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# RESULTS OF MAGNETIC SURVEYS OF THE MAGNETOSPHERE AND ADJACENT REGIONS

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# RESULTS OF MAGNETIC SURVEYS OF THE MAGNETOSPHERE AND ADJACENT REGIONS

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ABSTRACT

Magnetic field observations in the magnetosphere and in the adjacent regions are reviewed. Extensive observations of the positions of the magnetosphere and the bow shock have been made below about geomagnetic latitude 65°; frequent movements of the magnetopause and the bow shock are inferred from multiple encounters. The magnetopause thickness is estimated to be of the order of the ion cyclotron radius. The interplanetary magnetic field is convected into the magnetosheath, and comprises the ordered background field in the magnetosheath; irregular fields are superimposed on the ordered magnetic field. The magnetosphere tail is found to be well-defined at distances near 80 $R_e$ (earth radii) and appears to exist at 1000 $R_e$ in a wake-like form. A region of weak magnetic field near the solar ecliptic plane, which is often called the neutral sheet region, separates the earthward field in the northern half of the tail from the oppositely directed southern half. The plasma sheet occupies a larger volume than the magnetically defined neutral sheet, and extends well into the magnetosphere. The magnetic field in the near-tail region often shows shell-like structures with well-defined discontinuities between neighboring shells. Both the magnetic field and the charged particle content of a ring current have been measured during magnetic storms. A proton belt of lesser intensity has been observed even during magnetically quiet periods. Appreciable diamagnetic effects of the plasmas in the outer magnetosphere are indicated. Sudden magnetic variations are observed in the near-tail region near the magnetic midnight meridian following the onsets of magnetic bays. A few quantitative models of the magnetosphere have been presented.

## 1. Introduction

The continuous plasma flow in the solar wind confines the geomagnetic field in a limited volume of space surrounding the earth. This region is called the magnetosphere because the magnetic field to a large extent controls the behavior of the charged particles contained therein. The outer boundary of the magnetosphere is termed the magnetopause. The solar wind carries with it a magnetic field, and the velocity of its flow exceeds that of a magnetosonic wave in the medium, thus creating a detached bow shock ahead of the magnetopause as in a supersonic flow of a fluid in the presence of a blunt body. The region between the bow shock and the magnetopause is referred to as the magnetosheath, or the transition region, in which the plasma flow and the magnetic field contain varying degrees of irregularity. The confinement of the geomagnetic field in the magnetosphere results in a distortion of the geomagnetic field, and the interaction between the solar wind and the geomagnetic field leads to a formation of a long geomagnetic tail. These two consequences of the solar wind engender a necessity of extensive magnetic survey by spacecraft. The past several years have witnessed significant advancements in the exploration of this type. The major features of the achievements in this field are summarized in the present brief review.

Observations of the magnetopause, the bow shock, the magnetosheath, and the tail are discussed in Sections 2 to 5. Results of a recent study of the OGO 1 and 3 satellite data taken in the near-tail region are summarized in Section 6. The magnetic field disturbances observed in the magnetosphere are discussed in Section 7. Brief accounts of quantitative models of the magnetosphere are given in Section 8. The magnetic field structures in the magnetosphere are largely determined by the mutual interactions between the plasmas and the magnetic field, and hence the effects of plasmas are discussed wherever appropriate, though the paper primarily concerns the magnetic observations. It is mentioned here that the scope of the present review is limited mostly, if not entirely, to the results obtained by the workers in the United States.

## 2. The Magnetopause

Early measurements aboard Pioneers 1 and 5 launched in 1958 and 1960, respectively, indicated a termination of the earth's magnetic field beyond some distance from the earth (Sonett et al., 1960; Coleman et al., 1960 a,b), but because of the incompleteness of the measurements neither the magnetopause nor the bow shock was identified. The first definitive identification of the magnetopause on the basis of the magnetic field and plasma measurements was made by Explorer 10, launched in March 1961, on the evening side near the meridian of 21 hours local time (Heppner et al., 1963; Bonetti et al., 1963). The observation showed that the magnetopause flares out on the evening side. Explorers 12 and 14 mapped the magnetopause from near the noon meridian to the dawn flank; and the observations indicated a similar flaring-out of the magnetopause on the dawn side (Cahill and Amazeen, 1963; Cahill, 1964 a,b). Observations by Explorer 18, launched in November 1963, identified the standing bow shock several earth radii upstream from the magnetopause (Ness et al., 1964). The existence of such a (collision-free) shock had been predicted theoretically by Zhigulev (1959), Zhigulev and Romishevshii (1960), Axford (1962), and Kellogg (1962).

Complete identifications of the magnetopause and the bow shock require observations of certain characteristics both in the magnetic field and plasma, namely for the magnetopause: a discontinuity in the magnetic field and the absence of streaming (solar wind) ions inside the discontinuity; and for the bow shock: a discontinuity both in the magnetic field and in the flux of the solar wind plasma. However, under normal conditions an observation of either the magnetic field or the plasma often suffices to locate the magnetopause or the bow shock. An abrupt termination of the quasi-trapped particles has also been used to identify the magnetopause. Recent studies of crossings of the magnetopause and the bow shock based primarily on magnetic field observations include those made with the data from Explorer 12 (Cahill and Patel, 1967), Explorer 18 (Ness et al., 1964; Ness, 1965), Explorer 21 (Fairfield and Ness, 1967), Explorer 28 (Ness, 1967), OGO 1 (Holzer et al., 1966; Heppner et al., 1967) and Explorer 33 (Behannon, 1968); and more data are being accumulated by OGO's 3 and 5 and other satellites. Determinations based on plasma or/and energetic particle measurements have been made on Explorer 12 (Freeman et al., 1963), Explorer 18 (Bridge et al., 1965; Wolfe et al., 1966), Velas 2A and 2B (Gosling et al., 1967), and OGO's 1 and 3 (Vasylinunas, 1968); in particular, Gosling et al. (1967) have made a detailed statistical study of the positions of the magnetopause and the bow shock by the Vela satellites at about 17 $R_e$ (earth radii) and at ecliptic latitudes up to $\pm$ 63°.

Summarizing these observations the following general remarks are made concerning the positions of the magnetopause and the bow shock.

