Aust. J. Phys., 1985, **38**, 981–97

Magnetic Reconnection in the Earth's Magnetotail*

Edward W. Hones, Jr

University of California,
Los Alamos National Laboratory,
Los Alamos, NM 87545, U.S.A.

Abstract

Over the past few years satellite observations of the plasma sheet in the Earth's magnetotail during magnetospheric substorms have established beyond reasonable doubt that magnetic reconnection occurs in the magnetotail and that it plays a central role in the substorm process. The features seen at Earth by which substorms were originally identified (e.g. the auroras and geomagnetic disturbances) are simply superficial manifestations of a more fundamental physical process—the magnetosphere divesting itself of stored energy and plasma that was acquired earlier from the solar wind. It does so by shedding a part of its plasma sheet. This is accomplished by magnetic reconnection near the Earth that severs the plasma sheet, forming a plasmoid that flows out of the tail and that is lost to the solar wind. Recognition of the existence of plasmoids and our developing understanding of them have been important elements in confirming the occurrence of reconnection in the magnetosphere. In an analogous way, the best evidence for the occurrence of reconnection on the Sun has come from observations of closed magnetic configurations (plasmoids) in the solar wind and in the corona. But while magnetic reconnection is certainly the key ingredient in solar flares and substorms, analogies between them should not be carried too far, because there are basic differences in the environments in which they prevail and in the physical processes that lead to their occurrence.

1. Introduction

Nearly 40 years ago Giovanelli (1946) pointed out the probable importance of magnetic neutral points in the development of solar flares. He visualized them as regions where conditions would be suitable for the excitation of atoms by collision with electrons accelerated in the induced electric fields of evolving sunspots. From that idea and through the efforts of many people, notably Hoyle (1949), Dungey (1953, 1961), Sweet (1958), Parker (1957) and Petschek (1964), the concept of magnetic reconnection as we presently view it was developed. Today it is widely believed that magnetic reconnection does indeed explain the sudden large energy releases that characterize solar flares and intense auroral brightenings called auroral or magnetospheric substorms. Furthermore, reconnection has been found to play important roles in several areas of fusion research, and interest in it has arisen in relation to some astrophysical objects.

* Paper presented at the R. G. Giovanelli Commemorative Colloquium, Part II, Tucson, Arizona, 17–18 January 1985.

0004-9506/85/060981$02.00

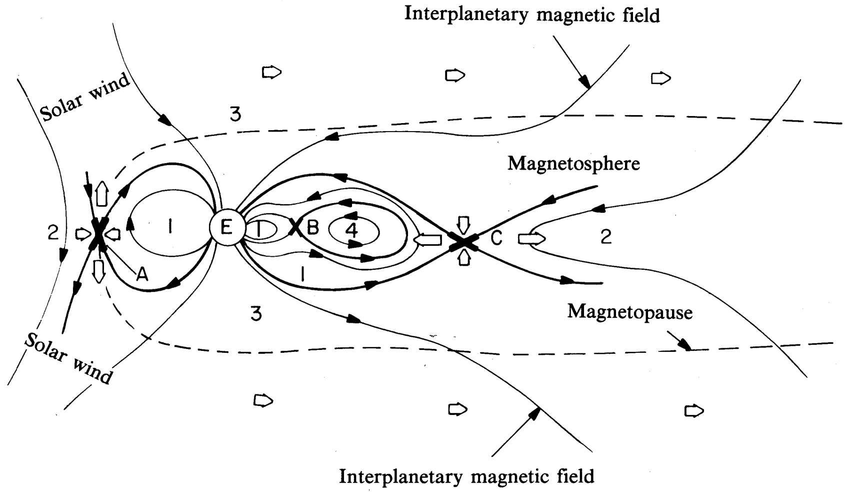

Fig. 1. Sketch of the solar wind–magnetosphere plasma system (not to scale). Solid curves are magnetic field lines with arrows indicating their direction, while the open arrows show the plasma bulk flow. The dashed curve is the magnetopause, the boundary between the solar wind dominated regime and the Earth dominated regime. Actual distances are Earth (E) to A $\approx 10 R_E$; E to B $\approx 15 R_E$; E to C $\approx 100 R_E$; and magnetotail diameter 40–60R_E.

