

SOLAR CYCLE EFFECTS
ON THE PRIMARY COSMIC RAY SPECTRUM
AND ON
THE ENERGETIC PROTON INTENSITY
IN THE EARTH'S RADIATION BELT.

THESIS
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ABSTRACT

The heavy primary cosmic rays and the charged particles in the Van Allen Belts around the Earth, were detected by a Cerenkov Counter aboard the satellite Ariel I, during the period May-June, 1962. These data have been utilised here to establish the heavy primary cosmic ray spectrum for that particular period in the solar cycle. This spectrum is then used along with two others at different times in the solar cycle, to examine the modulation of the heavy primary spectrum over the solar cycle. The cut-off rigidities obtained by Quenby-Wenk's analytical method are checked with the help of these cosmic ray data and the change of rigidities with height are plotted at two representative heights above the surface of the Earth.

The Van Allen belt particle data are analysed for their temporal stability in terms of the diurnal variation, day to day variation, and long-term or solar cycle variation. In the light of the findings here, the origin and loss mechanisms of the inner belt protons are discussed.

The artificial radiation belt, produced by the 'starfish' nuclear explosion of July 9th, 1962, is analysed to establish its spatial distribution, decay and loss mechanisms.

CONTENTS

	<u>Page.</u>
ABSTRACT.	ii
GENERAL INTRODUCTION.	1
CHAPTER I. <u>CUT-OFF RIGIDITIES AND HEAVY PRIMARY ENERGY SPECTRUM FROM ARIEL I.</u>	
1.1. Introduction.	4
1.2.. Historical Development.	5
1.3. Analysis of the data.	9
a. Cut-off Rigidities.	
b. Energy Spectrum of Heavy Primary Cosmic Rays.	
1.4. Discussion of the Result.	22
1.5. The Modulation of the Heavy Primary Cosmic Ray Spectrum over the solar cycle.	23
CHAPTER II. <u>TIME VARIATIONS IN THE VAN ALLEN RADIATION BELTS.</u>	
2.1 Introduction.	34
2.2 Motion of Charged Particles in the Geomagnetic Field.	36
2.3a. Origin.	39
2.3b. Loss Processes.	40
2.3c. Time Variations from the Loss Processes in the Atmosphere.	40
2.4. Choice of Co-ordinate System.	43
2.5. Plan of Analysis.	44
2.6. Analysis of Observational data.	44
2.7. Discussion of Results.	55

CHAPTER III. ORIGIN AND LOSS PROCESSES OF THE
INNER VAN ALLEN BELT.

3.1.	Introduction.	59
3.2.	Historical Development.	60
3.3.	Averaging the Atmosphere.	64
3.4.	Evidence from Ariel data.	65
3.5.	Discussion.	81

CHAPTER IV. THE ARTIFICIAL RADIATION BELT FROM
THE 'STARFISH' NUCLEAR EXPLOSION.

4.1.	Introduction.	85
4.2.	Present Work.	88
4.3.	Analysis and Interpretation of the data,	89
4.4.	Conclusions.	105
4.5.	Artificial Radiation from Nuclear Detonations on Johnston Island.	106

CONCLUSIONS.	110
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ACKNOWLEDGEMENTS.	112
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REFERENCES.	113
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GENERAL INTRODUCTION

1.

The satellite Ariel I carried two detectors from Imperial College Cosmic Ray group primarily for the determination of the heavy primary cosmic ray spectrum in 1962, a time near the solar minimum. A Cerenkov detector with a threshold energy of 50 MeV recorded particles with $z \geq 6$, over the latitude range $\pm 54^\circ$. A Geiger Counter, Anton 302 was used to exclude any contribution to the above data from the inner radiation belt protons.

Durney et al. (1964) and Engel (1964) analysed some of the data from these two detectors and the following, very briefly, are their main results:

(i) The heavy primary cosmic ray rigidity spectrum has a slope of -1.5 ± 0.15 in the rigidity range 8.5 GV to 16.5 GV and -1.2 in the range $2.5 < R < 8.5$ GV. This suggests that the modulation mechanism was effective only below 8 GV at that time of the solar cycle.

(ii) The location, qualitative decay and the origin of the artificial belt produced by the 'Starfish' nuclear explosion has been established.

(iii) A study and estimate of the consequences of satellite aspect has been made.

(iv) The altitude variation of cosmic ray intensity (recorded by the Geiger Counter) has been found and compared with the theoretical results.

(v) The latitude spectrum of cosmic rays recorded by the Geiger Counter has been presented.

(vi) Time variations of lower boundary of the inner belt and outer boundary of the outer belt have been studied in a rough way. Some bursts of radiation have been detected below the lower boundary of the trapping region and explained as the result of the nuclear bursts in the atmosphere.

The work in this thesis utilizes the rest of the data for an addition to and extension of these results. The following, in brief, are the main results obtained here.

(i) The heavy primary cosmic ray spectrum has finally been shown, using the points from this analysis and Durney's (1964), to have a slope of -1.533 ± 0.079 above 8.5 GV and -1.072 ± 0.026 below it.

(ii) The solar cycle variation of the heavy primary cosmic ray spectrum is fitted to Parker's simple solar wind model and the rigidity dependence of the modulation function is given.

(iii) The cut-off rigidities of Quenby and Wenk have been shown to be correct within $\pm 10\%$ over the greater part of the Earth's surface.

(iv) The stability of the inner Van Allen belt (May-June, 1962) has been shown and ^{at} the same time, variations in the Outer Belt have been given.

(v) The solar cycle variation of the intensity of the inner Van Allen belt is suggested. Neutron albedo source and atmospheric loss processes are found to be inadequate to explain the long-term variation.

(vi) Extensive mapping of the quasi-stable artificial electron belt has been done and the decay time has been calculated for specific L and B values.

(vii) The softening of the spectrum towards higher L-values is confirmed, using the total number of data available.

(viii) Longitude dependence of the artificial electrons with $h_{\min} \leq 200$ km has been shown.

(ix) The nuclear burst particles observed below the inner belt are shown to have been electrons.

CHAPTER I

CUT-OFF RIGIDITIES AND HEAVY PRIMARY ENERGY SPECTRUM FROM ARIEL I.

1.1. Introduction.

Galactic cosmic rays can only arrive at the surface of the Earth with a minimum momentum which is dependent on the position and the direction of arrival of the particle. This is generally expressed in terms of magnetic rigidity, defined as the ratio of the momentum to the charge of the particle, and is known as the threshold or cut-off rigidity. Values of threshold rigidities must be known correctly to obtain the primary spectrum from the intensity distribution of cosmic rays over the surface of the earth. The rigorous way to evaluate these threshold rigidities is to integrate particle trajectories in the Earth's magnetic field. But this involves a forbidding amount of computation even for a reasonable coverage of the Earth's surface. Approximate methods have therefore been developed by several people to calculate these threshold rigidities.

Experimental surveys of cosmic ray intensities show that the simple dipole and eccentric dipole representation of the Earth's field are inadequate to explain their distribution over the surface of the Earth. The effect of the non-dipole components of the Earth's field on the particle trajectories is to introduce important perturbations as shown by Rothwell and Quenby (1958). Quenby and Webber (1959) took into account in an approximate way, the non-dipole field up to and including the

sixth-order term in the spherical harmonic expansion of the magnetic potential and produced a world map for the corrected threshold rigidities. These were later modified by Quenby and Wenk (1962) who applied different corrections to them at high and low latitudes.

The accuracy of the Quenby-Wenk threshold rigidities was investigated by using data from the latitude survey of heavy primary cosmic ray intensities recorded by a Cerenkov detector on the satellite Ariel I. Geographic contours of constant threshold rigidity, corresponding to contours of equal counting rate, were constructed at two mean altitudes over the surface of the Earth. These were then compared with the contours of calculated values of Quenby-Wenk threshold rigidity.

The rigidity spectrum for heavy primary cosmic rays had been obtained by Durney et al. (1964) with the data from the same detector recorded in an altitude range of 400 km to 800 km. The data from 800 km to 1200 km were used here to obtain the rigidity spectrum by a method similar to that used by Durney et al. (1964).

1.2. Historical Development.

The motion of cosmic rays in the Earth's magnetic field has been treated by a method due to Störmer who investigated the nature of the trajectories of electrons in the geomagnetic field during his studies of the aurora. His prediction of an east-west asymmetry in the intensity of cosmic rays was proved to be true by the experimental observations of Johnson and Street (1933). Later on other experiments proved that cosmic rays consist predominantly of positive particles.

Störmer's theory when applied to a simple dipole representation of the Earth's field ascribes a minimum rigidity to a cosmic ray particle for arrival from infinity at a particular position on the surface of the Earth. This cut-off rigidity varies with latitude, azimuth, and zenith angles. At the equator, it is larger for arrival from the eastern horizon than from the western horizon.

The intensity of particles arriving above such cut-offs was calculated by Lemaitre and Vallarta (1933) who applied Liouville's theorem to cosmic ray geomagnetic effects, assuming that the distribution of cosmic rays at infinity is isotropic. After integrating a large number of trajectories they deduced that the sky seen from a point of observation can be divided into the following four regions, if the effect of the impenetrable Earth was taken into account:

- a. Störmer cone, inside which particles with a given rigidity are forbidden,
- b. Main cone outside which particles with a given rigidity are allowed,
- c. The penumbra which lies in between the above two cones and within which some directions are allowed and some are forbidden, for particles of a given rigidity,
- d. Shadow cone inside which particles cannot arrive as their paths intersect the Earth at some other point (Vallarta, 1932, Schwartz, 1959).

The penumbra is only important at low latitudes so that the high latitude Störmer cut-off values can be taken to be the true cut-off rigidities, except those at large zenith angles.

As experimental measurements of the distribution of cosmic ray flux at different points on the surface of the earth (Compton 1933; Compton and Turner 1937; Bowen et al., 1938; Neher et al., 1953) proceeded, it became more and more evident that large differences exist between the flux contours and the geomagnetic surface field contours, though in general, they follow each other. The 1955 survey of surface field showed that the earth's magnetic field is better represented by an eccentric dipole and the flux contours were then related to these field contours (Kodama et al., 1957; Webber, 1958) and modified cut-off rigidities were calculated. The theoretical flux contours thus obtained showed better agreement with the experimental values.

Jory (1956) and Schwartz (1959) were the first to take into account the effect on cut-off rigidities of some of the non-dipole terms in the spherical harmonic expansion of the field but their geomagnetic equator more or less corresponded with the line of maximum cut-off rigidities. Simpson et al. (1956) and Kodama and Myazaki (1957) concluded that the differences between the theoretical and experimental flux contours could be explained as due to the longitude displacement of the position of the eccentric dipole. However, the discrepancies

between the flux and field contours became more obvious as the distributions of solar flare particles were studied (e.g. Pfozter, 1958; Marsden and Wilson, 1958). Disagreement between measured and predicted values of α -particle cut-off rigidities (McDonald, 1956; Waddington, 1956) emphasized the need for an accurate theoretical representation of the geomagnetic field. Rothwell and Quenby (1958), Sandstorm (1958) and Storey (1959) measured the effects of geomagnetic field anomalies on the flux distribution and the conclusion was that the non-dipole parts of the field have to be taken into account for an accurate representation of the geomagnetic field.

One can now try to integrate the trajectories of the particles, but the equations become very complicated with the inclusion of non-dipole terms in the field representation. Approximate methods were therefore presented by several authors. Rothwell (1958) proposed a simple correction to the threshold values by relating them with the local geomagnetic field values and the dip angle. But Quenby and Webber (1959) presented another method, more accurate and general, in which they took into consideration the magnetic field line geometry at high latitudes and the contribution of the spherical harmonic terms of order less than six to the geomagnetic field, for latitudes less than 20° . They then extrapolated the values at high and low latitudes to obtain the cut-off rigidities at intermediate latitudes. Quenby and Wenk (1962) made a revision of these values using calculations by Hultquist (1958) of the geometry of the field lines at high latitudes. In the low latitude

region they took into account the penumbral effect. Using the intensity data obtained at aeroplane altitude by Katz et al. (1958) they related the low latitude thresholds at various positions to the calculated thresholds at the equator where the penumbral effects are zero. They illustrated the accuracy of their theoretical distribution with the data from three major solar flares. Other experimenters (Pomerantz and Agarwal, 1962; du Plooy et al., 1963) confirmed the general accuracy of their values, and the validity of the method was checked by Bland (1962) and Hedgecock (1964) by an analogue computer technique.

Machine calculations of the threshold rigidities at specific positions on the Earth's surface have been performed by several people (Schwartz, 1959; Kasper, 1959; Kellogg, 1960; Vallarta, 1961; McCracken, 1962), who integrated the equations of motion of the particles in a simulated geomagnetic field closely representing the actual one. The Quenby-Wenk threshold rigidities were found to be closely similar to these values.

1.3. Analysis of the data.

(a). Cut-off Rigidities.

The orbits obtained in the period 27th. April to 8th. June, 1962, were divided into two height groups, one for below 800 km another for above 800 km. The total number of orbits in each group were then classified according to their equatorial crossing positions in longitude, each class falling within 20° intervals. Latitude cruves were then plotted for each of these classes of orbits. As the counting rates from the Cerenkov detector were at two levels of attenuation, the

attenuated values were normalized to unattenuated values for plotting the latitude curves. From these curves, a representative one being shown in Fig.1, and the counting rate versus rigidity curves, shown in Fig.2, one is able to find out, for each latitude point along an orbit, the counting rates corresponding to a particular rigidity. Thus two world maps were produced for two mean altitudes with contours of equal rigidity corresponding to contours of equal intensity, as shown in Fig.3 and Fig.4. Equal rigidity lines given by Quenby-Wenk values on the surface of the earth, as shown in Fig.5, were used as reference lines, with which lines obtained at the two mean heights of 600 km and 1000 km were compared. Rigidity values were read off at every 10° interval of longitude, and 10° interval of latitude from 0° to 50°N and 0° to 50°S . The region of 0° to $\pm 10^\circ$ was excluded due to lack of data and low statistical accuracy. The root mean square percentage difference between the high altitude (1000 km) and low altitude (600 km) values, and the low altitude and Quenby-Wenk's values were found to be about 10%. The differences were also found between low altitude and Kondo and Kodama (1965) values and Kondo and Kodama (1965) and Quenby-Wenk values which come out to be of the same order.

From this we conclude that the average values given by Ariel I data only confirm Quenby-Wenk threshold model to 10%. As this is the order of magnitude by which it differs from Kondo and Kodama's model, it is not possible to prefer one to the other.

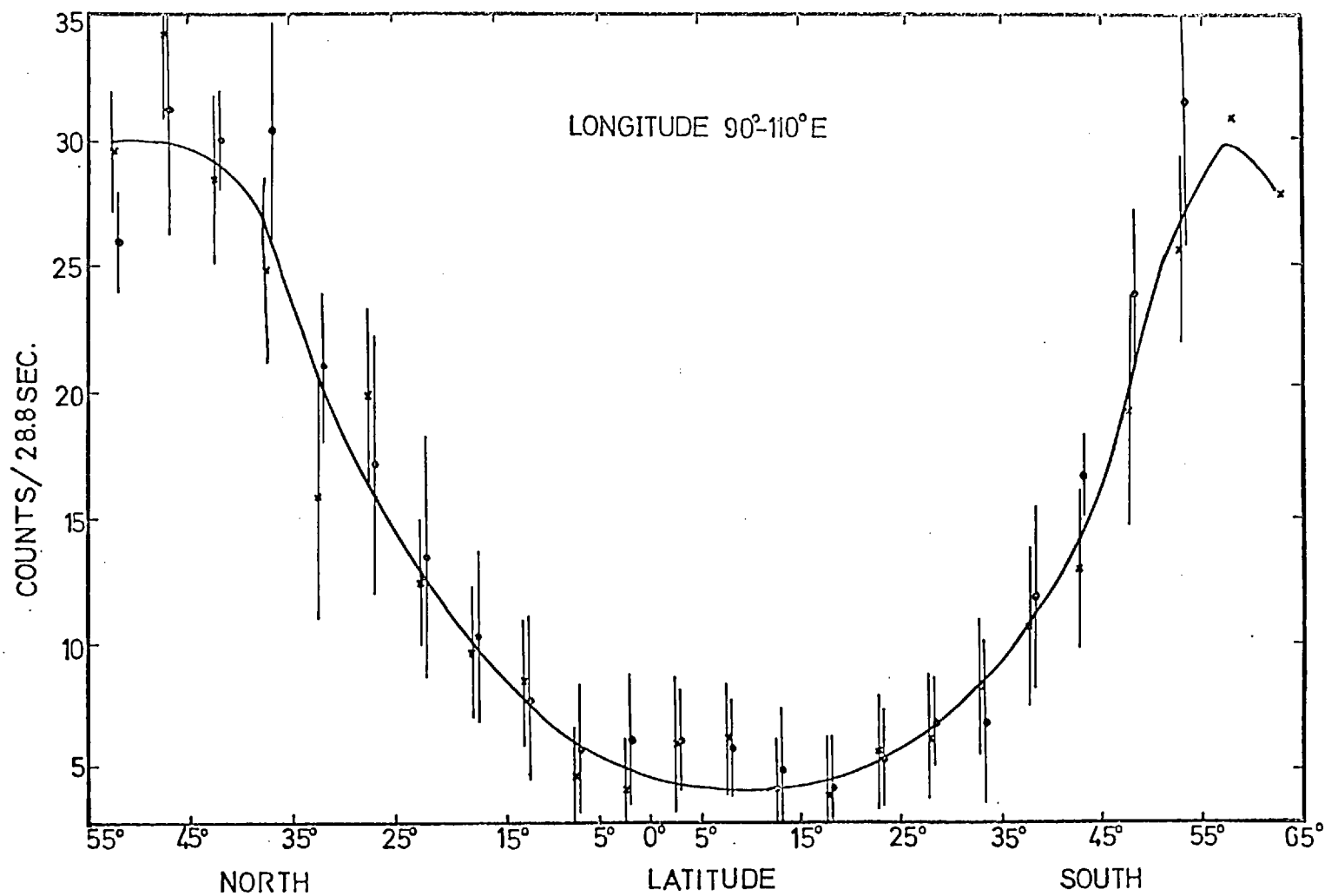


Fig.1. Intensity Variation of Cosmic Rays ($Z \geq 6$) with latitude (geographic).

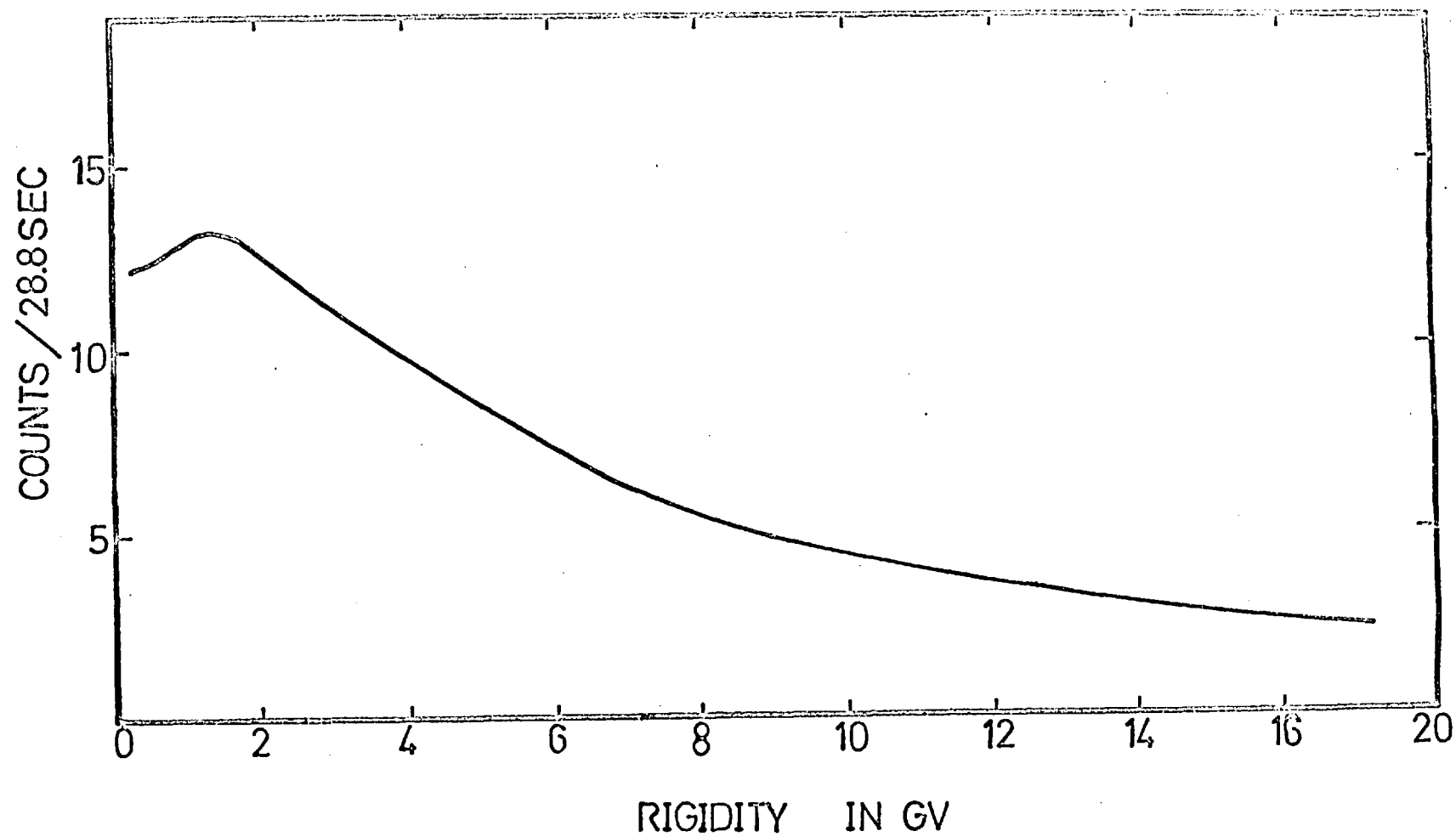


Fig.2. Variation of Cerenkov Counter rate with rigidity.

(b). Energy Spectrum of Heavy Primary Cosmic Rays.

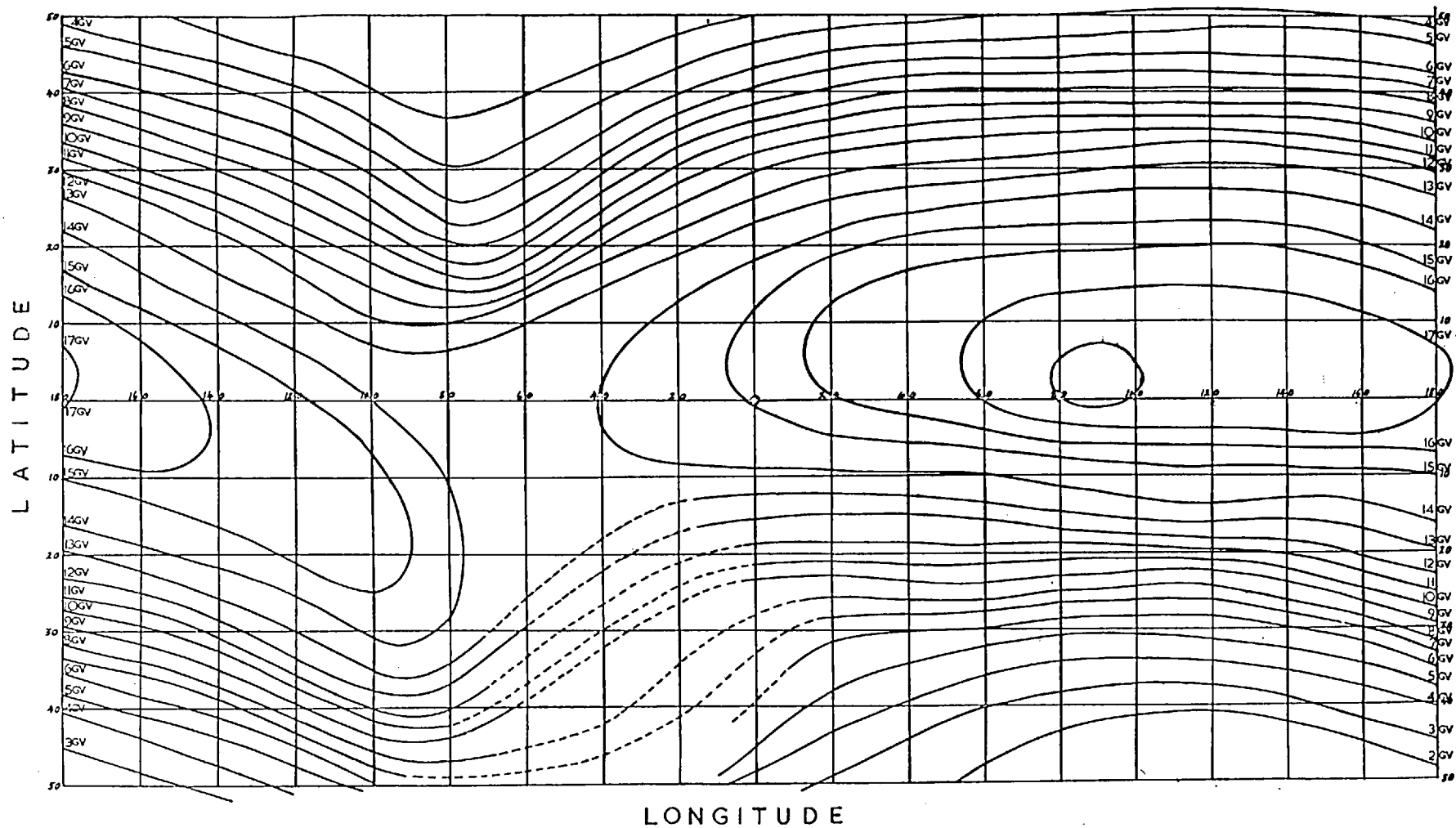
A Cerenkov counter detected the primaries with $z \geq 6$ and the counting rate as a function of latitude was recorded. Quenby-Wenk's threshold rigidities for particles vertically incident on the surface of the Earth were used to sort out the data. A correction was applied to the Quenby-Wenk values for the altitude of the satellite. It was assumed that the threshold rigidity at the satellite, R_s , is related to that at the ground level by

$$R_s = R_{\text{MIN}} \left(\frac{r_e}{r_e + h} \right)^2$$

where R_{MIN} is the Quenby-Wenk threshold value appropriate to the latitude and longitude of the satellite, r_e is the radius of the earth and h the satellite altitude. Except at low latitudes the threshold rigidity R_{MIN} does not vary widely with the direction of incidence and the value appropriate to vertically incident particles proves to be a sufficiently good approximation. Durney (1964) used for the equatorial region a mean value of the threshold rigidity weighted over all directions and this value was never different from that for vertical incidence by more than ~ 1 GV.

