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ABSTRACT

The earth's magnetopause is the boundary between a hot tenuous plasma in the magnetosphere and a cooler denser plasma in the magnetosheath. Both of these plasmas contain magnetic fields whose directions are usually different but whose magnitudes are often comparable. Efforts to understand the structure of the magnetosphere have been hampered by the variability and complexity of this boundary. Waves on the magnetopause surface propagate toward the magnetotail with poorly known velocities that can range anywhere within an order of magnitude of 10 km/sec. Typical thicknesses are probably on the order of a few hundred km which is a few times the gyroradius of a thermal proton. Although conclusive direct evidence for a field component, B_n, across the magnetopause has not been found, this lack of evidence may reflect the difficulty in determining B_n in the presence of magnetopause waves rather than the real absence of this component. Considerable indirect evidence exists for an open magnetosphere, but the importance of the reconnection process thought to produce open field lines has recently been questioned.

INTRODUCTION

The outer boundary of the earth's magnetic field (the magnetopause) remains one of the most important yet least understood regions of the magnetosphere. It is important since the physical processes occurring at the magnetopause control the entry of solar wind plasma, momentum, and energy into the magnetosphere. It is poorly understood because its study involves many of the most difficult problems of both experimental and theoretical space physics.

Experimental difficulties arise because this thin boundary region is almost constantly moving with an unknown and variable velocity relative to an observing spacecraft. Experimental sampling rates have often been inadequate to resolve the microstructure of the magnetopause, especially those for plasma experiments which must measure hot anisotropic plasmas whose densities are particularly tenuous on the magnetosphere side of the boundary.

The magnetopause is difficult to understand from a theoretical standpoint because it involves many of the most complex problems of magnetized hot anisotropic plasmas. Whereas MHD theory is generally applicable within the large volumes of the magnetosphere and magnetosheath, the thin boundary region separating them is undoubtedly dominated by microprocesses which involve large gradients and non-linear effects. Even the appropriate boundary conditions to impose on a theoretical model are not clear, partly because of experimental uncertainties and the fact that conditions are variable in time, but also because these boundary conditions require knowledge of plasmas at distant points along field lines which thread the region of the magnetopause. This latter constraint means that it is impossible to begin to understand the magnetopause microstructure without considering the overall field topology and whether field lines cross the magntopause (Willis, 1978). Naturally it is the microstructure which determines the topology, all of which means the problem should be solved in a self consistent manner.

Unfortunately, virtually all theories presuppose either the presence or absence of this field component across the boundary and the resulting theories shed no further light concerning its existence. Experimental studies have been unable to clearly confirm or refute the existence of this normal component for reasons that will be discussed in this paper.

In this review we will first consider the general question of magnetosphere topology, considering the accumulated indirect evidence that has argued for field lines crossing the boundary. Next we will illustrate the general appearance of the magnetopause and discuss the boundary conditions imposed by the magnetosphere and magnetosheath. Then we will investigate the microstructure of the magnetopause, reviewing wave motion of the boundary and the difficulties involved in determining thicknesses and field components normal to the boundary. Finally, we will review high latitude observations and conclude with suggestions as to what appears to be the most promising approaches to further studies of the magnetopause.

THE GEOMAGNETIC FIELD CONFIGURATION

For many years opposing views of the geomagnetic field configuration have centered around the question of the field component across the magnetopause. In the "open model", magnetosphere and magnetosheath fields "reconnect" or "merge", in a process that converts magnetic field energy into particle kinetic energy.

In this process the fields of the magnetosheath become interconnected with those of the magnetosphere such that they form a rotational discontinuity at the magnetopause. Since these reconnected field lines are equipotentials under the usual MHD assumption, the $\vec{V} \times \vec{B}$ electric field associated with magnetosheath flow is transmitted down field lines to the polar cap ionosphere. These low altitude electric field are indeed observed and are thought to be important in driving magnetosphere plasma convection. Since these field lines cross the magnetopause, an electric field must exist tangent to the magnetopause.

This "open model" has enjoyed considerable success over the years. It correctly predicted that geomagnetic activity would be enhanced when the interplanetary field assumed the southward orientation which is most favorable for reconnection. The theory is consistent with inward motion of the magnetopause under southward-interplanetary-field conditions (Aubry et al., 1970) which is associated with an increase in tail field magnitude and radius. This open configuration easily explains the entry into the tail of both cosmic ray particles (e.g., Paulikas, 1974) and electrons of several hundred ev energy (Mizera and Fennell, 1978). A north-south asymmetry in this entry process and its dependence on interplanetary sector polarity is particularly well explained by an open model and, indeed, seems difficult to explain in any other manner. Also the existence of open field lines provides a simple explanation for plasma flows in the polar cusp and plasma mantle (Haerendel et al., 1978).

The original and traditional alternative to the open model, the "closed model", assumes that there is no field component across the magnetopause. In this closed mode the magnetopause is a tangential discontinuity which isolates field lines of the magnetosheath from those of the magnetosphere. This model has difficulty explaining both the observed entry of energetic particles to the polar caps and the entry of solar wind plasma to the magnetosphere. The plasma entry is presumably through a diffusion mechanism which is not well understood, but must be very efficient. These facts, along with the superior predictive ability of the open model, caused the closed model to lose favor.

In recent years, however, doubts as to the importance or even the existance of reconnection have led some workers toward a modified version of the closed model. These doubts have been raised primarily by Heikila (1975; 1978) who noted that the electric field tangent to the magnetopause in the open model would generally have a component aligned with the magnetopause current system that flows there. A large amount of energy should be dissipated which is just that energy that reconnection theory predicts should be converted into that of a flowing plasma (Sonnerup, 1976). Heikkila calculated this energy dissipation as $\sim 5 \times 10^{18}$ ergs/sec, a power that probably should have been observed by spacecraft, yet has not been detected (Haerendel et al., 1978; Heikkila, 1978). This negative result is interpreted by Heikkila as evidence for the absence of reconnection. Since evidence from particle entry seems to require open field lines, some authors (Heikkila, 1978; Haerendel et al., 1978; Johnson, 1978) now favor a model which retains the interconnected field lines while questioning the importance of the reconnection process.

BOUNDARY CONDITIONS AT THE MAGNETOPAUSE

Although observations of the magnetopause were performed on some of the earliest spacecraft, there have been few if any published examples of comprehensive measurements showing electrons, protons and magnetic fields across the magnetopause. Such data from the IMP-6 spacecraft are shown in Figure 1. The 15 second averages of the magnetic field magnitude, B, latitude and longitude angles θ and ϕ, and standard deviation δ are shown in the bottom four panels. Plasma data measured by the Los Alamos plasma experiment (Hones and Bame, private communication, 1978) is shown at the top with 108-second time resolution. Quantities shown are density n, average energies for protons and electrons, and flow vectors. Every second measured flow vector is shown, with downward directed vectors representing flow from the sun, dusk to the left and dawn to the right. In this example and on this time scale, the magnetopause is readily identified at 2:50 UT by the discontinuity in all the measured parameters. In going from the magnetosphere to the magnetosheath the plasma density changes from 0.7 to 35 particles/cc while the average proton and electron energies go from 11 Kev and 1.1 Kev to 600 ev and 60 ev respectively. The average energy is almost equivalent to a temperature since flow energies are relatively small near the magnetopause. These density and temperature changes tend to offset each other, so the change in plasma β [$= \frac{n\kappa(T_p+T_e)}{B^2/8\pi} \approx (n\bar{E}_p-1/2nm_pV^2)/(B^2/8\pi)$] is not large and β is near unity on either side of the boundary.

This quantity, β, is shown in Figure 2 along with the 1.28-second magnetic field averages and plasma n and $\vec{V}$. The trace above the field magnitude represents the total (field plus plasma) energy density or pressure and is associated with the right hand scale. The slightly higher magnetosheath pressures may represent a real time increase which moved the boundary in past the spacecraft. The single high point in energy density may result from time aliasing of the plasma data. A second close approach to the magnetopause probably occurred at 3:01 where the magnetosheath flow direction is perturbed and the field angles become closer to their magnetosphere values. Note that the boundary layer that is almost always present in at least a narrow region at the magnetopause (Eastman et al., 1976) is not resolved in this relatively coarse-resolution plasma data.

The interplanetary field at the time of the above example was of 11.8 γ magnitude and southward orientation ($\theta = -25^{o}$, $\phi = 343^{o}$). From our knowledge of the magnetosheath (e.g., Fairfield, 1976a) it is clear that interplanetary fields are convected into the magnetosheath where they tend to become draped over the magnetosphere. An interplanetary field with a southward component will create a large angle discontinuity with the northward directed dipole field at the low and mid-latitude magnetopause. This is the case in Figure 1. A northward directional interplanetary field will be more closely aligned with the dipole field and thus produces a much smaller angular discontinuity.

An example when the interplanetary field was 12.6 γ and northward ($\theta = 39$, $\phi = 145$) is shown in Figure 3 and also with higher resolution data in Figure 4. In these figures the magnetopause can be located at approximately 11:16 on the basis of the characteristic changes in density and average energy. In this case the magnetic field data cannot clearly locate the magnetopause except by the increase in fluctuations as indicated by δ. Notice that the magnetosheath field is actually larger than the magnetosphere field, a situation that is typical near the dawn and dusk flanks (Heppner, 1967; Ogilvie et al., 1971) and sometimes found even near noon

(Fairfield, 1976b). Figure 4 shows that β is actually higher in the magnetosphere than in the magnetosheath. The higher observed pressure in the magnetosphere is probably due to a slight overestimate in n, but confirmation that magnetosphere plasma pressure exceeds magnetosheath pressure can be deduced independently from the field data.

