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PLASMA PARAMETER β IN THE MIDNIGHT MAGNETOSPHERE: FROM THE NEAR-EARTH PLASMA SHEET TO THE PLASMAPAUSE

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PLASMA PARAMETER β IN THE MIDNIGHT MAGNETOSPHERE: FROM THE NEAR-EARTH PLASMA SHEET TO THE PLASMAPAUSE

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July 1971

A B S T R A C T

Using the Rb magnetometer observations on OGO 3 and Frank's (1971) estimates of plasma energy density based on proton and electron flux measurements on the same satellite, plasma parameter β, i.e. the ratio of plasma energy density to the magnetic field energy density, is evaluated in the magnetosphere near midnight. The observations, obtained on six successive inbound passes on June 23 to July 3, 1966, were made near the dipole equator and covered geocentric distances roughly 10 to 3 R_e. It is shown that near midnight, β normally exceeds unity just outside the plasmapause even during magnetically quiet period with Kp = 0 to 1. Existence of a peak in β near the inner edge of the high β region appears to be a part of the structure of this plasma region. The proton belt which Frank has referred to as the 'extra-terrestrial ring current' is an essential part of the high β belt, but is not the main cause of the equatorial depression of the magnetic field in the inner magnetosphere, because the distribution of ΔB, defined as the deviation of the scalar B from the magnitude of a reference field, is entirely different from that expected from his proton belt. Both the radial distribution and the magnitude of β are highly variable from one pass to the next over a time span of approximately two days, suggesting that the plasma in this region is nearly always dynamically active. The 'trapping boundary' for higher-energy electrons ($E \gtrsim 40$ kev) is found near the point at which the field gradient changes noticeably from that of a dipolar field to a smaller gradient. The position of the trapping boundary also varies considerably between successive passes.

Introduction

For the study of dynamics of the magnetosphere the plasma parameter β, i.e. the ratio of the plasma energy density to the magnetic field energy density, is an important factor. With the Goddard Space Flight Center magnetometer observations on the OGO 1, 3 and 5 satellites a continuous effort has been made to identify high β regions in the magnetosphere. The results from OGO 1 showed that there is a high β region at low geomagnetic latitudes near the dawn meridian between the geocentric distance of 10 or 11 R_e (earth radii) and the magnetopause (Heppner et al., 1967). More recent results from OGO 5 give examples in which this high β region near the geomagnetic equator extends toward the subsolar region to past 10 hours local time; the high β region becomes progressively narrower as the magnetopause distance decreases towards noon, making positive identification of this region more difficult. The existence of a high β near-tail region and the shell-like structure of this region in the nightside magnetosphere have been discussed with OGO 3 observations (Sugiura et al., 1970).

The electron energy density decreases rapidly at the earthward edge of the plasma sheet (Vasyliunas, 1968; Frank, 1968; Schield and Frank, 1970); the location of this plasma sheet inner edge near midnight is at a geocentric distance of about 6 to 8 R_e during magnetically quiet periods (Schield and Frank, 1970; Frank, 1971). Frank (1971) has given a summary of his OGO 3 observations in the near-earth region of the plasma sheet, according to which the seat of the "extraterrestrial ring current" overlaps with the earthward edge of the plasma sheet. In a series of papers (e.g., Frank, 1967a, 1967b, 1970) he had reported on the observations of low-energy protons in the magnetosphere, which lead him to a model of the quiet-time "extraterrestrial ring current" centered at about 6.5 R_e. On the basis of an analysis of extensive Rb magnetometer data from OGO's 3 and 5 Sugiura et al. (1971) have shown that at quiet times the magnetic field distribution does not indicate the presence of a doughnut-shaped ring current belt at the location where Frank's "extraterrestrial ring current" of low-energy protons resides. Thus, the latter proton belt, though its existence is, of course, not questioned, is not an entity that would correspond to the usual concept of the ring current.

The purpose of the present paper is to present the distribution of the plasma parameter β in the region extending from the near-earth plasma sheet to the plasmapause in the vicinity of the midnight meridian. The calculation of β was made using the proton and electron energy densities given by Frank (Figures 1 to 6 in his 1971 paper) and the simultaneous field observations by the GSFC Rb magnetometer on the same satellite. In as much as Frank's particle energy densities were obtained from his measurements the β values given below can be considered as being <u>in-situ</u> evaluations of β, only with the limitations stemming from the assumptions made in the deduction of particle energy densities.

<u>Distribution of β</u>

To my knowledge no reliable data for β exist for the region of the magnetosphere dealt with here; hence, plots of β, the magnitude B of the magnetic field, and ΔB, defined as the observed B minus the magnitude of a reference field, are presented in Figures 1 to 6 for all the six cases shown in Frank's (1971) paper. Figures 1 to 6 below correspond respectively to Figures 1 to 6 in Frank's paper. In his presentation proton and electron energy densities are plotted as functions of L;

in Figures 1 t· 6 here, three quantities, β, B, and ΔB are plotted against UT, and scales are given for dipole latitude, radial distance, L, and local time underneath the curves. The positions of the plasmapause and the trapping boundary for higher-energy particles as given by Frank are indicated in each figure. The region of present interest lies within about one hour of midnight and between geocentric distances 9 to 3 R_e; dipole latitude decreases from roughly 20^{o}N to 0^{o} as the satellite traverses the relevant region on its inbound passes on which the data presented here were taken.

