"On Inward Motion of the Magnetopause Preceding a Substorm"

Michel P. Aubry*, Christopher T. Russell
and Margaret G. Kivelson
University of California, Los Angeles

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Institute of Geophysics and Planetary Physics
University of California
Los Angeles, California 90024

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*ESRO-NASA University Research Associate on leave from Groupe de Recherches Ionospheriques du CNRS (Paris)

ABSTRACT

On March 27, 1968 the UCLA magnetometer on board the inbound OGO 5 satellite recorded an inward motion of the magnetopause by about 2 Re in two hours. It is shown that this inward motion was associated with a reversal of the vertical component of the interplanetary field from northward to southward, the solar wind momentum flux remaining constant. The inward shift did not produce any compression of the magnetospheric cavity which implies a transfer of magnetic flux from the dayside magnetosphere to the tail; the growth phase of a substorm was observed less than half an hour following the beginning of the inward motion. It is emphasized that the position of the magnetopause after the inward shift cannot be explained in terms of the available models.

Introduction

Studies of the relation between the orientation of the interplanetary magnetic field and the geomagnetic activity recorded by ground observatories have indicated that a southward oriented interplanetary field seems to be more effective for triggering magnetic substorms, micropulsations and, in general, is correlated with an elevated Kp index (Fairfield and Cahill, 1966; Rostoker and Falthammar, 1967; Schatten and Wilcox, 1967; Wilcox, et. al., 1967; Zelwer, et. al., 1967; Nishida, 1968). There is rather general agreement that during a substorm, owing to tangential stress between the magnetosphere and the solar wind, magnetic flux is continually moved into the tail; this magnetic flux is stored and the corresponding energy is released sporadically producing substorms (Axford 1965, Atkinson, 1966; Siscoe and Cummings 1969). If the tail magnetic flux increases before substorms, the magnetic flux on the dayside magnetosphere should decrease and consequently the dayside magnetopause should be closer to earth. This has been proved theoretically by Unti and Atkinson (1968); however, from their two dimensional Chapman-Ferraro model, they concluded that the inward displacement of the nose associated with an increase in the tail flux was rather small. From an experimental point of view, Patel and Dessler (1966) studied the relation between the magnetopause radius and the three hour a_p index. The results were too scattered to allow any conclusion to be drawn, but the three hour a_p index is certainly not the relevant parameter to be considered if one wants to delineate the time sequence just before a substorm.

It seems logical to assume the existence of some change in the dayside magnetopause associated with the substorm sequence, e.g., inward motion before the substorm, and outward motion produced by the increased ring current after the substorm. If the triggering of substorms is related both to the orientation of the interplanetary field and to the position of the dayside magnetopause there should be some relation between the latter quantities.

From a theoretical point of view, the study of the shape and position of the magnetopause is based on the assumption of equilibrium of the pressure on the two sides of the boundary, (Mead and Beard, 1964; Lees, 1964; Spreiter, et. al., 1966; Spreiter and Alksne, 1969). The external pressure is obtained from various models of the interplanetary magnetic field and of the solar wind plasma flow, and may include elastic or inelastic collisions of the particles with the boundary. The internal pressure is supplied by the magnetic field alone; the magnetic field is the sum of the earth's field plus the field of the magnetopause surface currents, which may be calculated self-consistently, or from an image dipole. Schield (1969) has added the effect of a ring current.

The orientation of the interplanetary field is not considered as a relevant parameter of the boundary position in these studies except in the papers of Lees (1964) and Shield (1969). These calculations predict an increase of the nose distance when the orientation of the magnetic field changes from horizontal (parallel to the main plasma flow) to vertical southward. This prediction disagrees with the phenomenological argument we have presented above, which as we shall demonstrate, is borne out by our observations.

The aim of this paper is to present observations of the following time sequence: a reversal of the vertical component of the interplanetary magnetic field from northward to southward is immediately followed by a significant inward motion of the magnetopause and later by a substorm. The data presented covers an interval of less than three hours on March 27, 1968 during a sequence of multiple crossings of the magnetopause. OGO-5 was inbound, and this allowed us to detect an important inward motion of the magnetopause. We use primarily data from the UCLA triaxial fluxgate magnetometer aboard the OGO-5 satellite. The necessary information about the experiment is provided in Section 2. The solar wind parameters measured from the MIT and Ames experiments aboard Explorer 35 were kindly made available by Dr. J.H. Binsack of MIT and Drs. C.P. Sonett and D.S. Colburn at Ames. Together these experiments demonstrate that the inward shift was not caused by an increase of the solar wind momentum flux but can be clearly associated with a reversal of the vertical component of the solar wind magnetic field. The position of the boundary after the reversal, as stated, does not fit with the theoretical prediction of Lees (1964). This suggests that corrections should be made to the models of the laminar flow interaction of the solar wind with the geomagnetic cavity. A study of ground magnetograms shows the beginning of a substorm growth phase (McPherron, 1969) less than half an hour after the beginning of the inward shift of the dayside magnetopause. These various data are presented in Section 3 and discussed in Sections 4 and 5.

2. The Experiment:

OGO-5 was launched on March 4, 1968 into a highly elliptic orbit with an apogee of 24.4 Re geocentric and perigee at an altitude of 300 km. The height of perigee, however, has increased at a rate of over an earth radius per year with a corresponding decrease in apogee. Apogee initially was at 0900 LT and due to the earth's orbital motion occurred at successively earlier local times for succeeding orbits. The orbital plane was so inclined that outbound passes crossed the magnetopause well above the magnetospheric equator whereas inbound passes crossed the magnetopause close to the magnetospheric equator.

The satellite carried an extensive set of energetic particle and magnetic and electric field experiments. In this paper we will be concerned mainly with the identification of the magnetopause traversals. For this purpose, we have used principally data from the UCLA triaxial fluxgate magnetometer.

This instrument is described in detail in a later article on the structure of the magnetopause during this same period (Aubry, et. al., 1970). We have also examined data from the UCLA energetic electron spectrometer, the JPL solar wind experiment, and the Lockheed ion mass spectrometer to corroborate our identifications. Descriptions of these experiments are given by Kivelson, et. al., (1970); Neugebauer, (1970) and Harris and Sharp, (1969).

3. Observations

On March 27, 1968, the inbound OGO-5 satellite recorded multiple crossings of the magnetopause during an interval of more than two hours, from 1700 to 1915 UT. The one minute averages of the magnetic field in the geocentric solar magnetospheric (GSM) coordinate system from 1500-2100 UT are shown in Figure 1.

In Figure 2, 4.6 second averages of the magnetic field data in the reference system of the satellite are presented for the time interval from 1719 to 1919 UT. The figure consists of three panels. Each panel refers to the same time interval and contains forty minutes of data. The three components B_{XS}, B_{YS} and B_{ZS} of the magnetic field in the reference system of the satellite as well as the total field B_T appear in each panel. In this paper we will be concerned mainly with B_{XS} which is the component of the magnetic field along the XS axis of the satellite reference system. For the period considered this axis is nearly antiparallel to the Z_{GSM} axis (the angle varies between 170° and 180°) and crossings of the magnetopause appear as reversals of B_{XS}, which is positive in the magnetosheath and negative in the magnetosphere. In order to avoid any ambiguity, these two regions are labelled in Figure 2 for the first crossings.

