C.N. Pq

IONOSPHERIC ELECTRON CONTENT MEASUREMENTS IN REGIONS OF LOW MAGNETIC DIP ANGLES AND THROUGH THE BRAZILIAN MAGNETIC ANOMALY

by

FERNANDO DE MENDONÇA

TECHNICAL REPORT LAFE-14
(PRELIMINARY)

SUBMITTED TO THE COSPAR'S
FIFTH INTERNATIONAL SPACE SCIENCE SYMPOSIUM,
FLORENCE, ITALY

C
N
A
E

Comissão Nacional de Atividades Espaciais
Laboratório de Física Espacial
São José dos Campos — S.P.
Brasil

May 1964

IONOSPHERIC ELECTRON CONTENT MEASUREMENTS IN REGIONS OF LOW MAGNETIC DIP AND THROUGH THE BRAZILIAN MAGNETIC ANOMALY

by

F. DE MENDONÇA

Comissão Nacional de Atividades Espaciais
São José dos Campos (SP), Brasil

ABSTRACT

Differential Doppler measurements made with harmonically related frequencies transmitted from satellites are utilized for calculation of the latitudinal and diurnal variations of the total electron content of the ionosphere. These preliminary measurements, performed during April, 1963, with the satellite Anna-1-B, cover areas with subionospheric points from the vicinity of the magnetic equator to about -40^{o} dip, and between longitudes of 35^{o} and 60^{o} W. Mainly two distinct fenomena are noticed in the ionosphere of this region. The first is that a latitudinal maximum value of the total electron content developes at the magnetic equator at sunrise and moves way toward higher dip angles for the whole day possibly due in part to diffusion in the higher ionosphere along the magnetic field lines. The second pheno-

menon is that there is a marked increase in electron content in the region which geographically correspondes to the area of the Brazilian anomaly of the earth's magnetic field in the South Atlantic. This enhancement in electron content is atributable to ionization caused mostly by high energy particles of the artificial belt, which have mirroring points in levels well into the ionosphere at the magnetic anomaly.

1. INTRODUCTION

Total ionospheric electron content I (t), i. e., the integration of the electron density N from ground level to a given height, has been determined by many investigatiors utilizing propagation characteristics of radio waves transmitted from satellites.

A description and comparison of the variφous methods utilized in calculations of I (t) has been done by Garriott and de Mendonça (1), and one of the processes shown in their paper is applied here for reduction of differential Doppler measurements data obtained from the satellite 62601 (Anna-1-B) at São José dos Campos Station. Collection of data begun early April 1963 and has continued in a routine basis without interruptions since then, with satellites of the same series, providing many hundreds of satellites passages up to the time of this writing. The work reported herein is based on 75 passages of Anna during the first 30 days of observations (April 11 through May 11, 1963), which was a period of low magnetic activity.

Work is continuing and a paper which is in preparation will present a seasonal variation of transequatorial electron content.

The satellite Anna-1-B is in an almost circular orbit (apogee 1080 km, perigee 1170 km) with inclination of 50^{o}. The harmonically related frequencies which were used (162 and 324 Mc) permit one to disregard not only the effects of the earth's magnetic field on the waves propagation [(2)] but also permit the use of observations which had maximum elevation angles as low as 25^{o} above the horizon [(3)].

The linear gradient aproximation was assumed in calculating I (t) by means of a best fit procedure to particular intervals of time (chosen initially by inspection of the raw data) during each passage. Afterwards the mentioned assumption would be check for consistency and corrections applied when necessary.

Two features of the latitudinal variations of the electron content I (t) will be discussed in this preliminary paper, namely the increases in the values of I (t) in the ranges of the equatorial anomaly and of the South Atlantic or Brazilian magnetic anomaly.

Some of the results will be compared with measurements which were made with the Canadian topside sounder satellite (Alouette), as reported by King et al. [(4)].

2. DATA REDUCTION METHOD

The satellite Anna transmitted the fundamental and its second harmonic in the frequencies of 162 and 324 Mc/s respectively. Due to dispersion these signals were affected differently by the presence of the ionosphere. Detecting them by means of phase-locked receivers, dividing the higher frequency by their harmonic relationship, one obtains a beat frequency which can be shown [3], when proper approximations are performed, to be given by

$$f_b = (1/\lambda)\,(d/dt)\,(P_1 - P_2) = (K/cf)\,\left[(m^2-1)/m^2\right](d/dt)\int N ds \qquad \text{(I)}$$

where

f_b - beat frequency at the receiver output

λ - free space wavelenght of the lower frequency

P - phase path lenght $\int \mu ds$

m - the harmonic relation of the waves

N - electron density

K - a constant (40. 3 in MKS units)

From rise to set of the satellite this frequency will go through zero beat at least once. For convenience one may choose the moment when the beat is zero (proximal point) for reference time, and by counting cycles versus time from this reference one is in fact performing an integration of equation (I). Then

$$I\,(t) = \int_0^{h_s} N dh = \left[\cos \chi_m\, cfm^2/K\,(m^2-1)\right]\,\left[\int f_o dt + C\right] \qquad \text{(II)}$$

In the reduction of data for this paper the constant of integration C was determined by means of a root-mean-square minimization procedure assuming a linear gradient of I (t) to sections of every run and using an IBM - 1620 computer.

The other input parameters in the program which were dependent in the geometry of the system were obtained from orbital elements of the satellite and were provided to us by the Applied Physics Laboratory of the Johns Hopkins University.

From the computer output, comprised of I (t), subsatellite geographic coordinates and height, we determined the electron content I (t) in terms of the subionospheric point magnetic dip angle, local time, geographic latitude and the relative time from the principal zero beat (proximal point) as shown in Fig. 1.

The subionospheric point was chosen to be given by the projection on the ground of a point along the ray whose height was 350 km, because ionosounding information to provide us with F region distribution informations was not available to most of the area of interest.

3. THE EQUATORIAL ANOMALY IN N_{max}

Maeda et al. [5] in 1942 and independently Appleton [6] in 1946, using F region critical frequency measurements from many ionospheric stations indicated a geomagnetic control of the distribution of ionization in the F region for low values of sun's zenith distance. As a consequence of this control, the noon equinox conditions of critical frequencies were such that the values were lower at the magnetic dip equator than at neighboring regions. In fact it was observed that the noon critical frequencies fo F2 increased with increasing dip angle in both hemispheres up to a certain point around 30° dip and then decreased from there on toward the poles.

In the same year Mitra [7] (1946) considered the nature of the source of the magnetic control and pointed out as plausible the assumption that the charged particles were of terrestrial origin, and that the ions and electrons formed in the high atmosphere in the equatorial belt were guided north and south coming down to lower levels along the lines of force of earth's magnetic field and contributing to the ionization density of the F region. Since then, many paper have been published about the equatorial anomaly. Martin [8] in 1955, concluded that the principal cause of the equatorial anomaly was the divergence of the vertical drift velocity and mentioned that diffusion was not the dominant factor. Rishbeth et al. [9] discussed the anomaly in the absence of electromagnetic drifts and thermal effects, considering only plasma diffusion parallel to the magnetic field lines. The study is made by integrating the equilibrium continuity equation for the particular case of a specified monochromatic ionizing radiation, a loss term varying exponentially and a constant scale height H. The integrations are performed along the dipole field lines, and they concluded [9] that the process of diffusion alone is inadequate to account for the characteristics of the actual ionosphere, since the calculated latitude of the 'crest' of N_{max} is not more than 12^o instead of typical 15^o to 20^o of magnetic latitude and also the equatorial 'valley' in N_{max} is too shallow in relation to values obtained from vertical incidence sounders. Using a computer program with best fit polynomials rather than Runge-Kutta process [9], and parameters varying more widely than Rishbeth et al. we arrived at the same conclusions. Another mechanism which may play a role in explaining the anomaly, namely physical processes which take into consideration the pitch-angle distribution of photoelectrons, has been proposed by Mariani [10].