A descriptive characterization of magnetic activity level for the period covered and the Kp values for the 3-hourly intervals overlapping, or adjacent to, the period are indicated in the caption for each figure. Except for the time interval on June 25, 1966, covered by Figure 2, all other cases represent quiet conditions. In particular, the interval from about 0530 to 0900 UT on June 27, shown in Figure 3, was very quiet, as evidenced by the low Kp value of 0+ prevailing throughout the first nine UT hours of this day.

In all examples the existence of a high β region beyond the geocentric distance of the plasmapause is evident. The distance between the plasmapause and the peak β is approximately 1 to 2 R_e for the average quiet condition represented by Figures 1, 4, 5, and 6. For the very quiet period of June 27 (Figure 3) the plasmapause coincides with the location of steep gradient of β, and the high β region begins approximately 0.5 R_e inside this position. According to the positive ion spectrometer measurements made by Taylor et al. (1968) on the same satellite, the decrease of hydrogen ion density at the plasmapause was very steep on this pass (Figures 7 in their paper), making the plasmapause position clearly identifiable. Thus, on the basis of Frank's estimate of plasma energy density, β reached unity just inside the plasmapause on this quiet day, the $\beta \gtrsim 1$ region slightly overlapping the plasmasphere. However, the possibility that the plasma energy density was an overestimate and that the plasmapause was the boundary between the plasmasphere and the high β region can probably not be ruled out without closer examination. In all other five cases β begins to rise at about the location of the plasmapause. It is, however, of significance that β became high (~ 1.5) immediately outside the plasmapause even though Kp was as low as 0+ during the first nine hours of this day; thus the existence of the high β region just outside the plasmapause seems to be a quasi-steady state of matter of the magnetosphere.

Along the inbound pass of June 25 shown in Figure 2 there are two sudden increases in β each followed by a subsequent gradual decrease. These steep β increases are accompanied by a sudden decrease in B. They belong to the type of magnetic field changes that Sugiura et al. (1970) considered as being essentially spatial structures of the nightside magnetosphere. No notable substorms with distinct onsets coinciding with the two sudden field changes were found in the available ground magnetic data including the AE index. The magnetic field structures in the near-tail region will be discussed in a separate paper, and are not discussed further here.

It is of interest to note that the magnetic field can be quite steady even when β is near or greater than unity, as is seen especially in Figures 3 and 6.

Distribution of Negative ΔB

In a recent report Sugiura et al. (1971) have presented average contour maps of ΔB in the noon-midnight and dawn-dusk meridian planes based on extensive magnetic field data from OGO's 3 and 5. One of the important features shown was the existence of a disk-like region of large negative ΔB values near the dipole equator in the inner magnetosphere extending inward to geocentric distances less than 3 R_e even during magnetically quiet periods. Their results showed that this equatorial field depression, or the inflation of the inner magnetosphere, cannot be caused by the proton belt which Frank called the "extraterrestrial ring current" (Frank, 1971, and his earlier papers referred to therein). Frank's proton belt is centered near 6.5 R_e at quiet times. As might be expected this proton belt is an essential part of the hump in β just outside the plasmapause, which is called the high β belt below. However, the ΔB curves in Figures 1 to 6 indicate that this high β belt cannot be the seat of the currents responsible for the steady decrease in ΔB, reaching a minimum at a geocentric distance less than 4 R_e. In general, the minimum is in the vicinity of the dipole equator in agreement with the ΔB contour maps given by Sugiura et al. (1971). The present results suggest that the existence of the high β belt is a part of the structure of the inner boundary region of the plasma sheet. Frank (1971) mentioned that "there is no distinguishable 'boundary' between the plasma sheet proton distributions and those of the ring current," and that "these two proton distributions merge in an apparently continuous manner." Thus, he suggested that "an examination of simultaneous measurements of the local magnetic field might possibly provide evidence of a boundary between these two regions." The present study of simultaneous measurements finds no such boundary, suggesting that the two proton distributions merging in a continuous manner need not be grouped into two separate regions. However, it is tempting to associate the high β belt with the auroral belt on the earth, because the position of the former maps roughly onto the auroral latitudes according to the field model of Sugiura et al. (on the basis of Figure 10 in their 1971 paper). This question is left for a future detailed study of the OGO 3 and 5 results.

The intensity and the distribution of the ring current are highly variable with magnetic activity (Sugiura et al., 1971). At disturbed times the ring current expands to larger distances than during quiet times (besides its being intensified in the inner part) so that a field decrease at the synchronous orbit of 6.6 R_e may parallel to that on the ground, as has been observed by ATS 1 (Cummings and Coleman, 1968).