Figure 3 gives the position of the satellite at the time of the observation. The first clear encounter of the boundary took place at 1700 UT (Fig. 1) when the geocentric distance of the satellite was 12.81 Re, (point A in Fig. 3). The field amplitude was about the same on both sides of the boundary; only the horizontal component varied. The data from the UCLA energetic electron spectrometer, the JPL solar wind experiment and the Lockheed ion mass spectrometer confirm that OGO-5 entered the magnetosphere at 1700.

At 1730 a sequence of multiple crossings began, lasting until 1915. The structure and the oscillations of the boundary during this sequence are studied in an accompanying paper (Aubry, et. al., 1970). We are interested here only in the average inward shift of the magnetopause. This sequence of multiple crossings can be clearly divided into two parts: before 1840 and after 1840. From 1730 to 1840 (points B and C in Figures 2 and 3) the appearance of the magnetopause crossings is consistent with a constant mean magnetopause position about which the boundary oscillated with a period of from 3.5 to 6 minutes. As the satellite proceeded radially inwards towards this mean position it spent successively less time in the magnetosheath and more time in the magnetosphere during each oscillation. Around 1800 UT the time spent in each region was about equal. This we take as the mean location of the magnetopause during the interval: 11.6 Re geocentric radial distance. From 1800 to 1830, the pattern of crossings continues as OGO-5 moved inwards away from the mean position, successively spending a larger fraction of each oscillation within the magnetosphere.

From 1840 to 1916 (points C and D in Figs. 2 and 3) a new pattern of crossings is evident. The general aspect of the data changes owing to the presence of short period oscillations (1 minute) with nearly the same amplitude as the long period ones (5 to 7 minutes). Moreover, the particle flux detected from 1840 to 1905 UT was extremely variable even on the magnetospheric side of the boundary. During this period, the satellite repeatedly was located inside the magnetosheath. In contrast, between 1818 and 1840 the satellite moved back and forth between the magnetosphere and the sheet of current, but did not reach the magnetosheath. Consequently, this sequence of data after 1840 corresponds to a new inward motion of the average magnetopause. The last crossing of the boundary occurred at a distance of about 9.9 Re.

So far we have discussed only the position of the magnetopause; however, there was a very important change in the magnetosheath field that can be seen in Figure 1. The field in the magnetosheath was northward before 1700 (GSM Z component positive in Figure 1) and become southward after 1730. Indeed at each crossing after this time the field in the magnetosheath appears to have been southward (GSM Z component negative).

The data from the NASA-Ames magnetometer aboard the Lunar Orbiter Explorer 35 satellite were kindly made available by C.P. Sonett and D.S. Colburn. The variation of the orientation of the interplanetary field is shown in Figure 4. The position of the moon is also shown in this figure. The direction moon-earth makes an angle less than 12^{o} with the X GSM axis and we neglect this angle in the following argument. The velocity of the solar wind at the time of observation was 470 km/sec (J. Binsack personal communication). Owing to the presence of fluctuations in the direction of the interplanetary field, it is difficult to give the precise time of the reversal of this field but one may reasonably claim that it occurred between 1710 and 1715. This reversal, convected by the solar wind, had to travel to the magnetopause. We know the average direction of the projection of the interplanetary magnetic field in the equatorial plane (Fig. 4). If we use the model of Spreiter and Alksne (1969) showing the deformation of magnetic field lines between the bow shock and the magnetopause, it appears that the reversal had to travel less than 60 Re in the interplanetary medium before any perturbation reached the magnetopause near 0900 LT. That gives an upper limit of 14 minutes for the travel time, so the field reversal should have reached the magnetopause between 1724 and 1729.

On the satellite Explorer 33, at this time in the afternoon magnetosheath, the NASA-Ames magnetometer detected the reversal of the magnetosheath field between 1721 and 1727. At 1731 OGO-5 recorded the magnetopause moving inward and measured a mainly horizontal magnetic field just outside the magnetopause. We cannot determine, however, whether the spacecraft actually entered the magnetosheath at this time or penetrated only the current sheet of the magnetopause. During the next pass into the magnetosheath, 10 minutes later, OGO-5 measured a southward field.

There appears undoubtedly to be a relation between the reversal of the field and the inward motion of the magnetopause. However, owing to the inaccuracy in the reversal time (blurred by magnetic field fluctuations) and to the uncertainty about a complete crossing at 1731, it is difficult to compute accurately the time constant involved in this relationship. Let us emphasize that the MIT experiment aboard Explorer 35 detected no change in the solar wind momentum flux associated with the change in the magnetic field orientation. This point will be discussed later. After 1812, Explorer 35 passed behind the moon and so we cannot check the orientation of the interplanetary magnetic field after this time, but the magnetosheath field remained southward till the end of our observation.

Let us analyze more carefully the inward shift of the boundary. The projection of the orbit of OGO-5 in the GSM equatorial plane is shown in Figure 3. From 1700 to 1915 UT (points A and D on the graph) the distance between the spacecraft and this GSM equatorial plane varied from 1.7 to 0.04 Re. At 1700 the satellite detected the magnetopause at A, at a geocentric distance of 12.8 Re; the last crossing took place at D, at about 10 Re. If we assume that the general shape of the magnetopause did not change during this period, this implies an inward motion of the nose from A' to D'.

To compute A' and D' we use the relation

$$R = \frac{C}{1+\varepsilon\cos\phi} \qquad (1)$$

This is the equation of an ellipse with one focus at the earth and with an eccentricity, ε. The angle ϕ is the sun-earth-satellite angle. Using magnetopause crossings from the orbits surrounding this orbit we find $\varepsilon = .35$ gives the best fit to our data. We may then take this equation and use it to find the positions of the nose, A' and D', when the magnetopause was encountered at A and D. Doing this we obtain distances of 11.7 and 9.5 Re. The corresponding equatorial cross sections of the boundary are drawn in Figure 3. Position D, however, does not appear to be an average position of the boundary.

Taking the average position over the last sequence of crossings, CD, we get a geocentric distance of 10.4 Re and a corresponding nose distance of 9.8 Re.

Summarizing the above observations, it appears that during about 2 hours following the reversal of the interplanetary field (from northward to southward) the magnetopause almost continuously but not uniformly moved radially inwards. The extrapolated position of the nose changed from 11.7 to 9.8 Re. The velocity of the OGO 5 satellite normal to the boundary, due to a fortunate coincidence roughly matched the change of the magnetopause location until 1915.

4. The Possible Causes of the Inward Motion

Almost all instruments capable of resolving the magnetopause have observed multiple magnetopause crossings. Most studies have centered on the oscillatory motion of the boundary (Heppner, et. al., 1967; Smith and Davis, 1970). Cummings and Coleman (1967) have studied the non-periodic motion but at a disturbed time. During our interval (1700 to 1900 UT) DST was moderate (-22 to -28γ) and K_p was 3. What, then, was the cause or combination of causes of the inward motion? The solar wind momentum flux might have changed, the ring current might have decreased, and the interaction between the solar wind and the cavity might have changed, or, in other words, the effective viscosity at the boundary might have been altered.

4.1 Change in the Solar Wind Momentum Flux

The data from the MIT experiment aboard Explorer 35 for the time of our observations were kindly made available to us by Dr. J. Binsack. The following values of the parameters of the solar wind plasma flow were measured.

