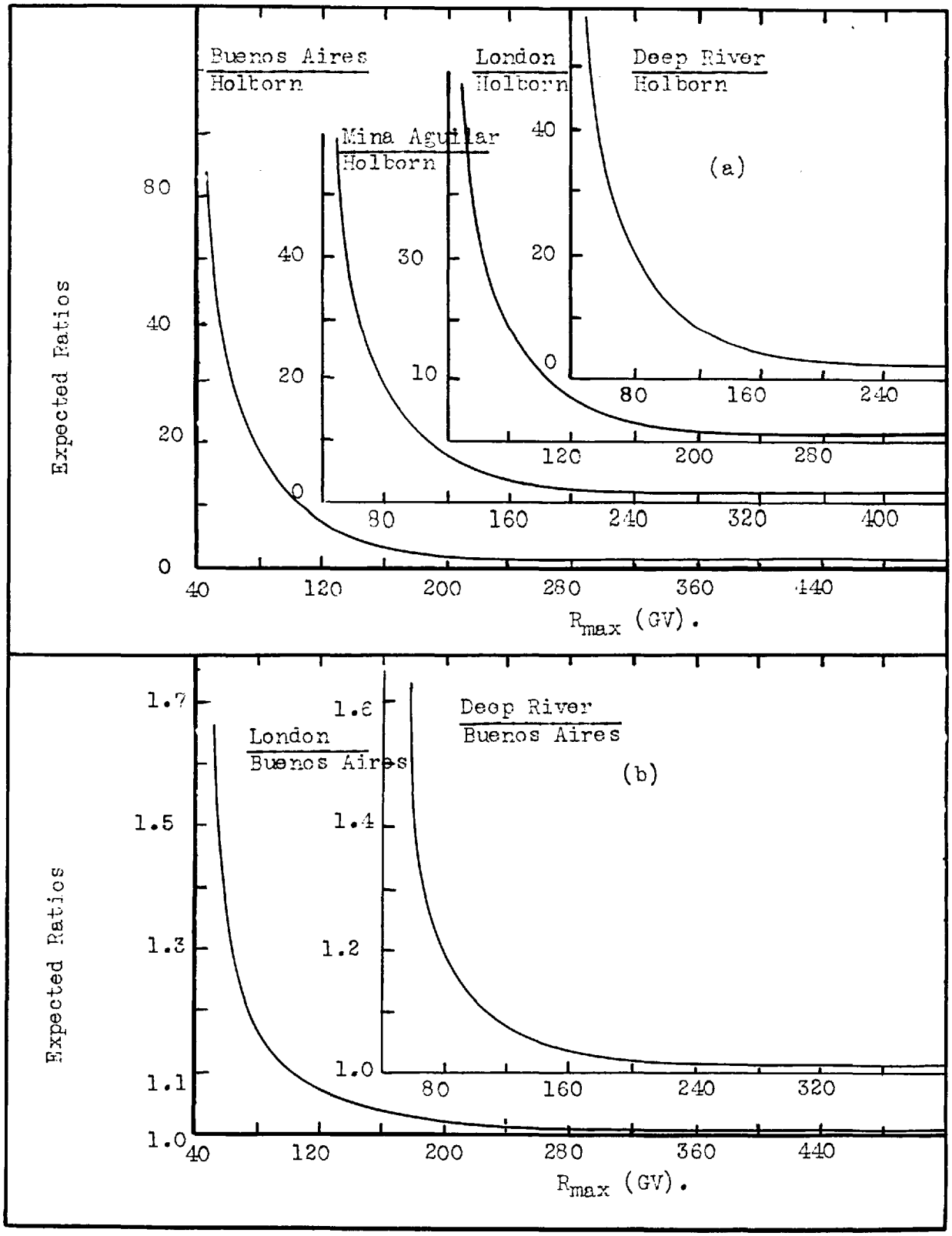


Fig. 7.4 The curves showing the predicted manner in which the ratios between intensity variations at different stations (as indicated in the figure) depend on the values of R_{max} of the modulation function $f(R) \sim -A$ or 0, for $R \lessgtr R_{max}$.

Table I

Ratios	Observed Ratios		Calculated			
			(a) $f(R) = -A$ or 0 for $R <$ or $> R_{max}$ R_{max} in Gv		(b) $f(R) = AR^{-\gamma}$ Ratios	
	1961-62	1963	1961-62	1963	1961-62 $\gamma=0.8$	1963 $\gamma=1.1$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
London(S.L.) Underground	10.0 ± 1.2	25.0 ± 3.0	~ 100	~ 70	~ 11.5	~ 25
Deep River(S.L.) Underground	12.8 ± 1.5	29.0 ± 4.0	~ 100	~ 65	~ 11.6	~ 26
Mina Aguilar(M.A.) Underground	5.9 ± 0.9	13.3 ± 1.5	~ 125	~ 75	-	-
Buenos Aires(S.L.) Underground	5.0 ± 1.0	-	~ 125	-	~ 6.6	-
London(S.L.) / Buenos Aires(S.L.)	2.1 ± 0.4	-	< 20	-	~ 1.8	-
Deep River(S.L.) / Buenos Aires(S.L.)	2.5 ± 0.5	-	< 20	-	~ 1.9	-

must be emphasised here that though the calculated values for underground meson intensity may be in error due to the uncertainty in the response curve for the underground detector, the error involved cannot explain away the large discrepancy found in the case of type II modulation function.

The differences between the ratios obtained in 1961-62 and those obtained in 1963 appear to show that the rigidity dependence of the Forbush decreases may change from event to event. Although it was necessary to average the data over a number of Forbush decreases in order to obtain a significant result from the underground measurement, the ratios given in column 2 represent the average characteristics of Forbush decreases but this may not be typical of any particular Forbush event. From that point of view it would appear better

to study the rigidity dependence of the Forbush decrease events individually. Unfortunately, however, the ratios of the September 1963 Forbush decrease in neutron intensities at high latitude stations to that at Buenos Aires (a low latitude station) could not be obtained due to the lack of data from Buenos Aires. Hence the September 1963 event could not be studied in greater detail. In spite of some uncertainties, it would appear from the foregoing analysis that the type I modulation function, $f(R) \propto R^{-\gamma}$ would give a better fit to our results than the type II modulation function, where f(R) is assumed to be a constant up to a certain upper rigidity limit. The calculated values of the exponent γ ($\sim .8$ to 1.1) in this experiment are in very good agreement with those calculated by Russian workers (Kuzmin et al 1963) who obtained the values of γ for Forbush decrease events during 1958 to 1962 that lie between $\sim .8$ to 1.2.

7.5 Summary

(i) The Forbush decreases observed underground during 1961-62 have been studied by the method of superposed epochs; the Forbush decrease event observed in September 1963 has been studied individually.

(ii) The rigidity dependence of the decreases has been studied by using two types of modulation function,

(a) $f(R) = A\, R^{-\gamma}$ (type I)

(b) $f(R) = -A$ or 0 for $R \lessgtr R_{max}$ (type II).

