BEHAVIOR OF THE TOPSIDE IONOSPHERE DURING A GREAT MAGNETIC STORM

by

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ABSTRACT

Variations in the electron density distribution of the topside ionosphere (including the height of the F_2 peak) obtained from Alouette I during the great magnetic storm of 17-18 April 1965 are analyzed. Both, enhancement and depletion of topside ionization are observed depending on the phase of the magnetic storm. Specifically, enhancement is associated with the positive phase and the asymmetric part of the main phase, while depletion of the topside ionosphere occurs during the symmetric part of the storm main phase over a latitude range corresponding to L values greater than 3. Associated with this depletion is a redistribution of ionization indicating that the topside ionosphere during the symmetric main phase consists primarily of O^+ (with H^+ being depleted). The enhancement of topside ionization during the positive phase of the storm appears to be associated with the compression of the daytime magnetosphere during that phase of the storm. The depletion seems to be associated with the expansion of field tubes due to the presence of the high energy-density ring current plasma as observed on satellites causing an upward flux from the topside ionosphere. A similar upward flux could also arise from a sink of thermal plasma in the magnetosphere due to the local energization of this plasma.

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INTRODUCTION

Magnetic storm effects on the bottomside F region have been studied extensively, first by using f_oF2 data and later using the true height-electron density data (Rishbeth, 1963; Obayashi, 1964). The effects on the topside ionosphere, however, remained unexplored until recently. With the availability of satellite data, it has become possible to study the magnetic storm effects in the topside ionosphere also. Enhancements in the topside electron density at high latitudes during periods of magnetic disturbances have been reported by Sayers (1964), Willmore and Henderson (1965) and Reddy et al (1957). Both increases and decreases in the topside electron density have been reported by King et al (1967). According to the latter, decreases in topside electron density during magnetic storms usually appear where the magnetic dip is greater than some value in the range from 20^o to 60^o.

For a better understanding of the storm effects on the topside ionosphere, it appears necessary to study these effects during different phases of a magnetic storm. We have investigated the topside ionospheric behavior at middle and high latitudes during different phases of the great magnetic storm of 17-19 April 1965 (see, Meng and Akasofu, 1967) using the available topside ionograms from the Alouette I satellite. Use is also made of ground-based ionosonde f_oF2 data in the present investigation. During the 17-19 April 1965 storm, magnetic field measurements within the magnetosphere were made on board the Explorer XXVI satellite (Cahill, 1966). These measurements indicated a storm-time magnetospheric ($2 \leq L \leq 5$) inflation centered at $L = 3.5$. The development of the main phase was found to be asymmetric and has been interpreted as caused by the rapid growth of a large body of charged particles (at energies $E < 100$ keV) in the late afternoon and evening sectors. (Recent satellite observations by Frank, 1967 show that the ring current plasma consists primarily of protons, with a small contribution of electrons, both in the energy range 200 eV $< E <$ 50 keV). The recovery phase was more symmetric and was attributed to the inflation of the inner magnetosphere by a belt of charged particles centered at $L \sim 3.5$ in the equational plane, representing a ring current. The storm of 17-19 April 1965 exhibited a main-phase decrease of $\sim 150\gamma$ at low-latitude ground stations and a magnetospheric field change $\Delta B/B \sim 0.5$ at $L \sim 3.5$.

In the present investigation, bottom-and-topside data during the storm of 17-19 April 1965 have been analyzed with a view of studying the stormtime behavior at L values corresponding to the position of stormtime magnetospheric inflation.

BEHAVIOR OF THE TOPSIDE IONOSPHERE DURING THE 17-19 APRIL 1965 MAGNETIC STORM

A. Changes in maximum electron density NmF2 during the storm. As the effects of magnetic storms on NmF2 or f_oF2 have been studied quite extensively, we first present an analysis of the behavior of NmF2 during the 17-19 April 1965 magnetic storm.

For the study of the NmF2 behavior at middle and high latitudes during the magnetic storm, we have used f_oF2 data obtained from ground-based ionosondes, corresponding to the following stations:

Station	Geograph Lat	Geograph Long	L
White Sands	32.4	107°W	1.7
Boulder	40.0	105°W	2.3
Ft. Belvoir	38.7	77°W	2.6
Ottawa	45.4	76°W	3.6
Kenora	49.9	97°W	1.2

The percentage departure of NmF2 on the storm day 18 April 1965) from that on prestorm quiet day (16 April 1965) for different Universal Times (U.T.) was derived for the above stations and is shown as a function of the magnetic shell parameter L in Figure 1. These data are representative of the departure of NmF2 during the main and recovery phases of the storm from quiet-time NmF2 values. Fig. 1 shows that the maximum depletion of NmF2 occurs at $L \sim 3$ for 1700 U.T. to 2300 U.T.. It is interesting to note that the maximum inflation of the magnetosphere during the storm occurs at L ~ 3.5 (Cahill, 1966), i.e. at about the same L value as the region of maximum depletion of NmF2.

Shown in Figure 2 is the percentage change in NmF2 during the storm from prestorm quiet day (16 April 1965) at Ft. Belvoir (L ~ 2.6), as a function of U.T. along with the magnetogram at Honolulu. It can be seen from this figure that the depletion in NmF2 occurs simultaneously with the main phase decrease in the magnetic field H. However, the ionospheric depletion appears to last throughout most of the recovery phase of the magnetic storm. It may be noted that Thomas and Venables (1966) reported that the nature of ionospheric behavior during magnetic storms depends upon the time of onset of the storm main phase.

B. Analysis of topside ionosphere data from Alouette I satellite. Topside ionograms from Alouette I satellite available at times during the magnetic storm were reduced to true-height-electron density profiles using a parabolic lamination technique (Jackson, 1967). Also, ionograms corresponding to some magnetically quiet days were reduced for control purposes. The topside data to be presented here correspond to longitudes near the 75°W meridian.

Figure 3 shows the constant altitude contours of electron density for three passes on 16, 17 and 18 April 1965 plotted against L at 600 Km. The approximate local time of these three satellite passes is ~ 0900 hrs. and the universal time is ~ 1600 hrs. 16 April is considered as a control day, the daily sum of K_p indices being 7 on that day. The storm sudden commencement (SSC) occurred at 1313 U.T. on 17 April 1965. Thus, the electron density contours on 17 April shown in Figure 3 correspond to about 2 hours after the sudden commencement of the storm. From Figure 3 it can be seen that there is an increase in electron density at 400 km on 17 April compared to that on the control day, the increase being smaller at higher L values. At heights greater than 400 km, the increase in electron density is smaller throughout the L range under consideration, i.e. from L ~ 2.5 to 7.5. In fact, there is no appreciable change at 1000 km altitude.

The electron density data from 18 April shown in Fig. 3 correspond to about 1600 U.T.. By this time, the storm main phase ring current has already become symmetric (Cahill, 1966). Comparing the behavior on 18 April with that on the control day we note an increase in electron density at higher altitudes, i.e., from 600 km to 1000 km; at 400 km, from L=3 to 5, there is virtually no change.

The vertical profiles of electron density on 16 and 18 April at 1600 U.T. (0900 LMT) at L=3.5 are shown in Fig. 4. The height of the maximum (hmF2) increased on 18 April compared to the control day by more than 100 km. Though the electron densities at 400 km (~375 km geopotential height) are about equal, NmF2 on 18 April is much lower than that on 16 April in agreement with the bottomside results shown in Fig. 1. (Thus, storm-time changes in NmF2 may not necessarily be representative of changes at constant altitudes.) It can be seen from Fig. 4 that the vertical slope of electron density profile (scale height) on 18 April remains almost constant, indicating no appreciable change in ion composition, i.e. 0^+ is the dominant constituent up to at least 1000 km but at a higher temperature. On the other hand, the electron density profile on 16 April shows a change in scale height which could be attributed to the transition from heavier to lighter ionic (0^+ to H^+) constituents.