Velocity: 470 km/s

Proton density: 3 cm^{-3}

Temperature: 9.10^{4} °K

The fluctuations of the hourly averages around these values were less than about 10% between 1200 UT and 2300 UT on March 27.

Now we can apply the formula given by Shield (1969) relating the distance of the nose to the parameters of the solar wind.

$$n(cm^{-3}) \quad v^2 \quad (100\ km/sec) \quad \left(\frac{R_N}{10}\right)^6 = 91.45 \quad f^2/K \qquad (2)$$

where n is the proton density,

v is the solar wind velocity

R_N is the geocentric distance of the nose in earth radii

f^2/K is the parameter of the interaction between the solar wind and the magnetospheric cavity.

We obtain with $f^2=1$ (image dipole) and K=1 (inelastic collision)

R_N = 10.55 Re

Equation 1 allows us to draw the corresponding boundary (thick line in Fig. 3). We note that the Mead and Beard model (1964) would give a nose distance of 10 Re.

If we want to explain the shift in the position of the boundary by a change in the momentum of the solar wind we should find either -- a variation in velocity $V_2 - V_1$ such that

$$\frac{V_2}{V_1} = \left(\frac{11.7}{9.8}\right)^3 = 1.7$$

which is ruled out by the Explorer 35 measurement -- or a variation of density by a factor of 3 which could be caused by an increase of the number of protons or by a change in the composition of the solar wind leading to approximately 70% protons and 30% alpha particles. The increase in proton density is ruled out by the measurements of Explorer 35, and the alternate hypothesis is highly improbable (Robbins, et. al., 1970). Thus, we can reasonably consider that this shift of about 2 Re of the magnetopause position is not produced by an increase of the solar wind momentum.

4.2 Decrease in the Ring Current

The shift could have been caused by a decrease of the ring current; such a decrease should correspond to a decrease of the negative DST component. This DST is plotted in Fig. 5 and a small decrease of the negative component by 7γ is observed after 1700. (It will be shown in section 5 that this 7γ variation corresponds effectively to a decrease of the ring current). Shield (1969) computed the equatorial magnetic field produced by the quiet time ring current and obtained 40γ at the ground, so the 7γ change corresponds to a less than 20% decrease of the ring current. Also, from the values given by Shield (1969, Table 2) it is possible to check that the total disappearance of the ring current would produce a relative decrease of the nose distance by 10%. So the 20% decrease in the ring current can only account for a 2% relative decrease of this nose distance, i.e., about 0.2 Re and cannot explain the observed 1.9 Re inward shift.

4.3 Change in the Interaction Between the Solar Wind and The Magnetospheric Cavity

We may try to relate the boundary displacement to a change of pressure associated with a change of the parameter of interaction, f^2/K, in Eq. (2). From this relation, knowing the density and velocity of the solar wind as well as the distance of the nose, one can compute the value of f^2/K. This gives

$$f^2/K = 1.9 \text{ for } R_N = 11.7 \text{ Re}$$

$$f^2/K = 0.6 \text{ for } R_N = 9.8 \text{ Re}$$

We cannot discuss the first value of 1.9 because at this time (1700 UT) the interplanetary magnetic field was northward and so had a component parallel to the geomagnetic field; no theoretical values of f^2/K are available in this case. But from the numbers given by Shield (1969, Table 2) for other cases, such a value of f^2/K is not unreasonable. On the contrary, the other extreme value $f^2/K = 0.6$, obtained in the antiparallel case, is definitely outside the range of theoretical expectation, 1.5 to 3.5 (Shield 1969). Therefore, it seems unlikely that the inward shift could be related to a change in the solar wind laminar flow pressure on the boundary.

The reversal of the magnetosheath field just before 1730 could have another consequence: it could produce a reconnection of the interplanetary and geomagnetic field and consequently an increase in the drag due to a normal component of the magnetic field to the boundary (Levy, et. al., 1963, Sonnerup and Cahill, 1967). We show in another paper (Aubry, et. al., 1970), that although no steady reconnection occurred at the boundary near the satellite, an extremely variable and non-steady tangential discontinuity with transient normal components was observed.

5. Consequences of the Inward Motion

We saw in section 3 that the magnetopause moved radially inwards from 1700 until at least 1915 UT. This amounted to a change of nose position of 11.7 to 9.8 Re. In section 4, we saw that the only possible explanation of this was a change in the nature of the solar wind - magnetosphere interaction, presumably from a condition of laminar flow to some other state. The cause of this change was the appearance of a southward component in the external field. In this section we will investigate the effects of this motion of the magnetosphere.

We can check first whether the shift produced any compression of the magnetic field inside the magnetopause. Such a compression should be associated with an increase in the surface currents on the magnetopause and so should produce an increase in the ground magnetic field and a larger increase in the magnetic field just inside the boundary.

To calculate the ground magnetic field we use the formula given by Mead (1964) relating the variation ΔB_1 of the equatorial ground magnetic field to the variation of the geocentric distance R_N of the nose between 11.7 and 9.8 Re.

$$\Delta B_1 = \frac{25,000}{R_{N1}^3} \left[\left(\frac{R_{N1}}{R_{N2}} \right)^3 - 1 \right] \qquad (3)$$

$$\sim 11\gamma$$

If the shift produced a compression of the magnetospheric cavity, the horizontal component of the magnetic field at the equatorial stations should have increased by $+11\gamma$ between 1700 and 1900; this would appear as a variation of 11γ in the DST during this period of time. Figure 5 does show an increase of 7γ in the hourly average after 1700, as previously discussed in section 4.

To calculate the magnetic field B_2 just inside the magnetopause due to the surface currents we again use Mead's model (Mead, 1964, Eq. 10′). For 0900 LT in the equatorial plane just inside the boundary, assuming that this boundary is defined by equation 1, B_2 can be written

$$B_2(\gamma) = \frac{41250}{R_N^3}$$

For R_N = 11.7 we obtain 26γ, and for R_N = 9.8 we obtain 44γ, i.e., a variation of 18γ between 1700 and 1900 UT. Fig. 1 shows that the difference between the total field inside the magnetosphere and the dipole field between 1700 and 1900 remains roughly constant with a value between 20 and 30γ, and ΔB_2 is about zero.

Observing ΔB_1 (7γ) on the ground not associated with ΔB_2 at the magnetopause implies that the variation of the ground magnetic field was not due to a compression of the magnetospheric cavity. Thus, a decrease of the ring current must have been responsible for this change. This justifies a posteriori our discussion in paragraph 4.2.

If there is no compression of the magnetic field inside the cavity, the inward shift of the boundary implies a transport of magnetic flux from the front part of the magnetosphere to the tail. A very crude estimate of this transport can be made. Assuming that the equatorial sections of the boundary are semicircular with initial and final radii of 11.7 and 9.8 Re and that the magnetic field is vertical with a 50γ amplitude, this represents a flux of about 10^{16} Maxwell transported in two hours, which implies a flux rate of the order of 10^{12} Maxwell per second. That is comparable to the flux rates assumed by Atkinson (1966), namely, 10^{11} to 10^{13} Maxwell per second carried into the tail before substorms. The flux in a tail of 20 Re radius with a 20γ magnetic field is about 10^{17} Maxwell. So the shift of the boundary should produce an increase of the tail magnetic flux of about 15%.