These ~ 10 Kev magnetospheric protons with densities approximately 1/cc in the outer magnetosphere have only been measured in recent years and their presence is not generally appreciated. They are invariably present, however (see Haerendel et al., 1978 for several examples), and mean that β is seldom much less than unity in the outer magnetosphere.

It can also be seen in Figure 3 that during the first hour that the spacecraft is within the magnetosheath the field magnitude is decreasing, while the density is increasing from 4 to 10. This decrease undoubtedly indicates the presence of the plasma depletion layer predicted theoretically (Zwan and Wolfe, 1976) and recently detected by Crooker et al. (1978). This depletion occurs when interplanetary field lines oriented approximately perpendicular to the earth-sun line become draped over the magnetopause, and the plasma particles with smaller pitch angles escape along the field. This situation is illustrated schematically in Figure 5b.

A field oriented more along the earth-sun line is predicted to have a very small value near the subsolar point and might look like those drawn in Figure 5a. Such magnetosheath fields are less apt to exhibit draping. Furthermore, being downstream of a parallel bow shock, they are highly variable. An example is shown in Figure 6 (Interplanetary $B = 3.8\ \gamma$, $\theta = -6^{\circ}$, $\phi = 331^{\circ}$) where multiple crossings of the magnetopause are apparent at the boundaries of high field regions where angles return to the direction seen later during an extended magnetosphere traversal. Although no plasma data are available for this example, it can be confidently presumed that $\beta >> 1$ in the magnetosheath and the pressure balance across the magnetopause is primarily between the magnetosphere field and the magnetosheath plasma. Although this latter situation is commonly supposed to be typical, we emphasize that a distribution of $\beta_{sphere}/\beta_{sheath}$ covers the entire range between small values and those somewhat greater than unity. On the one hand solar wind kinetic pressure balances geomagnetic field pressure to the extent that average positions of the magnetopause are adequately predicted. On the other hand, the local pressure balance at the magnetopause is often between the field and plasma on both sides of the boundary. Apparently, magnetosheath processes associated with field-line draping and the plasma depletion layer often convert directed solar wind kinetic energy into magnetosheath magnetic field energy.

In view of results suggesting that micropulsations are though to be due to the Kelvin-Helmholtz instability of the magnetopause (Southwood, 1974) and that such micropulsations are more frequent when the interplanetary field is aligned near the earth sun line (e.g., Greenstadt and Olson, 1977), it is interesting to speculate that the magnetopause stability may be related to the interplanetary field orientation. Perhaps the stronger magnetosheath fields associated with perpendicular orientation tend to stabilize the magnetopause, whereas weaker fields associated with earth-sun alignments favor instability. Further evidence supporting this conjecture is the observation of Howe and Siscoe (1972) that tail boundary motions are more frequent near dawn. A spiral interplanetary field does not drape itself as in orderly a manner on the dawn side as on the dusk side (Behannon and Fairfield, 1969).

MAGNETOPAUSE MICROSTRUCTURE

When the magnetopause is investigated on time scales less than a minute, quantities that appear to change simultaneously on the scales of Figures 1-4 now begin to exhibit differences. According to Neugebauer et al. (1974) a common pattern is for the field strength, the field angle and the ion flux to all change together on the magnetosphere side of the boundary, with the angle and flux changes extending out further into the magnetosheath. Low energy electron fluxes also need not change in coincidence with the field changes (Ogilvie et al., 1971). Kaufmann and Konradi (1973) found that the angle change took notably longer than the field magnitude change on about half the orbits they studied.

An example of 80 ms IMP-6 magnetic field data across the magnetopause is presented in Figure 7. Field magnitude is shown at the bottom along with three orthogonal field components. The B_n component is that in the minimum variance direction (see below) and B_y is aligned near the magnetosphere field direction. In this example the field rotates through an angle of 150° between 2:01:30 and 2:04:30 with most of the rotation taking place during a relatively long interval of almost 2 minutes. Plasma data for this event (Eastman and Hones, 1978) show a well developed boundary layer with appreciable densities and flow velocities persisting until $\sim$ 2:12. The waves at frequencies near the proton gyrofrequency (0.46 Hz in a 30 γ field) can be seen in the field reversal region near 2:03 as well as at earlier times in the magnetosheath. Such waves are often seen in this region (Neugebauer et al., 1974; Fairfield, 1976b) and may be important in the diffusion of particles into the magnetosphere (Eviatar and Wolf, 1968). Fairfield (1976b) has noted the similarly of these waves to those in the magnetosheath which he identified as ion cyclotron waves.

The occurrence of waves at frequencies above the proton cyclotron frequency is not an outstanding characteristic of the magnetopause. The magnetopause can normally be identified in the data taken at these frequencies (e.g., Holzer et al., 1966) but it is usually apparent only as the boundary between emissions that are characteristic of the magnetosheath or the magnetosphere (Russell et al., 1974; Neugebauer et al., 1974). Neugebauer et al., do, however, present one example (their Figure 13) where waves unique to the magnetopause may be present.

Another characteristic of high resolution magnetic field data across the magnetopause that has been noted by several authors (Aubry et al., 1971; Neugebauer et al., 1974; Fairfield, 1976b) is its variability from one crossing to another. Even crossings separated by only a few minutes in time can have quite different appearances in terms of time scale, fluctuation level and angle change. It is, of course, this variability that makes experimental studies so difficult.

MAGNETOPAUSE MOTIONS

Spacecraft passing through the magnetopause region often experience multiple encounters with the magntopause (e.g., see Figure 6). This fact implies that the boundary is usually moving relative to its average location with velocities which must be or the order of or larger than spacecraft velocities which are typically 1 to 2 km/sec. Higher magnetopause velocities are implied by the Voyager 1 spacecraft which passed through the magnetopause region at 11 km/sec on its way to Jupiter and still saw seven crossings of the boundary (M. Acuna, private communication).

Velocity estimates are difficult to obtain with measurements from a single spacecraft and they range from the low spacecraft velocities up to hundreds of km/sec. Holzer et al. (1966) used a simple model of uniform oscillatory motion with peak to peak amplitude of 0.5 R_E and period 20 minutes to obtain a velocity of $\sim$ 10 km/sec. Much higher velocities were estimated by Aubry et al. (1971) in a study of multiple crossings during a two-hour interval when the magnetopause moved gradually inward with an inbound spacecraft. They concluded that the multiple crossings were due to waves on the magnetopause surface that were propagating tailward with magnetosheath-like velocities of $\sim$ 200 km/sec. Such waves were thought to occur in two distinct period ranges of $\sim$ 5 minutes and $\sim$ 10 seconds. The Kelvin-Helmholz instability was proposed as a possible source of these waves.

This evidence for tailward propagating waves on the magnetopause follows from an analysis that was originally proposed by Kaufmann and Konradi (1969) and is illustrated in Figure 8. In the presence of such tailward propagating boundary waves, a spacecraft located in the magnetosheath near the boundary will see the magnetopause pass over it while this boundary has a normal in the direction indicated by the solid vector. As the wave passes over the spacecraft it will re-enter the magnetosheath while the normal is oriented in the direction illustrated by the dashed vectors. A wave propagating sunward would reverse the vector tilts for the same sense of crossing. Aubry et al. (1971) computed magnetopause normals with the variance analysis technique (described below) and found that the vectors were tilted in a more tailward direction for magnetosheath to magnetosphere crossings as is expected for tailward propagating waves. Ledley (1971) confirmed this result with a more extensive analysis using 31 crossings on 13 different days at local times between 4 and 10 hr. When his crossings are grouped according to the sense of the crossing, the average normal directions for the two groups are found to differ by about 30 degrees. Furthermore, the individual angles within each group are rather well separated from those of the other group; this fact suggests that these tailward propagating waves are probably present most of the time and are of primary importance in producing the multiple crossings. Fairfield (1976b) found similar evidence for tailward propagating waves on a day with 36 crossings of the dawn magnetotail boundary near $X = -25\ R_E$. Howe and Siscoe (1972) carried out a statistical study utilizing lower time resolution plasma data from 250 crossings on 11 passes through the magnetotail. They found that characteristic separation times between crossings were 15 min. and 1 hour and velocities were typically 10 to 20 km/sec.

We can summarize our knowledge of magnetopause motion by stating that the evidence for surface waves propagating tailward is quite convincing. These waves are probably responsible for most of the observed multiple crossings and the Kelvin-Helmholz instability is their likely cause. The unknown velocity of the magnetopause and the spatial scale of the variation remain major obstacles in studying the microstructure of the magnetopause.

MAGNETOPAUSE THICKNESS

The thickness of the magnetopause is an important parameter that can be compared to that predicted by theory. If the relative velocity between the boundary and the spacecraft is known, the thickness is easily determined as the product of velocity and the observed crossing time. Durations for magnetopause crossings generally range from a few seconds to a few minutes when they are determined from magnetic field changes. Heppner (1967) suggested one minute as a typical crossing time for non-multiple encounters which presumably occur with lower velocities. Sonnerup (1976) found an average of 24 seconds for 57 crossings that occurred on 19 different OGO-5 passes. These numbers may vary some depending on whether the field magnitude change or the angle change is considered, but such variations are probably small compared to changes from one encounter to another.

Figure 9 compares various experimental determinations of magnetopause thickness with the gyroradius prediction of the simple kinetic theories (e.g., Willis, 1971, 1975). A minimum experimental thickness can probably be taken as 1 or 2 km/sec times 1 minute and is seen to correspond to the maximum theoretical prediction of $\sim$ 100 km. More typical numbers of 30 seconds times 5 to 10 km/sec give values several times the thermal gyroradius. The magnetosheath flow speeds of 200 km/sec give even greater thicknesses, even if they are associated with rapid 2 to 4-second crossing durations. Two additional experimental determinations shown in Figure 9 are probably even more reliable as they are independent of assumptions about wave motion or boundary recurrence frequency.