In view of so many approaches to the problem, with no simple solution completely explaining the anomaly, it seems that the general trend of opinions is that the anomaly is caused by a combination of the several factors mentioned above.

Until recently the anomaly was studied only with the usual information obtained from common vertical incidence sounders. Lately the results (4) from the Canadian Topside Sounder Satellite have shown that the topside anomaly is very pronounced, and controled by the magnetic field. In fact it is shown (4) that well above N_{max} ambipolar diffusion along the magnetic field line, not only could by itself account for the anomaly, but also it would be difficult to explain the extra ionization in the topside in any other way. Even a simplified theory (11) provides a good match to observational results. A paper in preparation will present the integration of the equilibrium continuity equation when additional terms for thermal effects and electrodynamic drifts are represented by simple functions of height and latitude.

Up to here, the anomaly has been presented in terms of N_{max}. It will be seen that it also appears when one considers the latitudinal variation of the total electron content $I = \int Ndh$.

4. THE EQUATORIAL ANOMALY IN $\int Ndh$

Top and bottom side sounding complement one another in providing total content (4), however difficulties arise in view of the presence of strong horizontal gradients of ionization of the F region and discrepancies in the determination of N_{max} obtained in simultaneous measurements.

Figure 1 presents measurements of total content obtained from one satellite passage, utilizing the method already described in this paper. The low latitude 'crest' in I is associated with the equatorial anomaly and moves away from the magnetic dip equator from morning until late afternoon as shown in Fig. 2. Note that the anomaly in I does not move as far out from the dip equator as the anomaly in N_{max}, see for instance a report by Wright [12] for a period of an active Sun, in which the northerly anomaly peak reach geomagnetic latitudes of approximately 22°N between 1400 and 2000 hours (local time at 75°W). The results presented in Fig. 2 are however in accordance with the measurements [4] made with the Alouette satellite from Singapore concerning not only the time of widest dip angle coverage of the topside N_{max} anomaly, namely approximately 1600LT, but also the fact that the dip angles of I_{max} are smaller than the ones for N_{max} at a given time. During the period of the measurements reported herein, the satellite's transmitter was operating on the solar mode only, thus we were unable to acquire night data. Figure 3a, 3b, and 3c present the positions (dip angle versus longitude) of the subionospheric point of the satellite passages considered in the present paper. The lines are thickened to show increases of the values of total content.

Practically the whole period of observations was magnetically quiet. There was however one sudden commencement (Sc) about 1800UT on April 30 (day 120/63) starting a magnetic storm with Kp reaching values (above 6) which were largest in the interval of ± 40 days from the event. An abnormal behavior of I (t) was associated with this storm as can be seen in Fig. 4, where 4 passages with I_{max} having subionospheric points between 1615 and 1715LT are displayed. The curve for the quiet day 119 was normal both in values of I and dip angle of I_{max}. The first curve of day 120, obtained about one hour after Sc shows a moderately increased value of content without much variation of the dip angle of I_{max}. The second curve of day 120 was obtained about 2 hours after the first curve, i. e., three ~~and a half~~ hours after Sc, yet within the same range of local time for the subionospheric points. This second curve of day 120 shows a very high value of content, i. e., the highest by a factor of 2 from the largest content observed during the full period of observations presented in this paper. Not only the values of content were very high but also, I_{max} at the time considered was much closer to the dip equator than usual. Figure 2 presents the positions (dip angle versus local time) of I_{max} for the disturbance under consideration. Note also in Fig. 4 that for this second passage of day 120, I_{min} is at zero dip and about 30 percent lower than I_{max}, a fact which is not in accord with the results reported by King et al. [4] for topside content in disturbed days. However the curve for the following day, May 1st (121/63) in the same figure shows, first the absence of the equatorial "trough" in a similar way to the Alouette's electron content for the topside [4] in a storm day, and second it shows that the values of electron content are very much lower than the content measured in the initial phase of the storm. They differ by a factor of almost 5 for the maximum values of content on two consecutive days at the given time. The variations of content during disturbances are also consistent with results obtained previously for higher latitudes [3].

5. ELECTRON CONTENT THROUGH THE BRAZILIAN ANOMALY

It can be observed, in the previous figures, and on Fig. 5a, b, c, that, mainly in the morning, the electron content exhibits enhanced values at a second range of higher magnetic dip angles. As the day progresses, the Sun's ionizing radiation, and the motion of the equatorial anomaly fill the 'valley' between the two 'crests' shown in Fig. 1, and eventually the crest at the higher latitude is masked most of the time by the abundant ionization produced by solar radiation. The positions of these higher latitude 'crests' are associated with the so called South Atlantic or Brazilian Anomaly of the magnetic field. In Figure 2 the Brazilian anomaly 'crests' are represented by small squares, and it can be seen that, unlike the crests produced by equatorial anomaly, they do not vary with local time. Their position are also very well correlated with the electron flux contours at heights of the order of 300 km reported by Hess [13], who utilized satellite radiation measurements made during July 1962 right after the Starfish experimento. If instead of magnetic dip angles in Fig. 2, one were to use the McIlwain [14] parameter L, as shown in Fig. 6 (which is reproduced from Harrison et al. [15]) it could be seen that the Brazilian anomaly crests would be in the interval L = 1.24 ± 0.02 at 350 km. This is in coincidence with values of L in the South Atlantic, where King et al. [16] observed patchs of spread-F on topside ionograms, however the last occasion on which spread-F was observed on their measurements in the mentioned region was October, 1962, i. e., six months before the measurements reported in the present paper. The extra ionization necessary to form the Brazilian anomaly 'crest' must be caused by corpuscular dumping into the anomaly as measured by Vernov et al. [17] with a low altitude satellite (1960ρ), and Krasovskiy et al. [18] with satellites Cosmos 3 and 4. Probably the main contribution to the corpuscular ionization is from the energetic electrons of the artificial belt with long lifetimes. See for instance the paper by Welch, Kaufmann and Hess [19] considering that our measurements were performed between about 2.3 and 2.5 x x 10^7 sec after the Starfish experiment.

6. SUMMARY

General features of the equatorial anomaly in total electron content have been described in the present work based on satellite measurements utilizing differential Doppler techniques. The anomaly develops early in the day at the magnetic equator and moves out to regions of L = 1.16 at 350 km corresponding to dip angles of about 23°. It does not move as far as the anomaly in N_{max} for the same region. Although only one magnetic storm was considered, it showed that disturbed conditions tend to maintain the anomaly peak I_{max} closer to the equator, and with large variations in content. These variations in content provide continuity and are consistent with measurements made at higher latitudes using the same method of observations. A second 'crest' in electron content is shown to exist in the area of the Brazilian anomaly produced by corpuscular ionization.

ACKNOWLEDGEMENT

I thank the staff of the Space Physics Laboratory of CNAE, specially

Mr. F. Walter for programming the problem in FORTRAN; the Computational Centers of the University of São Paulo and of the Instituto Tecnológico de Aeronáutica in São José dos Campos for permitting the use of their IBM - - 1620 computers, and Mr. C. H. Buerkle of the Tranet 008 Station for data collection and ephemerides.

REFERENCES

1. Garriott, O. K. and F. de Mendonça, 1963, J. Geophys. Res. 68, 4917.

2. de Mendonça, F. and O. K. Garriott, 1962, J. Geophys. Res. 67, 2062.

3. de Mendonça, F., 1963, Radio Astronomical and Satellite Studies of the Atmosphere (Amsterdam: North-Holland), p. 289.

4. King, J. W., D. Eccles, P. A. Smith, P. Dannahy, A. Legg, E. O. Olatungi, K. Rice, G. Webb and M. Williams, Document RRS/I.M. 112- -D.S.I.R. Radio Research Station, Ditton Park, Slough, England, (1963).