Trapping Boundary

The positions of the 'trapping boundary' for energetic electrons ($E \gtrsim 40$ kev) given by Frank (1971) are indicated in Figures 1 to 6. The example on June 23 in Figure 1 shows very clearly that the trapping boundary is near the location at which a transition from the dipolar field to a more tail-like field with a less steep gradient takes place. In the case of June 25, Figure 2, the trapping boundary coincides with the inner one of the two sudden changes in B, which is near the termination of the dipolar field gradient. The June 29 case in Figure 4 is similar to the June 23 pass. For June 27 and July 1, in Figures 3 and 5 respectively, the trapping boundary appears to be a little farther out than might be expected, but still can be considered as being near the transition from the dipolar to the tail-like field. On July 3, Figure 6, the field was very smooth and the trapping boundary was at a considerably greater geocentric distance ($\sim 9\ R_e$) than in other cases.

It is noted that generally the decrease in ΔB toward small geocentric distances either begins near the trapping boundary or takes a fresh start near it. In the case of July 3, Figure 6, the ΔB decrease begins more gradually than in other cases without any distinctive starting point; this is likely to be related to the exceptionally smooth decrease of B with increasing radial distance without any outstanding changes. The direct causal relation between the equatorial negative ΔB region and the trapping region is not obvious at this stage. However, the fact that ΔB begins to decrease near the trapping boundary, which in turn is near the termination of the dipolar field, is consistent with a thought that those particles with pitch angles near 90° causing the equatorial negative ΔB (or the disk-like ring current) drift out of the region when the magnetic field deviates from the dipolar configuration appreciably, or scattered out by the irregularities that are usually associated with the region outside the termination of the primarily dipolar field. The trapping boundary at low altitudes has been studied extensively (e.g., Fritz, 1970; earlier papers referred to therein). It would be of great value in deducing the field configuration if in the future this boundary is located simultaneously at low altitude, high latitude regions and at distant equatorial regions.

Conclusions

Plasma parameter β normally exceeds unity just outside the plasmapause near midnight even during magnetically quiet periods. There appears to be a hump in β near the inner front of the high β region. Simultaneous magnetic field observations indicate that the proton belt observed by Frank (1971 and his earlier papers) and referred to as the 'extraterrestrial ring current' is not producing the major part of the equatorial negative ΔB, confirming the same conclusion drawn based on statistical results from OGO's 3 and 5 (Sugiura et al., 1971). Frank's proton belt appears to be a part of the structure of the inner boundary region of the plasma sheet. The quiet-time ring current must be produced by equatorially trapped particles whose distribution extends inwardly to distances less than 4 R_e, and whose maximum intensity is probably at 3 to 4 R_e. The identification of these particles has not as yet been positively made.

The trapping boundary for higher-energy electrons ($E \gtrsim 40$ kev) is generally found, as is anticipated, near the point at which the field gradient changes from that of a dipole field to a smaller gradient. The position of the trapping boundary varies considerably as does the front edge of the high β region even when magnetic activity as represented by Kp is as low as 0 or 1. Both the radial distribution and the magnitude of β in this region are also highly variable even at magnetically quiet times. These features suggest that dynamics of the plasma in the near-earth plasma sheet region is nearly always active. Using the recent results of OGO 3 and 5 scalar field analysis, the high β belt roughly maps onto the auroral belt on the earth.

Acknowledgements

This investigation is part of the study of the results from the OGO 3 and 5 magnetometer experiments being undertaken together with Drs. J. P. Heppner, B. G. Ledley, and T. L. Skillman, to whom I wish to express my deep gratitude. I am indebted to Dr. J. P. Heppner for helpful comments.

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FIGURE CAPTIONS

Figure 1. β, B, and ΔB from the near-earth plasma sheet to the vicinity of the plasmapause for June 23, 1966, during a relatively quiet period; Kp for the two 3-hourly intervals 03-06 and 06-09 hours UT was 1- and 1o.

Figure 2. β, B, and ΔB for June 25, 1966, during the main phase to the recovery phase of a weak magnetic storm; Kp for the two 3-hourly intervals 03-06 and 06-09 hours UT was 3+ and 3o.

Figure 3. β, B, and ΔB for June 27, 1966, for a very quiet period; Kp was 0+ throughout the three 3-hourly intervals 00-03, 03-06, and 06-09 hours UT.

Figure 4. β, B, and ΔB for June 29, 1966, for a relatively quiet period; Kp for the 3-hourly interval 06-09 hours UT was 1-. Kp was 1+ prior to this interval, and was 0+ after it.

Figure 5. β, B, and ΔB for July 1, 1966, during a period relatively quiet but following weak magnetic activity. Kp for 06-09 UT was 1+, which was preceded by 2o and 2-, and followed by 2-.

Figure 6. β, B, and ΔB for July 3, 1966, during a period relatively quiet but following weak magnetic activity. Kp for 06-09 UT was 1-, which was preceded by 2- and 2o, and followed by 1o.