Kaufman and Konradi (1973) used the finite gyroradii of 140 Kev protons to determine the speed and thickness of the magnetopause. They determined the proton gradient near the magnetopause from the east-west differences in proton fluxes whose gyrocenters were at greater and less distances from the magnetopause. Then the rate of change of proton flux was taken as a measure of how rapidly the gradient, and presumably the magnetopause, was moving past the spacecraft. A study of 14 crossings occurring within 45^{o} of the earth-sun line on moderately disturbed days with high proton fluxes indicated that magnetopause velocities were usually less than 20 km/sec. These authors suggested that higher velocities sometimes occurred and were associated with simple isolated waves propagating along the magnetopause.

Another method that has been used to estimate magnetopause thicknesses utilizes a maximum in the field strength that is sometimes seen interior to the angle change at the magnetopause (Neugebauer et al., 1974). This feature seems to occur in cases when the angle change is especially large. These enhancements are seen on boundary crossings in both directions and hence are not simple field compressions. They occur only in the presence of trapped particles and are not seen on tail field lines without such particles. Examples can be seen near 19:28 and 19:43 in Figure 6. These characteristics led Neugebauer et al. (1974) to suggest that these increases are due to the loss of particles within one gyroradius of the boundary, the reduced diamagnetic effect of the particles leading to the enhanced field. Since the enhanced field regions typically have a width that is about the same as the angle change, determining the width of the enhancement is equivalent to determining the width of the current sheet. Not having good magnetospheric plasma measurements, these authors presumed a magnetopause thickness of 100 km and suggested that $\sim$ 1 Kev particles are an important constituent of the magnetosphere plasma in this region. Since more recent observations indicate that 10 Kev particles are more typical of the magnetosphere, we may turn this argument around and suggest that several hundred km gyroradii associated with 10 Kev particles are a more likely value for the thickness of these regions.

The collection of information on magnetopause thickness summarized in Figure 9 seems to indicate that magnetic field changes at the magnetopause usually takes place over a distance of at least several thermal ion gyroradii. This conclusion is reached by using techniques which do not require estimates of boundary motions and it is consistent with the more numerous studies which must use these more uncertain estimates. The frequently cited number of a 100 km thermal gyroradius for an experimental thickness is probably somewhat low. More accurate future determinations of magnetopause thickness are more apt to be on the higher side than the lower side of this few hundered km figure, particularly if magnetopause waves are moving at magnetosheath-like velocities.

THE SEARCH FOR ROTATIONAL DISCONTINUITIES

The observation of rotational discontinuities at the magnetopause would constitute direct evidence for an open magnetosphere and hence a search for these structures has been the subject of a number of papers (see references in Sonnerup and Ledley, 1974). The identifying characteristics of a rotational discontinuity are as follows (e.g., Sonnerup and Ledley): 1) the existence of a non-zero field component along the direction normal to the magnetopause; 2) a positive sign to this field component in one hemisphere and a negative sign in the other; and 3) a particular sense of rotation of the tangential component across the discontinuity. In a strict MHD rotational discontinuity the total field strength does not change across the discontinuity, but Sonnerup and

Ledley (1974) have introduced the term "rotational form" to extend the MHD concept to a more realistic situation where anisotropic plasma pressures permit the field magnitude to change across the discontinuity. The search for the B_n component has received primary attention in most studies with the rotation of the tangential component being emphasized only by Sonnerup.

The primary difficulty encountered in studying magnetopause discontinuities is identifying the direction normal to the discontinuity. This normal is usually determined by the "minimum variance" technique originally introduced by Sonnerup and Cahill (1967). In this method the magnetic field measurements are used to select the normal direction, n, that minimizes the quantity $\sum_i (\vec{B}_i - \langle\vec{B}\rangle)\cdot\hat{n}$. Here B_i are the vector measurements made throughout the magnetopause region and $\langle\vec{B}\rangle$ is the average over the interval. The primary weakness of this method is that it asssumes that the normal direction does not change during the spacecraft traversal of the structure. As we have discussed above, there is considerable evidence that waves on the boundary surface often change the boundary orientation by angles as large as tens of degrees on time scales that are not appreciably longer than spacecraft crossing times. Note that a change in $\hat{n}$ of only 1° in a 60 γ field can introduce a change in B_n as large as 1 γ.

The net result of many minimum variance studies is that they have failed to identify rotational forms in the great majority of crossings and have only possibly identified them in a small subset of selected crossings. Sonnerup and Ledley (1974) present their two best examples of rotational forms which they extracted from a set of 50 crossings.

Supporting their identification is the observed normal component and the fact that the tangential component was found to rotate through an angle of almost 270° in the "correct" sense rather than through the smaller angle of $\sim 90^{\circ}$. Detracting from the credibility of their analysis is the fact that their normal direction was highly dependent on the length of the data interval they analyzed. Using their preferred analysis interval, B_n was -8.9 γ. Using data from a sub-interval, they obtained an n that was 55° different from the first and a normal component that was +7.2 γ. We must conclude that rotational forms have not been convincingly identified, but we should appreciate that this may be due to difficulties in identifying them and not because they do not exist.

While pursuing the search for B_n it is useful to consider what value of B_n ought to be observed in a model of an open magnetosphere. To do this we might estimate that flux leaving the near-earth magnetosphere ($\chi > -20\ R_E$) might be equivalent to that flux leaving the earth between 77° and 80° latitude within 3 hours of local noon which is $\sim 1000\ \gamma\ R_E^{\ 2}$.. If such flux exited through a 5 R_E x 10 R_E area of the dayside cusp, it would produce a rather large 20 γ normal component. On the other hand, if it were distributed over the magnetosphere surface sunward of $X = -20\ R_E$, it would give a virtually undetectable normal component of only $\sim 0.5\ \gamma$. Hence, the question of whether normal components are uniformly distributed or whether they exist in isolated regions is quite important.

Stern (1973) has suggested that normal components will be restricted to limited spatial regions. He noted that if interplanetary field lines were connected to magnetosphere field lines along an extended east-west line along the dayside magnetopause, the solar wind electric field when projected down to the ionosphere would be an order of magnitude larger than that which is observed. To reduce this electric field he proposes that the field lines leave the magaetosphere through an area of limited extent in the dawn-dusk direction but which extends very far down the tail. This concept is very similar to the model of Morfill and Quenby, (1971) which was based on observations of the entry of energetic particles. With this picture much of the magnetopause and tail boundary might be a tangential discontinuity with only a limited region or "window" corresponding to a rotational discontinuity. This window would be observed rather infrequently and might explain the infrequent observations of B_n. Although an extensive search for B_n on the boundary of the tail has not been carried out, Fairfield (1978) has noted that the tail is skewed slightly toward the expected location of such a window. This window should change for different interplanetary sector polarities as the tail is found to do.

THE HIGH LATITUDE MAGNETOPAUSE

With the discovery of the dayside polar cusp and plasma on high latitude field lines of the "entry layer", considerable interest has focused on the nature of the high latitude magnetopause. Whereas early magnetic field studies of the low latitude portion of the cusp (Fairfield and Ness, 1972) were frequently unable to identify a clear boundary amid the large fluctuations of this high latitude region, more recent HEOS satellite studies which use plasma data (Hansen et al., 1976; Paschmann et al., 1976) are usually able to do so. (In 21 of 25 cases in the study by Haerendel et al., 1978.) The highest latitude portion of the cusp (the boundary of the plasma mantle) is almost always readily identifiable (Haerendel et al., 1978). Hansen et al., (1976) conclude that the outer boundary of the entry layer is a tangential discontinuity, but in view of the difficulties involved in determining boundary normals and the large fluctuations in this region, this conclusion should be taken with some reservation. Haerendel et al. (1978), on the other hand, suggest that reconnection occurs at the boundary of the entry layer but in spatially limited regions and in a sporadic time-dependent manner. This reconnection is proposed as accompanying an eddy diffusion process which is the primary means of particle entry. In support of this picture, Haerendel et al. note that high field pulses with durations of a fraction of a minute sometimes occur in the low latitude boundary layer. They propose that these pulses are manifestations of stressed field lines which are being pulled downstream by flowing plasma elements that have reconnected in the cusp.

A further study of the boundary of the entry layer (Fairfield and Hones, 1978) utilized more rapidly sampled data from the IMP-6 spacecraft. Figure 10 shows magnetic field data sampled at 80 msec intervals: B is the field magnitude and θ and ϕ are latitude and longitude angles in solar magnetospheric coordinates. Plasma density n and velocity v are shown for every spacecraft spin ($\sim$ 13 sec). In the shaded regions the density is slightly lower, the field magnitude higher, and the field direction points in a generally duskward direction as is expected for a distorted dipole field near 9:00 LT. These characteristics identify the shaded region as entry layer. The velocities seen on this orbit are quite variable on a time scale of minutes, although successive 13-second determinations are usually similar in direction. We note such surprising flows as (1) duskward and sunward flow in the high density region at 14:00 and 14:08 which is directed exactly opposite to the flow that is expected in this region and which is indeed seen at 14:14 and (2) dawnward flow in the lower density region at 14:21 but duskward flow in the same region at 14:24:30. These measurements are very suggestive of the turbulent eddies proposed by Haerendel et al., (1978).

SUMMARY

The earth's magnetopause is usually readily identified by a change in magnetic field magnitude and orientation and a change in plasma density and temperatures. The location of the magnetopause is predicted by the pressure balance between the solar wind kinetic pressure and the geomagnetic field pressure. However, the local pressure balance at the magnetopause is often between a denser magnetized plasma in the magnetosheath and a hot tenuous magnetized plasma in the magnetosphere, both plasmas having β values not far from unity. A large magnetosheath field becomes particularly important in the pressure balance when interplanetary fields oriented perpendicular to the earth-sun line are associated with the development of a magnetosheath plasma depletion layer adjacent to the magnetopause. The general appearance of the magnetopause structure is further controlled by the interplanetary field since southward fields tend to produce large angle changes across the magnetopause while northward fields produce smaller angle changes. Since the angle change across the magnetopause is a direct measure of the magnetopause current system, it is clear that the interplanetary field is controlling the pattern of magnetopause current flow.

