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PRESSURE-DRIVEN MAGNETOPAUSE MOTIONS AND ATTENDANT RESPONSE ON THE GROUND

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Abstract—The terrestrial magnetopause suffered considerable sudden changes in its location on 9–10 September 1978. These magnetopause motions were accompanied by disturbances of the geomagnetic field on the ground. We present a study of the magnetopause motions and the ground magnetic signatures using, for the latter, 10 s averaged data from 14 high latitude ground magnetometer stations. Observations in the solar wind (from *IMP* 8) are employed and the motions of the magnetopause are monitored directly by the spacecraft *ISEE* 1 and 2. With these coordinated observations we are able to show that it is the sudden changes in the solar wind dynamic pressure that are responsible for the disturbances seen on the ground. At some ground stations we see evidence of a "ringing" of the magnetospheric cavity, while at others only the initial impulse is evident. We note that at some stations field perturbations closely match the hypothesized ground signatures of flux transfer events. In accordance with more recent work in the area (e.g. Potemra *et al.*, 1989, *J. geophys. Res.*, in press), we argue that causes other than impulsive reconnection may produce the twin ionospheric flow vortex originally proposed as a flux transfer even signature.

INTRODUCTION

This paper concerns the mapping of field and plasma disturbances from the solar wind to the outer edge of the terrestrial magnetosphere and then to the high latitude ionosphere and to disturbances recorded on the ground below. We use data from a serendipitous arrangement of spacecraft and ground stations to trace the movement of the magnetopause in response to changes in solar wind conditions and then to examine the origin of a series of rapid (minute time scale) perturbations recorded in high latitude magnetograms in the same general (afternoon) local time sector as the spacecraft.

The relationship between solar wind conditions (velocity, pressure and magnetic field strength and direction) and magnetospheric and ionospheric motions is of fundamental importance in solar–terrestrial physics. The magnetopause is a free boundary between the solar and terrestrial plasma regimes. In this paper we examine how it responds to changes in external pressure (dynamic, field, or gas). The overall response of the magnetospheric cavity to a pressure rise from outside is to shrink, but the detailed behaviour is complex. The magnetosphere and ionosphere are a coupled system which may oscillate and may also exhibit a large transient response when departures from equilibrium occur.

In steady state, the mapping of plasma motions is straightforward: the flow at each point on the flux tube has to be just such that the (frozen-in) magnetic field does not change with time. The flow field and the electric field are related by the frozen-in field condition

$$\mathbf{E} = -\mathbf{V}\times\mathbf{B}.$$

Thus magnetic field-lines are electrostatic potentials and the mapping of flow from the magnetosphere to the ionosphere depends only on the geometry of the (steady) background field.

In steady state, ion–neutral collisions in the ionosphere absorb momentum from the flow system and an overall distribution of magnetic stress must be set

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up to maintain the ionospheric flow. Parallel current flow is a natural concomitant (see e.g. Southwood and Hughes, 1983). In unsteady situations, matters are more complicated. In the extreme case where magnetospheric flows change so rapidly that momentum cannot be supplied to the ionosphere fast enough for the ionospheric flow to keep up with the magnetospheric motion, the ionospheric part of flux tubes does not move and the ionospheric electric field is negligibly small. The effect is sometimes called "line tying" (see e.g. Coroniti and Kennell, 1973) and the ionosphere looks as if it is perfectly conducting.

On intermediate time scales, the ratio of ionospheric electric field–magnetospheric electric field is generally lower than the steady state ratio. On such time scales, the magnetic stress is not evenly distributed along the magnetic field-lines and magnetohydrodynamic waves propagate back and forth along closed field-lines (Southwood and Hughes, 1983), whilst standing Alfvén structures form where tubes are open (see e.g. Wright and Southwood, 1987). As in steady state, field-aligned currents are expected to flow. The transverse or Alfvén magnetohydrodynamic wave mode is the only mode that carries field-aligned current and thus will normally be involved. The mode has the special property of being strictly field-guided (in a uniform plasma). Alfvén mode motion localized to given flux tubes in the magnetosphere at a given time will remain so localized at later times. There will be a similar localization in the ionosphere.

Any sudden surge or rapid change in magnetospheric flow conditions will lead to magnetic stress imbalance between magnetosphere and ionosphere regardless of the precise source of the flow change. One case which has excited a lot of recent interest has concerned the imprint that reconnection at the Earth's magnetopause might leave on the ionosphere. In particular, the ionospheric signature of flux transfer events (FTEs; Russell and Elphic, 1978), which have been commonly attributed to localized reconnection taking place in a short-duration (of order 2 min or less), bursty manner, has recently received much attention.

Early studies of the magnetic field in FTEs (Cowley, 1982; Paschmann *et al.*, 1982; Saunders *et al.*, 1984) established the presence of a nett field-aligned current of a few 10^5 A flowing into or being drawn out of the ionosphere. Later theorizing (Southwood, 1985, 1987) and case studies (Rijnbeek *et al.*, 1987) suggested that bipolar currents flow along the flanks of a central core of reconnected flux. Mapping the pattern down to the ionosphere gave a prediction of the electric field, current and localized flow in the ionosphere. Using these ideas, McHenry and Clauer (1987) modelled the expected response in magnetometers located at high latitude on the ground. Amongst their important results they predict that a ground magnetic observatory should detect a bipolar magnetic field perturbation in the North–South direction for an FTE perturbation moving poleward over the station. The sense of the signature changes depending on model and observer's position. The scale size of the perturbation is 1–2 (depending on model) times the characteristic dimension of the reconnected flux tube's foot in the ionosphere. Typically, this is expected to be 100–200 km, but could be very different since it depends on, amongst others, the field topology of flux transfer events (Southwood *et al.*, 1988; Scholer, 1988) and the magnetosheath field strength (Freeman and Southwood, 1988).

A number of transient signatures recorded at low altitudes or on the ground have been imputed to localized reconnection at the Earth's magnetopause. An early report by Lanzerotti *et al.* (1986) identified a signature at one ground station whose characteristics matched fairly well those predicted by one of the current systems noted above. Subsequently the interpretation was somewhat weakened (Lanzerotti *et al.*, 1987). Todd *et al.* (1986) reported short-duration flow bursts from the Eiscat radar system and showed these to be consistent with the Southwood (1987) model of impulsive reconnection. In a further study (Todd *et al.*, 1988) pulsations following a poleward-moving flow burst were also seen. Certain types of pulsations have been found to be positively correlated with a southerly IMF orientation (Gillis *et al.*, 1987) and hence, indirectly, with FTEs since these strongly correlate with southward magnetosheath and interplanetary field components (Rijnbeek *et al.*, 1984; Berchem and Russell, 1984; Southwood *et al.*, 1986).

There are, however, other causes besides reconnection for rapid changes in the magnetospheric flow conditions. For example, sudden changes in the solar wind dynamic pressure will move the magnetopause and thus also the plasma inside the magnetosphere. It is likely that any sudden change would also have oscillations directly associated with it. Furthermore, there may be sources of oscillations in the magnetosphere other than transient changes in ionospheric–magnetospheric stress balance. For example, surface waves can be caused by the Kelvin–Helmholtz instability on the boundary (Southwood, 1968). Therefore it is important to distinguish between those signatures due to impulsive reconnection and those due to other causes.

Caution in identification of ground signatures of FTEs has recently been urged (Friis-Christensen *et al.*, 1988; Potemra *et al.*, 1989). Potemra *et al.* (1989)

study a pulsation event recorded by the Eiscat cross magnetometer array. The two types of response identified, a 5 min period "ringing" and a 10 min driven oscillation, are attributed to variations in solar wind dynamic conditions, although the possibility of an IMF-controlled origin could not be excluded completely. Friis-Christensen *et al.* (1988) provide strong evidence for the presense of a signature like that predicted in the model presented by Southwood (1987) but at the same time provide compelling evidence that the source is not an FTE. Using recordings from a latitudinal chain of magnetometers in Greenland, they infer a large-scale (about 10^3 km across) travelling twin vortex. The speed of motion of the pattern across the array (of order 10 km s^{-1}) is, however, inconsistent with what one would expect for an FTE, where the pattern would move at the same speed as the convection speed of the plasma in the centre of the event and would be unlikely to exceed 1 km s^{-1} much (of order the ionospheric sound speed).

The study reported here grew out of a search for high latitude ground signatures of FTE occurrence. Indeed, some of the recordings we present match the predictions for ground signatures of FTEs (McHenry and Clauer, 1987 and references therein). Nonetheless, the occurrence of FTEs at high altitude is not a satisfactory explanation. In the paper we use a fortuitous conjunction of spacecraft and ground magnetometer data. One spacecraft is in the solar wind and two spacecraft are near the magnetopause, which they cross and re-cross repeatedly. We are able both to measure changes in the solar wind conditions and follow the corresponding magnetopause motions directly. Careful timing of signals establishes a casual relationship between the two. Simultaneously, the high resolution (10 s) ground magnetometer data from a wide baseline range of stations register oscillations of amplitude ~ 100 nT and period ~ 6 min.

In the next section we present a data overview. We show *ISEE* 1 and 2 spacecraft data for several magnetopause crossings which occurred in quick succession, data related to conditions in the solar wind, and ground magnetometer data at 10 s resolution from 14 high latitude stations. A thorough analysis of the data is then presented in the subsequent section.

A critical parameter to establish is the likely delay time between sites in space and on the ground. We calculate propagation times for a disturbance to reach the subsolar magnetopause, and then relate perturbations recorded at the various sites. By direct observation of the magnetopause boundary motions we deduce that the signals recorded on the ground were due to sudden changes of solar wind ram pressure. The response seems to be a function of latitude. On some magnetic shells resonant Alfvén wave oscillations are excited while elsewhere oscillations do not appear or are strongly damped. The signal pattern in the latter case is shown to be similar to signatures predicted by theory for FTEs. However, we conclude that the signals are not associated with reconnection at the magnetopause, and that the agreement with modelled ground FTE signatures is purely coincidental.