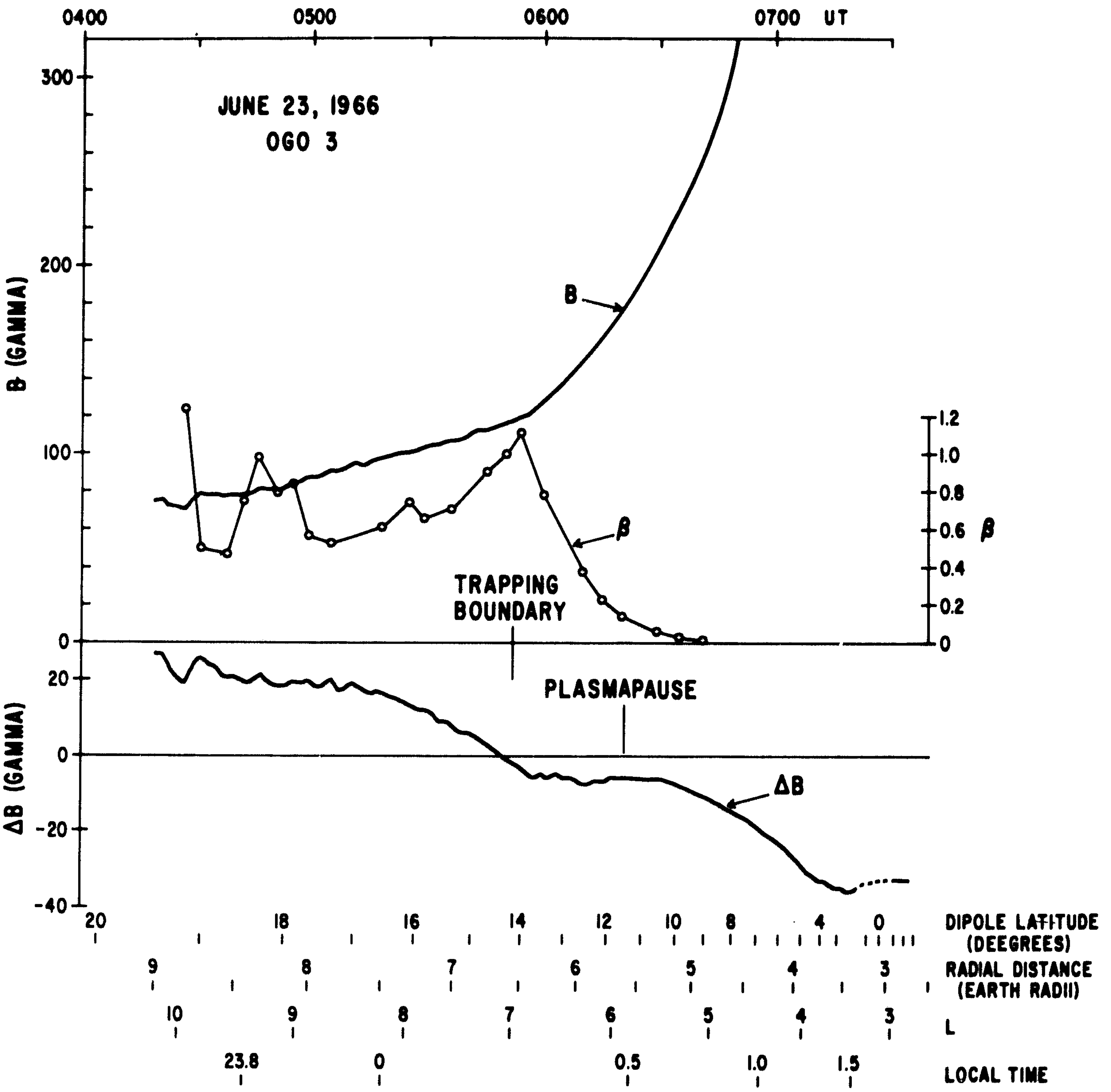
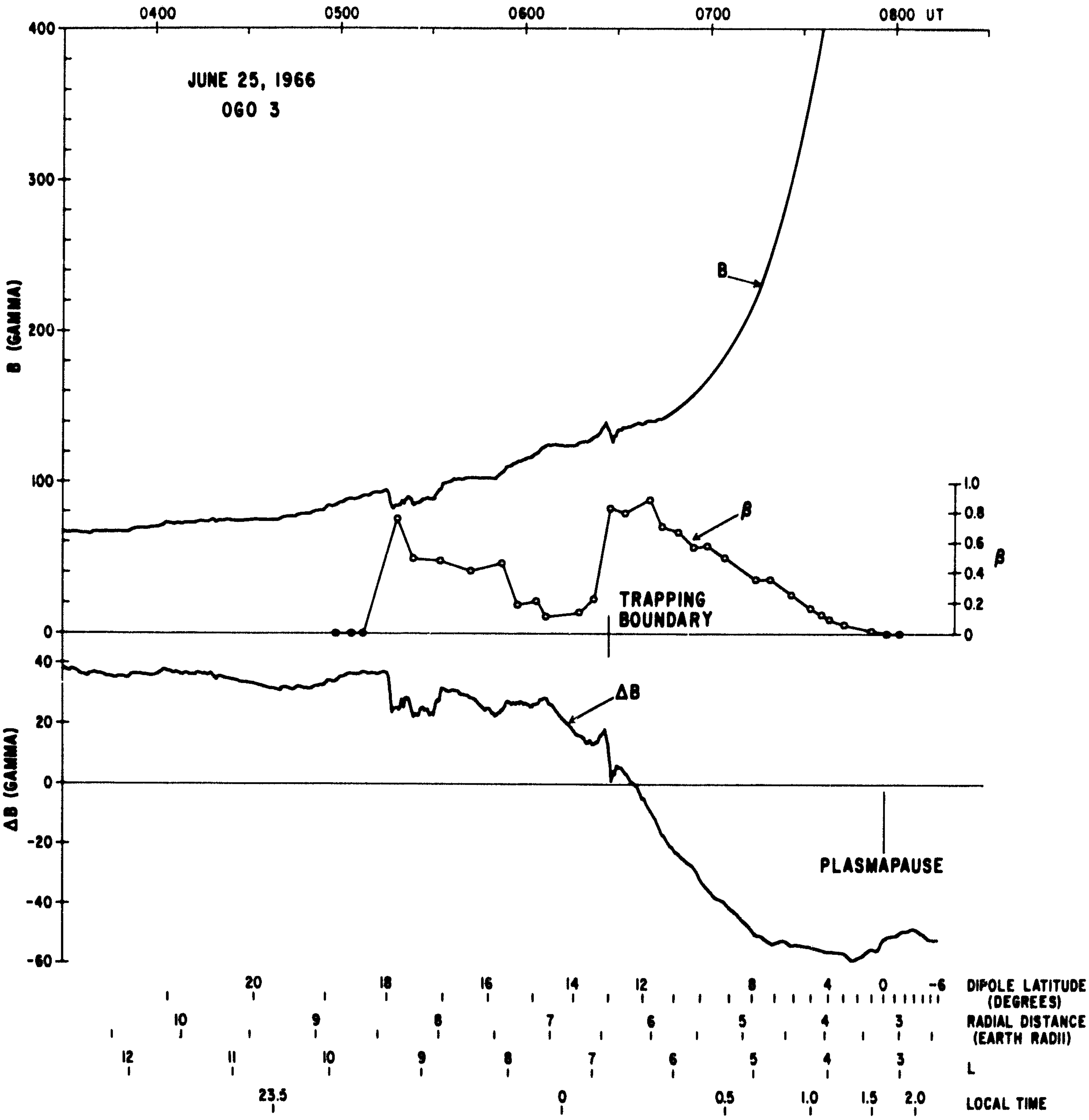