The detailed structure of the magnetopause often differs appreciably from one orbit to the next and even on crossings separated by only a few minutes in time. The change in angle across the magnetopause often takes longer than the change in magnitude, with the angle change extending further out toward the magnetosheath. Changes in particle flux need not correspond exactly to field changes but this does not necessarily imply that pressure balance is not maintained across the magnetopause. Fluctuations near the proton gyrofrequency are quite common and may be important in the diffusive entry of particles which form the boundary layer. Waves at frequencies above the proton gyrofrequency have not been reported as an outstanding characteristic of the magnetopause.

Good evidence exists for tailward propagating waves on the magnetopause with periods as low as a few seconds. These waves cause the boundary to move with velocities that are probably near 10 km/sec but could easily be larger or smaller by a factor of 10 at various times. These velocities are usually larger than those of the observing spacecraft and hence multiple boundary crossings are commonly seen. Thirty seconds is a typical time for the boundary to pass over the spacecraft, so a likely thickness for the magnetopause current sheet is a few hundred kilometers or a few magnetosheath-thermal-proton gyroradii. These thicknesses are near but probably somewhat larger than the larger of the possible thicknesses predicted by kinetic theories.

Magnetopause waves probably change the boundary normal direction by at least several degrees during a crossing interval. In this situation, the normal field component that would be expected in an open magnetosphere cannot be accurately determined with the minimum variance technique. This difficulty may account for the lack of direct supporting evidence for an open magnetosphere - a model that is supported by an extensive body of indirect evidence. An alternative explanation for the lack of an observed normal component may be that this component exists in a spatially isolated region that is infrequently sampled by spacecraft.

The high latitude magnetopause forms the outer boundary of the entry layer, but its magnetic structure is not obviously different from that at lower latitudes. Suggestions that this region is the site of reconnection arise not from direct evidence for reconnection but more from a lack of evidence for low latitude reconnection along with a desire to preserve the concept of open field lines which explain so many observations. The suggestion that high latitude reconnection is localized, time-dependent and associated with eddy diffusion is supported by observed variability in the fields and flows. The magnetopause model indicated by a considerable body of data has open field lines, but the lack of energy dissipation near the magnetopause has cast some doubt on the importance of the reconnection process that is thought to produce them.

FUTURE STUDIES

Further insights into magnetopause processes can be derived from both direct and indirect observations of these processes. Direct observations by the dual ISEE spacecraft should yield considerable information on magnetopause motion, thickness and time variations. Normal component determinations will probably remain difficult, but the limitations on how well they can be measured should become clear. Three-dimensional plasma observations should clearly indicate the presence or absence of flows resulting from reconnection. With more accurate knowledge of thicknesses and a better determination of real spatial variations it should be increasingly possible to classify various structures and determine their dependence on upstream conditions and on the state of the magnetosphere.

Indirect inferences of magnetopause processes can be obtained by continued comparisons of interplanetary field orientations with various magnetosphere measurements such as solar particles, micropulsations and magnetospheric electric fields and current systems.

Theoretical studies must attempt to include such important parameters as magnetosheath magnetic fields and magnetosphere plasmas. The concept of idealized MHD rotational discontinuities must be abandoned in favor of the more complicated structure associated with hot anisotropic plasmas. Continued attempts must be made to bridge the gap between the kinetic and fluid approaches to the magnetopause.

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FIGURE CAPTIONS

Figure 1. IMP-6 magnetic field and plasma data on a pass through the region of the magnetopause and the bow shock. The magnetopause is clearly evident as a discontinuity in all parameters at 2:50.

Figure 2. Higher time resolution magnetic field data for the pass shown in Figure 1. The total energy density (plasma plus field) is shown above the field strength along with plasma β, density and velocity vectors.

Figure 3. Magnetic field and plasma data on a pass through the magnetopause. The interplanetary field happened to be aligned nearly parallel to the local geomagnetic field and the magnetopause can only be identified by the plasma discontinuity and increase in field fluctuations.

Figure 4. Higher resolution magnetic field data for the pass shown in Figure 3. Magnetosheath field strengths are larger than those of the magnetosphere causing magnetosphere β to exceed that in the magnetosheath.

Figure 5. A schematic illustration of: (a) an interplanetary field aligned with the earth sun line which creates a field that is weak and variable in the magnetosheath, and (b) an interplanetary field perpendicular to the earth sun line which is associated with field lines that are draped over the magnetosphere and form the plasma depletion layer.

Figure 6. Magnetic field data illustrating multiple magnetopause crossings that occurred when the interplanetary field was weak and oriented within 35^{o} of the earth sun line. The magnetopause is

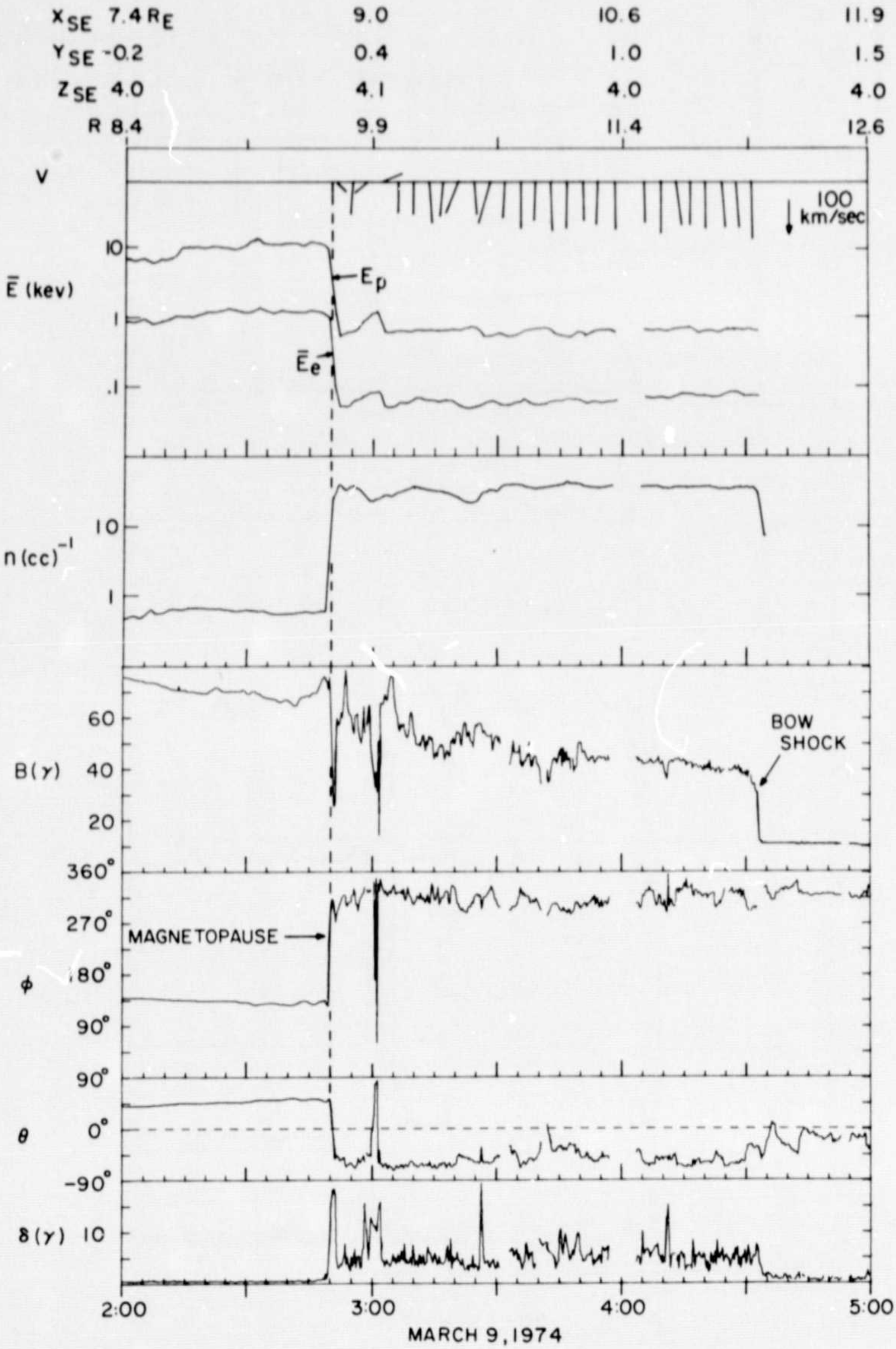
identified as the boundary of the high field regions within which the field attains the orientation seen later during an extended spacecraft traversal of the magnetosphere.

Figure 7. Magnetic field magnitude and three components sampled at 80 millisecond intervals across a magnetopause current sheet. A 0.5 γ average component along the calculated magnetopause normal, B_n, is small compared to the variations in this component during the crossings.

Figure 8. A schematic illustration of how magnetopause normals are differently oriented when tailward propagating waves cause the spacecraft to enter or exit the magnetosphere.