5. Maeda, K., H. Uyeda and H. Shinkawa, 1942, Rep. Res. Phys. Inst. Rad. Waves, Nos. 1, 2 and 3.

6. Appleton, E. V., 1946, Nature, 157, 691.

7. Mitra, S. K., 1946, Nature, 158, 668.

8. Martin, D. F., 1955, Conf. on Physics of the Ionosphere, Cambridge (London: Physical Society), p. 254.

9. Rishbeth, H., A. J. Lyon and M. Peart, 1963, J. Geophys. Res. 68, 2559.

10. Mariani, F., 1964, J. Geophys. Res. 69, 556.

11. Goldberg, R. A., P. C. Kendall and E. R. Schmerling, 1964, J. Geophys. Res. 69, 417.

12. Wright, J. W., 1962, "Vertical Cross-sections of the Ionosphere Across the Geomagnetic Equator", N. B. S. Tech. Note 138.

13. Hess, W. N., 1963, J. Geophys. Res. 68, 667.

14. McIlwain, C. I., 1961, J. Geophys. Res. 66, 3681.

15. Harrison, R. E., K. W. Hubbard, F. L. Keller and J. I. Vette, 1963, Plots of Constant B and Constant L for Various Longitudes, Report TDR-169(3510.-41)TR-4, Aerospace Corp., California.

16. King, J. W., P. A. Smith, D. Eccles and H. Helm, Doc. No. RRS/I.M. 94, D.S.I.R., Radio Research Station, Ditton Park, Slough, England, 1963.

17. Vernov, S. N., I. A. Savenko, P. I. Shavrin, V. YE. Nesterov, and N. F. Pisarenko, 1962, Geomagnetism and Aeronomy (A. G. U. Translation), Vol. II, Nº 1, 31.

18. Krasovskiy, U. I., YU. I. Gal'Perin, V. V. Temnyy, T. M. Mulyarchik, N. V. Dzhordzhio, M. A. Marov and A. D. Bolyunova, 1963, Geomagnetism and Aeronomy (A. G. U. Translation), Vol. III, Nº 3, 338.

19. Welch, Jr., J. A., R. L. Kaufmann and W. N. Hess, 1963, J. Geophys. Res. 68, 685.

CAPTIONS

Fig. 1 - Total electron content determined from differential Doppler measurements. The low latitude "crest" is associated with the equatorial anomaly and the second "crest" with the Brazilian anomaly.

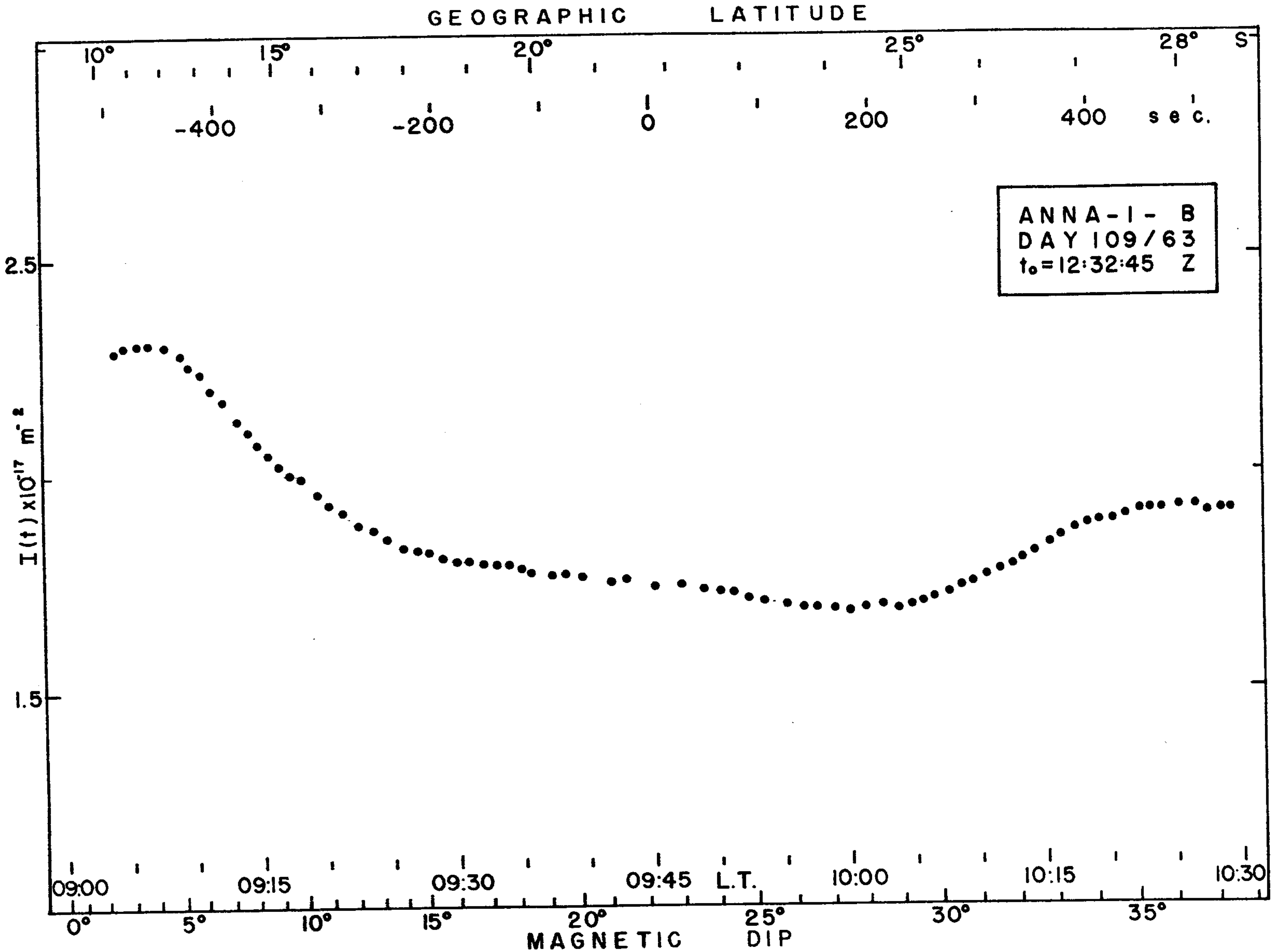
Fig. 2 - Diurnal variation of magnetic dip of the equatorial anomaly "crest" for quiet (⊙) and disturbed days (X). The (⊡) indicate the position of the crest associated with the Brazilian anomaly. All the values are for subionospheric points.

Fig. 3a, b, c - Positions of the subionospheric points during passages of the satellite. Numbers with three digits represent the day of the year (1963) and the ones with four digits represent the local time of the point considered. Small circles indicate the peaks of electron content and thickening of the lines indicate enhancements of content.