In many systems of magnetized plasmas, magnetic field lines can be divided into several classes on the basis of their topological properties. One such system is sketched in Fig. 1. This represents the Earth's magnetosphere, enveloped in the flowing solar wind which is threaded by the interplanetary magnetic field (IMF), i.e. the magnetic field pulled from the Sun by the solar wind. In this system four classes of field lines are identified: (1) 'closed' field lines connected to the Earth at both ends; (2) 'interplanetary' field lines that do not connect to the Earth at all; (3) 'open' field lines connected to the Earth at one end and to the IMF at the other; and (4) 'magnetic loops' that connect neither to the Earth nor to the IMF. Surfaces called separatrices (thick curves in Fig. 1) separate the regions of different topology (i.e. 2 from 3, 1 from 3, and 1 from 4), and these intersect or close upon themselves along so-called X lines (indicated at A, B and C in Fig. 1).

Fig. 1 is an adaptation from the classic paper by Dungey (1961) who suggested that magnetic field lines in the flowing solar wind 'reconnect' with magnetic field lines of the Earth in the manner shown. The reconnection process involves transporting magnetic flux across separatrices from one region to another, and this is accomplished at the X lines. For example, an interplanetary field line (region 2) brought to the front of the magnetosphere by the solar wind meets an oppositely directed closed line (region 1) at A. The two lines break where they touch at the X line and immediately reconnect to create two open field lines (region 3) that connect to the north and south polar caps of the Earth. Similarly, two open field lines, reconnecting at C, create an interplanetary field line and a closed field line. A closed field line, reconnecting at B, creates a magnetic loop (region 4) and a shorter closed line. Both the complexity and the importance of the magnetic reconnection process arise from the fact that in all cases of physical interest, magnetic field lines are closely coupled to the mechanical behaviour of plasma, so topological changes of the magnetic field must include transfer of plasma across separatrices as well. In fact magnetic reconnection has been defined as the process whereby plasma flows across a surface that separates regions containing topologically different magnetic field lines (Vasyliunas 1975).

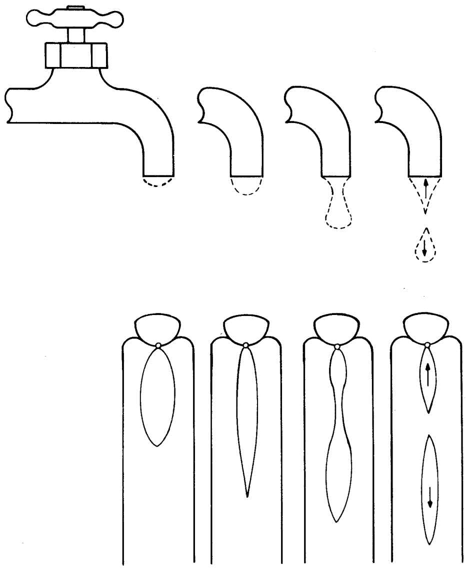

Fig. 2. Analogy between the plasma sheet severance and plasmoid formation and the behaviour of water dripping from a leaky faucet. [From Hones (1979*a*).]

This paper will emphasize one aspect of magnetic reconnection shown in Fig. 1, namely, reconnection of closed field lines, as at B, that results in the formation of a magnetic loop structure (4) which, in magnetospheric research, is called a 'plasmoid'. Plasmoid formation and release is a rather unique and predicted consequence of magnetic reconnection in a magnetized plasma system. As such, it is a feature that has been sought in both solar and magnetospheric observational research as an indication that magnetic reconnection is involved in dynamical processes in those systems. Plasmoid formation and release constitute a mode of energy and plasma storage and sudden release that is somewhat analogous to the formation and release of water drops from a leaky faucet. Fig. 2 illustrates the analogy. Water accumulates, causing the drop to enlarge until its weight can no longer be restrained by surface tension; it then necks down and suddenly breaks, some of the water falling and the rest being pulled rapidly back up into the faucet. The lower part of Fig. 2 shows the analogous behaviour of the plasma sheet in the Earth's magnetotail. Plasma accumulates in the plasma sheet until it can no longer be restrained by the distended magnetic field. The plasma sheet then necks down and is suddenly severed by reconnection, allowing its tailward portion to escape. Its upper portion snaps earthward, projecting plasma into the ionosphere where it causes an auroral substorm.

We shall next discuss, by way of introduction, the search for evidence that plasmoids are released from the Sun, implying the occurrence of reconnection there during flares. We shall then describe in Section 3 the very strong evidence for plasmoid formation and release from the Earth's magnetotail. Finally, we comment in Section 4 on the similarities and dissimilarities of the situations on the Sun and in the magnetotail, and possibilities for cross fertilization between the two research areas.