Data on 18 April around 1200 U.T. (0900 LMT) were also available (not shown) and were compared with the control day data. The behavior of electron density at this time (1200 U.T.) is about the same as that at 1600 U.T. on 18 April discussed above.

It has been shown by many workers, that there is a marked local time dependent asymmetry in the stormtime behavior of f_oF2. During the main phase of the magnetic storm, f_oF2 shows an increase in the afternoon quadrant and a decrease in the morning quadrant at high latitudes (Obayashi, 1964). Also, magnetic field measurements in the magnetosphere by Cahill (1966) indicate that the development of the magnetospheric ring current is asymmetric in local time and only at later stages of the main phase, the ring current becomes symmetric. For the 17-19 April magnetic storm, it was inferred (Cahill, 1966) that the ring current was asymmetric up to about 1200 U.T. on 18 April 1965. In view of these observed local time asymmetries, it is of interest to study the topside ionospheric behavior in the afternoon quadrant during the asymmetric part of the main phase, i.e., before 1200 U.T. on 18 April 1965. For this purpose, topside ionograms from Woomera, Australia available at ~ 1100 U.T. (~ 2100 LMT) have been reduced to true height electron density profiles. The resulting constant altitude contours of the electron density for 18 April together with those for a control day,(14 April 1965) are shown in Figure 5. The coverage of the data on 18 April was only up to $L = 3.2$.

The topside electron density for 18 April 1965 at 1100 U.T. (~ 2100 LMT) shows a large increase at all heights above 400 km. At $L < 3$ the increase amounts to about an order of magnitude; at $L \sim 3.2$, the increase corresponds to a factor of two. On 18 April 1965, the electron density shows a sharp trough at $L = 2.2$ which corresponds to the well-known high latitude trough (Muldrew, 1965). On the control day the presence of the trough is also indicated although the exact position of the trough on this day could not be definitely identified because of lack of data.

Vertical electron density profiles are shown in Figure 6 for L $\sim$ 3 at $\sim$ 2100 LMT and $\sim$ 1200 U.T.. These profiles show no appreciable change in the vertical slope of electron density on 18 April indicating that O^+ is the dominant ionic constituent (but at a higher temperature) up to at least 1000 km.

Constant altitude electron density contours for 18 April (corresponding to $\sim$ 2200 U.T. and $\sim$ 1900 LMT) during the recovery phase of the storm are shown in Figure 7. Also shown in the same figure are data for 25 April corresponding to the same local time as that for 18 April and data from 17 April at $\sim$ 2240 U.T. (1940 LMT). 25 April is used as a control day since the daily sum of planetary magnetic indices K_p is only 8 on that day. The U.T. corresponding to the data on 25 April is different from the U.T. corresponding to the data on 17 and 18 April. However, it can reasonably be assumed that there are no appreciable changes in electron density related to U.T. on 25 April and thus data on this day can be considered as control day data for comparison purposes. Figure 7 shows that there is a large depletion in the electron density at all altitudes from L = 3 onwards to higher L values on 18 April compared to the control day. This observation corresponds to the recovery phase of the storm when the ring current is symmetric. The reason for the fact that the topside ionosphere shows the maximum depletion at L $\sim$ 4.5 whereas the NmF2 data (Fig. 1) shows it at L $\sim$ 3, is due to a redistribution of the topside ionosphere compared to the control day resulting from temperature and mean ionic mass changes on 18 April, the storm day. Topside N-h profiles on 18 and 25 April at L = 3 and 4.8 are shown in Figure 8 which indicate this behavior.

Referring back again to Figure 7 in which electron density behavior on 17 April (2100 U.T., 1900 LMT) are also shown, it can be seen that there is a general increase in the density on 17 April compared to the control day. This observation corresponds to the initial (positive) phase of the magnetic storm. Thus, it appears that the increase in topside electron density observed at 2 hours after the SSC (Fig. 3) continues throughout the initial (positive) phase of the magnetic storm.

Comparison of scale heights at two altitudes in the topside ionosphere (i.e. 500 km and 800 km) on 18 April (during the recovery phase) and on 25 April has been made to study the redistribution of ionization. We have plotted the ratio H_{800}/H_{500} (a crude measure of scale height gradient) as a function of L, where H_{800} and H_{500} are the plasma scale heights $H = k(T_e + T_i)/m_+g$ at 800 and 500 km respectively. Fig. 9 shows this ratio for 17 April (2240 U.T.) 18 April (2100 U.T.), and 25 April (0100 U.T.). It is evident that the scale height ratio is lower on 18 April compared to that on 25 April, indicating a higher mean ionic mass on 18 April at 800 km than on 25 April. There is no marked change in the ratio on 17 April compared to that on 25 April. This is emphasized even more by the fact that the temperature on the storm day is expected to be higher than on non-storm days. This result indicates a depletion of lighter ionic constituents on the storm day at $L > 3$. Such a conclusion was also reached by Watt (1966) from his study of the plasma scale height in the topside ionosphere as a function of K_p.

DISCUSSION OF OBSERVATIONAL RESULTS

Topside sounder observations indicate that significant ionospheric changes, i.e., both enhancement and depletion of ionization, occur during different phases of the magnetic storm at $L \gtrsim 3$, corresponding to the location of the main and recovery phase ring current. Such enhancements and depletion during different times of the magnetic storm were also reported by Titheridge and Andrews (1966) and by Hibberd and Ross (1967) from total electron content measurements. The behavior of the topside ionosphere during different phases of the magnetic storm is summarized in Figure 10. Shown in the same figure is also the Honolulu magnetogram H trace to illustrate the different phases of the magnetic storm of 17-19 April 1965. Following the sudden commencement and throughout the initial (positive) phase of the storm, the ionization in the topside ionosphere is enhanced at all altitudes from the height of the maximum (hmF2) to 1000 km for $3 < L < 7$. This enhancement in ionization, may be due to the compression of the dayside magnetosphere during the initial phase of the storm which would lead to a downward transport of ionization along field tubes. This overall increase in the topside electron density is not likely to be due to possible heating effects as in that case the N-h profile would be different (Thomas, 1966). It is interesting to note that during the initial phase, there appears to be no appreciable change in the scale height, implying the absence of marked heating effects at that time.

During the main phase of the storm, the electron density distribution in the topside ionosphere, both in the morning and evening quadrants shows no marked change in scale height with altitude, indicating that O^+ is the dominant ionic constituent but that the plasma temperature is higher. In the morning quadrant, the electron density exhibits a decrease at the hmF2 level and an increase at higher altitudes. In the evening quadrant, the enhancement of ionization is even more pronounced and extends from the hmF2 level to higher altitudes. This marked difference between the morning and evening quadrants in the behavior of the topside ionosphere (from hmF2 to higher altitudes) during the early stages of the main phase of the magnetic storm represents a strong local-time dependent variation. Such, local-time dependent asymmetry has been observed in the f_oF2 variations from ground-based ionosonde studies at high latitudes (Obayashi, 1964). This asymmetry in the f_oF2 behavior is generally attributed to electromagnetic drifts due to the ionospheric currents present during the storm main phase. It is interesting to note that a polar substorm was in progress during the asymmetric main phase of the storm under consideration. During these times there will be strong ionospheric currents flowing in and around the midnight quadrant. It is likely that the local-time dependent behavior of the topside ionosphere during the asymmetric main phase is associated with the ionospheric currents flowing at that time. Satellite drag observations show an increase in the neutral temperature during magnetic storms (Jacchia and Slowey, 1964). This stormtime heating could also affect the electron density distribution. In fact, the changes in topside electron density observed in the morning quadrant resemble those obtained by Thomas (1966) from a theoretical analysis of the effect of temperature changes on electron density distributions.