(i) The average shapes and positions of the magnetopause and the bow shock are in general agreement with theoretical results based on gas dynamical models (e.g., Ness, 1967; Heppner et al., 1967; Gosling et al., 1967; for theoretical models: see e.g., Spreiter and Briggs, 1962 a,b; Midgley and Davis, 1963; Mead and Beard, 1964; Mead, 1964; Spreiter et al., 1966). (ii) The magnetopause and the shock are frequently in motion, often resulting in multiple crossings by a satellite on any one orbit (e.g., Holzer et al., 1966; Heppner et al., 1967; Gosling et al., 1967). (iii) There appears to be an east-west asymmetry in the average shapes of the magnetopause and the bow shock; the line with respect to which these shapes are symmetric deviates from the earth-sun line toward west by 2 to 4 degrees. This tilt is roughly in agreement with that expected from the aberration of the solar wind flow direction due to the earth's orbital motion about the sun (Gosling et al., 1967). (iv) Since geomagnetic activity as expressed by Kp is related to the solar wind (Snyder et al., 1963), a question immediately arises as to whether or not the position of the magnetopause is related to magnetic activity. The answer to this question has been given in both affirmative (e.g., Gosling et al., 1967) and negative (e.g., Patel and Dessler, 1966; Heppner et al., 1967). This is due to the circumstance that the position of the magnetopause at any instant of time depends in a complex way on a number of parameters both in the solar wind and in the magnetosphere besides the most obvious dependence on the solar wind velocity. The magnetic pressure in the (magnetosheath) solar wind and the non-uniform plasma pressure inside the magnetosphere are examples of the factors that are likely to contribute significantly in determining the position of the magnetopause. Thus, though the <u>average</u> position of the magnetopause is related to magnetic activity as has been reported by Gosling et al. (1967), its <u>instantaneous</u> position is not always related to magnetic activity. However, there are cases such as times of sudden commencements or sudden impulses in which the solar wind pressure changes abruptly and therefore a corresponding adjustment of the magnetopause position is obviously expected (e.g., Heppner et al., 1967; Gosling et al., 1967).

Figure 1 shows the magnetopause and bow shock encounters by the OGO-1 satellite; the positions are projected onto the solar ecliptic plane by rotating the radial distances along circles in earth-centered solar-ecliptic meridian planes. The plotted crossing points are corrected for variations in the geomagnetic latitude $\chi_{ss}$ of the subsolar point, using an expansion factor $K = (1 + 3 \sin^2 \chi_{ss})^{1/6}$; see Ness et al. (1964) for the meaning of this factor.

A magnetopause crossing typically involves a time scale of about 1 minute, but because of the motion of the magnetopause the crossing time can be considerably shorter. Although it is not possible to determine the thickness of the magnetopause from a traversal by one satellite, a study of numerous crossings by OGO 1 indicates that the thickness must be of the order of 100 km under normal conditions; this scale length is nearly the cyclotron radius of the ions in the average solar wind (Heppner et al., 1967). At the magnetopause the solar wind particles are reflected away by the combined effects of the Lorentz force and the polarization electric field; the latter is created because of the larger mass-charge ratio for the protons than for the electrons. If the initial velocities of the ions and electrons in the solar wind are equal and unidirectional without thermal motion, the thickness of the boundary layer is of the order of the *characteristic* electron cylotron radius, $c/\omega_{pe}$, where c is the velocity of light and $\omega_{pe}$ ($=\sqrt{4\pi e^2 n_e/m_e}$, where e, $m_e$, and $n_e$ are the charge, mass, and number density of the electrons, respectively) is the electron plasma frequency (Ferraro, 1952). Taking the density to be 1 to 10 $cm^{-3}$, this scale length is 5.3 to 1.7 km, which is shorter than the value estimated from the observations by one to two orders of magnitude. This seems to mean that the electrostatic field in the boundary layer is short-circuited by the thermalized electrons. According to the OGO 1 and 3 observations the magnetic field transition from the magnetosphere to the magnetosheath is sometimes smooth, but at other times involves considerable irregularity. Under normal conditions, changes in the magnitude and the direction of the magnetic field characterize the transition. At times the transition takes an exceptionally long interval of time during which the magnetic field magnitude changes rather gradually but with irregularities superimposed on the gradual change. Gosling et al. (1967) have reported that there are magnetopause traverses in which the magnetosheath solar wind "gradually builds up or fades away over a rather long period". Sonnerup and Cahill (1967) have studied the Explorer 12 magnetopause crossings and have shown that the magnetopause is generally a tangential discontinuity, that is, a discontinuity in which the magnetic field component normal to the discontinuity surface is zero. However, they have found a few cases in which the normal component was substantial; in these cases the magnetopause is a rotational discontinuity. Recently Aggson et al. (1968) have observed large electric field fluctuations in a wide range of frequencies below several hundred Hz in the magnetopause; whether or not there exist large electrostatic fields there is not certain. In summary the structure of the magnetopause and the precise nature of the interaction between the solar wind and the magnetosphere are not as yet known.

## 3. The Bow Shock

Observations of the bow shock positions have been mentioned in the preceding section. According to the OGO 1 results the time involved in crossing the shock is generally 1 to 10 seconds. Movements of the shock appear to be more frequent and with greater speed than those of the magnetopause. With the OGO 1 observations the average velocity of the shock has been estimated to be a few to 10 km/sec and the average amplitude of the oscillation to be a few thousand km; these statistical estimates are based on an idealized mode in which the shock oscillates between two extreme positions with a constant velocity (Heppner et al., 1967). Similar estimates have been given by Holzer et al. (1966) on the basis of their observation of a.c. magnetic field.

At the shock and in its vicinity, coherent waves of frequencies near 1 Hz and irregular fluctuations of frequencies greater than several Hz are often observed in the magnetic field (Heppner et al., 1967). Recent electric field observations on OGO 5 by Aggson et al. (1968) are consistent with the earlier interpretation that waves near 1 Hz are wave packets generated in the shock and propagating upstream in the solar wind in the whistler mode (Heppner et al., 1967). The mechanisms of the generation of these coherent waves and irregular fluctuations are not as yet understood. The structure of a collision-free shock has been a subject of intensive study by plasma physicists, and several theoretical models have been presented (e.g., Fishman et al., 1960; Auer et al., 1961, 1962; Camac et al., 1962; Kellogg, 1964; Tidman, 1967, Kennel and Sagdeev, 1967 a,b). However, neither the observations nor the theories appear to be adequate to clarify the physical picture of the magnetosphere bow shock.