In the preliminary analysis of the data Durney et al. (1964) chose their entire number of orbits from below 800 km for reasons given below:

- i. Earth's shadowing effect is small at altitudes less than 800 km (aspect effect),
- ii. Uncertainty in the Quenby-Wenk threshold rigidity values is more as altitude increases,



CONSTANT

RIGIDITY

LINE ($< 800\text{KM}$)

FIG. 3

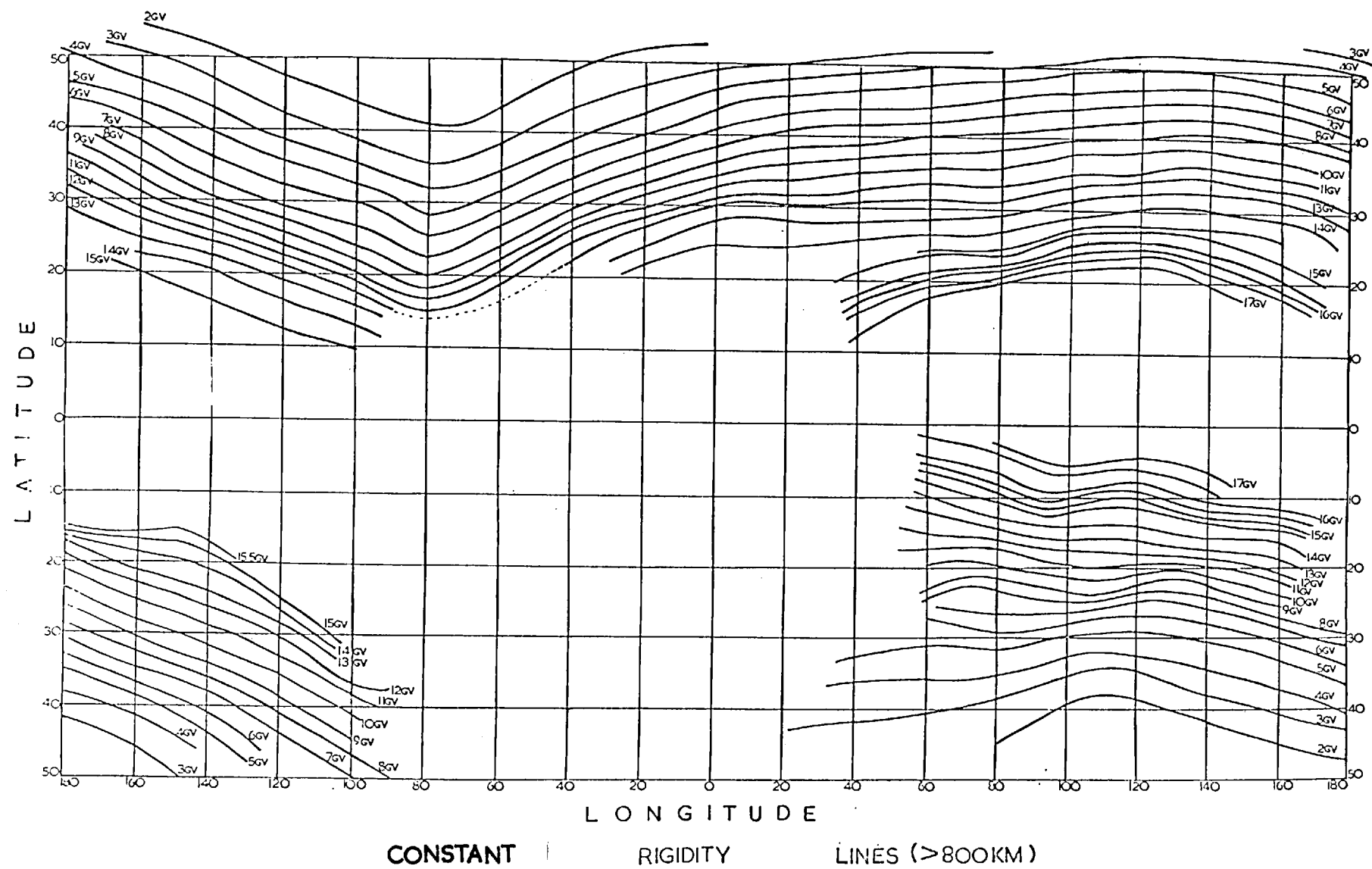


FIG.4

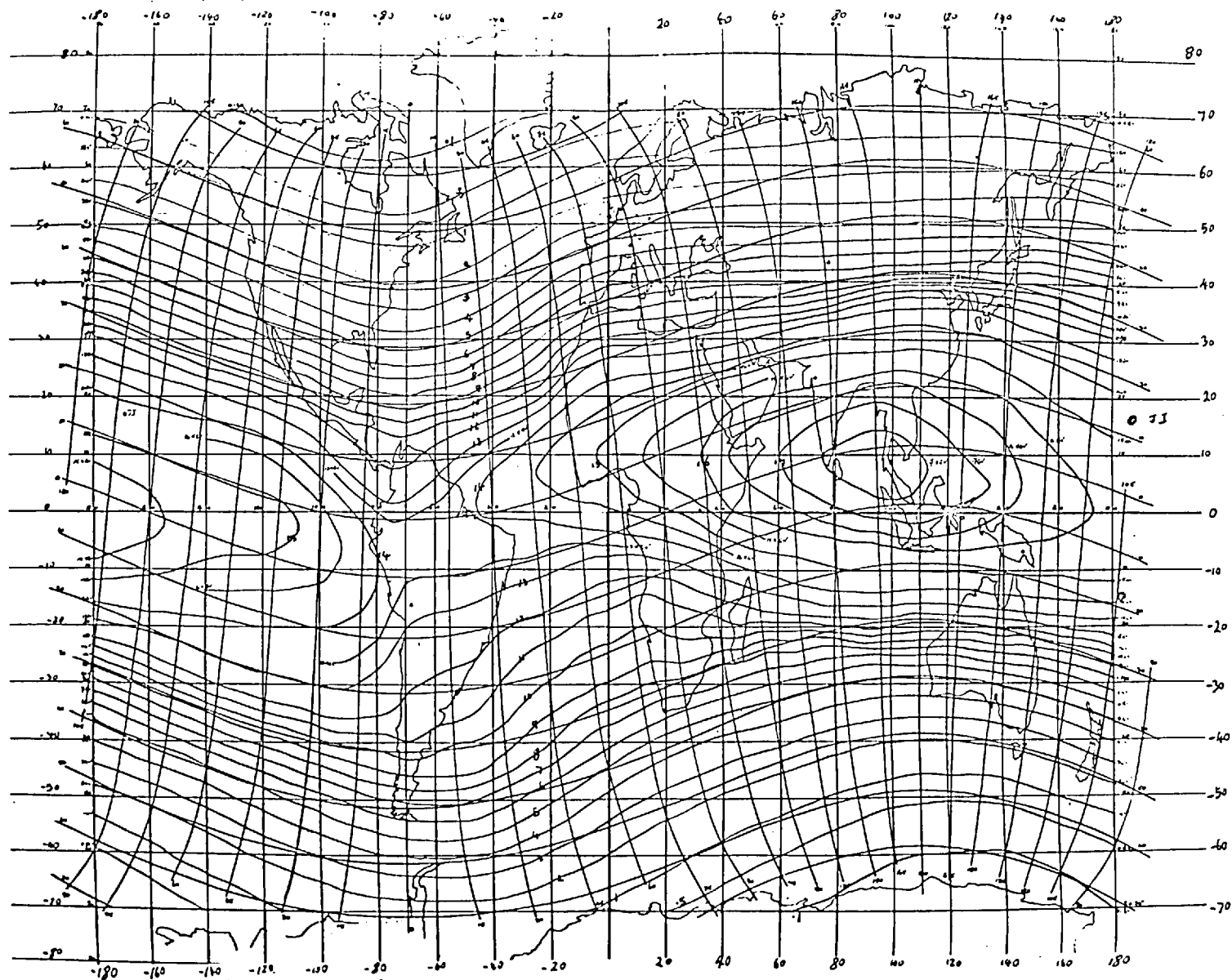


FIG. 5

- iii. Altitude effect on the counting rate is less in this range.

The data analysed in this work were all from the region between 800 km and 1200 km. As a result the expected sources of error are the altitude variations, uncertainty in Quenby-Wenk values and the aspect effect of the satellite on the counting rates. All these were investigated in addition to the corrections which were applied to the data by Durney (1964). These investigations are listed below:

(a) The Fall-Off of Cerenkov Light for Slow Particles.

When a charged particle passes through a medium the intensity of Cerenkov light radiated is proportional to $(1 - \frac{1}{\beta^2 n^2})$, where n is the refractive index of the medium. The detector sensitivity is, therefore, expected to diminish with diminishing R_{MIN} for particles with a given z . Underestimation of the flux of low rigidity primaries, which would result from the above effect, can be avoided if the drop in the detector sensitivity could be compensated for. This could only be achieved by making the gain of the phototube independent of the particle velocity or, in other words, proportional to $(1 - \frac{1}{n^2 \beta^2})^{-1}$. As this cannot be done experimentally, 'in situ' determination of the counting rate as a function of the gain, seemed to be the answer. Durney (1964) used his data to plot the curves shown in Fig.6. The upper two curves are for the period day 117 to day 138, for two levels of attenuation, the lower two curves are for the period when the sensitivity of the Cerenkov detector

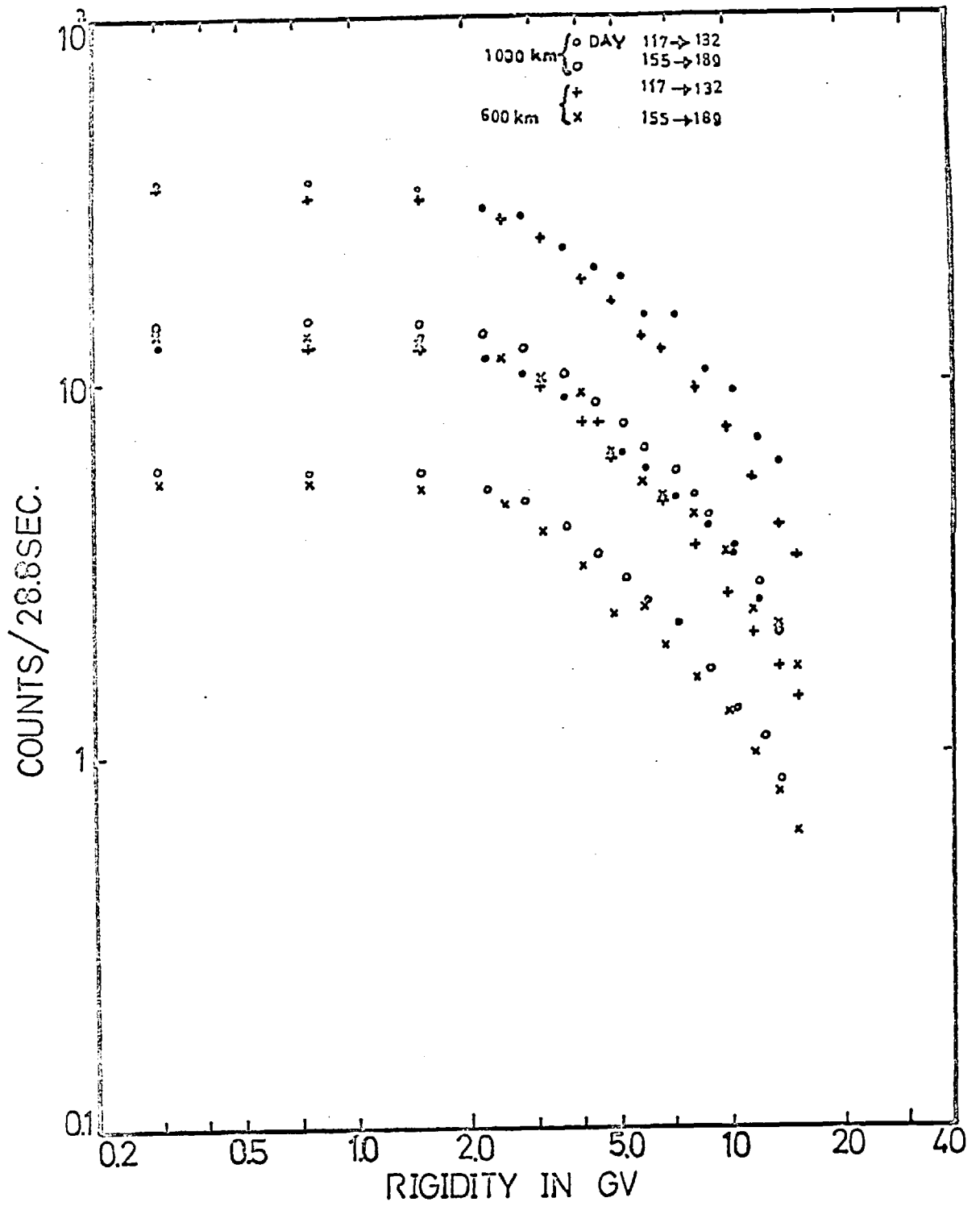


Fig.6. Integral Counting Rates at four attenuation levels.

was at a diminished level (Durney, 1964; Engel, 1964). Points obtained with the data used here were also plotted in Fig. 6. These curves were utilised to get calibration at three levels of attenuation for various rigidities, as shown in Fig. 7. From the relation $R = m\beta c^2 / ze\sqrt{1 - \beta^2}$, β for a particular rigidity is calculated. Therefore from Fig. 7, and the expression $(1 - \frac{1}{n^2\beta^2})^{-1}$ for a gain required for compensation, one can obtain the corrected counting rates for that rigidity.

(b) Threshold Rigidity Corrections.

Quenby-Wenk's threshold rigidities give the values appropriate for particles arriving at the surface of the earth from the zenith. As the detector was at a certain height above the surface and had a wide angle of acceptance, the effect of both of these on the cut-off values had to be taken into account. The first correction was made by using the relation

$$R_s = R_{MIN} \left(\frac{r_e}{r_e + h} \right)^2$$

for the average height of 1000 km. The modification introduced by the second effect was taken into account by accepting the effective, equatorial cut-off rigidity for a point on the surface of the earth calculated by Durney (1964). This is 15.9 GV, whereas the Quenby-Wenk value for such a point is 14.9 GV. The deviation from the vertical cut-off value is, therefore, the most at the equator, falling off as one goes towards higher latitudes being zero at the poles. Thus the corrected

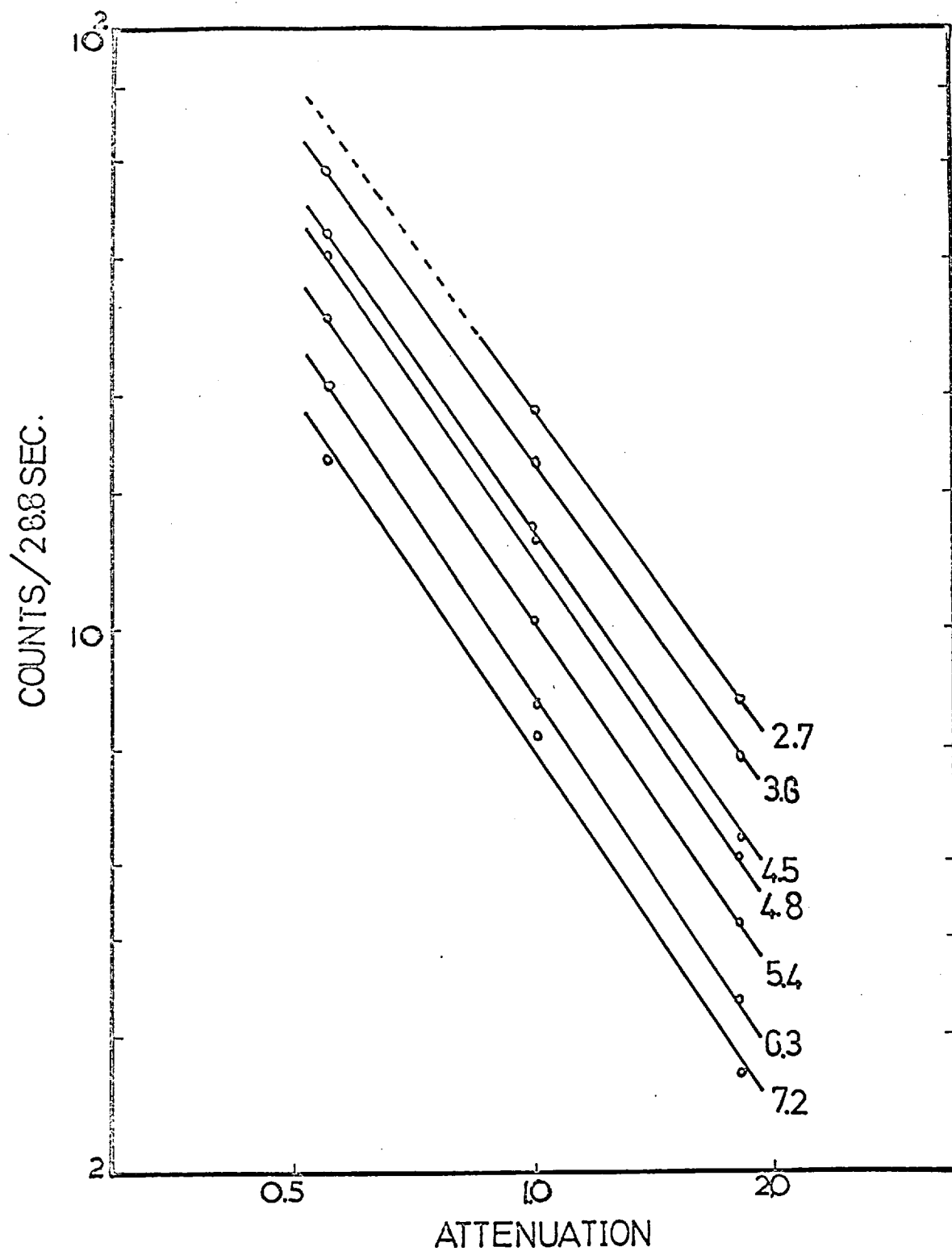


Fig.7. Calibration curves giving the count rate as a function of attenuation for various rigidities.

values at 1000 km came out to be $R_s = 0.8 R_{MIN}$.

(c) Earth's Shadowing Effect.

The angle between the direction of spin axis of the satellite and the local vertical, called the aspect angle, changes continuously as the vehicle traces out its orbit. Because of this there would be a variation in the counting rate due to the varying portion of the sensitive solid angle that is blocked by the Earth and the body of the satellite. During the period day 130 to day 140 the orbits of the satellite were such that the aspect angle was varying from nearly 0° to nearly 180° , i.e., in some parts of the orbits the detector was pointing towards the earth and in other parts, away from the earth. This will produce a difference in counting rate averaged separately over the northern and the southern hemisphere. The data from this period were used, in height and rigidity groups, to investigate this effect, and the mean difference for counting rates with the small rigidity values come out to be :

$$\text{attenuated level difference} - (2.97 \pm 1.44)\%$$

$$\text{unattenuated level difference} + (3.14 \pm 2.73)\%$$

As the uncertainty remaining in the Quenby-Wenk values even after corrections applied to them will introduce errors larger than this, we can neglect here any correction due to the aspect effect.

(d) Second Altitude Effect.

Apart from the effect of altitude on the rigidity of the particles, there will be another effect of altitude on the counting rates. The increase in altitude causes the solid angle subtended by the Earth at the satellite, to decrease and this in turn increases the sensitive solid angle of the detector. As a result the counting rate increases. During day 155 to day 165 the apogee and the perigee occurred at the northern and southern extremities of the satellite orbits. In these high latitude regions there is no change of cut off rigidity due to the first altitude effect, because the latitude spectrum has a plateau in that region. The average counting rates in the northern and southern hemispheres during this period, therefore, are expected to show a difference which reflects the above effect. This difference came out to be:

$$\begin{array}{ll} \text{attenuated} & (5.8 \pm 2.5)\% \\ \text{unattenuated} & (10.7 \pm 2.2)\% \end{array}$$

as estimated by Durney (1964). For unattenuated levels the difference is rather high. In our case the effective height variation estimated for the extreme ends of the rigidity ranges, i.e., $P = 3$ to 4 GV and $P > 16$ GV, is only 46 km, and as such the correction is negligible.

1.4. Discussion of the Result.

After applying corrections (a) and (b) we get the rigidity spectrum as shown in Fig.8. The counting rate at the highest rigidity point has

been normalized to that obtained from Durney's (1964) curve.

It can be seen that analysis presented here gives an integral rigidity spectrum of the heavy primary cosmic rays which shows a change of slope around 8.5 GV. From the α -particle spectrum (2 to 5 GV) measurements of McDonald and Webber (1962) during a period near the last solar minimum, it can be assumed that the slope of the unmodulated heavy primary spectrum is also - 1.5. That is the slope given by the higher rigidity end of the spectrum in Fig.8. The change of slope, at 8.5 GV, to - 1.07 can therefore be used to give the rigidity dependence of the solar modulation in the period considered (May & June, 1962). It may be represented by

$$I_e = I \left(\frac{R}{R_0} \right)^{0.43} \quad \text{for } 2.5 < R < R_0$$

where

I_e = intensity of primary cosmic rays with rigidities
greater than R at the earth,

I = intensity of cosmic rays at infinity,

R_0 = 8.5 GV.

1.5. The Modulation of the Heavy Primary Cosmic Ray Spectrum over the Solar Cycle.

The heavy primary cosmic ray spectrum in the latitude sensitive region has been established in the last section, for May-June, 1962, a period near minimum in the solar cycle. This provided an inducement to study the long-term variation in the heavy primary spectrum, as, at least, one other very satisfactory measurement was available for the

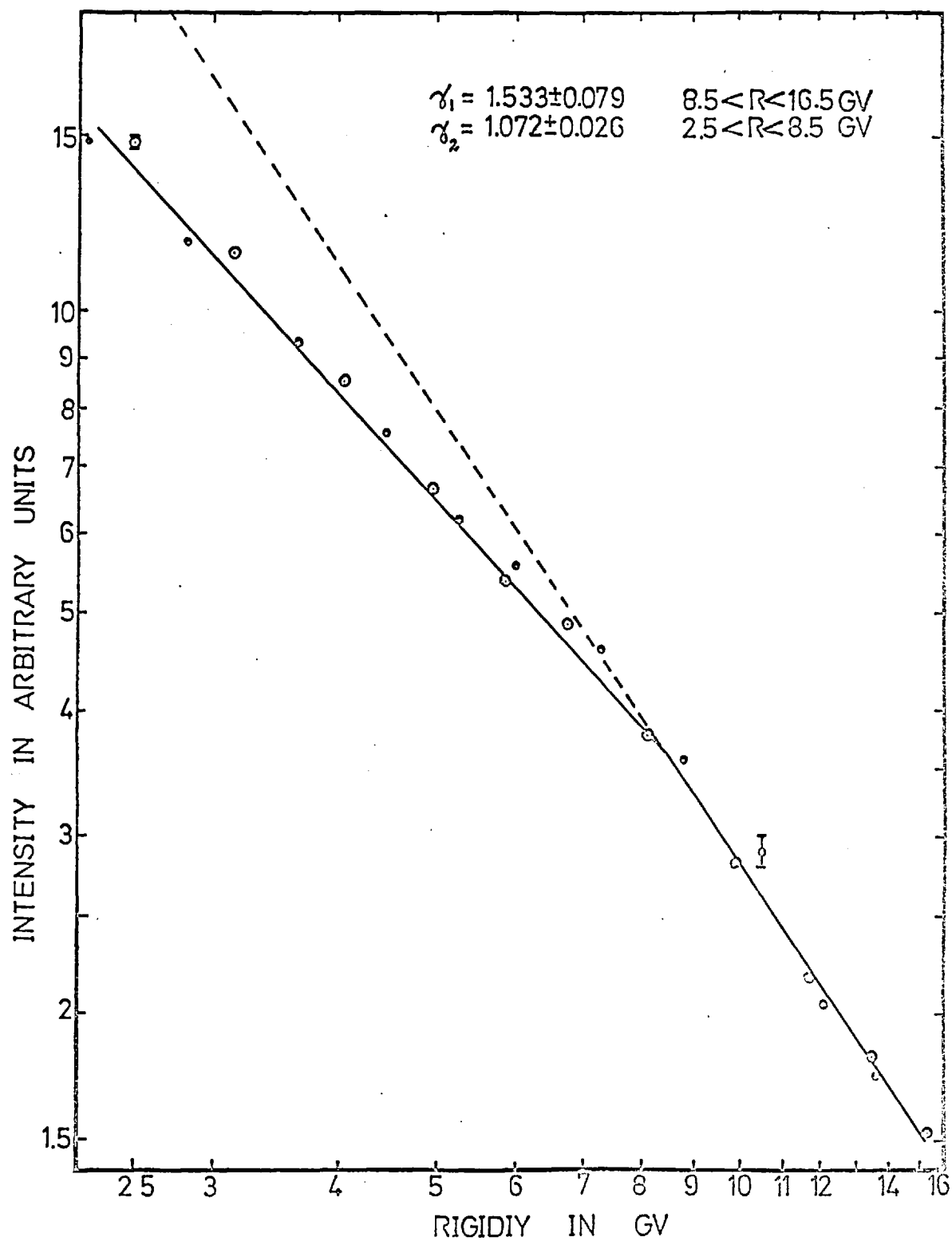


FIG.8. RIGIDITY SPECTRUM.

year 1960 (Pomerantz et al., 1960), a period near maximum in the solar cycle. Apart from these two one could also take into account Webber's (1965) balloon measurements, carried out in 1963—1965. All these three measurements give the integral rigidity spectrum of primary cosmic rays with $z \geq 6$. For comparison between these spectra, it was necessary to consider a base spectrum representing the galactic spectrum. This was difficult as the evidence from the recent solar minimum showed that even at the minimum there was some residual modulation present in the recorded intensities. It was, therefore, decided that these spectra will be compared by normalizing them at some higher rigidity where the modulation for all the three could be taken to be the same. A solar minimum integral spectrum, through this point, with a slope of -1.5 was accepted.

At present the discussions which are being carried on, on the modulation are mainly based on particular models of the interplanetary field adopted for convective modulation with anisotropic diffusion and isotropic diffusion. In addition to the convective modulation here, additional modulation due to energy losses have also been investigated (Quenby, 1966). Modulation by electrostatic fields has been the topic of intense discussion by Frier and Waddington (1965) and Nagashima et al. (1966). Here only the convective modulation with isotropic diffusion will be considered.

If the magnetic conditions in the interplanetary space are such that a regular spiral field cannot exist, then the diffusion coefficient is isotropic. The density of particles in the vicinity of the earth will then be given by

$$n_e = n_\infty e^{-3/\beta \int_R^\infty \frac{u}{\lambda(P)} dr} \quad (1)$$

where n_e is the particle density at the Earth, n_∞ is the particle density at infinity or the unmodulated density, β is the particle velocity in terms of the velocity of light, u is the solar wind velocity, r is the distance from the sun and λ the mean free path of the particles.

λ depends both on r and P , the particle rigidity. β is a constant here as it is being assumed that the adiabatic deceleration in the presence of a radially diverging solar wind is negligible. Eq. (1) can be written as

$$n_e = n_\infty e^{-\frac{3u(R - R_o)}{\beta\lambda}} \quad P \leq 5GV \quad (2)$$

if it is assumed that the solar wind velocity u is independent of r out to a point where $1/\lambda$ is non-vanishing (Parker, 1963); R_o is the

distance to the boundary of the solar active region inside which the modulation is effective. Eq. (2) is valid for $P \leq 5$ GV when certain values for the interplanetary magnetic field B and scale size of the scattering centres are assumed (Quenby, 1965). For a rigidity $P \geq 5$ GV,

$$n_e = n_\infty e^{\frac{-3u(R - R_0)}{\beta\lambda}} \left(\frac{P_M}{P} \right)^2 \quad P \geq 5 \text{ GV} \quad (3)$$

where P_M is the rigidity at which the radius of gyration of the particles becomes equal to the scale-size of the scattering centre. With the experimental values of the differential intensities j_e at different times in the solar cycle and the solar minimum intensity $j_{\min}$, one can calculate u , λ , or R_0 , in turn, using some plausible values of the other parameters.

Analysis of the Spectra.

As experimentally one always gets the modulated primary spectrum, the least variation in modulation is expected at the highest rigidity point in the spectrum . The highest rigidity point at which it was possible to get a measurement was at a cut-off rigidity ~ 16.5 GV. From the regression curve drawn by plotting the measurements at this rigidity against the Mount Washington neutron monitor intensities, one can get the intensity of heavy primary particles at 16.5 GV, corrected to sunspot minimum point in the solar cycle. It was 1.35 ± 0.08 particles /m²-ster-sec (Webber, 1962). All three spectra were, therefore, normalized to this value at ~ 16.5 GV. The reference spectrum (sunspot minimum) was taken to be the one with a slope of -1.5 through the point at 16.5 GV. This was prompted by the suggestion of Webber (1965) that the data between 4.5 GV and 16.5 GV for sunspot minimum indicate an integral spectrum for S nuclei with this exponent. Fig.9 gives the three measured integral spectra along with the reference spectrum, in the range of rigidity 1.5 GV to 16.5 GV. The slopes of the different spectra were analytically calculated in two cases (Ariel I and Webber, 1965) with the third one given by Pomerantz et al. (1960).

Modulation Function.

This is generally defined as the ratio of the differential intensity at a given rigidity at any time in the sunspot cycle, to that at sunspot minimum. For computing these ratios the differential spectra were

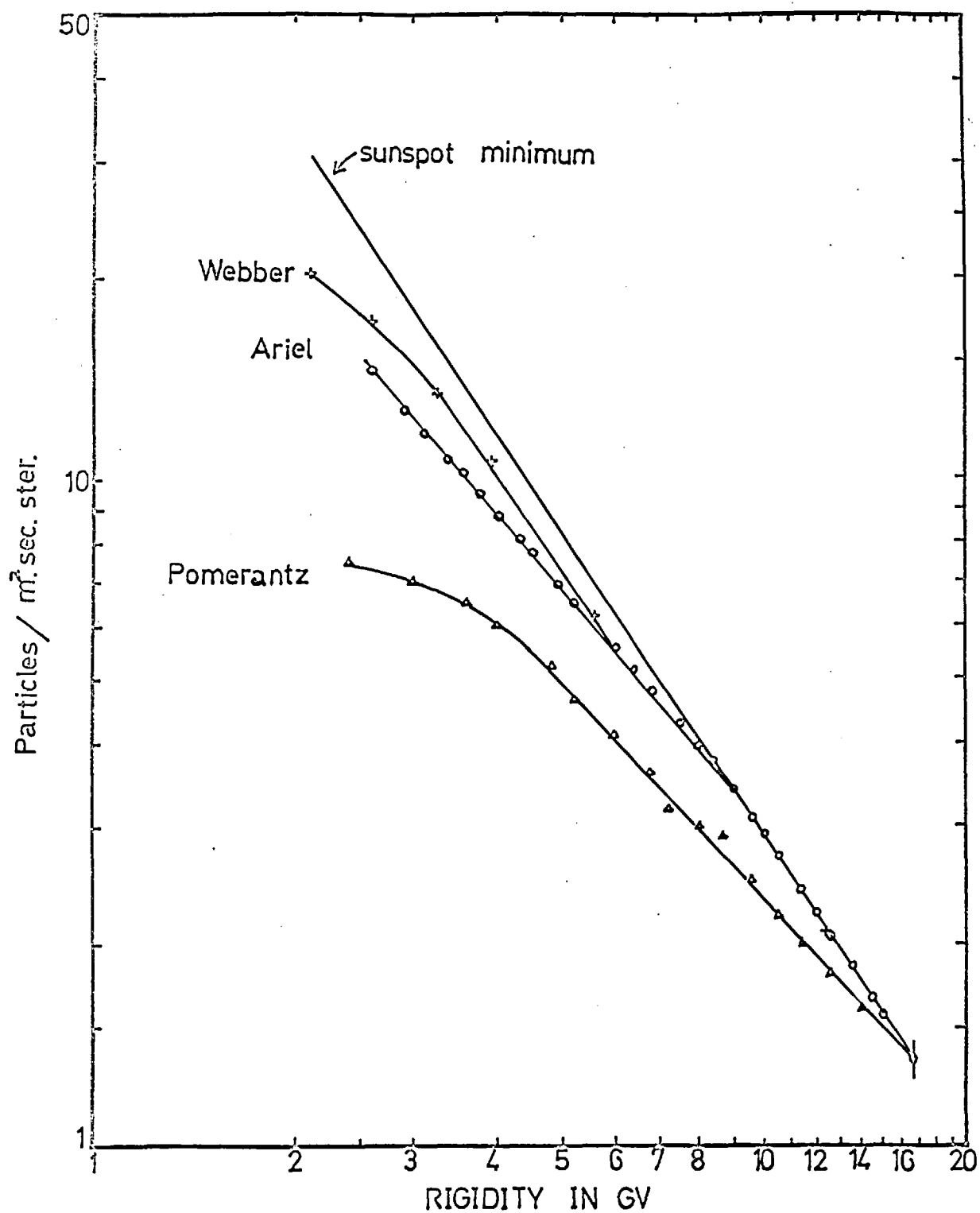


Fig.9. Integral rigidity spectra of heavy primary cosmic rays.

analytically calculated from the three integral spectra, along with the errors on each point. It was then possible to calculate the ratios $j_{1959}/j_{\min}$. In Fig. 10a one can see the variation of these ratios with rigidity. The gradual decrease of the degree of modulation as sunspot minimum is approached is quite smooth. The modulation is shown to be effective down to lower and lower rigidity as the sunspot minimum is approached. This is due to the assumed slope of -1.5 for the sunspot minimum spectrum. For an unmodulated galactic spectrum with a different slope, of course, the picture will change.