0400
0500
0600
0700
UT
JUNE 23, 1966
OGO 3
B (GAMMA)
300
200
100
0
B
β
TRAPPING
BOUNDARY
1.2
1.0
0.8
0.6
0.4
0.2
0
PLASMAPAUSE
ΔB (GAMMA)
20
0
-20
-40
ΔB
20
18
16
14
12
10
8
4
0
DIPOLE LATITUDE
(DEEGREES)
9
8
7
6
5
4
3
RADIAL DISTANCE
(EARTH RADII)
10
9
8
7
6
5
4
3
L
23.8
0
0.5
1.0
1.5
LOCAL TIME

FIGURE 1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0500
0600
0700
0800 UT
JUNE 25, 1966
OGO 3
B (GAMMA)
B
β
TRAPPING BOUNDARY
ΔB
ΔB (GAMMA)
PLASMAPAUSE
DIPOLE LATITUDE (DEGREES)
RADIAL DISTANCE (EARTH RADII)
L
LOCAL TIME

FIGURE 2

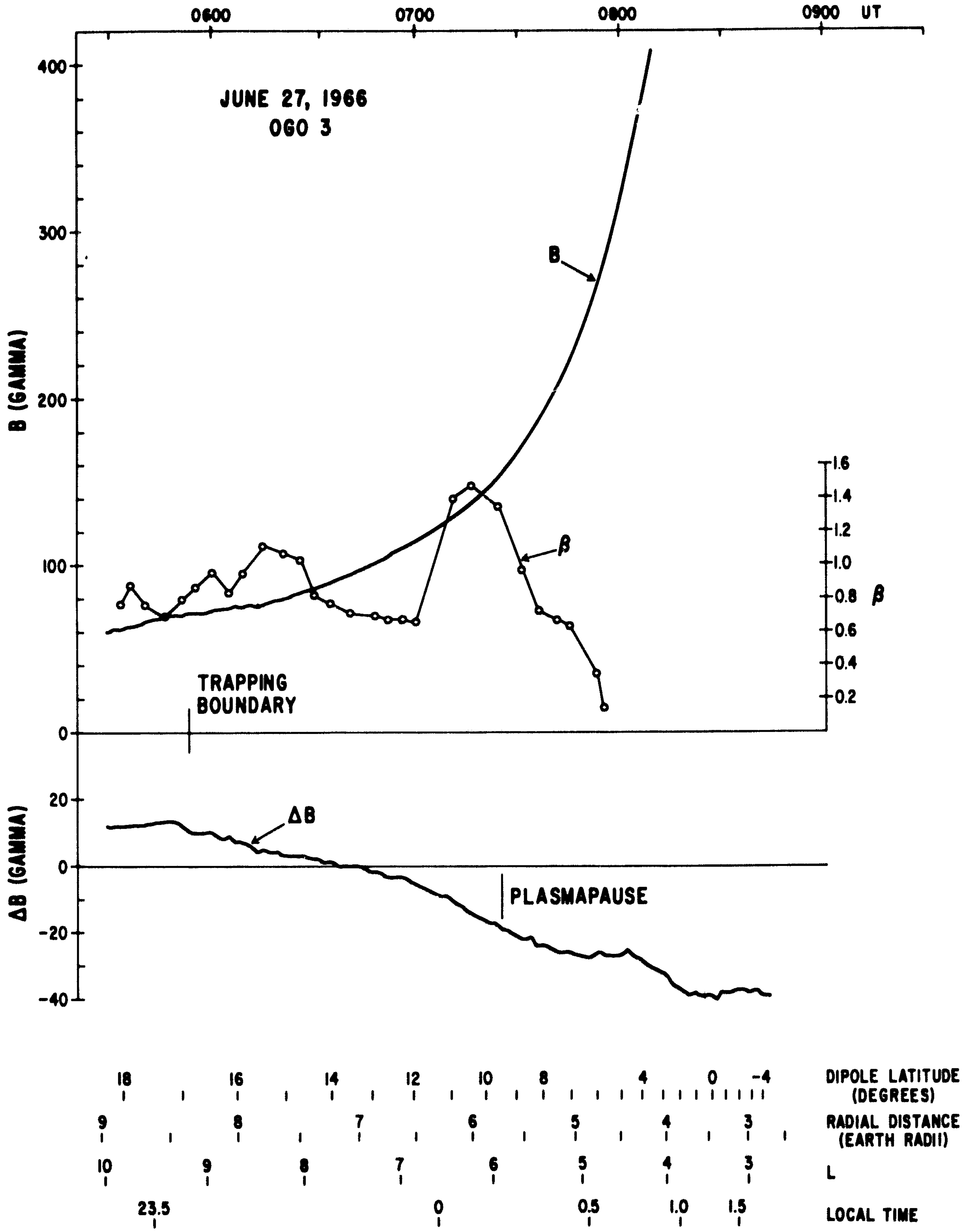

0600
0700
0800
0900 UT
JUNE 27, 1966
OGO 3
B (GAMMA)
B
β
TRAPPING
BOUNDARY
ΔB (GAMMA)
ΔB
PLASMAPAUSE
DIPOLE LATITUDE
(DEGREES)
RADIAL DISTANCE
(EARTH RADII)
L
LOCAL TIME

