THE MAGNETOSPHERIC PLASMAPAUSE AND THE ELECTRON DENSITY TROUGH AT THE ALOUETTE I ORBIT

M. J. RYCROFT AND J. O. THOMAS

Department of Physics,

Imperial College,

University of London,

England.*

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* Part of the work was carried out in the Space Sciences Division, NASA Ames Research Center, Moffett Field, California, U.S.A.

ABSTRACT

The location of the magnetospheric plasmapause or 'knee' and the position of the electron density minimum or 'trough' at the orbit of the Alouette I satellite near 1000 km have been derived from whistler data and from topside ionograms respectively. A statistical study of the dependence of both knee and trough positions on the degree of magnetic disturbance and on local time during the summer of 1963 reveals that, in general, within the statistical scatter, the geomagnetic field lines on which each occur are the same. During the local night, the equatorial radial distance to the center of the plasmapause is described by the relation: $R_p = 5.64 - (0.78 \pm 0.12)\sqrt{K_p}$ earth radii, whereas the field line through the center of the electron density trough is best described by the equation: $L_T = 5.64 - (1.09 \pm 0.22)\sqrt{K_p}$.

It is inferred that the plasmapause in the magnetosphere and the trough near the exospheric base are related phenomena, and that a sharp decrease of plasma density occurs beyond a particular field line, the position of which depends on local time and on the degree of geomagnetic activity. For magnetically quiet conditions ($K_p = 0$), this line of force corresponds to $L \simeq 5.6$ near midnight, whereas for moderate magnetic activity ($K_p = 3$) its L value is approximately 4. The radial distance at which this field line crosses the equatorial plane decreases at a rate of approximately 0.1 earth radii/hour throughout the local night. The geomagnetic latitude at which the field line concerned reaches an altitude of 1000 km is approximately 57° at 02.00 L.T. for $K_p \simeq 3$, and decreases at a rate of $1.8° \pm 0.4°$ per unit increase of K_p.

1. INTRODUCTION

In this paper, the relationship between two experimentally observed features of the plasma distribution in the interacting ionosphere-magnetosphere system is examined. The first of these is the high-latitude electron density minimum or 'trough' observed at the Alouette I satellite approximately 1000 km above the earth (section 2). The second is the sudden, order-of-magnitude decrease in the electron density at a few earth radii in the magnetosphere known as the plasmapause or 'knee' (section 3). Information concerning the distribution of electrons in the equatorial plane, and hence the plasmapause, has been obtained from studies of whistler observations (Helliwell, 1965), whilst information on the high latitude trough is readily available from routine topside ionograms recorded by the Alouette satellites. Recently, both plasmapause and trough have been studied by direct satellite measurements of ion densities.

In order to illustrate one of the phenomena under discussion, the electron density at the Alouette I orbit is plotted, on two occasions at the same local time and only three days apart, against Mc Ilwain's (1961) parameter L in Figure 1. It is evident in both cases that, as L increases, the electron density decreases, reaches a low value and suddenly increases, so that the distribution appears to have the form of a 'trough'. It has been suggested (Thomas and Dufour, 1965) that this electron density trough, most evident over North America during the local night, is a demarcation region between the decaying, solar-produced plasma and magnetospherically induced (auroral) ionization. Less is known of ionospheric electron density variations in the magnetic conjugate area due, partly, to the paucity of telemetry stations, and also to complications introduced by the precipitation of radiation-belt particles in the vicinity of the South Atlantic geomagnetic anomaly.

Sharp (1966a) has also considered the sudden increase in electron density polewards of the trough (referred to as the 'cliff' in Figure 1) to be the result of ionization caused by external (auroral) agencies. It is therefore believed that the L-shell dependence of electron density such as illustrated in Figure 1 is indicative of two distinct production mechanisms, each of which is dominant in different regions of space. At low L values the electron density near 1000 km altitude depends largely upon the cosine of the solar zenith angle during the day, whereas at L values around 7 it depends upon aurorally associated corpuscular radiation (Rees, 1963). Since the intensities of auroral phenomena fluctuate markedly, the composite electron density variation resulting from the addition of the two effects exhibits a complex behavior. Two representative examples are shown diagrammatically in Figure 2.

The trough and the cliff are clearly evident on both occasions in Figure 1. It should be noted that, when the planetary magnetic index K_p at the time of observation was the greater, both of these features of the topside ionosphere occurred at a lower L value. [illegible]

Thomas and Dufour (1965) commented upon the possible association between:

(i) The rapid change in proton abundance near L = 4 at 1000 km predicted by them, and subsequently observed by Barrington, Belrose and Nelms (1965), Shawhan and Gurnett (1966), and also the Ariel I satellite (R.L.F. Boyd and A.P. Willmore, private communication, 1966),

(ii) The plasmapause observed by Carpenter (1963), and

(iii) The electron density troughs near L = 4 evident in the topside ionosphere from the night-time observations of Thomas and Sader (1963, 1964) as minima near dip latitudes of 60°, and in the observations near the F region peak of Muldrew (1965) and of Sharp (1966a).

It is the purpose of this paper to pursue this suggestion by performing a statistical study of both trough and plasmapause observations made during the summer of 1963, by investigating whether the trough and the plasmapause are related, and by quantitatively establishing the nature of the association. The positions of the phenomena are first specified by their geomagnetic field lines. Changes in these positions are then noted as the values of other variables, such as magnetic activity (K_p and A_p indexes) and local time, change.

The position of a well-defined feature of the ionosphere-magnetosphere interacting system can be specified by the particular line of force of the earth's magnetic field passing through it. It is convenient to use either the geomagnetic latitude of the foot of the field line or McIlwain's parameter, L. If the geomagnetic field were taken to be a simple dipole, L would be exactly the distance (in earth radii) at which the line of force crossed the equatorial plane. For the actual geomagnetic field the L value of a line of force is approximately this.

In connection with studies of energetic particles trapped in radiation belts, O'Brien (1963) introduced the invariant latitude of a point at the earth's surface, Λ, defined by

$$L \cos^2 \Lambda = 1 \quad . \tag{1}$$

If the geomagnetic field were a pure dipole field, Λ would be the geomagnetic latitude or dip latitude of that point. This relation may be generalized to any height h above the earth's surface, of radius R_E, with Λ' being the generalized invariant latitude defined by

$$L \cos^2 \Lambda' = 1 + (h/R_E) \quad . \tag{2}$$

The generalized invariant latitude of a point at the altitude of the Alouette I satellite, h_s, given by

$$\Lambda' = \text{arc cos} \left[(1 + (h_s/R_E))/L \right]^{\frac{1}{2}} \quad , \tag{3}$$

differs from the local value of the dip latitude typically by 2° (Thomas, Rycroft, Covert, Briggs and Colin, 1965).

2. ELECTRON DENSITY TROUGH

Since the launching, on September 29 1962, of the Alouette I satellite into a near polar orbit, it has become possible to monitor a number of important parameters of the topside ionosphere at intervals of approximately 1^{o} in geomagnetic latitude. In the topside sounder experiment carried aboard the satellite, the time delay between transmission of a radio pulse and its reception at the satellite after reflection is measured and recorded as a function of frequency. From the resulting topside ionograms, the electron density profile between 1000 km and the F2 region peak can be deduced by one of many available techniques. Computer programs designed for this purpose in use at the NASA Ames Research Center, Moffett Field, California, were discussed at a recent conference, (Thomas, Rycroft, Colin and Chan, 1966a). The electron density N_s at the satellite, the altitude of which varies between approximately 1000 and 1050 km, can be deduced readily from a measurement of the frequency, $f_x S$, at which the Extraordinary trace has zero range, combined with a knowledge of the magnetic field strength at the observational point (Thomas and Sader, 1963, 1964, Thomas, Rycroft, Covert, Briggs and Colin, 1965). Typical curves showing how the electron density distribution in the topside ionosphere depends on time and location are given by Thomas, Rycroft, Colin and Chan (1966 b) and by Thomas and Rycroft (1968).

A noticeable feature of the night-time latitudinal variation of N_s over North America is its gradual decrease beyond 30^{o} geomagnetic latitude. A trough, or minimum, is reached near 60^{o} dip latitude. Beyond the trough, which was observed soon after Alouette I was launched on topside ionograms recorded at Stanford University by Thomas and Sader (1963, 1964) and discussed in detail by Dayharsh and Farley (1965) using the same data, the magnitude of N_s is often observed to increase rapidly with latitude. This sudden increase, referred to as the electron density cliff, seems to occur near the low latitude edge of the auroral zone. These features are apparent at all altitudes in the night-time topside ionosphere (Figure 9, Thomas, Rycroft, Colin and Chan, 1966b) but are not seen at a mid-latitude telemetry station, such as Stanford, during the day.

The corresponding trough at the peak of the F2 layer has been called the "Main Trough" by Muldrew (1965), who found it to be more striking at night, and to exist at higher latitudes during the day. It has also been investigated from ion trap measurements between altitudes of 288 km and 359 km by Sharp (1966a), who has termed it the "Midlatitude Trough". It is also observed below the peak of the F region at an altitude of 180 km (Sharp, 1966b). An examination of world-wide contours of plasma frequency at the F2 layer peak (for example, see Martyn, 1955) reveals that a trough is present near 60^{o} geomagnetic latitude during the local night at all seasons, and at epochs of both low and high sunspot activity. Liszka (1965) has noted an electron density trough at the F layer peak from ground based ionosonde records taken by several stations in Scandinavia during November 1964. He also reports a manifestation of the same phenomenon in the latitudinal variation of the total electron content between Kiruna and the S-66 satellite (at $\sim$ 1000 km altitude), derived from differential Faraday rotation observations. At high latitudes and altitudes above 2000 km, the night-time electron density, deduced from Alouette II satellite data, reaches very low values ($\gtrsim 10^{2} cm^{-3}$) but, significantly, the cliff is not generally observed (J. Chapman and E. Hagg, private communication, 1966 Hagg, 1967, and Nelms and Lockwood, 1967).