The intensity reduction $\Delta J/J_{\min}$, where J is the integral intensity at a particular rigidity, showed a P^{-1} dependence, as shown in Fig. 10b, during the solar minimum. But at solar maximum, the rigidity dependence was more like $P^{-0.7}$ at higher rigidities.

It was then possible to look for the parameters in Parker's simple solar wind model which fit the experimental data at our disposal. In a review article on time variations Quenby (1965) has shown that Parker's isotropic diffusion model can be fitted to the Ariel data if the solar active region is taken to be extended out to 3 A.U., at that particular period. Using the values of different parameters chosen by Quenby (1965) an attempt was made to fit the model to all the spectra considered. It was found that, from 1959-60 to 1965, an order of magnitude change of the mean free path was needed, if the velocity of the solar wind was kept constant at $4 \cdot 10^7$ cm/sec and R_0 at 3 A.U. On the other hand, keeping the mean free path constant at an order of 10^{11} cm, a variation between

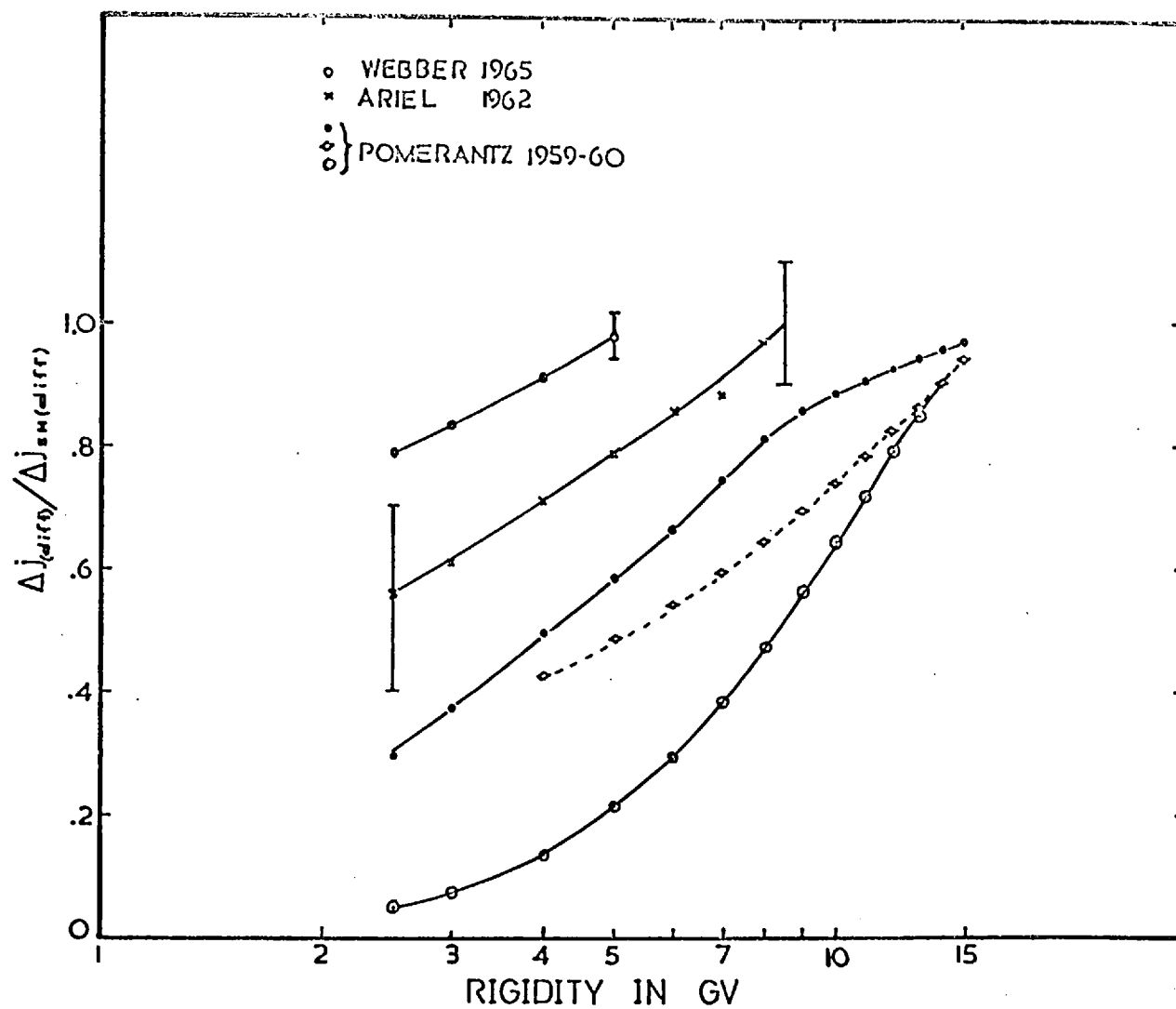


Fig.10a. Variation of the fractional depression in differential intensity.

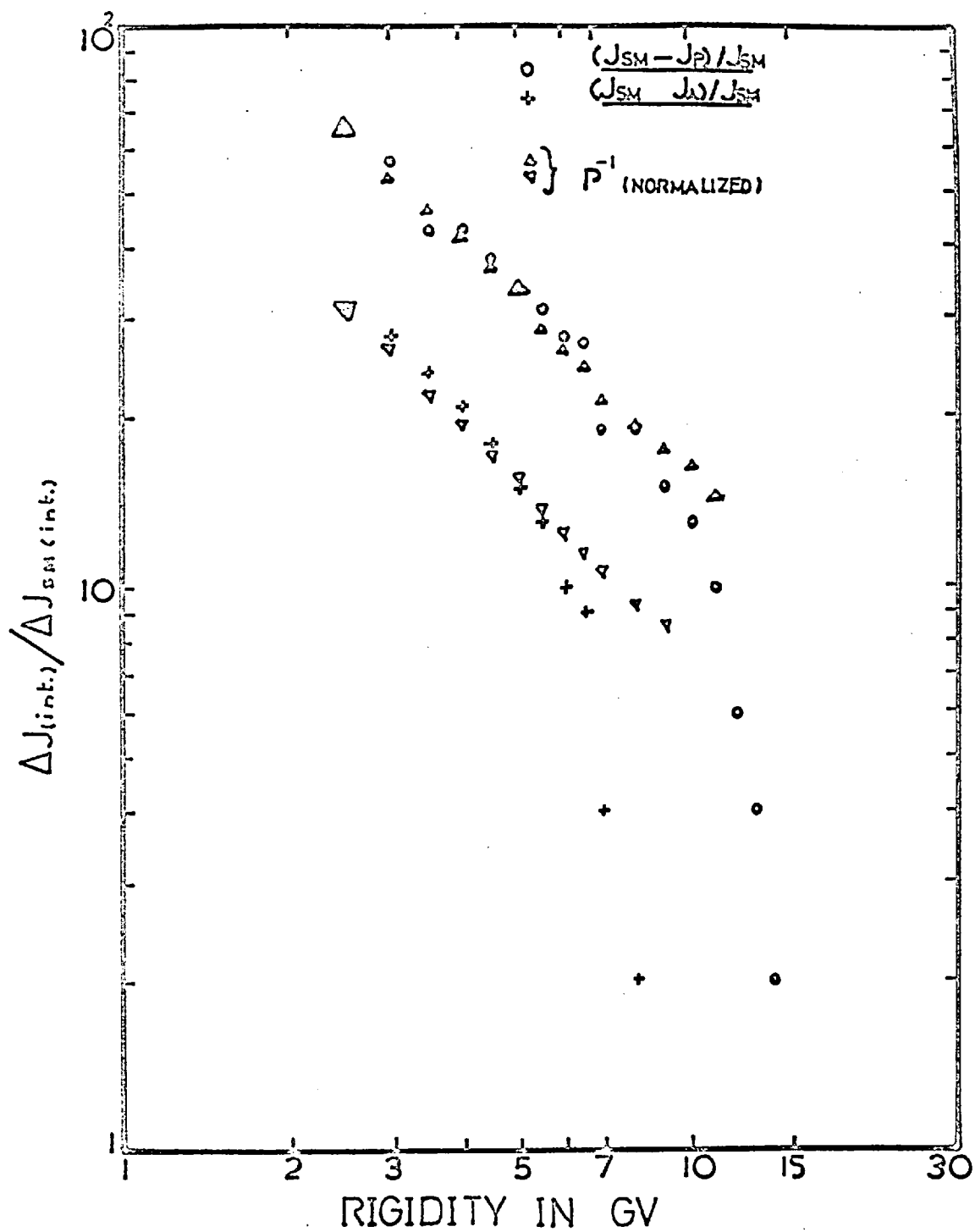


Fig.10b. Rigidity dependence of the fractional depression in integral intensity.

the order of 10^7 cm/sec to 10^8 cm/sec of the solar wind velocity was obtained over this period. This could not be true in the light of the present experimental evidence which give the variation in velocity by a factor of 2 only. The calculation of the factor $(R_0 - R)/\lambda$, however, showed that with $\lambda = 1.2 \cdot 10^{11}$ cm, the value of R_0 was ~ 8 A.U. at solar maximum and ~ 4 A.U. at solar minimum. Taking $\lambda = 2 \cdot 10^{12}$ cm at solar minimum a value of R_0 of the order of 40 A.U. was obtained. Quenby (1966), taking the point of balance between the solar wind pressure and the galactic field as the termination point of the solar cavity, and assuming spherical symmetry, obtained a value of the order of 30-50 A.U. He also showed, taking into consideration all available α -particle and proton measurements of 1963 and 1965, that between $1 \text{ GV} \leq P \leq 15 \text{ GV}$, $\lambda \propto P$, throughout the solar cycle. But in this case, an anisotropic diffusion model with $\lambda \propto r^2$ was considered.

It is concluded, therefore, that Parker's convective isotropic diffusion model with λ of the order of 10^{12} cm explains the experimental data on heavy primaries fairly well, in the rigidity range 1.5 GV to 16.5 GV, during the years 1960 to 1965.

TIME VARIATIONS IN THE VAN ALLEN RADIATION BELTS.2.1. Introduction.

The discovery of a high flux of charged particles trapped in the geomagnetic field by Van Allen et al. (1958) opened up a new field of investigation for the scientists who were engaged in the study of energetic solar particles and cosmic rays. Many theoretical and experimental investigations have already been carried out but we are still far from a complete understanding of the origin of these particles.

One of the most effective ways to attack the problem of the origin of these particles is to observe and study systematically the time variations of their intensity. Immediately after the discovery of the trapped particles, Yoshida et al. (1960) and McIlwain (1961) demonstrated the high degree of temporal stability of the inner belt, for two separate periods in 1958. Hoffman et al. (1962) placed an upper limit of about 10% on the time variations of the inner belt proton components due to magnetic storms, for August and September 1959. Freden and White (1960) showed that the activity associated with the large solar flares of May 10, 1959, had little or no effect on the flux of trapped protons in the inner belt. With Sputnik 3, Vernov and Chudakov (1960) noted that the absolute intensity of radiation in the inner zone remained constant with an accuracy up to 15% in the course of a month. Brown and Gabbe (1964) found no gross temporal variations of the inner belt protons during July 19, 1962 to July 16,

1963. McIlwain (1964) found that no change larger than 10% occurred at $L \leq 2.0$ when the intensity of protons at $L \approx 2.5$ decreased by more than a factor of 10 within a 7-hour period on September 23rd, 1963. Pizella et al. (1962) performed an extensive study of the inner zone with Explorer VII data for a period of October 13, 1959 to December 31, 1960. The detector, an Anton 302 Geiger tube, was sensitive to electrons with $E > 1.1$ MeV and to protons with $E > 18$ MeV. Significant time variations in the count rate existed in the region $1.25 < L < 2.50$, and the changes appeared to occur in discrete steps which were temporally correlated with major solar proton events and/or geomagnetic storms. Depending on the time increment or L-shell, the changes could be increases or decreases. However, the count rates on L-shells, at the end of the period exceeded those for the beginning of the period by a factor of 3 for $1.2 < L < 1.8$ and by a factor of 10 for most of the remaining shells. Valerio (1964) studied protons of energy from 40 MeV to 110 MeV observed on Injun 3. He found a time decay only at the lower edges of the inner belt but found the intensity to be extremely stable elsewhere. Zmuda et al. (1965) studied the temporal and spatial behaviour of protons in the inner zone in the region of the South Atlantic Anomaly, during the period July-Dec., 1961.

Study of the temporal fluctuations of intensity of the outer Van Allen belt and its association with solar and geomagnetic disturbances was made by several authors (Rothwell & McIlwain, 1960; Arnoldy et al., 1960; Rosen & Farley, 1961; Fan et al., 1961; Van Allen & Lin, 1960;

Forbush et al., 1961; Forbush et al., 1962). The magnitude of the intensity in the vicinity of 3.5 earth radii has been observed to vary by nearly 2 orders of magnitude (Van Allen, 1961). The fluctuations in the outer belt have been divided into two classes by Rosen (1963). Long term secular variations and daily variations in the structure of the radiation belts may be grouped into one class; intense unusual fluctuations, rising and falling a few orders of magnitude within a few minutes form the second class. The former is a characteristic of the structure of the outer radiation belt. The latter is associated with geomagnetic storms. O'Brien (1962) studied the lifetime of low energy outer zone electrons and their precipitation in the atmosphere to find any association of them with the aurora.

The data obtained over a period of two and a half months, from 26th. April, 1962 to 8th. July, 1962, recorded by an Anton 302 Geiger counter on board the satellite Ariel I, have been used to find any temporal variations occurring in the two belts at that time. The lower layer of the inner zone was chosen to investigate the relation of any variation there with the exosphere density variations and Ap indices.

2.2. Motion of Charged Particles in the Geomagnetic Field.

Before proceeding with a discussion on the origin of and the loss processes for the trapped particles, one must be clear about the nature of the motion of charged particles in the geomagnetic field.

Störmer (1955) was the first to derive an integral equation of motion of charged particles in a dipole field. His treatment, however, is not particularly suitable for particles which are trapped in the geomagnetic field. The complex trajectories of such particles can be dealt with by an approximate method due to Alfvén (1963), and this method can be applied directly to the particles trapped in the Earth's field. The motion of trapped particles in the geomagnetic field can be described in terms of the following three components.

- a. A rapid gyration or rotation around the field lines.
- b. An oscillation of the 'guiding centre' along the field lines.
- c. A drift in longitude around the Earth.

An adiabatic invariant can be associated with each of these components of motion and the above description is only applicable during the time when these adiabatic conditions remain unviolated.

Mathematical definition of the three invariants.

The gyration of a charged particle about a line of force generates a current loop. The magnetic moment μ of this loop can be shown to be given by

$$\mu = \left(\frac{1}{2} n v^2 / B \right) \gamma$$

where B is the total magnetic field, including that generated by all

other particles, m , the particle rest mass, $v_{\perp}$ its velocity perpendicular to the field line and $\gamma = (1 - \frac{v_{\perp}^2}{c^2})^{-\frac{1}{2}}$. If the variation of B is slow enough so that the particle motion is periodic, then μ is an adiabatic invariant of motion and is generally known as the first adiabatic invariant.

The constancy of the magnetic moment leads immediately to the second component of the motion: oscillation between two mirror points. The magnetic field at either of these points is given by

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

where B_0 and α_0 are field strength and the pitch-angle at some reference point. The second adiabatic invariant can then be defined by

$$I = \oint m v_{\parallel} dz$$

where $v_{\parallel}$ is the component of velocity parallel to B and integration is over a north-south cycle. Northrop and Teller (1960) show that I is also conserved in the presence of slowly-varying electric fields.

Northrop and Teller (1960) also defined the third adiabatic invariant, called the flux invariant

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

where the integration is over a surface whose boundary is the line traced out by one of the mirror points in its azimuthal drift.

An elaborate discussion on the Störmer, Alfvén, and McIlwain treatments of the movement of charged particles in the dipole and near dipole fields is available in H. Elliot's (1963) review article on Van Allen Belts.

2.3.a Origin.

The origin of trapped particles has not yet been established conclusively. There are three possibilities which have been suggested by a number of authors. Singer (1958), Kellogg (1959) and Vernov et al. (1959) suggested independently that the cosmic ray flux which is incident upon the Earth's atmosphere, and which generates neutron albedo, leads to the trapping of both electrons and protons in the geomagnetic field. A solar origin for the particles was suggested by Gold (1959), the particles acquiring energies in the solar atmosphere and then escaping to the Earth where they eventually get trapped in the geomagnetic field.

Lencheck's (1962) treatment shows that solar flare generated protons most probably give rise to neutron albedo from which trapped protons are originated. But there still exists a contribution to the trapped protons due to albedo arising from galactic cosmic rays (Lencheck and Singer, 1962; Pizella et al. 1962). Recently Valerio (1964) showed that to a reasonable approximation the neutron albedo source strength given in the literature was capable of accounting for the observed equilibrium distribution at $L \leq 1.5$. The neutron albedo theory, however, cannot account for the large number of trapped

electrons observed in the outer radiation zone. The solar origin theory had to be discarded as Pioneer V failed to encounter a large body of radiation in interplanetary space, which ought to exist to make the theory tenable. Dessler (1958) tried to explain the existence of trapped electrons in the radiation belts by a mechanism in which the particles are accelerated in situ in the geomagnetic field. The exact mechanics of this process has not yet been established.

2.3b Loss Processes.

Charged particles may be removed from the trapped condition for different reasons. They can be completely removed or they may lose their energy so that they fall below the threshold of the detector. The complete removal may occur due to scattering into the loss cone by interaction with the atmosphere, breakdown of the adiabatic invariance due to scattering by hydromagnetic waves, and charge exchange. Collisions with atoms, electrons and ions will cause loss of energy without a loss of the intensity of the trapped particles. The importance of the different processes is entirely dependent on the nature and energy of the particles. Loss of energy by interactions with the atmosphere is important for protons, but scattering is more important for electrons.

2.3c Time variations from the Loss Processes in the Atmosphere.

The possibility of a daily variation in the inner zone proton flux exists for the following reason. The geomagnetic field, because of its eccentricity has an anomalous region over the South Atlantic.

Here the contours of constant field values come down to their lowest level, compared to the other longitude regions. As the trapped protons are moving along constant B-L lines, they come down into the densest atmosphere there, as they drift in longitude around the earth. Now, there exists a daily variation in the atmospheric density, due to solar EUV and probably some corpuscular (source unknown) heating (Harris and Priester, 1962) as well. A so-called bulge of density is formed which will travel around in longitude. As the trapped particles will be encountering this bulge the loss of particles will be a maximum at one particular time of the day. A diurnal variation of trapped proton flux will, therefore, result. (This is also true for any other flux of particles which might encounter this bulge). And this diurnal variation will be most pronounced in the South Atlantic Anomaly region. The idea here is to look for this by trying to find any correlation of the phase of the semi-diurnal variation in the upper atmosphere pressure wave. One can also calculate the half-life of the lower layer of the inner belt protons. In the later case one can expect to get a half-life of less than a day if the predicted effect is present.

Apart from the diurnal variation in exospheric density, some day to day variations in density are also observed, and it will, therefore, be worthwhile to try to correlate these with the day to day variation in intensity.

One can also expect long-term or 11 year variations in inner zone intensity if the neutron albedo produced by galactic cosmic rays is the main source of inner belt protons, and atmospheric losses are the main loss processes. This is due to the fact that changes in the upper atmosphere density occur during the solar cycle, with a phase opposite to it. One then expects an overall increase in flux values towards the solar minimum as the source strength increases (11-year change in cosmic ray intensity) and the same time the density of the upper atmosphere decreases. The effect will again be most pronounced in the B-L region corresponding to the minimum altitudes.

The study of the long-term variation in the inner radiation belt requires flux values from two or more different periods in the solar cycle. In this case it was possible to use Explorer IV data (McIlwain, 1961) because the detector on it was similar to that on the Ariel. Both the detectors were Anton 302 counters and the shielding and energy thresholds were as follows. In the direction in which the amount of absorbing material for the Ariel detector was a minimum, the counter was effectively shielded by 0.73 gm/cm^2 Eccofoam, 1.13 gm/cm^2 lead, 1.01 gm/cm^2 aluminium and 0.4 gm/cm^2 iron. Electrons with energies of 7.4 and 10.5 MeV had probabilities of direct penetration of 10% and 50% respectively. The corresponding threshold for protons was 50 MeV. The response of the counter to electron bremsstrahlung was very low and the efficiency for γ -ray detection was about 0.4%. The product of counter efficiency for charged particles and the omnidirectional

geometrical factor was $\sim 0.5 \text{ cm}^2$. The proton threshold for Explorer IV detector was 43 MeV. The correction for this difference in threshold has been made by using a differential energy spectrum of the form $E^{-1.7}$ (Elliot, 1966). The correction turned out to be very small.

2.4. Choice of Co-ordinate System.

To arrange the data in a readily comprehensible system of coordinates, McIlwain's L-values will be used here. The array of data points obtained by the Ariel I detector have each been assigned a particular L-value, according to the geographic position represented by latitude, longitude and altitude. The concept of L-values was first put forward by McIlwain (1961). The Earth's field differs from any possible dipole representation by more than 20% at the surface, and 4% at a geocentric distance of 3 Earth radii. Use of a pure dipole coordinate system, therefore, gives a confused picture. The points in space which have the same values of B and the longitudinal invariant, I, form a ring in each hemisphere. Thus particles mirroring at two points with the same B-value will trace out a complete shell around the Earth as they drift in longitude. This magnetic shell is labelled by L and the parameter L is defined in such a way that if the magnetic field of the Earth was a perfect dipole field, a magnetic shell would be labelled by an L equal to its equatorial radius. The orbit of any trapped particle can, therefore, be defined entirely by two quantities: the L-value of the shell on which particles are drifting and the magnetic field value B at the mirror points.

2.5. Plan of Analysis.

With the coordinates B and L we have the counting rate $R = R(L, B, t)$, and the recorded data are reduced to a two-dimensional array in terms of the positional coordinates. In the array we regard B as the variable and L as the parameter to classify the data.

The analysis was planned in the following way :

a. Particular magnetic shells were selected, which have values of L corresponding to the lower layer of the inner belt. The values of L selected were $L = 1.130$ to $L = 1.180$ by steps of 0.01.

b. The counting rates at those L-values were tabulated along with the B-values at those points and the time t.

If the view that B and L are sufficient for describing the distribution of the trapped particles is correct, we must find the counting rate R to be a single-valued well-defined function of B for each value of L. Departures from such a relationship would be regarded as due to the time variation at that value of L.

2.6. Analysis of Observational data.

Pizella et al. (1962) showed that it is quite valid to assume that the time variations in their case are of such a nature as to simply translate the curves of $\log R$ against B/B_{eq} vertically, without change of slope i.e. for a given L, R changes by the same factor irrespective of B/B_{eq} . This is assumed to hold in the present case. The assumption

mentioned above can be employed explicitly to eliminate B as a parameter and thus to reveal long-term variations, in which only one parameter, L, is retained.

The analysis was developed through the following steps:

- a) LogR was plotted against B for each selected L, for the entire period, a representative curve being shown in Fig. 11. The number of data points thus obtained in the plane (logR, B) were fitted by polynomials such that the analytic expressions were obtained for the reference curves

$$\log R = f(B, L)$$

with L as a parameter having discrete values for the various members of the family of curves.

- b) Employing the assumption stated above, all counting-rate data for each L for the entire period of observation were 'reduced' to a common value of B, specifically $B = 0.214$ gauss, by means of the following expression.

$$R(t, 0.214, L) = \exp [\log R(t, B, L) - f(B, L) + f(0.214, L)]$$

This procedure corresponds, from a graphical point of view, to moving, in the plane (logR, B), the point $\log R(t, B, L)$ parallel to the reference curve $R = f(B, L)$ until it comes to the value of $B = 0.214$ gauss. The quantity $R(t, 0.214, L)$ is called the reduced value of $R(t, B, L)$.

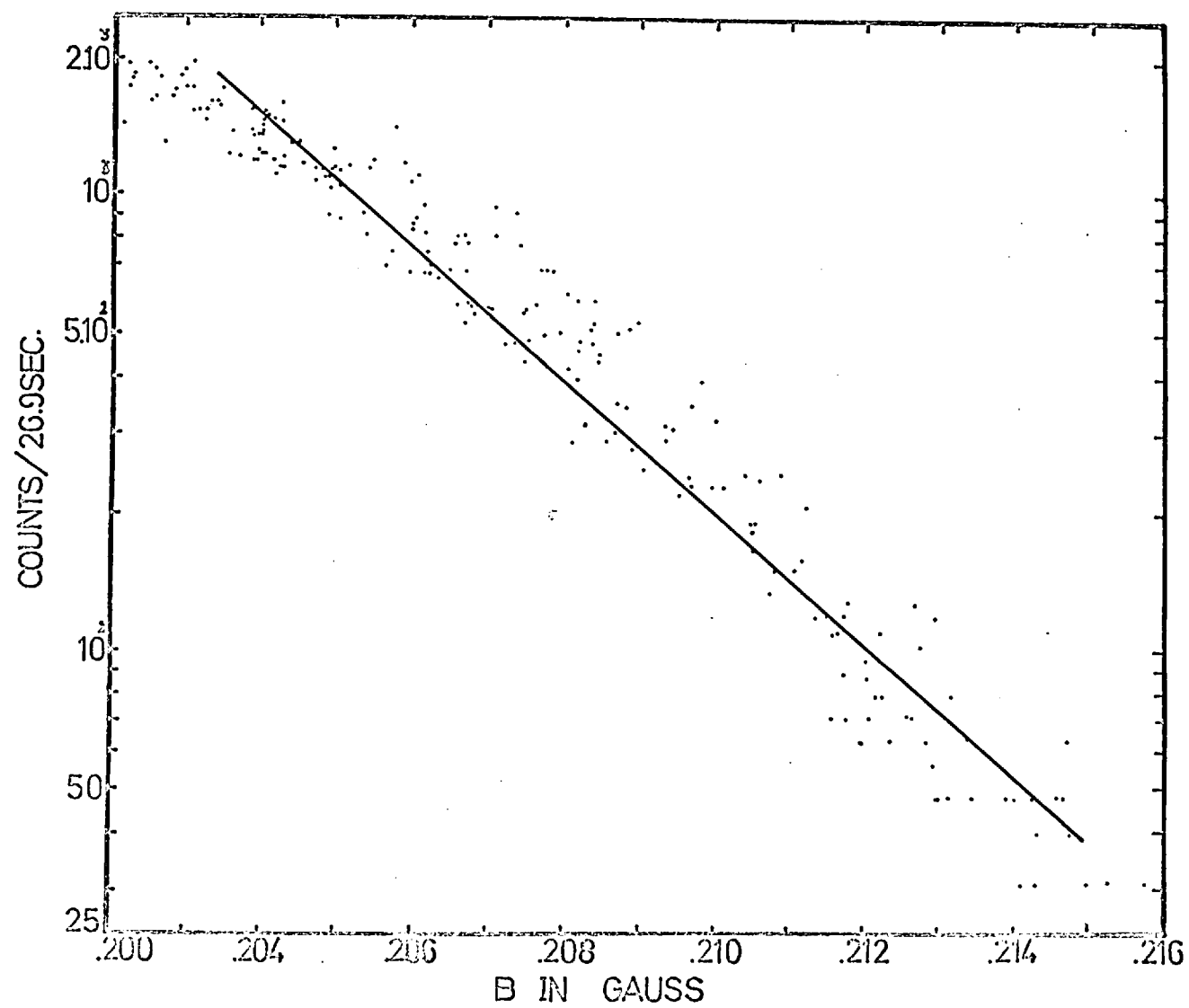


Fig.11. Variation of Geiger Counter rate with B, at L=110

At the end of these operations all data were reduced to a common value of B and were thus only a function of t for each L .

Calculations necessary for the above analysis were carried out with an Elliott 803 computer. Counting rates obtained above $B = 0.200$ gauss were eliminated because of the saturation of the Geiger Counter. Also the counting rates at and below $16/26.9$ sec. were ignored to eliminate the cosmic ray background. The background rate at each L -value, in this case, was obtained from the cosmic-ray latitude spectrum given by A. Engel (1964) who used the data recorded with the same counter.

The reduced count rates at each hour of the day were then tabulated. Averages of these counts, obtained at the same hour on all days, were taken, and 24 data points were obtained in this way for the investigation of the average daily variation in the period considered. Daily averages of these counting rates were used to find any long-term variation in the same period.