## 4. The Magnetosheath

The region between the bow shock and the magnetopause is called the magnetosheath, or the transition region. Observations of the magnetic field behaviors in this region have been made extensively (e.g., Cahill and Amazeen, 1963; Ness et al., 1964; Coleman, 1964; Holzer et al., 1966; Siscoe et al., 1967; Heppner et al., 1967). The magnetic field in the magnetosheath is generally characterized by the predominance of irregularities. The degree of irregularity, however, varies considerably in different regions of the magnetosheath and at different times. Observed field fluctuations have periods, in spacecraft reference frames, from a fraction of one second to several minutes or even longer. Average power spectral densities have been estimated (Holzer et al., 1966; Siscoe et al., 1967), but their generality has not been adequately tested. Interpretations of such power spectra are difficult since spatial field irregularities convected by the magnetosheath solar wind (to be mentioned below) cannot be distinguished from temporal fluctuations generated in the magnetosheath. Although the magnetosheath field can be generally characterized by the presence of irregularities, there are times when the magnetic field is so quiet and steady that without plasma data it is difficult to identify the region with certainty; examples of such cases have been found in the OGO 1 and 3 observations.

By simultaneous observations on two satellites in interplanetary space, identifiable signatures in the magnetic field have been found to be convected downstream by the solar wind plasma, indicating that the magnetic field is "frozen" in the plasma; this feature has been demonstrated with the observations by Explorer 28 and Pioneer 6 (Ness, 1966) and by Explorers 18 and 21 (Fairfield, 1967). It has been shown further that the interplanetary magnetic fields are convected into the magnetosheath and wrap around the magnetosphere, the lines of magnetic force tending to align themselves tangent to the magnetopause (Fairfield and Ness, 1967; Fairfield, 1967). It thus appears that the background magnetic field in the magnetosheath is essentially ordered as in interplanetary space and that irregular fields are generated in the magnetosheath and are superimposed on the ordered field. This picture is in general agreement with the theoretical results using gas dynamical models (Spreiter et al., 1966; Alksne, 1967).

## 5. The Magnetosphere Tail

The Explorer 10 magnetic observations made in 1961 showed that the earth's magnetic field at large distances was greatly distorted on the night side, being stretched out and, below the ecliptic plane, pointing away from the earth (Heppner et al., 1963). Observations by Explorer 14 indicated in 1962 that the direction of the earth's magnetic field was predominantly away from the earth beyond some distance to apogee at 16.5 $R_e$

near the midnight meridian (Cahill, 1964b, 1966a). The Explorer 18 observation, made in 1965, provided a detailed mapping of the magnetic field of the magnetosphere tail (Ness, 1965). An important aspect of this observation is the finding of a sheet-like region, near the solar ecliptic plane, in which the magnetic field magnitude is extremely small and often near zero. This region has frequently been referred to as the neutral sheet, and across the neutral sheet the magnetic field direction is nearly reversed. Speiser and Ness (1967) have studied the magnetic field near the neutral sheet and deduced an equivalent current system in the neutral sheet. The Explorer 33 data have shown that the tail extends to at least 80 $R_e$ in a well-defined form (Ness et al., 1967; Behannon, 1968; Mikalov et al., 1968). The observations on Pioneer 7 have indicated that the tail may extend to 1000 $R_e$ (Ness et al., 1967; Fairfield, 1968a). Wolfe et al. (1967) described their plasma observations at these large distances by Pioneer 7 as a "wake" because of the lack of a well-developed, steady feature.

Increases in the tail field observed by Explorer 18 during periods of high geomagnetic activity were interpreted as being an indication that additional field lines are transferred from the magnetosphere proper to the tail (Behannon and Ness, 1966). Using the magnetic field observations from three satellites, namely, OGO 1 located deep in the tail and Explorer 28 and Explorer 33 both situated outside the bow shock, evidence for such a transfer of an additional magnetic flux to the tail at the time of a sudden commencement has been presented (Sugiura et al., 1968a); here the Explorer 28 and Explorer 33 observations provided the position of the interplanetary discontinuity (responsible for the sudden commencement) outside the magnetosphere, and OGO 1 observed a magnetic field increase in the tail before the interplanetary discontinuity reached this distance behind the earth. According to the energetic electron (≥ 280 kev) observations on the APL satellite 1963 38C, the low-altitude, high-latitude electron trapping boundary in the midnight meridian collapses toward lower latitudes simultaneously with an increase in the tail field observed by Explorer 18, and these observations have been interpreted as being due to the flux transfer (Williams and Ness, 1966). Thus the magnetic field in the tail is directly related to the solar wind compression of the magnetosphere.

The neutral sheet region as defined by magnetic observations is thin, being only a fraction of one earth radius (Ness, 1967). The existenence of this region of weak magnetic field implies a presence of plasmas with sufficient density. Early observations of electrons by Gringauz et al. (1960 a,b), Freeman (1964), Frank (1965), and Vernov et al. (1966) are, retrospectively, suggestive of the existence of an equatorial plasma sheet. The observations by the Vela satellites of electrons and protons with energies greater than 100 ev in the tail have now established the existence of such a plasma sheet across the tail (Bame et al., 1966, 1967). According to the Vela observations, the electrons in the plasma sheet typically have a broad, quasi-thermal energy spectrum, peaked anywhere between a few hundred ev and a few kev, with a non-Maxwellian high-energy tail. The thickness of the plasma sheath in the tail is 4 to 6 $R_e$ at the distance of $\sim 17\ R_e$; and the sheet flares out to about twice that thickness toward the dawn and dusk boundaries. Recent plasma observations by Vasyliunas (1968) and Frank (1967 a,b) on OGO satellites have shown that the night-side plasma sheet extends well into the magnetosphere from the flanks to the front side.