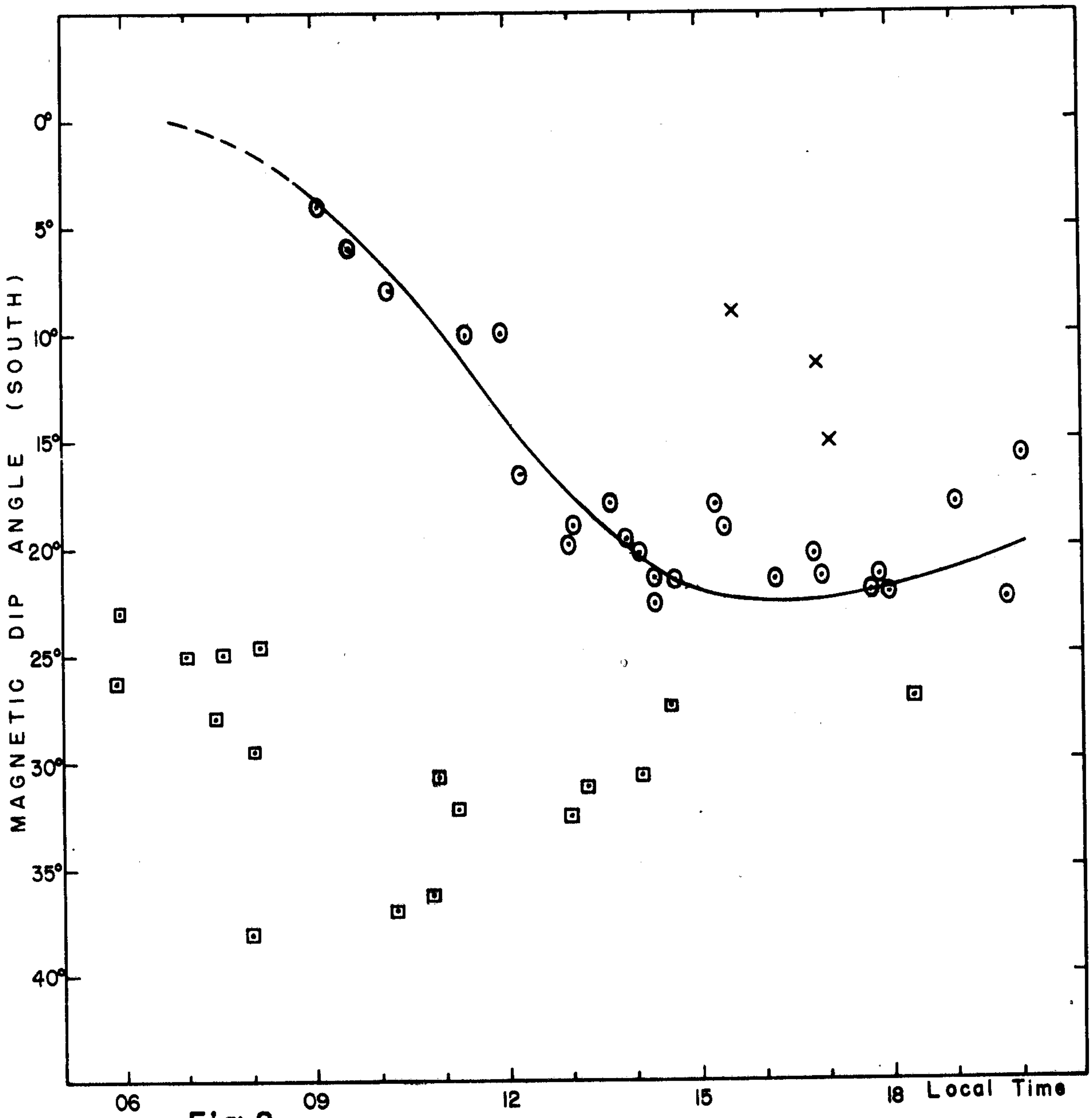
Fig. 4 - Variations in I associated with the magnetic disturbances of April 30, 1963.

Fig. 5a, b, c - Values of I versus dip angle of most of the passages during the period of observation. Numbers in parenthesis indicate day of the year 1963, the other numbers are the local time of the subionospheric point at begin and end of the passages.

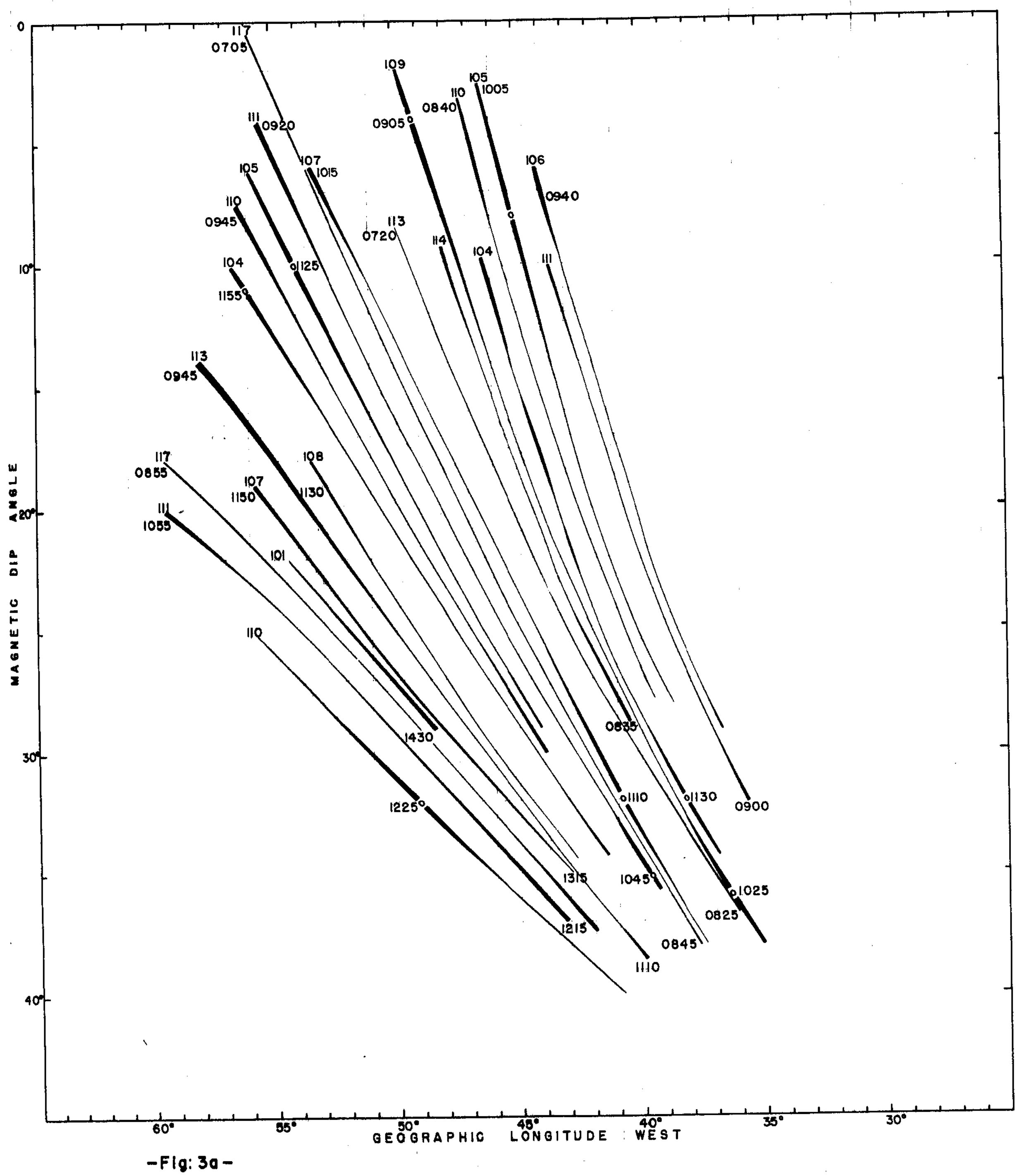
Fig. 6 - Plot of B and L for longitude 40^{o}W calculated with the Jensen and Cain 48-term expansion of the magnetic field, reproduced from Harrison et al. [15]


GEOGRAPHIC LATITUDE
10°
15°
20°
25°
28°
S
-400
-200
0
200
400
sec.
ANNA-I- B
DAY 109/63
t₀=12:32:45 Z
2.5
1.5
I(t) x10¹⁷ m⁻²
09:00
09:15
09:30
09:45
L.T.
10:00
10:15
10:30
0°
5°
10°
15°
20°
25°
30°
35°
MAGNETIC DIP