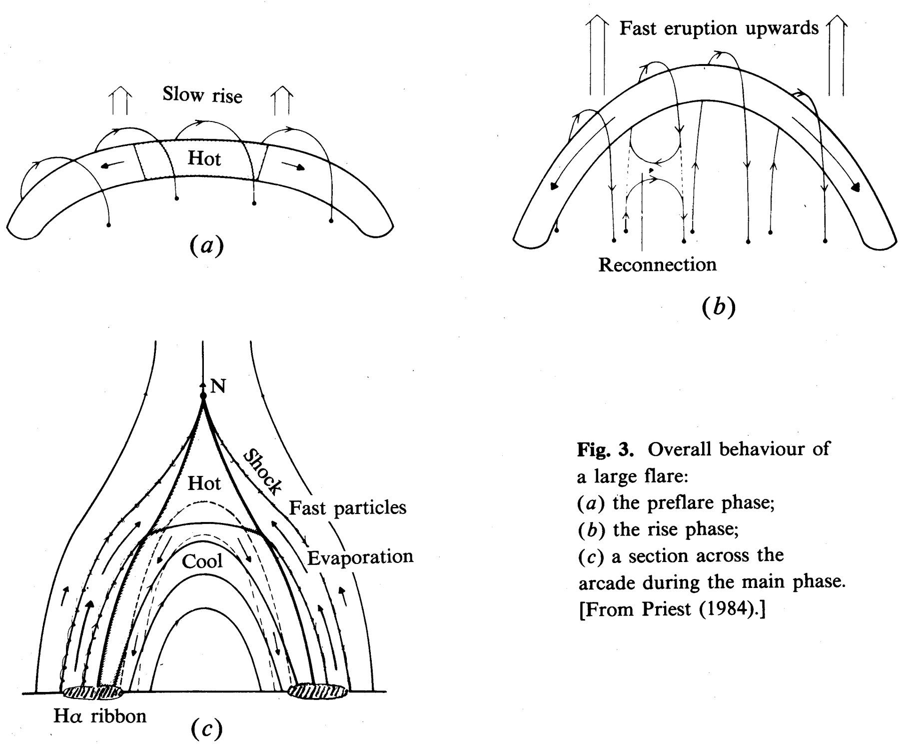

Fig. 3. Overall behaviour of a large flare: (*a*) the preflare phase; (*b*) the rise phase; (*c*) a section across the arcade during the main phase. [From Priest (1984).]

2. Plasmoids from the Sun

A schematic diagram of the behaviour of a large (two-ribbon) flare, as modelled by Kopp and Pneuman (1976), is shown in Fig. 3. During the preflare phase a large flux tube with its overlying magnetic arcade rises slowly in response to slow photospheric motions of its foot points. At some critical amount of shear the configuration becomes unstable and erupts outward (the rise phase). Alternatively, the onset of the rapid eruption may take place when the arcade field lines have been stretched out so much by the slow rise that they begin to reconnect by the tearing mode instability. In the main phase, reconnection continues and creates hot loops and ribbons as the field closes down (i.e. as reconnected field lines contract back toward the surface). The erupting flux tube, enveloped by the closed loops of reconnected arcade field lines (constituting the plasmoid in this scenario), has long since disappeared from view.

Outbursts of material from the Sun have been known to occur and the coronagraph carried by the Skylab satellite provided an opportunity to examine their magnetic structure. Many of these sudden mass ejections were observed, typically appearing as large magnetic loops rooted at the Sun, yet expanding outward through the corona at speeds of the order of 400 $\mathrm{km\,s^{-1}}$ (Gosling *et al.* 1974). However, none have been found that appeared disconnected from the Sun, nor have examples been found of 'returning loops', i.e. Sun-tied contracting closed loops left from the reconnection process (MacQueen 1980).

However, other studies have provided indirect evidence that closed magnetic loop structures *do* flow out from the Sun in the solar wind. Ordered IMF configurations with radial dimensions of a few tenths of an AU, at 1 AU, and characterized by higher