6. The Near-Tail Region

While the overall shape of the magnetosphere is determined by the pressure balance between the earth's magnetic field and the solar wind, the magnetic field structure inside the magnetosphere, in particular, at geocentric distances beyond several earth radii is, to a great extent, dependent on the plasmas in the magnetosphere. Behaviors of the plasmas in the near-tail region appear to play an important role in the dynamics of the magnetosphere and in high-latitude disturbance phenomena. The term "near-tail region" is used here to refer to the region near the (earthward) tip of the plasma sheet where the ratio, $\beta$, of the plasma kinetic energy density to the magnetic field energy density is nearly unity or greater. The following discussions on the magnetic field structure in the near-tail region are mainly based on the OGO 1 and 3 observations.

Figure 2 shows an example of the variation in the magnitude, B, of the magnetic field along an inbound orbit of OGO 3, covering distances from about 16 to 6 $R_e$. The steady field from beyond 16 $R_e$ to about 11.3 $R_e$ is the tail field under relatively quiet conditions. The steady field is abruptly terminated by a sudden decrease in B and is followed by a region of irregular field. Sudden changes and irregularities in the magnetic field in the near-tail region, such as are seen in Figure 2, are generally not associated with any notable magnetic variations on the ground and are interpreted as being spatial structures (Sugiura et al., 1968b). However, near the magnetic midnight meridian a sudden field change is often observed in this region following the onset of a negative bay on the ground; such a change has been taken to mean a magnetic field collapse in the near-tail region caused by the bay (Heppner et al., 1967;

Sugiura et al., 1968a), as will be discussed in Section 7. The spatial structures discussed here should be distinguished from these temporal variations associated with bay disturbances. The beginning of the irregular field at about 11.3 $R_e$ in Figure 2 is interpreted as the satellite's entrance into a high $\beta$ region. Whether or not the sudden magnetic field change that often characterizes the beginning of an irregular field corresponds to the plasma sheet boundary remains to be studies in the future. However, a preliminary comparison of the magnetic field data with plasma observations indicates that when $\beta$ becomes nearly equal to, or greater than, unity, magnetic field irregularities seem to appear (Sugiura et al., 1968b). Hence this threshold need not be precisely the boundary of the plasma sheet, and the former may be the surface within which $\beta \gtrsim 1$. Normally only one large, sudden field change is observed in one pass, but there are passes in which more than one such change are encountered. This suggests that the magnetic field in the near-tail region has shell-like structures and that the large sudden changes are magnetic field discontinuities between successive shells. The orbital characteristic, i.e., the inclination of 31° of the OGO 3 satellite is probably the reason for its normally passing one discontinuity on each inbound orbit; the latitude of the satellite was too high to see these discontinuities on its outbound passes during the first several months after launch. Figure 3 shows a magnetic field profile frequently observed when the satellite passes the geomagnetic equator in the near-tail region. The region of the large, box-like depression of the magnetic field is taken to be the central part of the plasma sheet.

Figures 4 and 5 illustratively summarize the structure of the magnetosphere discussed in this and preceding Sections, the two figures showing the main features in the equatorial cross section and in the noon-midnight meridional cross section, respectively. The shell-like discontinuities discussed above are indicated in Figure 5. The region containing the discontinuities is likely to be connected to the auroral belts by the lines of magnetic force.

7. Disturbance Field Variations

(1) The storm-time ring current:

Early observations of the magnetic field decrease produced by a storm-time ring current include those made by Luniks 1 and 2 (Dolginov et al., 1961; Dolginov and Pushkov, 1963), Explorer 6 (Smith et al., 1960; Smith and Sonett, 1962), Explorer 10 (Heppner et al., 1963), Explorers 12 and 14 (Cahill and Amazeen, 1963; Cahill, 1964 a,b), and Electron 2 (Eroshenko et al., 1965). More recently, Cahill (1966b, 1968) has made an extensive survey of the ring current field with Explorer 26, and has shown that the region of large field decrease varies from one storm to another, ranging from L=2.5 to 5.3.

Low energy protons (150 kev < E < 4.5 Mev) were observed by Explorer 12 (Davis and Williamson, 1963). On the basis of these data Akasofu et al. (1962) constructed a model ring current. The observation of the proton belt was confirmed by Explorers 14 and 15 (Davis, 1965). The most complete observations of the charged particles of the ring current are those made by Frank (1967c) on OGO 3. As an example, for the storm of July 8, 1966, he observed enhanced fluxes of 200 ev - 50 kev protons between L=3 and 7 with a peak at 3.7, and electron fluxes in the same energy range from L=3 to beyond 7.5. It was shown that the energy spectra and spatial distributions of the protons and electrons in the ring current vary with time in a complex manner.

A ring current has been found to exist even during magnetically quiet periods (Davis and Williamson, 1963; Frank, 1967c). The magnetic field decrease at the earth's surface due to the quiet-time proton belt has been estimated by Hoffman and Bracken (1965) to be 9$\gamma$ using the proton data from Explorer 12.

(2) Magnetic bays (or polar substorms):

The OGO 1 and 3 satellites have provided observations of magnetic variations in the near-tail region associated with magnetic bays, or polar substorms (Heppner et al., 1967; Sugiura et al., 1968a). Summarizing their results, the important features are as follows. (i) A sudden change is observed in the near-tail region in association with a magnetic bay if the satellite is nearly in the same meridian plane as the center of the bay disturbance on the earth. (ii) The onset of the bay at the earth's surface precedes the sudden change in the near-tail region. (iii) If the satellite is in the region away from the equator where normally $\Delta B$ (= the observed minus the theoretical field) > 0, the change is a decrease in B; whereas if the satellite is in the equatorial region where normally $\Delta B < 0$, the change is an increase. (iv) The change in the direction of the magnetic field is such as to approach the theoretical dipolar field. These features are interpreted to mean that the tubes of magnetic force passing the equatorial near-tail region collapse, following the bay onset; the tubes of force initially collapsing are probably those that are connected to the ionosphere in the general area of the bay onset, i.e., the region in which the negative bay begins abruptly. After the collapse of these flux tubes a re-arrangement of the neighboring tubes must take place to adjust to a new pressure balance, but a sudden large change in the field is observed only in the collapsing tubes. It is thought that the plasma is drained from these tubes of force partially by precipitation into the ionosphere and partially by convection into other regions of the magnetosphere. According to Cummings et al. (1968), recent observations by the ATS 1 satellite in a synchronous orbit at 6.6 $R_e$ indicate a magnetic field depression in the dusk-to-midnight sector during magnetic bay activity. This is interpreted by these authors as being due to a "partial ring current". The creation of the partial ring current may be related to the drainage of the plasma in the near-tail region metnioned above. The picture of the magnetic field collapse in the near-tail region at the time of a bay is consistent with the observations of the electron behaviors in the tail plasma sheet by the Vela satellites at about 17 $R_e$ (Hones et al., 1967).