It is with variations in the position of the center of the night-time trough (where the electron density N_s, as deduced from Alouette I observations telemetered to Stanford, reaches a minimum value) with changing magnetic activity that this paper is concerned. However, before undertaking a statistical study of the position of the trough and its movements, it is necessary to consider the distribution of observations taken between May and July 1963 (Thomas and Rycroft, 1968). Coordinates of the observational points in the local time and K_p index plane at which N_s reached a minimum value near 60° dip latitude ($L \sim 4$) are distributed at random. As there is no systematic trend or bias in the distribution of observational data, statistical methods of analysis are applicable.

3. WHISTLER OBSERVATIONS

In a review paper, Carpenter and Smith (1964) have discussed the reduction of whistler observations to electron density profiles in the equatorial plane. From measurements of a whistler's nose frequency (the frequency of minimum time delay), the minimum gyrofrequency along the path can be estimated and, assuming an undistorted dipole field, the distance of the ray path in the equatorial plane can be found. Since most of the delay and dispersion occur in this region, the electron density in the equatorial plane can be determined. In general the electron density, N, falls off smoothly out to a geocentric distance of $\sim$ 3.5 earth radii, where N is $\sim$ few hundred per cc. Often whistlers also have small-time-delay, low-nose-frequency components which can be interpreted as indicating the reduced electron content of a tube of force at larger distances from the earth. The region in the equatorial plane across which the electron density may decrease by an order of magnitude or more is comparatively narrow, only fractions of an earth's radius thick. This sudden electron density decrease (Carpenter, 1963) is referred to as the plasmapause or knee.

Carpenter (1966) has recently published results on the position of the plasmapause during July 1963 as deduced from whistlers recorded at Eights and Byrd Stations, Antarctica. The average width of the knee region was calculated from some of these data, and found to be ~ 0.4 earth radii. Half this value, namely 0.2 earth radii, was added to the equatorial distance inside the knee (when only this was given) to ascertain the radial distance to the center of the knee approximately. The equatorial distance to the center of the plasmapause, R_p, found for all these data, is used for the statistical study. The distribution of these observations with local time and K_p index is also random. Since the average values for the two ensembles differ only insignificantly, statistical methods of analysis and comparison can be used with confidence.

Carpenter (1966) has shown qualitatively that the knee appears closer to the earth as time progresses through the local night, and as magnetic activity increases.* Variations in R_p as the degree of magnetic activity changes are shown in Figure 3. These have already been quantitatively discussed in a preliminary manner (Rycroft, 1966). In that paper, the different indices by which magnetic agitation observed at the earth's surface can be measured, and also the influence of solar-terrestrial relationships on magnetic activity, were reviewed.

4. RESULTS

* Footnote. Carpenter and Stone report the discovery of a more rapid inward motion of plasma at a geocentric distance ~ 4 earth radii, associated with a polar substorm (Planet. Space Sci., 15, 395-397, 1967).

the point $K_p = 0o$ with zero gradient. These relations were chosen for their mathematical simplicity, rather than for their physical significance. The equations of the regression curves were computed, as were the standard errors of the coefficients multiplying the chosen variables. The standard error, a measure of the statistical uncertainty of the equation of regression, was considerably smaller than the scatter of the individual data points. If the better fitting curve were a straight line, the correlation coefficient between the two variables was calculated. The program also computed the percentage of the root mean square deviation of the observations that could be accounted for by the regression, together with its significance in the form of the F ratio (Tucker, 1962, Table III, for example), from which the probability that the regression relation might occur by chance was found. These quantities, pertaining to the results of the present analysis, are given in Table 1. The probability that the regression relation might be produced by chance is found, in each case considered here, to be less than 0.1%, extremely remote.

A general quadratic relation was also fitted to the data points. The improvement of fit, as measured by the increase in the percentage of the deviation of the observations explained by the relation, was found not to be sufficiently great as to warrant attempts at physical justification of the more complicated equation.

In Figure 4, the L value of the position of the minimum electron density in the trough at the Alouette I orbit, L_T, during the summer night is plotted against K_p. Again a parabolic regression is better than a linear one. Comparision of Figures 3 and 4 reveals a striking similarity in the two ensembles of data points and between the two parabolas describing the variation of the night-time knee and trough positions with varying K_p index. In fact the coefficients multiplying $\sqrt{K_p}$ differ by less than the sum of their standard errors (Table I). That these equations defining the line of force through the center, or minimum, of the night-time trough in the electron density at the Alouette I orbit and through the center of the knee, the point of inflexion in the equatorial plane electron density distribution, are identical for zero K_p, and separated in the equatorial plane by only 0.6 earth radii for $K_p = 4o$, is an indication that the two phenomena are closely related.

Further correlations between the positions of the trough and the plasmapause are now investigated. Another measure of magnetic activity useful in this regard is the daily A_p index. This index is well suited to studies of trough observations made during the local night at Stanford, which occurs between universal times of approximately 05.00 and 13.00 hours. The L value of the center of the trough, L_T, defined by the minimum N_s observed on consecutive ionograms near $L = 4$, and as presented in Figure 4, is plotted against the A_p index at the time of the observation in Figure 5. One point, at $L = 3.84$, $A_p = 43$, is omitted from this figure. A parabolic regression to the data points (with a very high significance figure) is also shown. A similar analysis was undertaken relating the L value of the center of the trough to the A_p index on the day prior to that on which the observation was made. Considerably more scatter was then apparent.

The L values of lines of force at which an abrupt decrease of the current to a mass spectrometer aboard the GOG-A spacecraft occurs is also plotted in Figure 5 (Taylor, Brinton and Smith, 1965). These observations were made at magnetic latitudes near 20° in the night-side magnetosphere during October and November 1964. The sudden decrease in the concentration of both hydrogen and helium ions, recently further investigated by Taylor, Pharo and Brinton (1967), is clearly a counterpart of the knee in the electron density distribution deduced from whistlers, and is thus also associated with the main trough in the topside ionosphere.

Since the same observations have been used in Figures 4 and 5, it is important to test the consistency of the results. Table 2 shows how the A and K indices of magnetic activity at a mid-latitudinal station are derived from corrected estimates of the range of the magnetic fluctuatio in each three-hourly interval (Chapman, 1963). The corresponding L values of the center of the N_s trough are computed from the A_p and K_p parabolic regression equations given in Table 1 for Figures 4 and 5. The ratio of these XXXXXXXXXX values is shown in Table 2. Within the statistical standard deviations of the regressions, this ratio is essentiall unity over the range $0o \leqslant K_p \leqslant 5o$, confirming the self-consistency of the relations. Thus either regression equation may, with similar certainty, be used to illustrate the variation in the position of the N_s trough with changing magnetic activity.

In Figure 6, the generalized invariant latitude Λ' (defined by equation (3)) of the position of the center of the night-time trough in N_s (data from Figure 4) is plotted against K_p. A linear regression fits the data almost as well as the parabolic regression in Figure 4 and is the more convenient analytical form. When the K_p index increases from 0o to 4o, the latitude of the center of the trough decreases from 61.2° to 54.0° on average. Muldrew (1965) has reported similar relationships between trough positions at the F region peak and K_p.

4.2 DIURNAL VARIATIONS

The diurnal variation in the position of the electron density trough remains to be discussed. In Figure 7 the magnetic dip latitude (derived from the local dip angle at the satellite, Thomas, Rycroft, Covert, Briggs and Colin, 1965) at which N_s reaches a minimum value is plotted against local time. Plotted data are shown by open circles for $K_p \leq 2+$ and dark circles for $K_p \geq 3-$; a tendency for the dark circles to fall at lower latitudes may be noted. There is also a tendency for the trough to occur at lower latitudes after local midnight. This trend may be seen in another way. For each observation, the difference between the observed L value of the center of the trough and that computed from the parabolic regression on K_p, ΔL_T, is calculated and plotted in Figure 8 against local time. The two-hourly average value of this difference, plotted as a cross, is positive before local midnight and negative at dawn. It is therefore shown that the position of the trough (having removed variations due to changes in magnetic activity) varies with local time. The repletion of this trough and its motion to lower latitudes as dawn progresses is also evident from Figure 11 of the paper by Thomas, Rycroft, Colin and Chan (1966b).

A similar procedure is followed in Figure 9 giving the diurnal variation in the position of the center of the knee in the magnetospheric equatorial plane electron density distribution. Average values of the difference between observed and regressive equatorial distances are plotted at hourly intervals as crosses. The trend, shown by the continuous line, is identical to that of Figure 8. This fact further supports the tenet that at any instant a single line of force of the geomagnetic field passes through the center of the N_s trough and the center of the knee. For an average value of $K_p = 3o$, the equatorial plane geocentric distance to the center of the knee is ~ 4.8 earth radii at 21.00 L.T., ~ 4.3 at 01.00 and ~ 3.7 at 06.00. The point at which the line of force through the trough and the plasmapause crosses the equatorial plane moves closer to the earth during the local night at a rate ~ 0.1 earth radii/hour. In terms of the field line's invariant latitude at the earth's surface, (defined by equation (1)), the approximate positions are 63° at 21.00 L.T. and 59° at 06.00.

4.3 FURTHER RELATIONS

On eight occasions in July 1963, between local times of 19.00 and 23.00 hours, it was possible to measure both the position of the knee (from Byrd and Eights Stations records) and that of the trough (from ionograms telemetered to Stanford) almost simultaneously in universal time. These values are plotted in Figure 10. Also shown is the best fit linear relation, together with the standard errors of the intercept and gradient. Since the correlation coefficient is large and the slope of the graph not far from 45°, it can again be concluded that the two phenomena lie on the same line of force. The relationship between the knee and the trough has thus been successfully demonstrated both for individual events (Figure 10), and statistically during the summer of 1963 (Figures 3 and 4).