(iii) The rigidity dependence of the decreases has been such that the type I modulation function is found to be consistent with the observations, while the type II modulation function is found to give inconsistent results.

(iv) The rigidity dependence of the decreases in 1961-62 has been such that the best fit to the observations is obtained if $f(R) \propto R^{-.8}$. In 1963 the rigidity dependence which gives the best fit is obtained if $f(R) \propto R^{-1.1}$,

CHAPTER VIII

27-DAY VARIATIONS

8.1 Introduction

Apart from the non-periodic Forbush decreases observed in cosmic ray intensity often in association with several solar and geophysical phenomena, another type of variation in cosmic ray intensity has been found to occur at 27-day intervals and is known as the 27-day variation. Unlike the sudden and large decreases in cosmic ray intensity during Forbush decrease events, the 27-day variations are characterised by slow and small increases and decreases taking place at 27-day intervals - the intervals corresponding to the synodic period of rotation of the sun. The sun is not a rigid body and the period is a function of the latitudes of the sun and varies from about 25 days at the equator to about 32 days at 80°.

The earlier studies of the 27-day variations were made by ionisation chambers and meson telescopes at sea level and were mostly concerned with establishing the character of the variations with regard to two aspects: (i) whether the variation is a periodic or recurrent phenomenon and (ii) whether the variation is of primary origin or a temperature effect.

Hess (1936), Hess and Graziadei (1936) Gheri and Steinmaurer (1942) and others have studied the 27-day variations and found that the variations are periodic phenomena; the amplitudes of the variations being about .1-.5% of the mean. Forbush (1938) showed that the process consisted of a series of isolated quasi-periodic variations existing for several solar rotations. Monk and Compton (1939), Gill (1939), Hogg (1950) and others have shown that the 27-day variations represent the recurrence tendency of an individual phenomenon, the extreme values being repeated at the same time intervals. The amplitudes and phases of the variations vary from one cycle to another.

This view is now well-established and it is now generally believed that the 27-day variations are indeed recurrence phenomena. The variations may persist for several solar rotations and then subside; they may start again with a different phase. An extreme case of stable repetition of 27-day wave over several solar rotations has been reported by Mori et al (1964) who have found that the neutron data show 27-day waves which persisted for 18 solar rotations during 1962-63.

The question about the nature of 27-day variations remained unsolved for a long time because of the uncertainties in correcting the data for temperature variations in the atmosphere. It was only after the neutron monitors came into operation that the question was finally settled. Simpson et al (1952) studied the neutron intensity records for 1951-52 and found a recurrence tendency in the neutron intensity variations in a series of 27-day periods. This result definitely established that the 27-day variations in cosmic ray intensity is a property of the primary radiation and not of atmospheric origin.

Geomagnetic and solar activity (respectively measured by K_p , C_p or A_p-indices and sunspot numbers) also show a 27-day variation of the type found in cosmic ray intensity. It was, therefore, natural to look into the relations between 27-variations in cosmic ray intensity and those of geo-magnetic and solar activity. However, the earlier studies (Elliot 1952) showed that there is no detailed correspondence between the cosmic ray intensity and geo-magnetic field variations which suggested that the two variations are not directly connected.

In the mean time Simpson (1954) made an interesting study of this relation by a neutron monitor flown in an Aircraft. He observed that the day to day variations in neutron intensities measured by the neutron monitor at latitudes above and below the knee of the intensity-vs-latitude curves were similar, so that the 27-day variations observed at sea level during this period could not be produced by

geo-magnetic field variations.

Later on, in 1955, Simpson et al (1955) studied the connection between the passage across the central meridian of the Unipolar regions (so named because the magnetic lines of force emerge out of the sun from these regions but do not return to the sun again) and the 27-day variations in cosmic ray intensities measured by neutron monitors at Climax and Chicago and an ionisation chamber at Freiberg. They found that the maximum intensities of the neutron or hard components occur on the days when the Unipolar regions cross the central meridian. They have suggested that this relation can be ascribed to the solar modulation of primary cosmic rays arriving from spaces outside our solar system.

These two experiments have shown definitely that the 27-day variations in cosmic ray intensity and geo-magnetic activity are not causally connected but both of them are undoubtedly controlled by solar atmospheric conditions.

Meyer and Simpson (1954) have found that the amplitudes of 27-day variations in intensity and K_p -indices show a very close positive correlation with solar activity - the amplitudes were found to be the highest during the period of maximum solar activity gradually decreasing to a minimum as the solar activity decreased to a minimum. Subsequent studies by several other workers have also confirmed this dependence of the amplitudes of 27-day variations on solar activity (Venkatesan 1958; Forbush 1959; Walt 1959 and others). For example, Forbush studied the hard component data from Huancayo from 1936 to 1955 and found that the amplitudes of cosmic ray intensity and geo-magnetic activity decreased to a minimum during the minimum of solar activity. Similarly, Walt found that the amplitude in cosmic ray intensity decreased from about 3% during the years of maximum solar activity to about .5% in years of minimum solar activity. They

have also found that the amplitudes of cosmic ray intensity and K_p -indices are positively correlated.

However, the relation of the variations in cosmic ray intensity and geo-magnetic activity has been found to differ widely from one observation to another. A close negative correlation between the two variations has been found by Meyer and Simpson (1954) and Venkatesan (1958) while Forbush (1958), Walt (1959) and others found that there is a negative correlation between the two variations but the minima (or maxima) of the intensity were found to occur about 1-2 days after the maxima (or minima) of K_p -indices. On the other hand, Van Heerden and Thambyahpillai (1955) also found a negative correlation between the two variations but the minima (or maxima) of the intensity were found to occur about 5 days before the maxima (or minima) of K_p -indices.

Venkatesan (1958) critically examined this lack of detailed correspondence between the 27-day variations in cosmic ray intensity and K_p -indices. He has analysed the ionisation data from Huancayo from 1937 to 1955 and has found that this lack of correspondence between the two variations is due to the property of the interplanetary space existing in different years of the solar cycles, so that K_p -maxima (or minima) may precede the minima (or maxima) of cosmic ray intensity in some years and follow in some other years.

Kodama (1959) has found that there is in general a negative correlation between the 27-day variations in cosmic ray intensity and solar activity but in certain periods of minimum solar activity, the correlation may become positive. He thinks that there are two competing processes in operation - the ejection of magnetised clouds from the sun which depress the cosmic ray intensity and the solar generation of cosmic rays. So, if the former is predominant a negative

correlation will be observed but if the latter is predominant (as in the solar minimum epoch) a positive correlation will be observed.

It is, therefore, clear from the above discussion that while it is well-established that the amplitudes of 27-day variations in cosmic ray intensity and the indices of geo-magnetic activity show a positive correlation with the cycle of solar activity, the relation between the 27-day variations in cosmic ray intensity and the indices of geomagnetic activity shows a significant difference from one year to another.