Transverse magnetic field perturbations suggestive of field-aligned current have been observed by the APL satellite 1963 38C (Zmuda et al., 1966, 1967). These variations are found at the satellite altitude of 1100 km along the auroral oval. Significance of large-scale field-aligned electric fields and currents is now being recognized, but no direct observations of them have so far been presented.

## 8. Magnetosphere Models

Unlike the description of the geomagnetic field near the earth's surface, usefulness of an analytical representation of the magnetic field in the magnetosphere will be greatly limited unless spatial as well as temporal variabilities are in some way incorporated. Several attempts have been made to represent the magnetospheric field analytically. Mead (1964) and Midgley (1964) expressed the scalar magnetic potential of the field from the magnetopause surface current in spherical harmonic series. Williams and Mead (1965) expressed the magnetic field in the trapping region as the sum of the main (dipole) field, $\underset{\sim}{B}_d$, the field from the magnetopause surface current, $\underset{\sim}{B}_s$, and the field from the neutral sheet current, $\underset{\sim}{B}_T$, to obtain a theoretical model for the diurnal variation in the trapped electrons. In their model $\underset{\sim}{B}_T$ is given by an infinitely thin sheet current in the equatorial plane in the back of the earth; the current flows from infinity to infinity in the direction perpendicular to the sun-earth line, the direction of the current being from the dawn to the dusk side so as to create the tail field. The (uniform) current intensity and the positions of the front and rear edges of the current sheet are taken to be adjustable variables to fit the observation. The adiabatic motion of energetic particles in such a model magnetospheric field has been investigated by Mead (1966) and Roederer (1967). While this model represents several gross average characteristics of the magnetic field in the trapping region, there are intrinsic limitations in its applicability both from the geometric and physical idealization of the neutral sheet current.

Based on the extensive magnetic data from Explorers 18, 21, and 28, Fairfield (1968b) has derived an average configuration of the magnetic field in the outer magnetosphere between 5 and 18 $R_e$. In particular, he drew contours of equal magnetic field magnitude in the equatorial plane, and attempted to establish, from the consideration of flux conservation, the relationship between the equatorial crossing points of lines of magnetic force and the positions of their feet at the earth's surface. This 'graphical' model represents some average features of the magnetospheric field configuration, but the spatial coverage of the observational data used is not adequate to bring out the effects of the plasmas in the equatorial region.

## 9. Conclusions

Gross features of the magnetic fields in the magnetosphere and its vicinity have been explored in the past several years by extensive spacecraft observations. The positions of the magnetopause and the bow shock have been mapped at various latitudes below about 63°, and their frequent movements have been inferred. The observed general characteristics of the magnetospheric field have been found to be in gross agreement with the theoretically expected distortion of the geomagnetic field by the solar wind. The magnetospheric tail is now known to extend well beyond the moon's orbit, and may reach 1000 $R_e$ in a wake-like form. The existence of a plasma sheet in the magnetosphere and in the tail has been established. The diamagnetic effects of the plasmas have been observed, indicating that the magnetic field configuration of the magnetosphere is distorted appreciably by the plasmas. Therefore, in a magnetic field model for the magnetosphere the effects of the plasmas must be taken into consideration.

While the overall configuration of the geomagnetic field in space is known, detailed magnetic field structures and dynamical processes operating in the magnetosphere are not as yet well established. Outstanding fundamental questions that are still awaiting definitive answers include, for instance: the precise nature of the solar wind-magnetosphere interaction at the magnetopause, the structure of the bow shock, the reason for the existence of the extended tail, the origin of the plasmas in the magnetosphere and in the tail, the processes causing high latitude disturbances, and various particle acceleration mechanisms. Some of these problems appear to be interrelated, but some may be related to still other important processes that have so far escaped our observation.

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## FIGURE TITLES

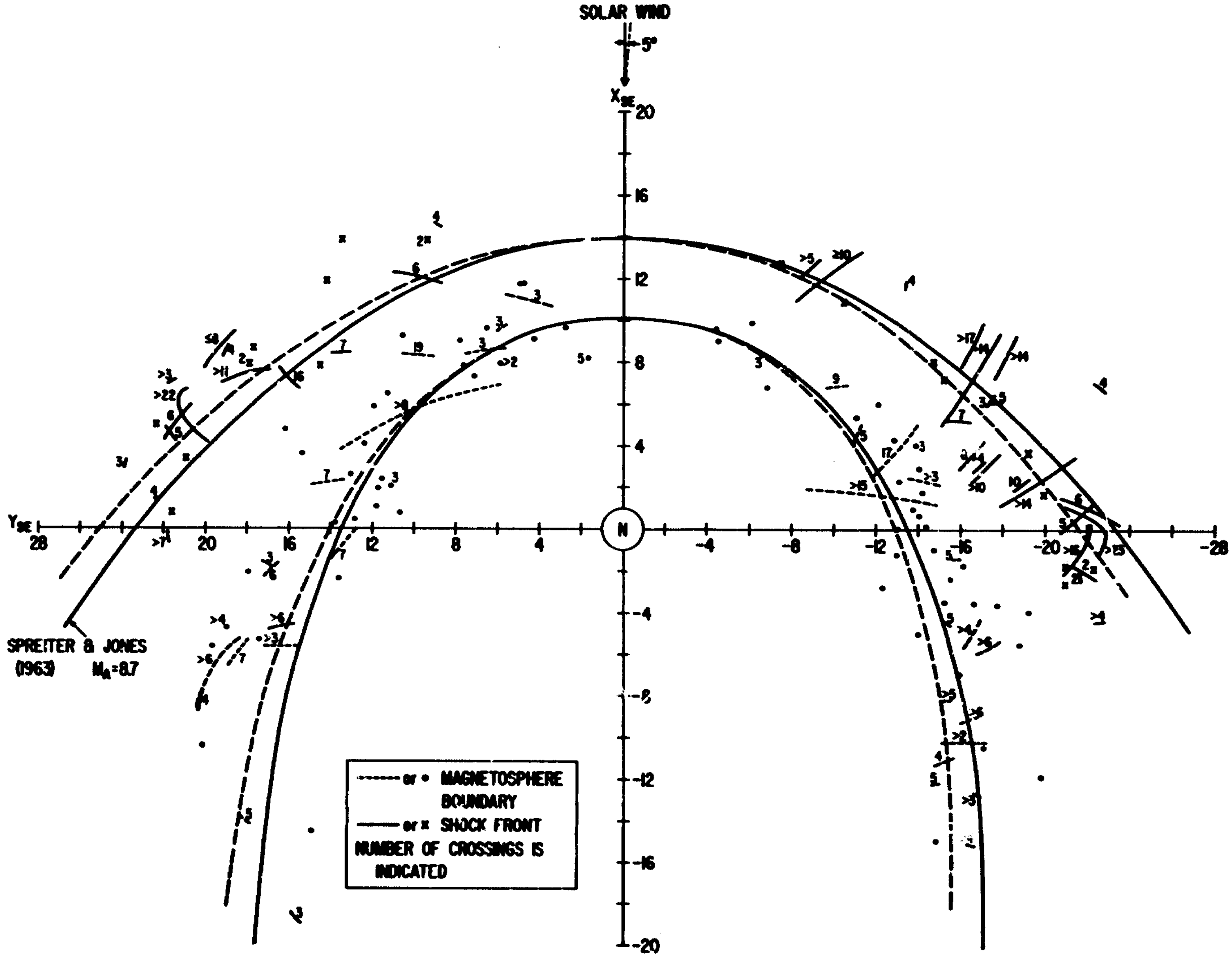
Figure 1. The magnetopause and bow shock encounters by the OGO 1 satellite. The positions are projected onto the solar ecliptic plane by rotating the radial distances along circles in ecliptic meridian planes.