It is interesting to note that other prominent features of the topside ionosphere follow the same tendency to occur at lower latitudes under conditions of enhanced magnetic activity. Figure 11 shows that the center, or average position, of the auroral cliff forming the polewards edge of the trough occurs on average at L = 8.4 for zero K_p and at L = 4.4 when $K_p = 4o$. A temperature increase in the topside ionosphere associated with the center of the auroral zone behaves similarly (Figure 15, Thomas, Rycroft, Colin and Chan, 1966b). A morphological review of auroral precipitation studies has been presented by Piddington (1965). While magnetic storms are in progress, auroras are visible from the earth's surface at lower magnetic altitudes, that is at lower L values, than usual (Chapman, 1963). Speiser (1965) has calculated such a behavior assuming the aurora to be generated by charged particles accelerated by electric fields in the neutral sheet of the geomagnetic tail, in which the ambient magnetic field strength varies.

It appears therefore that, as the solar wind pressure increases, the entire magnetosphere is compressed and particular field lines, on which prominent features of the magnetospheric-ionospheric interacting system are to be found, cross the equatorial plane closer to the earth, being tied to the earth's surface at lower latitudes.

It seems odd that the region in the ionosphere where $\delta N/\delta L$ at 1000 km is zero, corresponding to the minimum of the trough, is associated with the region in the equatorial plane where $\delta N/\delta L$ is a maximum, corresponding to the plasmapause, where this quantity is typically -500 electrons/cc/earth radius. It might have been expected that the plasmapause would be associated with the mid-latitude region where the rate of decrease of N with latitude was greatest, that is with the equatorwards edge of the trough (where $\delta N/\delta L$ at 1000 km $\simeq -3 \times 10^3$ electrons/cc/earth radius). It should be noted however that there are marked diurnal and latitudinal modulations of the density and ion composition of the topside ionosphere controlled by ionizing electromagnetic radiations from the sun (Thomas, Rycroft, Colin and Chan, 1966b) in this region. Further study of the rate of decrease of ionization as the trough is approached would be worthwhile.

Alternatively it might have been expected that the plasmapause would be associated with the auroral cliff. However this is a comparatively local phenomenon in the topside ionosphere which is not observed by the Alouette II satellite above ~ 2000 km (Hagg, 1967, Nelms and Lockwood, 1967). It is believed that the enhanced ionization below the Alouette I satellite at ~ 1000 km altitude results from the bombardment of the auroral ionosphere by energetic particles, and the consequent upwards diffusion of warmer plasma along, and to a lesser extent across, lines of force of the geomagnetic field. Now it is well known that the position of the auroral zone under conditions of average magnetic activity ($K_p \sim 3$) falls at an L value ~ 7 at local midnight (Akasofu, 1965, Piddington, 1965). But since conditions for whistler propagations to the far reaches of the magnetosphere are unfavourable, the properties of the low density, collisionless (Alfvén and Fälthammar, 1963) plasma near the equatorial plane of the magnetosphere for $L \sim 7$ are not well known. The connection between ionospheric and magnetospheric parameters is uncertain at large L values, whereas at lower L values, inside the knee, parameters of the exospheric plasma can be explained to first order on the diffusive equilibrium, dipole field model of Thomas and Dufour (1965).

4.4 LIMITATIONS

Table 1 shows the percentage of the deviation in the observations that is accounted for by the best fit regression whose equation is given in the appropriate figure of Figures 3, 4, 5, 6, 10 and 11. The remainder of the deviation may be accounted for in the following ways:

1. Imprecision of the measurements. Since one ionogram is recorded each 18 seconds, during which time the satellite travels about 1°

in latitude, or about 0.3 in L value at these latitudes, the error in the determination of the L parameter of the minimum value of N_s is not less than ± 0.3. Also, in this latitude range, traces on the ionogram become spread and thus difficult to read accurately. It may even by impossible to read $f_x S$ on consecutive ionograms at all, in which case the error in the determination of the position of the trough may be doubled or trebled. The error in the determination of the position of the knee, bearing in mind the reservations made in section 3, is $\sim$ 0.3 earth radius.

2. Data obtained over several hours have been considered together. Since a marked diurnal variation in the position of the trough has been reported by Thomas, Rycroft, Colin and Chan (1966b), and herein, and in that of the knee by Carpenter and Jewell (1965), and by Carpenter (1966), scatter is introduced by this selection of the data. It is notable, however, that both trough and knee move to lower L values as local time increases beyond midnight, as the dawn progresses.

3. The K_p index of magnetic activity, an average world-wide three-hourly index, may not be a good measure of the intensity of the (unknown) magnetospheric phenomenon responsible for the changing positions of both the plasmapause and the trough.

4. Insufficient data have been collected for very good statistical results. To repeat the analysis including observations made during conditions of solar maximum when magnetic activity on earth is greater would be worthwhile. The results presented here should be considered as being preliminary.

5. CONCLUSIONS

It has been demonstrated within experimental error that the center of the night-time trough of electron density at the Alouette I orbit ($\sim$1000 km altitude) and the center of the knee in the equatorial plane electron density distribution, the plasmapause, fall, at any one time, on the same geomagnetic field line ($L \sim 4$). This relationship is shown diagrammatically in Figures 12 and 13. Contemporaneous measurements have been made on eight individual occasions, for which the correlation coefficient between the radial distances to the pertinent field lines in the equatorial plane is 0.73 (Figure 10). The relation has also been derived statistically. Scatter amongst the observations of the positions of both the ionospheric electron density trough and the magnetospheric plasmapause, evident in several Figures, has been reduced by regression techniques. It is noteworthy that the two features exhibit a common regression curve with changing K_p index of magnetic activity and local time. The equations best describing the variation of the position of the minimum of the summer night-time trough in N_s with K_p (Figures 4 and 6) are:-

$$L_T = 5.64 - (1.09 \pm 0.22) \sqrt{K_p}, \quad \text{and}$$

$$\Lambda' = 61.22^\circ - (1.80^\circ \pm 0.38^\circ) K_p.$$

The best fit equation for the center of the knee, derived from whistler observations (Figure 3), is:-

$$R_P = 5.64 - (0.78 \pm 0.12) \sqrt{K_p} \quad \text{earth radii.}$$

It is inferred from the statistical tendency for the plasmapause and the trough near the exospheric base to lie on the same lines of force that they are basically related phenomena. It is reasonable to suggest that a general decrease of plasma density occurs beyond a particular field line ($L \sim 4$) whose precise position depends on magnetic activity and on local time.

There is, however, a departure from the first-order effect of perfect one-to-one correlation between the knee and trough positions as K_p takes on large values. The center of the trough, that is the position of minimum electron density, falls at a systematically lower L value than the geocentric distance to the center of the plasmapause (in earth radii). For example, a comparison of Figures 3 and 4 reveals that, when $K_p = 4o$, $L_T = 3.46$ and $R_P = 4.08$ earth radii. Or using the results shown in Figure 10, when $L_T = 3.46$ then $R_P = 4.16$ earth radii. Thus for higher values of K_p, it is the position of the polewards edge of the trough, the cliff, which is better correlated with the plasmapause position; for $K_p = 4o$ then, according to Figure 11, $L_{cliff} = 4.35$.

The L value of the field line through the trough and the knee decreases at a rate of ~ 0.1 earth radii/hour during the local night, as illustrated by the horizontal arrows in Figure 13. In the lower part of this figure the vertical arrows denote the changes in electron density at the Alouette I orbit as local night progresses, with local time changing from 21.00 to 05.00. The electron density lies within the range where double headed arrows are shown, exhibiting little systematic dependence on local time. The marked time variations of electron density in the topside ionosphere are thought not to manifest themselves in the magnetospheric electron density profile (see Figure 17, Angerami and Carpenter, 1966). The electron content of a tube of force, of unit cross-sectional area at an altitude of 1000 km, has been calculated on the basis of different models inside and outside the knee by Angerami and Carpenter (1966). At latitudes where Λ' is greater than $\sim 57^{\circ}$, the tube electron content is almost an order of magnitude lower than at lower latitudes.

One explanation of the association between XXXXXXXXXXXXX the night-time trough and the knee is possible in terms of a flow pattern for the magnetospheric plasma (Dungey, 1961) in which plasma flows towards the sun beyond $L \sim 4$, and is sucked out of the ionosphere along a line of force $L \sim 4$. Nishida (1966) has proposed another magnetospheric convective system, incorporating effects due to the earth's rotation and the magnetospheric tail. Another explanation is related to plasma out-flow through the knee due to the flute, or hydromagnetic interchange, instability there (Sonnerup and Laird, 1962, Scarf, Bernstein and Fredricks, 1966). The plasma would then be dumped into the high latitude ionosphere, and recycled.

Details of the association reported here need to be investigated further, by both theoretical and experimental means. A coordinated project using two or more satellites would be fruitful.

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Table 1

Figure Number	Features Correlated	Regression Relation	Number of data points	Percentage of RMS deviation of observations explained by the relation	Correlation Coefficient	F ratio
3	Equatorial distance of night-time, July 1963, knee in whistler profile vs. K_p. *	$R_p = 5.64 - (0.78 \pm 0.12)\sqrt{K_p}$ earth radii	102	30%	-	43.2
4	L value of night-time, summer 1963, minimum of trough at Alouette I orbit vs. K_p. *	$L_T = 5.64 - (1.09 \pm 0.22)\sqrt{K_p}$	45	37%	-	25.6
5	L value of night-time, summer 1963, minimum of trough at Alouette I orbit vs. A_p.	$L_T = 6.04 - (0.62 \pm 0.13)\sqrt{A_p}$	34	42%	-	23.3
6	Generalized invariant latitude of night-time, summer 1963, minimum of trough at Alouette I orbit vs. K_p.	$\Lambda' = 61.22^\circ - (1.80^\circ \pm 0.38^\circ)\, K_p$	45	34%	0.58	22.1
10	Equatorial distance of knee in whistler profile vs. L value of minimum of trough at Alouette I orbit on same days, July 1963, 19.00 - 23.00 L.T.	$R_p = (0.54 \pm 0.18)L_T + (2.28 \pm 0.77)$	8	-	0.73	-
11	L value of midpoint of auroral cliff, the polewards edge of the trough at Alouette I orbit near $L \sim 4$, vs. K_p.	$L = 8.43 - (2.04 \pm 0.32)\sqrt{K_p}$	45	49%	-	40.7
-	L value of low latitude edge of cliff at Alouette I orbit vs. K_p.	$L = 6.55 - (0.65 \pm 0.11)\, K_p$	45	46%	0.68	36.3

* It should be noted that, for all values of $K_p > 0$, $L_T < R_p$. Thus the correlation between the L value of the low latitude edge of the trough and R_p is only poor.