DATA OVERVIEW

Solar wind and magnetopause observations

In this paper we study a 3 h period from 23:30 to 02:30 U.T. on days 252–253 (9–10 September 1978). During the interval the *IMP* 8 spacecraft was in the solar wind on the dawn flank of the magnetosphere. Its position in geocentric solar magnetospheric (GSM) coordinates was (9.9, −32.2, 1.2) at 22:00 U.T. and (12.3, −31.9, 2.9) at 02:05 U.T., where distances are given in Earth radii, R_E. Five minute averaged plasma and field data from the *IMP* 8 spacecraft are shown in Fig. 1 for a 5 h interval 22:00–03:00 U.T. The panels show from top to bottom: density, n (per cubic centimetres); bulk speed, V (kilometres per second); GSM X-, Y-, Z-components of the interplanetary magnetic field (IMF), and, finally, the total field strength, B (nanoteslas).

Up to $\sim$23:05 U.T. the data show fairly typical solar wind densities, velocities and field strengths. In the data gap between 23:05 and 00:05 U.T., all three components must have changed sign at least once: they all start zero or positive at 00:05 U.T. but were negative before. B_Z is continuously positive from 00:05 U.T. onwards. From 00:05 to 00:45 U.T. the IMF is fairly steady and primarily northward. At 00:55 U.T. the density increases sharply as does B_Z and the field strength. Subsequently there is a further increase in field magnitude. The field remains northward.

At the same time, the *ISEE* 1 and 2 spacecraft are inbound, just South of the magnetic equator and in the mid-afternoon local time sector (15:08–15:42 L.T.). Magnetic field data from the two spacecraft are shown in Figs 2a–c for the period of interest. The field data of Figs 2a–c are 12 s averages sampled every 4 s. They are plotted in GSM coordinates, the dark trace corresponding to measurements on *ISEE* 2. *ISEE* 1 plasma data (at 100 s resolution) have been used to confirm the identification of the region which this spacecraft is in.

The radial distance, local time and latitude of *ISEE* 2 are shown at half-hourly intervals underneath the time axis in the figures. *ISEE* 2 is the leading spacecraft

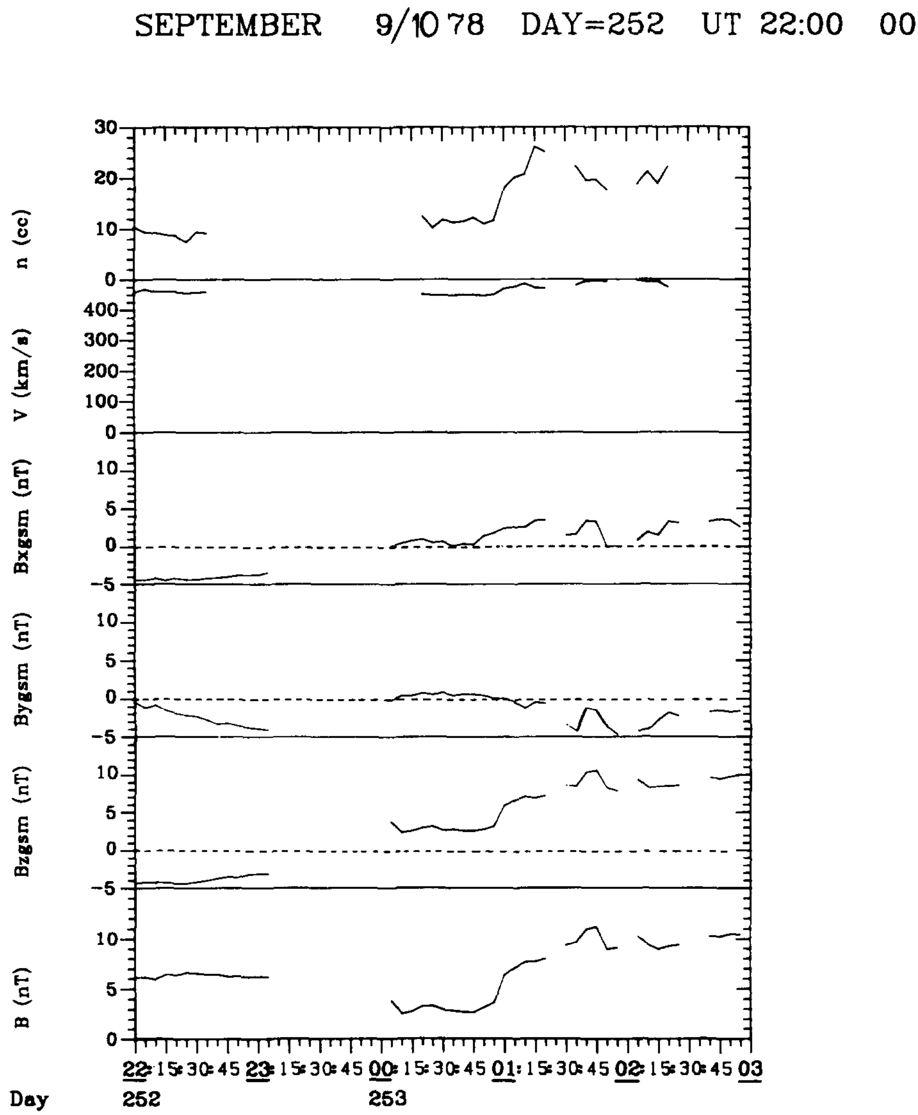

FIG. 1. FIVE MINUTE AVERAGED SOLAR WIND PLASMA AND MAGNETIC FIELD DATA FROM *IMP* 8 FOR THE INTERVAL 22:00–03:00 U.T., 9–10 SEPTEMBER 1978.
From top to bottom the panels are: density (per cubic centimetres), bulk speed (kilometres per second), IMF components (nanoteslas) in GSM coordinates, and total field magnitude (nanoteslas).

and is displaced earthward and westward of *ISEE* 1. At 01:00 U.T. the GSM components of the spacecraft separation vector from *ISEE* 2 to *ISEE* 1, $\mathbf{r}_{21}$, were (1599, 916, 280) km. The total distance between the spacecraft increased monotonically from 1600 km (at 23:30 U.T.) to 2240 km (at 02:30 U.T.). Figure 3 illustrates the spacecraft positions projected on the GSM X–Y plane. A typical magnetopause and bow shock location are shown. The angle of the *ISEE* 2 trajectory with respect to the GSM X–Y plane decreased steadily from $-3°$ to $-9°$. The separation vector $\mathbf{r}_{21}$ also lay close to this plane.

Figure 2 shows that the spacecraft start the interval in the magnetosheath, where the field points South and West (negative B_Y). *ISEE* 2 makes what are possibly partial entries into the magnetosphere at times indicated by the guidelines at a1, a2, a3 in Fig. 2a. From the bipolar B_X variation, a2 is probably an

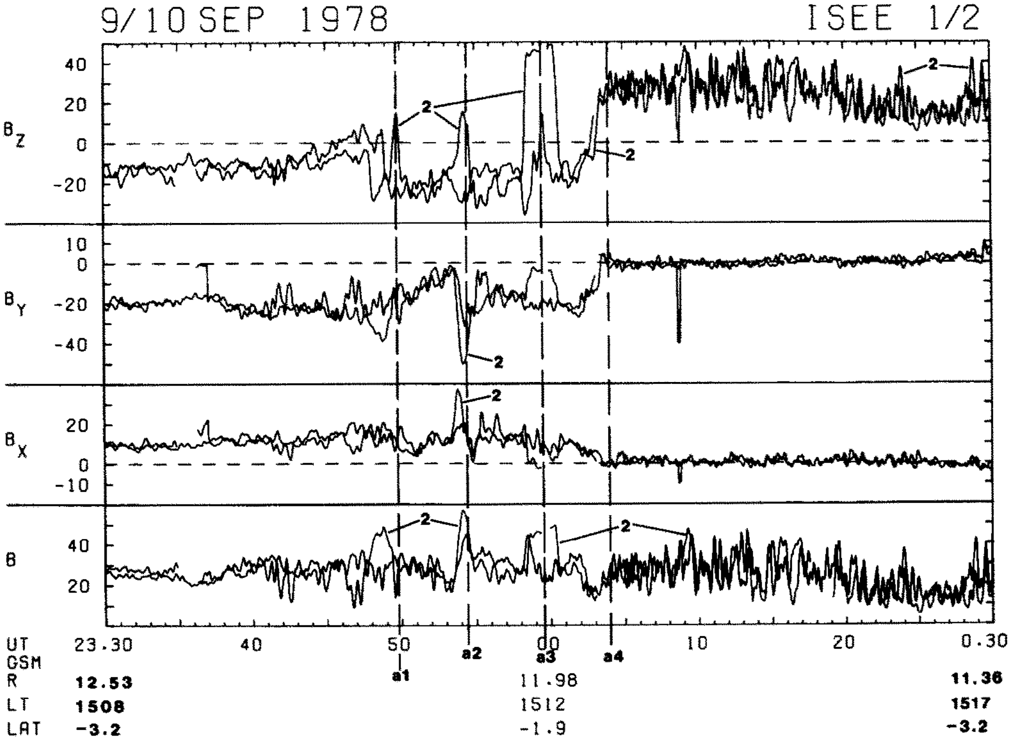

FIG. 2a.

FIG. 2. MAGNETIC FIELD DATA IN GSM COORDINATES FOR THE INBOUND PASS OF THE *ISEE* 1 AND 2 SPACECRAFT.