Figure 2. An example of the profile of the magnitude B of the magnetic field along an inbound orbit of the OGO 3 satellite. The sudden decrease in B near 23 hours UT represents a shell discontinuity in the near-tail region.

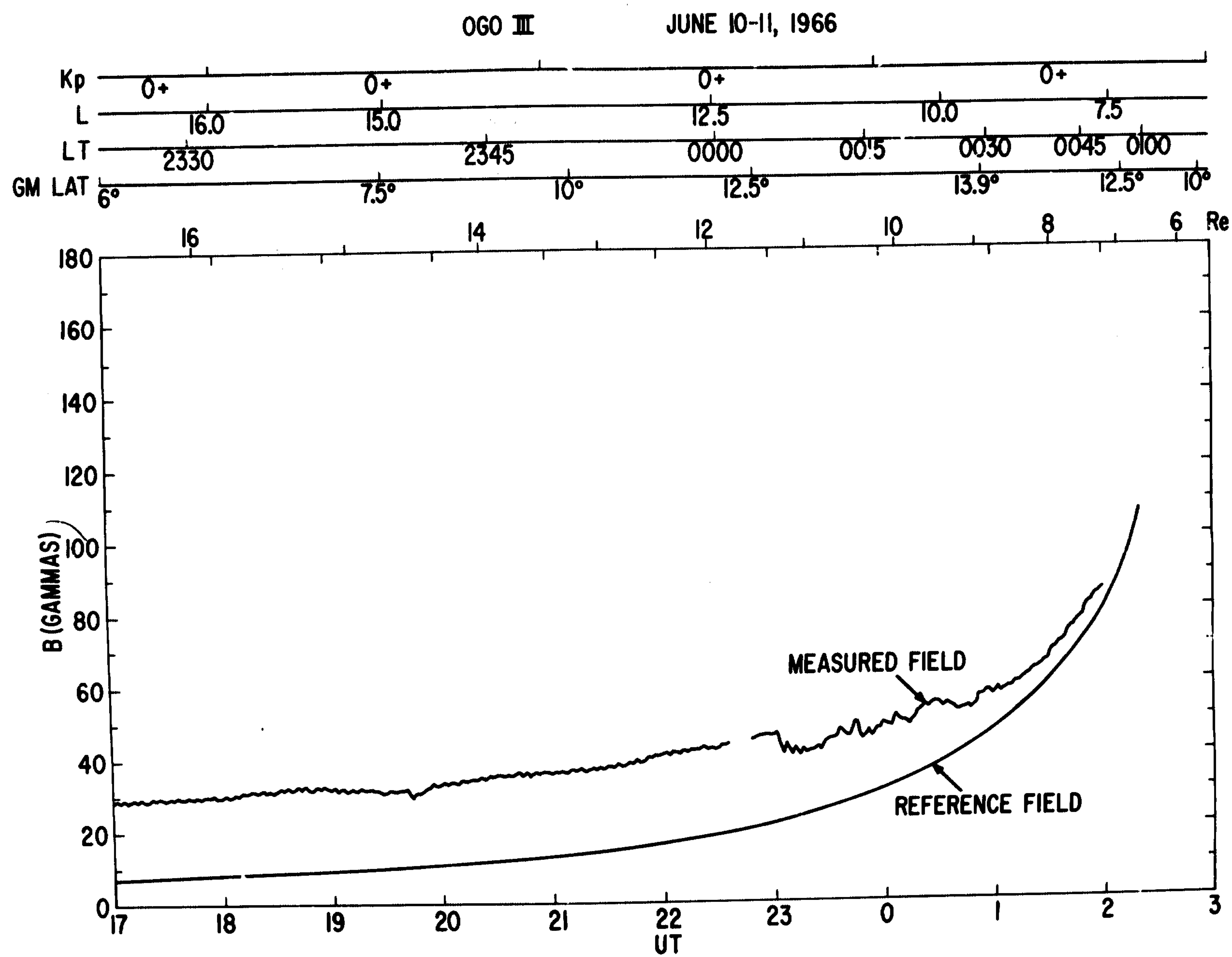
Figure 3. An example of a sudden magnetic field decrease observed when the OGO 3 satellite crosses the geomagnetic equator in the near-tail region.

Figure 4. Illustration of the magnetosphere in the equatorial cross section; dots represent the presence of plasmas.