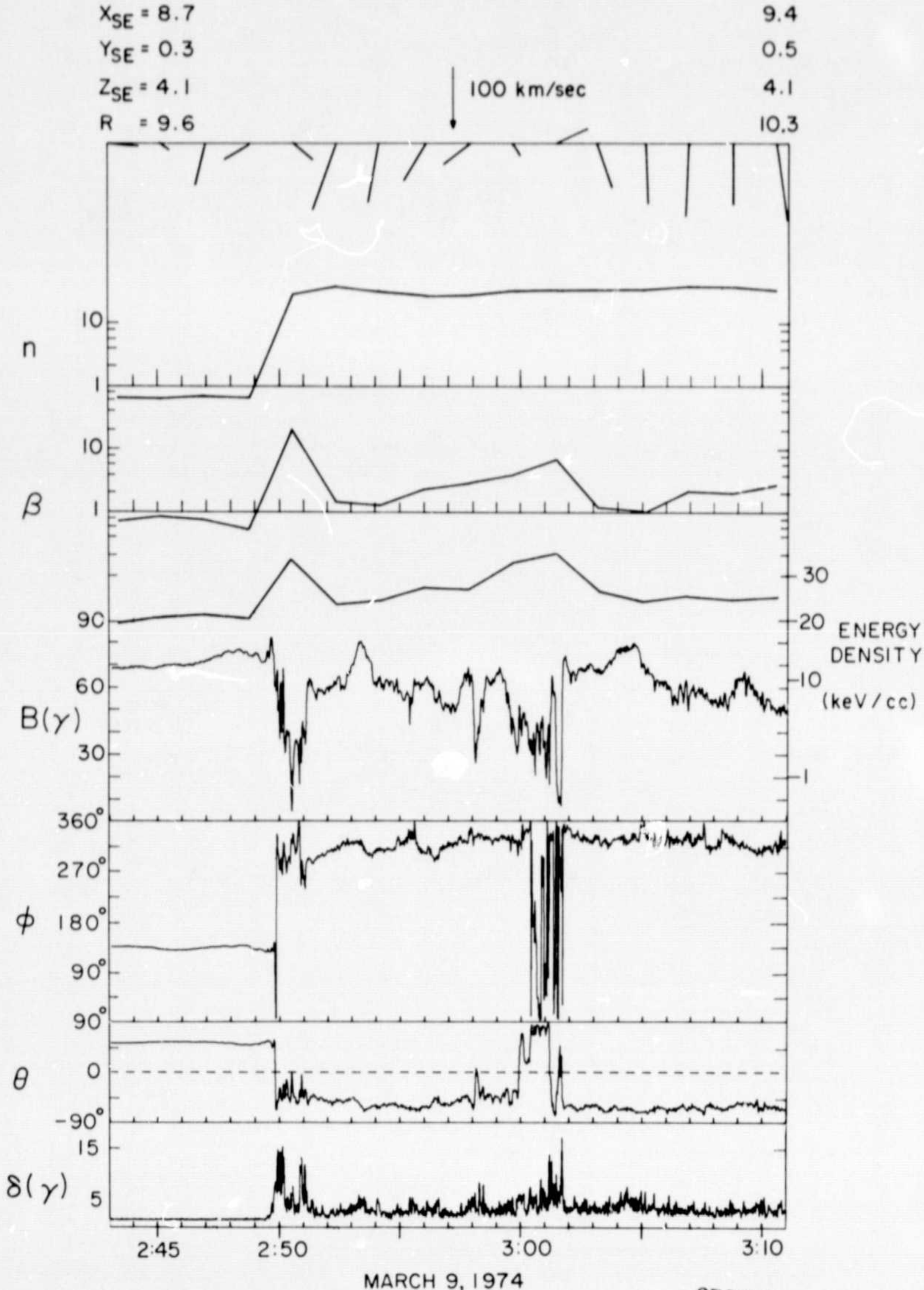
Figure 9. Illustrating how various experimentally determined magnetopause thicknesses are all at or above the gyroradius predictions of kinetic theory.

Figure 10. Multiple crossings of the boundary between the high latitude entry layer (shaded regions) and the adjacent magnetosheath like regior. The flow vectors assume various orientations at different times and are suggestive of turbulent eddies near this boundary.



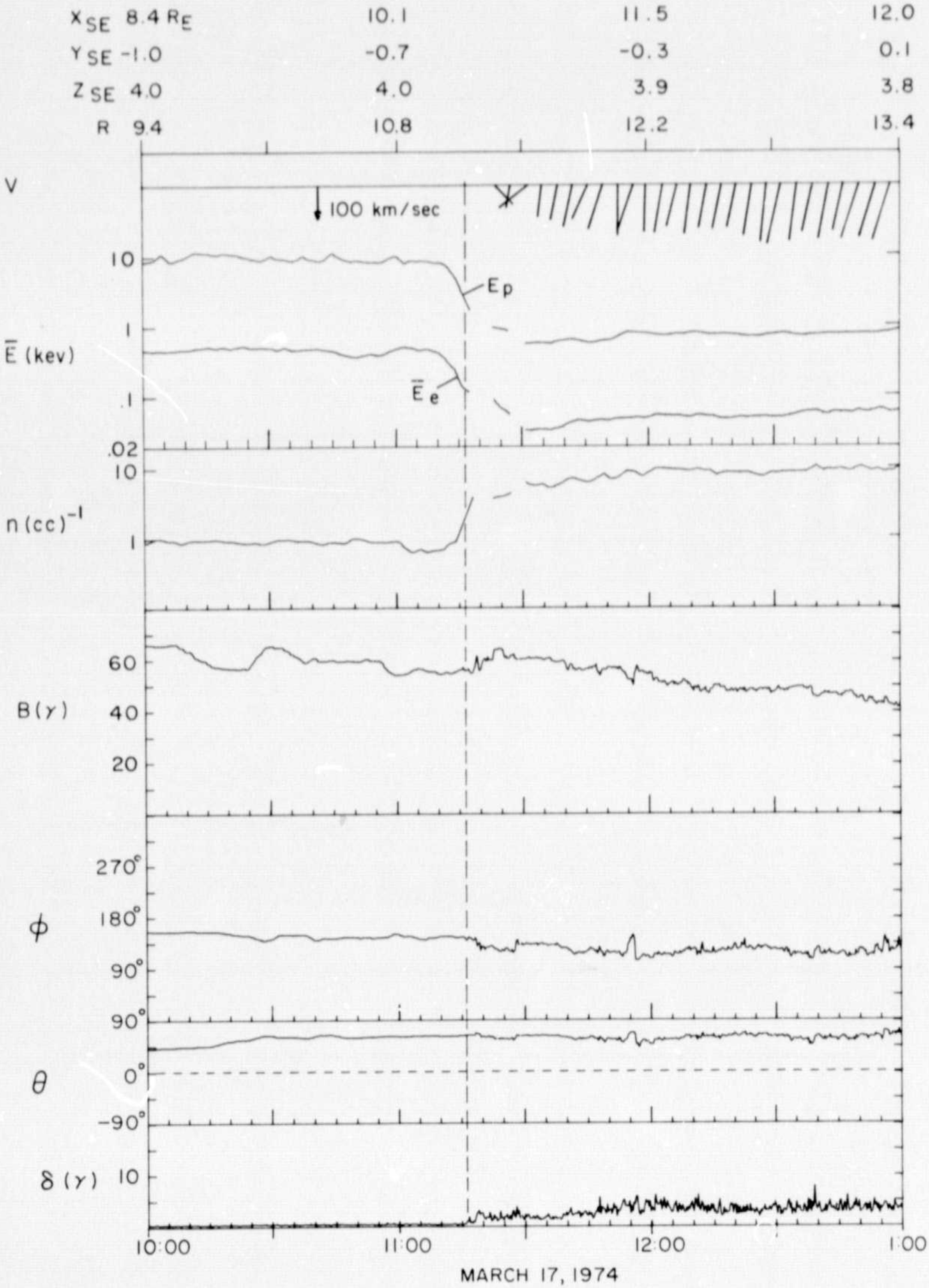
X_{SE} 7.4 R_E 9.0 10.6 11.9
Y_{SE} -0.2 0.4 1.0 1.5
Z_{SE} 4.0 4.1 4.0 4.0
R 8.4 9.9 11.4 12.6
V
100 km/sec
$\bar{E}$ (kev)
10
1
.1
E_p
$\bar{E}_e$
n(cc)$^{-1}$
10
1
B(γ)
60
40
20
BOW SHOCK
360°
270°
MAGNETOPAUSE
φ
180°
90°
90°
θ
0°
-90°
δ(γ)
10
2:00
3:00
4:00
5:00
MARCH 9, 1974

Figure 1



X_{SE} = 8.7
Y_{SE} = 0.3
Z_{SE} = 4.1
R = 9.6
100 km/sec
9.4
0.5
4.1
10.3
10
n
1
10
β
1
90
ENERGY DENSITY (keV/cc)
30
20
10
1
60
B(γ)
30
360°
270°
φ
180°
90°
90°
θ
0
-90°
15
δ(γ)
5
2:45
2:50
3:00
3:10
MARCH 9, 1974

Figure 2



X_{SE} 8.4 R_E
Y_{SE} -1.0
Z_{SE} 4.0
R 9.4
10.1
-0.7
4.0
10.8
11.5
-0.3
3.9
12.2
12.0
0.1
3.8
13.4
V
100 km/sec
10
1
.1
.02
$\bar{E}$ (kev)
E_p
$\bar{E}_e$
10
1
n(cc)$^{-1}$
60
40
20
B(γ)
270°
180°
90°
φ
90°
0°
-90°
θ
δ(γ)
10
10:00
11:00
12:00
1:00
MARCH 17, 1974