8.2 The Rigidity Dependence of 27-day Variations

The studies of 27-day variations using neutron and ionising components of cosmic rays have shown that the variations are rigidity dependent - the effect is more pronounced in the low rigidity part of the primary spectrum. Fonger (1953), Meyer and Simpson (1954) reported a ratio of about 4 to 5 between the amplitudes of 27-day variations in the nucleonic component to the ionising component. Simpson et al (1955) found that the amplitude of the neutron component was about 3 to 4 times higher than that of the muon component. Van Heerden and Thambyahpillai (1953) on the other hand found the ratio to be of the order of ~2.3 Glokova and Inozemtsev (1960) have studied the 27-day variations during 1957-58 from 11 stations (nucleonic and hard component) and have found that the ratios of the amplitudes of the nucleonic components to those of the hard components are about 3.5 on the average for all medium latitude stations.

The 27-day recurrence tendency at higher rigidities (R ~100 Gv) has also been recently reported by Sandor et al (1962a) from the analysis of the underground data at Budapest (40 m.w.e.) during 1958-60. The mean amplitude of the 27-day variation was found to be of the order of ~1%. Mathews (1962) also found

a pronounced 27-day variation at Holborn (60 m.w.e.) to coincident with those in the sea level intensity.

All the above results have shown that the amplitude of 27-day variation depends on the rigidity of the particles detected. The rigidity dependence of 27-day variations has been studied by Glokova and Inozemtseva (1960) and others and it has been found that the rigidity dependence of 27-day variations and Forbush decreases is the same, so that both the phenomena are caused by the same modulation mechanism. However, the studies of the rigidity dependence of 27-day variations at higher rigidities have not been made so far.

In the following sections the available data from Holborn for three years (1961-64) will be used to study the relation between 27-day variations in cosmic ray intensity underground and geo-magnetic activity as well as the rigidity dependence of the variation in cosmic ray intensity. The observed rigidity dependence of 27-day variations will then be compared to that for Forbush decreases found in the previous chapter.

8.3 Experimental Results about 27-day Variations at Holborn

In order to study the 27-day variations underground the daily intensities from different telescopes were added up and the average daily values were corrected for all atmospheric effects (i.e., for the barometric, decay and positive temperature effects) using the coefficients as found in Chapter III.

The data will be presented corresponding to three years referred to as periods 1961, 1962 and 1963-64. It will be noted that the period 1961 has been included into the present analysis, even though Mathews (1962) has already analysed the data for this period, for the following reasons: he used different pressure and temperature coefficients (i.e., -.042% per mb and +.036% per ^{o}C respectively

as compared to -.037% per mb and +.041% per ^{o}C in the present case) and he did not apply any corrections for the μ-e decay effect. So, to make intercomparison of the variations observed during different periods it was thought necessary to analyse the data for the period 1961 as well using improved methods of correction.

The corrected data have been analysed by the method of superposed epochs (Chree and Stagg 1928) i.e., two or three days in each calender month showing highest intensities were selected and entered in a vertical column under the day-number n = o (epoch-day). The intensity values for the subsequent days following the epoch-day were entered into separate vertical columns under day-numbers n = 1,2,.. 86. This procedure was repeated for different months and entered into corresponding columns with n = 0,1, ...86. The average value of each column was obtained and the percentage deviations of each column from the 86-day mean were calculated. These percentage deviations from the mean, plotted against day-number, n, will be called the positive waves. A similar procedure was followed in selecting two or three days in each month showing lowest intensities and the variations obtained will be called the negative waves.

The selection of the data has been made in the following way: The standard deviations for daily intensities during 1961-62 were $\sim$.09% and during 1963-64 were $\sim$.05%. Since the day to day variations underground were not very much different from the corresponding standard deviations during 1961-62, days of highest (or lowest) intensities could not be well separated from the background fluctuations. On the other hand, sea level neutron monitors show larger variations and the selection of the data becomes very easy. It is also possible in this case to remove from the analysis days during Forbush decrease events which may be observed at sea level but may not be seen (or may be masked by the background variations) in the underground records. As a result , selection of the data was made

according to the neutron monitor records at Imperial College, London and all results presented in this chapter will be obtained in this way.

The results of the analysis of the underground data by the method of superposed epochs are shown in Fig. 8.1. The curves a,b,c respectively correspond to the positive waves for the periods 1961, 1962 and 1963-64. The negative waves were also obtained during 1961 and 1962 and are shown in this figure superposed on the curves a and b. The curves for the period 1961 have been obtained from December 1960 to June 1961, since the 27-day variations appeared to have died down during the rest of the period. The negative wave for the period 1963-64 has not been calculated because during this period the 27-day variations seem to have almost disappeared. The curves have been plotted on the same scale - the ordinate showing the percentage deviations from the means and the abscissa the day-numbers n. The 27-day intervals have been marked by dotted vertical lines parallel to the ordinate. It can be seen that the underground intensity shows recurrence tendency at an interval of 27-day periods. It is also found that the amplitude of the variations has gradually diminished from 1961 to 1963-64.

In order to investigate the relationship between 27-day variations in the cosmic ray intensity and the A_p -indices of geomagnetic activity, the positive waves in A_p -indices corresponding to the three periods have been calculated and are shown in Fig. 8.2 (curves a,b,c). The selections of the epoch-days have been made according to the neutron intensity level, as mentioned above. In order to show the negative correlation between 27-day variations in cosmic ray intensity and A_p -indices, the waves of A_p -indices have been plotted in reverse scale. Comparison of the curves in Figs. 8.1 and 8.2 clearly show that the maxima in cosmic ray intensities correspond to the minima in A_p -indices. Fig. 8.2 (curves a,b,c) als