ISEE 2 measurements are the heavier trace. Position data for *ISEE* 2 are given at the bottom of each plot at 30 min intervals. Vertical guidelines a1–a10 are explained in the text. (a) 23:30–00:30 U.T., 9–10 September 1978; (b) 00:30–01:30 U.T., 10 September 1978; (c) 01:30–02:30 U.T., 10 September 1978.

observation of a flux transfer event (FTE). At this time the magnetosheath B_Z-component is negative; surveys (Rijnbeek *et al.*, 1984; Southwood *et al.*, 1986) have shown that FTE occurrence is highly correlated with southward sheath field components.

The guideline a4 marks where the field turns northward. However, this is not an entry into the magnetosphere. Rather, we interpret the direction change as the sheath response to the change in IMF orientation detected in the *IMP* 8 data. Precise timing comparison with *IMP* 8 is precluded by a data gap (see Fig. 1). *ISEE* 1 plasma data (not shown) retain the characteristics of the magnetosheath across a4, and reveal that the sheath density increased suddenly at a4 from values $n \sim 30$ to 50 cm^{-3}, a value which persists until *ISEE* 1 encounters the magnetosphere at ~00:42 U.T. The magnetosheath field fluctuations have a different character after a4 to the disturbances seen before, being predominantly in the Z-component and containing higher frequency components. The spacecraft remain in the new field regime for about 30 min. The mean field remains low until *ISEE* 2 detects magnitudes comparable with those encountered in the magnetosphere proper at about 00:40 U.T. The perturbations seen in the ecliptic plane at a1–a3 are usually precursors of a magnetopause crossing when reconnection is ongoing. Evidently, the northward magnetosheath field orientation after a4 has switched off such variations in a very effective way. Fortuitously for this observation, the boundary has been moved away from the spacecraft by the dynamic pressure increase coincident with the field reorientation.

Figure 2b shows encounters with the magnetosphere. From plasma data (not shown) *ISEE* 1 crossed the magnetopause at 00:47 U.T. (a6), where it encountered the much stronger, less disturbed field of the magnetosphere. The magnetosheath and magnetosphere fields are almost exactly parallel, though of unequal strength. *ISEE* 2 appears to have encountered the strong field region about 5 min earlier

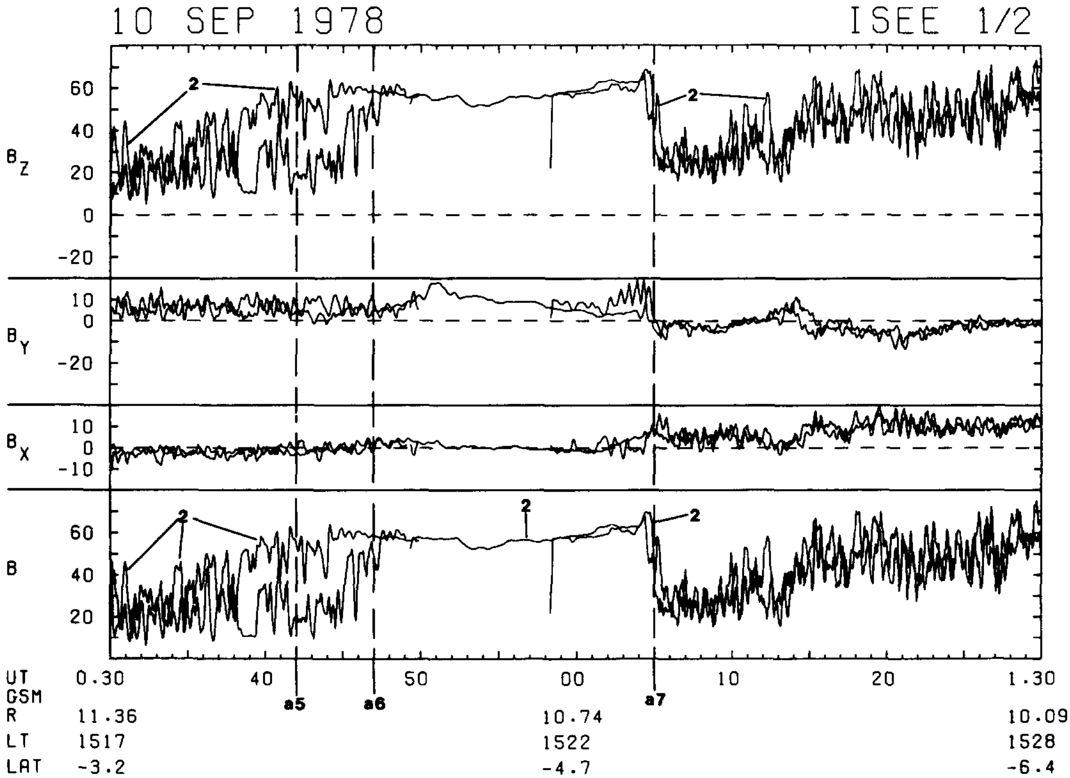

FIG. 2b.

(a5), though the external field orientation makes precise identification of this magnetopause crossing somewhat problematic.

The magnetopause is unlikely to be moving much as the spacecraft enter the magnetospheric field; the *ISEE* 1 and 2 field increases are well separated in time. Using the speeds of the spacecraft and their separation at this time we can infer that the magnetopause was not moving faster than 1 km s^{-1} in the radial direction.

The spacecraft remain in the magnetosphere for ~20 min, exiting abruptly at a7 (01:05 U.T.), the trailing spacecraft first. In contrast with the entry, *ISEE* 1 and 2 exits are very closely spaced in time. Inter-spacecraft timing gives an inward magnetopause speed estimate of ~90 km s^{-1}. (For comparison, one can note that the Alfvén speed for a 50 nT field in a 100 cm^{-3} plasma is ~100 km s^{-1}; the boundary speeds deduced here and later in the paper are comparable with this value.)

A study of Fig. 2c shows that both spacecraft started in the sheath at 01:30 U.T. and were firmly in the magnetosphere by 02:10 U.T. In between these times each spacecraft crossed the magnetopause boundary five times. We determine this from plasma data for *ISEE* 1 and the magnetic field data shown in Fig. 2c; using the plasma data we can determine which region *ISEE* 1 was in, and using the magnetic field data we can determine whether *ISEE* 2 was in the same region as *ISEE* 1. Whenever there is a large magnetic shear between *ISEE* 1 and 2, e.g. at ~01:44 U.T., we infer the spacecraft to be on opposite sides of the magnetopause. From this analysis we infer that both *ISEE* 1 and 2 were in the magnetosphere at a8 (01:46 U.T.) and a9 (01:57 U.T.) and in the sheath at ~01:51 U.T. and at a10 (02:02 U.T.). Overall, we conclude that *ISEE* 2 (nearest the Earth) entered the magnetospheric field during the large transverse (B_X, B_Y) perturbations at 01:43 U.T. and exited into the magnetosheath at 01:48 U.T., re-entering the magnetosphere at 01:54 U.T. In the vicinity of a8, *ISEE* 1 grazes the magnetospheric field, makes a pair of brief entries into this field again either side of a9, and enters the terrestrial regime finally at 02:03 U.T. just after a10.

During these crossings there are some interesting points to note. In the period 01:48–01:54 U.T. when we identify both spacecraft to be in the sheath, the

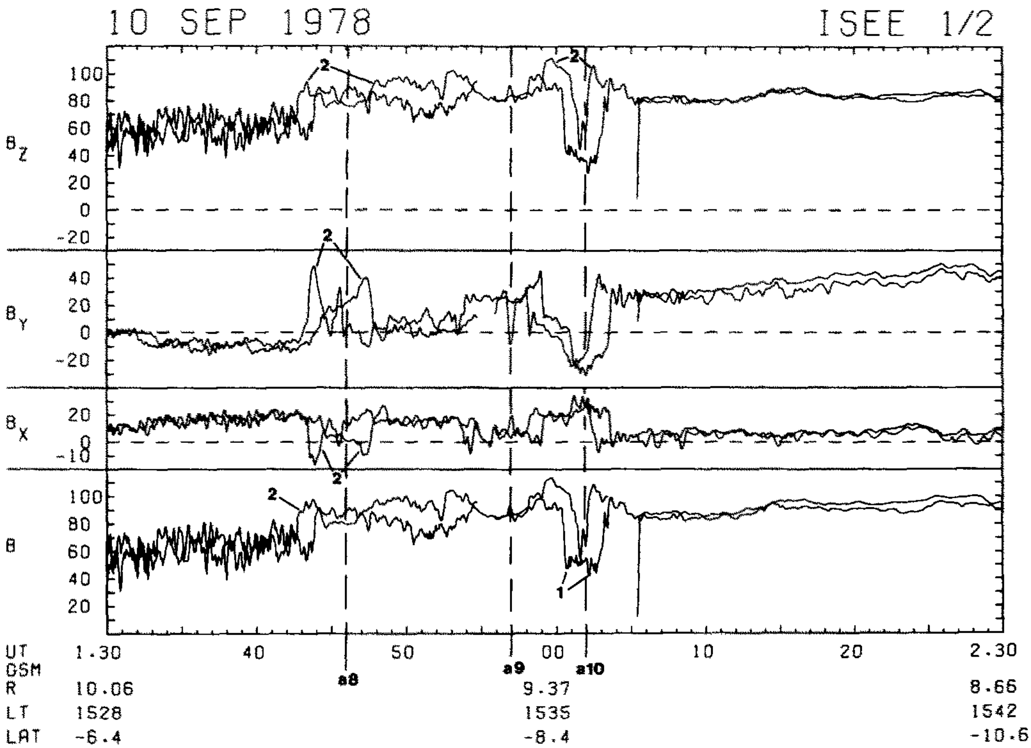

FIG. 2c.