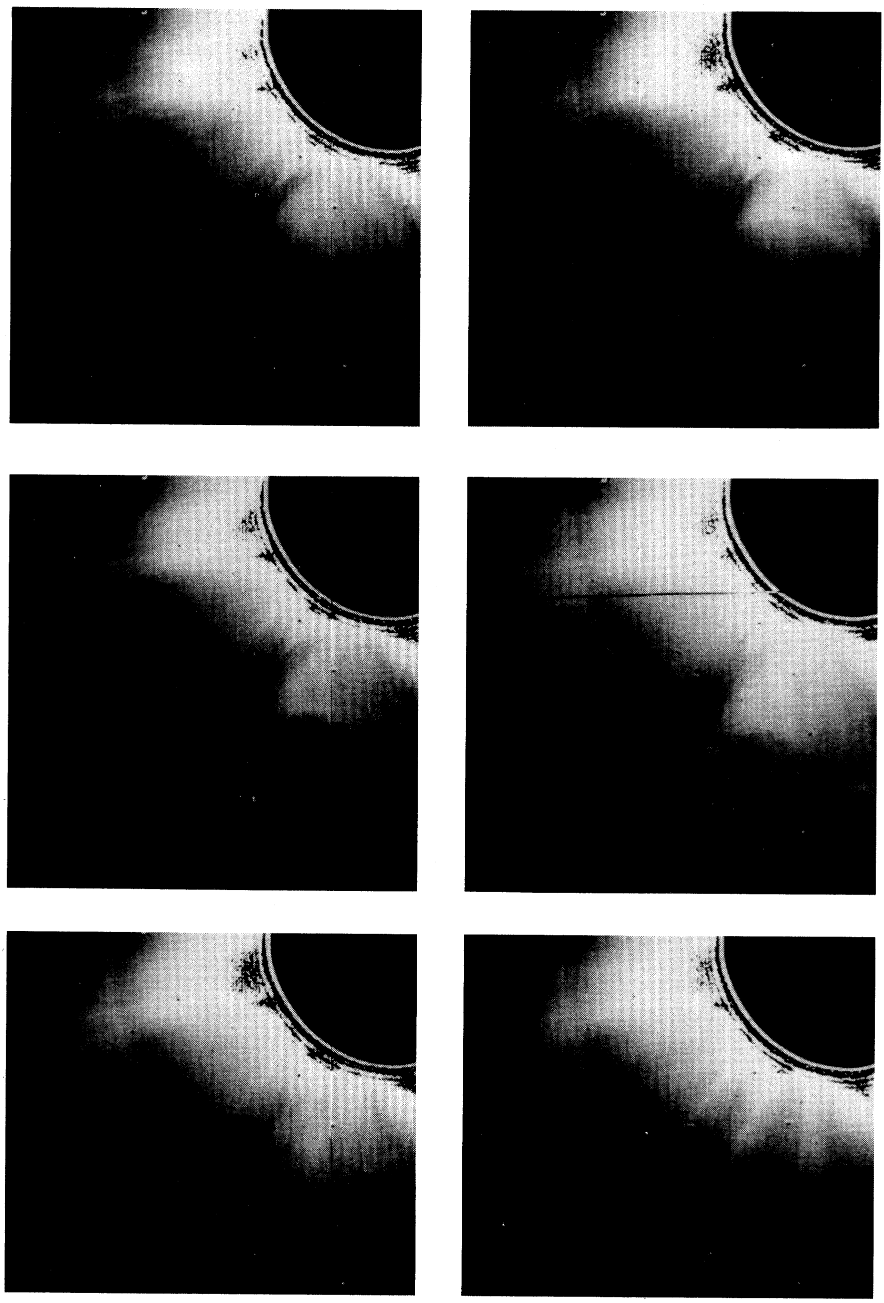

Fig. 4. Coronagraph/polarimeter images showing the progress of a concave upward structure on March 16, 1980. The times for the frames from left to right and downward are 0642, 0734, 0800, 0818, 0910 and 1358 UT. North is to the upper left and east to the lower left. The radius of the first brightest diffraction ring surrounding the occulting disc is $1{\cdot}61\,R_S$. The length of one side of a frame is approximately $5{\cdot}5\,R_S$. [From Illing and Hundhausen (1983).]

than average field strengths and a rotation of the field vectors parallel to a plane have been observed. These configurations, inconsistent with a simple model of a magnetic 'tongue' connected to the Sun, are called magnetic clouds (Burlaga and Behannon 1982). Anomalously low temperatures of solar wind protons (Gosling *et al.* 1973) and electrons (Montgomery *et al.* 1974) have also been found and are suggestive of solar wind plasma trapped in 'magnetic bottles' and cooling adiabatically as these confining magnetic configurations expand. Bidirectional anisotropies of energetic solar protons and electrons (Palmer *et al.* 1978) and solar wind electrons (Bame *et al.* 1981) have also been found and cited as consistent with the confinement of these particles in closed magnetic bottles. The reduced temperatures and bidirectional distributions were observed in the 'driver gas' behind interplanetary shocks associated with solar flares.