During the recovery phase of the storm when the ring current has become symmetric, the entire topside ionosphere is being depleted. From an analysis of scale heights, it is inferred that the mean ionic mass is higher than on the quiet day, indicating that the lighter ions (protons) are largely depleted.

An order of magnitude estimate of the upward flux F ($F \sim \frac{\Delta N}{\Delta t} \cdot H$) associated with the depletion of ionization in the topside ionosphere gives a value of about $10^7 cm^{-2} sec^{-1}$. This value approaches the estimate for the limiting upward flux of protons, which can be supported by the available supply of neutral hydrogen (Geisler, 1967). Thus, the observed stormtime depletion of protons in the topside ionosphere appears to be consistent with upward fluxes close to the limiting flux. During the storm main and recovery phase, the inner magnetosphere is inflated, resulting in the expansion of field tubes around the equatorial plane. For a main phase decrease of $\sim 150\gamma$ representative of this storm the field line at L = 3 is estimated to be displaced by about $0.3R_e$ and at L = 4, the displacement is about $1R_e$ (Davis, private communication). This expansion of the field tubes would lead to a reduction in the local density of thermal plasma at those L values. This reduction could cause an increased upward flux in the topside ionosphere along the connecting field tubes, which in turn results in a reduction of ionospheric electron densities. Assuming that the expansion of field tubes has taken place during the time of development of the main phase of the storm ($\sim$ 3 hrs), the upward flux from the topside ionosphere that could be caused by the expansion of field tubes is estimated be about $4 \times 10^6 cm^{-2} sec^{-1}$.

There could also be a possible sink of thermal plasma in the magnetosphere at L = 3 to 5, if a fraction of thermal plasma is locally energized in the magnetosphere to contribute to the ring current plasma. Because of its connection to the ionosphere this sink would also cause an upward flux of ionospheric plasma to replenish the loss of thermal particles in the magnetosphere, leading to a depletion of ionospheric electron density. Assuming again that the local energization of the thermal plasma in the magnetosphere takes place during the time of development of the storm main phase ($\sim$ 3 hrs) and from the estimates of energy and energy density of the ring current particles (Cahill, 1966), the upward flux from the topside ionosphere required to replenish the depleted thermal plasma in the magnetosphere is estimated to be about $10^6 cm^{-2} sec^{-1}$.

From the above discussion, it is evident that the nature of the magnetic storm effects on the topside ionosphere strongly depend on the phase of the magnetic storm. Increases or decreases in electron density occur depending upon the phase of the storm. It appears that there is a close association between ionospheric and magntospheric changes during a magnetic storm, especially during the development and decay of the magnetospheric ring current plasma. This fact points out the importance of studying the detailed time history of magnetic storm effects in the topside ionosphere. Statistical studies of storm effects on the topside ionosphere using indices like K_p alone may not lead to very meaningful results because of the strong dependence of topside ionosphere behavior on the phase of the storm.

We hope that in the future, it may become possible to study the concurrent behavior of the ionospheric and magnetospheric thermal plasma, the ring current plasma, as well as magnetic variations and possibly electric fields on board of spacecraft. Such simultaneous observations should help to shed more light on the physical processes responsible for the observed magnetic storm behavior.

FIGURE CAPTIONS

Figure 1 - Percentage change in NmF2 as a function of L at different Universal Times.

Figure 2 - Percentage change in NmF2 from 16 April 1965 at Fort Belvoir ($L \sim 2.6$) and magnetogram H trace at Honolulu as functions of Universal Time.

Figure 3 - Constant altitude electron density contours on 16, 17 and 18 April as functions of L.

Figure 4 - Vertical profiles of electron density on 16 April (control day) and 18 (storm day) at $L = 3.4$.

Figure 5 - Constant altitude electron density contours on 14 and 18 April as functions of L.

Figure 6 - Vertical profiles of electron density on 14 April (control day) and 18 (storm day).

Figure 7 - Constant altitude electron density contours on 17, 18 and 25 April (control day) as functions of L.

Figure 8 - Vertical profiles of electron density on 18 April (storm day) and 25 (control day).

Figure 9 - Ratio of scale heights H_{800}/H_{500} (at 800 km and 500 km) as a function of L.

Figure 10 - Behavior of topside ionosphere during the 17-19 April 1965 storm during different phases of the storm. The Honolulu magnetogram H trace is also shown to illustrate different phases of the storm.

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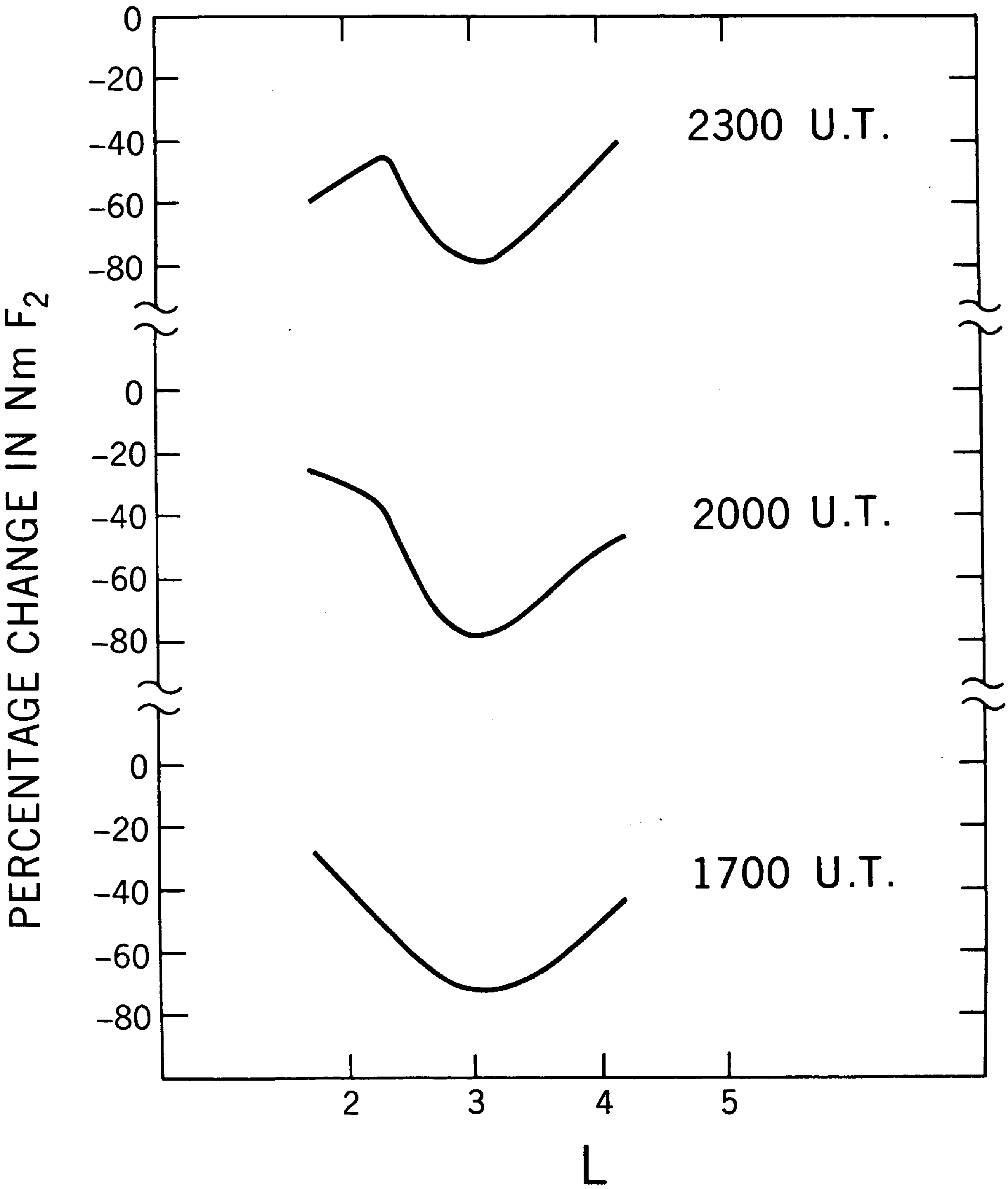