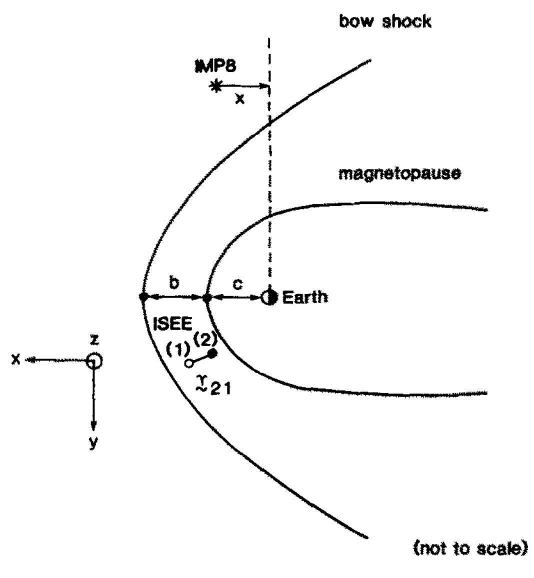

FIG. 3. A SCHEMATIC SHOWING THE RELATIVE POSITIONS OF THE SPACECRAFT IN THE ECLIPTIC PLANE AND TYPICAL BOW SHOCK AND MAGNETOPAUSE.

field strength is larger than recorded in both previous and later sheath encounters. Our interpretation that the larger field is indeed that of the magnetosheath is supported by the fact there is a corresponding proportionate rise (about 30%) in the total field value recorded 7.5 min earlier at *IMP* 8 upstream in the solar wind (see Fig. 1, bottom panel). The sheath field fluctuations evident in the earlier, weaker field have lower amplitude at this time. Also the sustained difference in the field magnitude measured at the two spacecraft is anomalous for a circumstance where both spacecraft are believed to be on the same side of the magnetopause. The gradient detected is larger than that detected later in the magnetosphere. Similar field gradients were detected for briefer periods in the sheath in the preceding 30 min.

The symmetrically nested signatures seen by the two spacecraft which bracket the final encounter with the magnetosheath centered on a10 are notable; using them, we infer an inward followed by an outward radial velocity of 28 km s^{-1} of the magnetopause boundary. There are clear field compressions on exit and on re-entry at a10. In the sheath at ~02:02 U.T.,

TABLE 1. GROUND MAGNETOMETER STATIONS

Station	Code	Geomagnetic latitude (°)	Geomagnetic longitude (°)
Sachs Harbour	SAH	75.2	266.2
Cape Parry	CPY	73.9	270.9
Inuvik	INK	70.6	266.2
Arctic Village	AVI	68.1	255.3
College	COL	64.8	257.1
Talkeetna	TLK	63.0	256.9
Pelly Bay	PEB	78.7	321.1
Eskimo Point	EKP	71.0	322.4
Back	BCK	67.6	324.4
Gillam	GIM	66.3	324.9
Norman Wells	NOW	69.2	278.8
Fort Simpson	FSP	67.2	287.2
Lynn Lake	LYL	66.0	315.8
Fort Smith	FSM	67.3	299.6

the spacecraft see a field which is weaker than at the last encounter and more strongly westward (i.e. B_Y more negative). This is also similar to the IMF behaviour about 7.5 min earlier (see Fig. 2). After a10 the spacecraft are unmistakeably in the magnetosphere, which has a northerly and easterly orientation as appropriate for a terrestrial field at this L.T. sector.

Ground magnetometer recordings

The ground stations used in this study are listed in Table 1. The perturbations of the geomagnetic field at eight ground stations from the Alaska and Churchill chains over the 2.5 h interval from 00:00 to 02:30 U.T. are shown in Fig. 4. Figures 4a–c present the field components in the geomagnetic North–South (X), East–West (Y) and vertical (Z) directions, respectively. Positive values correspond to northward, eastward and downward directions. The data are unfiltered and the box height corresponds to 200 nT. The Universal Time is shown along the bottom of the figure and in each panel is shown the station code, its latitude, and its magnetic local time (M.L.T.) along the time axis. The stations can be seen to be well distributed in latitude and local time on the afternoon side of Earth.

We shall concentrate in this paper on ground signatures detected in the interval from 01:00 to 02:15 U.T. Shortly after 01:00 U.T. all stations shown detect a perturbation of the geomagnetic field. There are also oscillations evident between ~01:40 and ~02:00 U.T., again at all stations (see vertical guidelines). The pulsations commencing near 01:00 and 01:40 U.T. will be considered separately.

The perturbation at station AVI just after 01:00 U.T. is very closely linearly polarized and it is also continuous for two–four cycles. Elsewhere, however, the character of the signal is different and the polarization is more elliptical, e.g. at station SAH. It is interesting to note that the pulsation onsets are at slightly different times at each station, indicating propagation of the disturbance. We analyze this in the next section.

Near 01:40 U.T. pulsations recommence. It is apparent that there occur subsequent impulses to the initial one. For example, at station CPY, which at 01:00 U.T. showed only a half cycle oscillation the oscillation now appears to persist for several cycles but the second cycle is of a larger amplitude than the first. Looking at the signal at AVI, the pulsations appear in two discrete packets with a phase skip of ~180° at 01:52 U.T. This suggests that the geomagnetic field is responding to discrete impulses.

ANALYSIS

Signal timing and magnetopause motion

In order to correlate the data from the *IMP* 8 spacecraft with those from the *ISEE* spacecraft and the ground based magnetometers, we need an estimate of the time delay for signals to propagate between the observing sites. In the magnetosphere propagation is via one or other of the magnetohydrodynamic wave modes. In the magnetosheath and in the solar wind, any disturbance propagation velocity will be superposed on the velocity of the plasma. In much of the volume of the sheath and everywhere in the solar wind, the plasma convection velocity is much larger than the wave speed; in what follows we shall assume that disturbances in these regions are convected with the plasma and ignore propagation effects other than in the magnetosphere. We also shall assume that the initial disturbance fronts in the solar wind are effectively propagating radially from the Sun.

Consider an interplanetary discontinuity convecting earthwards with the plasma and whose front is perpendicular to the vector $\mathbf{V}_{SW}$. From *IMP* 8 data (not shown) the solar wind flow velocity vector, $\mathbf{V}_{SW}$, is closely aligned, to better than 6°, with the GSM X-axis. The contributors to the total delay (D) between detection by *IMP* 8 in the solar wind and reception on the ground or at the *ISEE* spacecraft are the following: the time for the discontinuity to travel from the nose of the bow shock to the nose of the magnetopause (D_1) minus the time it takes for the discontinuity to reach *IMP* 8 from the nose of the bow shock (D_2). To this difference must be added the residual delay, D_3, for the effect of the discontinuity to be detected at the particular recording site (spacecraft or ground-based station). D_3 is either the time for the magnetopause reconfiguration at noon to

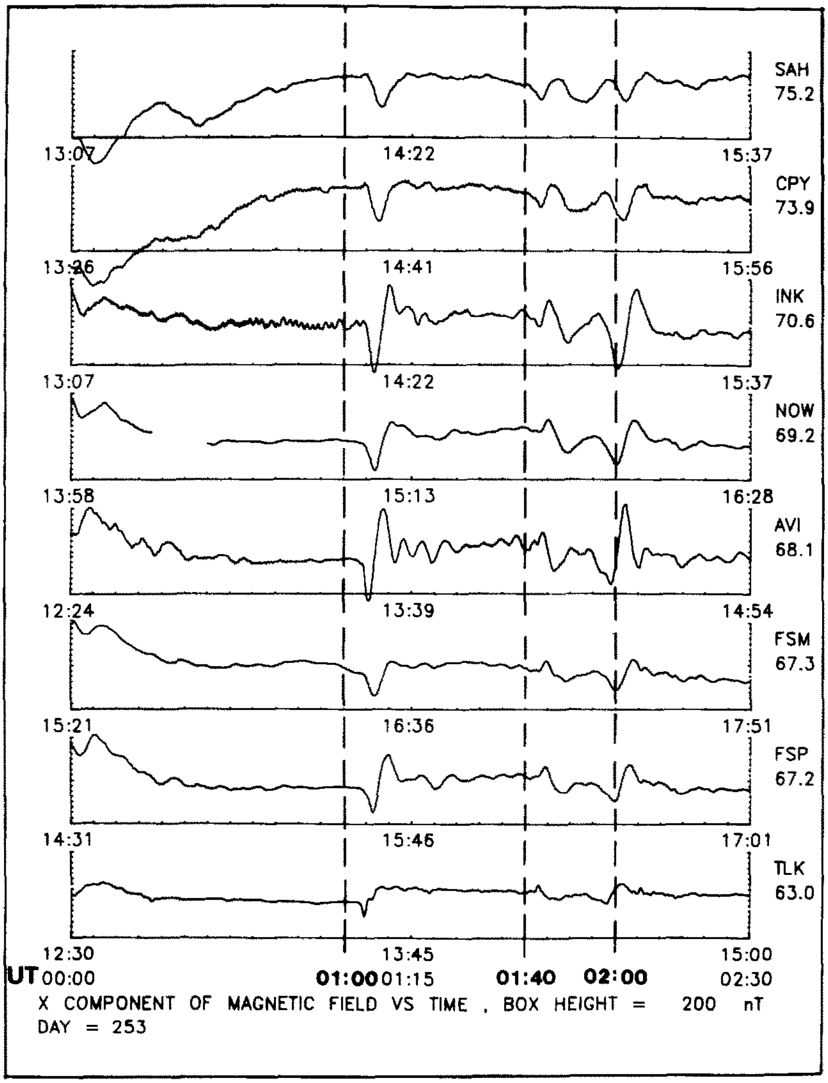

FIG. 4a.

FIG. 4. X-, Y-, Z-COMPONENTS OF THE GEOMAGNETIC FIELD FROM EIGHT NORTHERN HEMISPHERE GROUND STATIONS IN THE INTERVAL 00:00–02:30 U.T., 10 SEPTEMBER 1978.