FIGURE 3

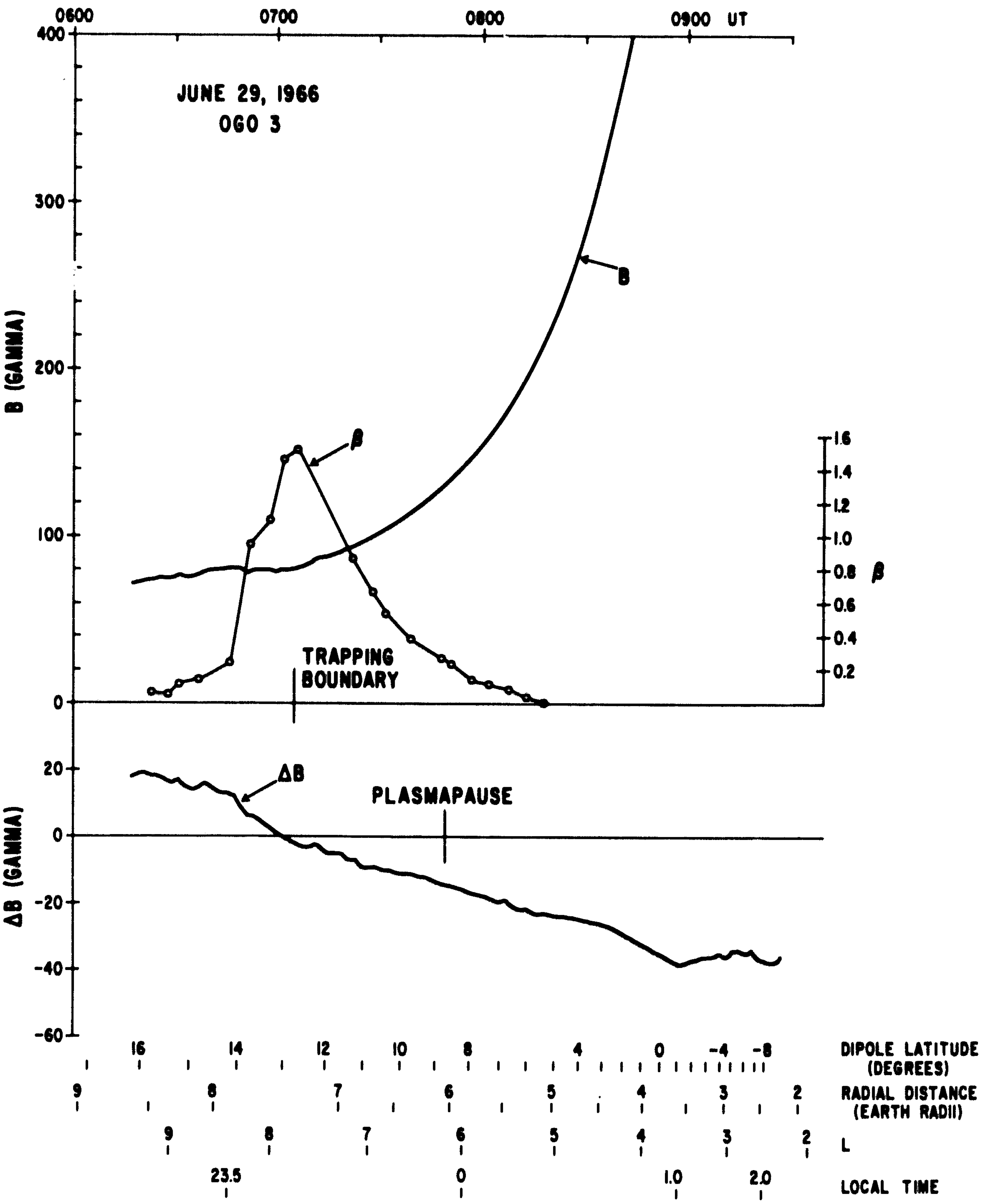
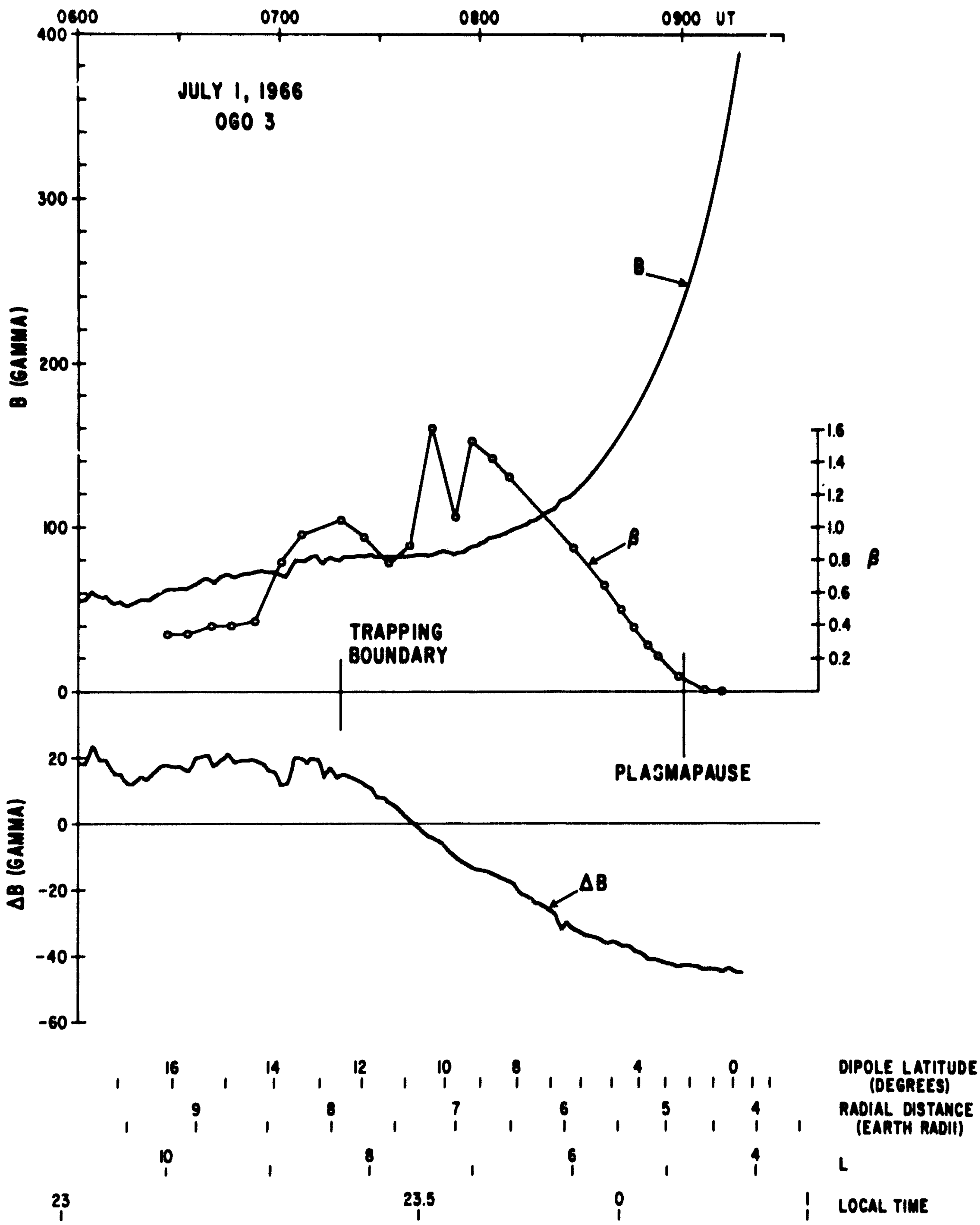

0600
0700
0800
0900 UT
JUNE 29, 1966
OGO 3
B (GAMMA)
B
β
TRAPPING
BOUNDARY
ΔB
PLASMAPAUSE
ΔB (GAMMA)
DIPOLE LATITUDE
(DEGREES)
RADIAL DISTANCE
(EARTH RADII)
L
LOCAL TIME