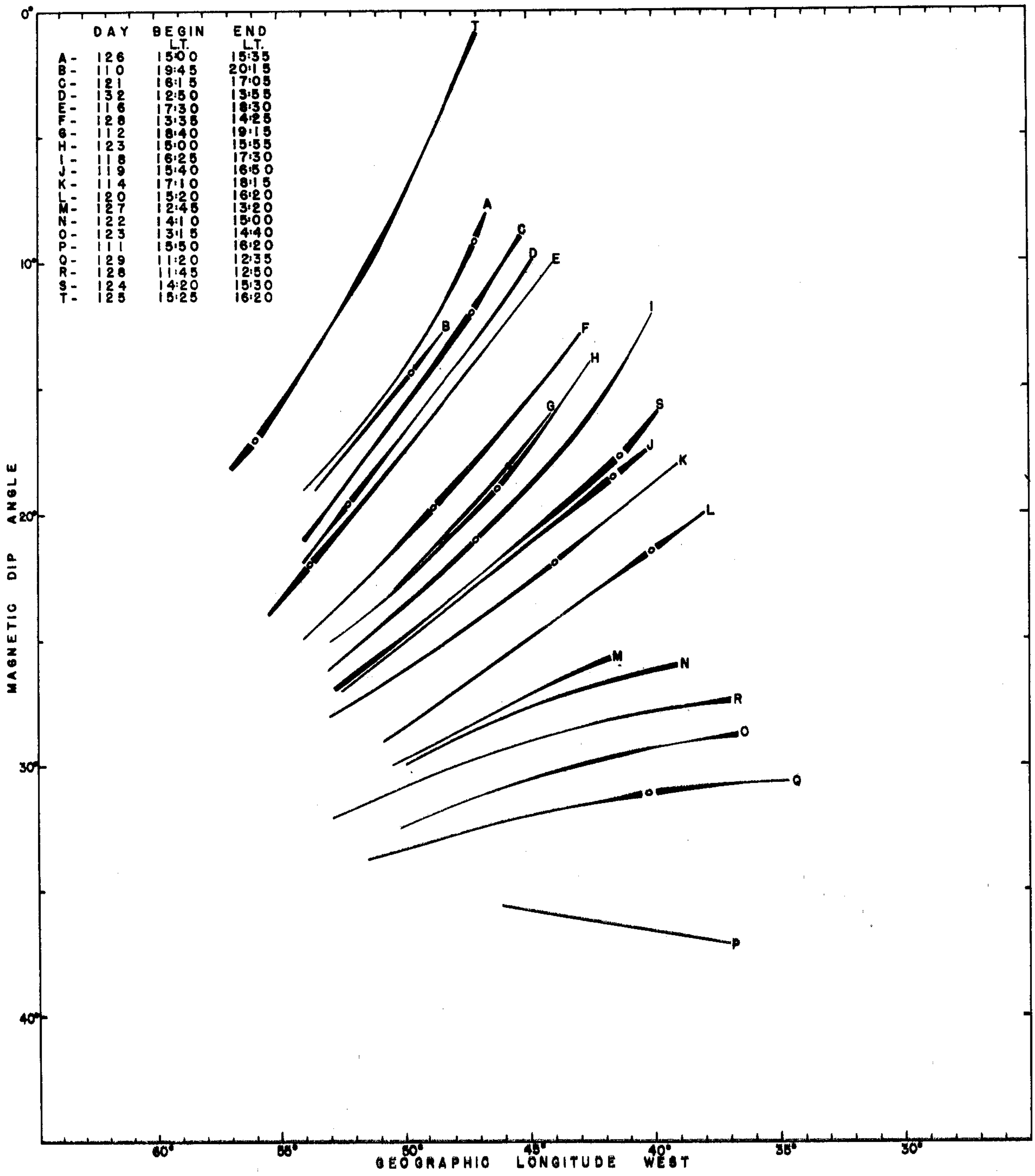
-Fig. I-


MAGNETIC DIP ANGLE (SOUTH)
0°
5°
10°
15°
20°
25°
30°
35°
40°
06
09
12
15
18
Local Time