The final results of the foregoing analysis are given in Fig. 12a, Fig. 12b, and Fig. 12c and Fig. 13. The daily variation curve is plotted in terms of universal time and then transferred to the local time of Singapore, as shown in Fig. 14. This is done to correlate this variation with the pressure-wave in the equatorial region around the height of observation. The only information obtainable about the pressure-wave was that from wind-velocity measurements in the F-2 region over Singapore. In Fig. 12a the 'reduced' and averaged counting rates are plotted as a function of days, for each of the values of L , and Fig. 13 gives the counting rates normalized to the average

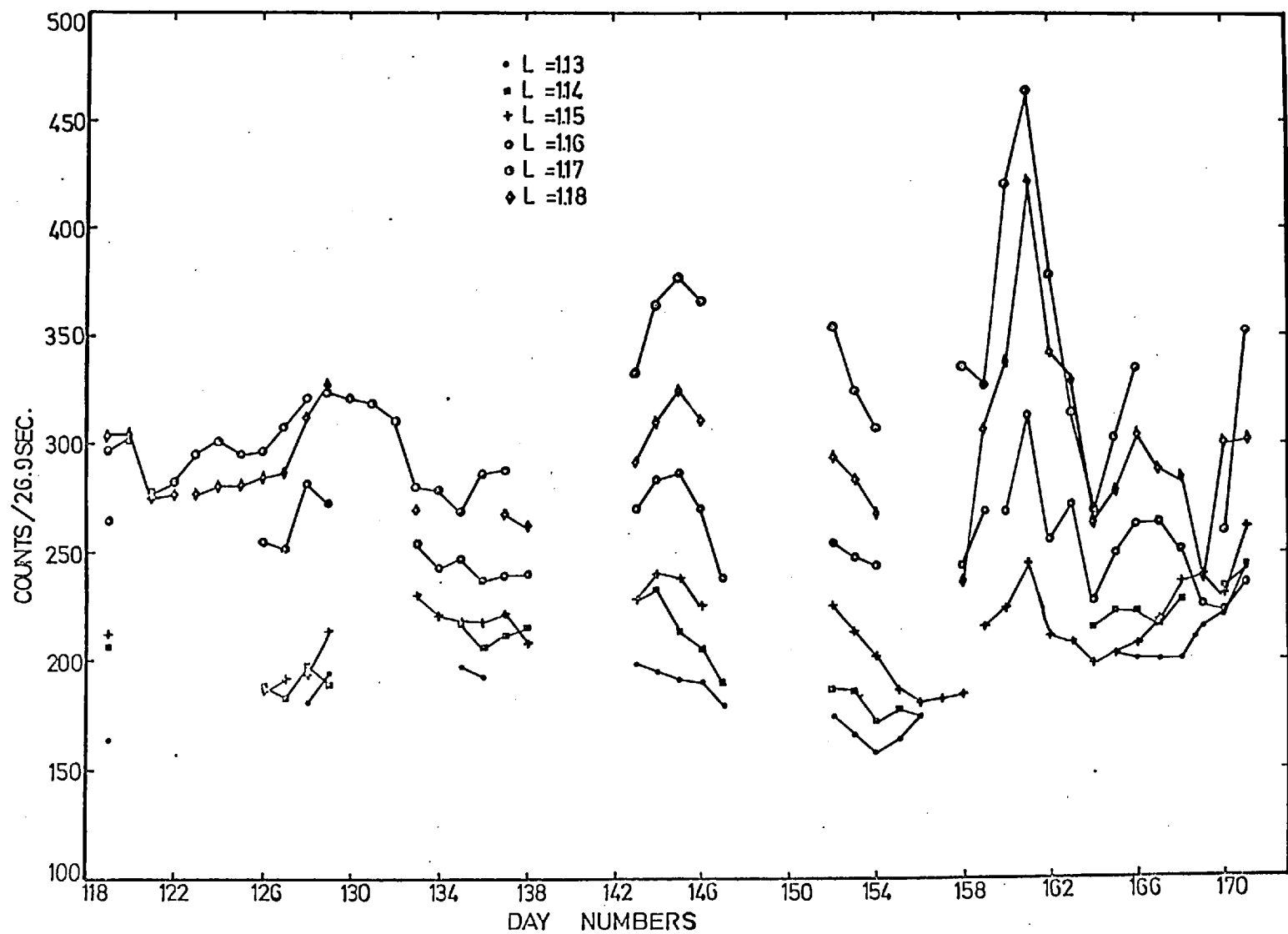


Fig.12a. Reduced count rate at different L's as a function of time.

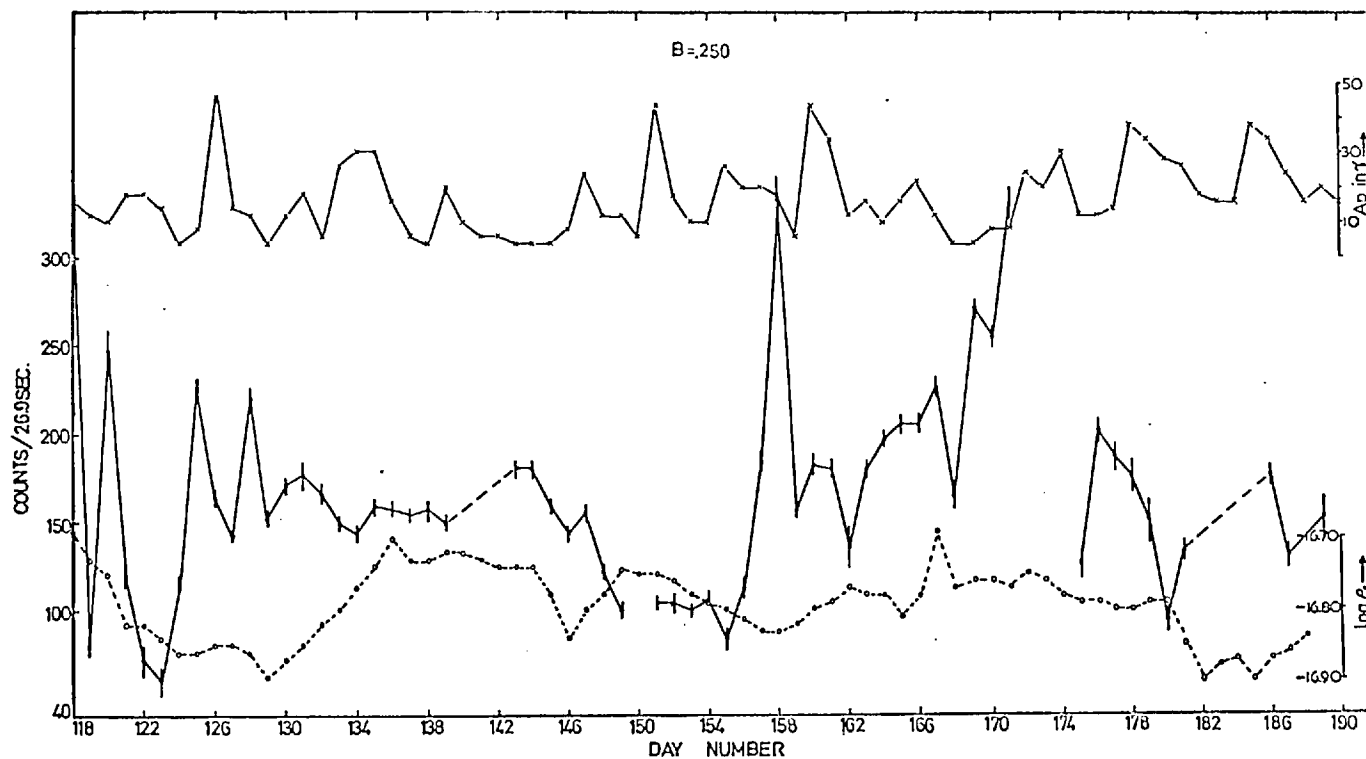


Fig.12b. Reduced count rate at L=155 as a function of time.

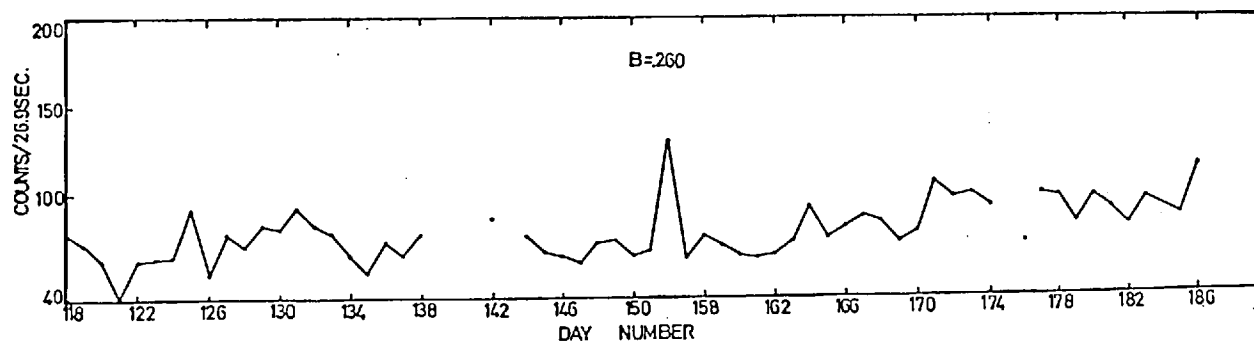


Fig.12c. Reduced count rate at L=200 as a function of time.

value for all L's. In Fig. 13 we also plot the daily averaged A_p values, and the values of $\log \rho_s$. Here ρ_s is the density at a standard height obtained from the satellite-drag data of the period of this investigation, the data being supplied by King-Hele (private communication).

Correlation coefficients were calculated for counting rates at each of the L-values, with A_p and $\log \rho_s$. The correlation coefficients with density were found to vary from negative to positive as L increases and the correlation coefficients with A_p -values varied the opposite way. However, when the coefficients were tested for their significance, they had to be rejected as insignificant. This was confirmed by the fact that no correlation of A_p or $\log \rho_s$ with the L-averaged values of the counting rates (all normalized to the average counting rate at $L = 1.18$) was apparent. The storm-time relation between ρ and K_p , as given by Groves (1961) did not seem to give any significant correlation between them at the period of our observation, even with higher group of ΣK_p -values.

Outer Zone.

Counting rates at several L-values, corresponding to the regions occupied by the outer zone, and in different intervals of B-values, were plotted as a function of day numbers to find any time variation in the outer zone. Starting at $L = 3.5$ examination of data was carried out up to $L = 7$ and at each L-value, several regions of B were chosen. It was found that a definite pattern in the day-to-day variation comes out, this being most pronounced in the region of the 'horn'

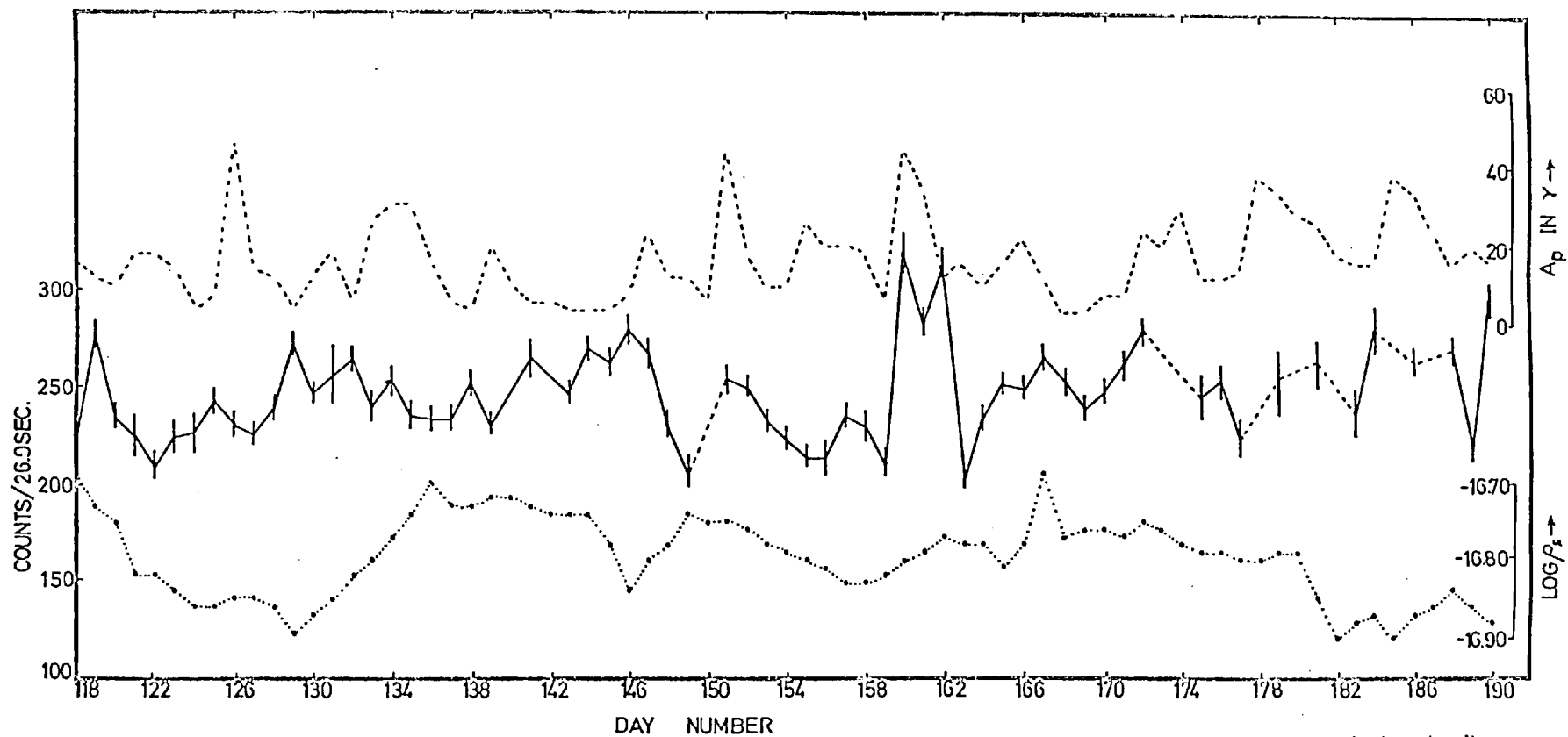


Fig.13. Day to day variation in intensity of the lower layer of the inner belt and its correlation with exospheric density and solar activity.

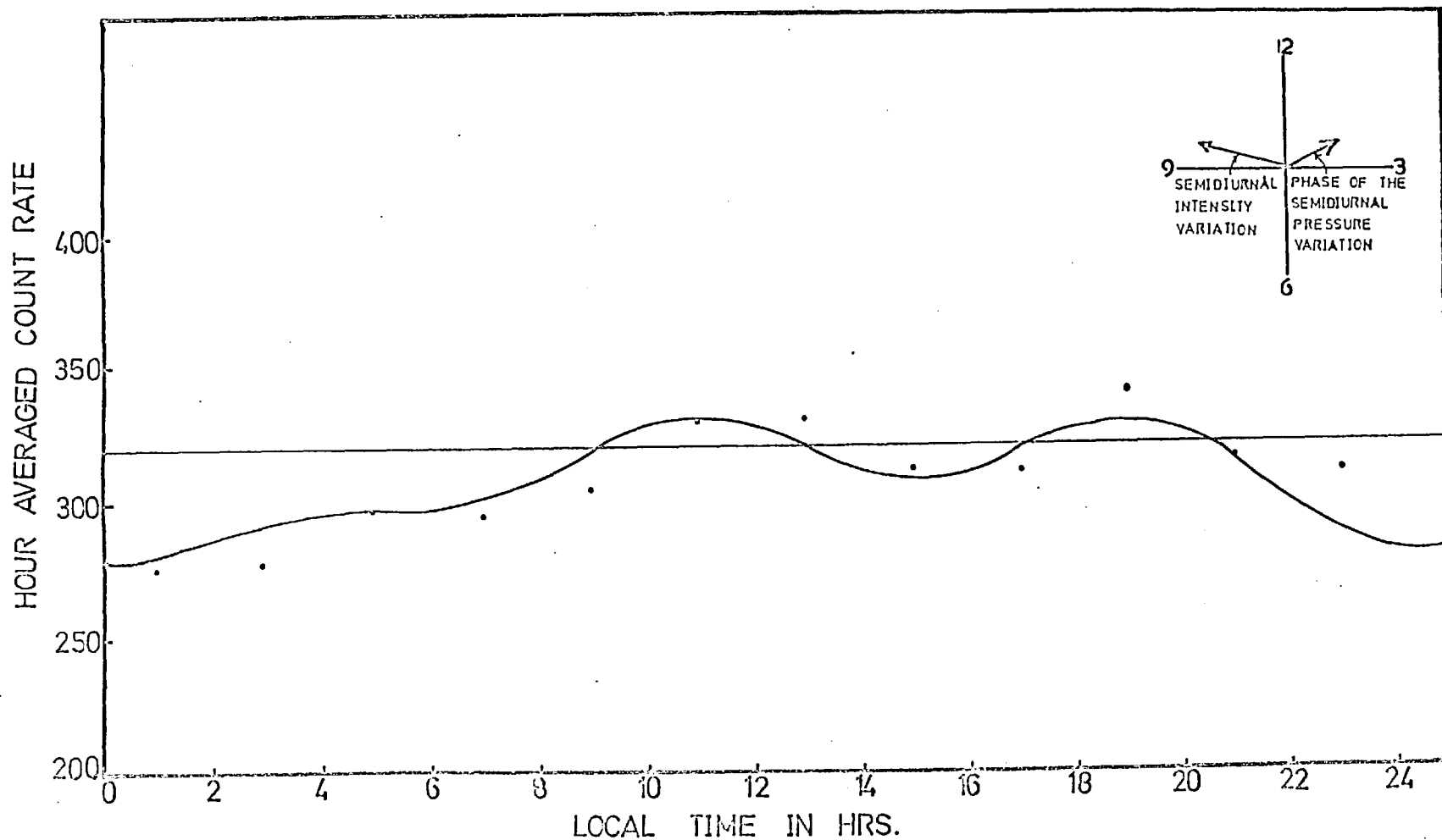


Fig.14. Daily variation of the lower layer of the inner belt.

which leads to the heart of the outer zone ($L \sim 4.5$ e.g. Engel, 1964). The amplitude of the variations fall off as one goes towards the higher or lower value of L , from the above mentioned value, but the nature of the variation remains the same. The variation at $L = 4.55$ and $B = 0.400$ gauss is shown in Fig.15.

The region of maximum intensity of the inner zone was also examined to see whether any time variation of the intensity was apparent in this region which could relate to that in the outer zone. To do this a very small range in L was selected (e.g. $L = 1.5$ to 1.6). It should be possible to obtain a smooth curve for only spatial variation of the counting rate. As the data, when plotted against B , showed quite a large scatter, attempts were made to find any day-to-day variation there. The counting rates corrected for B and reduced to the values at $B = 0.25$ gauss showed a day-to-day variation of $\sim 40\%$, four times as much as in the lower layer of the same zone. But the variation here had no similarity with that in the outer zone, and no correlation with A_p indices or density values could be found either. The same analysis was carried out further for $L = 2.00$, where the variation was again found to be very small.

To verify that whatever variation was obtained in the outer zone, did exist, B -values were plotted against day numbers to find any grouping in B which could give rise to spurious time variations. But the points indicated no correlation between B and day numbers.

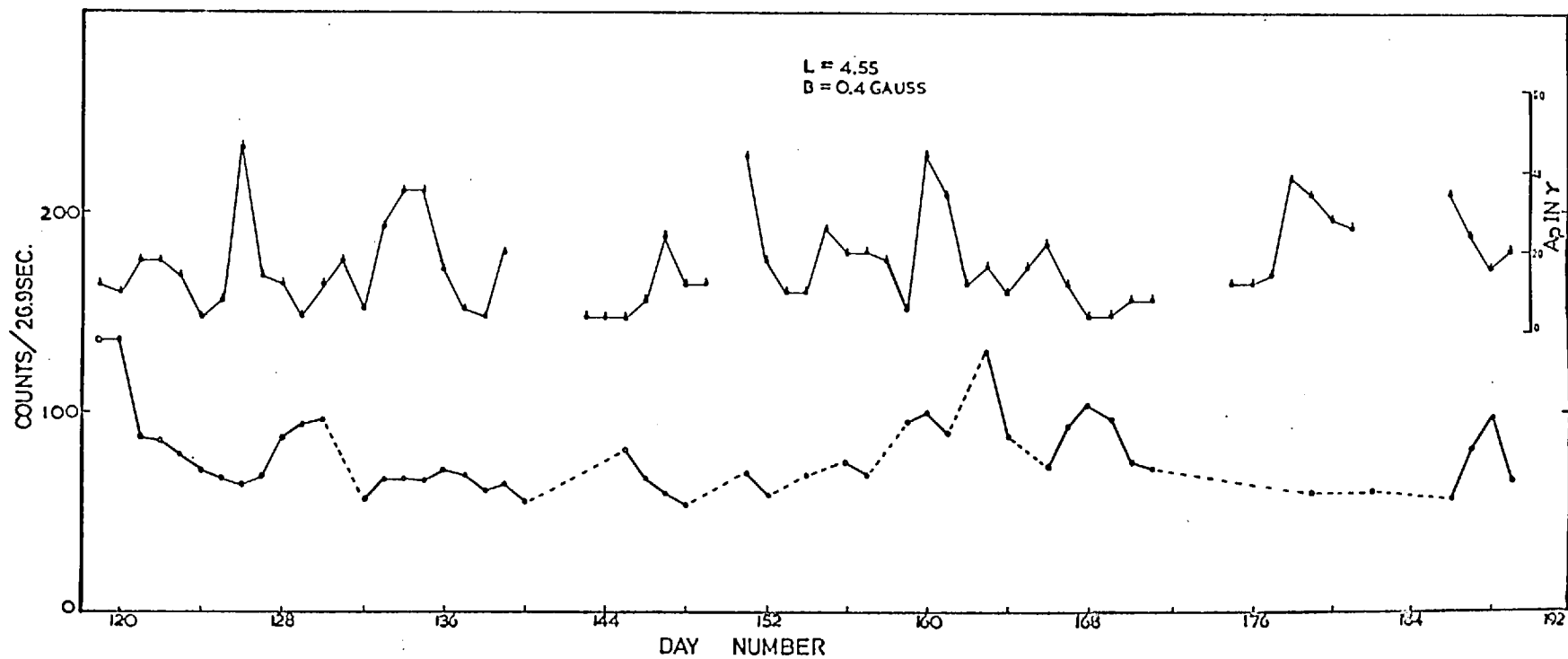


Fig.15. Day to day variation of the intensity of the outer belt.

The Flux Contours.

Counting rates of 3/sec, 10/sec., 30/sec, and 50/sec. were plotted in B-L coordinates to get the flux contours of the inner belt for the period of observation.

To get the time-averaged curves, contours were drawn for two different times in the total period and final contours for May & June, 1962, were obtained. These were compared with those obtained from the unshielded Geiger counter on Explorer IV (McIlwain, 1961). The Ariel contours, as shown in Fig. 16, indicated that the inner belt proton flux remained the same or even decreased from 1958 values. Fig. 17 shows the same contours in R- λ space.

2.7. Discussion of Results.

In the period of 27th. May to 8th. June, 1962, the intensity of Van Allen particles in the inner zone was found to be reasonably stable. The lower layer showed only a 10% variation while the heart of the inner zone showed a 40% variation in day-to-day averages. As the 'slot' region showed such a small variation, the larger variation in the heart of the zone is perhaps because of the higher proton flux present there. Nowhere in the inner zone is the variation in intensity related in any way, to that of A_p indices or exospheric density.

In the outer zone also the intensity variation is uncorrelated with the magnetic activities or density variations. The level of intensity here decreased by nearly a factor of 2 from day 117 to 140 and

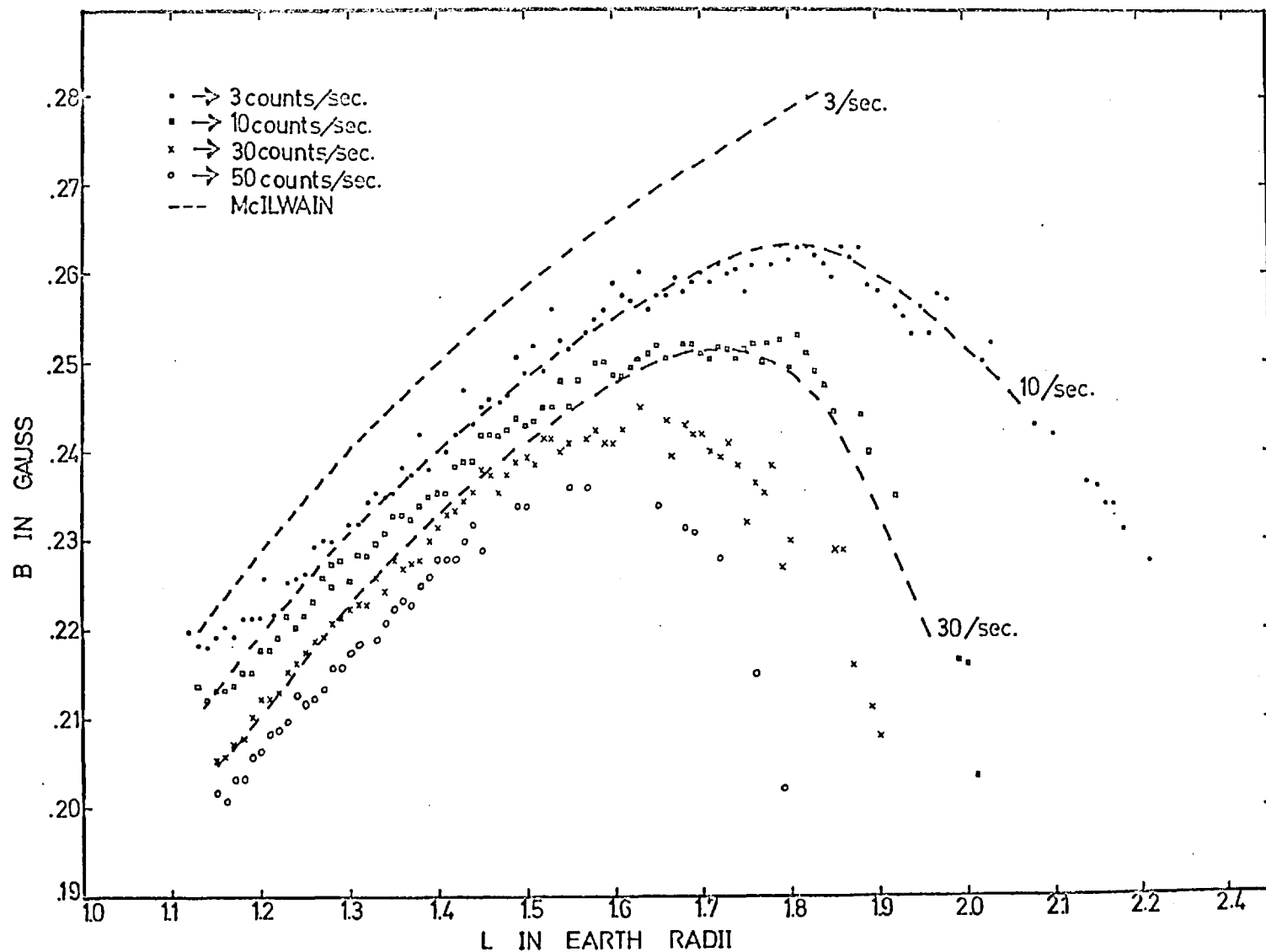


Fig.16. Omnidirectional constant count rate contours (Inner Belt) in L-B space.

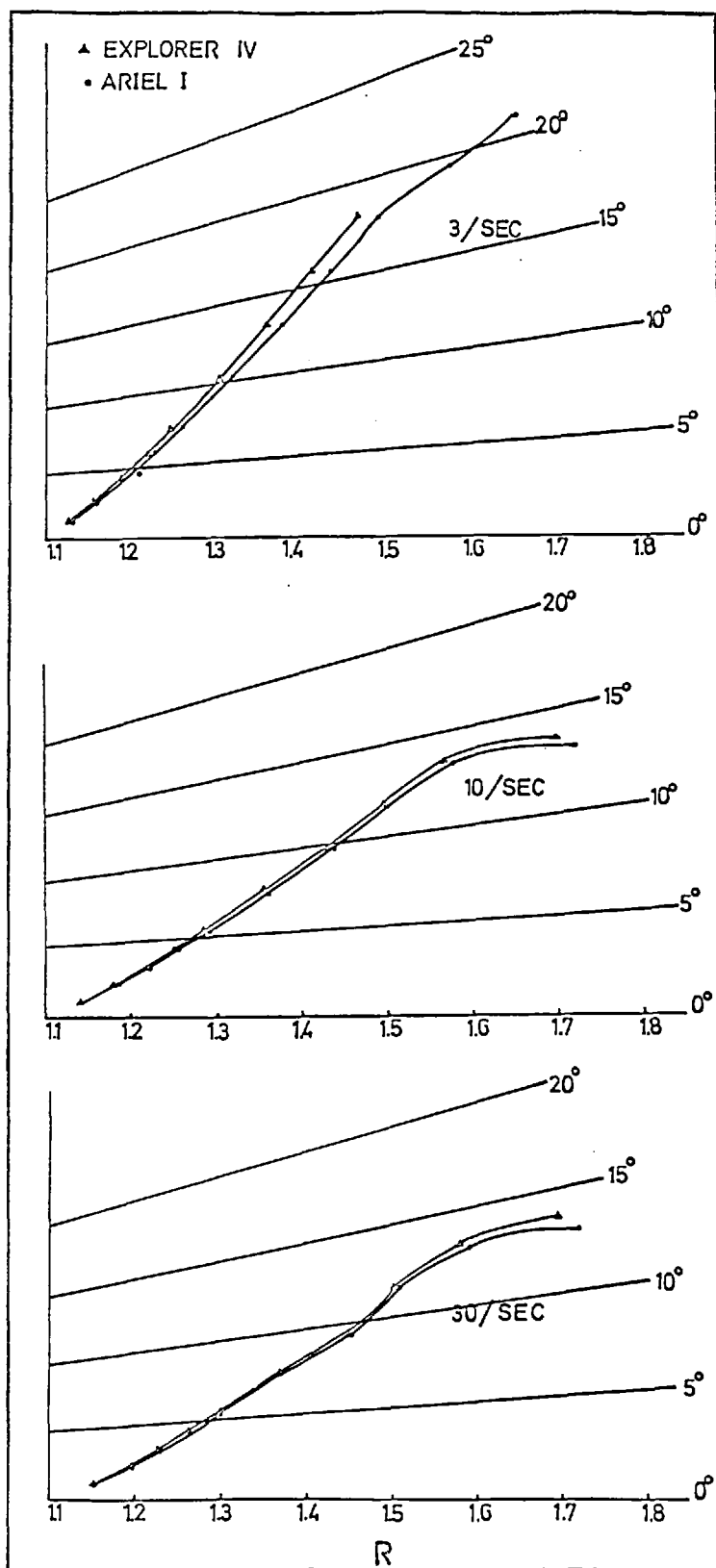


FIG.17. INNER BELT OMNIDIRECTIONAL COUNT RATE
CONTOURS IN R - λ SPACE.

showed an increase by a factor of ~ 1.5 around day 164, decreasing to the previous level after that. The initial decrease from a higher value of intensity is possibly the recovery from the enhanced intensity due to the magnetic storm proceeding the flight of Ariel (Engel, 1964). But the later increase could not be explained by any processes connected with solar flares or magnetic storms.