TABLE 2

Comparison of A_p and K_p regressions for L value of center of N_s trough

Range of fluctuations, in γ	0-5	5-10	10-20	20-40	40-70	70-120
A index, mean range of fluctuations, in 2 γ	1.25	3.75	7.50	15.0	22.5	47.5
Equivalent K index	0o	1o	2o	3o	4o	5o
Ratio of L values of center of N_s trough, computed from A_p regression to that computed from K_p regression	0.95±0.03	1.07±0.07	1.1±0.1	1.0±0.2	0.9±0.2	0.6±0.3

FIGURE CAPTIONS

Figure 1 The electron density at the Alouette I orbit on two occasions during the local night in June 1963, as a function of L value. The upper graph shows observations made on June 4 1963, 02.40 to 03.10 L.T., K_p 1-, and the lower graph those taken on June 7 1963, 02.08 to 02.36 L.T., K_p 5-. Both the trough and the cliff are apparent on each occasion.

Figure 2 Schematic / diagrams showing two possible ways in which the density of plasma near 1000 km altitude at night varies with McIlwain's parameter L. The dashed curve illustrates the variation of electron density due to decaying photoionization and the dotted curve that associated with auroral corpuscular radiation. It it the sum of these two effects, shown as the solid curve, which is observed experimentally.

Figure 3 The radial distance to the center of the knee in the equatorial plane electron density distribution, deduced from whistlers observed during the local night in July 1963, as a function of the K_p index of magnetic activity. A best-fit regression line is also shown.

Figure 4 The L value of the position of minimum electron density at the Alouette I orbit, the center of the trough, deduced from ionograms recorded at Stanford during the local night (21.00 to 06.59) in the summer of 1963, as a function of the K_p index of magnetic activity. A best fit regression line is also shown.

Figure 5 The L value of the center of the night-time electron density trough at the Alouette I orbit as a function of the daily A_p index of magnetic activity. A best-fit regression line is also shown, as are the positions of the sudden current loss to the OGO-A mass spectrometer (Taylor, Brinton and Smith, 1965).

Figure 6 The generalized invariant latitude, Λ', of the night-time electron density trough at the Alouette I orbit as a function of the K_p index of magnetic activity. The best fit linear regression is also shown.

Figure 7 Graph summarizing the two main effects which determine the latitudinal position of the electron density trough at the Alouette I orbit.

(1) The trough tends to move to lower latitudes as dawn approaches;

(2) At a certain local time, the trough tends to exist at a lower latitude when $K_p \geq 3$ (dark circles) than when $K_p \leq 2+$ (open circles)

the straight line serves as a line of demarcation, guiding the eye between these two regimes.

Figure 8 The difference between the observed L value of the trough and that computed from the parabolic regression lines of figure 5, as a function of local time. This quantity tends to be positive at dusk and negative at dawn. Two-hourly average values are shown as crosses.

Figure 9 The difference between the observed R_p value of the knee and that computed from the parabolic regression line of figure 4, as a function of local time. This quantity also tends to be positive and dusk and negative at dawn. Hourly average values are shown as crosses.

Figure 10 The radial distance to the center of the knee in the equatorial plane electron density distribution, deduced from whistlers, correlated with the L value of the center of the electron density trough at the Alouette I orbit (19.00 to 23.00 local time), the observations being made on the same day during July 1963. The probability that such a high correlation coefficient, 0.73, would be attained if the variables were, in fact, unrelated is only 4%.

Figure 11 The L value of the midpoint of the auroral cliff, the polewards edge of the electron density trough at the Alouette I orbit, deduced from ionograms telemetered to Stanford during the local night in the summer of 1963, as a function of the K_p index of magnetic activity.

Figure 12 Diagram illustrating the result that a particular line of force of the geomagnetic field ($L \sim 4$) passes through both the minimum of the electron density trough at the Alouette I orbit and the center of the magnetospheric plasmapause.

Figure 13 Diagram illustrating the result that the centers of the plasmapause and trough lie on the same geomagnetic line of force, typically $L \sim 4$, or $\Lambda' \sim 57^\circ$, for $K_p \sim 3$ at 02.00 local time. Typical magnetospheric and ionospheric profiles are shown, together with their behavior with changing local time.

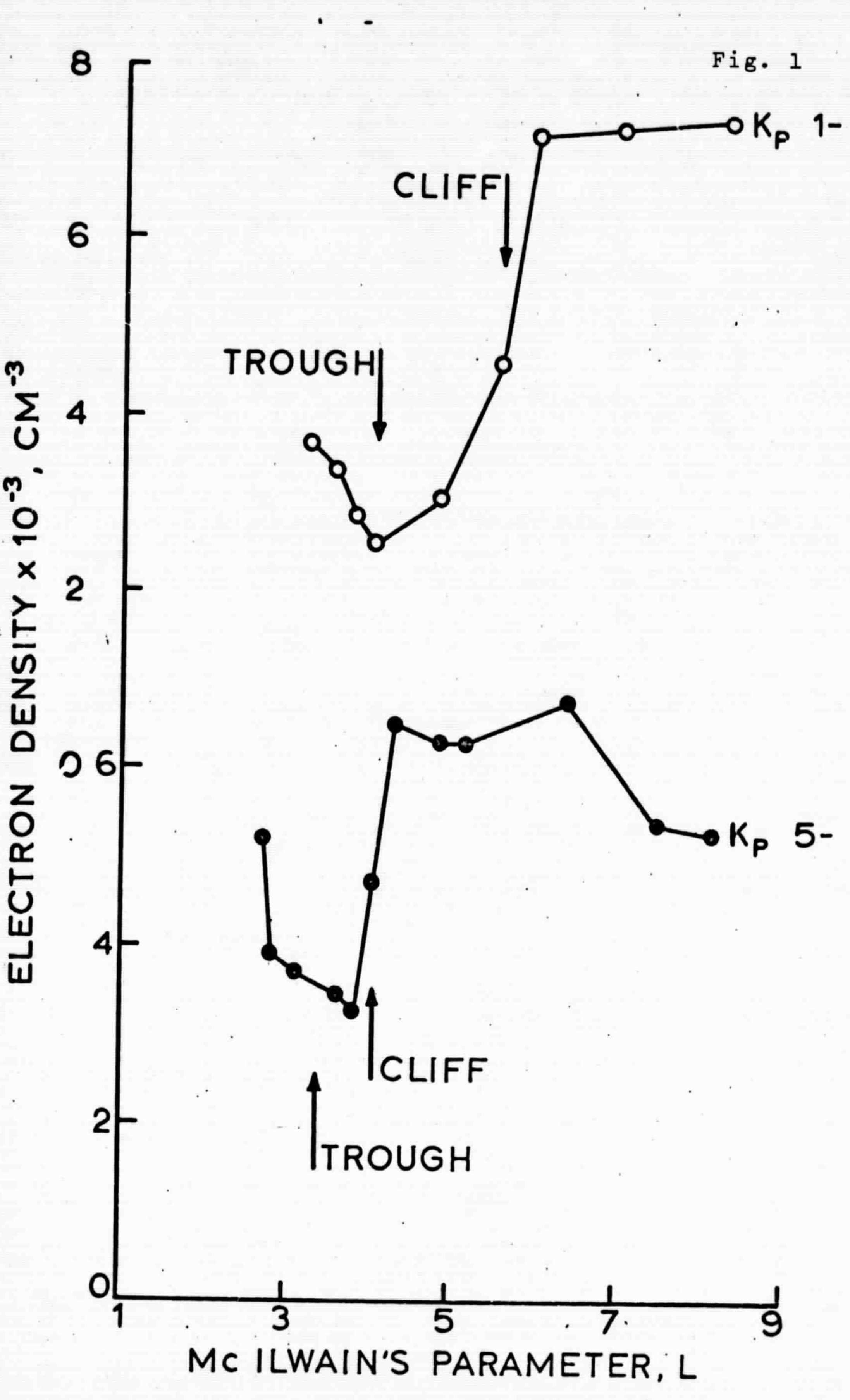


Fig. 1
8
6
4
2
0 6
4
2
0
1
3
5
7
9
ELECTRON DENSITY x 10-3, CM-3
Mc ILWAIN'S PARAMETER, L
TROUGH
CLIFF
KP 1-
KP 5-
CLIFF
TROUGH