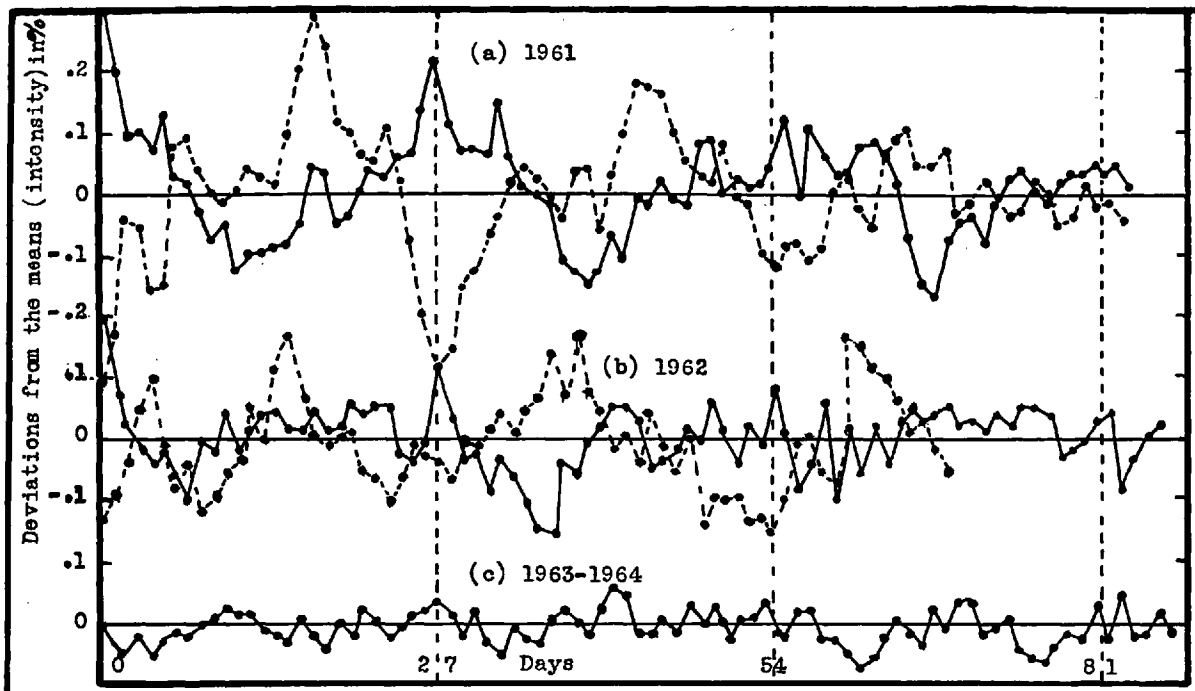


Fig.8.1. The 27-day variations in meson intensity at Holborn over the periods from 1961 to 1963-1964.

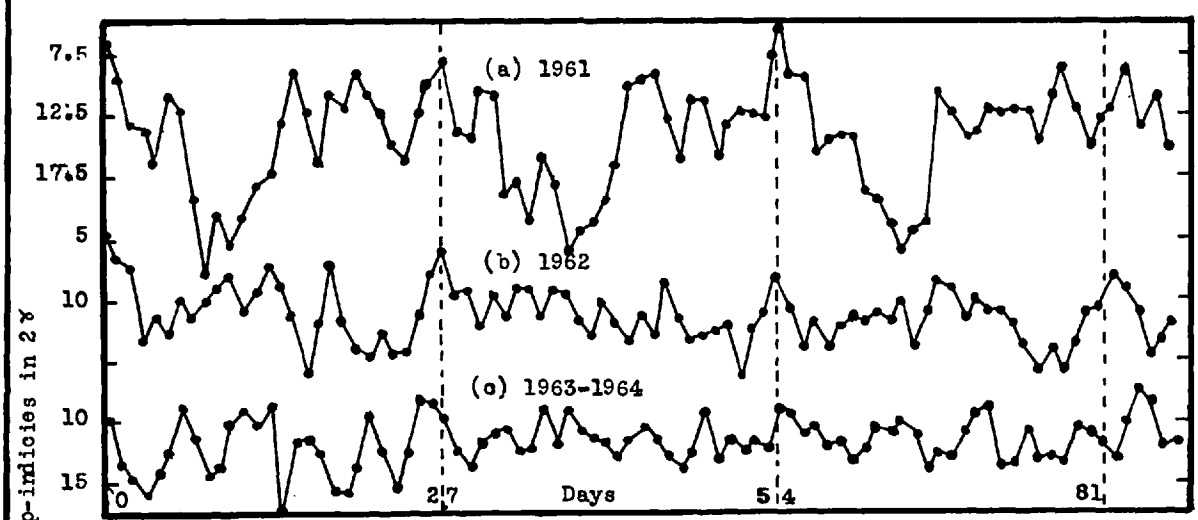


Fig.8.2. The 27-day variations in Ap-indicies over the periods from 1961 to 1963-1964.

shows the gradual diminution of the amplitudes of 27-day waves in A_p -indices from 1961 to 1963-64 similar to the effect observed in the cosmic ray intensity.

The 27-day variations observed at two sea level neutron monitoring stations - London and Deep River - corresponding to the three periods have been plotted in Fig. 8.3, the selection of the epoch-days being made as mentioned above. The curves marked a,b,c refer to the positive waves observed at London and those marked a', b', c' refer to the positive waves observed at Deep River. The dotted lines parallel to the ordinate refer to the same 27-day intervals as in Figs. 8.1 and 8.2. Since there has been gradual increase in the level of neutron intensities from 1961 to 1963-64 as a result of the 11-year cycle of cosmic ray intensity variations, the curves in Fig. 8.3 have been plotted after adjusting for this long term trend.

Examinations of the Figs. 8.1 and 8.3 shows that similar variations have been observed both in nucleonic component at sea level and hard component underground except in amplitude - the amplitude being higher at sea level than underground. The curves in Fig. 8.3 also show that there has been a gradual diminution of the amplitudes of 27-day variations from 1961 to 1963-64 in sea level nucleonic intensities, similar to the effect observed underground and in A_p -indices of geo-magnetic activity.

8.4 Discussion of the Results and the observed Rigidity Dependence of 27-day Variations

The following characteristics of the 27-day variations have emerged from the foregoing analysis and are worthy of note:

(i) The results presented above definitely show that there is a tendency of the cosmic ray intensity underground to show a small variation at 27-day intervals. This tendency is found to be a recurrence phenomenon rather than a periodic phenomenon.