Figure 5. Illustration of the magnetosphere in the noon-midnight cross section; dots represent the presence of plasmas; $\Delta B$ is the difference field, i.e., the observed minus the reference field.



SOLAR WIND
5°
$X_{SE}$
$Y_{SE}$
N
SPREITER & JONES
(1963) $M_A$=8.7
MAGNETOSPHERE BOUNDARY
SHOCK FRONT
NUMBER OF CROSSINGS IS INDICATED


OGO III
JUNE 10-11, 1966
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14
12
10
8
6
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B (GAMMAS)
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160
140
120
100
80
60
40
20
0
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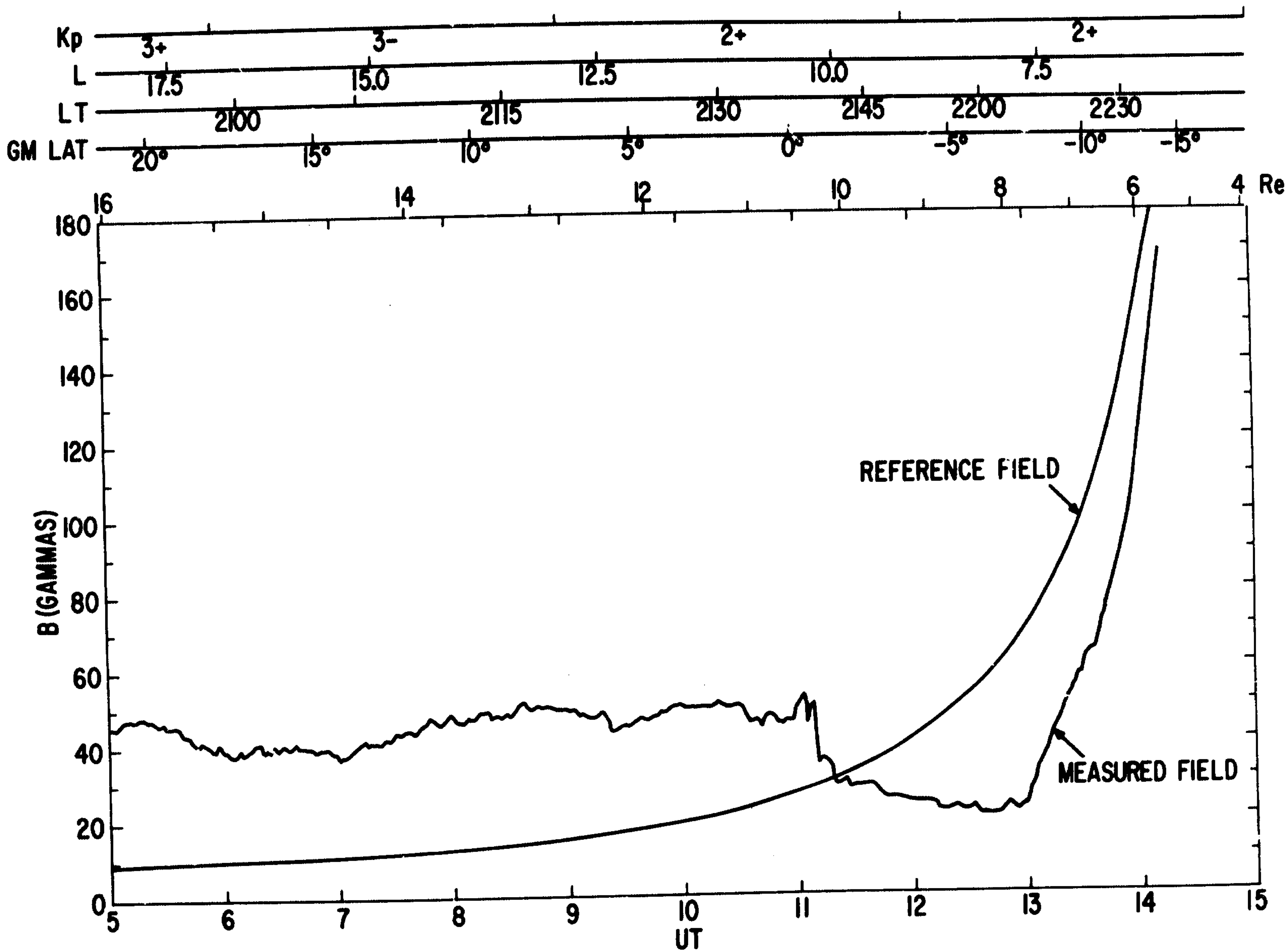
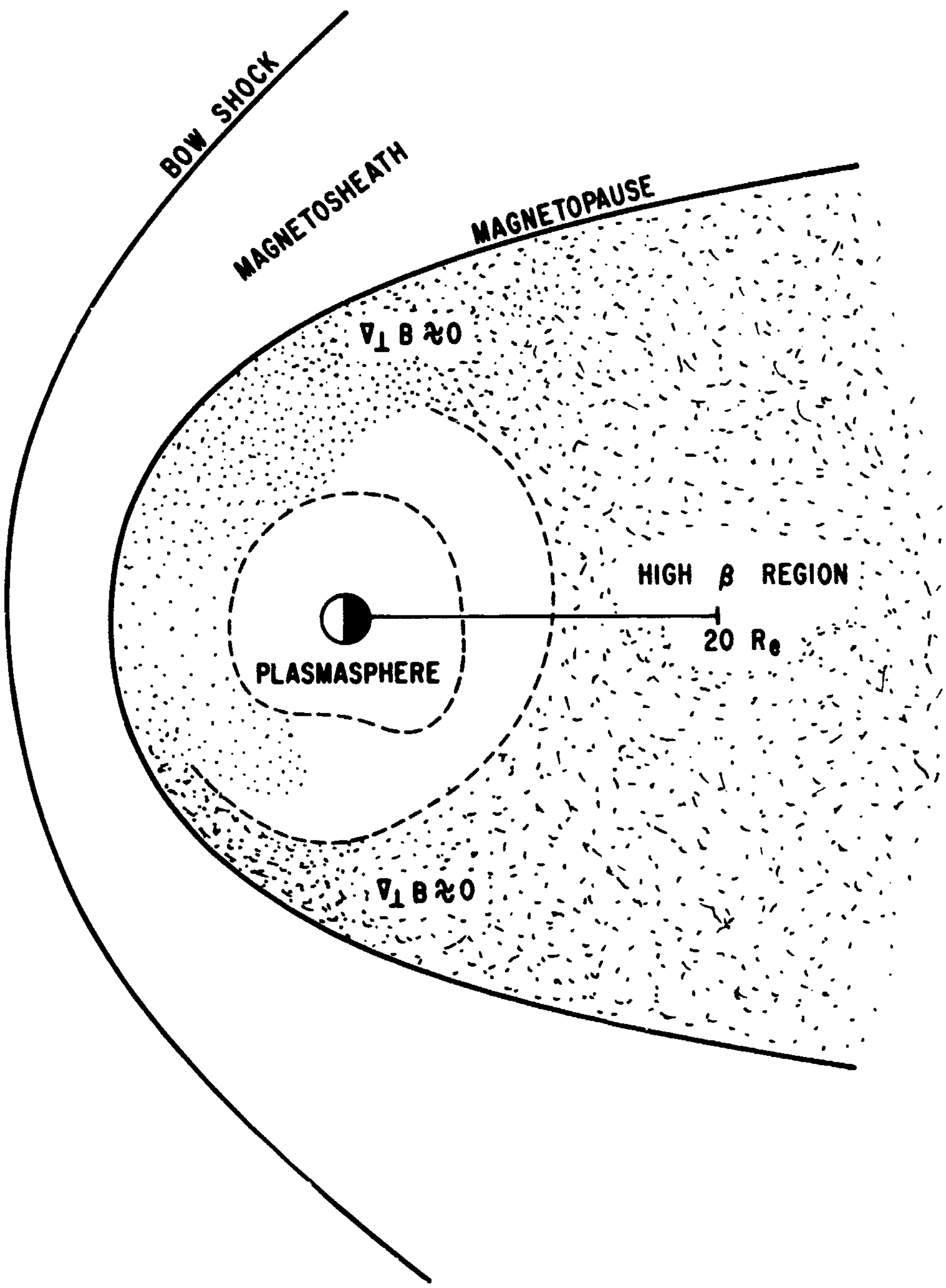
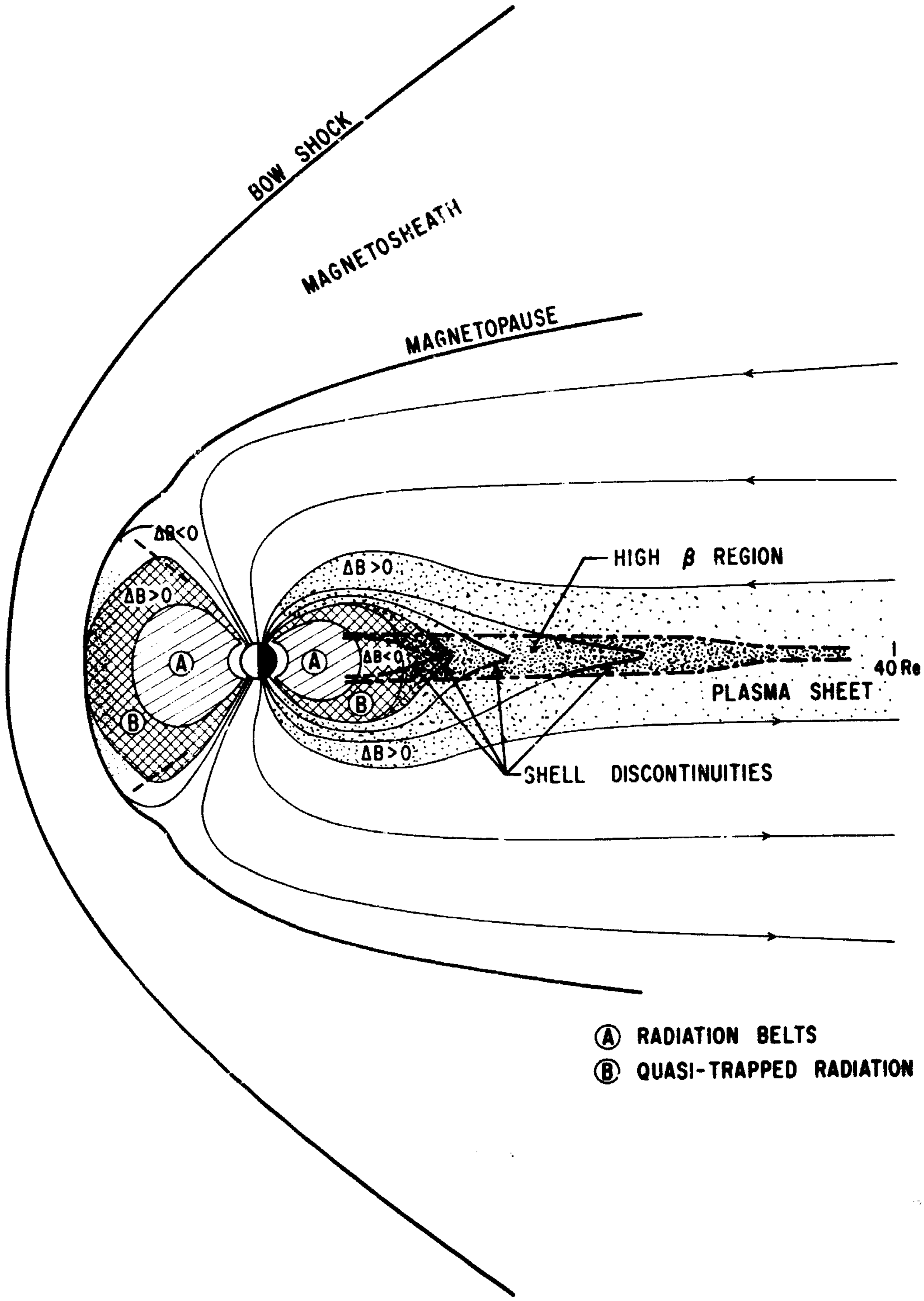
UT
MEASURED FIELD
REFERENCE FIELD

OGO III JULY 21, 1966






EQUATORIAL CROSS SECTION




NOON-MIDNIGHT CROSS SECTION