Were there any consequences of this increase in the tail magnetic flux? To check this, we looked at the data from several magnetic observatories located on the nightside of the earth. Their position at 1700 UT is shown in Figure 3. At 1900 UT Tashkent was at midnight local time. Note that Sodankyla is the only auroral zone observatory available at this time. The others are mid-latitude ones. In Figure 5 the magnetograms from these six stations are shown.

Examining Figure 5 we see that the growth phase of a substorm (McPherron 1969) begins at Sodankyla just before 1800. The beginning of the recovery phase of this substorm before 1930 is indicated by a dashed line in Figure 5. The deviation at the mid-latitude station is rather weak but there is little doubt that this substorm is responsible for the increase in the ring current (increase of the negative DST component) after 1900. A second substorm is recorded after 2200 UT.

The growth phase of a substorm is presumably a manifestation of enhanced magnetospheric convection and inward motion of the plasma from the tail (McPherron 1969). If this interpretation of the growth phase is correct, our observations suggest that a rather short delay, less than 30 minutes, existed between the beginning of the inward shift of the dayside magnetopause and the first noticeable return flux of plasma from the tail.

It appears then that the consequence of such an inward motion as we observed at this time, one producing no field compression and caused by a southward component, is the transport of flux to the tail. This transport increases the inward convection of plasma almost immediately. The ultimate result of this transport is a substorm.

6. Discussion

Much work has justifiably been done on correlating interplanetary parameters with magnetospheric indices of geomagnetic activity. Unfortunately, the geomagnetic indices generally used (K_p or a_p) respond to several kinds of geomagnetic phenomena, world-wide events or bay events for instance, and the various parameters characterizing the solar wind are intercorrelated themselves. So it is very difficult to determine the specific consequence in the magnetosphere of the change of only one solar wind parameter. Recently Hirshberg and Colburn (1969) have examined this question in depth, using both new observations and previous results. They confirmed the high correlation of a southward interplanetary field with geomagnetic disturbances, and found that the highest correlation occurred when the GSM coordinate system was used to describe the interplanetary field. As a hypothesis regarding the relation between the solar wind parameter and the magnetosphere, they suggested first that world-wide geomagnetic fluctuations would be associated with fluctuating large amplitude interplanetary magnetic fields, this association being independent of the field orientation and second that bay events would be associated with southward magnetic fields.

Our results confirm this second point, namely, the existence of a southward component of the interplanetary field leads to a substorm, or bay through the erosion of dayside magnetospheric flux resulting in increased total magnetic flux in the tail. It is presumed that the release from the tail sometime later of this flux which represents a storage of energy, provides the energy subsequently deposited in the magnetosphere during the substorm. Thus the correlation between K_p and the southward component of the interplanetary field arises through the magnetic effects of substorms. This, of course, agrees with the study of Rostoker and Falthammar (1967). On the other hand, this in no way implies that other solar wind parameters such as transverse fluctuations (Ballif, et. al., 1967) do not directly affect K_p and in fact our results say nothing about world-wide fluctuations.

In regard to the time constant involved, Hirshberg and Colburn (1969) have shown for a particular geomagnetic storm that the main phase followed the occurrence of a southward component of the interplanetary field within less than an hour. This main phase corresponds to the increase in the ring current subsequent to substorms (Davis and Parthasarathy, 1967), and let us note that the only difference between a classical substorm as observed by us and the sequence of substorms that lead to the main phase as observed by Hirshberg and Colburn (1969), may be simply the state of the solar wind at the time of the occurrence of the southward component. In our example the increase in the ring current as measured by the DST occurred 1.5 hours after the reversal.

Finally, regarding the absence of change in the solar wind momentum, our results agree with those of Gosling, et. al., (1967) who have shown that there was no change in solar wind momentum flux in association with the development of the April 17-18, 1965 storm. Unfortunately they had no magnetic field data.

Since the flux eroded from the dayside magnetosphere must appear in the tail, the question arises as to how this result agrees with previous measurements of the tail field. Feldman, et. al., (1970) have shown that far down the tail, the field strength is determined by the thermal pressure of the solar wind. Thus changing the total flux in the tail would merely change the tail radius at these distances. However, if we do increase the radius of the tail, we expect an increase in the tail field strength near the earth since we produce more flaring of the boundary in this region. Near the earth such a change in the tail field strength has been observed (Lazarus, et. al., 1968; Fairfield and Ness, 1970).

In summary our measurements are in agreement with previous observations. What we have added to the picture of the solar wind-magnetosphere interaction is the observation of the erosion of flux from the dayside magnetosphere following the reversal of the interplanetary field and preceding the substorm. In addition our results show that one cannot simply infer the instantaneous position of the magnetopause from a knowledge of the solar wind momentum flux and that within two hours the position of the magnetopause can vary significantly under apparent quiet solar wind conditions. This is important if one attempts to model the boundary currents to predict magnetospheric fields.

7. <u>Conclusion</u>

By using the data from the UCLA experiments on the OGO-5 satellite we have shown evidence for a change in the magnetopause position occurring between a reversal (northward to southward) of the interplanetary field and the occurrence of a substorm on the nightside of the earth.

Let us summarize our results.

On March 27, 1970 at 1700 the magnetopause position recorded by the inbound OGO 5 satellite corresponds to a nose distance of 11.7 Re. The solar wind parameters were measured by the MIT and NASA-Ames experiments aboard Explorer 35: The interplanetary magnetic field at this time had a northward component and from the measured value of the solar wind momentum flux, we determine the value 1.9 for the parameter f^2/K (Shield 1969) of the interaction between the solar wind and the magnetosphere.

After about 1710 the solar wind magnetic field turned southward at the moon. In about 14 minutes this reversal should have propagated to the magnetopause. At 1731 UT, OGO 5 recorded the magnetopause moving inward. From this time till 1915 UT multiple magnetopause crossings were recorded and the observed field in the magnetosheath was systematically southward. The last average position of the boundary is estimated to correspond to a nose distance of 9.8 Re.

During this whole period of time no change in the solar wind momentum flux occurred. A change in the parameter of interaction f^2/K could be responsible for the change in the nose distance, but the value of f^2/K corresponding to the last position of the nose is 0.6 and does not correspond to theoretical expectations for laminar flow at the boundary, (Lees 1964). On the other hand none of the multiple crossings present evidence for steady reconnection between the interplanetary and geomagnetic field (Aubry et. al., 1970).

From observation of the DST variation and of the field amplitude just inside the boundary, we may conclude that this inward motion of the boundary, beginning just before 1730, was not produced by a decrease of the ring current and did not produce a significant compression of the magnetospheric field, so the corresponding magnetic flux must have been brought entirely into the tail.

Between 1730 and 1800, the beginning of the growth phase of a substorm was recorded at the auroral zone magnetic observatory of Sodankyla. The expansion phase of this substorm after 1900 was observed also by several mid-latitude stations.

In this event, the delay between the reversal of the field at the boundary causing its inward motion and the ground observations of the return flow from the tail was less than half an hour.