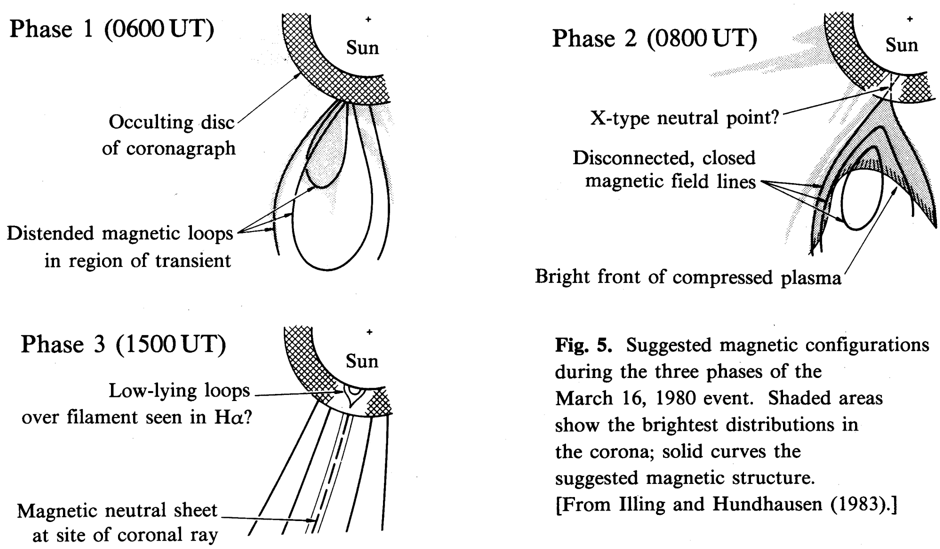

Fig. 5. Suggested magnetic configurations during the three phases of the March 16, 1980 event. Shaded areas show the brightest distributions in the corona; solid curves the suggested magnetic structure. [From Illing and Hundhausen (1983).]

The coronagraph/polarimeter on the SMM satellite has provided an observation of a coronal transient exhibiting features suggestive of a 'pinching off' of distended magnetic loops to form a disconnected closed magnetic structure in the solar wind and a lower lying set of closed loops that return to the Sun (Illing and Hundhausen 1983). In the second picture (0734 UT) at top–right of the sequence shown in Fig. 4, a band or 'front' of bright coronal material in the form of an arch can be seen that is concave upward (i.e. an orientation opposite to that of the loops seen in many coronal transients). The next two images (0800 and 0818 UT) show that the bright front has moved coherently outward, retaining its concave upward shape. As the front moves through the corona a fan of bright material seems to connect it to a narrow range of latitudes near the occulting disc (0910 UT). The edges of this fan move inward to form a central ray or streamer (1358 UT). Fig. 5 indicates a suggested evolution of the magnetic configuration, involving a disconnection of distended magnetic loops at an X line that was hidden behind the occulting disc. The plasmoid thus formed moves outward finally leaving a thin magnetic neutral sheet which overlays Sun-anchored magnetic loops. No flare or radio events were reported at this time, but an X-ray event was observed from 0610–0650 UT, possibly a signature of the energy release associated with the severance of the distended magnetic loops by magnetic reconnection.

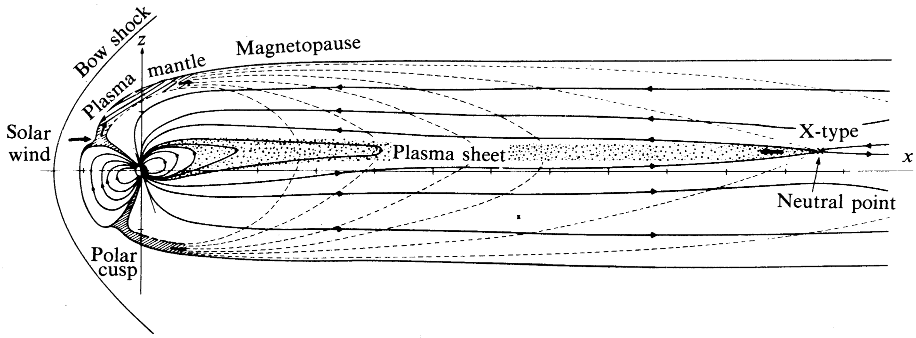

Fig. 6. Schematic representation of the quiet time configuration of the Earth's magnetosphere. [From Pilipp and Morfill (1978).]