Station code and geomagnetic latitude are shown to the right of each panel; magnetic local time underneath each panel. Universal Time, field component and vertical scale are given at the bottom of each figure. Vertical guidelines are referred to in the text.

propagate around to the mid-afternoon local times (in the case of the spacecraft) or the time for a disturbance to travel through the magnetosphere to a flux tube and down the flux tube to the ground observatory,

$$D = D_1 - D_2 + D_3.$$

The geometry is as shown in Fig. 3. Let b be the distance between the subsolar bow shock and the subsolar magnetopause and c the stand-off distance of the magnetopause boundary from the centre of the Earth. We then have

$$D_1 - D_2 = b/U - (b + c - x)/V_{SW}$$

where x is the GSM X-coordinate of *IMP* 8 ($\sim 11 R_E$) and U the mean plasma velocity in the sheath between

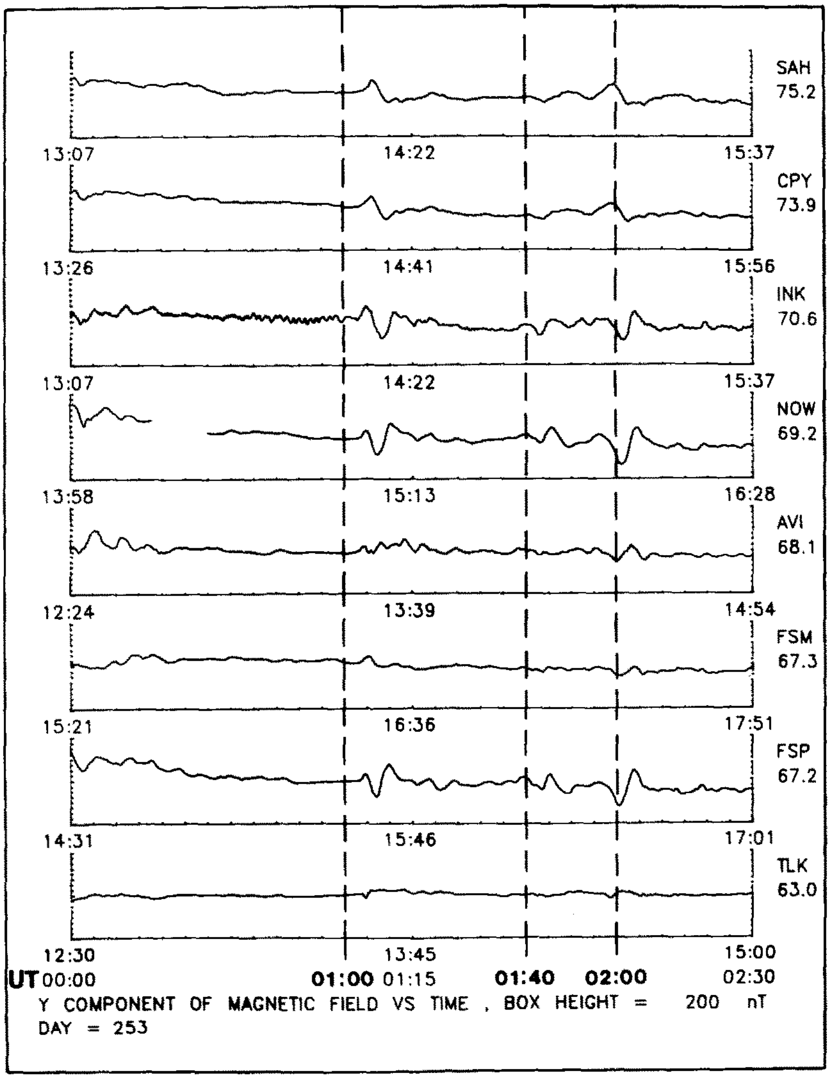

FIG. 4b.

the subsolar points on the bow shock and the magnetopause. Using Spreiter and Stahara's (1980) results, we find the average speed, U, should scale as $V_{SW}/8$. Following Fairfield (1971) we take $b/c \sim 0.33$. We take V_{SW} to be $\sim$480 km s^{-1} (Fig. 1), and the value of c to be $11R_E$. We then obtain for $D_1 - D_2$ a time difference of 5.5 min for the discontinuity to travel from *IMP* 8 to the subsolar magnetopause. Estimating the delay D_3 for the case of the spacecraft is difficult. Using Spreiter and Stahara's (1980) model we infer that it is positive and about 2 min. We estimate D_3 (for the case of the ground stations) to be $\sim$1–2 min. This is composed of the sum of the times for the fast mode wave to propagate from the magnetopause to the relevant ($L = 7$ for AVI) flux tube (a few tens of seconds) and the Alfvén travel time down the tube ($\sim$1 min). We obtain for both cases a total lag of about 7.5 min and shall use this figure for the remainder of this paper.

Good evidence for the reasonableness of the esti-

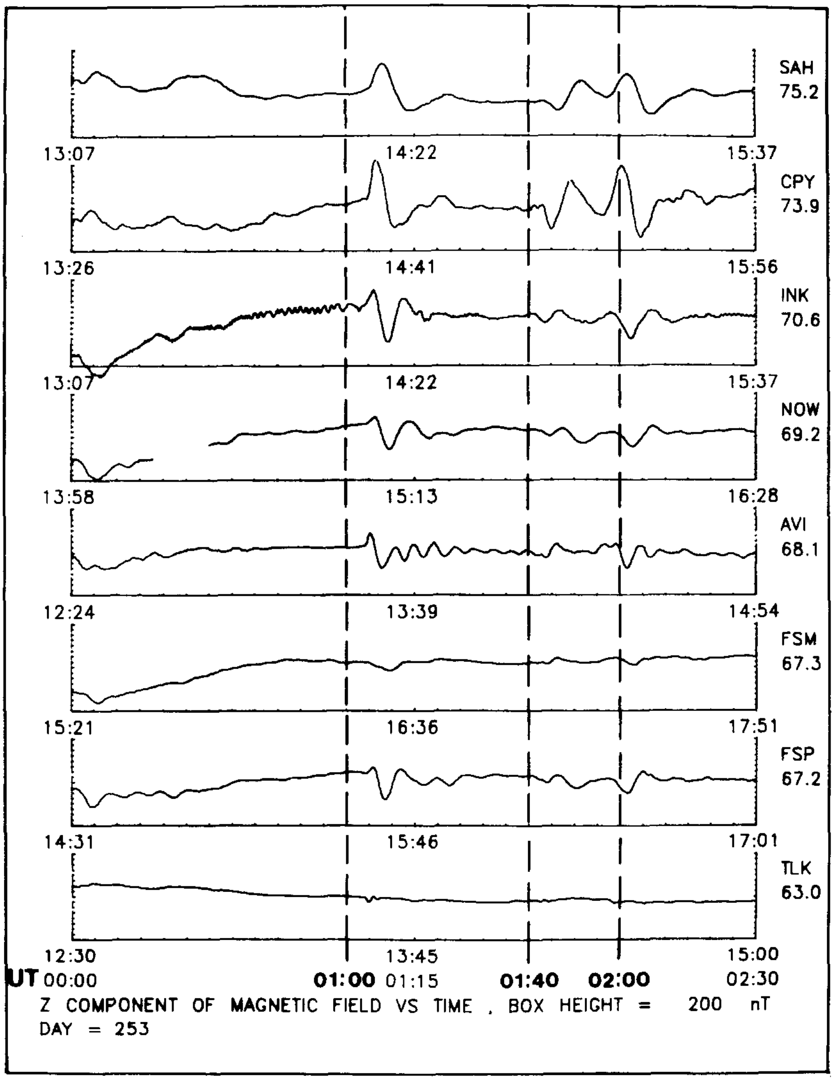

FIG. 4c.

mate of 7.5 min for the delay between *IMP* 8 and *ISEE* 1 and 2 is that it is entirely consistent with the rapid inward motion of the magnetopause detected in event a7 at 01:05 U.T. (where the radial velocity was deduced to be as high as $\sim$90 km s^{-1}) being caused by the sharp rise in the solar wind density recorded by *IMP* 8 between 12:55 and 01:00 U.T. Further circumstantial evidence that the association of these two events is correct is offered by the fact that the (noisy) field encountered by the *ISEE* spacecraft on exit has increased magnitude and an increasingly negative B_Y-component compared with the values detected earlier. These features are reflected in similar trends in the interplanetary field recorded at *IMP* 8 as the density rises.

We now take the postulated time lag and use it with the *IMP* 8 data to predict the variation of the magnetopause position with time. Now the stand-off distance of the subsolar magnetopause is known to scale with the solar wind ram pressure such that

$$C = G/[(nV^2)_{sw}]^{1/6}$$

(Schield, 1969). G is a scaling factor which allows for the non-dipolar nature of the field. We shall assume that such a relation describes the magnetopause location at all local times as a function of ram pressure. To determine a value for G at a given local time we need to calibrate using a low latitude magnetopause position recorded during a period in which solar wind parameters had remained steady. In the interval ~00:30–00:50 U.T., before the arrival of the steep density rise, the solar wind parameters measured by *IMP* 8 are quite steady (we find : $n \sim 11.5$ cm^{-3}, $\delta n \sim 0.7$ cm^{-3}; $V \sim 448$ km s^{-1}, $\delta V \sim 2.0$ km s^{-1}; $B \sim 2.8$ nT, $\delta B \sim 0.2$ nT, the symbol δ denoting the standard deviation). During the 20 min period both *ISEE* 1 and 2 (near 15:00 L.T.) cross the magnetopause just below the GSM equator (Fig. 2a, events a5 and a6). We use the radial crossing distance of *ISEE* 1 ($11.24R_E$) to obtain a value for G at 15:00 L.T., substituting in the equation above the quoted values of solar wind parameters. The numerical value for G thus derived is 129.4 ± 2.6, where n is measured in units of 1/(cubic centimetres), V is in kilometres per second and the distance C is given in R_E.