PERCENTAGE CHANGE IN Nm F_2
0
-20
-40
-60
-80
2300 U.T.
2000 U.T.
1700 U.T.
2
3
4
5
L

FIGURE 1

PERCENTAGE CHANGE IN $N_m F_2$ FROM 16TH APRIL 1965 AT FORT BELVOIR (L~2.6) AND MAGNETOGRAM H TRACE AT HONOLULU AS FUNCTIONS OF UNIVERSAL TIME

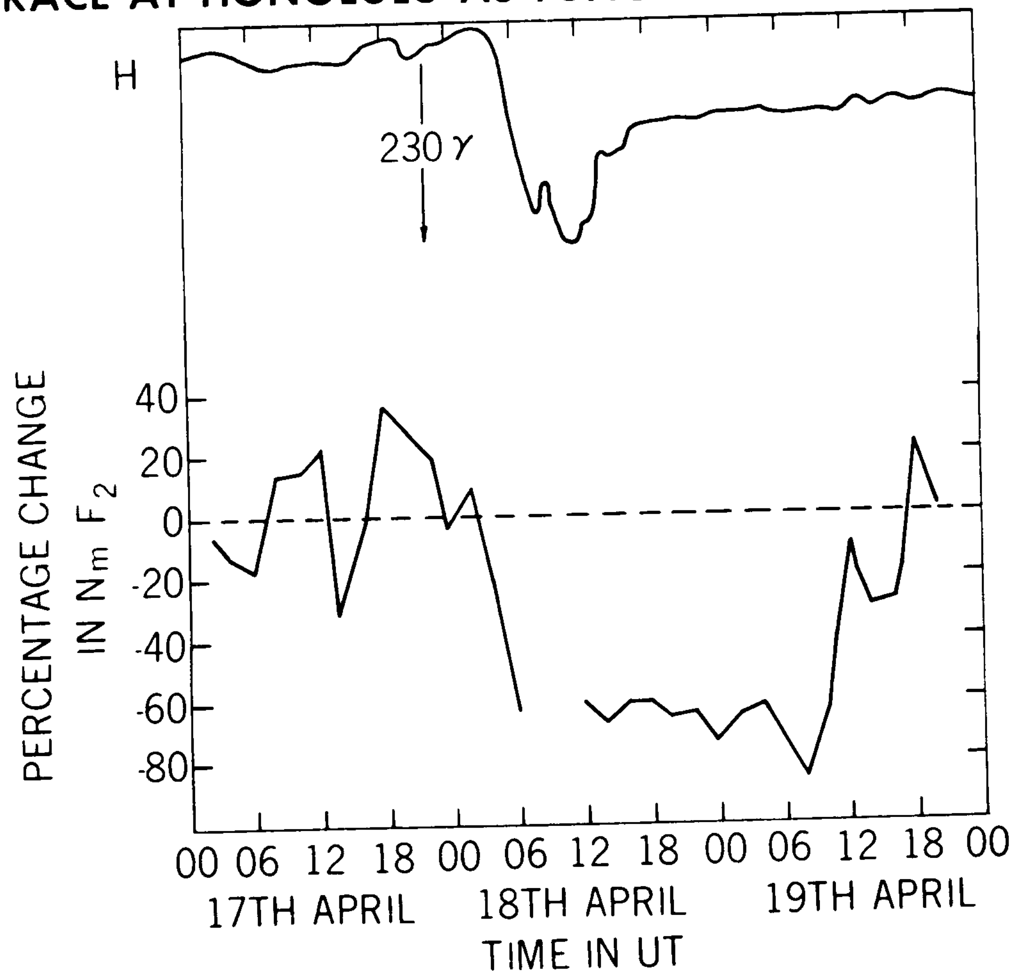


FIGURE 2

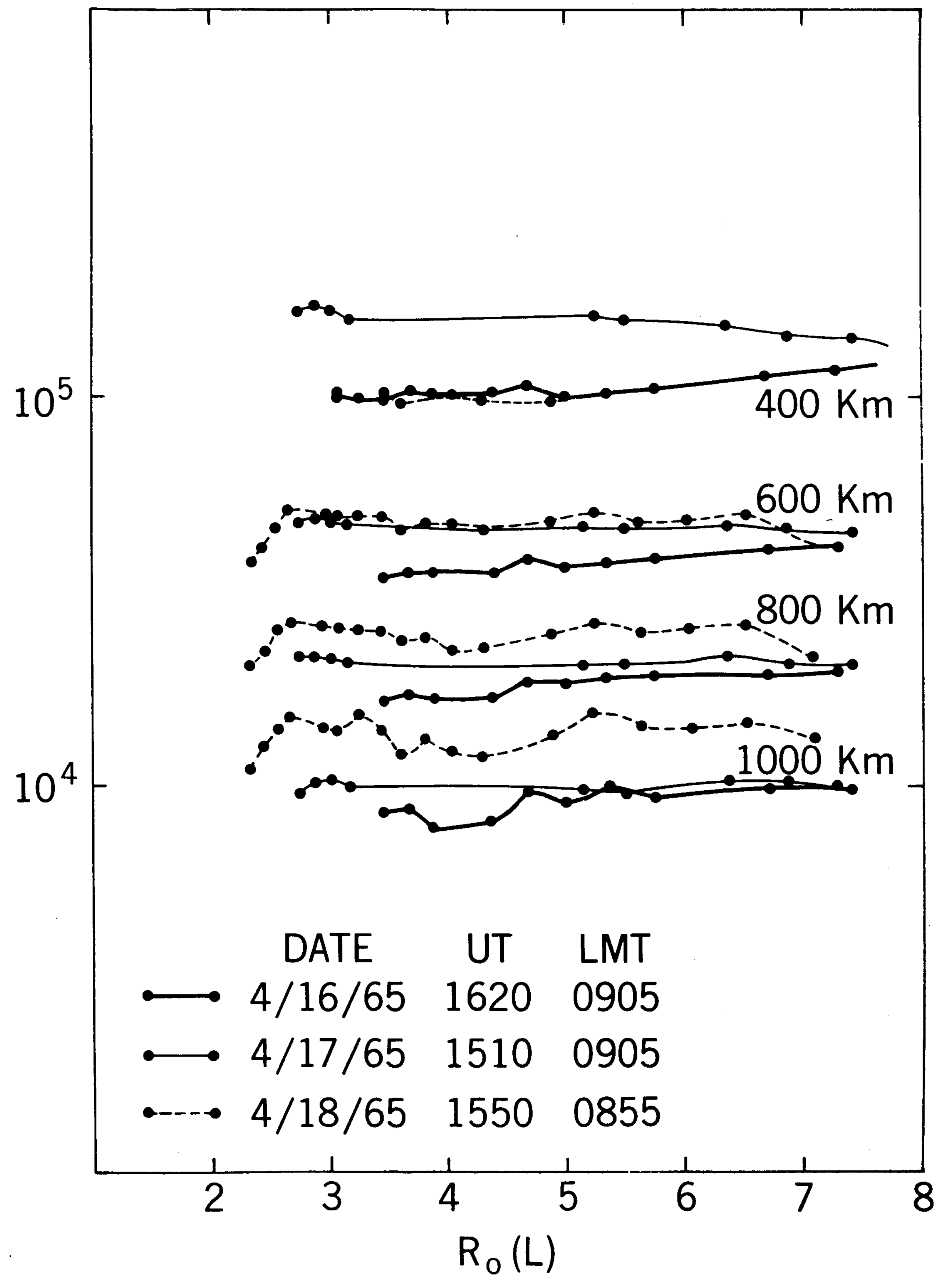
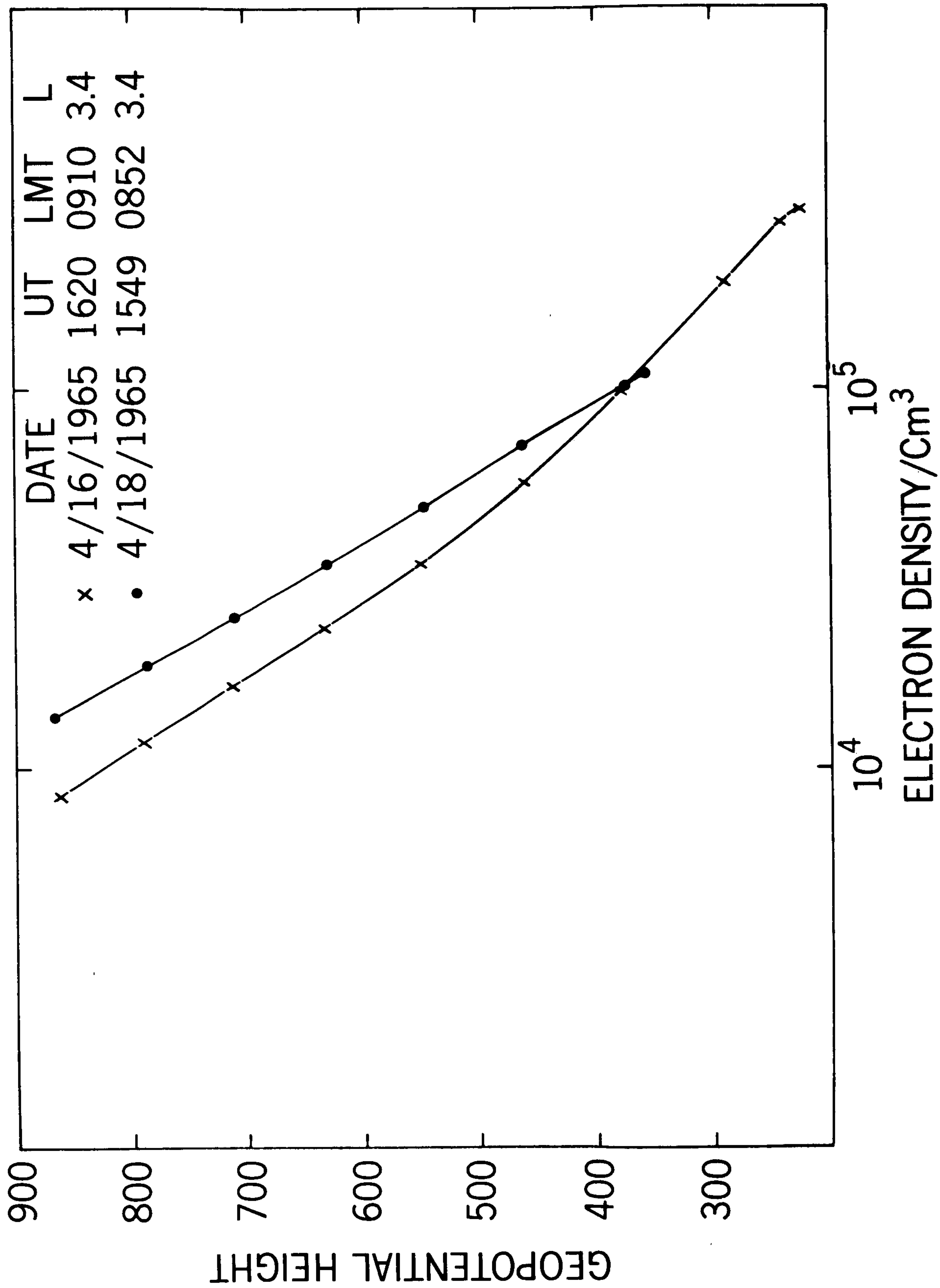
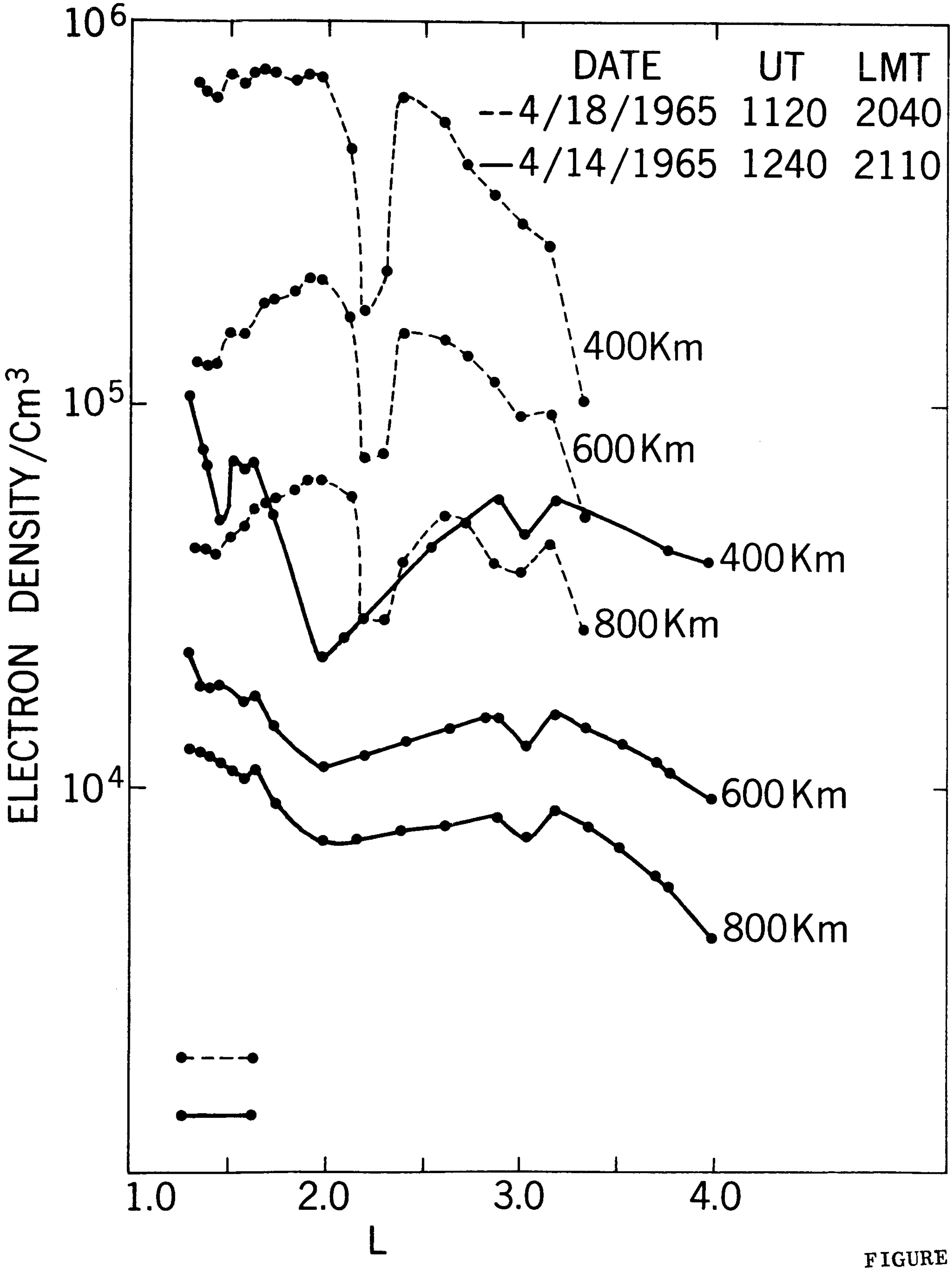