3. Plasmoids in the Earth's Magnetotail

To discuss the generation and release of plasmoids by the Earth's magnetotail we must first note the starting condition of the magnetosphere, i.e. its configuration during 'quiet times' between substorms, as depicted in Fig. 6. Magnetic field lines from the Earth are stretched far downstream, primarily as a consequence of their having become connected to the interplanetary field lines at the front of the magnetosphere, as illustrated in Fig. 1. (Note that reconnection at the front side is expected to occur most effectively when the IMF is directed southward, opposite to the direction of the Earth's field there.) The full length of the magnetotail is not known but data from two spacecraft, Pioneer 8 and Pioneer 7, that passed behind the Earth $\sim 500 R_E$ and $\sim 1000 R_E$ downstream (where the Earth radius R_E is 6370 km), indicated the presence of a tail at those distances (Bavassano *et al.* 1974; Walker *et al.* 1975).

The magnetotail is approximately cylindrical, with radius 20–30 R_E, and comprises three distinct plasma regimes. The plasma sheet, within which the magnetic field reversal occurs, contains relatively hot plasma (with an ion temperature of several keV) whose number density is of the order of 10^{-1} cm^{-3}. The sheet divides the tail in half. Immediately above and below it lie the tail 'lobes', regions of cold ($T_i \leqslant 1$ keV) and low density ($n \approx 10^{-2}$ cm^{-3}) plasma. Within the surface of the tail lies the plasma mantle or boundary layer. This contains a solar wind-like (i.e. cold and high density) plasma that is, in fact, solar wind plasma that has gained entry through the reconnection process at the front of the magnetosphere and that is flowing tailward at somewhat less than solar wind speeds. Far down the tail, at a distance of $\sim 100 R_E$ (see e.g. Zwickl *et al.* 1984) there is a magnetic neutral line. As illustrated in Fig. 6, plasma of the plasma mantle, convected toward the midplane (as shown by the dashed curves), is trapped earthward of this quiet time neutral line and projected earthward, maintaining the quiet time plasma sheet.

Auroral or magnetic substorms are periods of enhanced auroral and geomagnetic activity lasting from one to a few hours that signify increased dissipation of energy from the magnetosphere to the Earth. They are a response of the magnetosphere to a southward turning of the IMF, i.e. to enhanced coupling of the solar wind magnetic field and plasma to the Earth's magnetic field. As we shall discuss, the underlying physical process in the substorm phenomenon is the disconnection of a major portion of the plasma sheet, which then constitutes a plasmoid free to flow downstream and eventually out of the magnetotail (see e.g. Fig. 2). The disconnection results from