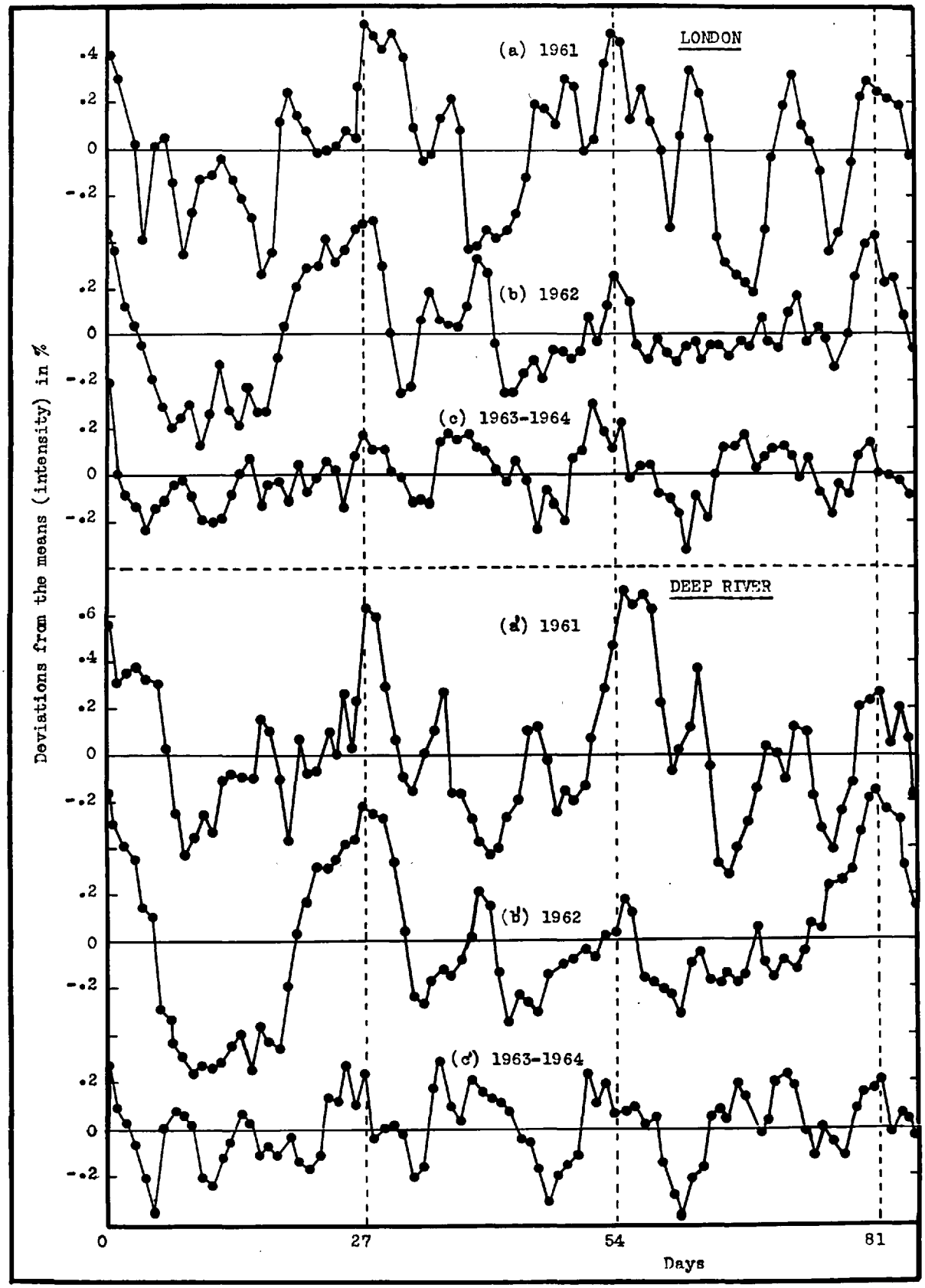


Fig.8.3. The 27-day variations in neutron intensities at London (a,b,c) and at Deep River (a',b',c') over the periods from 1961 to 1963-1964.

(ii) The same 27-day variations exist in neutron intensities at sea level. Since the underground data have been corrected for all known atmospheric effects and the selection of the epoch-days was made on the basis of the neutron intensity level, it is clear that the process which is operative in producing a 27-day recurrence tendency in the lower rigidity primaries as measured by the sea level neutron monitors is also operative in producing the same effect, though with a smaller amplitude, in the higher rigidity primaries as measured by the underground meson monitors at Holborn (R~100 Gv.).

(iii) The 27-day variations of cosmic ray intensities (nucleonic and muon components) and the A_p -indices of geo-magnetic activity show a very close negative correlation without any time lag or phase difference (Figs. 8.1, 8.2, and 8.3)

(iv) The amplitudes of the variations of both cosmic ray intensities and A_p-indices have been found to decrease gradually from 1961 to 1963-64, indicating that the amplitudes of the two variations depend on the degree of solar activity (Figs. 8.1, 8.2 and 8.3).

(v) The amplitudes of the variations underground were found to be smaller than those at sea level, indicating that the variations in cosmic ray intensity depend on the rigidity of the particles detected (Figs. 8.1 and 8.3.).

(vi) The rigidity dependence of the 27-day variations appears to be different from that of Forbush decreases. For example, the ratio of the amplitude of Forbush decreases in neutron intensity at London(S.L.) to that in meson intensity underground is found to be 10 ± 1.0 during 1961-62. The corresponding ratio for the 27-day variations is found to be $2.6\pm.3$.

The properties of the 27-day variations listed in (i) to (v) are found in agreement with those found by other workers but the property shown in (vi) appears

to show some discrepancy. Glokova and Inozemtseva (1960), Dorman (1963) have found that the rigidity spectra for primary variations are nearly the same for 27-day variations and Forbush decreases. Brown (1958) Webber (1962) and others also believe that the same modulation mechanism is responsible for Forbush decreases and 27-day variations and in fact the 27-day variations are the smaller Forbush decreases that are irregular and superposed and have a tendency to recur with 27-day periods, presumably connected with the rotational period of the active regions on the sun. Kuzmin et al (1963), however, have found a difference in rigidity dependence of the two variations in agreement with the present observation.

It will, therefore, be interesting to study the rigidity dependence of the 27-day variations in greater detail and compare this with the rigidity dependence found for Forbush decreases in the previous chapter.

In order to study the rigidity dependence of 27-day variations, the period 1961 was found to be the most suitable because the neutron data from several other stations were available for this period and also this period was characterised by large 27-day variations. The positive waves of the 27-day variations observed at Deep River (cut-off rigidity R_γ = .98 Gv), London (R_γ = 2.70 Gv), Rome (R_γ =6.4 G Mina Aguilar (R_γ = 12.6Gv) as well as at Holborn (60 m.w.e.) have been plotted in Fig. 8.4. To study the rigidity dependence the ratios of the amplitudes of 27-day variations at sea level to that underground were evaluated by scatter diagrams (Fig. 8.5) as well as by correlation analysis covering 86 days and are shown in Table I.

In this table are also shown the corresponding ratios found for Forbush decreases during 1961-62 and November 12-13, 1960 (Mathews, 1963). It has been stated in Chapter VII that the rigidity dependence of Forbush decreases for 1961-62