Fig. 2

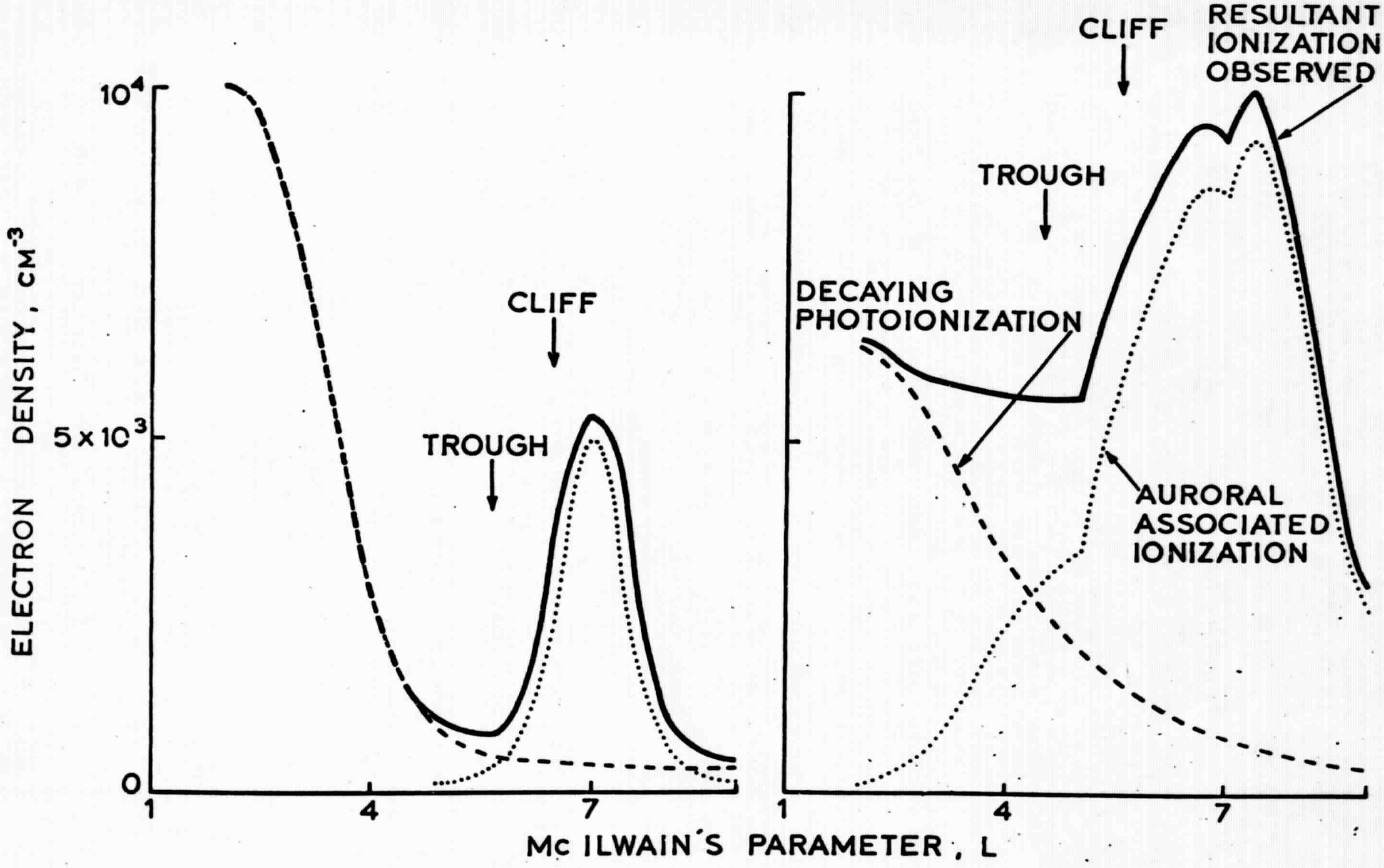
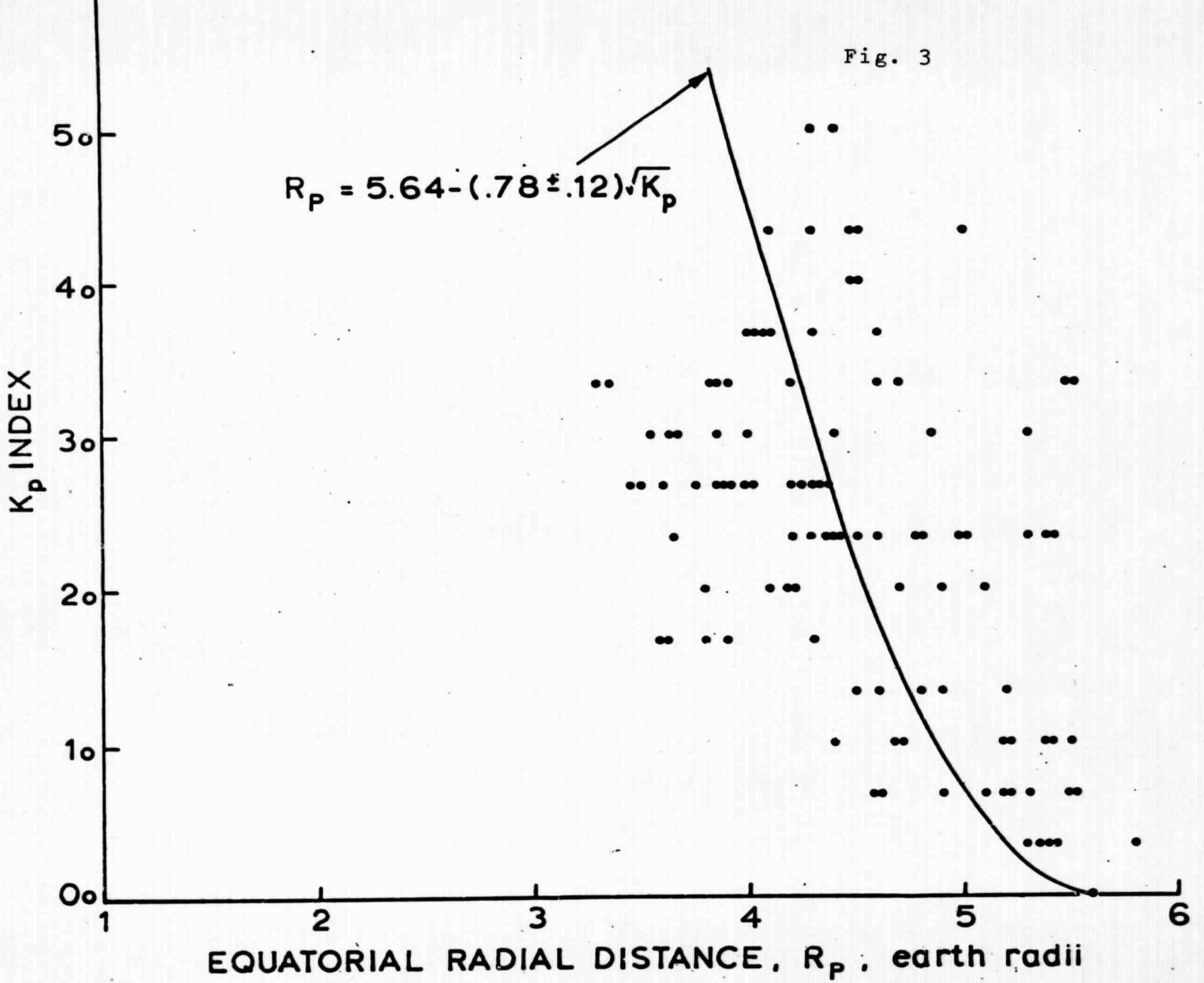

ELECTRON DENSITY, CM-3
10⁴
5x10³
0
CLIFF
TROUGH
1
4
7
DECAYING PHOTOIONIZATION
RESULTANT IONIZATION OBSERVED
AURORAL ASSOCIATED IONIZATION
Mc ILWAIN'S PARAMETER, L

Fig. 3



$R_p = 5.64 - (.78 \pm .12)\sqrt{K_p}$
K_p INDEX
5o
4o
3o
2o
1o
0o
1
2
3
4
5
6
EQUATORIAL RADIAL DISTANCE, R_p, earth radii