Having established a value for G appropriate for the *ISEE* spacecraft local time range, we can use the formula in conjunction with the *IMP* 8 spacecraft data to derive a time history for the magnetopause at that local time. The results are shown in Fig. 5 which displays the equatorial magnetopause radial distance vs the Universal Time of the (source) *IMP* 8 data. Using our estimated lag of 7.5 min, we show also on the abscissa the estimated time of arrival of the corresponding perturbations at the *ISEE* spacecraft location in the afternoon magnetosheath. Superposed on the plot are the positions of *ISEE* 1 and 2 with the times of their encounters with the magnetopause ascertained from the data shown in Fig. 2 indicated by solid circles.

The agreement between the actual and inferred crossings is remarkably good and suggests that our derived values for the time lag are not far wrong. The spacecraft are always located on the predicted side of the magnetopause whenever the *IMP* 8 data are available except in one period, namely the brief re-entries into the magnetosheath in the vicinity of 01:50 U.T. (between events a8 and a9). At 01:50 U.T. *ISEE* 2, the spacecraft closest to Earth is well inside the predicted magnetopause position. Subsequently, *ISEE* 2 briefly encounters the magnetosheath field again, as does *ISEE* 1, but at this time a data gap at *IMP* 8 precludes making a prediction. As we remark later, there are clear ground signatures at this time and we envisage that an increase in solar wind pressure was responsible for both the ground signatures and the incursions of the boundary detected by the *ISEE* spacecraft.

Shown in Fig. 6 is a plot of the effective radial component of the velocity of the magnetopause. The majority of the points have been derived from the 5 min resolution *IMP* 8 data. We have calculated the velocity by estimating the derivative of the position curve shown in Fig. 5. We also include on the plot the values of radial boundary velocity derived from interspacecraft timing of crossings where both spacecraft cross the magnetopause at similar times.

The speeds derived from the 5 min position predictions afforded by the *IMP* 8 data all lie below 10 km s^{-1} except for one value derived during the arrival of the pressure ramp just before 01:00 U.T. The points derived from timing actual spacecraft crossings give velocity estimates that are closer to instantaneous estimates. Despite this the values are often similar to those derived from the 5 min resolution estimates. As we have already reported, there is a very large apparent velocity (~90 km s^{-1}) recorded during the crossings coincident with the predicted arrival at *ISEE* of the large density ramp which greatly exceeds the 20 km s^{-1} derived from the *IMP* 8 data. Other large instantaneous velocity values are derived during the multiple boundary encounters recorded by the spacecraft between 01:30 and 02:00 U.T.

It is not surprising that the instantaneous values of velocity exceed those derived from 5 min averaged data. Changes in the external pressure applied to the boundary should produce motion on very short time scales, certainly much shorter than 5 min which, as we have pointed out elsewhere, is comparable with the time for changes to propagate far through the system and thus the time scale for the system to react against the external force.

The instantaneous velocities recorded are not outside the range expected given the size of the changes in the solar wind dynamic pressure recorded at *IMP* 8. To illustrate this, consider a free planar boundary subjected to a sudden change in the dynamic pressure due to a change in density on one side with a perfectly compressible fluid on the other. Assuming specular reflection, the boundary would move with a velocity given by

$$V_b = V_{sw}(1-(n_0/n_1)^{1/2})\cos\phi$$

where n_0 and n_1 are the density before and after the increase, respectively, and ϕ is the angle between the solar wind velocity vector and the magnetopause normal. Let us now use the values of density on either side of the ramp recorded near 01:00 U.T. At

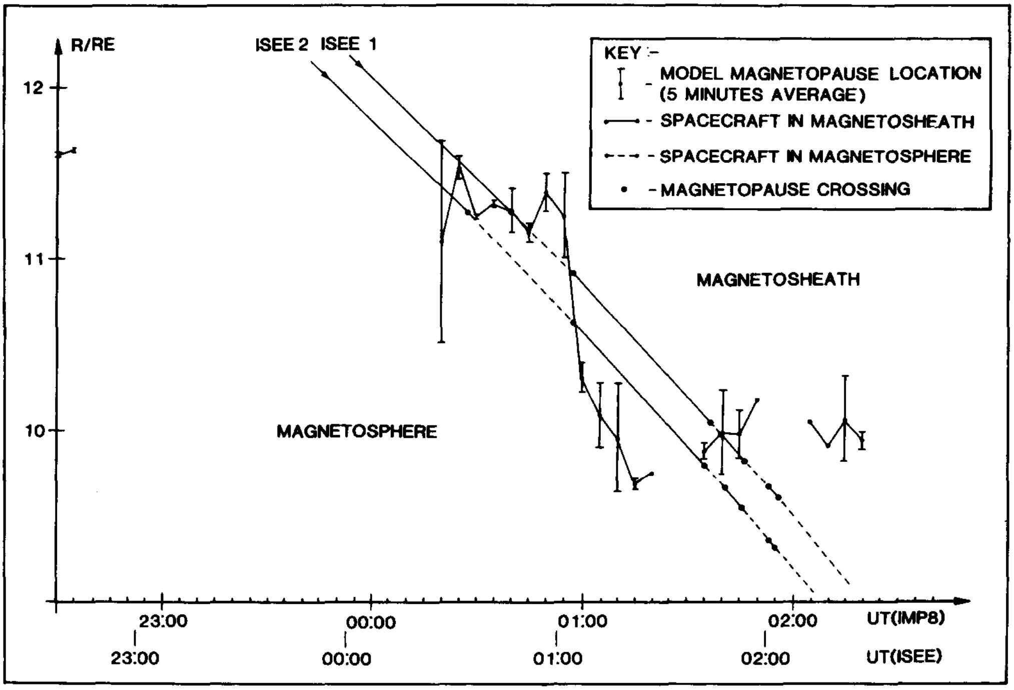

FIG. 5. *ISEE* 1 AND 2 TRAJECTORIES SUPERPOSED ON A MODELLED MAGNETOPAUSE LOCATION.
The expected magnetopause position was obtained from *IMP* 8 data suitably lagged, as explained in the text. Error bars for these measurements are shown by the vertical lines. Large solid circles on the *ISEE* trajectories represent observed magnetopause crossings.

00:55 U.T. the density at *IMP* 8 is $n_0 = 11.7\ \text{cm}^{-3}$, $V_{SW} = 449\ \text{km s}^{-1}$. Five minutes later, $n_1 = 18.1\ \text{cm}^{-3}$ and $V_{SW} = 469\ \text{km s}^{-1}$. For this local time we estimate $\phi = 30°$, using the gas dynamic model of Spreiter and Stahara (1980). The argument gives $V_b = 78\ \text{km s}^{-1}$. The level of agreement with the deduced instantaneous value from the inter-spacecraft timing (89 km s^{-1}) is reasonable. Also one may invert the argument and note that the derived velocities shown in Fig. 6 generally lying in a band between $\pm 5\ \text{km s}^{-1}$ can be produced by relatively minor changes in pressure.

Ground response to solar wind ram pressure changes and magnetopause motion

Figure 7 is a composite of several plots. Using the axis on the far left, we show the quantity $(nV^2)_{SW}$ derived from the *IMP* 8 data. The bar (labelled "reference") marks the period when the steady conditions were used to calibrate the formula used to predict the magnetopause position. Also shown are the instantaneous magnetopause velocities derived from *ISEE* 1 and 2 boundary crossings. (Note that the scale has been inverted with respect to that shown in the previous figure; inward velocity is shown measured positive.) Finally, the inset at the top gives the *X*-component (North–South) of the geomagnetic field recorded at AVI, at 68.1°N, again plotted with a 7.5 min time lag with respect to the solar wind data. The station AVI (Arctic Village) was chosen for display because it showed the clearest oscillatory response to the initial pressure impulse (see Fig. 4).

The most clear feature is that the start of the oscillations here, at 01:04 U.T., and hence those of the other stations as well (cf. Fig. 4), coincides with the sudden pressure increase. It seems likely that, in association with the rapid inward boundary motion recorded by the *ISEE* spacecraft, oscillations have been excited not only in the magnetosphere but also at the field-line feet in the ionosphere.

Further oscillations resume about 40 min later. Do these have the same origin as the earlier one? The first point to be made is that the oscillations appear to be occurring when the magnetopause mean motion is outwards and the dynamic pressure is decreasing. Hence, if the sources of the two sets of oscillations are analogous, they resemble transients of the system excited simply by changes in equilibrium conditions rather than being associated specifically with increases

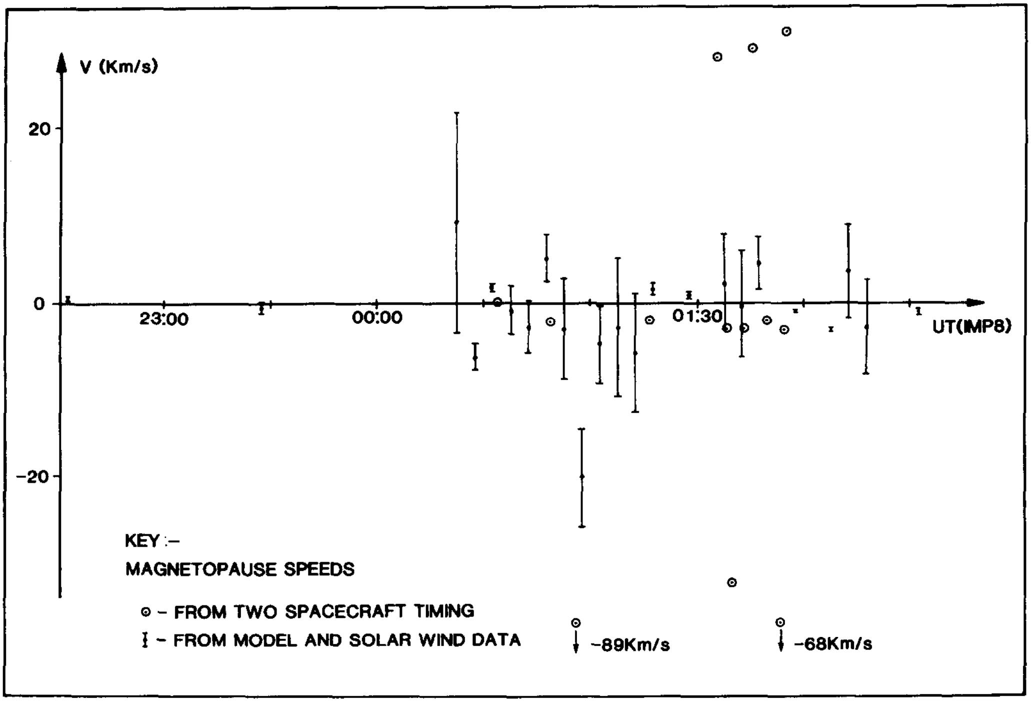

Fig. 6. Radial speeds of the magnetopause boundary vs Universal Time at *IMP* 8.
Solid circles with error bars represent those derived from a magnetopause model using the solar wind data. Open circles show speeds calculated from two-spacecraft timing.

in the dynamic pressure exerted on the magnetosphere.