400 Km
600 Km
800 Km
1000 Km
10^5
10^4
DATE UT LMT
4/16/65 1620 0905
4/17/65 1510 0905
4/18/65 1550 0855
2 3 4 5 6 7 8
R_o (L)

FIGURE 3



DATE UT LMT L
× 4/16/1965 1620 0910 3.4
• 4/18/1965 1549 0852 3.4
900
800
700
600
500
400
300
GEOPOTENTIAL HEIGHT
10^4
10^5
ELECTRON DENSITY/Cm^3

FIGURE 4



DATE UT LMT
4/18/1965 1120 2040
4/14/1965 1240 2110
400Km
600Km
400Km
800Km
600Km
800Km
ELECTRON DENSITY/Cm3
10^6
10^5
10^4
1.0
2.0
3.0
4.0
L

FIGURE 5

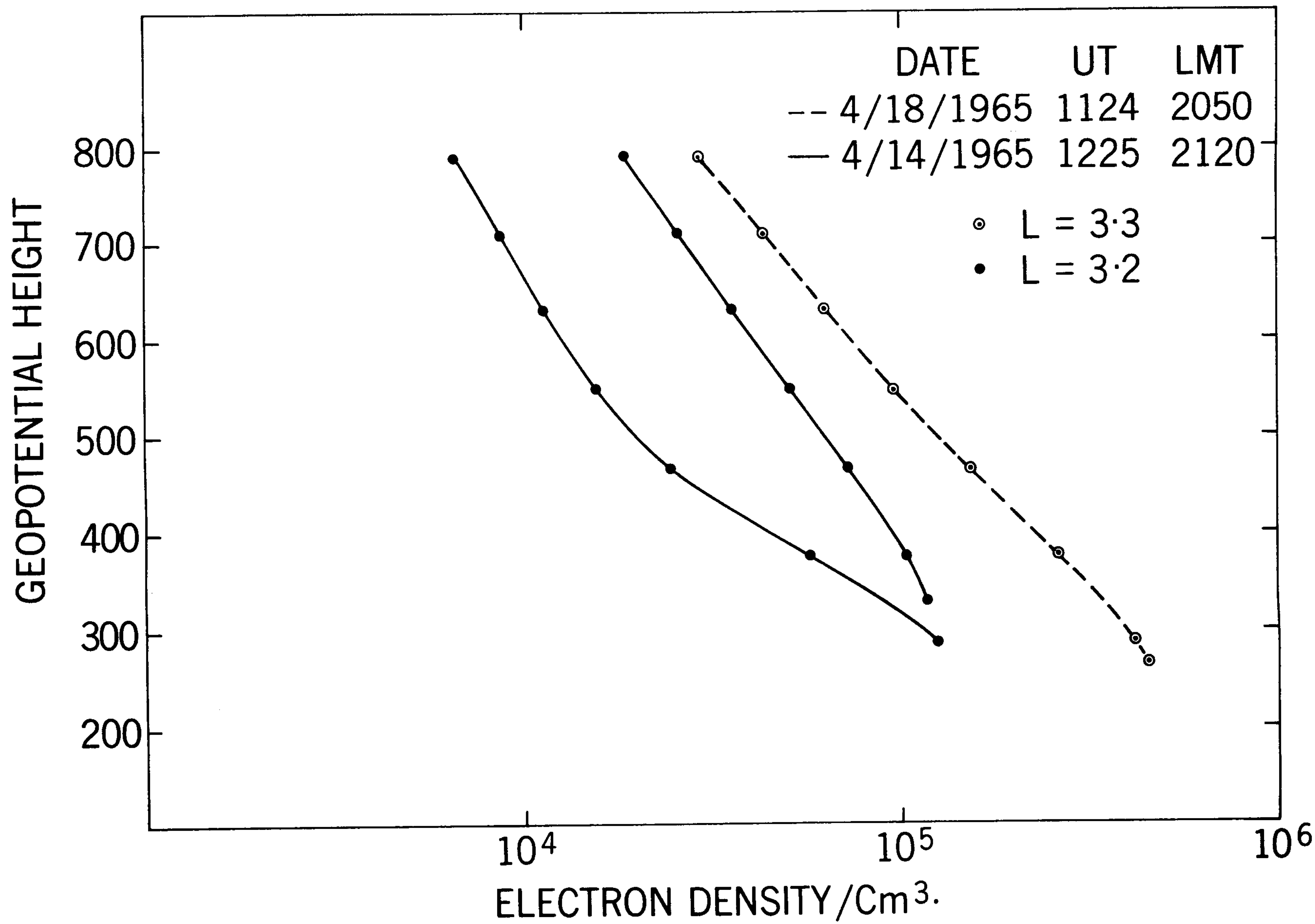
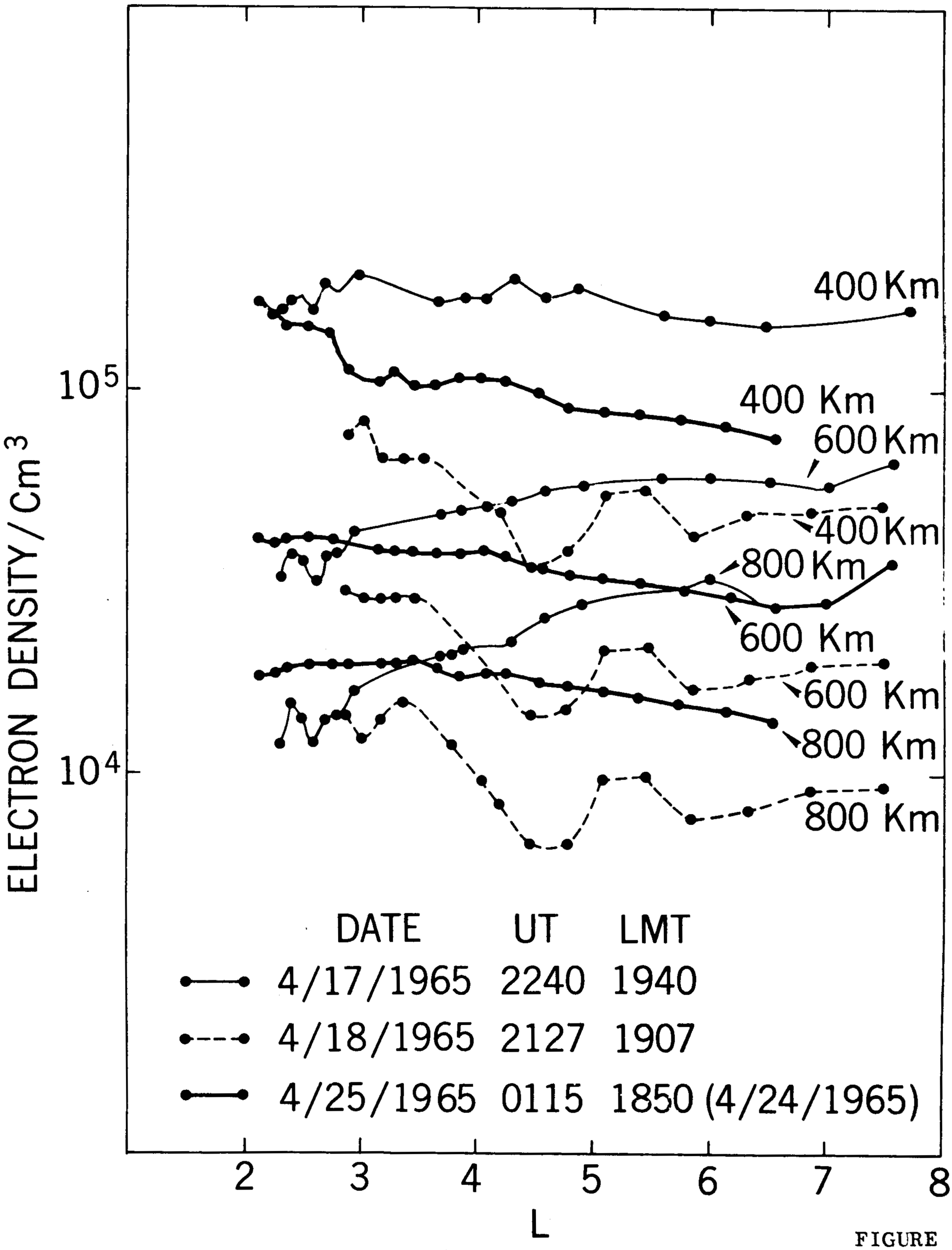