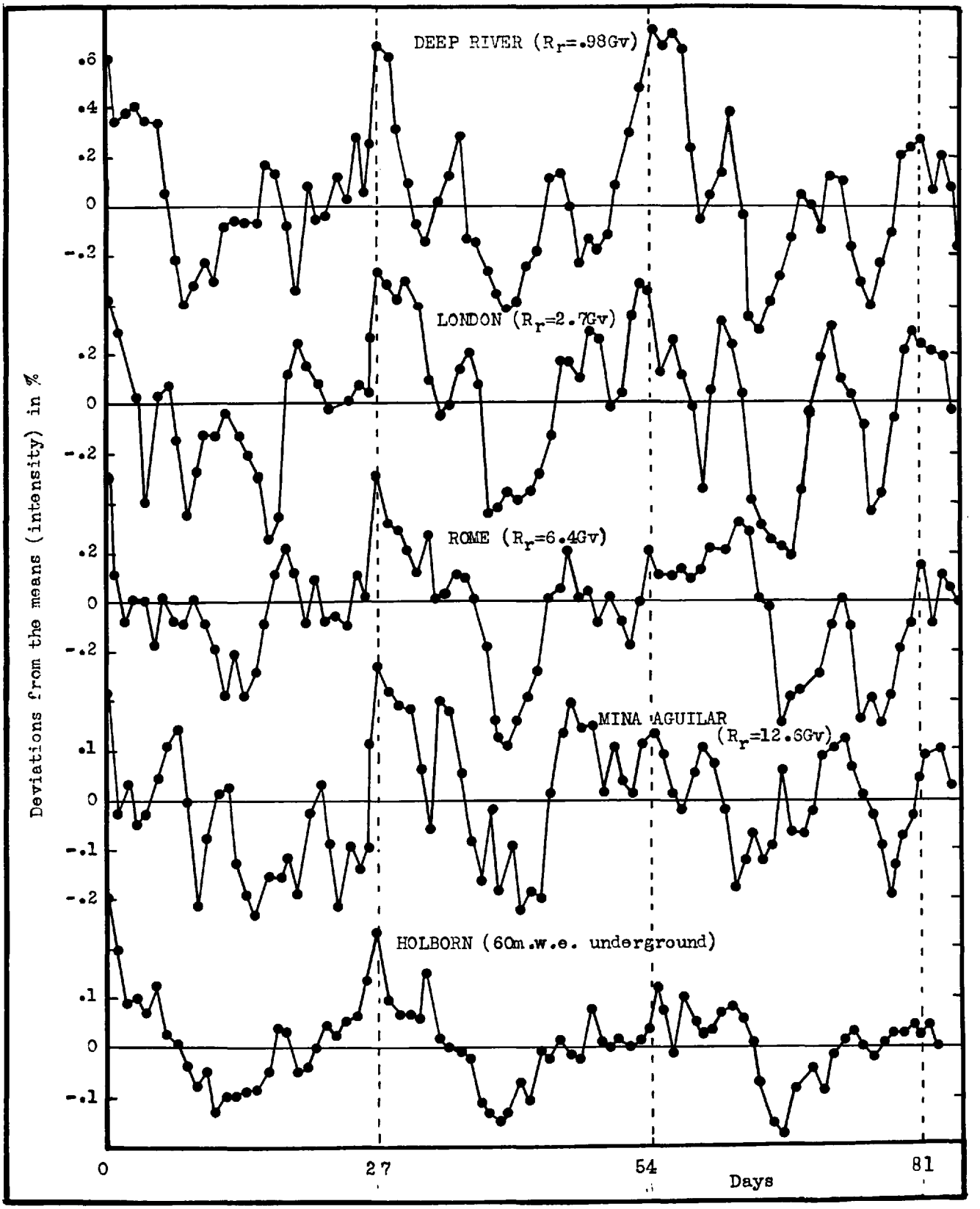


Fig.8.4. The 27-day variations in neutron intensities at different sea level stations and in meson intensity underground during 1961.

Table I.

Ratios	Observed ratios for 27-day variations during 1961	Observed ratios for Forbush decreases during	
		1961-62	November, 1960
London (S.L.) Underground	$2.56 \pm .29$	10.0 ± 1.2	~ 9.0
Deep River (S.L.) Underground	$2.87 \pm .32$	12.8 ± 1.5	
Mina Aguilar (M.A.) Underground	$1.00 \pm .20$	5.9 ± 1.0	
Rome (S.L.) Underground	$1.94 \pm .25$		

which can give best fit to the observations is $f(R) \propto R^{-.8}$. Now comparing the observed ratios for 27-day variations in Table I with those expected (Fig. 7.3 Chapter VII), it is found that the rigidity dependence for 27-day variations which gives best fit to the observations is $f(R) \propto R^{-\gamma}$, where γ lies between .2 and .3. This result thus indicates that the 27-day variations are possibly less rigidity dependent than Forbush decreases.

At this point it may be pointed out that since the underground data has been corrected for temperature and height variations the amplitude of the 27-day variations underground will depend on the amount of corrections applied, particularly if the atmospheric temperature variations show a 27-day variation in phase with cosmic ray variation underground. An attempt was, therefore, made to find some indication of a 27-day wave in the mean temperature of the 200-70 mb layer but no such wave was detectable. So, the observed difference in rigidity dependence for 27-day variations and Forbush decreases during 1961-62 cannot arise from improper temperature corrections.

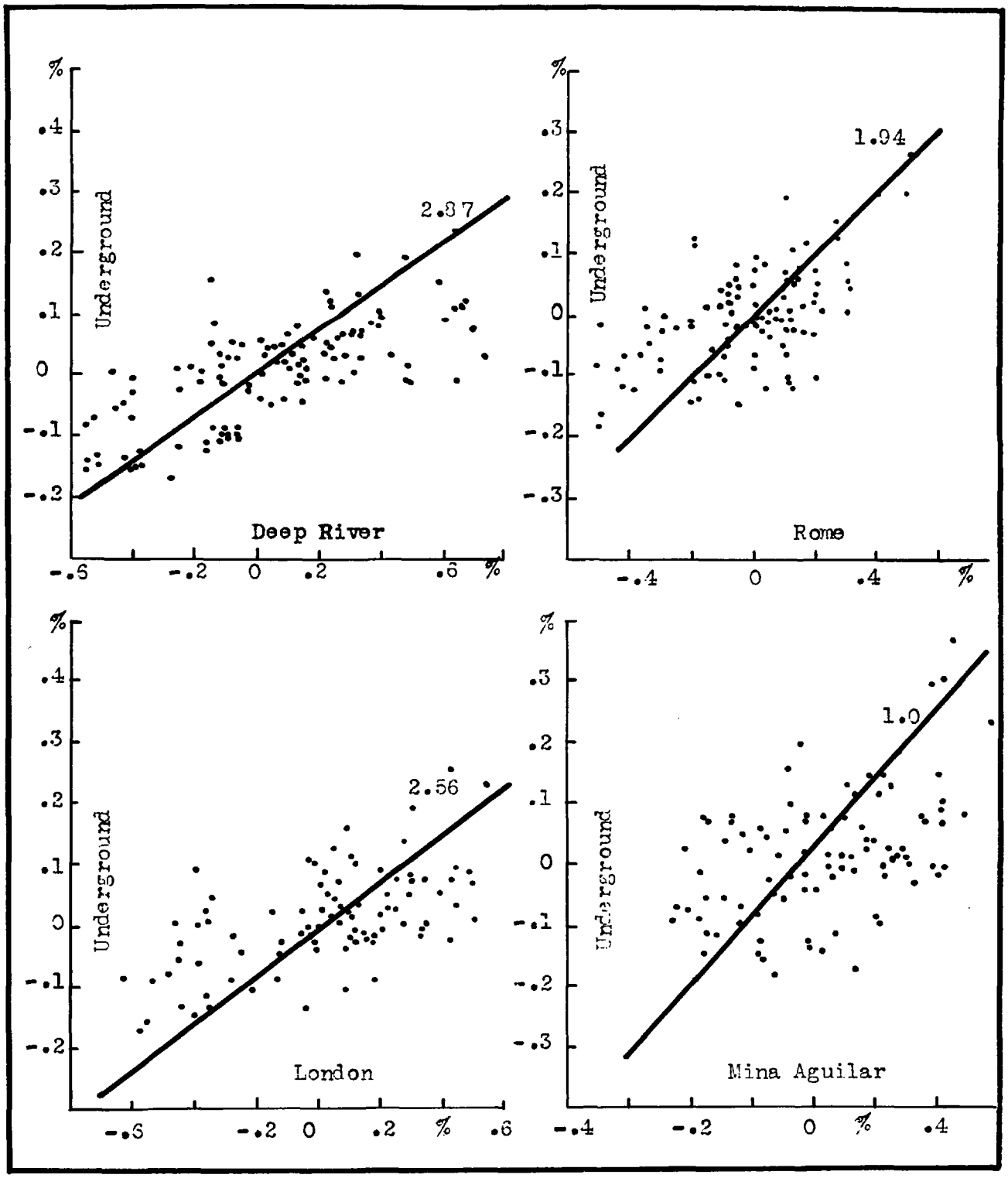


Fig.8.5. Scatter diagrams showing the regression lines of the daily amplitudes of 27-day variations in meson intensity underground on those in neutron intensities at different sea level stations during 1961.