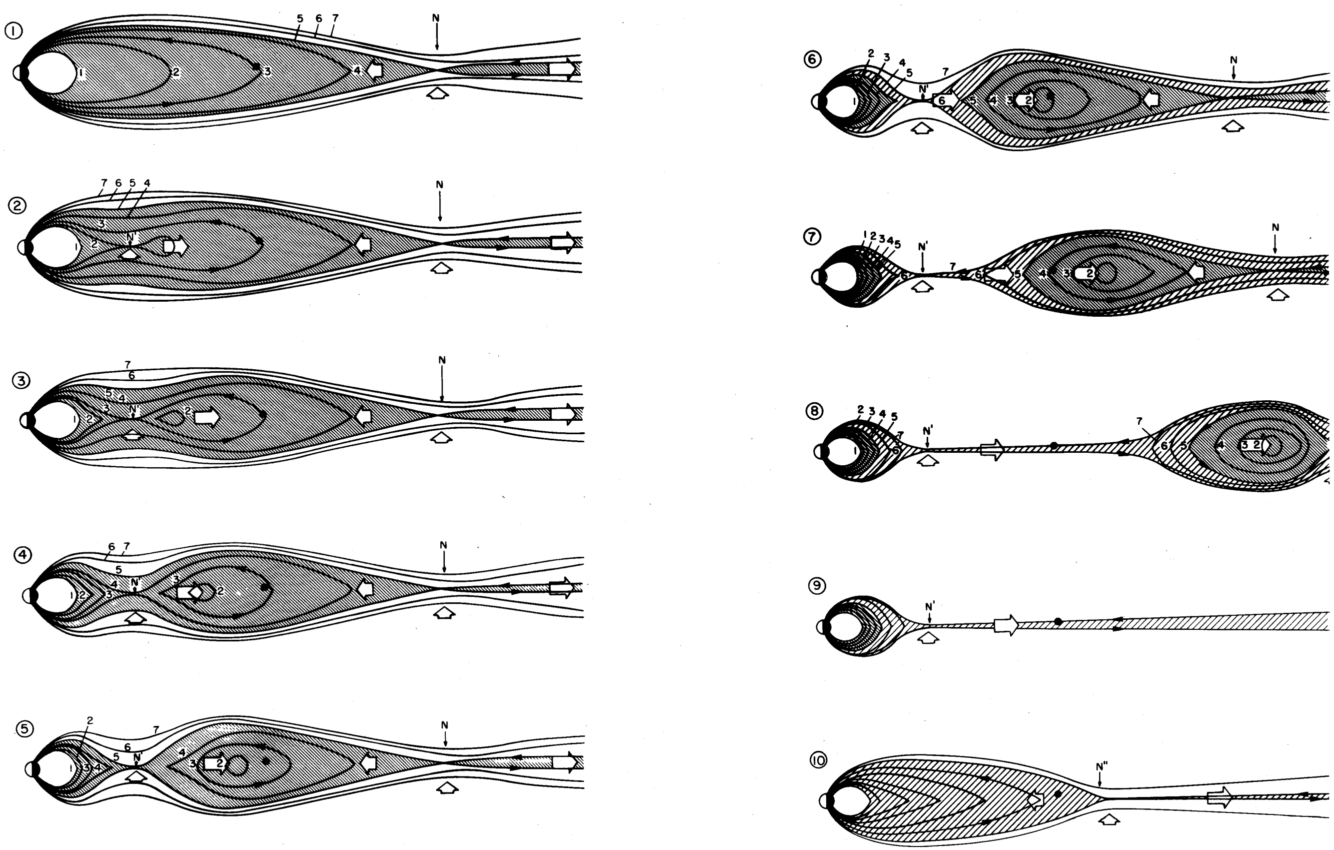

Fig. 7. Schematic representation of changes of the magnetotail plasma sheet, thought to occur during substorms. Shown are cuts along the midnight meridian of the magnetotail, where solid curves are magnetic field lines and open arrows indicate plasma flow. A distant neutral line is shown at $r \approx 60 R_E$ (note that recent measurements indicate that its position should be nearly $100 R_E$). The fine hatching indicates the plasma sheet, which contains (initially) the closed field lines 1, 2, 3, 4 and is bounded by the 'last closed field line' 5. Field lines 6 and 7 are in the lobe, outside the plasma sheet. [From Hones (1979*b*).]

magnetic reconnection that starts within the plasma sheet about 10–20R_E tailward of the Earth (Hones 1979*a*). The evidence for this process was drawn initially from plasma and field measurements by satellites in the near Earth part of the tail (i.e. within ~35R_E of Earth), but was subsequently confirmed in dramatic fashion by observations with a satellite much further (~220R_E) from Earth. We discuss first the initial near Earth discovery of the plasmoid generation process and then its confirmation at large distance.

(a) Observations in the Near Tail

Fig. 7 shows midnight meridian plane cross sections of the plasma sheet at ten sequential times, depicting the changes and processes that occur during a substorm. The processes probably do not prevail over the whole width of the plasma sheet, but over perhaps the central one-half of its width (Hones and Schindler 1979). Panel 1 shows the plasma sheet as it might appear about an hour before a substorm. During the next hour, and leading to the configuration of panel 2, a 'growth phase' occurs during which the plasma sheet field lines become more distended and the plasma sheet near the Earth probably becomes somewhat thinner. In panel 2 a 'substorm neutral line' or X line, N′, suddenly forms in the near-Earth ($r \approx$ 10–20R_E) sector of the plasma sheet (Hones 1979*b*). The commencement of reconnection of the distended magnetic field lines there marks (and is the cause of) the onset of the substorm's 'expansive phase'. The reconnection occurring at the new neutral line causes fast jetting of plasma both earthward and tailward. Earthward jetting plasma flows along field lines to the ionosphere where, by intermediate processes that are still not fully understood, it creates the auroras. Plasma also flows rapidly earthward in the equatorial plane resulting in plasma injection into the inner magnetosphere (e.g. to geosynchronous orbit at $r = 6 \cdot 6 R_E$), a feature commonly observed at the onset of the substorm expansive phase. (This rapid earthward 'collapse' of the field of the substorm neutral line is the analogue of water being drawn back into the faucet in Fig. 2.) The onset of reconnection (in panel 2) also results in a diversion of part of the dawn-to-dusk tail sheet current along field lines to the ionosphere where it flows westward, constituting a 'westward electrojet'.