Figure 3

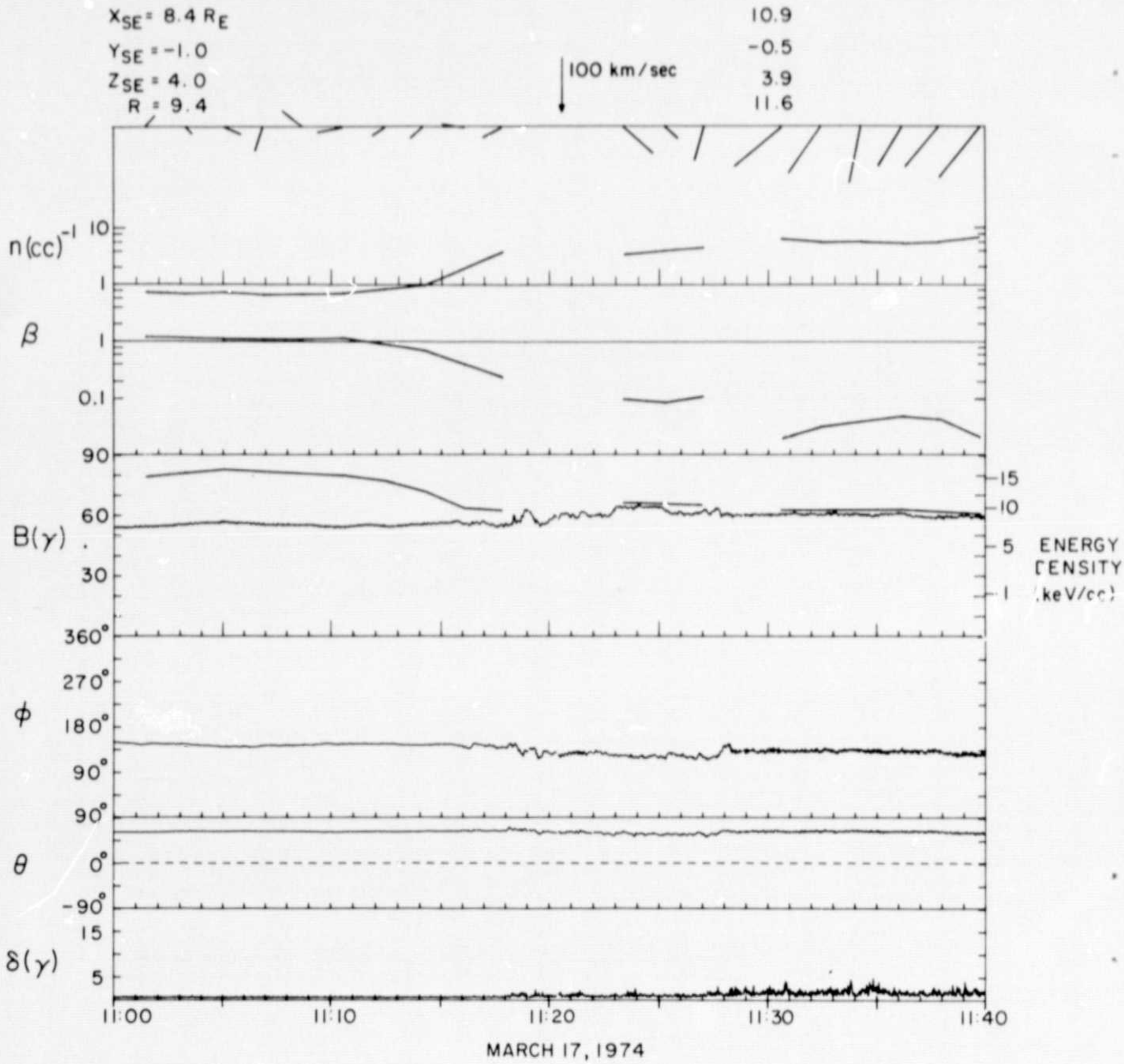

X_SE = 8.4 R_E
Y_SE = -1.0
Z_SE = 4.0
R = 9.4
10.9
-0.5
3.9
11.6
100 km/sec
n(cc)^-1
β
B(γ)
φ
θ
δ(γ)
ENERGY DENSITY (keV/cc)