DATE UT LMT
-- 4/18/1965 1124 2050
— 4/14/1965 1225 2120
L = 3·3
L = 3·2
800
700
600
500
400
300
200
GEOPOTENTIAL HEIGHT
10^4
10^5
10^6
ELECTRON DENSITY/Cm^3.

FIGURE 6



400 Km
400 Km
600 Km
400 Km
800 Km
600 Km
600 Km
800 Km
800 Km
10^5
10^4
ELECTRON DENSITY / Cm^3
DATE UT LMT
4/17/1965 2240 1940
4/18/1965 2127 1907
4/25/1965 0115 1850 (4/24/1965)
2 3 4 5 6 7 8
L

FIGURE 7

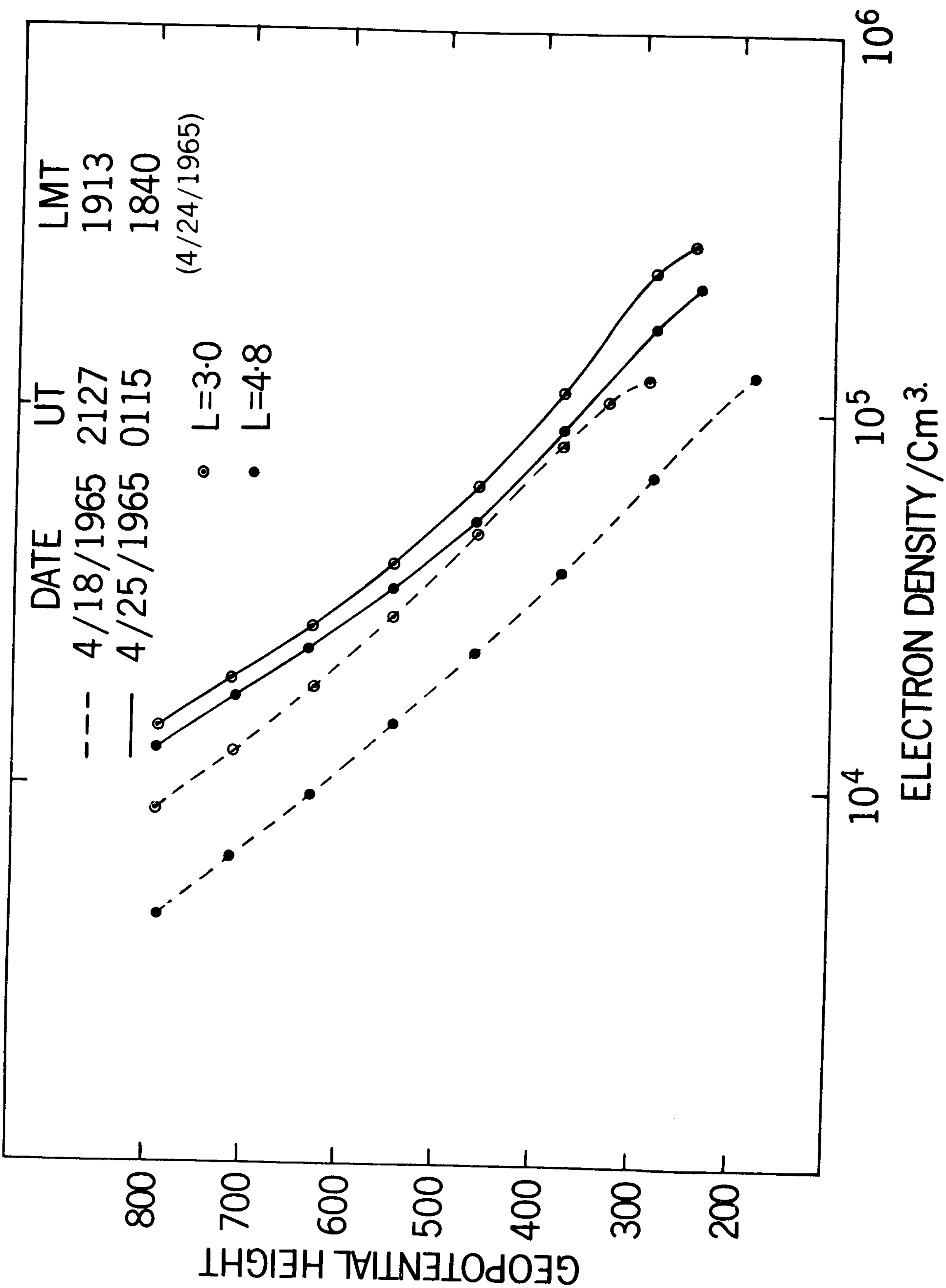

DATE UT LMT
- - - 4/18/1965 2127 1913
—— 4/25/1965 0115 1840
(4/24/1965)
L=3·0
L=4·8
GEOPOTENTIAL HEIGHT
800
700
600
500
400
300
200
10^4
10^5
10^6
ELECTRON DENSITY/Cm^3