In the inner zone, the flux decrease from the value on 1958, most possibly indicates that the neutron albedo source is not the only one for the inner zone protons. Any real variation in intensity there, could be a reflection of the variation in this source.

CHAPTER IIIORIGIN AND LOSS PROCESSES OF THE INNER VAN ALLEN BELT.3.1. Introduction.

The general features of the stability of the inner radiation belt over a period of two to three months (Chapter II) led us to investigate the solar cycle variation, if any, in the inner belt. The objective is to see whether from the omnidirectional and unidirectional flux distribution of protons in the inner belt, one can obtain the trend and character of the long-term variation of the high energy (> 50 MeV) protons when compared with the data recorded at an earlier time in the solar cycle (McIlwain, 1961) at comparable spatial positions. One can then proceed, using the averaged atmosphere for trapped protons, calculated from the proposed model atmospheres (Cornwall et al., 1965; Harris and Priester, 1962; Johnson, 1962), to estimate the source strength of these protons and any variation over the solar cycle. Effort was made to confirm or predict any dominant loss mechanism for these protons.

As the atmospheric density has been found to vary with the solar cycle, the number of protons lost from the inner belt should vary accordingly if the atmospheric loss is the only loss mechanism active in this region. Also a variation of the source strength with the solar cycle will be expected if the galactic cosmic ray neutron albedo and the solar cosmic ray neutron albedo are the two main sources.

The galactic cosmic ray flux has a very strong negative correlation with the sunspot numbers. The source strength should, therefore, increase towards the sunspot minimum and the loss of the protons should decrease at the same time. An overall increase of the flux towards the sunspot minimum is, therefore, expected.

3.2. Historical Development.

Measurements and mapping of the inner belt intensities and its energy spectra at different positions in space, have attained increasing precision since the discovery of the belt in 1958 (Van Allen et al., 1958). As soon as the nature of these particles was established, their origin, their lifetime and thus the processes by which they are lost from the trapping conditions, became the main subjects of activity in this field. Three source mechanisms have been advanced so far, to explain the origin of these trapped particles (see Chapter II). The first source mechanism, suggested by Singer (1958), postulated that the trapped protons were the decay-products of the neutrons created at the top of the atmosphere by the galactic cosmic rays. The cosmic ray neutron albedo decay theory (Crand) was quite successful in explaining the early measurements. As the rockets (Bame et al., 1963) and satellites produced results from detectors of improved efficiency and energy resolution, three distinct components of the proton belt could be distinguished namely, the high energy, the medium energy and the low energy components (Kellogg 1963).

The high energy component was found by some authors (Blanchard and Hess, 1964; Vernov et al., 1964) to be explained by the Grand source and others (Walt and McDonald, 1964; Pieper et al., 1965; Fillius, 1966) found the source to be extremely weak or inadequate. An attempt was made to explain the medium energy component on the solar proton albedo neutron decay (Spand) theory, because, then, it would have been possible to find the cause for their different spatial distribution. Lenchek and Singer's (1962) calculation showed this source to be again too weak (a factor of ten) to account for the part of the spectrum observed by Naugle and Kniffen (1961). Davis and Williamson (1963), Bame et al. (1963) and Fillius and McIlwain (1964) have shown that the spectrum rises steeply to very low energies having an enormous number of particles of 100 keV. This is not at all possible for an evaporation spectrum with a temperature of 1.5 MeV that would be expected of neutrons (Kellogg, 1963). Then the low energy portion will be further reduced because their lifetime is shorter. The calculation of 'Spand' also showed that no particles could be trapped below $L = 1.7$, and mirroring on the equator below $L = 3.5$ is not allowed. But both of these points were found to be untrue by Fillius (1966). Only the 10 MeV protons observed by Nerv at low altitudes (Naugle and Kniffen, 1961, 1963) could be explained by Spand.

Fillius (1966) examined all the data he obtained from Relay I measurements of the inner belt proton energy spectrum in the energy

range 1.1 to 63 MeV. He concluded that Grand source is inadequate by a factor of 10^4 at 1 MeV. Walt and McDonald (1964), after examining the influence of the earth's atmosphere on trapped protons and using the experimental data of McIlwain et al. (1964), concluded that in the energy range 18-35 MeV, at $L = 1.5$, either the source function is more complicated than the simple Grand source or the atmospheric collisions are not the only loss processes in this region. Zmuda et al. (1965), after a thorough study of the changes of the inner belt proton events, concluded that protons of energy $1 \text{ MeV} < E < 15 \text{ MeV}$ and $E > 40 \text{ MeV}$ are not affected. Pieper et al. (1965), however, found that at low L-values and high B-values their data show a decrease over McIlwain's (1961) proton flux, in contradiction to the theory that the flux, ought in fact, to increase because of the solar cycle decrease of the atmospheric density.

Injection of particles at the boundary of the magnetosphere by the solar wind and their diffusion towards the earth, is the third source mechanism suggested by several authors [Kellogg (1960) and Parker (1960)] . To accelerate these particles to higher energy as they move inwards, it was suggested [Davis and Chang, 1962; Nakada et al. 1965] that the diffusion takes place under a condition where the first two invariants of particle motion remain constant but the third is broken. This has obtained some experimental support in that the phase density of the particles at the equator has been found to

decrease as the particles approach the earth. The interpretation here is that the source of these particles is outside the region of the measurements [McIlwain, 1964, private communication to Fillius, 1966].

Fillius (1966), when trying to explain their result, pointed out that if the position of the peak of a profile is plotted against the energy threshold of the individual detectors, a regular and uniform pattern is obtained over three orders of magnitude of energy. The extrapolation of this curve to the boundary of the magnetosphere gives the proper value for the energy of protons in the solar wind. This explained why they observed only high energy particles at the lower L-values. To explain the decrease of the density of particles as they go inward, they had to postulate that some protons diffuse inwards, gaining energy until they reach the atmosphere and are lost; others diffuse outward and are lost again at the boundary of the magnetosphere.

The different losses which operate in the inner proton belt have been briefly discussed in the previous chapter. Here the atmospheric loss mechanism plays the most important part. The ionization is the main process, nuclear collisions are important only above 100 MeV; charge exchange is important below 1 MeV and elastic scattering is negligible [Cornwall et al., 1965] . Different authors have calculated the average atmosphere effective for the trapped proton population e.g. Cornwall et al. (1965), Valerio (1964), Hassitt (1965). Blanchard and Hess (1964) have computed the solar cycle variation of this

averaged atmosphere and Cornwall et al. (1965) have computed 1959 and 1962 atmospheres and the mean atmosphere, by taking into account the Harris and Priester (1962) model atmosphere smoothed into the Johnson (1962) atmosphere towards solar minimum. Valerio (1964) has used the Anderson and Francis (1964) model atmosphere to compute the average atmospheres for two lines of force. Hassitt (1965) again used the Anderson and Francis (1964) model and the Harris and Priester (1962) model which are the same except their hydrogen content.

3.3. Averaging the Atmosphere.

Cornwall et al.'s calculated average atmospheres were chosen to be used here because they are suitable for Explorer IV (1959) and Ariel I (1962) data. In their calculation they have used two different fits to the Earth's magnetic field, the Jensen and Whitaker (1960) with 512 and Jensen and Cain (1962) with 48 coefficients. The trajectories of the particles were computed in these magnetic fields with the constraints that the particles must stay on shells of constant L and mirror at constant B as they drift around the Earth. At a fixed L, the mean atmospheric density was computed for bounce paths along a particular magnetic field line for several different values of B. The particles were drifted a few degrees and the process was repeated. A final average atmospheric density was obtained at constant L-B for one drift orbit around the Earth. S, the parameter

giving the solar activity level, was taken to be 200 for 1959 and 100 for 1962. The densities were given in electrons /cm³.

In the calculation for the unidirectional intensity with assumed neutron albedo spectrum, the average atmosphere (1959;1962) calculated with a B fitted by 512 coefficients was used. Although Cornwall et al.'s calculation applies to protons with energy range 5 to 100 MeV, use of their calculation in this case was justified, because, essentially, the detector was detecting protons in the range of 50 to 100 MeV.

3.4. Evidence from Ariel data.

The Ariel I Geiger Counter measured the omnidirectional intensity of the protons (> 50 MeV) in the inner belt at a number of L-shells, starting from the lowest one ($L = 0.981$). These omnidirectional counting rates were therefore used to determine the directional intensities on L-shells 1.20 to 2, at different mirror points along the magnetic field lines. All these field lines cut the surface at or below latitude 15° . The observations did not extend as far as the equator although a large region of space was explored.

Farley and Saunders (1962) give a simple but sufficiently accurate method for calculating the unidirectional intensity at the mirror point, perpendicular to the field line, from the omnidirectional intensity at various points along a line of force. The expression used is

$$j_{\perp}(B_m) = - \frac{(B_m)^{3/2}}{\pi} \int_{B_m}^{B_{max}} \frac{\frac{d}{dB} \left(\frac{J(B)}{2\pi B} \right) dB}{(B - B_m)^{\frac{1}{2}}} \quad (1)$$

where

$j_{\perp}(B_m)$ = unidirectional intensity perpendicular
to the magnetic field vector at the mirror
point B_m ,

$J(B)$ = omnidirectional intensity at a point
with field intensity B ,

B_{max} = field value at which the particle intensity
drops to zero,

B_m = field intensity at the mirror point.

For each L-value, the omnidirectional counting rates of the Ariel Geiger counter were fitted to a curve of $J(B)/B$ versus B . A polynomial fit up to the second coefficient was used for all sets of data. The differentiated form of these equations was fed into equation (1), and finally the equation was numerically integrated by using an IBM 7090 computer. Values of B_{max} were obtained graphically by plotting counting rates against B , for each L-value. A small error was perhaps introduced in

the calculation, by this process, but it was not estimated. The errors on the computed intensities were not given either, because of the difficulty of tracing them through the integral. The same operation was carried out with McIlwain's data. As only a comparison between the unidirectional intensities at fixed B and L values recorded at different times in the solar cycle was being made, these errors would not affect the interpretation and conclusions presented here.

The unidirectional intensities* obtained both from the Ariel data and from McIlwain's published data are shown in Fig. 18a to 18d. The B_m 's are the mirror-point fields; each curve corresponds to a particular value of L. It can be seen that the unidirectional intensities are consistently lower in 1962, at the same B-L space. This has already been observed in the case of omnidirectional count-rates. But in addition to that it can be seen here that at lower L-values, in the low B-region, the Ariel intensities are actually greater than 1958 intensities but gradually get lower than 1958 values as the cut-off values of B are approached. At higher L-values, 1962 intensities are lower than 1958 values throughout the B-region observed. But here again, near the equatorial region, the difference gets smaller, without any actual crossover occurring.

* The unidirectional intensities in counts/sec.ster., were converted to counts/cm².sec.ster., after taking into consideration the fact that the Ariel Geiger Counter had a geometrical factor 30% higher than that of the Geiger Counter on board the Explorer IV (Elliott, 1966)

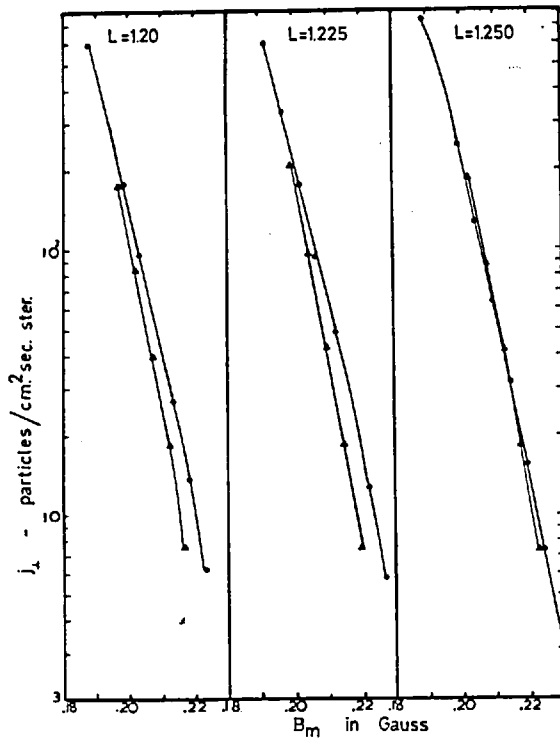


Fig.18a. Unidirectional intensities of Ariel I (>50 MeV) and Explorer IV (>43MeV) inner belt protons.

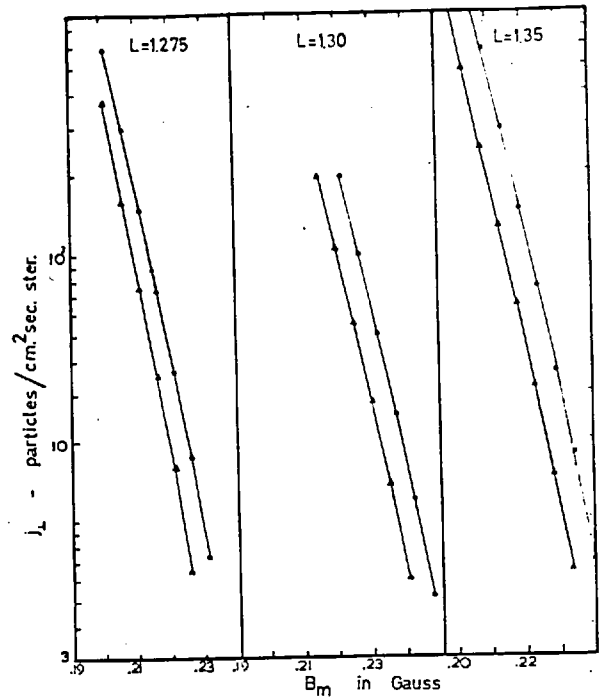


Fig.18b. Unidirectional intensities of Ariel I (>50 MeV) and Explorer IV (>43MeV) inner belt protons.

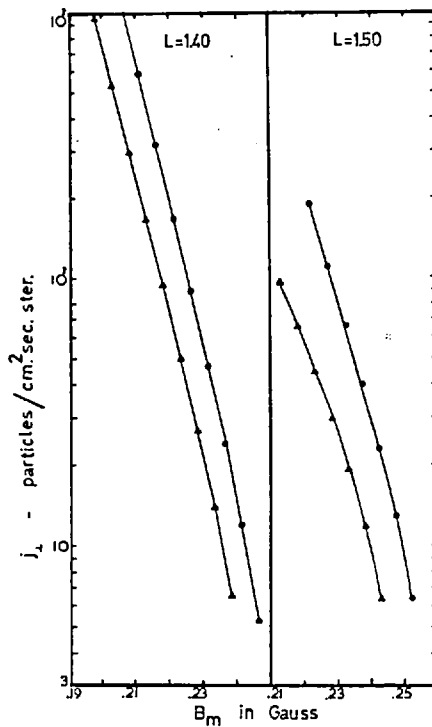


Fig.18c. Unidirectional intensities of Ariel I (>50 MeV) and Explorer IV (>43MeV) inner belt protons.

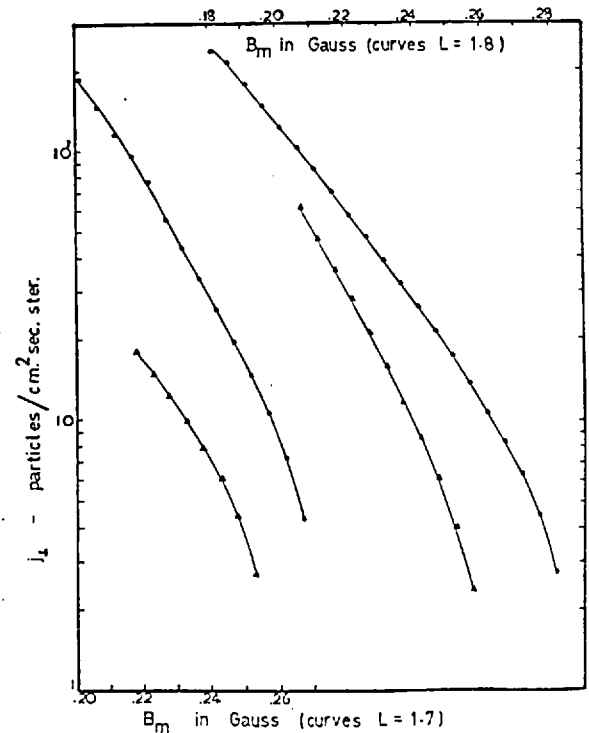


Fig.18d. Unidirectional intensities of Ariel I (>50 MeV) and Explorer IV (>43MeV) inner belt protons.

The lifetime of these particles may be obtained by imagining that the source is suddenly turned off and then calculating

$$T^{-1} = - \frac{\partial}{\partial t} (\log_e j_1) \quad (2)$$

Now, the continuity equation for proton distribution, with no source, can be solved for j_1 . Inserting the expression (2) into that equation gives (Dragt et al., 1966)

$$T = 6 \times 10^{11} \bar{\rho}^{-1} E^{1.3} \text{ sec} \quad (3)$$

Lifetimes obtained by putting the sunspot minimum densities and the mean densities into this equation and taking E to be 50 MeV, are given in Table 1; the L and B values are indicated.

The pitch-angle distribution of different L -values is given in Fig.19. This emphasizes the points made in a previous paragraph. At lower L -values the difference between the intensities is more at lower pitch-angles than at higher pitch-angles. At higher L -values this difference is more or less constant throughout. This agrees qualitatively with the lifetime calculation at higher B -values; the lifetime at these B -values (Table 1) is very short compared to the solar cycle.

Using Valerio's (1964) method for calculating the directional intensity of protons we obtained proton intensities perpendicular to the lines of force, as a function of L and B . Cornwall et al.'s (1965)

TABLE I

L in Earth radii	B in Gauss	$\bar{\rho}_{1959}$ in electrons /cm ³	T in years	$\bar{\rho}_{1962}$ in electrons /cm ³	T in years	$\bar{\rho}_{\text{mean}}$ in electrons /cm ³	T in years.
1.200	.205	2.7×10^7	0.11	2×10^6	1.52	1.3×10^7	0.24
	.210	5.0×10^7	0.06	4.5×10^6	0.66	2.23×10^7	0.14
	.215	1.05×10^8	0.03	1.15×10^7	0.27	5.0×10^7	0.06
	.220	2.6×10^8	0.01	3.8×10^7	0.08	1.15×10^8	0.03
1.300	.210	1.6×10^7	0.19	1.3×10^6	2.37	8.0×10^6	0.38
	.215	2.8×10^7	0.11	2.6×10^6	1.18	1.4×10^7	0.22
	.220	5.0×10^7	0.06	5.5×10^6	0.56	2.8×10^7	0.11
	.225	8.0×10^7	0.04	10^7	0.31	5.5×10^7	0.06
	.230	2.3×10^8	0.01	6.0×10^7	0.05	1.6×10^8	0.02
1.400	.210	-	-	6.0×10^8	5.13	3.2×10^6	0.96
	.215	-	-	9.5×10^5	3.20	5.5×10^6	0.56
	.220	-	-	1.8×10^6	1.71	10^7	0.31
	.225	-	-	4.6×10^6	0.67	1.9×10^7	0.16
	.230	-	-	10^7	0.31	3.6×10^7	0.08
	.235	-	-	3.2×10^7	0.10	8.0×10^7	0.04

-continued-

TABLE I -continued-

L in Earth radii	B in Gauss	$\bar{\rho}_{1959}$ in electrons /cm ³	T in years	$\bar{\rho}_{1962}$ in electrons /cm ³	T in years	$\bar{\rho}_{\text{mean}}$ in electrons /cm ³	T in years.
1.500	.220	-	-	6.7×10^5	4.60	4.2×10^6	0.73
	.225	-	-	1.2×10^6	2.56	7.5×10^6	0.41
	.230	-	-	2.5×10^6	1.23	1.45×10^7	0.21
	.235	-	-	7.3×10^6	0.42	2.40×10^7	0.13
	.240	-	-	1.9×10^7	0.16	4.80×10^7	0.06
1.800	.210	-	-	7.6×10^4	40.60	3.0×10^5	10.26
	.215	-	-	8.3×10^4	37.10	-	-
	.220	-	-	1.25×10^5	24.63	-	-
	.225	-	-	1.75×10^5	17.58	-	-
	.230	-	-	2.50×10^5	12.31	-	-
	.235	-	-	3.80×10^5	8.09	-	-
	.240	-	-	6.20×10^5	4.95	-	-
	.245	-	-	1.20×10^6	2.56	-	-
	.250	-	-	2.20×10^6	1.40	-	-
	.255	-	-	4.80×10^6	0.64	3.0×10^7	0.10

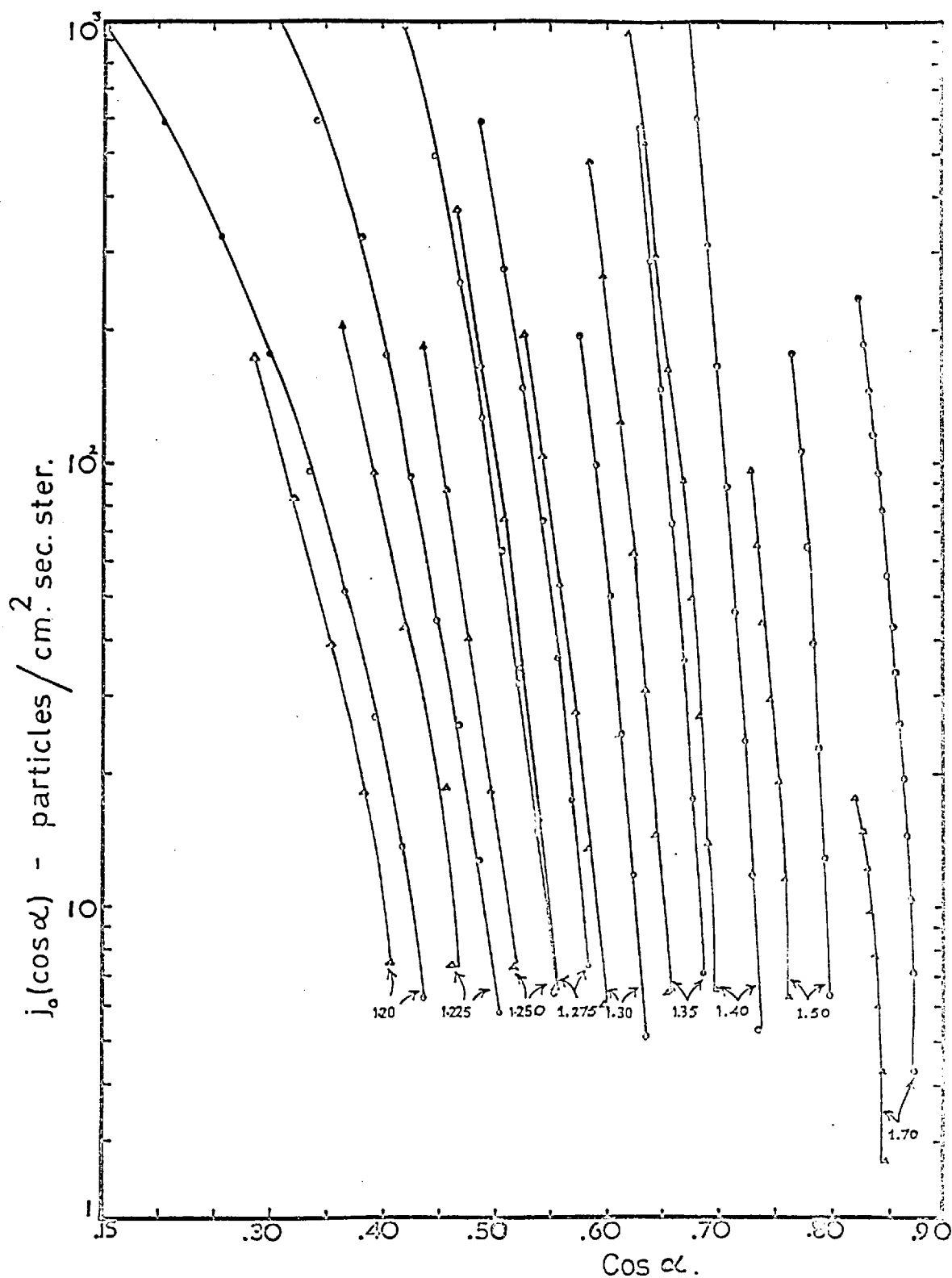


Fig.19. Pitch Angle Distribution of Protons from
Ariel I & Explorer IV.

averaged atmosphere for 1959 and 1962 were used for the above calculations. The ratio $f(L, B) = \frac{j_1^{(LB)}_{obs}}{j_1^{(L, B)}_{calc.}}$ can be considered here to be the fraction of decaying neutrons from 50 to 110 MeV which result in trapped protons. It is not identical to the neutron injection coefficient as defined by Lenchek and Singer (1962). With Explorer IV data these ratios for L upto 1.5, at all observed B-values show that the observed intensities are higher than those predicted by the neutron albedo source. Above L = 1.50 the ratios give quite reasonable values in regions far away from B_{max} and $B_{equator}$. The observed intensities near the cut-off region are much higher than the calculated ones and near the equatorial B-region (at higher altitudes) are much lower than the calculated ones. On the other hand, the ratios of $j_1^{obs(1962)}$ to the computed ones show, that the albedo source is in general weaker than that required for the whole range of L and B values.

In a recent paper Dragt et al. (1966) have given two quantities defined as the 'injection efficiency' X and the 'omnidirectional injection efficiency' X_0 , for the cosmic ray albedo neutron decay source. Their calculated values of X and X_0 could be used to compute the pitch-angle distribution and omnidirectional intensities of protons, along a line of force. The given spectrum in the expression for j_1 and J , was integrated over the limits 50 to 100 MeV. The values are given here in Table II at some particular L and B values where X and X_0 were available. It can be seen from Fig. 20 that both the solar cycle mean and the solar minimum intensities, computed in this way, are very much lower than the observed values.