Fig. 6

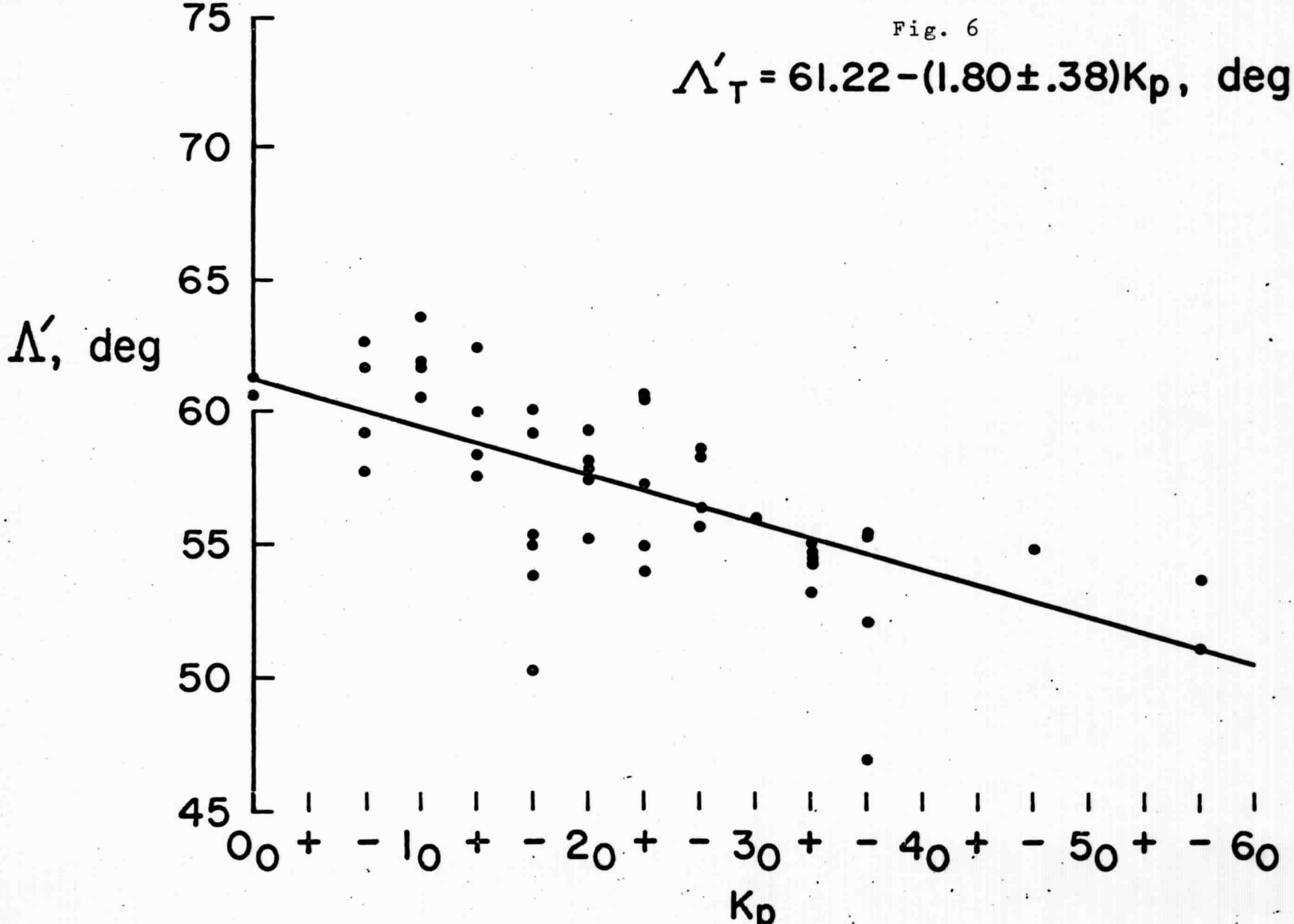
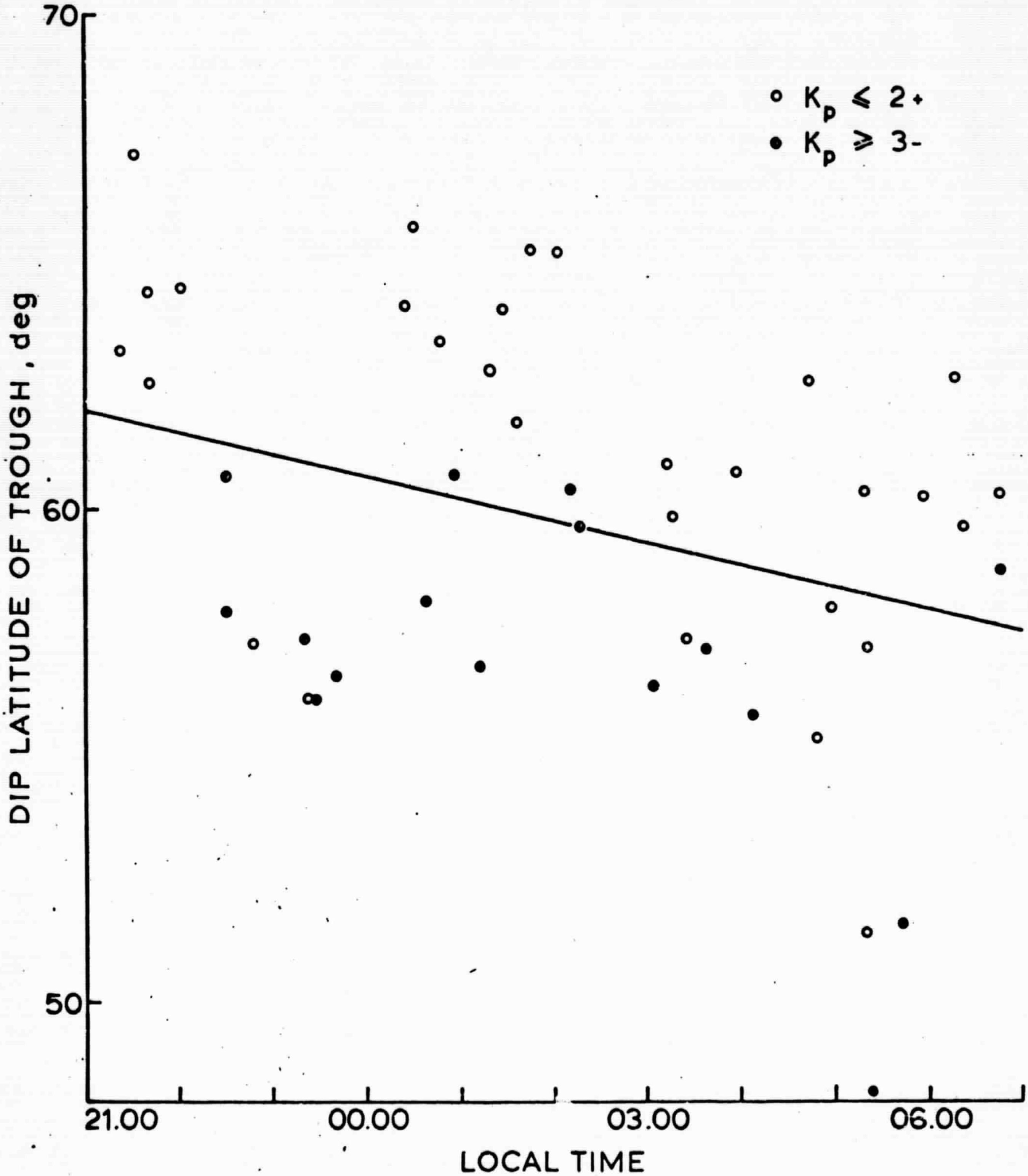

$\Lambda'_T = 61.22-(1.80\pm.38)K_p$, deg
Λ', deg
75
70
65
60
55
50
45
0_0 + - 1_0 + - 2_0 + - 3_0 + - 4_0 + - 5_0 + - 6_0
K_p

Fig. 7



70
60
50
DIP LATITUDE OF TROUGH, deg
○ $K_p \leqslant 2+$
● $K_p \geqslant 3-$
21.00
00.00
03.00
06.00
LOCAL TIME