We recalled in the discussion that the relation between the southward component of the interplanetary field and the substorms has been inferred in different ways by many authors. We have presented in this study the first observation of the complete sequence of events leading from a reversal of the interplanetary field from northward to southward, to a substorm through the inward motion of the dayside magnetopause. The only missing observation is the increase of the tail magnetic field prior to the substorm because we did not have data from the magnetospheric tail. From another point of view the simultaneous observation of a steady solar wind momentum flux and of a magnetopause moving inward subsequent to a reversal of the interplanetary field proves that the instantaneous position of the magnetopause cannot be always computed from the laminar flow theory alone.

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References

Akasofu, S.I. Polar and magnetospheric substorms, Reidel Publishing Company, 1968.

Atkinson, G., A theory of polar substorm, J. Geophys. Res., 71, 21, 5157-5164, 1966.

Aubry, M.P., M.G. Kivelson and C.T. Russell, Microstructure of the magnetopause. To be published.

Axford, W.I., Magnetic storm effects associated with the tail of the magnetosphere, ESRO conference on the magnetosphere, Stockholm, Nov. 15-18, 1965.

Ballif, J.R., D.E. Jones, P.J. Coleman, Jr., L. Davis, Jr., and E.J. Smith, Transverse fluctuations in the interplanetary magnetic field: a requisite for geomagnetic variability, J. Geophys. Res., 72, 17, 4357-4364, 1967.

Cummings, W.D. and P.J. Coleman, Jr., Magnetic fields in the magnetopause and vicinity at synchronous altitude, J. Geophys. Res., 73, 17, 5699-5718, 1968.

Davis, T.N. and R. Parthasarathy, The relationship between polar magnetic activity DP and growth of the geomagnetic ring current, J. Geophys. Res., 72, 23, 5825-5836, 1967.

Fairfield, D.H., and L.J. Cahill, Transition region magnetic field and polar magnetic disturbances, J. Geophys. Res., 71, 1, 155-169, 1966.

Fairfield, D.H. and N.F. Ness, Configuration of the geomagnetic tail during substorms. Preprint X-692-70164, NASA-Goddard Space Flight Center, 1970.

Feldman, W.C., J.D. Mihalov, C.P. Sonett, and J.H. Wolfe, Pressure balance across the distant magnetopause. Preprint NASA Ames Research Center, 1970.

Gosling, J.T., J.R. Asbridge, S.J. Bame, A.J. Hundhausen, and I.B. Strong, Measurements of the interplanetary solar wind during the large geomagnetic storm of April 17-18, 1965, J. Geophys. Res., 72, 7, 1813-1821, 1967.

Harris, K. Kent and G.W. Sharp, OGO V ion spectrometer, IEEE transactions on Geoscience electronics, GE-7, 2, 93-98, 1969.

Heppner, J.P., M. Sugiura, T.L. Skillman, B.G. Ledley and M. Campbell, OGO A magnetic field observations, J. Geophys. Res., 72, 21, 5417-5471, 1967.

Hirshberg, J. and D.S. Colburn, Interplanetary field and geomagnetic variations: a unified view, Planet. Space Sci., 17, 1183-1206, 1969.

Kivelson, M.G., M.P. Aubry and T.A. Farley, Electron flux asymmetries observed by back to back detectors on OGO-5, EOS, 51, 4, p. 386, 1970. (Abstract)

Lees, L., Interaction between the solar plasma wind and the geomagnetic cavity, AIAA Journal, 2, 9, 1576-1582, 1964.

Levy, R.H., H.E. Petschek and G.L. Siscoe, Aerodynamic aspects of the magnetospheric flow, AIAA Journal, 2, 2065, 1964.

Mead, G.D. and D.B. Beard, Shape of the geomagnetic field solar wind boundary, J. Geophys. Res., 69, 7, 1169-1179, 1964.

Mead, G.D., Deformation of the geomagnetic field by the solar wind, J. Geophys. Res., 69, 7, 1181-1195, 1964.

Neugebauer, M., Initial deceleration of solar wind positive ions in the earth's bow shock, J. Geophys. Res., 75, 4, 717-733, 1970.

Nishida, A., Coherence of geomagnetic DP-2 fluctuations with interplanetary magnetic variations, J. Geophys. Res., 73, 17, 5549, 1968.

Patel, V.L. and A.J. Dessler, Geomagnetic activity and size of magnetospheric cavity, J. Geophys. Res., 71, 7, 1940-1942, 1966.

Patel, V.L., L.J. Cahill, Jr., and A. J. Dessler, Magnetosheath field, geomagnetic index a_p and stability of magnetopause, J. Geophys. Res., 72, 1, 426-430, 1967.

McPherron, R.L., The growth phase of magnetospheric substorms, Publication No. 742, IGPP, University of California, Los Angeles, 1969.

Robbins, D.E., A.J. Hundhausen, and S.J. Bame, Helium in the solar wind, J. Geophys. Res., 75, 7, 1178-1187, 1970.

Rostoker, G. and C.G. Falthammar, Relationship between changes in the interplanetary magnetic field and variations in the magnetic field at the earth's surface, J. Geophys. Res., 72, 23, 5853-5864, 1967.

Schatten, K.H., and J.M. Wilcox, Response of the geomagnetic activity index to the interplanetary magnetic field, J. Geophys. Res., 72, 21, 5185-5192, 1967.

Shield, M.A., Pressure balance between solar wind and magnetosphere, J. Geophys. Res., 75, 5, 1275-1286, 1969.

Siscoe, G.L. and W.D. Cummings, On the cause of geomagnetic bays, Planet. Space Sci., 17, 1795, 1969.

Smith, E.J. and Leverett Davis, Jr., Magnetic measurements in the earth's magnetosphere and magnetosheath: Mariner 5, J. Geophys. Res., 75, 7, 1233-1245, 1970.

Sonnerup, B.U.O., and L.J. Cahill, Jr., Magnetopause structure and attitude from Explorer 12 observations, J. Geophys. Res., 72, 1, 171-183, 1967.

Spreiter, J.R., Summers, A.L. and A.Y. Alksne, Hydromagnetic flow around the magnetosphere, Planet. Space Sci., 14, 223-253, 1966.

Spreiter, J.R. and A.Y. Alksne, Plasma flow around the magnetosphere, Rev. of Geophysics, 7, 1 and 2, 11-50, 1969.

Unti, T. and G. Atkinson, Two dimensional Chapman-Ferraro problem with neutral sheet, 1. The boundary, J. Geophys. Res., 73, 23, 7319-7327, 1968.

Wilcox, J.M., K.H. Schatten and N.F. Ness, Influence of interplanetary magnetic field and plasma on geomagnetic activity during quiet sun conditions, J. Geophys. Res., 72, 1, 19-26, 1967.

Zelwer, R., P.C.B. Fernando and S.H. Ward, Interplanetary magnetic field data and corresponding geomagnetic effects for the storm of October 7, 1962, J. Geophys. Res., 72, 13, 3471-3482, 1967.

CAPTIONS

Fig. 1. Variation of the magnetic field versus universal time on March 27, 1968. The GSM reference system is used; B_T refers to the total field.

Fig. 2. Variation of the magnetic field as measured in the reference system of the satellite, versus universal time from 1719 to 1919 UT on March 27, 1968. The letters BCD refer to the position of the satellite as seen in Figure 3.

Fig. 3. Projection of the orbit of OGO-5 in the GSM equatorial plane at the time of the observations. The position of some magnetic observatories at 1700 UT is shown as well as the extreme extrapolated positions of the boundary.