TABLE II

J calculated						J observed
L in Earth radii	B in Gauss	$\bar{\rho}_{1962}$ in electrons / cm^3	$\bar{\rho}_{\text{mean}}$ in electrons / cm^3	$X_o \bar{\rho}_J$ ρ_{J1962} in $\text{cm}^2.\text{sec.}$	J_{mean} in $\text{cm}^2.\text{sec.}$	in $\text{cm}^2.\text{sec.}$
1.30	.205	7.0×10^5	4.6×10^6	.42 ~ 36	~ 5.45	~ 580
	.210	1.3×10^6	8.0×10^6	.35 ~ 16	~ 3.61	~ 302
	.220	5.5×10^6	2.8×10^7	.31 ~ 3.36	~ 0.66	~ 80
	.230	6.0×10^7	1.6×10^8	.28 ~ 0.28	~ 0.10	~ 20

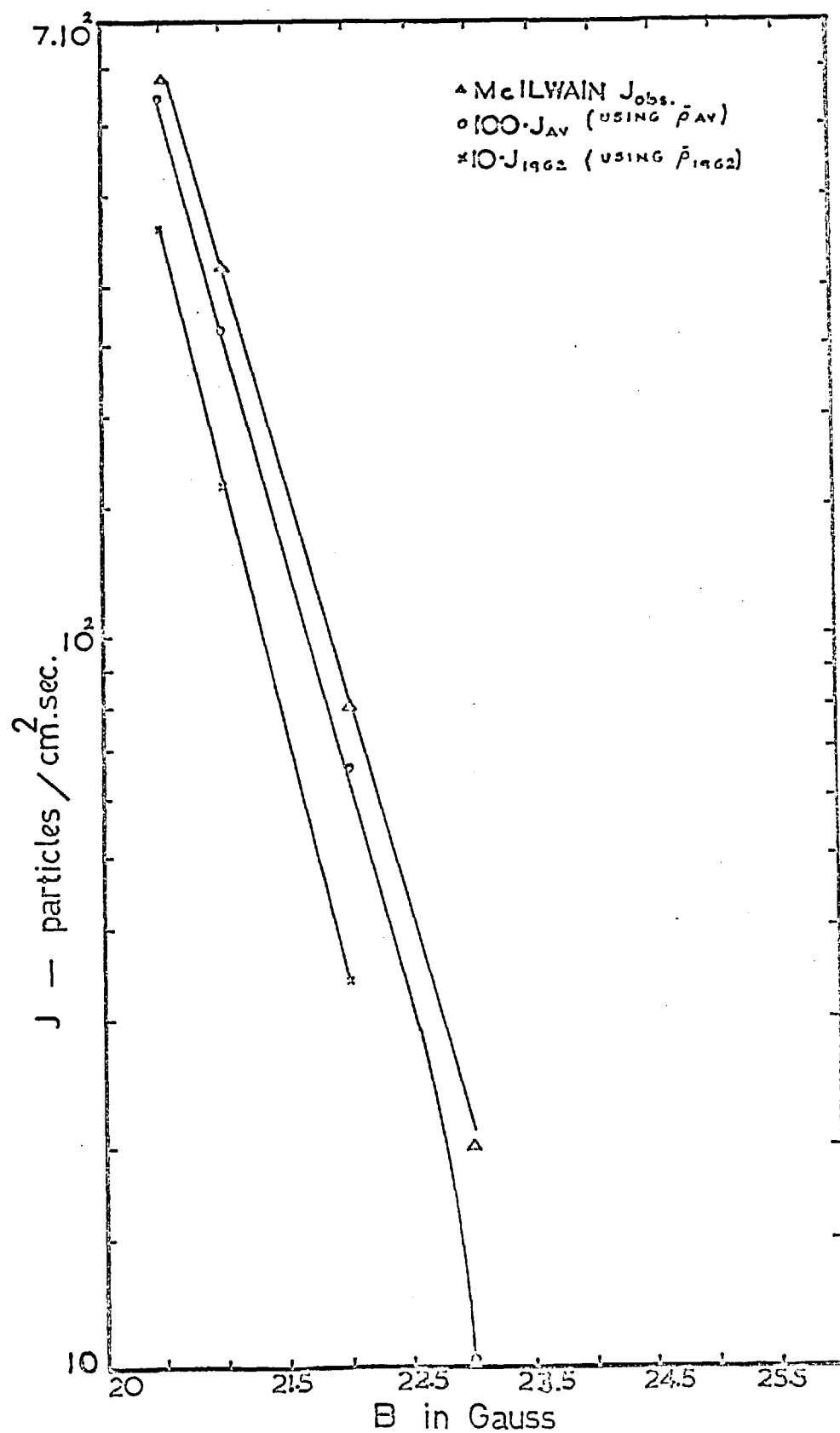


Fig.20. Calculated and Observed Intensities of Inner Belt Protons.

The decrease in intensity in the high energy proton population towards the sunspot minimum can be seen more clearly, if one plots the ratio $j_1(1962)/j_1(1959)$ at constant L 's against B_m , and also at constant B_m 's against L ; Fig. 21 and Fig. 22 give the respective distributions. It can be seen that at lower L -values the decrease is less, but the variation with B is quite steep. At higher L values the decrease is more, but the variation with B is practically zero. Fig. 22 emphasizes that at constant B -values the decrease is more at higher L -values than at lower ones. It also shows that, at constant B , the decrease is going the same way with increasing L , whatever the value of B . Thus keeping at a particular height, if one moves away from the equator, the decrease of j_1 from 1959 to 1962 increases and ultimately goes to an asymptotic value.

A comparison between $j_1(1959)$, $j_1(1962)$ and $j_1(1963)$ at $L = 1.8$ is given in Fig. 24, where Relay I results on protons with $E > 34$ MeV, in May to Sept., 1963, are plotted along with Ariel 1 and Explorer IV data. Taking the integral spectrum in this high energy region to be a power spectrum with an exponent of 0.7 (Elliot, 1966), the later values were corrected for the different energy thresholds of the detectors. Although 1963 values show an increase from 1959 values, it is still quite small for a period of 4 years in the solar cycle.

Keeping in mind that the source strength $\int s(E)dE$ is proportional to $j\bar{\rho}f(E)$, $j\bar{\rho}$'s were calculated for both 1959 and 1962. Fig. 23a and Fig. 23b show that across the L - B region, $j\bar{\rho}$ varies by two orders of magnitude, in both cases. The ratio of $S(E)$ to $j\bar{\rho}$ is expected to be

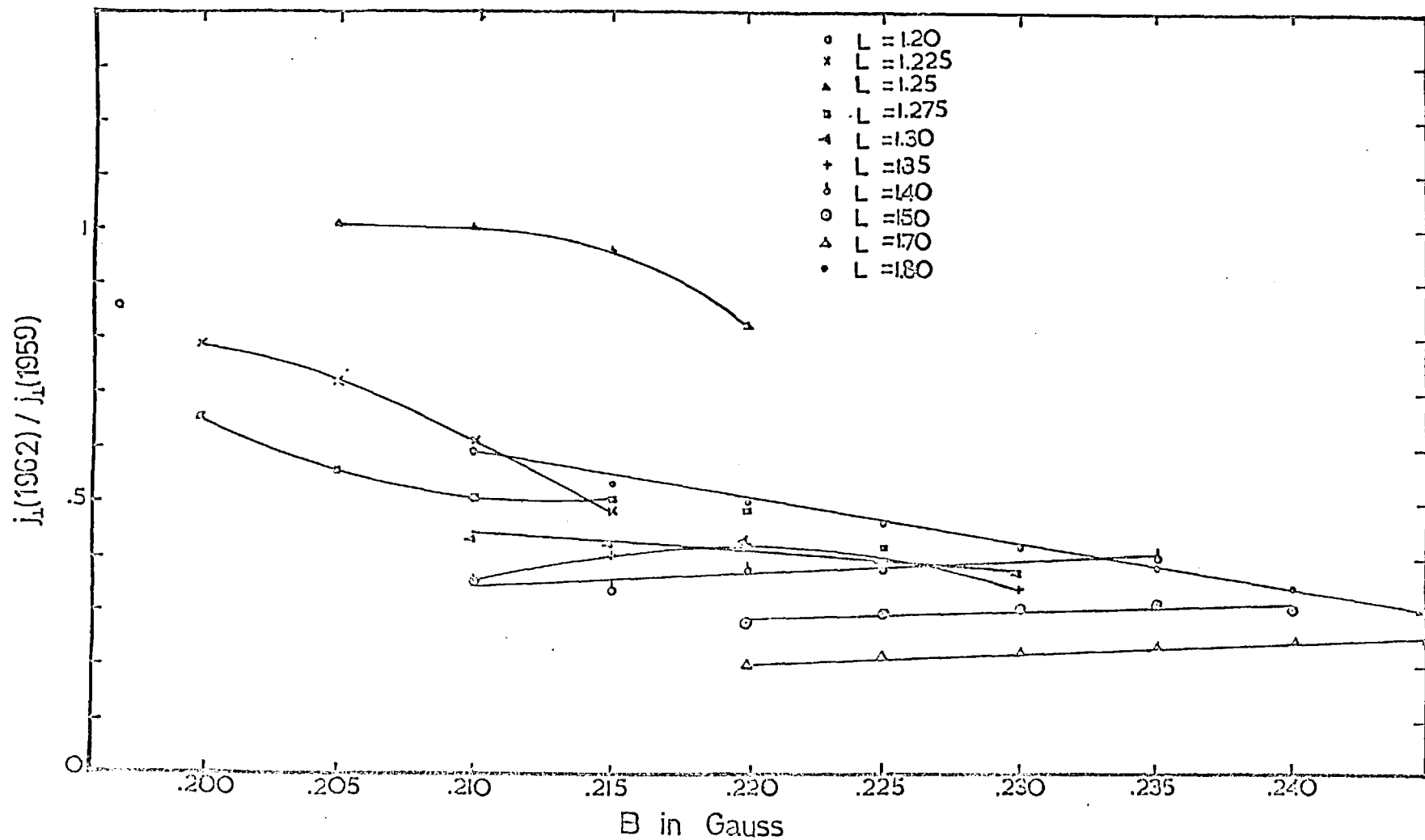


Fig.21. Variation of the ratio $j_L(1962)/j_L(1959)$ with B , at constant L 's

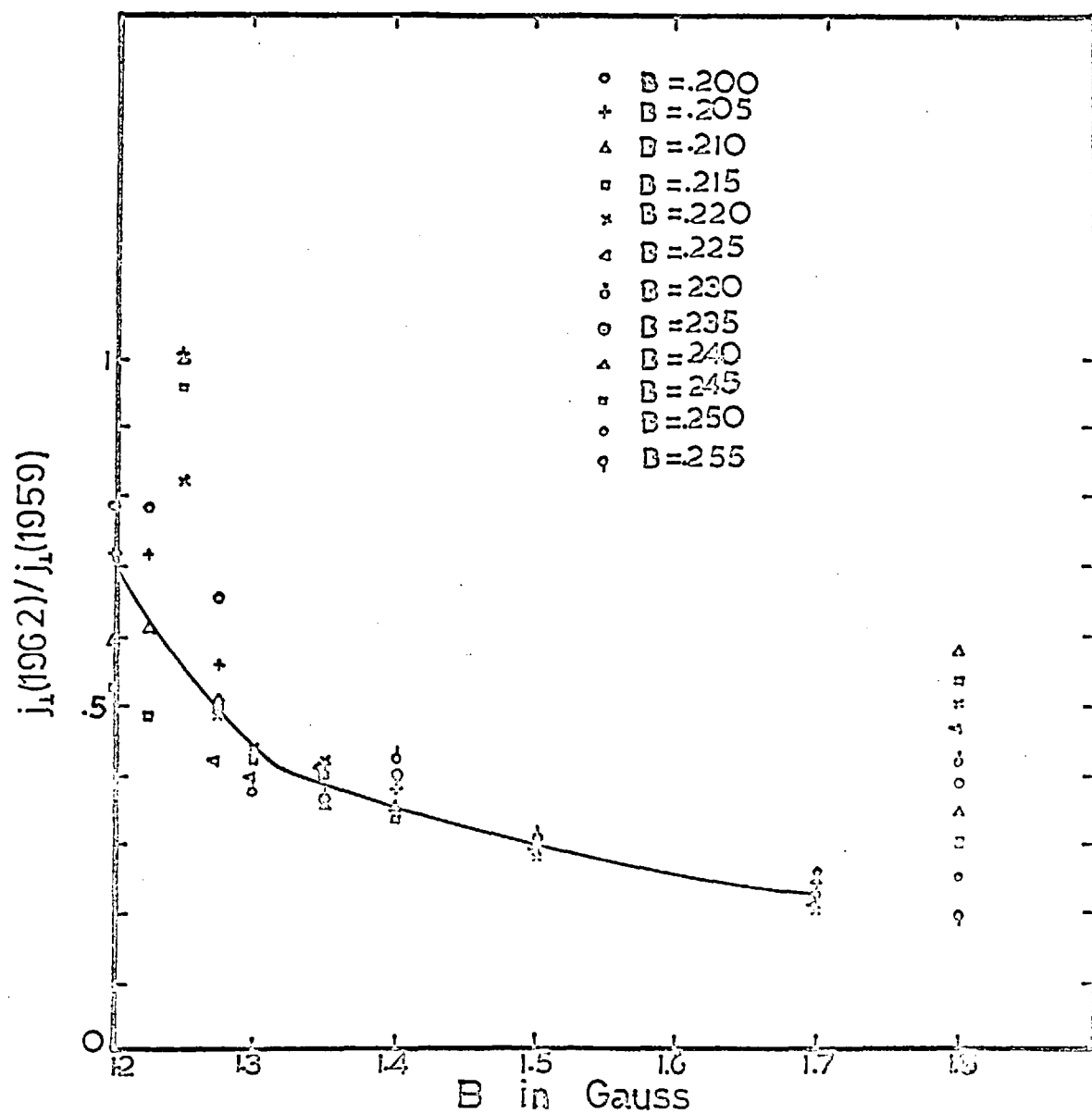
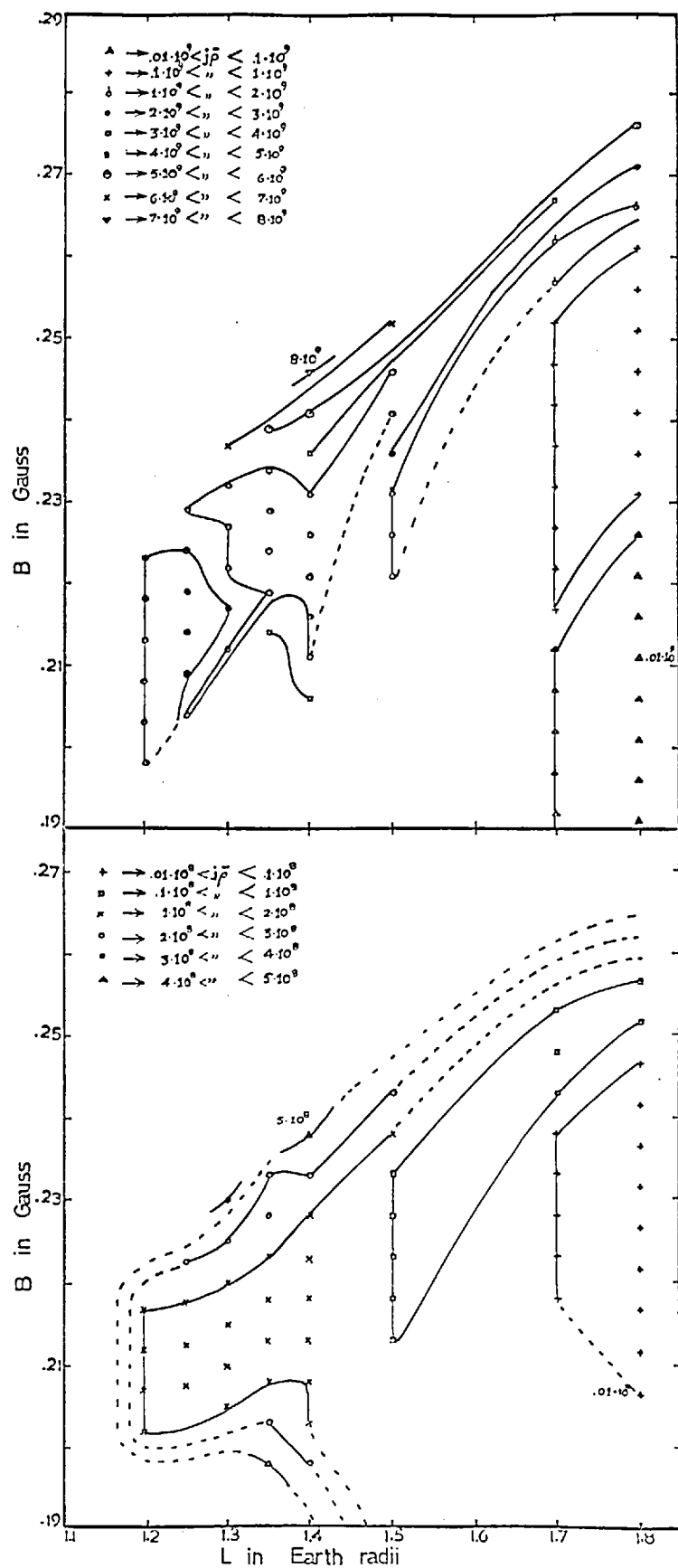


Fig.22. Variation of the ratio $j_L(1962)/j_L(1959)$ with L , at constant B 's.

Fig.23. Distribution of the product $j\tilde{\rho}$ in B-L space.

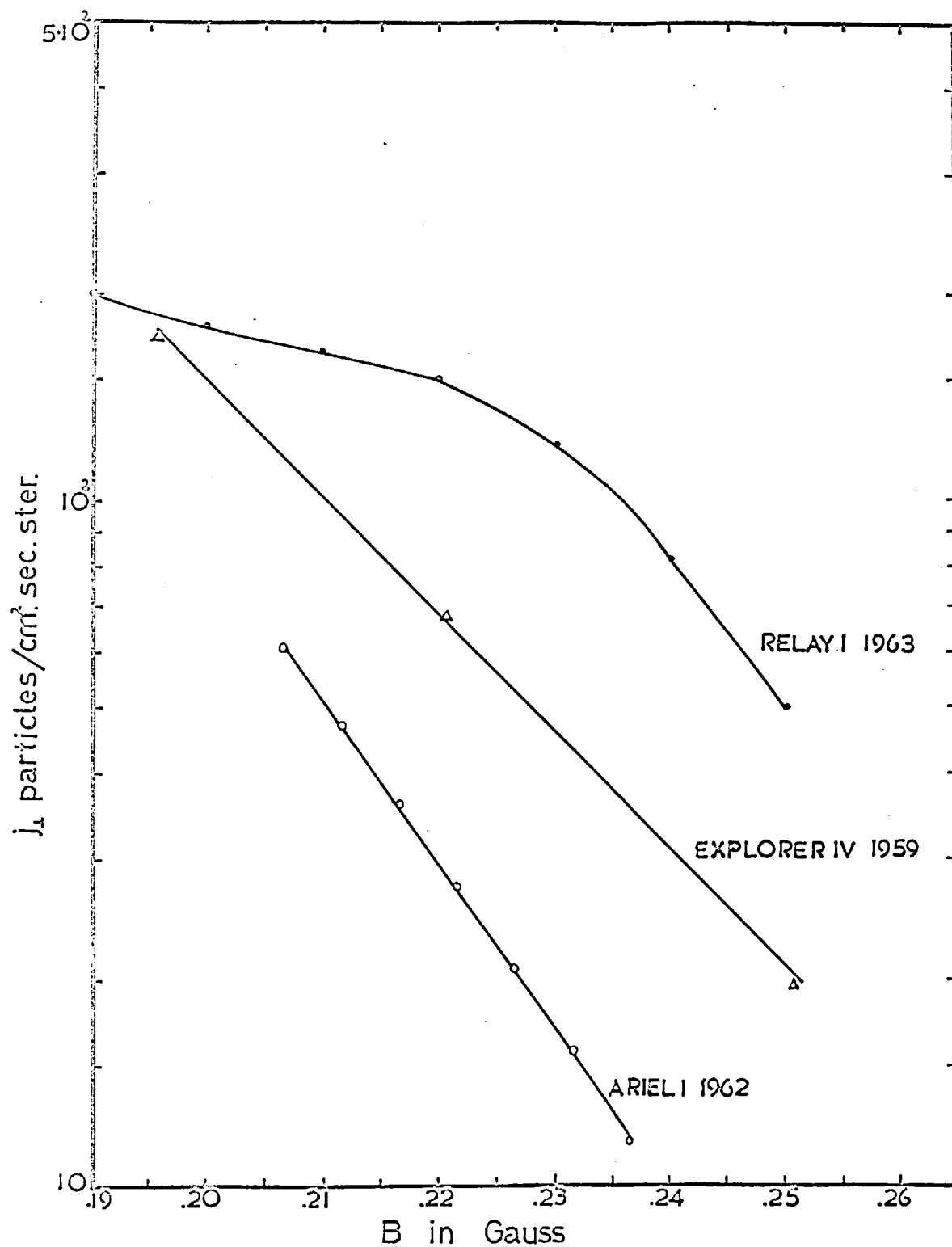


Fig.24. Unidirectional intensities of inner belt protons at $L=1.8$ (1959,1962,1963)

a constant in L - R space, if j is measured in a limited range of energy. In this case it is the integral intensity which is measured, and, therefore, it is difficult to say whether this variation in the j values is due to a variation in the energy dependence term, $f(E)$ or not. Apart from this it is also apparent that $j\bar{\rho}(1959)$ is one order of magnitude higher than $j\bar{\rho}(1962)$. Here, either the source strength or the loss processes or both must have contributed towards the variation of $j\bar{\rho}$ in the solar cycle.

Attempt was, therefore, made to fit the source function $S(E)$ (which is proportional to $j\rho$), to a sinusoidal wave with a period of 11 years. The only information on $S(E)$ available here is that the ratio $j\bar{\rho}(1962)/j\bar{\rho}(1959)$ is of the order of 10^{-1} . Thus, taking $j\bar{\rho}$ to be 1 in 1959 and 10^{-1} in 1962, and the appropriate constraint (e.g. $S(E)$ can never be negative), it is found that the minimum in $S(E)$ is seen to fall in the year 1962. Putting an error of a factor of 2 on our point in 1962, it can be shown that the minimum year varies between the middle of 1961 to the middle of 1963. The maximum of $S(E)$ will then fall between 1956 and 1958. This shows, at least, some qualitative connection between the source strength and the solar cycle.

3.5. Discussion.

The decrease of proton belt intensity towards solar minimum at $L < 2.0$ is likely to take place because of two reasons:

(i) the source strength of these protons decreases towards the

solar minimum and/or (ii) the loss processes are more active near solar minimum.

The cosmic ray neutron albedo decay source stays nearly constant throughout the solar cycle, being only 25% stronger at solar minimum. Thus, from the source strength point of view, the intensity, if anything, ought to increase towards solar minimum. The main loss processes, on the other hand, are assumed to be the atmospheric losses. The density of the exosphere varies by a factor of 10 during the solar cycle, going to a minimum near solar minimum. If the lifetime of these protons is long compared to the solar cycle, the effect of the variable atmosphere will average out; if, on the other hand, the lifetime is short compared to the solar cycle, the proton flux will follow the variations of ρ , assuming that the source strength stays nearly constant. For such a situation, we ought to find again an increase in the proton intensity in the regions where the variation of ρ is not very noticeable, and a decrease where the variation in ρ is most noticeable. This will give rise to a B-dependence in the solar cycle intensity variation, at a constant L-value.

The data analysed here show an overall decrease in the proton flux, from solar maximum to solar minimum. The pitch-angle distribution shows that at higher B-values the decrease is more than at lower B-values. A slight increase in source strength along with a large decrease in atmospheric density should give an increase of the flux by a factor of 10 to 20 [Blanchard and Hess (1964)]. Instead, we find a decrease,

by a factor of two. Thus, even if one does not take it to be a real decrease, an increase by a factor of 10 can be completely ruled out by the evidence from our data.

As the atmospheric density is definitely known to vary with the solar cycle and is actually the most effective one for the loss of protons in this region of the inner belt, we must conclude that the neutron albedo source is definitely not the main source of protons here.

Two sources could provide the protons for the inner belt which will have a similar solar cycle variation. First, the low-energy protons in the solar wind could provide an ample supply of inner belt particles. The idea was first advanced by Kellogg (1959), Parker (1960) and Harlofsen (1960). Presumably, the injection takes place at the boundaries of the magnetosphere and the particles diffuse inward. The way this diffusion occurs has been considered by Davis and Chang (1962) and Nakada et al. (1965). It is assumed that the first two adiabatic invariants are conserved and the third is broken. This has the effect of accelerating the particles to higher energies as they move inward towards the Earth.

The second source is the neutrons from the sun. At the moment there are only a few estimates and measurements of solar neutrons [see review by Biswas and Fichtel, 1965]. Roelof (1966) gives 10^{22} neutrons/

sec. MeV in the energy range 20 - 75 MeV, as the highest limit for the steady outflow from the sun. If the future measurements show that there are far more neutrons in the solar atmosphere than that predicted by the present estimates or shown by up-to-date measurements, then solar neutrons can be seriously considered to be one of the sources supplying protons to the inner belt. An experiment to measure the neutron flux from the sun is being carried out at the moment by some other members of the Cosmic Ray and Space Physics Group of the Imperial College.

CHAPTER IVTHE ARTIFICIAL RADIATION BELT FROM THE "STARFISH" NUCLEAR EXPLOSION.4.1. Introduction.

The high altitude nuclear explosion of July 9, 1962 produced a temporary artificial radiation belt of electrons, mainly from the decay of fission fragments and possibly involving other processes as well. The exact time, longitude, latitude, and height of the explosion, and the yield of the bomb were given in the literature (collected papers on the artificial radiation belt from the July 9, 1962, nuclear detonation, J.G.R. 68, 1963). The creation of this electron belt provided an opportunity to study the life time and assess the importance of different loss processes operating at different positions in space in the magnetosphere. As the artificial belt showed a distribution and time behaviour which were expected theoretically, the information obtained by studying this belt ought to be applicable to the natural electron belt as well.

The observations on these newly created trapped particles were made by a host of radiation detectors on the satellites, Injun, Telstar, Trasec, and Ariel. Among these, Telstar recorded particles only after the burst, but the other three made both pre- and postburst observations. Information gathered by them on the intensity, spectrum, spatial distribution and decay of the artificial belt are summarised here. (i) Telstar's detector was sensitive to electrons of energy

between 0.25 to 1.0 MeV. Brown and Gabbe (1963) produced flux maps for day 193 to day 212 inclusive. They showed that the intensity decreased exponentially with a time constant of about 4.5 days between L values of 2.2 and 3.0, and with a time constant of about 15 days at L = 2.0 and 3.5, creating a slot between inner and outer electron belts that had become pronounced by the end of July. At energies of about one MeV or more, a substantial number of electrons were detected. This, they emphasised, was consistent with the fission β -spectrum above 400 keV, but at lower energies more particles were observed than that expected from the β -spectrum. They did not find any spectral changes with either position or time.

(ii) Traac observations on the same belt, as reported by Pieper et al. (1963), showed that at L = 1.2 and B = 0.23 gauss, a decay by a factor of 50 occurred in an interval of $8\frac{1}{2}$ hours after the explosion. The flux contours prepared with the data taken between July 10 and 18, showed a shift of particle mirror points to higher values of B in the L-region ~ 1.7 to ~ 2.0 , on July 14, 1962. This, they argued, could also be due to an increase in the flux from an unknown source.

(iii) The Injun data (O'Brien et al. (1962)) showed by direct observation that a thin crescent centered on the magnetic shell L = 1.2 earth radii was formed by electrons of several MeV. They suggested by extrapolation, that for these electrons the intensity of the belt on the equator fell to about 1% at about L = 2.2.

(iv) Mozer et al. (1963) observed electrons with a fission-like

spectrum above 2Mev, in the region of the South Atlantic anomaly. A life time of ≥ 20 days was calculated. They found that the lifetime and the observed deficiency of fission electrons below 2 MeV, were consistent with the loss mechanism of atmospheric interactions. At higher L and B-values only natural electrons were seen by them.

Ariel was situated on the L = 3 shell when it detected the explosion-produced radiation. Both Geiger and Cerenkov counters were saturated six minutes after this. As shown by Durney et al. (1964) the saturation of the Cerenkov Counter accompanied by a Geiger counter rate 30/sec was an indication of the presence of fission β -particles. In practice, two belts of artificial particles were detected. One just on the L-shell which contained the point of explosion, passing 400 km over Johnston Island. Using the data from day 190 - 192, they presented the geographical distribution of this shell. The constant counting rate contours (only those which showed an excess over the pre-Starfish rates) in B-L co-ordinates were given for a region over the Johnston Island shell and a region west of this shell (east of the South Atlantic anomaly). The two B-L maps showed the heavy loss of particles in the lower L-shells in the South Atlantic anomaly. And lastly, they reported on the change of the electron spectrum with L-values. Taking the rates of the Geiger Counter corresponding to the point of saturation of the Cerenkov counter, and plotting these in L, they showed that at $L < 2$, the Geiger-to-Cerenkov counter ratios were consistent with the spectrum obtained from fission

fragment electrons. At higher L-values the spectrum was different. This, they interpreted, was due to the softening of the fission spectrum by the removal of electrons ~ 10 MeV, which were counted by the Geiger Counter with high efficiency.

4.2. Present Work.

In this chapter the objective is:

- (i) To study the longitude dependence of the particles with $h_{\min} \leq 200$ km.
- (ii) To investigate the transition from the loss of electrons due mainly to atmospheric scattering, to loss of electrons due to magnetic scattering or other causes, by plotting the decay curves.
- (iii) To calculate the decay constants for particles with $200 \text{ km} \leq h_{\min} \leq 400$ km and to observe the change of these constants with L-values.
- (iv) To find out the dependence of the decay constants on B-values, at constant L-values.
- (v) To establish constant counting rate contours in L-B regions using the data up to day 228.
- (iv) To study the change of the energy spectrum with L-values and to study the altitude dependence of the spectrum, taking all the available data into consideration.

4.3. Analysis and Interpretation of the data.

The background or pre-'Starfish' count rate.

From the Ariel measurements of pre-'Starfish' radiation in the region of investigation, the following count rates were obtained in the given L and B values.

L in earth radii	B in Gauss	Counts/26.9sec
1.55	.236	~ 1345
	.242	~ 807
	.247	~ 269
	.253	~ 81
1.90	.239	~ 269
	.260	~ 81
2.20	.230	~ 81
$2.0 \leq L \leq 2.30$	$0.25 \leq B \leq 0.32$	~ 40
$3.5 \leq L \leq 3.8$	$0.31 \leq B \leq 0.43$	~ 50
$4.3 \leq L \leq 4.7$	$0.37 \leq B \leq 0.42$	~ 60
$4.3 \leq L \leq 4.7$	$0.43 \leq B$	~ 50
$4.8 \leq L \leq 5.2$	$0.32 \leq B \leq 0.36$	~ 70
$4.8 \leq L \leq 5.2$	$0.37 \leq B \leq 0.42$	~ 55
$4.8 \leq L \leq 5.2$	$0.43 \leq B$	~ 50
$5.2 \leq L \leq 6.0$	$0.32 \leq B \leq 0.42$	~ 55
$5.2 \leq L \leq 6.0$	$0.42 \leq B$	~ 48
$6.0 \leq L \leq 7.0$		~ 48

From the compilation of Graphic Displays of Geomagnetic Geometry (G.E.C., Santa Barbara, California, 1965), the altitude lines $h_{\min}$ were obtained in the given B-L space. The counting rates relevant to these altitudes were chosen at the L-values considered further on.