Fig. 8

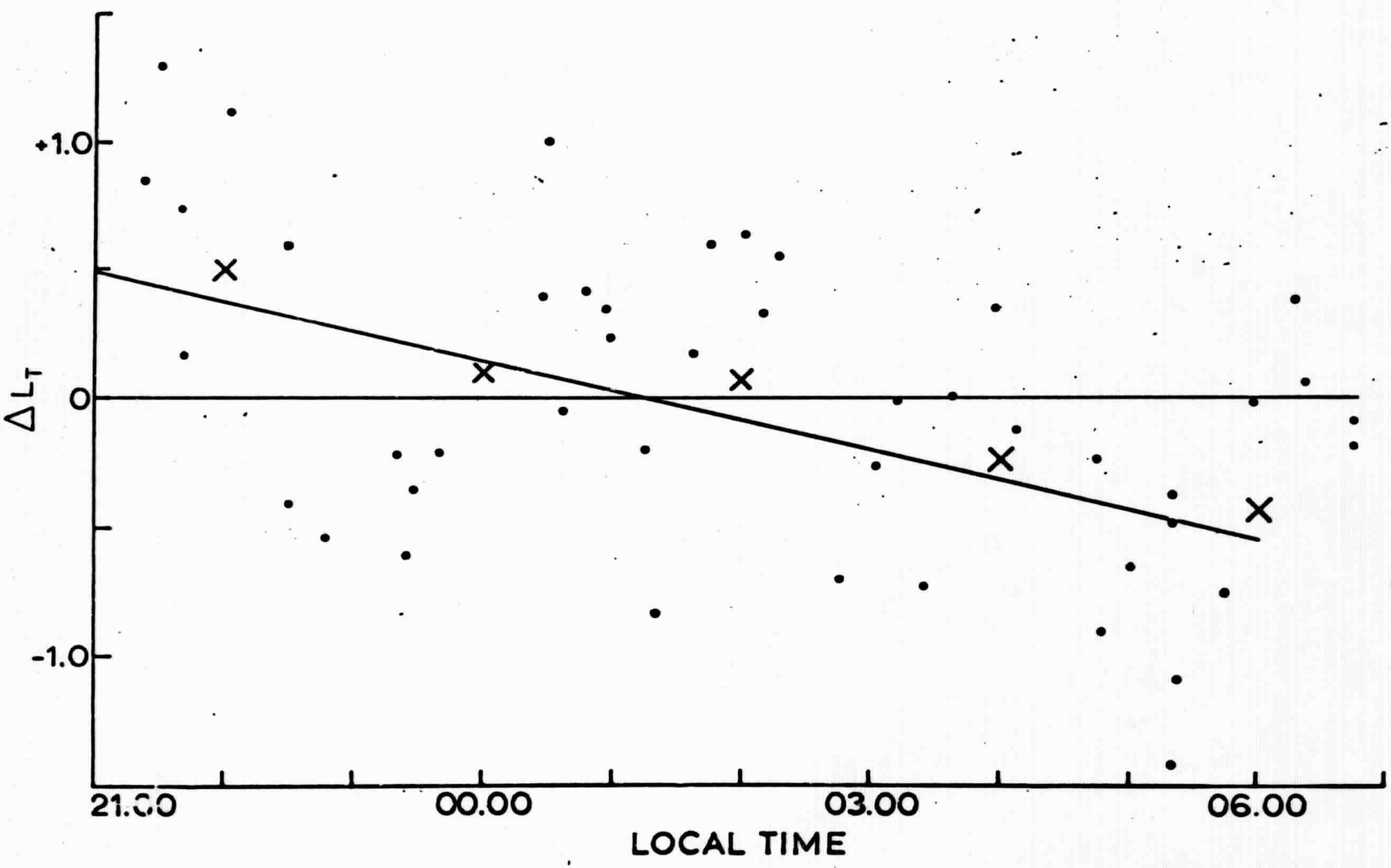


Fig. 9

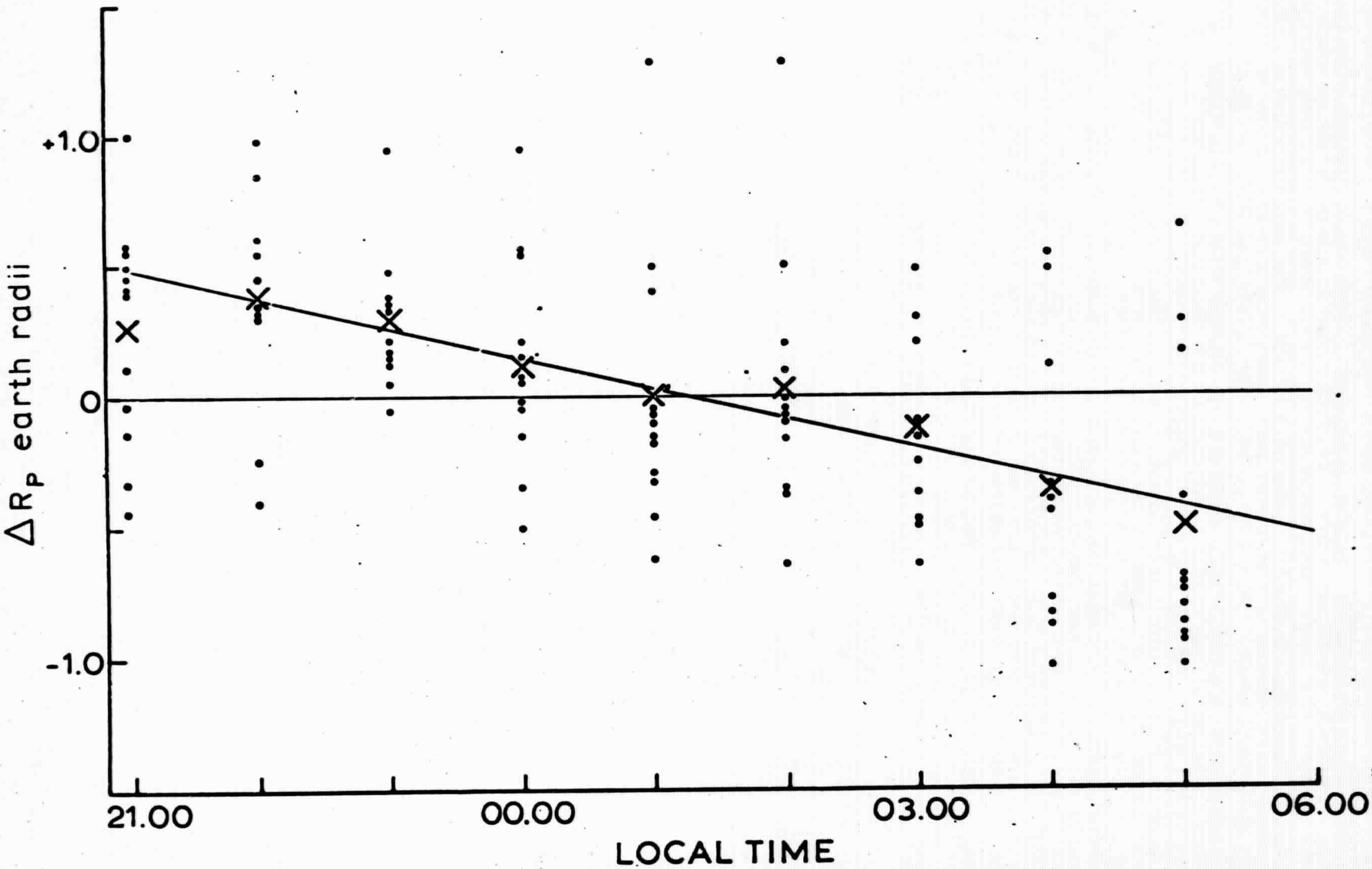
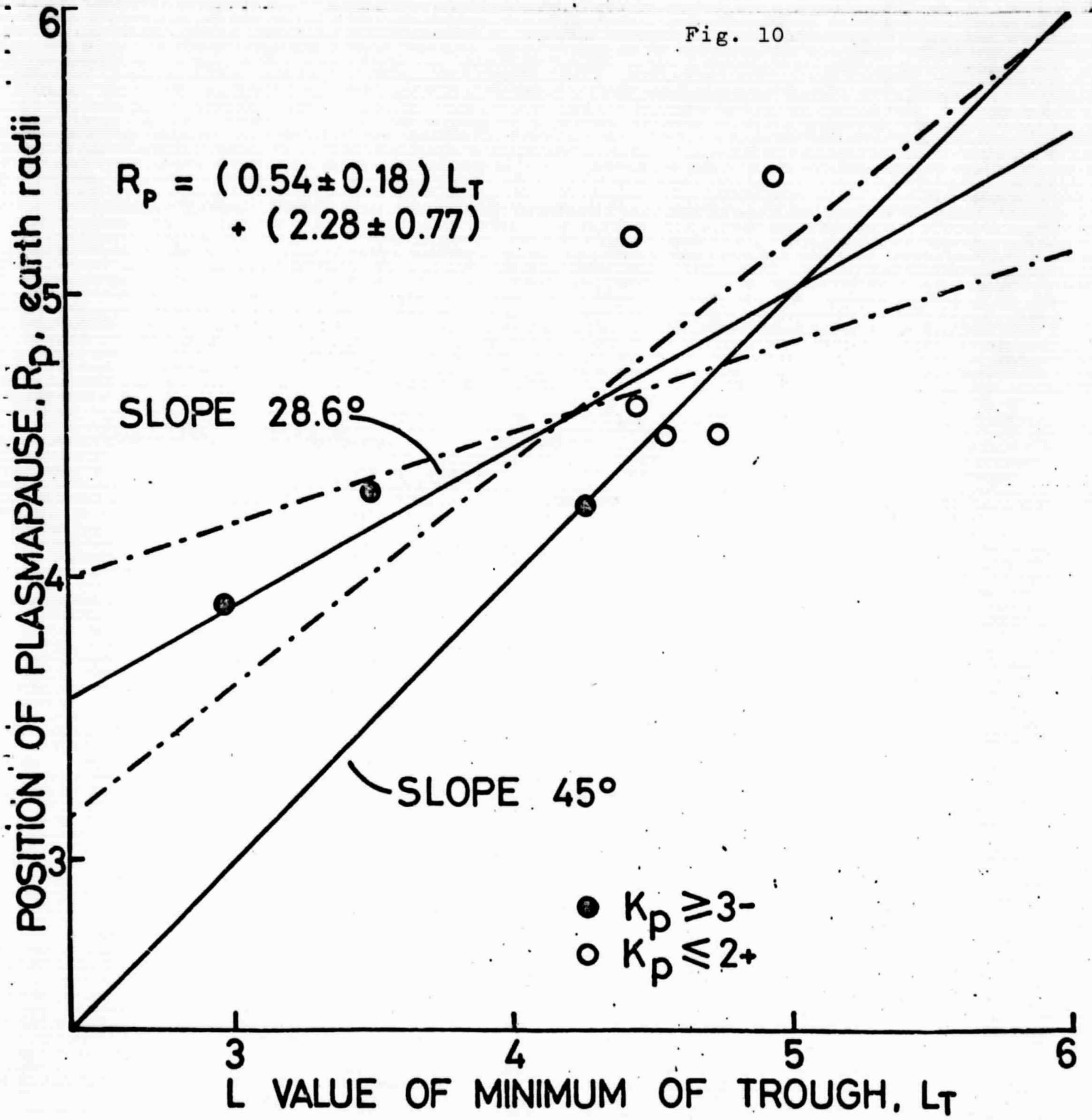


Fig. 10



$R_p = (0.54 \pm 0.18)\, L_T$
$+ (2.28 \pm 0.77)$
SLOPE 28.6°
SLOPE 45°
● $K_p \geqslant 3-$
○ $K_p \leqslant 2+$
POSITION OF PLASMAPAUSE, R_p, earth radii
L VALUE OF MINIMUM OF TROUGH, L_T
3
4
5
6