Secondly, the oscillations all fall within a period when the magnetopause was inferred to be oscillating, as the derived velocities in the lower plot show.

To assess this further we obtain the velocity profile of the magnetopause from the position and times of the *ISEE* 1 and 2 boundary crossings, also shifted by 7.5 min. The oscillations of the boundary agree very well with the oscillations on the ground. Whenever the ground magnetic field is at a temporally stationary point, the measured instantaneous magnetopause speed is close to zero. Such instances are labelled by the dashed vertical lines. When the ground magnetometers detect a rapid change in the Earth's magnetic field with time, the magnetopause was known to be moving rapidly. In particular, the last large excursion of B_X is well correlated with the in–out motion of the magnetopause at ~02:00 U.T. (a10 in Fig. 2). We thus conclude that the ground signatures seen between 01:04 and ~02:05 U.T. are due to magnetopause motion, in turn brought about by changes in the solar wind's dynamic pressure. We have observed the ground response to, first, a sudden magnetospheric compression (at ~01:00 U.T.) and, subsequently, a sustained "rattling" of the magnetospheric cavity (~01:40–02:05 U.T.).

Ground signatures of FTEs?

The only evidence of flux transfer event activity seen by *ISEE* 1 and 2 in the period we study was in the early stages when the IMF and sheath field were southward, the orientation propitious for reconnection. Measurement of the sheath field and the lagged solar wind field show a strongly, almost due, northward orientation throughout most of the period of interest here and, in particular, the ground signatures we have studied occur when the field exterior to the magnetosphere is almost purely northward. However, some of the signatures recorded in the magnetometers bear a strong resemblance to predictions of the signature produced on the ground by the occurrence of an FTE at high altitude.

The B_X, B_Y, B_Z perturbations in the interval 01:00–01:15 U.T. at the stations INK (geomagnetic latitude 70.6°, 14:06–14:21 M.L.T.) and FSP (geomagnetic latitude 67.2°, 15:30–15:45 M.L.T.) are shown in Figs 8a and b, respectively. We have compared them with the predicted ground magnetic perturbation from McHenry and Clauer's (1987) modelling of the

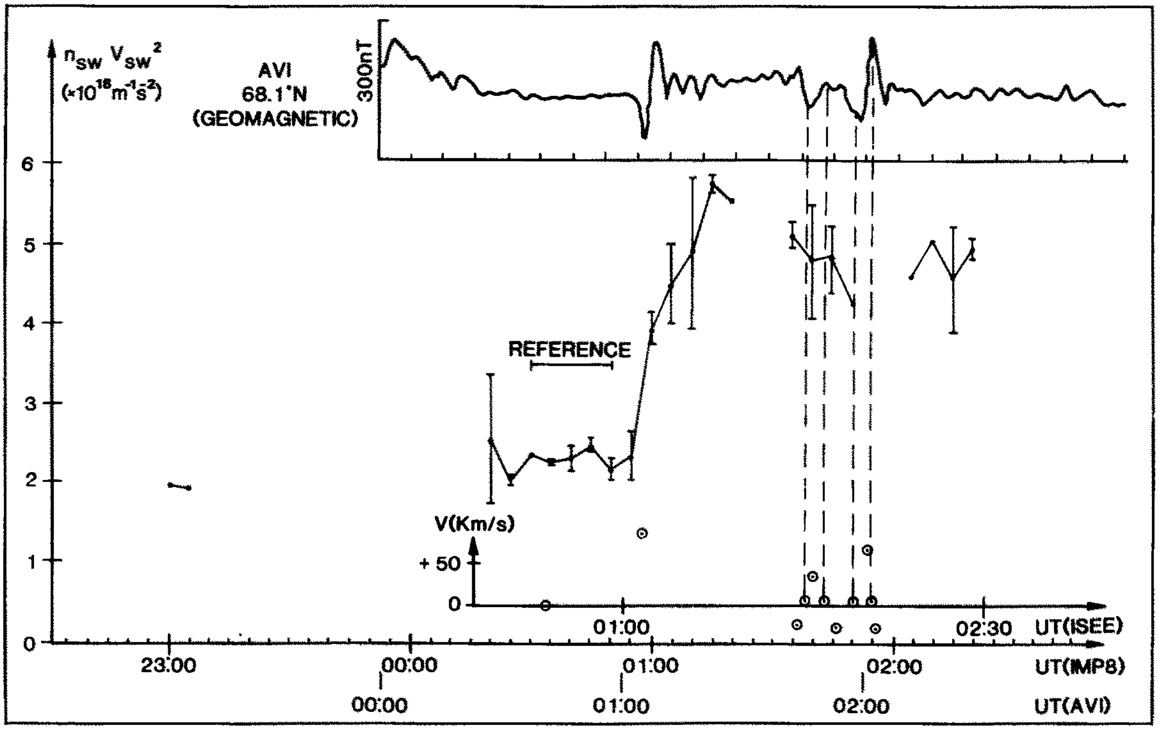

FIG. 7. THE SOLAR WIND RAM PRESSURE AS A FUNCTION OF UNIVERSAL TIME AT *IMP* 8.
The interval marked "reference" corresponds to the period of steady solar wind ram pressure. The inset shows the X-component of the geomagnetic field at AVI with a lag as derived in the text. The dashed vertical lines relate observations on the ground to measured magnetopause speeds (V; positive inwards). The latter are shown by open circles and are also lagged.

ground signatures of FTEs, assuming a trajectory through the foot of a reconnected flux tube. One signature assumes a net upward and downward current of 5.8×10^5 A along the flanks of the flux tube (Southwood, 1985, 1987) whose foot is moving poleward at 2.3 km s^{-1}. We show this superposed (dashed lines) on the measured traces in Fig. 8a.

A second model postulates an axial current (Saunders *et al.*, 1984; Lee, 1986) and predicts a different ground signature. For this case we consider a disturbance moving poleward and eastward over a station in the Northern Hemisphere at a speed of $\sim$400 m s^{-1} carrying a current of 3.3×10^5 A. The resulting magnetic signature is superposed on the measured traces in Fig. 8b. The values of speeds and currents have been chosen to match the perturbation most closely (see McHenry and Clauer, 1987 and references therein). In both cases the modelled B_Z variation have been scaled down from the theoretical value by a factor of 2. This is reasonable as the model takes no account of the finite conductivity of the Earth or nearby oceans (Lanzerotti *et al.*, 1986). For magnetometers located near the sea (e.g. INK) induced currents can be very important (Boteler, 1978).

The observations and predictions match very well using these conditions. But we have traced the cause of the pulsations to be due to the change in the solar wind dynamic pressure. Thus changes in the solar wind ram pressure can create a travelling signature in the ionosphere very like the moving flux tube signatures postulated by Southwood (1987) for FTEs. Similar conclusions have been drawn by McHenry *et al.* (1989). There is thus the further important lesson that FTE signatures in the ionosphere can be mimicked by a variety of sources. We support the view of McHenry and Clauer (1987) that, for an unambiguous isolation of the low altitude FTE signatures, a close matrix of stations is important but would add that concurrent space data is essential.

Global characteristics of the ground disturbance

Figure 9 shows an expanded plot of the X-component of the magnetic field from eight of the ground magnetometers. The oscillations at 01:40 U.T. are in fact seen on the ground at all but three of the 14

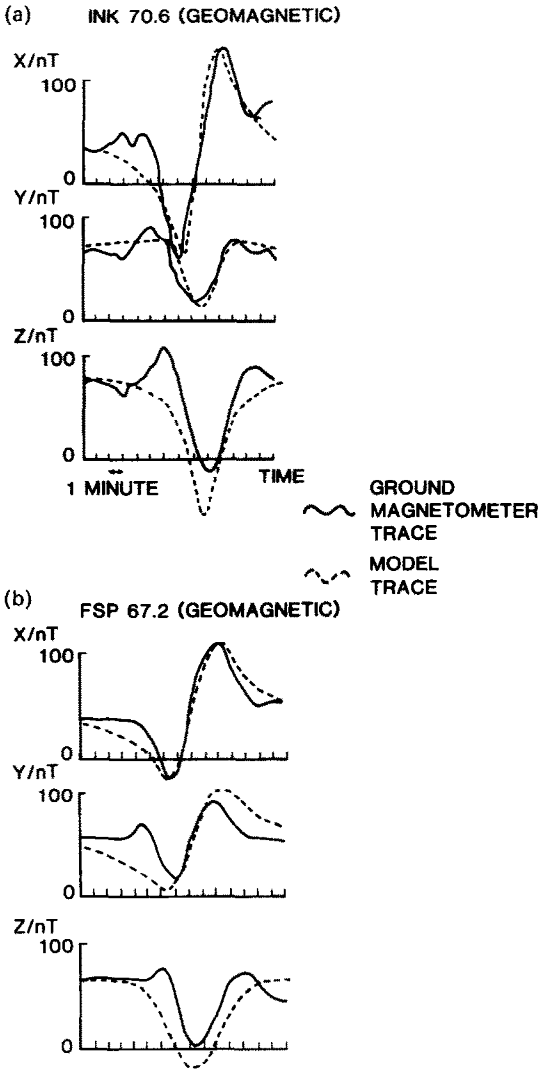

Fig. 8. Measured geomagnetic field components (solid line) at stations INK (a) and FSP (b).
The dashed lines show predicted field perturbations from two FTE models, as explained in the text.