This difference in rigidity dependence for the two effects (Forbush decrease and 27-day variation), however, may not necessarily mean that the modulation mechanisms for these two effects are different. Firstly, the rigidity dependence of the Forbush decrease events has been found to differ from event to event, presumably due to the different ways in which gas clouds emitted by the sun interact with interplanetary space. Secondly, all the evidence from sea level suggests that the 27-day and in fact all short term and long term variations are due to the modulation of galactic cosmic rays by stream of solar plasma emitted by the active regions of the sun. Now, if these active regions can emit solar protons to which neutron monitors are sensitive (as suggested by Simpson et al 1952), the depression produced in low energy cosmic radiation will be compensated somewhat by the arrival of solar cosmic rays which will be observed by the neutron monitors but not by the underground detectors. The depression in neutron monitors will be comparatively smaller in such a case and the ratio of the amplitude of 27-day variations in neutron monitors to that in meson detectors will be reduced, as is observed.

However, if the solar production of cosmic rays has power law spectrum with exponent as high as 5 to 7, then this filling up effect of the decreases by the solar production of cosmic rays should not be present in neutron monitors at an equatorial station that has high cut-off rigidity. Hence the ratios of the Forbush decrease and 27-day variation in neutron intensity at an equatorial station to those in meson intensity underground should not be different. To test this, Forbush decreases and 27-day variations in neutron intensities at Mina Aguilar (a high cut-off station) were analysed and the corresponding ratios of the variations at Mina Aguilar to those underground determined. The ratios are shown in Table I above.

It will be seen that the ratio for Forbush decreases is about 6 times larger than the corresponding ratio for 27-day variations. It is interesting to note that the ratios of Forbush decreases at low latitude stations (such as London and Deep River) to those underground are also about 5-6 times larger than the corresponding ratios for 27-day variations. There is thus some evidence that the possibility of two different modulation mechanisms being responsible for causing Forbush decreases and 27-day variations cannot be altogether ruled out.

8.5 Summary

(i) Complete three years' (1961 to 1963-64) data from Holborn (60 m.w.e. underground) have been analysed to study the 27-day variations. A 27-day recurrence tendency has been observed in underground meson intensity similar to that observed in sea level neutron intensities.

(ii) The 27-day variations in cosmic ray intensity (at sea level and underground) showed a close negative correlation with those in geo-magnetic activity as measured by A_p -indices. The amplitudes of 27-day variations in cosmic ray intensity and geomagnetic activity gradually decreased from 1961 to 1963-64, indicating a positive correlation with solar activity.

(iii) From the comparison of the amplitudes of 27-day variations at stations with different cut-off rigidities the modulation function specifying the rigidity dependence of 27-day variations was determined and this appeared to be different from the modulation function determined in the case of Forbush decreases. The 27-day variations appeared to be less rigidity dependent than the Forbush decreases.

(iv) The possible reasons for this difference in rigidity dependence for Forbush decreases and 27-day variations have been discussed and it was found that the possibility of two modulation mechanisms for these two effects cannot be altogether ruled out.

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Appendix I

The Regression Coefficients of the Correlation Analysis during 1961-63

Table I(a)

Temperature between layers	Period	$\beta_{IB.T\%/mb}$	$\beta_{IT.B\%/^{o}C}$
200-100 mb	1	$-.0301\pm.0101$	$+.0348\pm.0130$
	2	$-.0574\pm.0127$	$+.0430\pm.0316$
	3	$-.0326\pm.0102$	$+.0525\pm.0276$
	4	$-.0327\pm.0082$	$+.0435\pm.0270$
	5	$-.0380\pm.0076$	$+.0453\pm.0306$
	6	$-.0378\pm.0071$	$+.0443\pm.0153$
	7	$-.0375\pm.0086$	$+.0747\pm.0508$
	8	$-.0338\pm.0090$	$+.0431\pm.0240$
	9	$-.0388\pm.0025$	$+.0320\pm.0180$
	10	$-.0299\pm.0055$	$+.0473\pm.0161$
	11	$-.0334\pm.0059$	$+.0403\pm.0.88$

Table I(b)

Temperature between layers	Period	$\beta_{IB.T\%/mb}$	$\beta_{IT.B\%/^{o}C}$
200-70 mb	1	$-.0325\pm.0096$	$+.0434\pm.0163$
	2	$-.0506\pm.0139$	$+.0420\pm.0367$
	3	$-.0358\pm.0080$	$+.0543\pm.0249$
	4	$-.0338\pm.0088$	$+.0432\pm.0313$
	5	$-.0346\pm.0069$	$+.0542\pm.0247$
	6	$-.0373\pm.0067$	$+.0466\pm.0141$
	9	$-.0401\pm.0027$	$+.0307\pm.0120$
	10	$-.0296\pm.0057$	$+.0455\pm.0163$
	11	$-.0341\pm.0063$	$+.0396\pm.0219$

Table I(c)

Temperature Between layers	Period	$\beta_{IB.T\%/mb}$	$\beta_{IT.B\%/^{\circ}C}$
100-70 mb	1	$-.0343 \pm .0104$	$+.0636 \pm .0298$
	2	$-.0527 \pm .0098$	$+.0453 \pm .0422$
	3	$-.0376 \pm .0082$	$+.0596 \pm .0319$
	4	$-.0358 \pm .0075$	$+.0527 \pm .0342$
	5	$-.0346 \pm .0061$	$+.0648 \pm .0245$
	6	$-.0375 \pm .0065$	$+.0475 \pm .0139$
	7	$-.0328 \pm .0101$	$+.0193 \pm .0341$
	8	$-.0337 \pm .0116$	$+.0380 \pm .0350$
	9	$-.0418 \pm .0037$	$+.0180 \pm .0139$
	10	$-.0317 \pm .0059$	$+.0405 \pm .0163$
	11	$-.0364 \pm .0055$	$+.0546 \pm .0299$

Appendix II

The Differential Response Curves

The counting rate of a detector, $N(R_\wedge, h, t)$, at a depth, h, and at time, t, at a given latitude, $\wedge$, can be written as,

$$N(R_\wedge, h, t) = \sum_{Z} \int_{R_\wedge}^{\infty} M_Z(R, h) \frac{d J_Z(R, t)}{dR} dR \quad \ldots\ldots \quad (1)$$

where, $M_Z(R, h)$ is the 'multiplicity function' or the 'specific yield function' that gives the number of secondary particles which are recorded by the detector and have been produced at the depth, h, by a primary particle of charge, Z and rigidity, R.

$R_\wedge$ is the vertical threshold rigidity at the latitude, $\wedge$.

$\frac{d J_Z(R,t)}{dR}$ is the differential rigidity spectrum of the primary particles at time, t.