Fig. 11

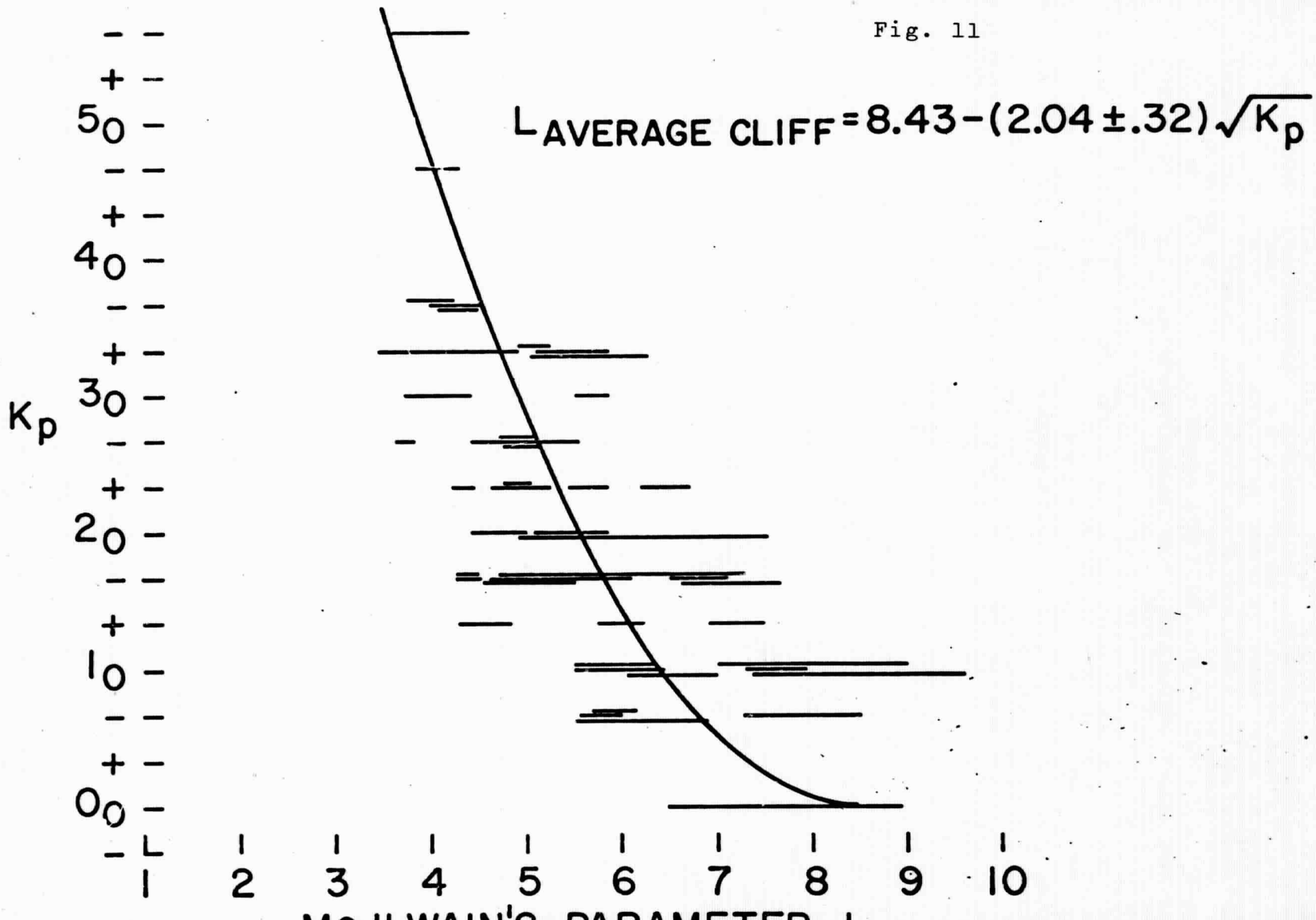
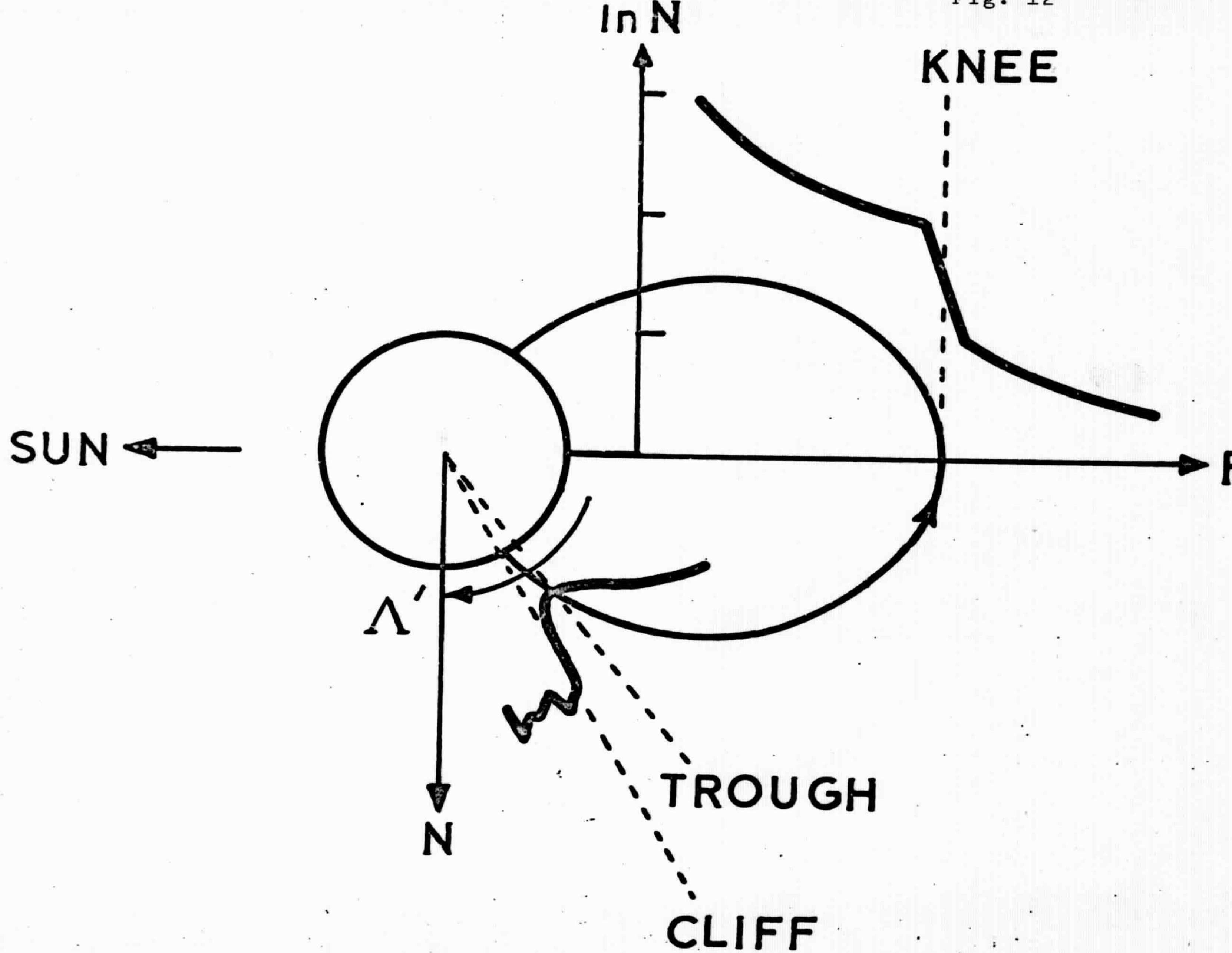
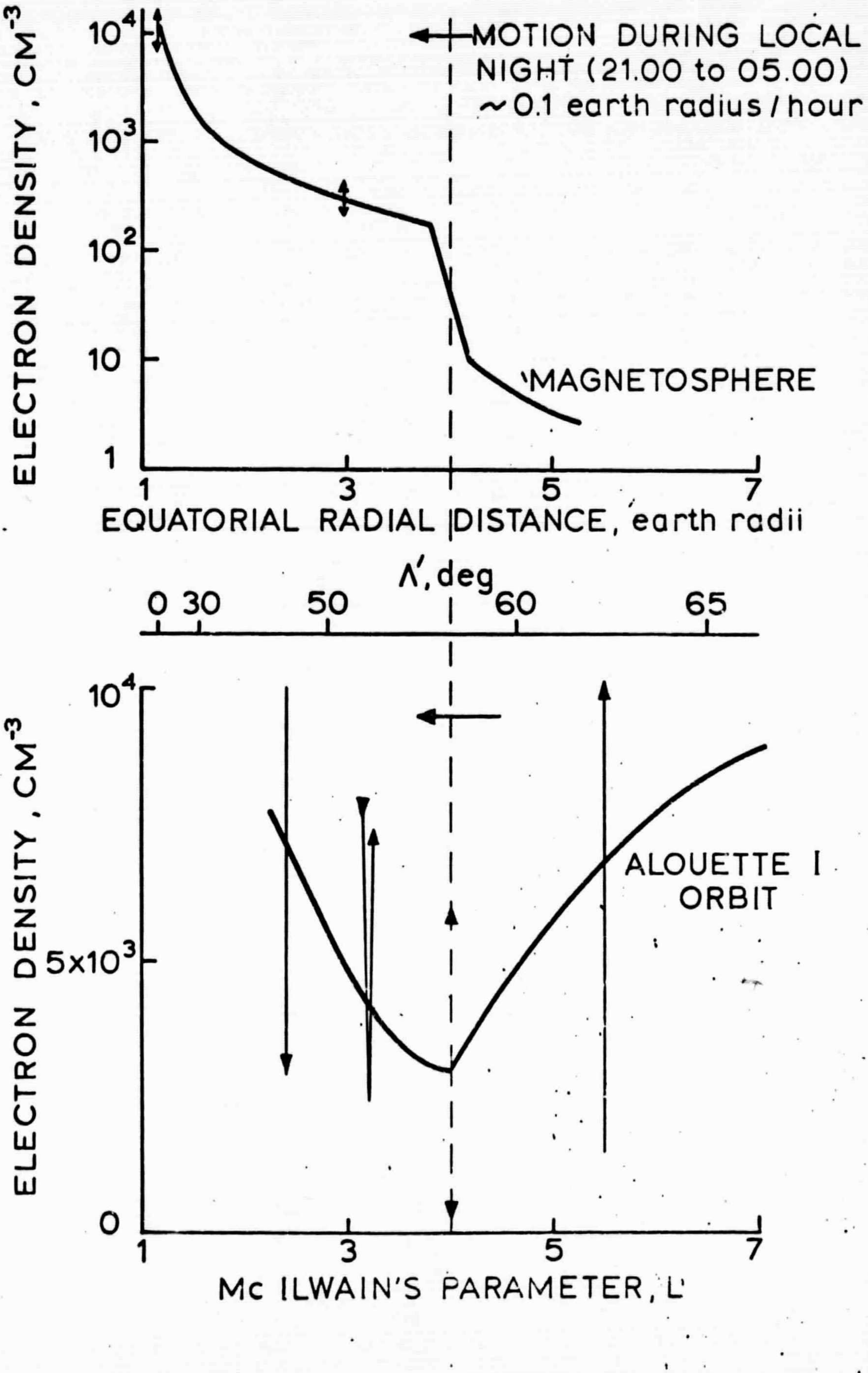

L AVERAGE CLIFF = 8.43-(2.04±.32)√Kp
Kp
50
40
30
20
10
00
1
2
3
4
5
6
7
8
9
10
MC ILWAIN'S PARAMETER, L

Fig. 12




ELECTRON DENSITY, CM^{-3}
MOTION DURING LOCAL NIGHT (21.00 to 05.00)
~0.1 earth radius / hour
MAGNETOSPHERE
EQUATORIAL RADIAL DISTANCE, earth radii
Λ', deg
ALOUETTE I ORBIT
Mc ILWAIN'S PARAMETER, L