Fig. 25a and 25d give the count rates (above the background rate) versus B west and east of the South Atlantic magnetic anomaly. All data with $h_{\min} \leq 200$ km were used, from day 190 to day 228 inclusive. The 360° longitude region was divided into four equal regions of 90° width each. The difference in the distribution of points in B-regions, before and after the anomaly, can be seen quite clearly. The large spread of points in one particular region is due to the large width chosen for the longitude interval. This was unavoidable because of the non-availability of a sufficiently large body of data. However, the dominance of atmospheric scattering is quite clear here. The interesting thing is, of course, the gradual change in the two distributions as one goes to higher L-values. From losses due mainly to the atmospheric collisions one comes to a situation, where a sort of equilibrium situation between loss by atmospheric scattering and filling up of the shell by magnetic scattering, occurs. This can be seen more clearly in Fig. 26 where at two L-values the data have been plotted against day numbers. For region III (before the anomaly) and region II (after the anomaly). The decay curves in these two regions are different for $L = 2$, but at $L = 3$, the leakage due to atmospheric scattering for these relativistic particles becomes less and less important and ultimately

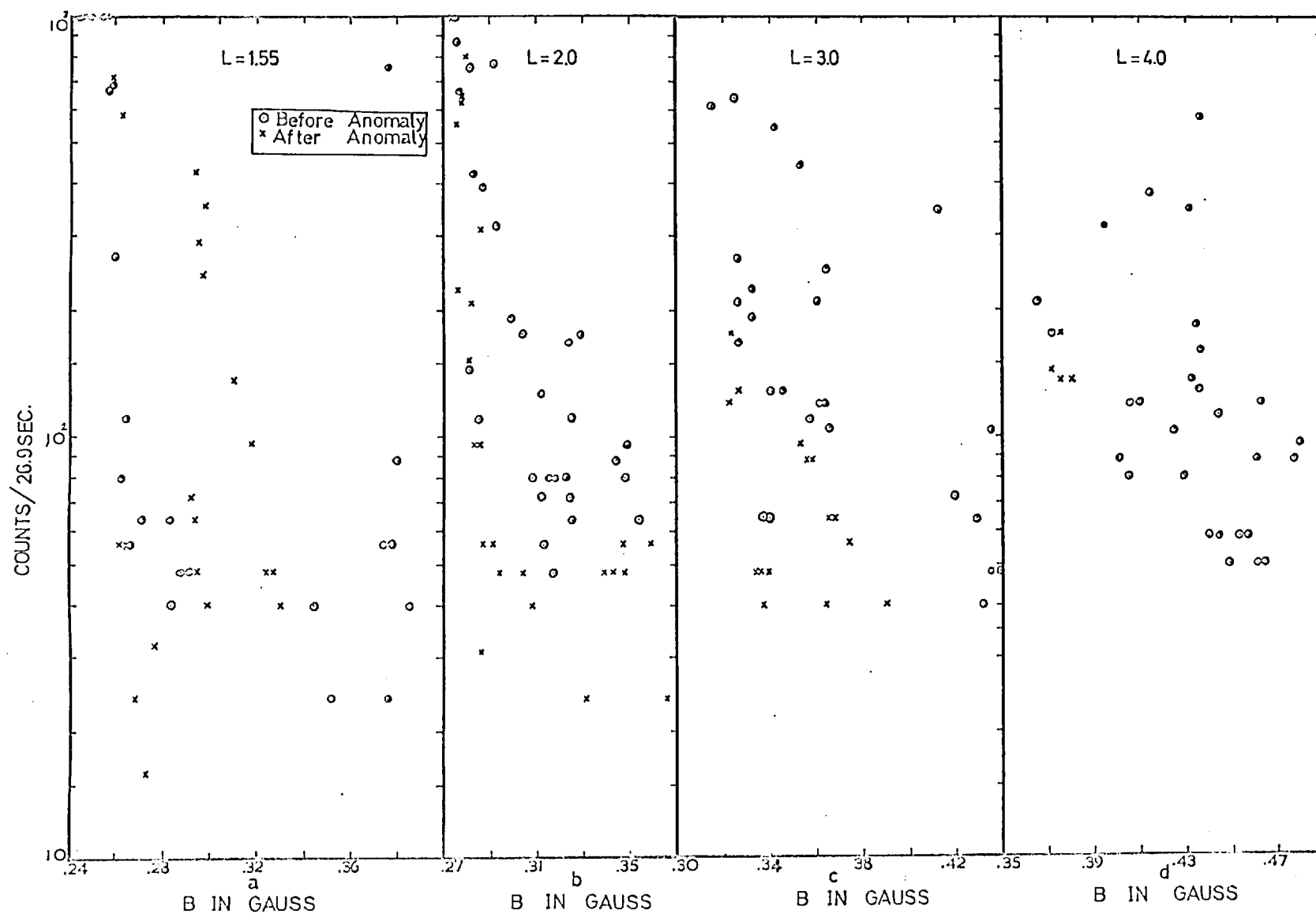


Fig.25. Particles with $h_{min} \leq 200\text{km}$ East and West of the Anomaly.

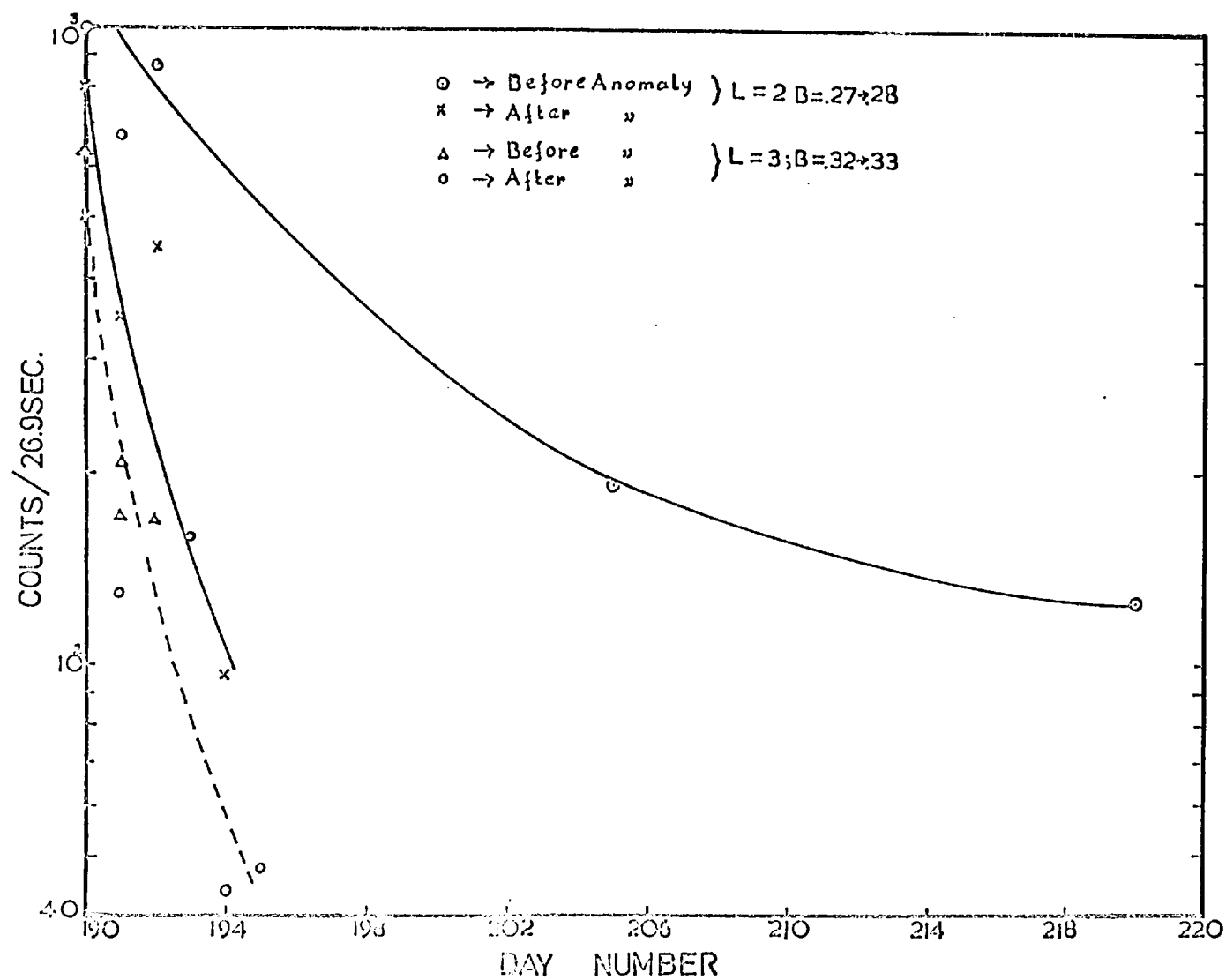


Fig.26. Particles with $h_{min} \geq 400$ km East and West of the Anomaly.

they are dominated by a loss due to some other process or processes.

The data which represented particles mirroring at an altitude of $200 \text{ km} \leq h_{\min} \leq 400 \text{ km}$ were chosen next. Taking different values of B at each L -value, it is shown in Fig. 27a and 27b that the character of the decay is always exponential, except on day 190. The decay is very rapid on that day and has a non-exponential character. The decay constant changes with B , at a constant L , the rate getting quicker as higher B -value is approached.

Particles which were mirroring with $h_{\min} \geq 400 \text{ km}$, were considered in a separate group. As enough data were not available, time decay plots at different L -values were made using all available data having wide distribution in B . Only in limited B -regions at $L = 3.0$ to 5.0 enough data could be gathered to plot meaningful curves (Fig. 28a to 28c). The difficulty which was faced here was the apparently high counting rates at $L \geq 3$ on day 205 onwards. After examining the data for any correlation with latitude, longitude, and altitude, it was evident that all these data were recorded near the apogee and in the longitude range east of the anomaly. The geographical latitudes of this region was always above 50°S which corresponds to the geomagnetic latitudes $50^\circ - 60^\circ$, over the longitude region covered. It is known that the outer belt electrons do come down to this height ($1100 - 1200 \text{ km}$), in this region of geomagnetic latitudes. These counting rates were, therefore, ignored when calculating the decay rates at $3 \leq L \leq 5$. Fig. 29a shows the

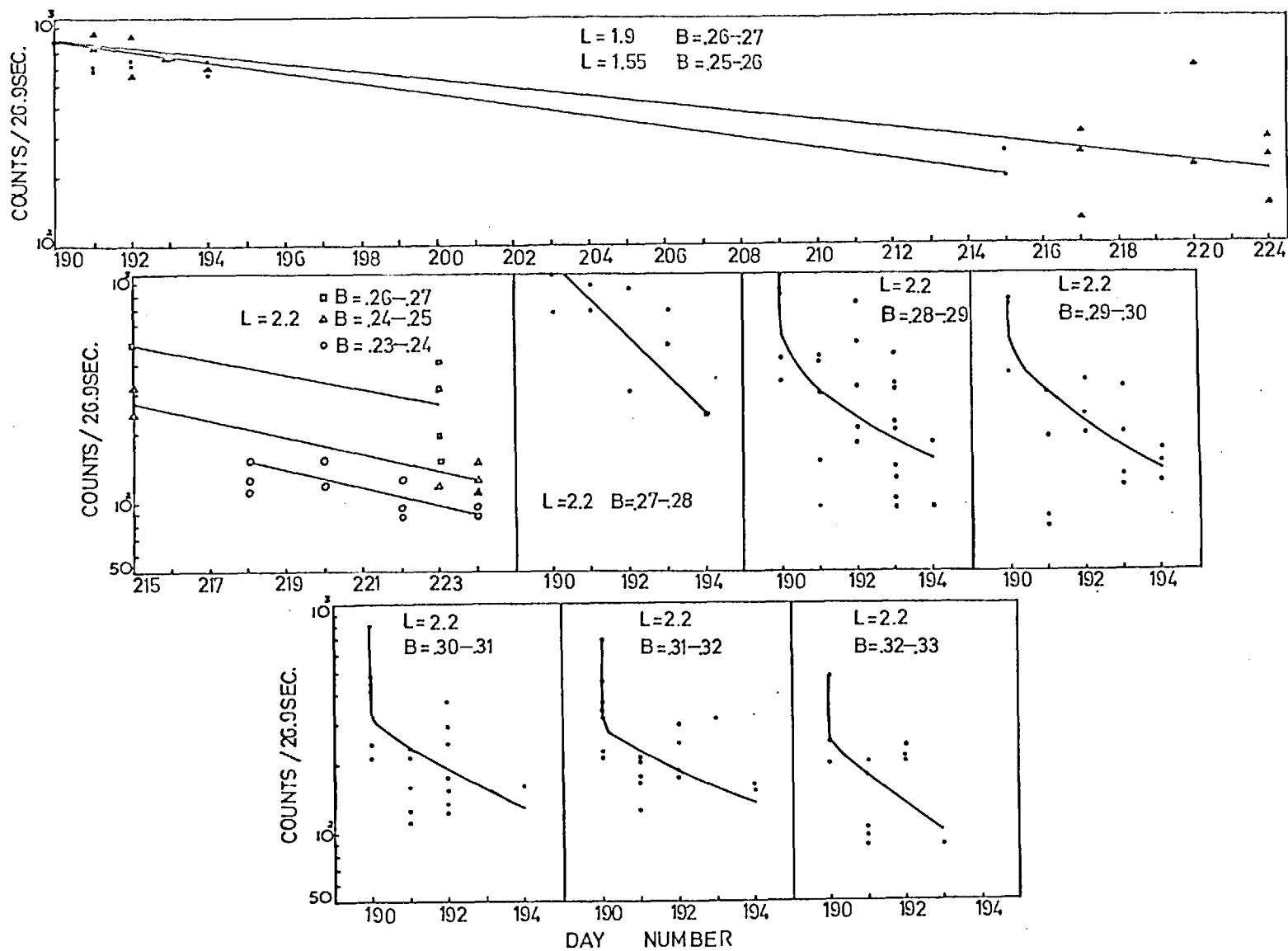


FIG. 27a. DECAY OF ELECTRONS WITH $200\text{KM} \geq H_{\min} \geq 400\text{KM}$.

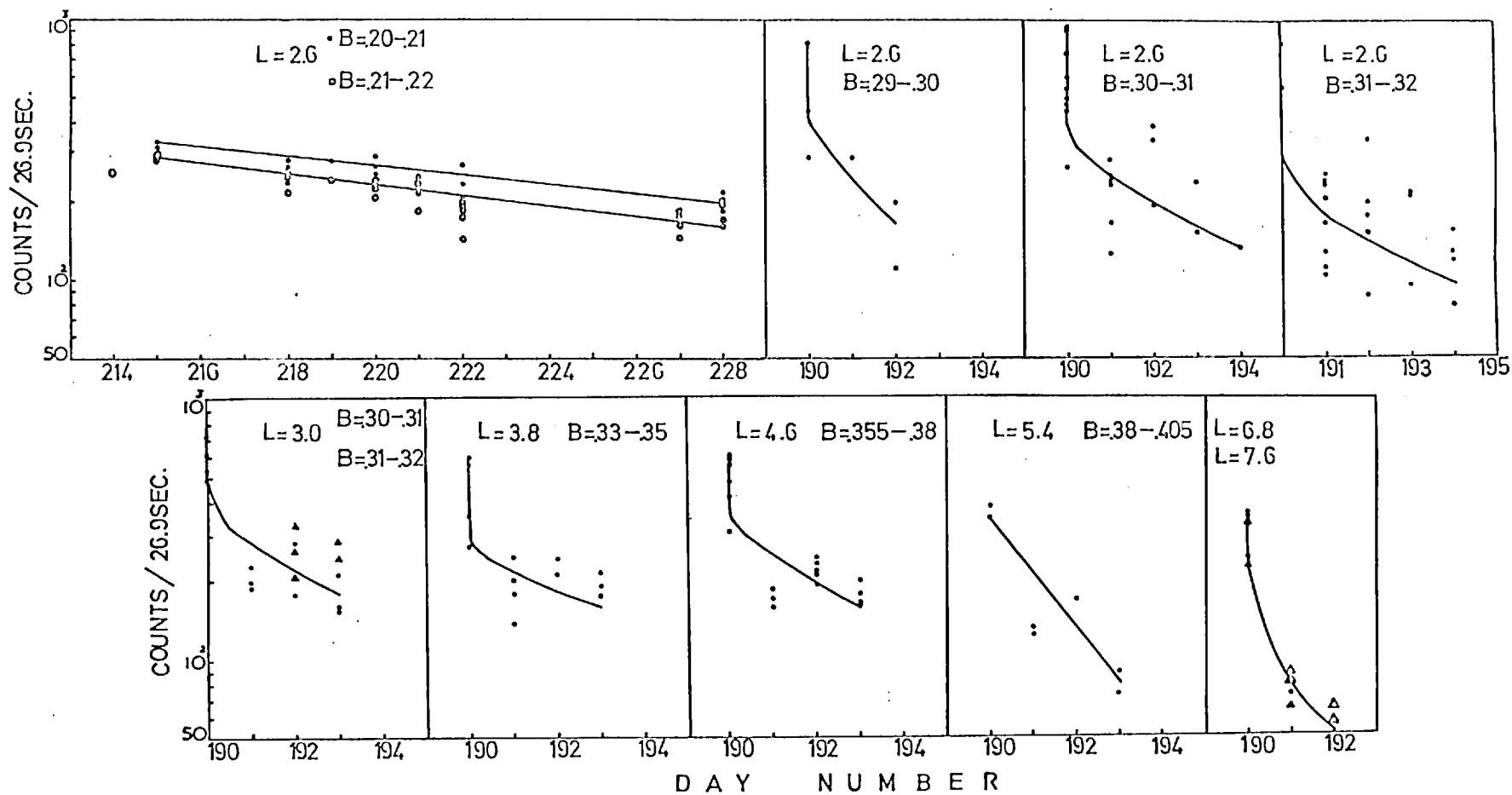


FIG. 27b. DECAY OF ELECTRONS WITH $200\text{KM} \geq H_{\min} \geq 400\text{KM}$

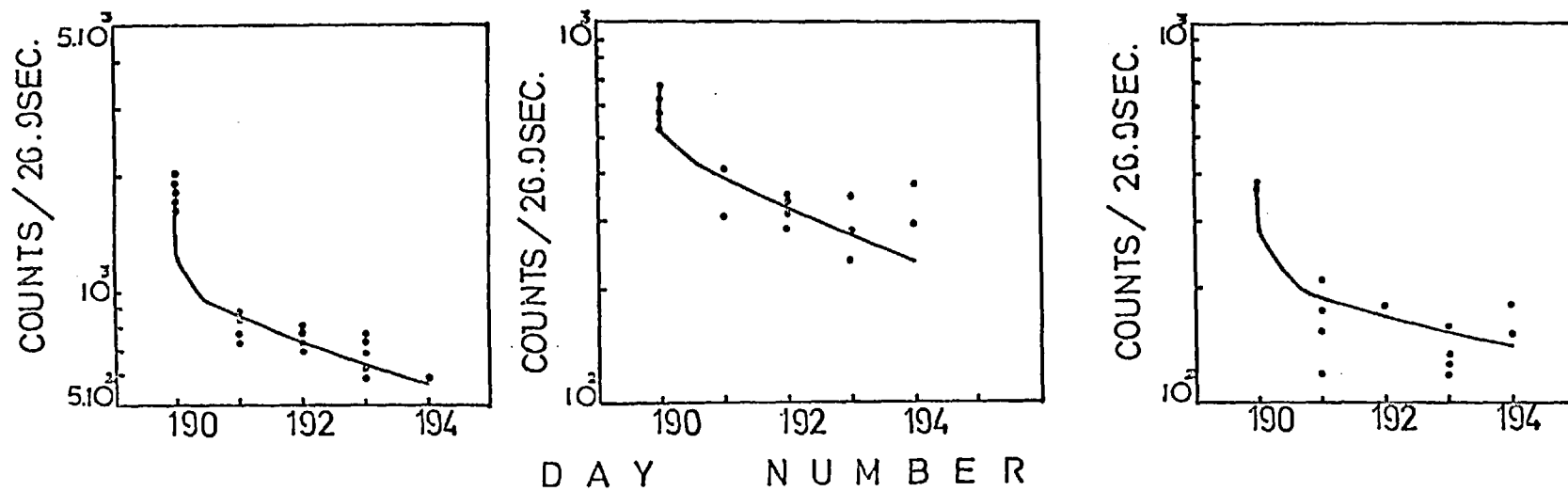


Fig. 28. Decay of electrons with $h_{\min} \geq 400\text{km}$.

dependence of τ on L-values, for particles at and above $L = 1.55$.

Fig. 29b gives the dependence of τ on B-values at $L = 2.2$ and $L = 2.6$.

In Fig. 31 the constant counting rate contours are plotted by using the data of the first five days after the burst. This was obtained from the counting rate versus B diagrams, given in Fig. 30a to 30j using the data of the same five days. Day 190 was a special case. As the intensity of the artificial belt was decaying away very rapidly on that day, the eye-estimated curves were accepted through the points of day 191 - 195, to obtain the points in L-B space for the contours in Fig. 31. Most of the particles beyond $L = 3.0$ decayed away very rapidly by day 195. Fig. 31, therefore, represents the quasi-static artificial electron belt distribution in L-B space on July 10 to 13.

The change of the energy spectrum with L-values has been demonstrated by Durney et al. (1964) using those counting rates of the Geiger Counter at which the Cerenkov Counter saturated. These data were plotted against L-values, after dividing the data into two groups, with $h_{\min} < 200$ km and $h_{\min} > 200$ km. The same investigation was carried out here with the data of the total period. Fig. 32 shows the distribution of these rates in L, the open circles and open triangles being the counting rates at $h_{\min} \leq 200$ km. It can be seen that the variation of the rates with L-values is the same for open

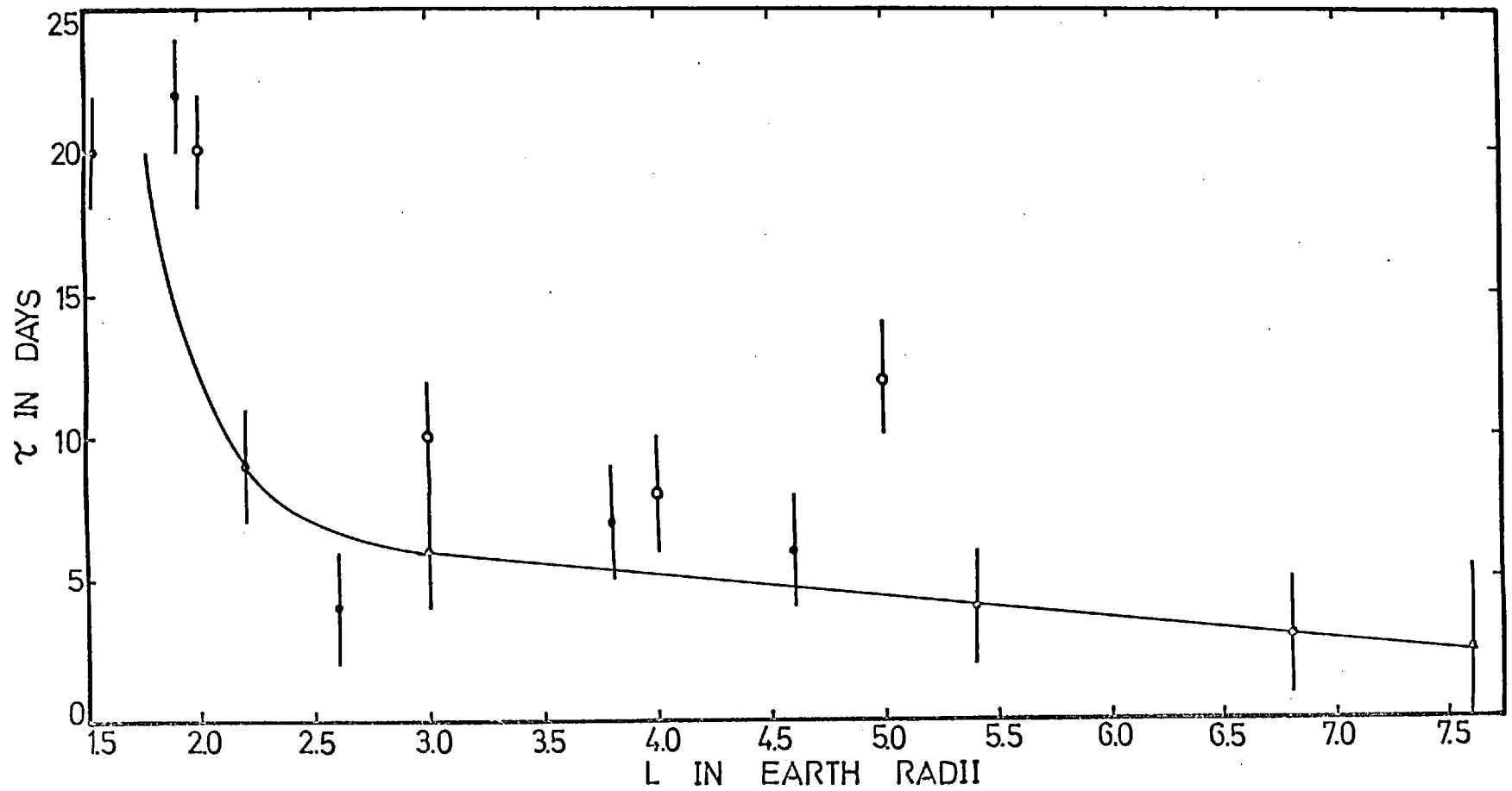


Fig.29a. Variation of decay constants with L values.

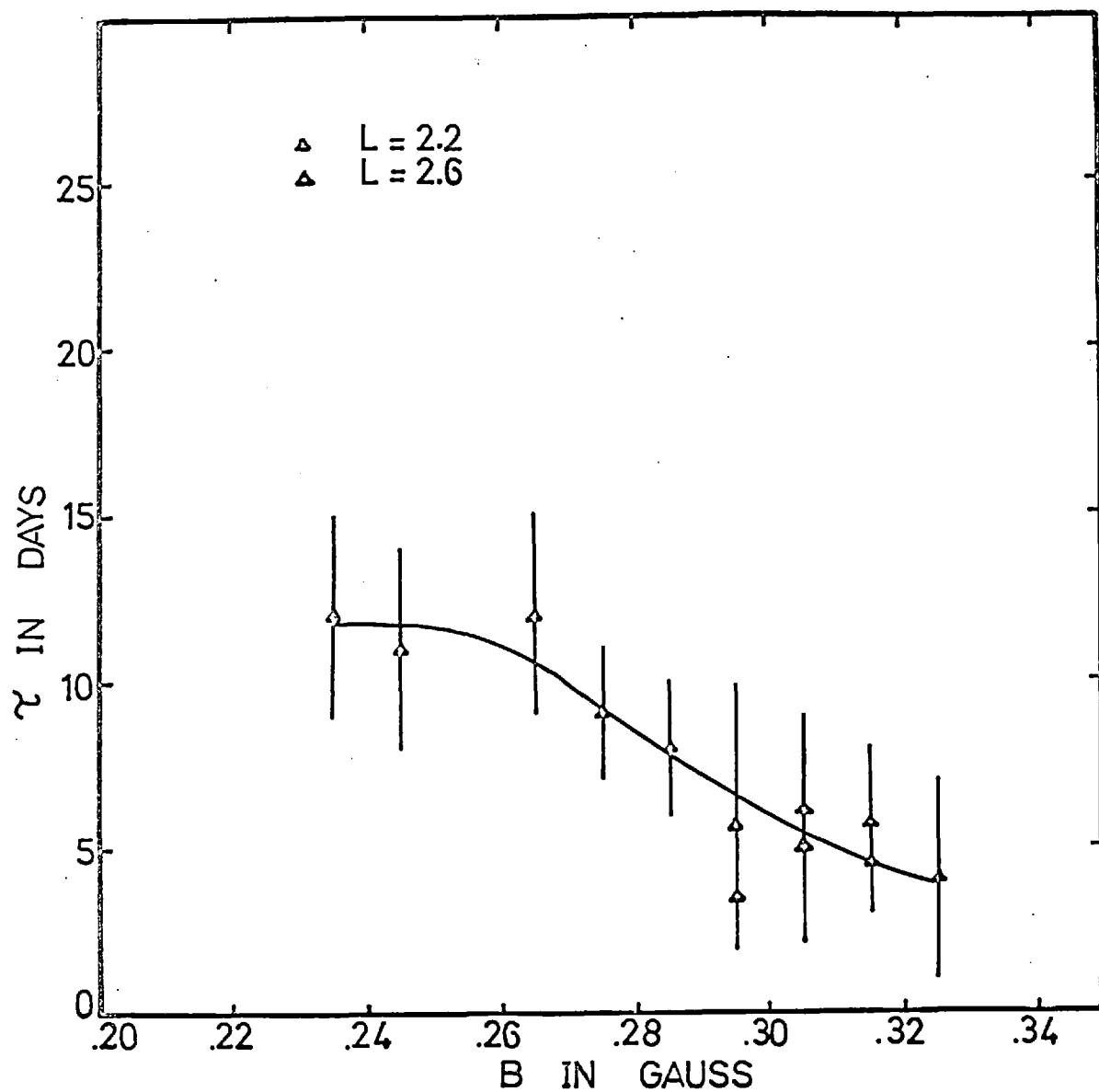


Fig.29b. Variation of decay constants with B at constant L's.