Now, differentiating eqn. (1) with respect to the differential rigidity spectrum and dividing each side by the eqn. (1) we get the relative variations, (neglecting Z)

$$\frac{\delta N(R_\wedge, h, t)}{N(R_\wedge, h, t)} = \int_{R_\wedge}^{\infty} \frac{\delta\left(\frac{dJ(R,t)}{dR}\right)}{\frac{dJ(R,t)}{dR}} W(R_\wedge, h, t)\, dR \quad \ldots\ldots\ldots (2)$$

where, $$\int_{R_\wedge}^{\infty} W(R_\wedge, h, t) = \int_{R_\wedge}^{\infty} \frac{\frac{dJ(R,t)}{dR} M(R,h)}{N(R_\wedge, h, t)} = 100\% \quad \ldots\ldots\ldots (3)$$

The function, $W(R_\wedge, h, t)$, is called the 'Differential response' or the 'Coupling coefficient' for the detector, and it can be seen from the eqn. (3) that $W(R_\wedge, h, t)$ can be determined from a knowledge of the primary spectrum and the multiplicity function which is, however, difficult to calculate. But it can be estimated in a simpler way from the geo-magnetic effects, as follows:

Differentiating partially the eqn. (1) with respect to $R_\wedge$, we find that,

$$\frac{\delta N(R_c, h, t)}{\delta R_c} = -\frac{dJ(R,t)}{dR}_{M(R_c, h)} \qquad \ldots\ldots (4)$$

Hence from (3) and (4), we get,

$$W(R_c, h, t) = \frac{\delta N(R_c, h, t)}{\delta R_c} \cdot \frac{1}{N(R_c, h, t)} \qquad \ldots\ldots (5)$$

The righthand side of eqn. (5) represents the geomagnetic effects and thus the response curves for rigidities up to 15 Gv can be obtained easily. Above 15 Gv, however, they are calculated by extrapolation. Dorman (1957), Webber and Quenby (1959) have previously derived differential response curves for different components of cosmic rays at different depths of the atmosphere. The shapes of the curves will depend greatly on the values of R_c used and the curves based on the latest values of threshold rigidities (according to Quenby and Wenk 1961) have been given by Webber (1962). These differential response curves for neutron components at 680 gm/cm^2, and at sea level as well as for meson components at sea level are shown in Fig. A.I.

The differential response curve for the underground recorder at a depth of 60 m.w.e. underground has been calculated following the method suggested by Dorman (1959), where he showed that if the differential response curve $W(R,h_1)$ at rigidity, R, at a depth, h_1, is known then the differential response curve at another depth, h_2, may be obtained from the eqn.,

$$W(R,h_1) = \frac{E_1}{E_2} \cdot W(R.\frac{E_1}{E_2}, h_2) \qquad \ldots\ldots (6)$$

where the righthand side is the differential response curve at rigidity, $R.\frac{E_1}{E_2}$, and depth, h_2; E_1 and E_2 are the minimum energies of mesons at

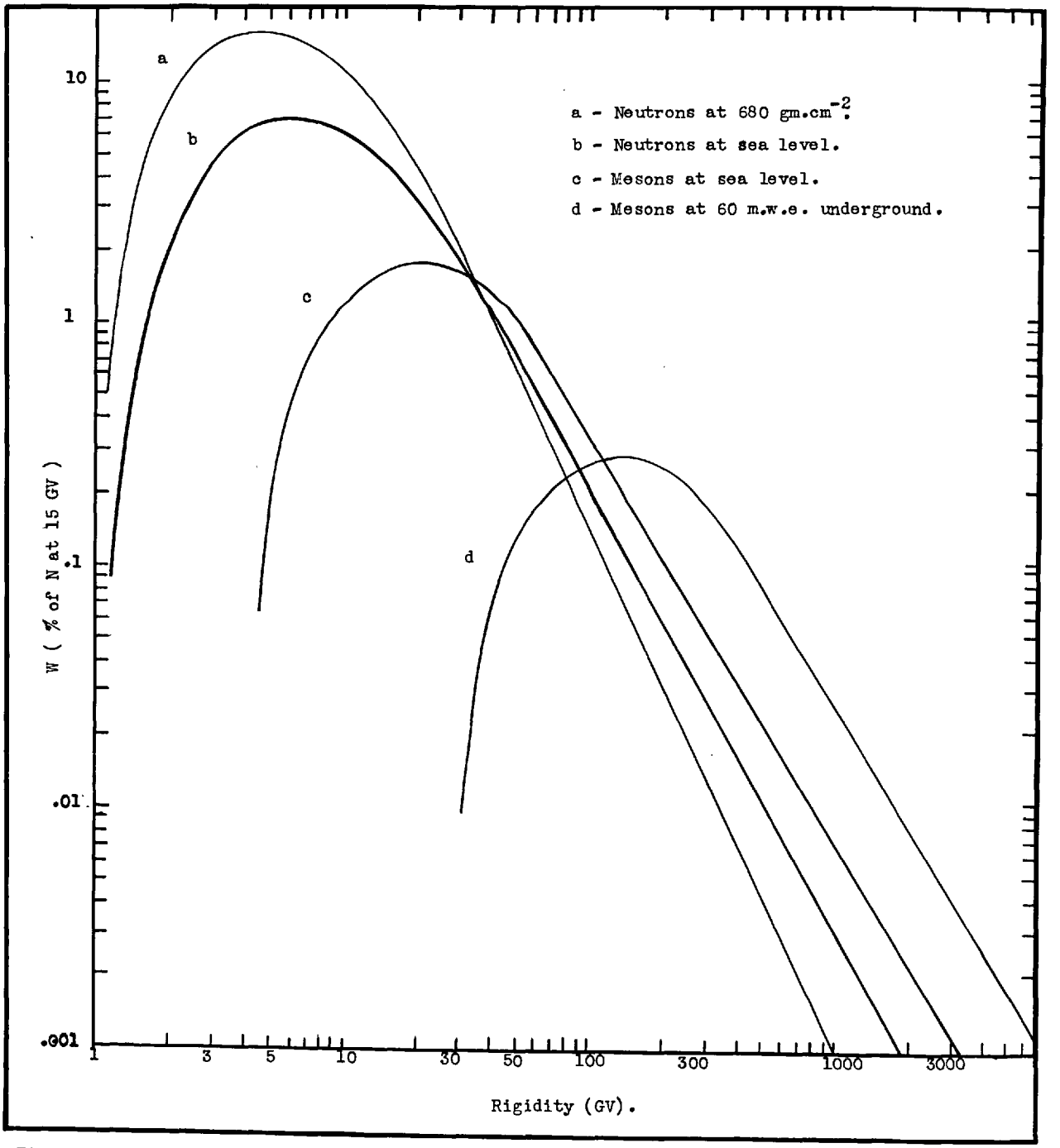


Fig. AI. The Differential Response Curves for different detectors.

production required for them to be recorded by the instruments located at depths, h_1 and h_2 respectively. The differential response curve for the detector at a depth of 60 m.w.e. underground has been calculated from the response curve for the sea level meson detector following the eqn. (6). This curve is also shown in Fig. A.I.

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