Fig. 4. Variation of the orientation and amplitude of the solar wind magnetic field as measured by the NASA-Ames experiment aboard Explorer 35 and position of the moon at the time of our observations. The meaning of the θ and ϕ angles in the XYZ solar equatorial reference system is explained at the bottom right of the figure.

Fig. 5. Magnetograms from the nightside observatories. The double arrows represents 50γ amplitudes at each station. The black dots on each axis indicate the crossing of the midnight meridian. A vertical dashed line after 1900 UT shows the beginning of the recovery phase of the substorm. The DST variation and the geomagnetic planetary three hours range K_p indices are shown at the bottom.

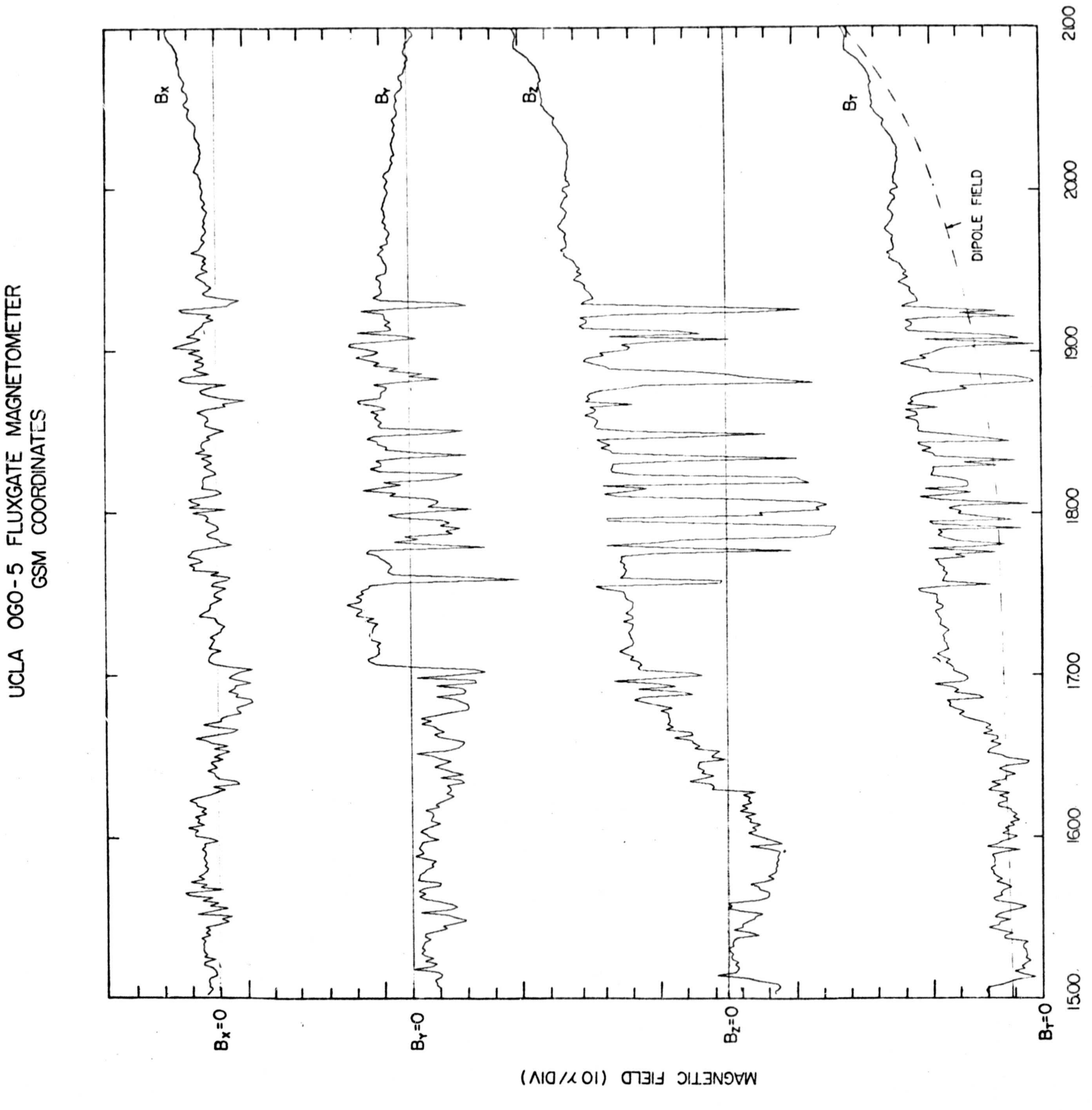
UCLA OGO-5 FLUXGATE MAGNETOMETER
GSM COORDINATES
Bx
By
Bz
BT
DIPOLE FIELD
Bx=0
BY=0
Bz=0
BT=0
MAGNETIC FIELD (10 γ/DIV)
1500
1600
1700
1800
1900
2000
2100
UNIVERSAL TIME (HOURS)

Fig. 1

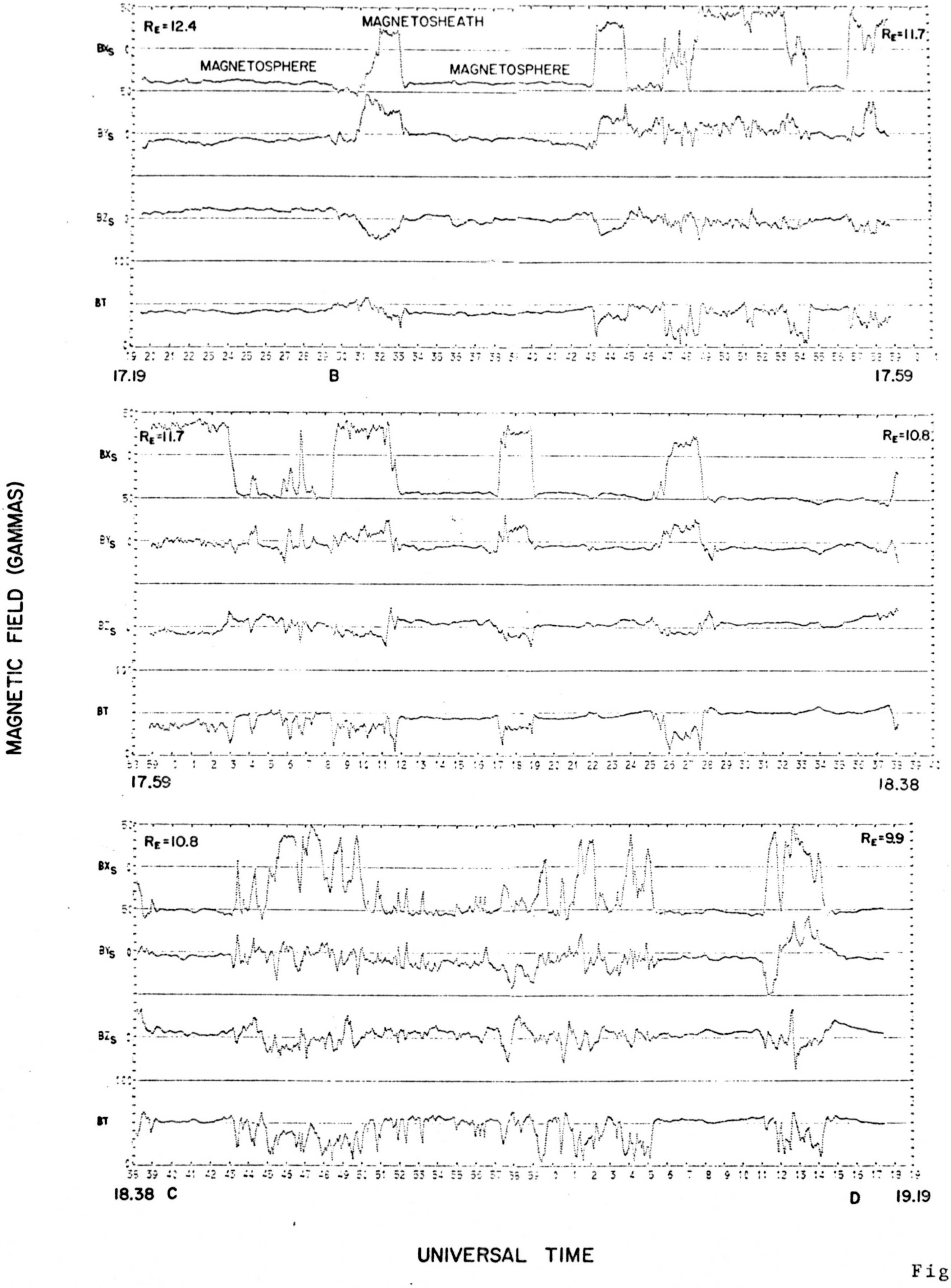
MAGNETIC FIELD (GAMMAS)
UNIVERSAL TIME
RE=12.4
MAGNETOSHEATH
MAGNETOSPHERE
MAGNETOSPHERE
RE=11.7
BXS
BYS
BZS
BT
17.19
B
17.59
RE=11.7
RE=10.8
17.59
18.38
RE=10.8
RE=9.9
18.38 C
D
19.19