11:00
11:10
11:20
11:30
11:40
MARCH 17, 1974

Figure 4

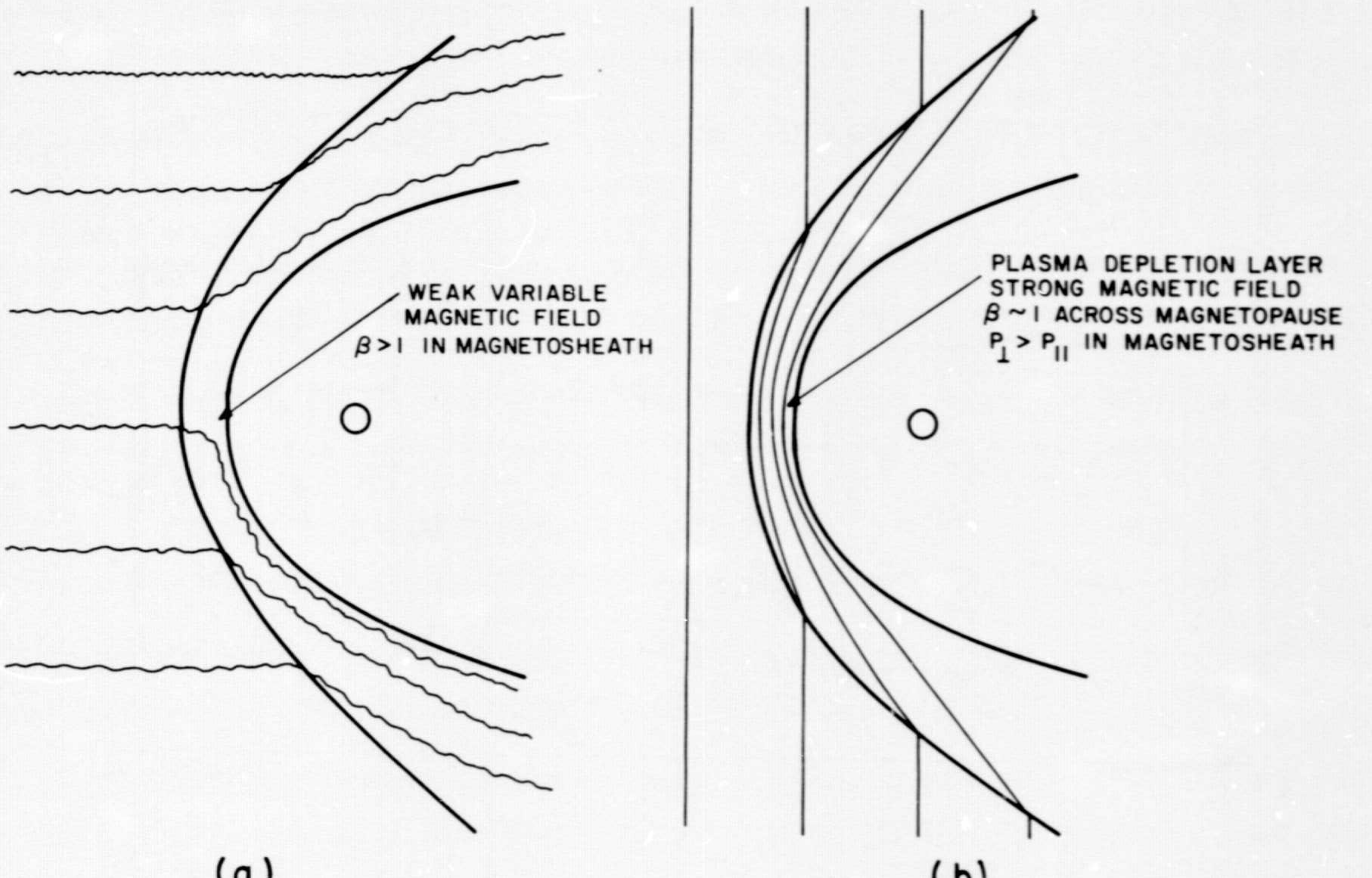
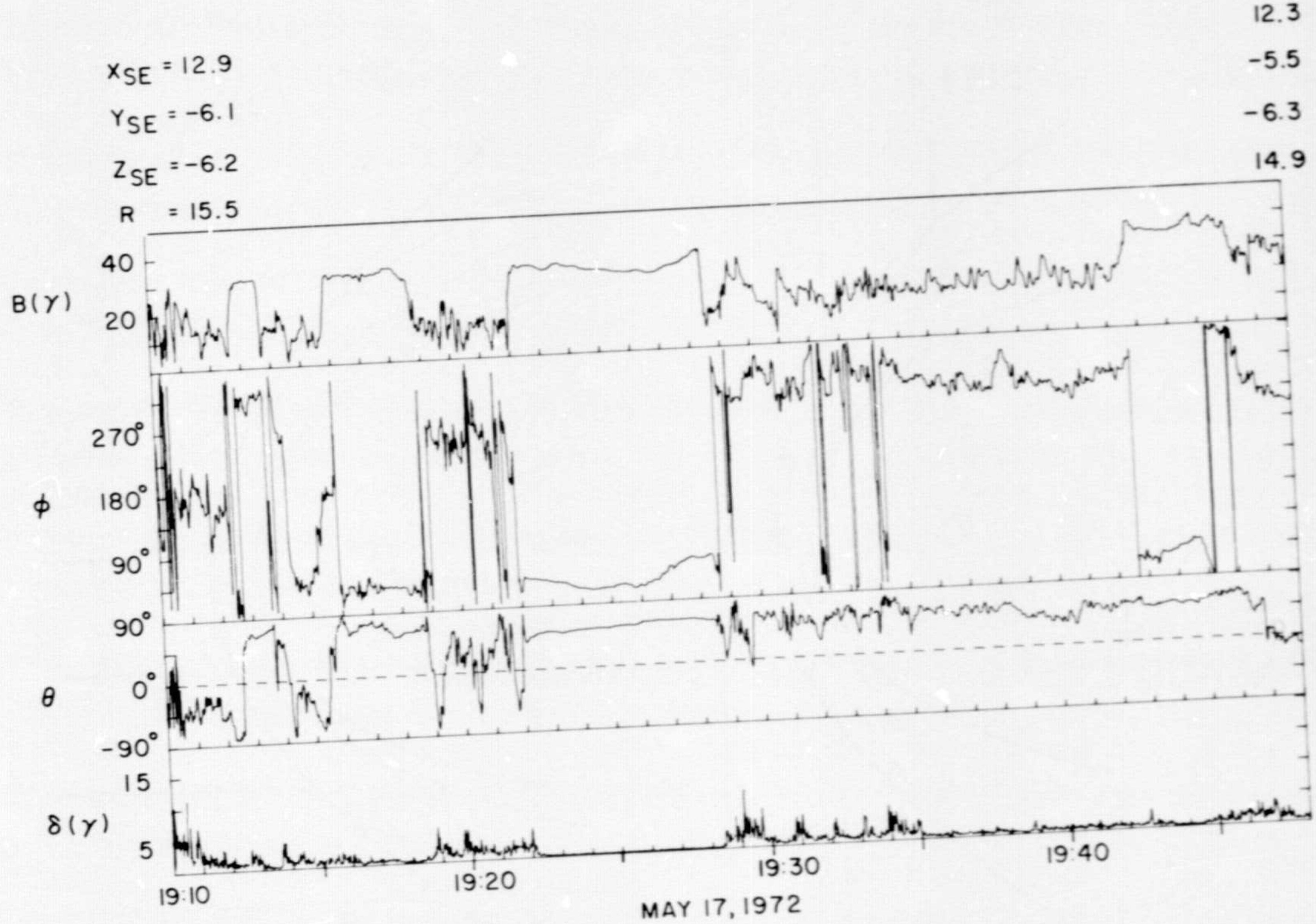
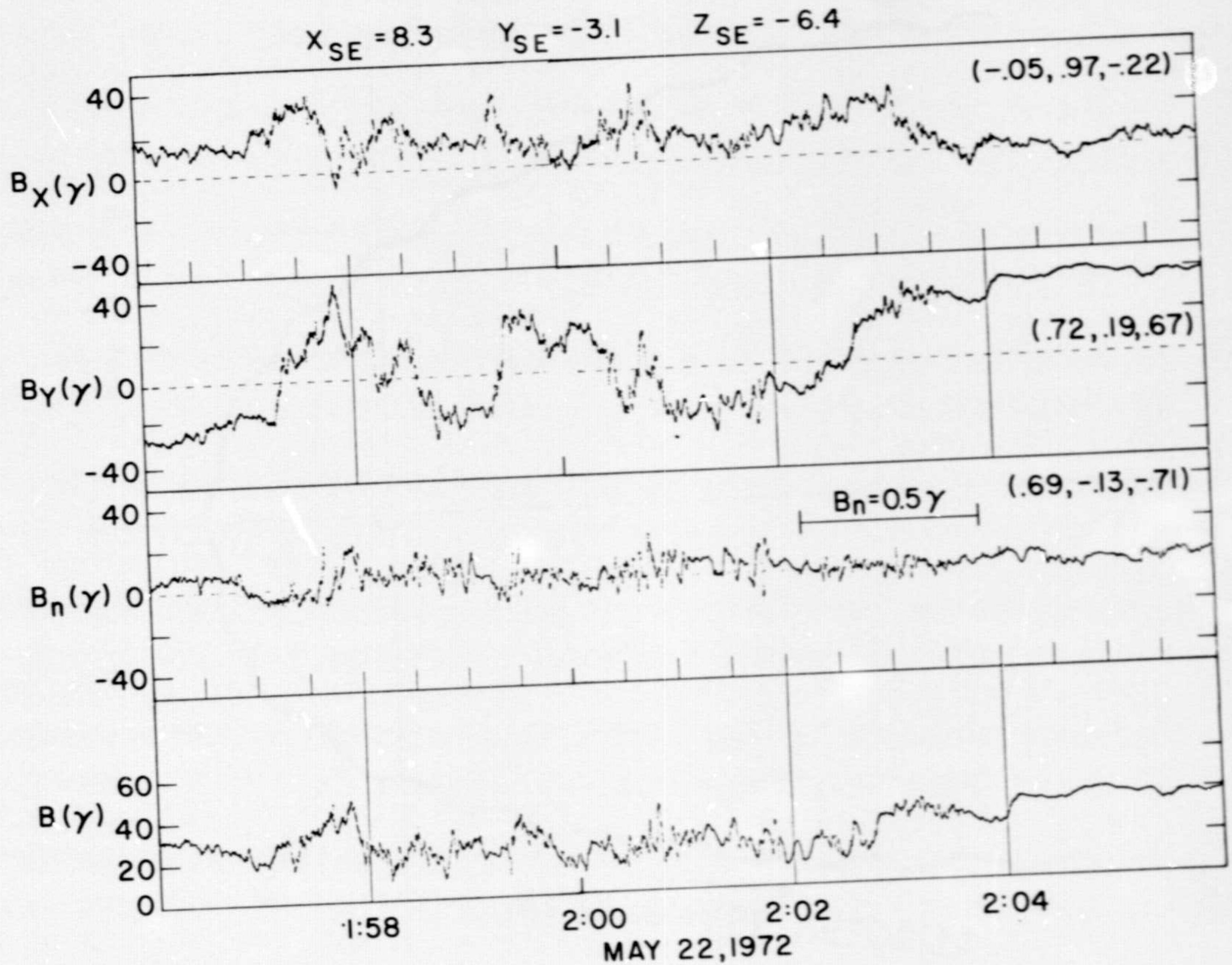