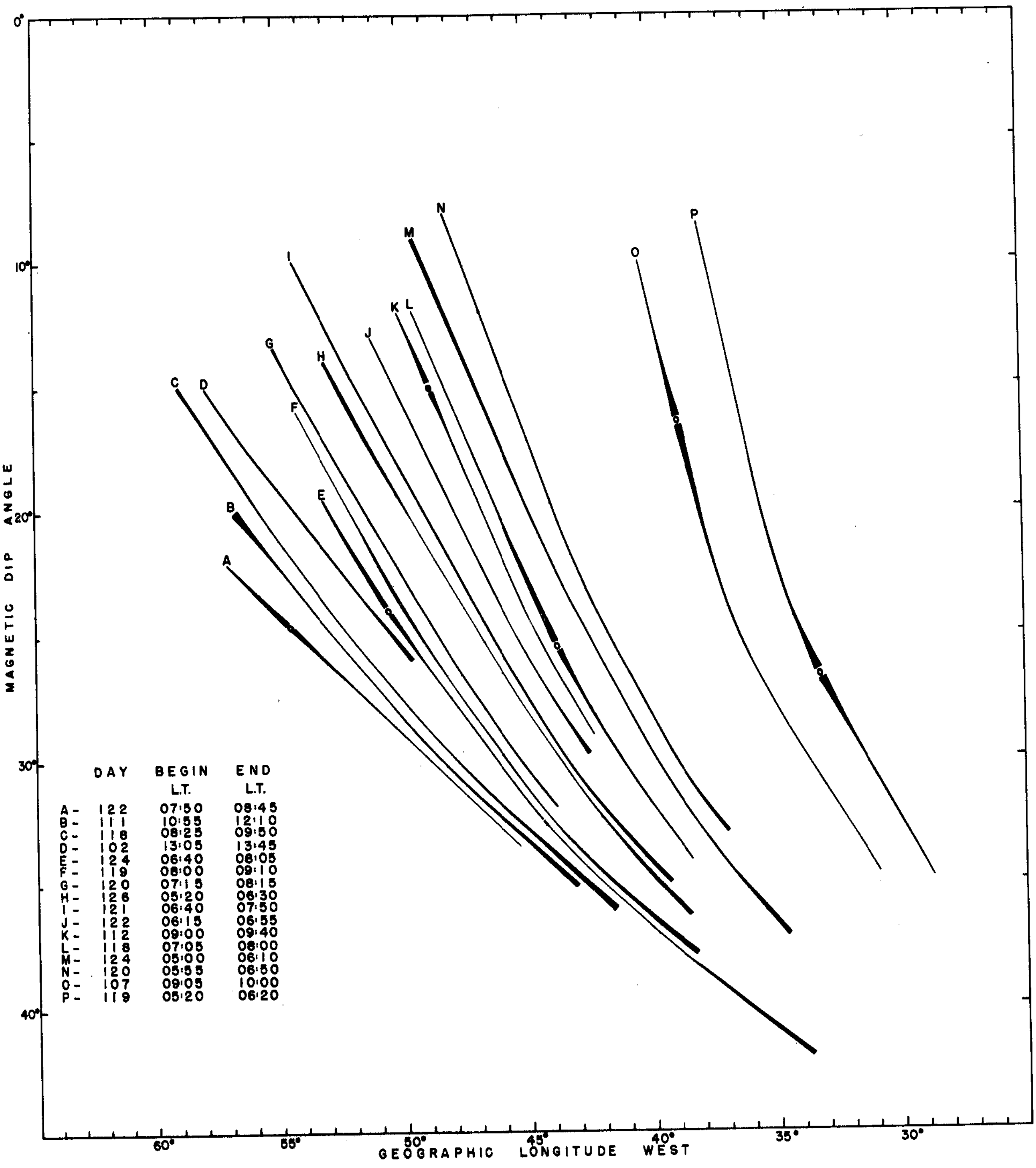
-Fig: 2-



-Fig: 3a-

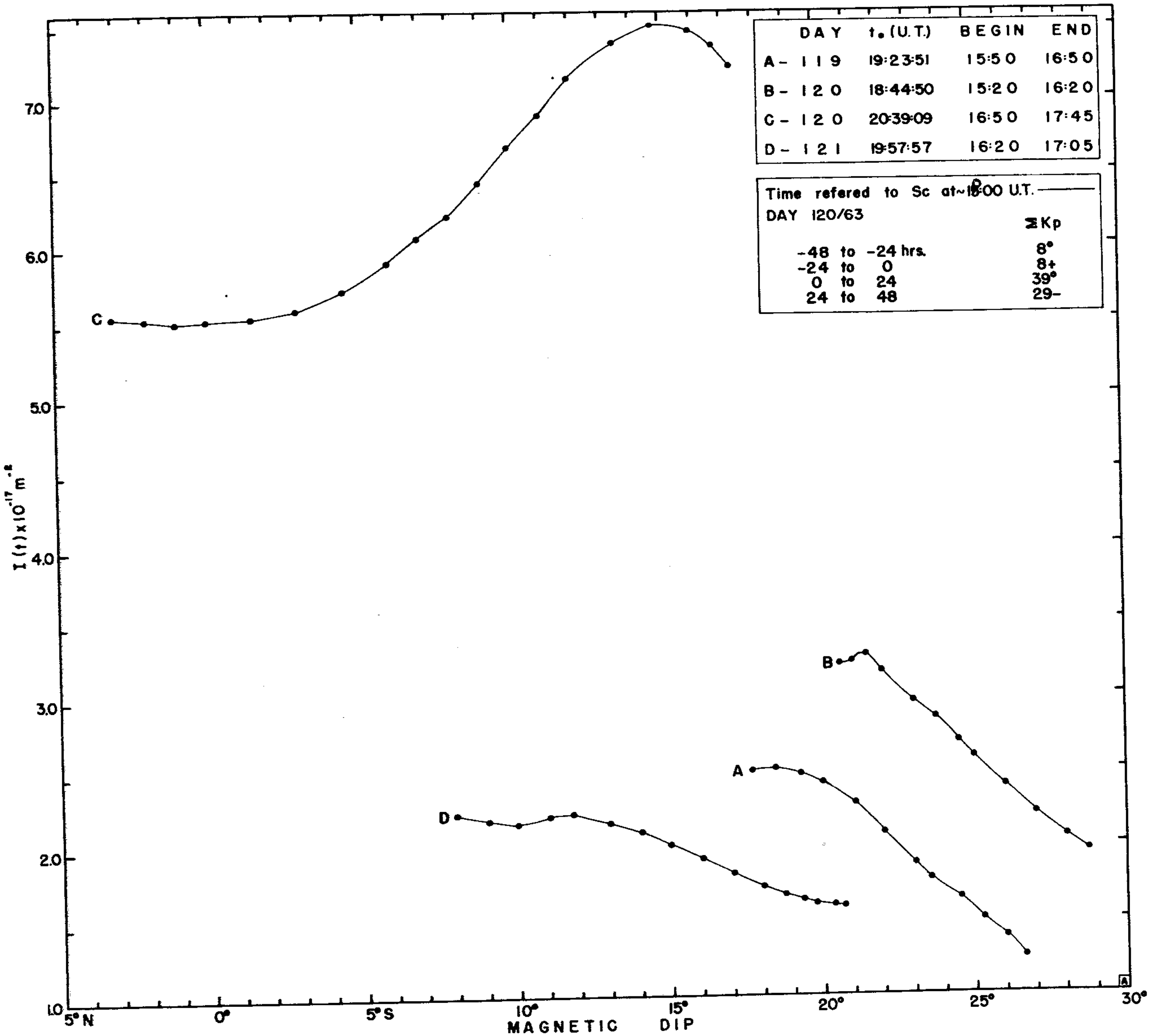

DAY BEGIN L.T. END L.T.
A - 126 15:00 15:35
B - 110 19:45 20:15
C - 121 16:15 17:05
D - 132 12:50 13:55
E - 116 17:30 18:30
F - 128 13:35 14:25
G - 112 18:40 19:15
H - 123 15:00 15:55
I - 118 16:25 17:30
J - 119 15:40 16:50
K - 114 17:10 18:15
L - 120 15:20 16:20
M - 127 12:45 13:20
N - 122 14:10 15:00
O - 123 13:15 14:40
P - 111 15:50 16:20
Q - 129 11:20 12:35
R - 128 11:45 12:50
S - 124 14:20 15:30
T - 125 15:25 16:20
MAGNETIC DIP ANGLE
0°
10°
20°
30°
40°
GEOGRAPHIC LONGITUDE WEST
60°
55°
50°
45°
40°
35°
30°