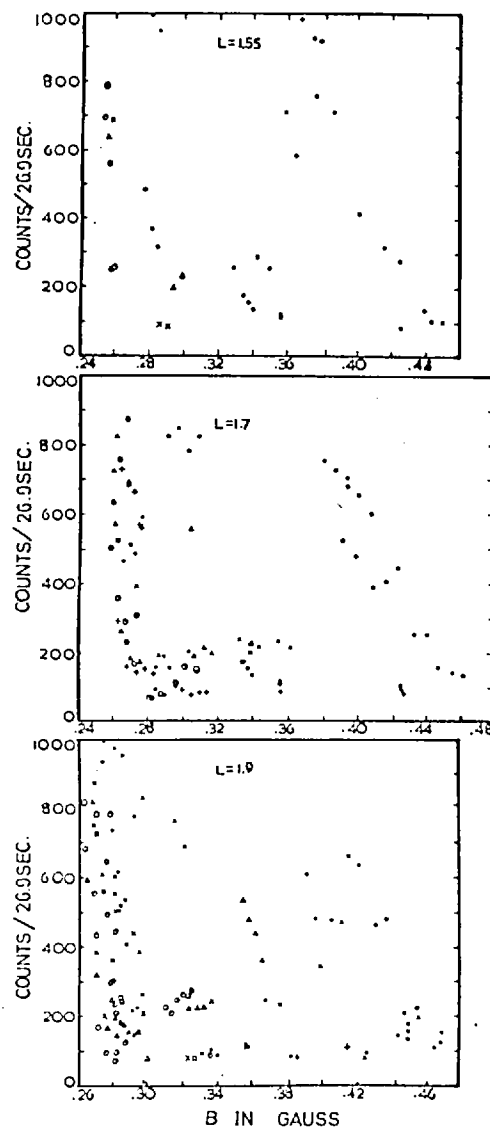


Fig.30a-c. Distribution of artificial electrons in B, at constant L's.

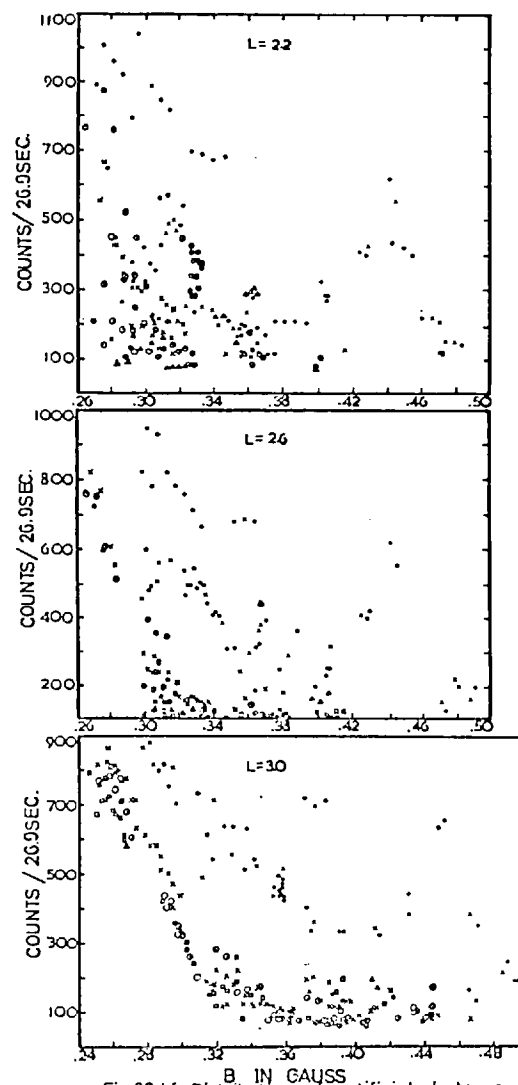


Fig.30d-f. Distribution of artificial electrons in B at constant L's.

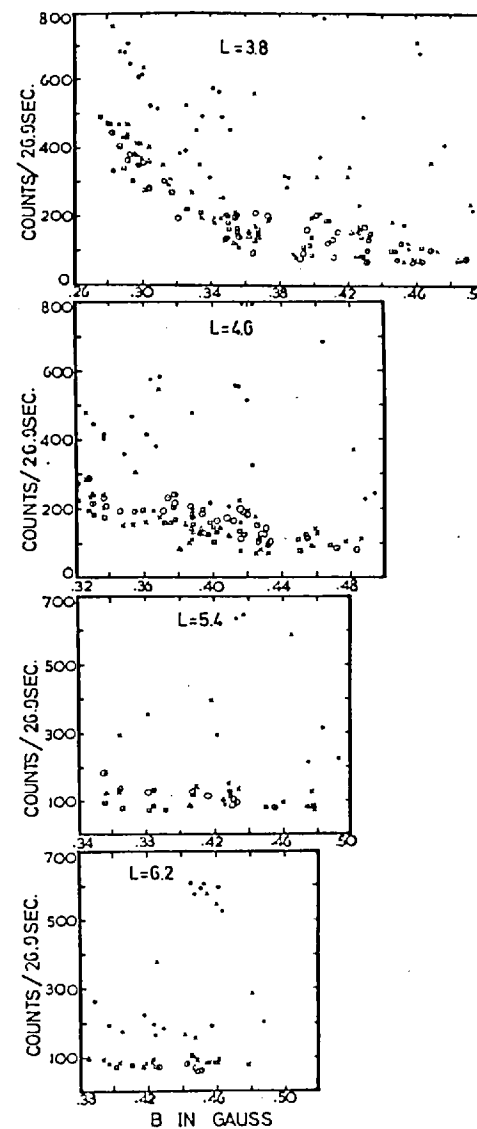


Fig.30g-i. Distribution of artificial electrons in B, at constant L's.

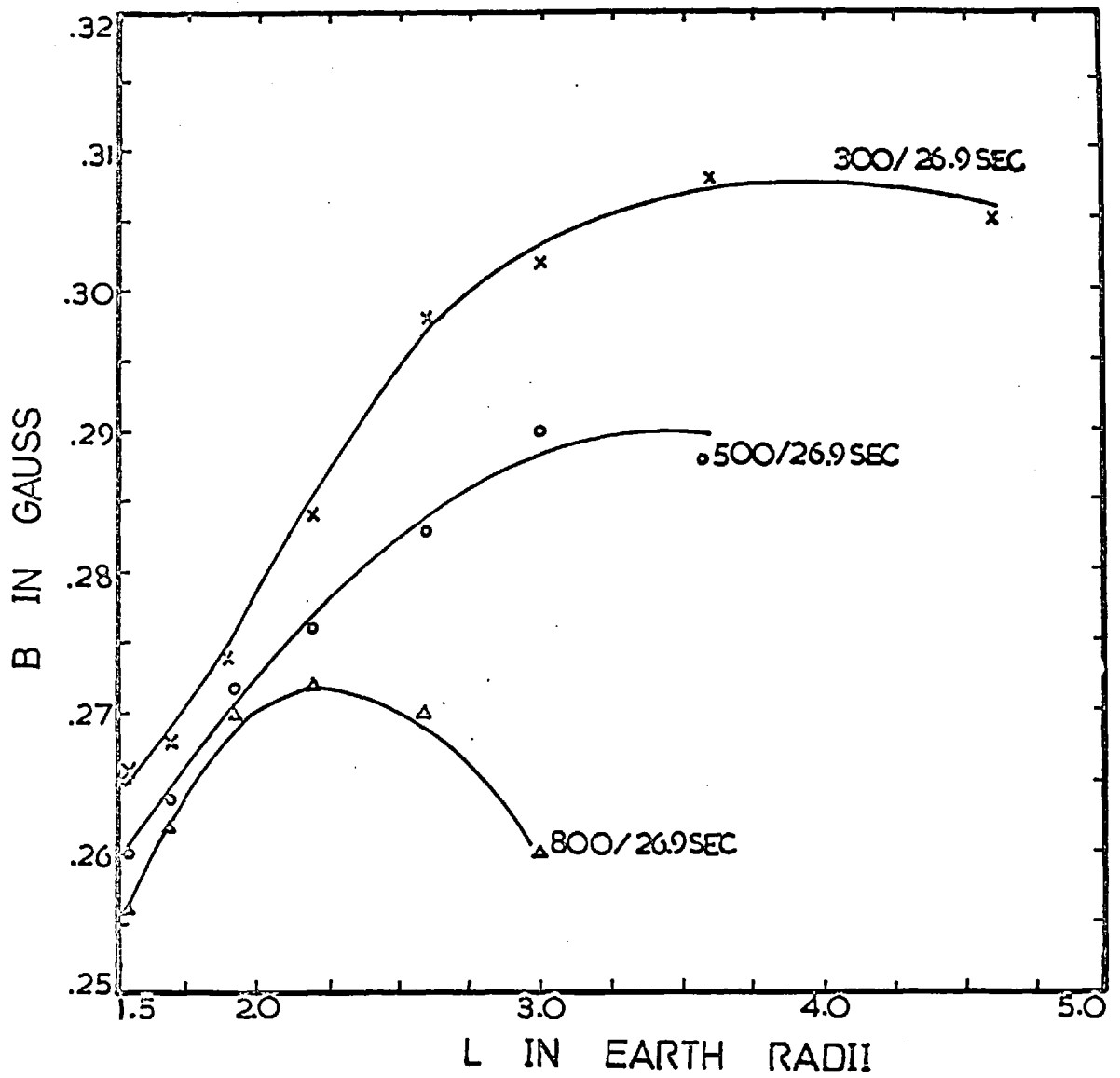


Fig.31. Constant count rate contours of the quasi-permanent electron belt in L B space.

circles and triangles as for closed circles and triangles; the triangles represent the data after day 192 and the circles the data before that. The energy spectrum changes with L-values, only for those particles which have $h_{\min} \geq 200$ km. The data recorded after day 192 show the time decay behaviour of the quasi-permanent belt, but the character of the energy spectrum or the trend to softening of the spectrum toward higher L-values remains the same.

Particles which have trajectories such that at some point during their drift, they approach within 200 km above the earth's surface, show a distribution (again using a range of Geiger Counter rates corresponding to the saturation of Cerenkov Counter) other than that expected from a fission β -spectrum. This was first pointed out by Durney et al. (1964) and is now confirmed here by a plot of the additional number of data available. Softening of the spectrum by ionization loss is the most probable explanation. One would then expect a progressive change of the spectrum with altitude. This can be demonstrated, as shown in Fig. 33, by plotting Geiger Counter rate corresponding to Cerenkov Counter saturation, against the ratio of B at the point of observation to the lowest value of B occurring anywhere at an altitude of 300 km on the same magnetic shell. The particles moving on shells with the values of this ratio greater than unity, approach within 300 km of the surface at some stage in their orbit. The magnitude of this ratio is, therefore, a measure of the closeness of their approach. Fig. 33 shows the total number of points

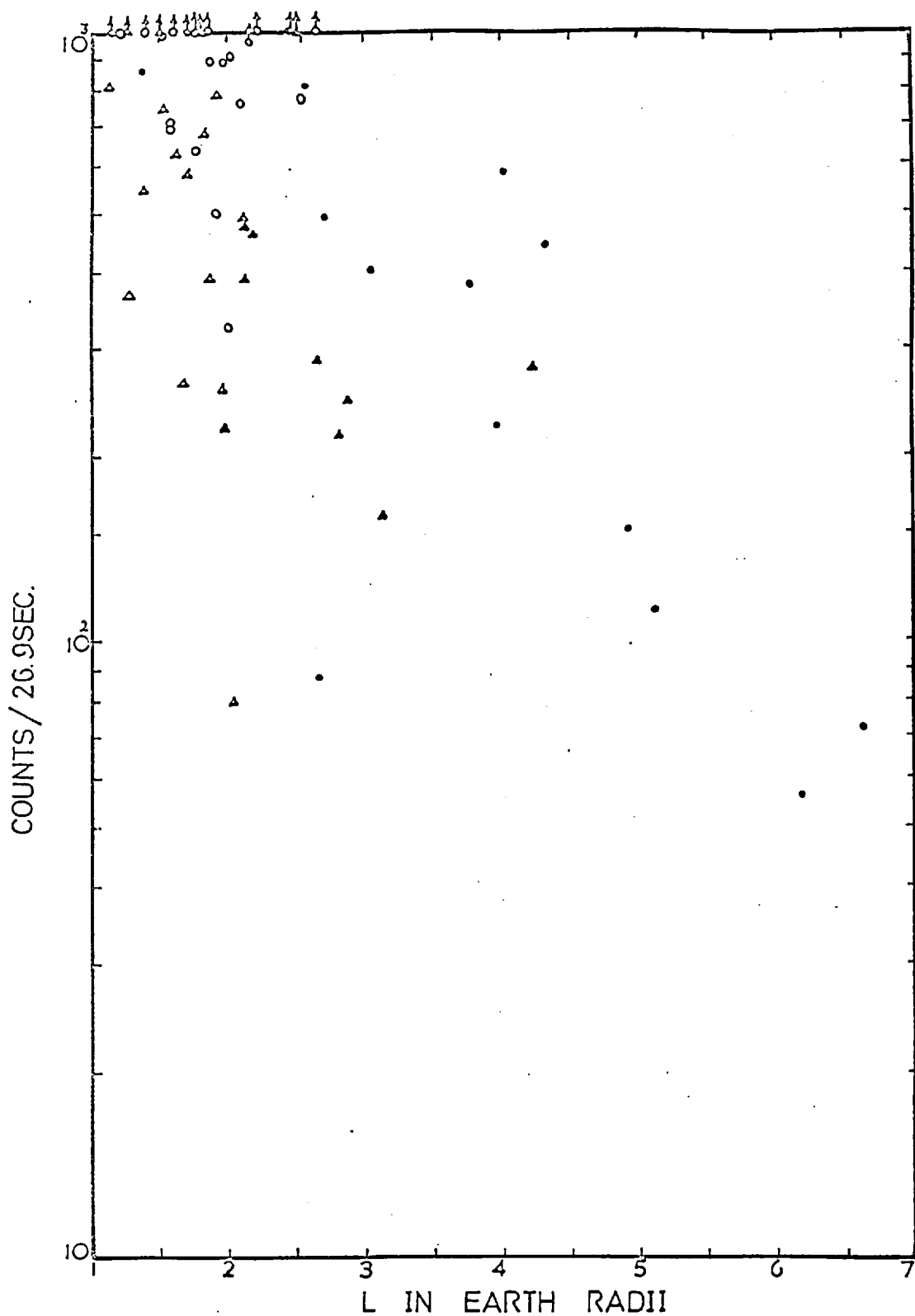


Fig. 32. Geiger counter rate corresponding to the saturation of the Cerenkov detector as a function of L.

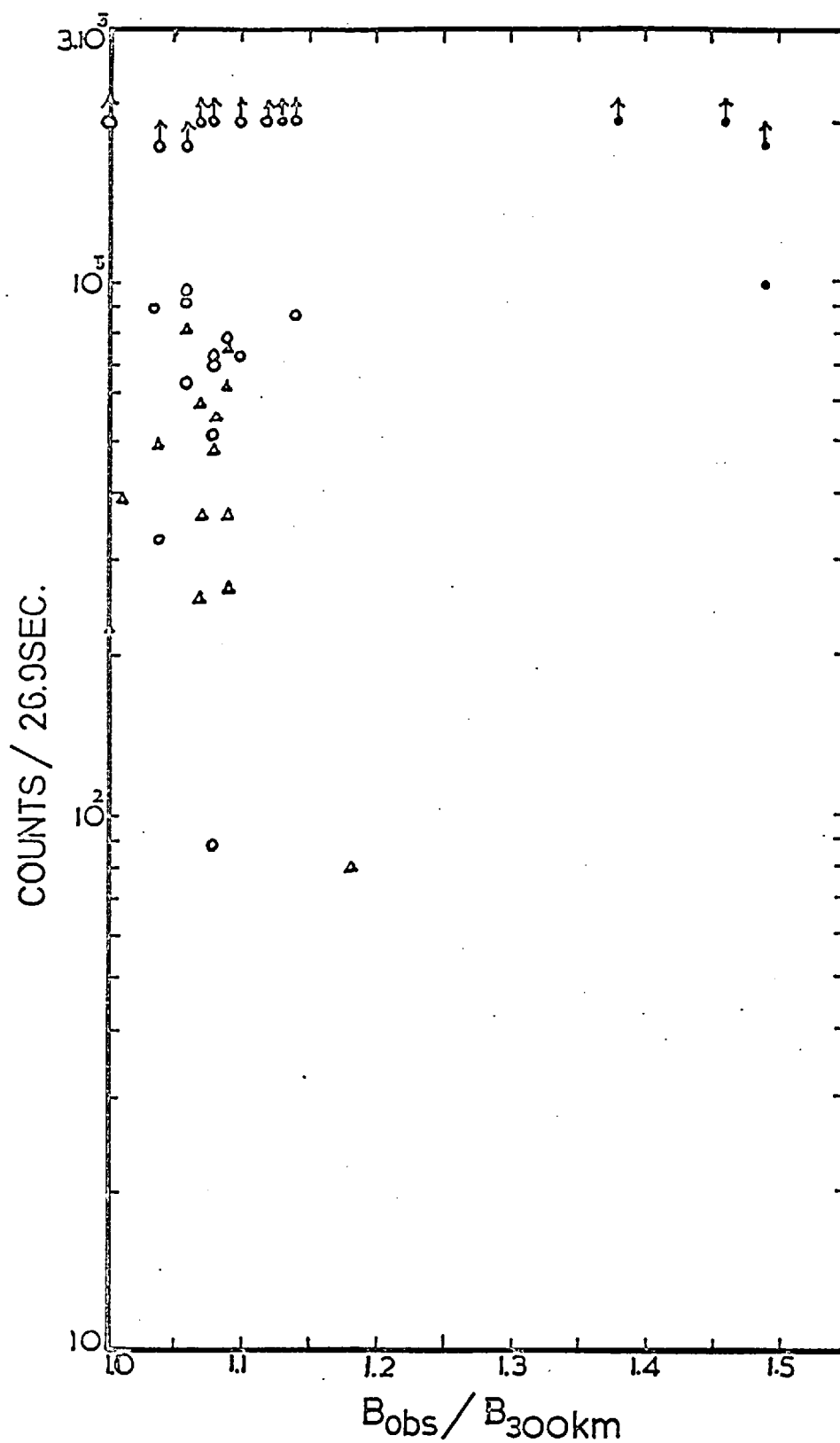


Fig. 33. Geiger counter rate corresponding to the saturation of the Cerenkov detector as a function of B_{obs}/B_{300km}

obtained by using all the data in the range $L = 1$ to $L = 2.5$ (day 190 to day 228).

4.4. Conclusions.

The following conclusions are drawn on the quasi-permanent artificial belt detected by Ariel I after the 'Starfish' nuclear explosion:

- (i) The trapped electrons with $h_{\min} \leq 200$ km show a definite longitude dependence. This supports the idea that for trapped particles, which dip very low into the atmosphere, the intensity depends on three parameters, L , B , and longitude.
- (ii) The decay characteristics of the trapped electrons most probably change with $h_{\min}$ but the difference in τ -values at $h_{\min} \geq 400$ km and $h_{\min} \leq 400$ km cannot be established beyond the experimental uncertainty.
- (iii) The decay constants are decreasing with increasing L tending to an asymptotic value beyond $L = 3.5$. This is inconsistent with the calculated values of τ considering atmospheric losses only. But the τ -values of the order of days as obtained here are inconsistent with the τ -values obtained by other workers in the same L -region.
- (iv) The dependence, if any, of decay constants on B , at $L \geq 2.0$, is not very clear.

(v) It is confirmed here that the trapped electron spectrum becomes softer with increasing L-values. The energetic electrons detected by Ariel I Geiger Counter were, therefore, being removed by some loss processes, most possibly by interaction with hydromagnetic waves (Durney et al. 1964), beyond $L \approx 2.0$.

4.5. Artificial Radiation from Nuclear Detonations on Johnston Island.

Engel (1964) noted that on several days in May and June, 1963, the Geiger Counter rates were above the background rate at some positions in space not occupied by the natural radiation belts. These were shown by him to be the radioactive fission products of the nuclear detonations on Johnston Island, but the nature of these products was not apparent.

The data recorded from the 27th May to 8th July, 1962, were examined thoroughly for any particles giving counts above the background rate but no additional dates were located, other than those given by Engel (1964). Keeping within the limits $L = 1.00$ and $L = 1.10$, and plotting the counting rates against day numbers, one can see in Fig. 34 the detonation particles standing out prominently against the background rate.

To determine the nature of these particles, high counting rates as well as the rates at the same geographic positions, on the day following these high counting rates, were plotted. It can be seen

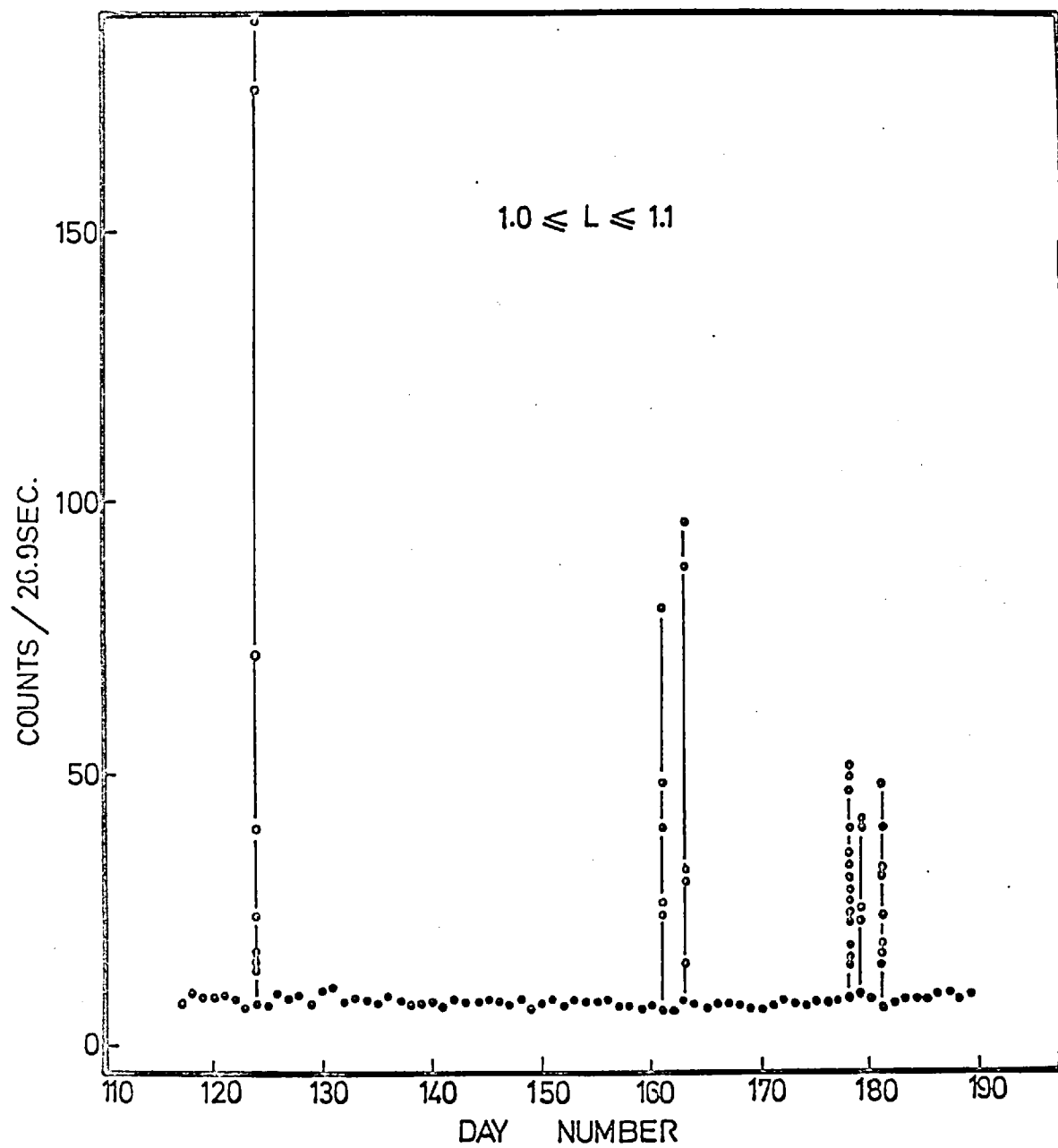


Fig.34. Geiger Counter rate below the inner radiation belt.

from Fig. 35, that all the particles detected are on longitudes east of Johnston Island. This can happen only if they are electrons. Gamma rays or neutral particles will show an uniform distribution on all longitudes, on both sides of Johnston Island, and positive particles will be distributed west of Johnston Island. It can, therefore, be safely concluded that the particles detected immediately after the nuclear bursts on Johnston Island, are electrons.

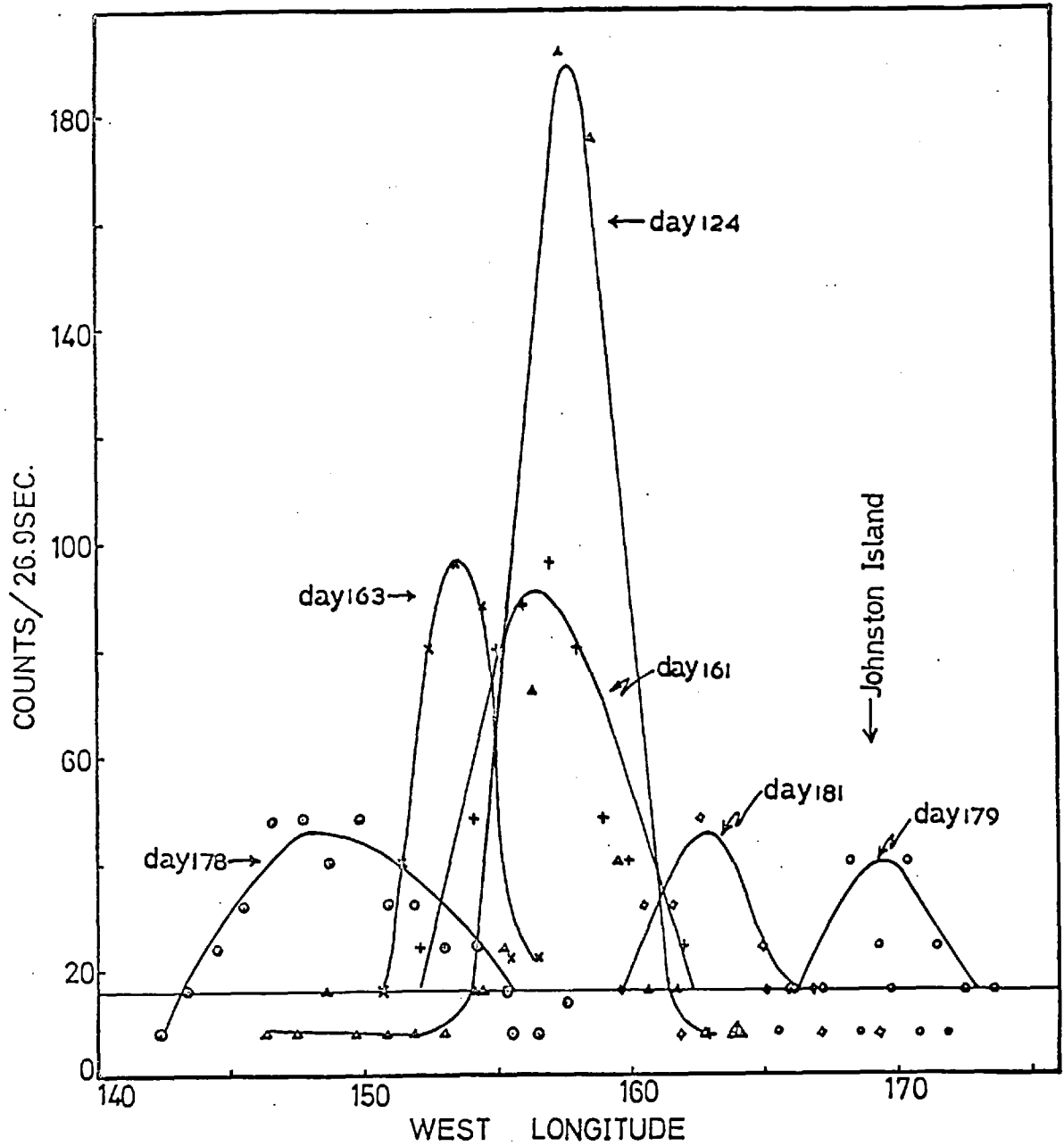


Fig.35. Longitude excursion of the nuclear burst particles detected below the inner belt.

CONCLUSIONS

110.

The main conclusions arrived at in this thesis are the following:

1. Primary Cosmic Rays.

(i) The heavy primary cosmic ray rigidity spectrum as seen by Ariel has a slope of -1.072 ± 0.026 below 8.5 GV ($2.5 < R < 8.5$ GV) and -1.533 ± 0.079 above this ($8.5 < R < 16.5$ GV).

(ii) The solar cycle variation of the modulation of the heavy primary spectrum is fitted to Parker's simple solar wind model and the rigidity dependence of the modulation function is given.

(iii) The Quenby-Wenk cut-off rigidities represent the true cut-offs within $\pm 10\%$ over most of the world.

2. Natural Radiation Belts.

(i) Temporal stability of the proton belt ($L < 2$) for two and a half month's period (May-June, 1962) is shown. At the same time the time variations present in the outer radiation belt is given.

(ii) Long-term or solar cycle variation in the inner radiation belt is suggested and the origin of and loss processes for the inner belt is studied in the context of this. Neutron albedo source and atmospheric loss processes are found to be inadequate to explain the long-term variation.

3. Artificial Radiation Belt.

The quasi-stable artificial electron belt produced by the 'starfish' explosion is extensively mapped. Decay time calculations at different B and L locations give values of the order of days, beyond L=2, in agreement with other observers.

(ii) The softening of the electron spectrum towards higher L-values is confirmed.

(iii) Particles with $h_{\min} \leq 200$ km have been shown to depend on longitude as well as on L and B.

(iv) The nuclear burst particles observed below the inner belt are shown to be electrons.

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