WEAK VARIABLE
MAGNETIC FIELD
$\beta > 1$ IN MAGNETOSHEATH
PLASMA DEPLETION LAYER
STRONG MAGNETIC FIELD
$\beta \sim 1$ ACROSS MAGNETOPAUSE
$P_{\perp} > P_{\parallel}$ IN MAGNETOSHEATH
(a)
(b)

Figure 5



X_{SE} = 12.9
Y_{SE} = -6.1
Z_{SE} = -6.2
R = 15.5
12.3
-5.5
-6.3
14.9
B(γ)
40
20
φ
270°
180°
90°
θ
90°
0°
-90°
δ(γ)
15
5
19:10
19:20
19:30
19:40
MAY 17, 1972

Figure 6



X_SE = 8.3 Y_SE = -3.1 Z_SE = -6.4
(-.05, .97, -.22)
(.72, .19, .67)
(.69, -.13, -.71)
B_n = 0.5γ
B_X(γ)
B_Y(γ)
B_n(γ)
B(γ)
40
0
-40
60
20
1:58
2:00
2:02
2:04
MAY 22, 1972

Figure 7

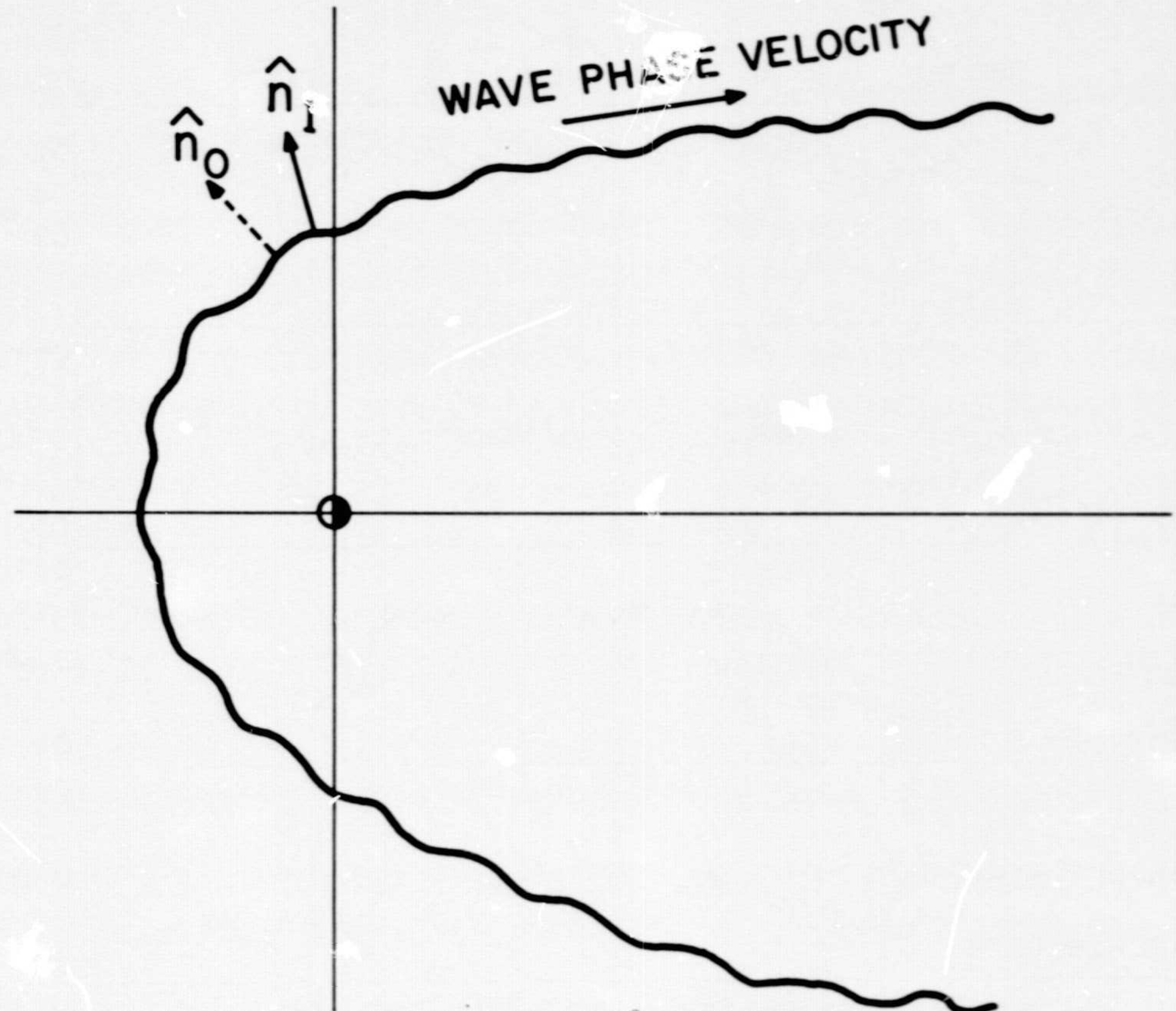
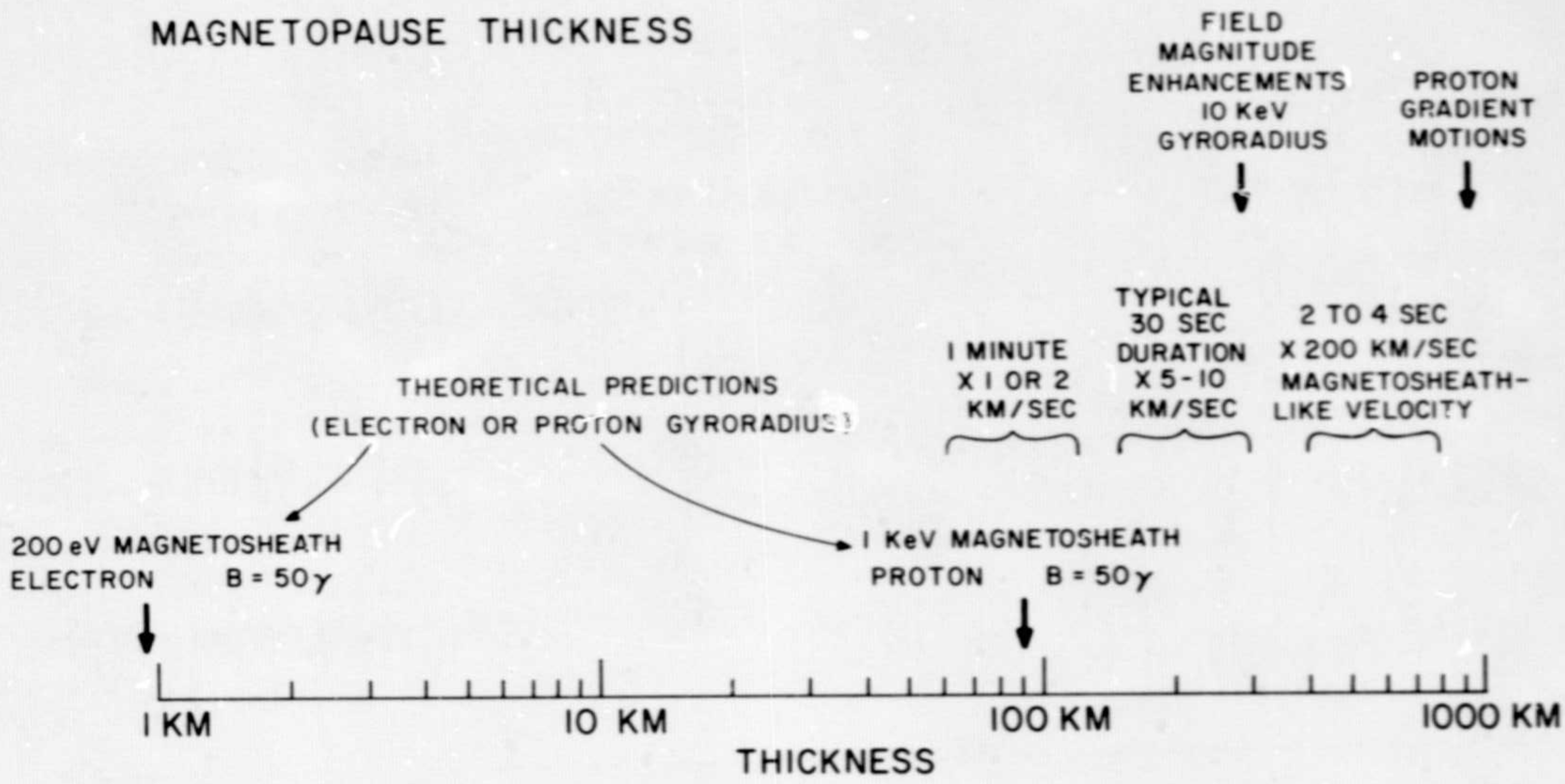


Figure 8



MAGNETOPAUSE THICKNESS
FIELD MAGNITUDE ENHANCEMENTS 10 KeV GYRORADIUS
PROTON GRADIENT MOTIONS
1 MINUTE X 1 OR 2 KM/SEC
TYPICAL 30 SEC DURATION X 5-10 KM/SEC
2 TO 4 SEC X 200 KM/SEC MAGNETOSHEATH-LIKE VELOCITY
THEORETICAL PREDICTIONS
(ELECTRON OR PROTON GYRORADIUS)
200 eV MAGNETOSHEATH ELECTRON B = 50γ
1 KeV MAGNETOSHEATH PROTON B = 50γ
1 KM
10 KM
100 KM
1000 KM
THICKNESS

Figure 9

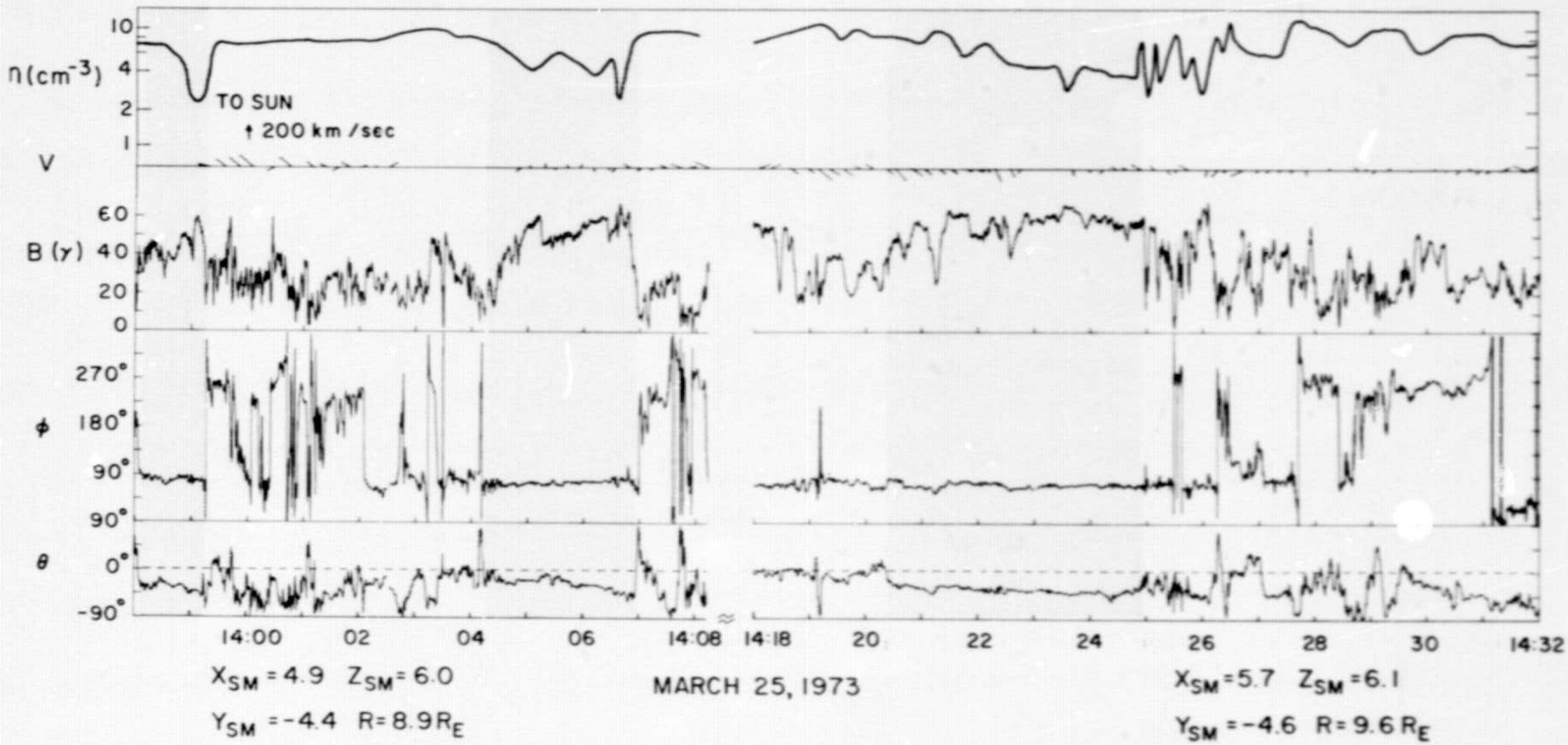

n(cm^-3)
10
4
2
1
TO SUN
↑ 200 km /sec
V
60
B (γ) 40
20
0
270°
φ 180°
90°
90°
θ 0°
-90°
14:00
02
04
06
14:08
14:18
20
22
24
26
28
30
14:32
X_SM = 4.9 Z_SM = 6.0
Y_SM = -4.4 R = 8.9 R_E
MARCH 25, 1973
X_SM = 5.7 Z_SM = 6.1
Y_SM = -4.6 R = 9.6 R_E

Figure 10