FIGURE 8

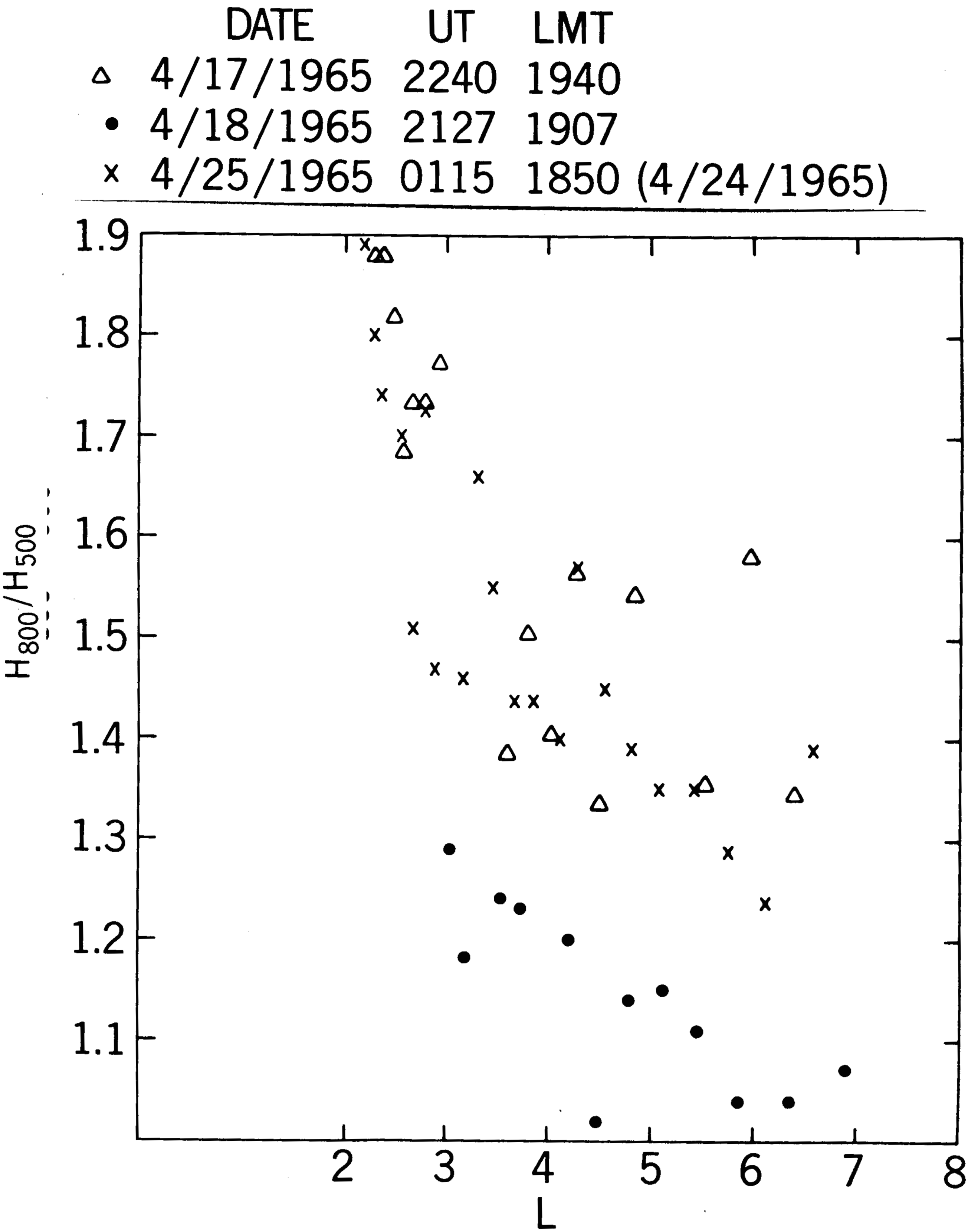
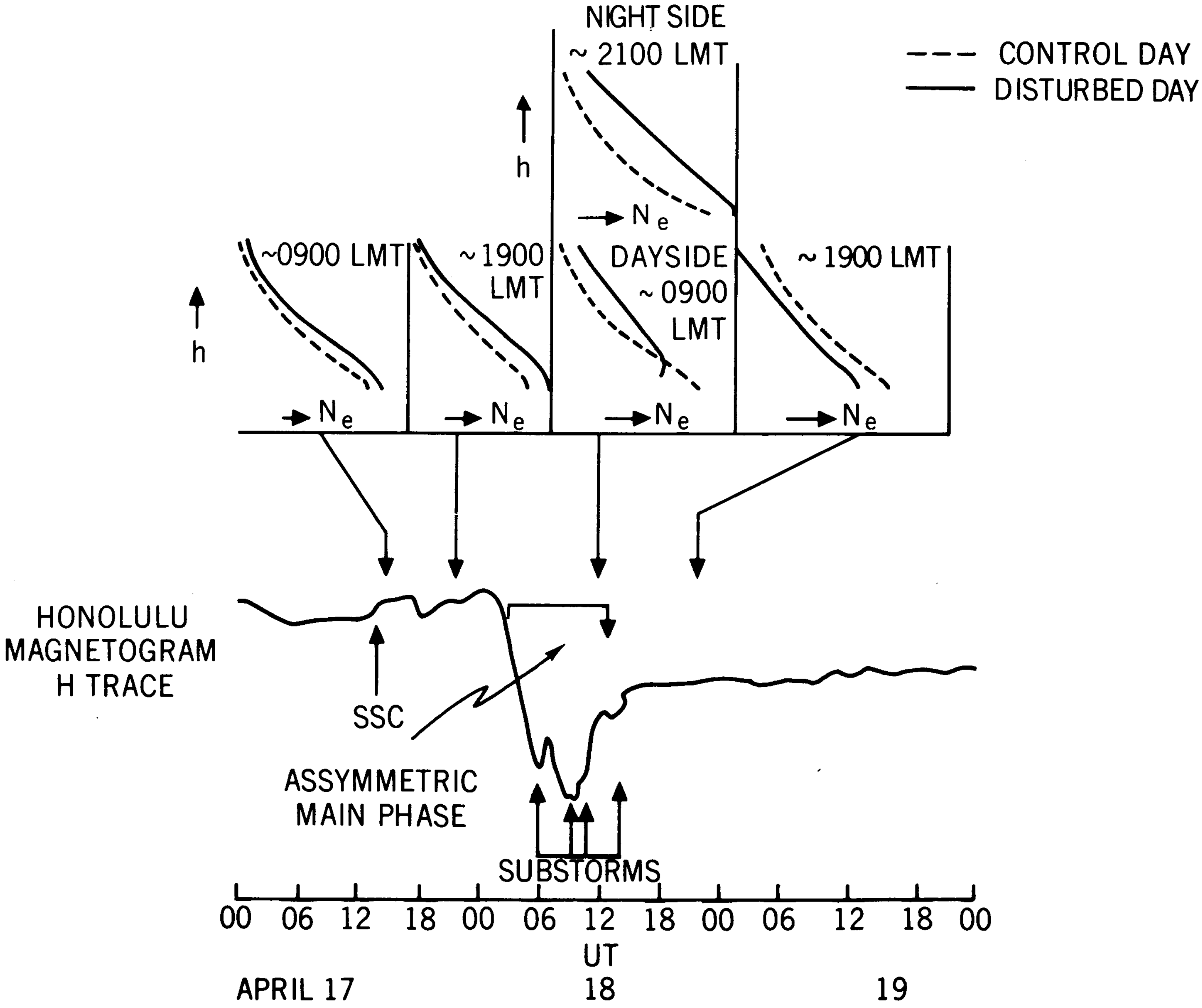

DATE UT LMT
△ 4/17/1965 2240 1940
● 4/18/1965 2127 1907
× 4/25/1965 0115 1850 (4/24/1965)
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
H800/H500
2
3
4
5
6
7
8
L

FIGURE 9



NIGHT SIDE
~ 2100 LMT
CONTROL DAY
DISTURBED DAY
h
h
Ne
~0900 LMT
~1900 LMT
DAYSIDE ~0900 LMT
~1900 LMT
Ne
Ne
Ne
Ne
HONOLULU MAGNETOGRAM H TRACE
SSC
ASSYMMETRIC MAIN PHASE
SUBSTORMS
00 06 12 18 00 06 12 18 00 06 12 18 00
UT
APRIL 17
18
19

FIGURE 10