stations that we have available to us. The station array extends over an area on the ground ranging from 63° to 75.2° in MLAT and 12:30 to 18:00 M.L.T., i.e. the whole of the high latitude afternoon ionosphere is encompassed. The interval plotted is now from 00:45 to 02:15 U.T. The box height corresponds to 100 nT but otherwise the format is the same as in Fig. 4. The top five panels show data from stations SAH, CPY, INK, NOW, AVI which are located at steadily decreasing latitudes but similar magnetic local times (within 1 h). Comparing the time of the first peak at each station for the ~01:00 U.T. oscillation there is a clear negative phase shift with increasing latitude. There is a similar phase shift with M.L.T. Comparing stations FSM and FSP (the sixth and seventh panels in the figure), which are just 0.1 of a degree of latitude apart, we see a negative phase shift with increasing local time. The same qualitative phase motion can be seen in the vertical component. The disturbance appears to propagate both northward and eastward on the ground corresponding to outward and tailward motion in the magnetosphere. The outward sense of direction is possibly attributable to the effect of field-line resonance. Using stations SAH and INK (at the same M.L.T. and average 74.5° magnetic latitude, MLAT), we infer the poleward component of velocity at ~14:10 M.L.T. to be 4.3 km s^{-1}. The meridional velocity component, inferred from the data at stations FSM and FSP at 67.25° magnetic latitude and ~16:00 M.L.T. is 10.8 km s^{-1}.

CONCLUSIONS

We have presented a study of magnetopause motion and associated ground magnetic field oscillations which appear to be caused by changes in the pressure of the solar wind. On the day in question the changes are caused in the main by changes (both increases and decreases) in the solar wind dynamic pressure and, in particular, by changes in the solar wind density. However, our interpretation of the magnetospheric signals, namely that they are simply the system response to varying pressure external to the magnetopause, means that similar effects would result from changes in solar wind magnetic field or gas pressure.

We have shown that changes in solar wind dynamic pressure can be large enough to give rise to boundary velocities of many tens of kilometres per second and have directly confirmed the occurrence of such velocities.

Through most of the interval studied the IMF had a strong northward component. For long stretches of the data, the fields inside and outside the magnetosphere were close to parallel. Thus magnetic reconnection-related coupling at the magnetopause is unlikely *a priori*. Indeed, the only flux transfer event signatures observed in space were detected before 00:04 U.T. when B_Z was of opposite sign.

We first considered the size of the lag to be expected between the detection of a pressure signature at the spacecraft in the solar wind and its arrival at the magnetopause and the detection of subsequent effects on the ground. The delay depends on the manner in which perturbations propagate both in the solar wind and in the terrestrial environment. We have made the particular assumption that the front in the solar wind

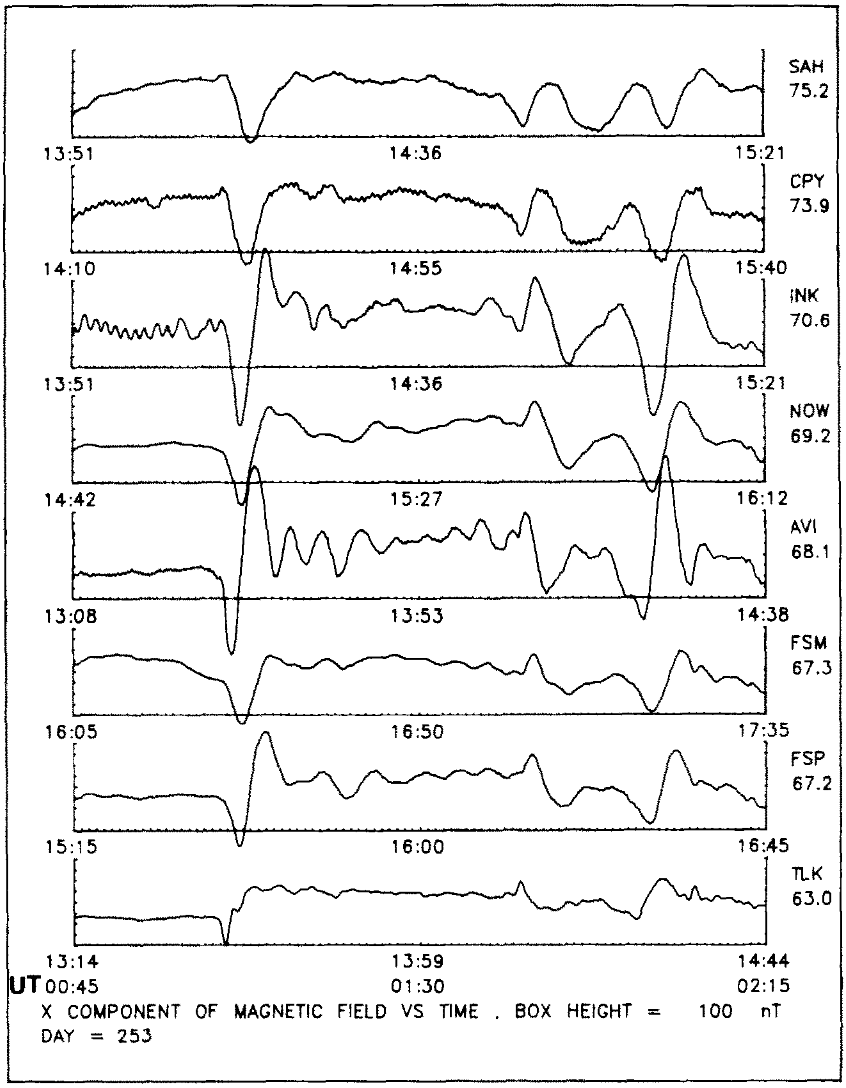

FIG. 9. X-COMPONENT OF THE GEOMAGNETIC FIELD FOR THE EIGHT GROUND STATIONS SHOWN IN FIG. 4. The scales are expanded.

is propagating radially from the Sun. Other inclinations of front are clearly possible and the delay at different points on the globe could be changed in a major way if there were non-radial propagation. Similarly we have assumed that the disturbance in the magnetosheath and magnetosphere moves with the plasma in the sheath but propagates as a magnetohydrodynamic wave within the magnetosphere. More detailed calculations are needed but there is every reason to believe that the figure used for the delay between interplanetary space and the ground is of the correct order.

We used magnetic field data from a variety of stations to monitor the ground signals whilst two spacecraft were in the magnetopause vicinity. The pressure changes have also been associated with magnetic perturbations, both pulse-like signals and oscillations detected on the ground. During a very rapid compression localized oscillations were recorded on the ground. Long-lasting (about four cycles) signals were clearly detected at only two stations; elsewhere pulse like changes (one cycle or less) were recorded. If the signals are due to resonant field-line excitation there may be some form of filter in the system that precludes magnetic shells at all latitudes being excited. Alternatively, it may be that some of the higher latitude stations such as INK, PEB, and CPY, do not see oscillations due to their being located at the feet of tubes which stretch into the polar cap and thus do not form a resonant cavity.

The pulse-like magnetic signatures could be modelled by the passage overhead of a dual current system like that proposed by Southwood (1987) for the ionospheric footprint of a flux transfer event. As we have already noted, there was no FTE activity recorded at the magnetopause at the time of these ground magnetic signatures. In addition the speed of motion of the disturbance pattern, 2.3 km s^{-1}, deduced for the Southwood pattern is very fast for actual material motion in the ionosphere (this is several times faster than the acoustic speed in the E-region). Thus, unlike in the FTE model of Southwood where in the core of the disturbance there is a flux tube of plasma moving bodily through the surrounding medium, it seems likely that the speed observed is the speed of a front moving through the plasma in the ionosphere and there is not actual material motion at the high speed detected. It is important to note that McHenry *et al.* (1989) also report isolated travelling vortices in the ionosphere which travel at speeds well above the acoustic speed.

The speed deduced if the Saunders *et al.* (1984) model is used is considerably slower (400 m s^{-1}). This could correspond to actual mass motion. The similarity of the models to the FTE signature predictions makes it very likely that there is localized field-aligned current flow in the perturbation.

In a second instance where oscillations were seen in the ground data the nett magnetopause motion was outward. We have obtained evidence from the spacecraft at the magnetopause that the boundary was moving at the same frequency as the signals detected on the ground and that there were similar fluctuations in the solar wind dynamic pressure in the solar wind proper. In this latter case the oscillations detected on the ground were observed over a much larger range of latitude and longitude.

The success of the FTE model ionospheric signatures in describing observations which were certainly not due to FTEs is important. The high deduced speed of the signature may preclude there being any mass transport in the centre of the disturbance and so in this respect the model does not fit, but the study does highlight the need for great care in identifying potential signatures of impulsive reconnection at low altitude.

The presence of a tailward convecting signature in the ionosphere almost certainly indicates that the source solar wind pressure perturbation is producing some nett anti-solar flux transport in the magnetosphere and ionosphere. How large the transport is needs further study; as we have pointed out the motion detected need not be a material motion. Similarly, if the oscillations are due to waves in the magnetosphere or on the magnetopause propagating tailward, they also represent a nett tailward plasma transport (Southwood, 1979).

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