FIGURE 4



0600
0700
0800
0900 UT
JULY 1, 1966
OGO 3
B (GAMMA)
400
300
200
100
0
B
β
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
TRAPPING BOUNDARY
PLASMAPAUSE
ΔB (GAMMA)
20
0
-20
-40
-60
ΔB
DIPOLE LATITUDE (DEGREES)
16
14
12
10
8
4
0
RADIAL DISTANCE (EARTH RADII)
9
8
7
6
5
4
L
10
8
6
4
LOCAL TIME
23
23.5
0

FIGURE 5

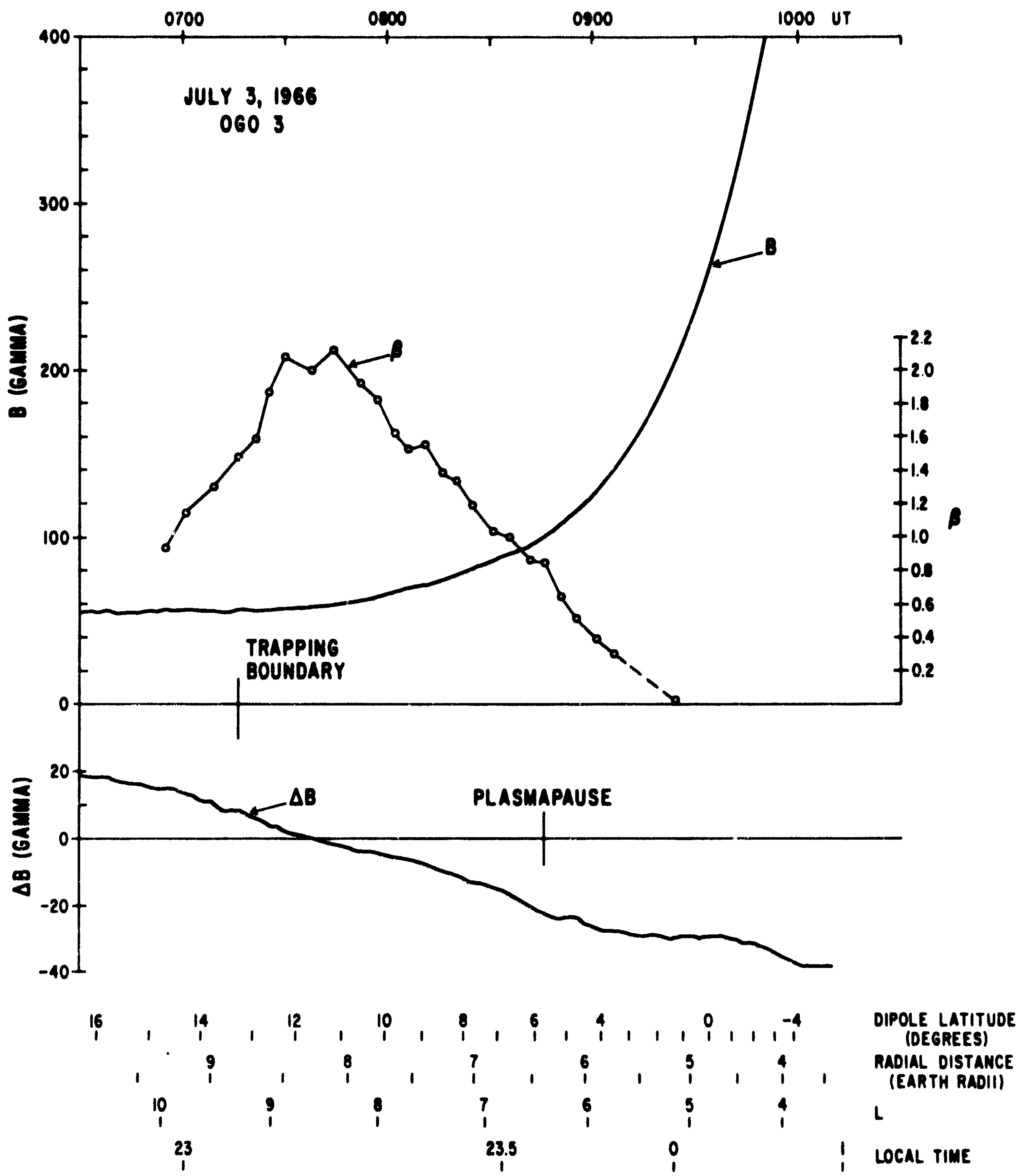

0700
0800
0900
1000 UT
JULY 3, 1966
OGO 3
B (GAMMA)
400
300
200
100
0
B
β
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
TRAPPING
BOUNDARY
ΔB (GAMMA)
20
0
-20
-40
ΔB
PLASMAPAUSE
16 14 12 10 8 6 4 0 -4
DIPOLE LATITUDE
(DEGREES)
9 8 7 6 5 4
RADIAL DISTANCE
(EARTH RADII)
10 9 8 7 6 5 4
L
23 23.5 0
LOCAL TIME

FIGURE 6