-Fig. 3b-

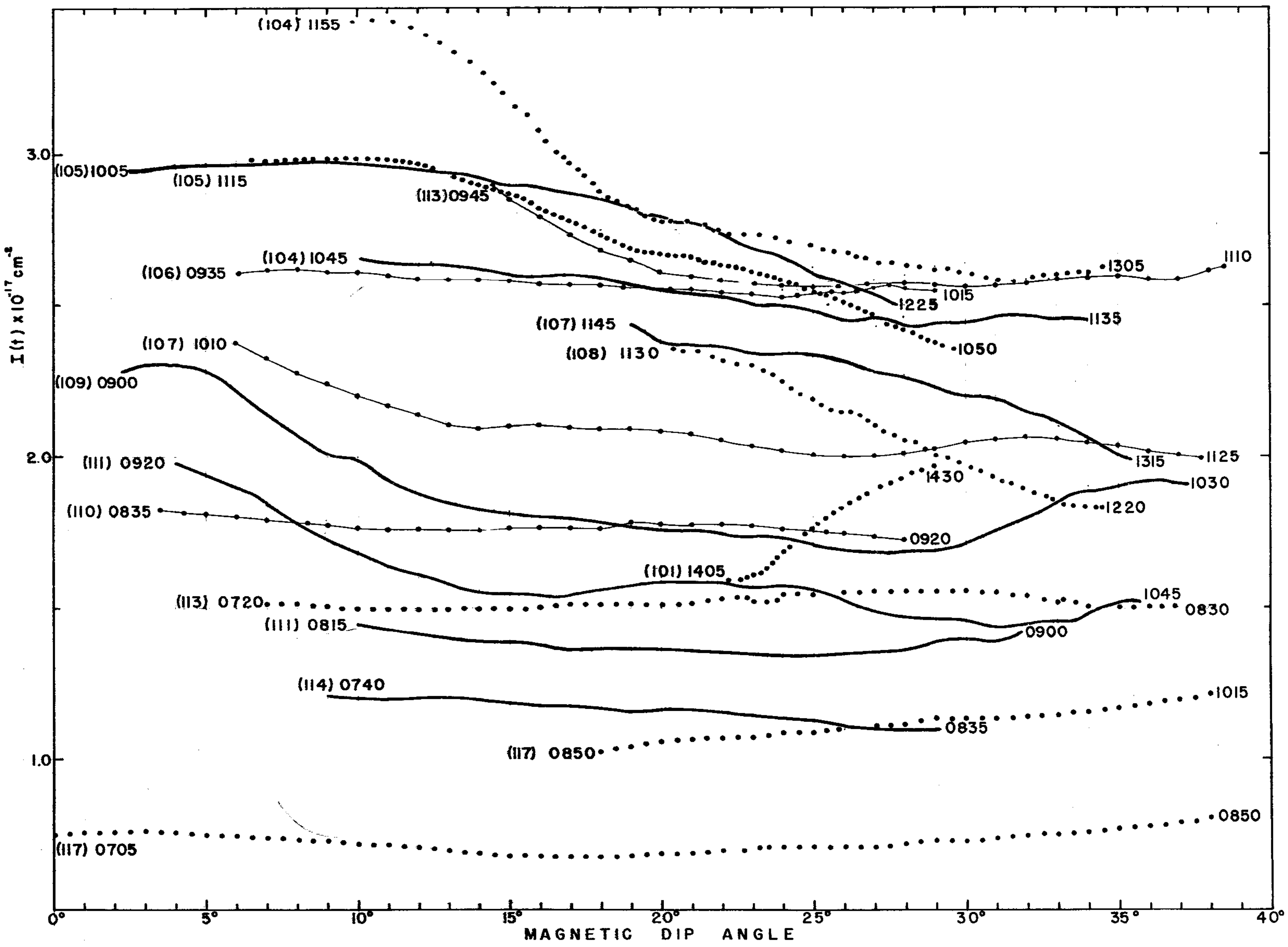


0°
10°
20°
30°
40°
MAGNETIC DIP ANGLE
60°
55°
50°
45°
40°
35°
30°
GEOGRAPHIC LONGITUDE WEST
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
DAY BEGIN L.T. END L.T.
A - 122 07:50 08:45
B - 111 10:55 12:10
C - 118 08:25 09:50
D - 102 13:05 13:45
E - 124 06:40 08:05
F - 119 08:00 09:10
G - 120 07:15 08:15
H - 126 05:20 06:30
I - 121 06:40 07:50
J - 122 06:15 06:55
K - 112 09:00 09:40
L - 118 07:05 08:00
M - 124 05:00 06:10
N - 120 05:55 06:50
O - 107 09:05 10:00
P - 119 05:20 06:20

— Fig: 3c —

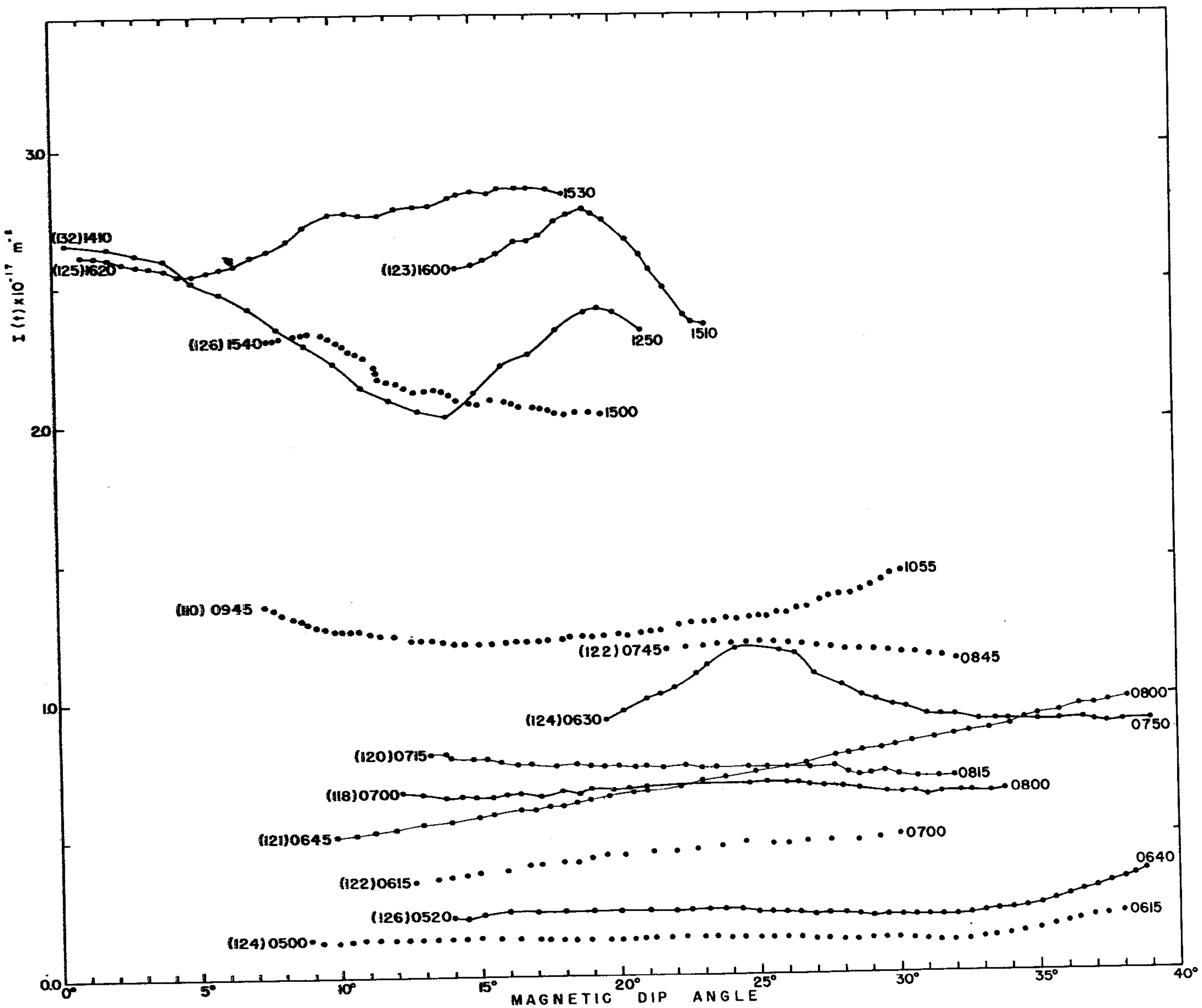

DAY t₀ (U.T.) BEGIN END
A - 119 19:23:51 15:50 16:50
B - 120 18:44:50 15:20 16:20
C - 120 20:39:09 16:50 17:45
D - 121 19:57:57 16:20 17:05
Time refered to Sc at~18:00 U.T.
DAY 120/63
ΣKp
-48 to -24 hrs. 8°
-24 to 0 8+
0 to 24 39°
24 to 48 29-
I (t) x 10^-17 m^-2
7.0
6.0
5.0
4.0
3.0
2.0
1.0
5° N
0°
5° S
10°
15°
20°
25°
30°
MAGNETIC DIP
A
B
C
D