Fig. 2

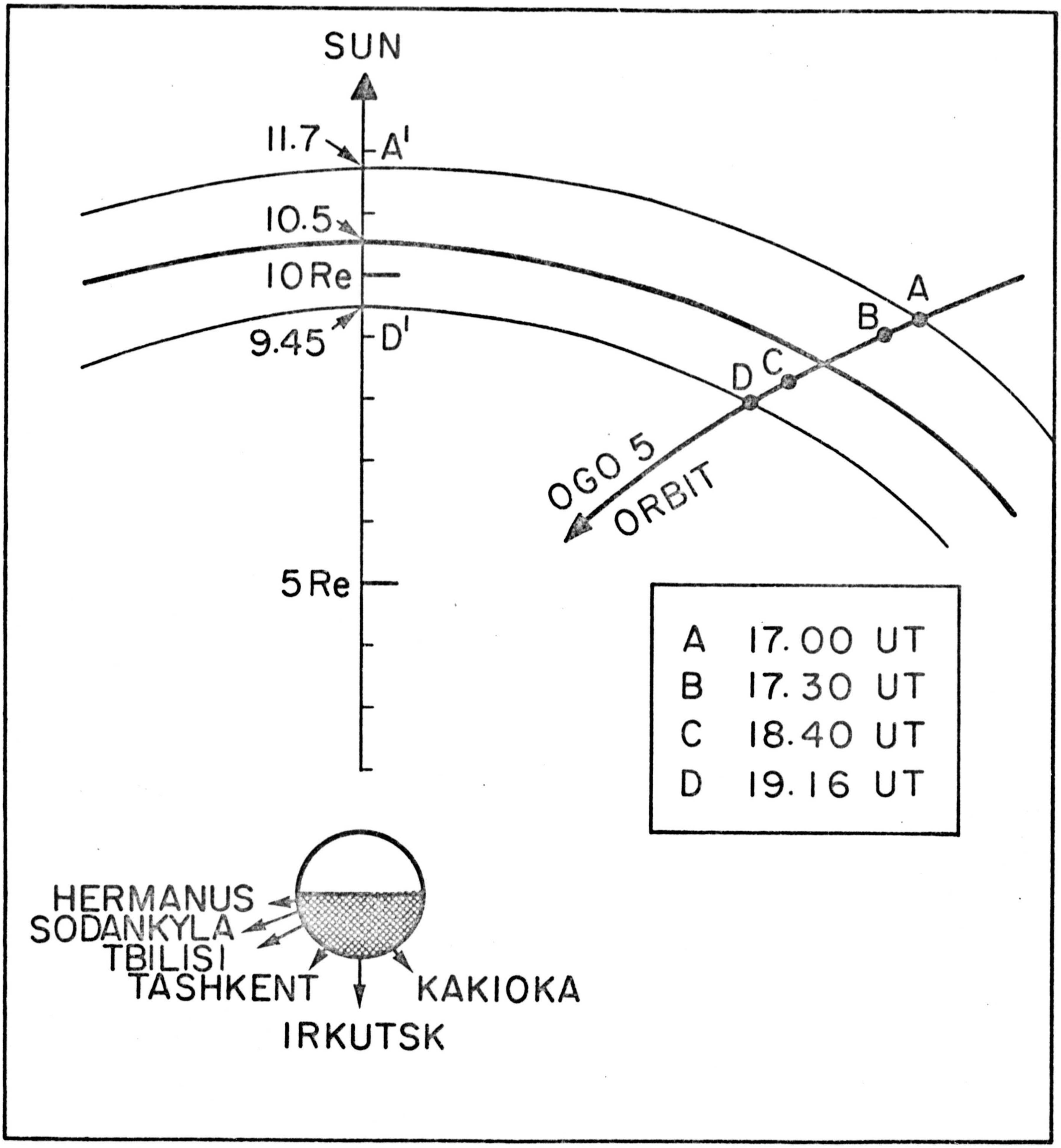
SUN
11.7
A'
10.5
10 Re
9.45
D'
5 Re
A
B
C
D
OGO 5
ORBIT
A 17.00 UT
B 17.30 UT
C 18.40 UT
D 19.16 UT
HERMANUS
SODANKYLA
TBILISI
TASHKENT
IRKUTSK
KAKIOKA