-Fig: 4-



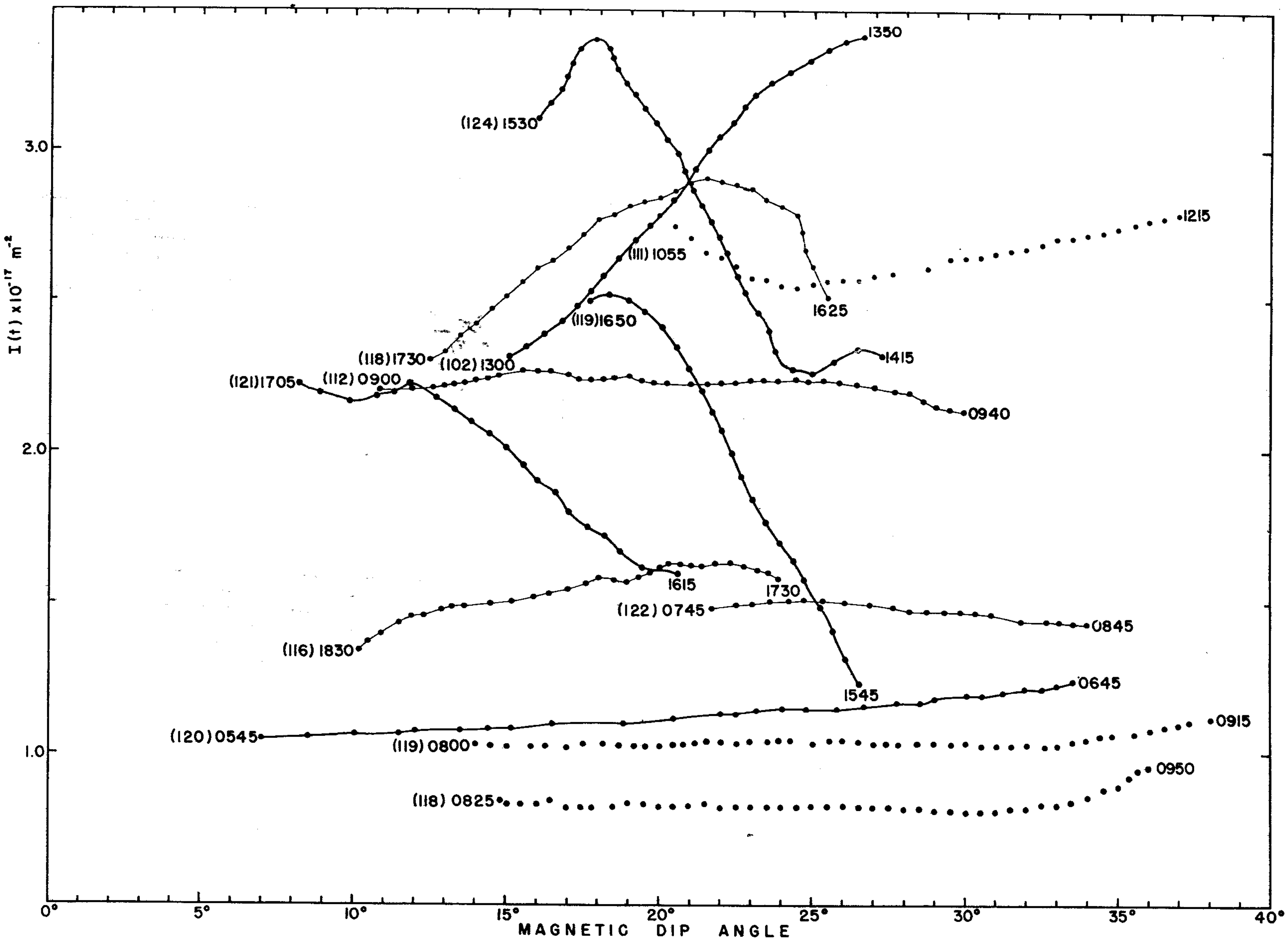
I(t) x 10⁻¹⁷ cm⁻²
3.0
2.0
1.0
0°
5°
10°
15°
20°
25°
30°
35°
40°
MAGNETIC DIP ANGLE
(104) 1155
(105)1005
(105) 1115
(113)0945
(104) 1045
(106) 0935
1305
1110
1015
1225
(107) 1145
1135
(108) 1130
1050
(107) 1010
(109) 0900
1315
1125
(111) 0920
1430
1030
(110) 0835
1220
0920
(101) 1405
1045
(113) 0720
0830
(111) 0815
0900
(114) 0740
1015
0835
(117) 0850
0850
(117) 0705

-Fig: 5a-

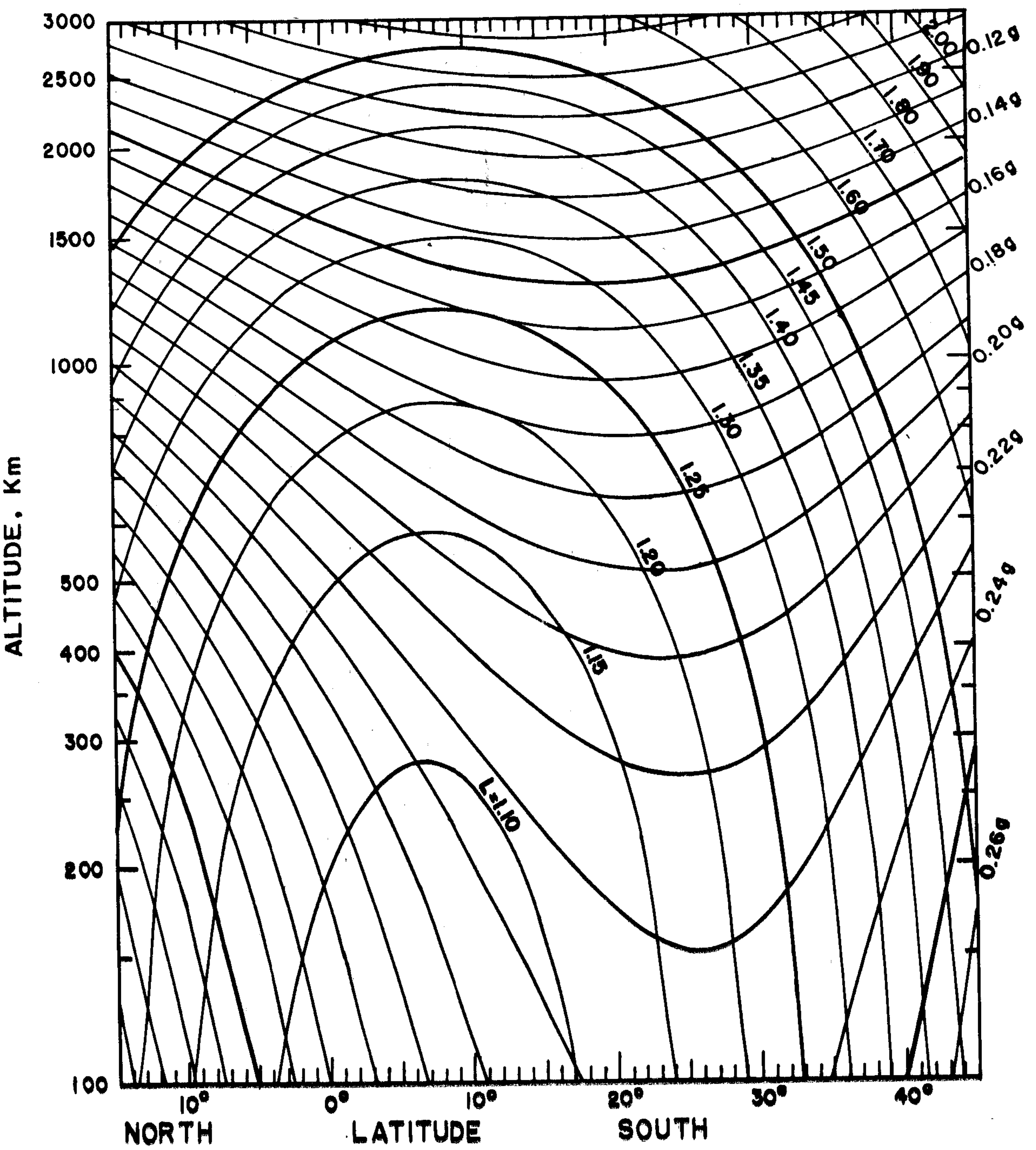


3.0
2.0
1.0
0.0
I (t) x 10⁻¹⁷ m⁻²
(132)1410
(125)1620
1530
(123)1600
1510
(126) 1540
1250
1500
(110) 0945
1055
(122) 0745
0845
(124)0630
0800
0750
(120)0715
0815
(118)0700
0800
(121)0645
0700
(122)0615
0640
(126)0520
0615
(124) 0500
0°
5°
10°
15°
20°
25°
30°
35°
40°
MAGNETIC DIP ANGLE

-Fig: 5b-


1350
(124) 1530
3.0
1215
(111) 1055
1625
I(t) x10^-17 m^-2
(119)1650
1415
(118)1730
(102)1300
(121)1705
(112)0900
0940
2.0
1615
1730
(122) 0745
0845
(116) 1830
1545
0645
(120)0545
0915
(119) 0800
1.0
0950
(118) 0825
0°
5°
10°
15°
20°
25°
30°
35°
40°
MAGNETIC DIP ANGLE

-Fig: 5c-


3000
2500
2000
1500
1000
500
400
300
200
100
ALTITUDE, Km
10°
0°
10°
20°
30°
40°
NORTH
LATITUDE
SOUTH
L=1.10
1.15
1.20
1.25
1.30
1.35
1.40
1.45
1.50
1.60
1.70
1.80
1.90
2.00
0.12g
0.14g
0.16g
0.18g
0.20g
0.22g
0.24g
0.26g

-Fig: 6-