Fig. 3

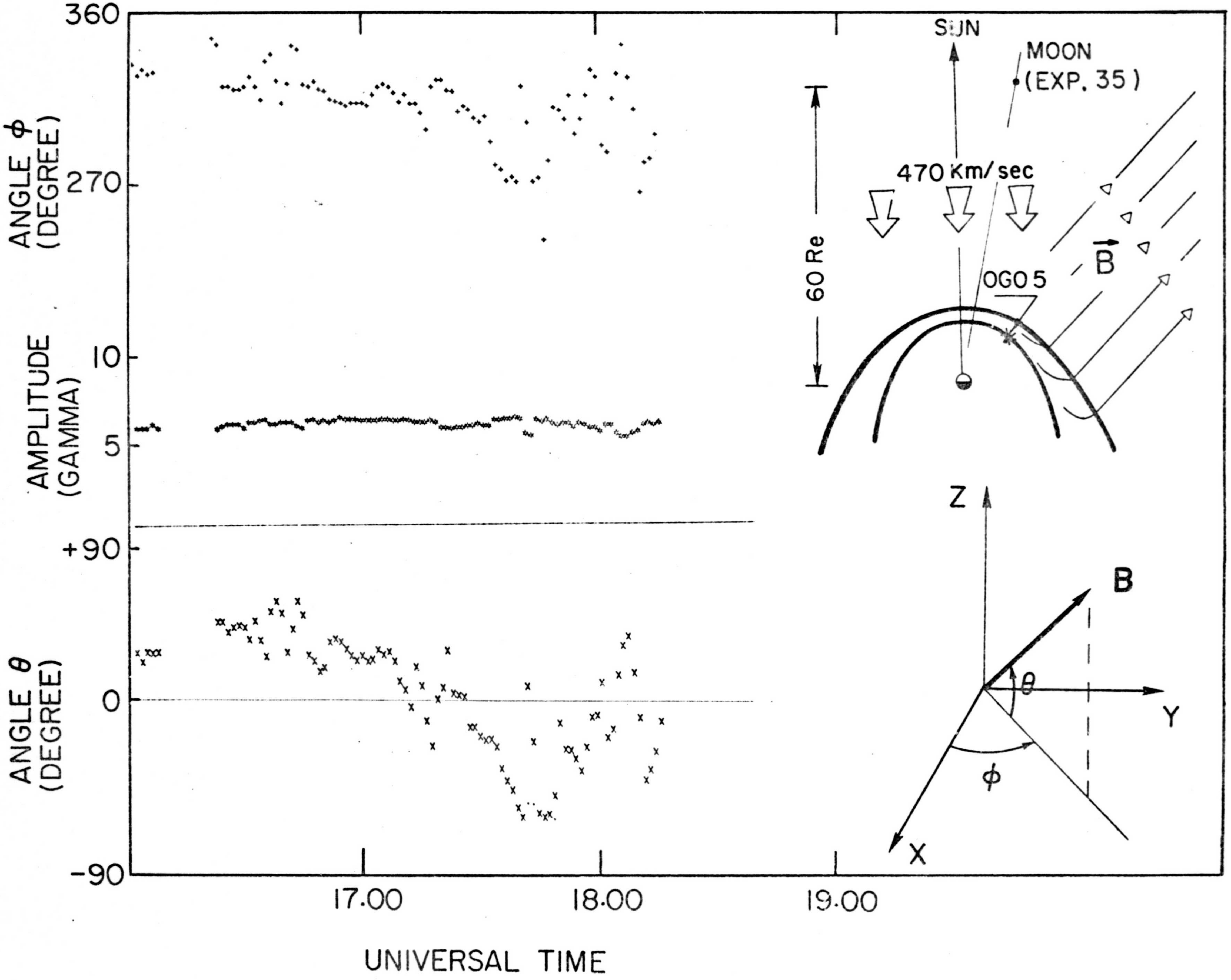
360
270
10
5
+90
0
-90
ANGLE φ (DEGREE)
AMPLITUDE (GAMMA)
ANGLE θ (DEGREE)
17.00
18.00
19.00
UNIVERSAL TIME
SUN
MOON (EXP. 35)
470 Km/sec
60 Re
OGO 5
B
Z
Y
X
θ
φ

Fig. 4

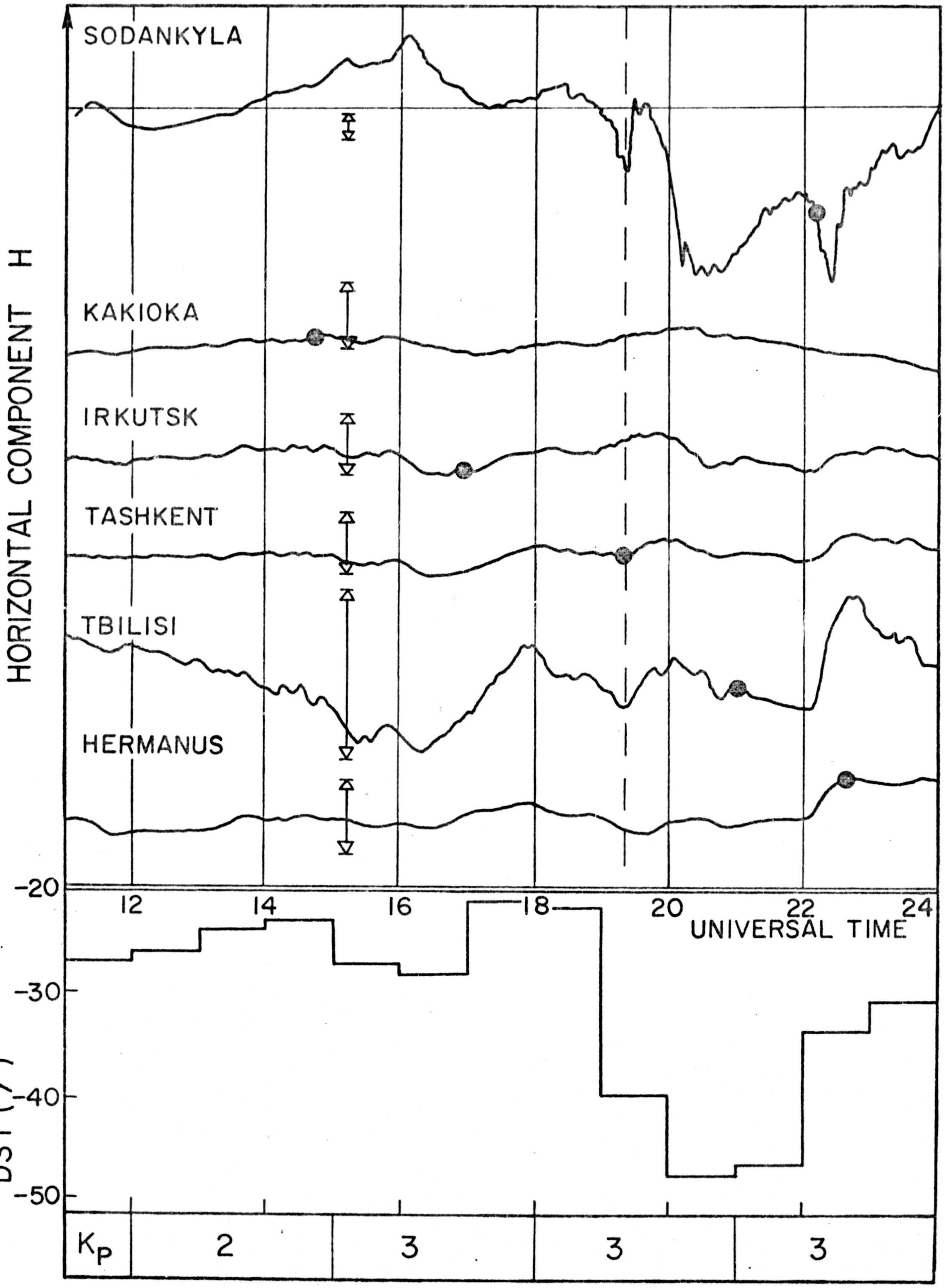
SODANKYLA
KAKIOKA
IRKUTSK
TASHKENT
TBILISI
HERMANUS
HORIZONTAL COMPONENT H
-20
-30
-40
-50
DST (γ)
12
14
16
18
20
22
24
UNIVERSAL TIME
K_P
2
3
3
3

Fig. 5