Reconnection continuing in panels 3 and 4 creates a structure of plasma threaded with closed magnetic loops, and in panel 5 the last closed field line (line 5) of the pre-substorm plasma sheet is pinched off by reconnection, leaving the plasma sheet tailward of N′ magnetically detached from the Earth. Panels 6, 7 and 8 show this detached plasma sheet, now a free plasmoid, accelerating tailward under the influence of pre-existing plasma pressure gradients. Another force accelerating the plasmoid is the magnetic tension of the newly reconnected lobe field lines (lines 6 and 7) that are wrapped around it and contracting tailward, producing a 'sling-shot' effect. We note that the plasma sheet section that is cut off to form the plasmoid extends from $r \approx 20 R_E$ to the distant neutral line, now known to be at $r \approx 100 R_E$ (rather than $r \approx 60 R_E$ as implied in Fig. 7). Thus, the plasmoid that moves out through the tail is ~80R_E long.

In panel 9 the plasmoid has departed but reconnection of lobe field lines continues at the substorm neutral line which remains at the location of its original formation. The plasma sheet downstream of N′ is very thin because the plasma accelerated in that direction can escape freely tailward along the now 'interplanetary' field lines (class 2 in Fig. 1). The sheath of newly reconnected lobe field lines that envelopes the departing plasmoid (e.g. in panel 8) is called the 'separatrix layer' because it is bounded by the field lines that (at any instant) connect to the neutral line and that thus constitute the separatrix between open lobe (class 3) and interplanetary (class 2) field lines. We shall see below that the separatrix layer is clearly identifiable in more distant tail observations and provides an important clue in the identification of plasmoids there.

Panel 10 shows the substorm neutral line (now labeled N″) retreating down the tail, still jetting plasma earthward and tailward as it goes. The plasma jetting earthward (and the new closed field lines that thread it) causes a progressive restoration of the plasma sheet toward its pre-substorm configuration.

Typical time scales of the transitions depicted in Fig. 7 are as follows: The beginning of reconnection (panel 2) probably coincides to within ~ 1 min with the onset of substorm signatures at Earth. The departure of the plasmoid's earthward end to distances beyond $\sim 35\,R_E$ is accomplished within 5–10 min of substorm onset. The tailward retreat of the neutral line can occur anywhere from 30 to 120 min after substorm onset. It is not presently known why the substorm neutral line remains immobile for so long, nor what causes it finally to move tailward which it seems to do at fairly high speed (perhaps 100 km s^{-1}). We do know, however, that the retreat of the neutral line is very often signalled at Earth by a rapid poleward surge (or 'poleward leap') of the westward electrojet (Hones *et al.* 1973; Pytte *et al.* 1978; Hones *et al.* 1984*c*; Hones 1985). This is indicated by a sudden subsidence of geomagnetic perturbation in the auroral zone and the simultaneous onset of perturbation at more poleward latitudes.

We now discuss the signatures of the processes in Fig. 7 that a satellite at $\sim 35\,R_E$ (depicted by the black dot) would see and later we examine satellite data to see what makes up these signatures. The satellite would see tailward flow of plasma starting with panel 2 and continuing as long as it is in either the plasmoid or the separatrix layer (i.e. through to panel 7 or 8, and possibly 9). If the satellite is far enough from the midplane to be outside the thin downstream plasma sheet, it would cease to detect the hot flowing plasma between panels 7 and 8. Initially the flowing plasma would be threaded with a northward magnetic field, but the field would quite soon become southward when the O line passes the satellite (between panels 6 and 7). Energetic electrons ($E > 100$ keV) are usually found to populate the plasma sheet during substorms, possibly accelerated in the reconnection process. Because of their very high speed ($\sim 40\,R_E$ s^{-1}) these electrons have been successfully used as probes of magnetic field topology. On closed field lines or on closed loops, as in a plasmoid, they have nearly isotropic angular distributions; on open field lines (or interplanetary field lines) in the tail they stream tailward from their source nearer the Earth. Thus, early in the interval of tailward flow (i.e. panels 2–7) the satellite would see isotropic energetic electrons. However, electrons would become tailward streaming as the trailing edge of the plasmoid passes (between panels 7 and 8), while the plasma would display decreasing density but continuing tailward flow.

During the interval ($\frac{1}{2}$–2 hr) depicted by panel 9 the satellite may or may not see the plasma sheet. If it did, it would see tailward streaming energetic electrons and tailward flowing plasma threaded with a southward magnetic field. When the neutral line retreats (panel 10) the satellite would detect earthward flowing plasma threaded with a northward magnetic field and an isotropic distribution of energetic electrons as it is enveloped by the expanding plasma sheet.

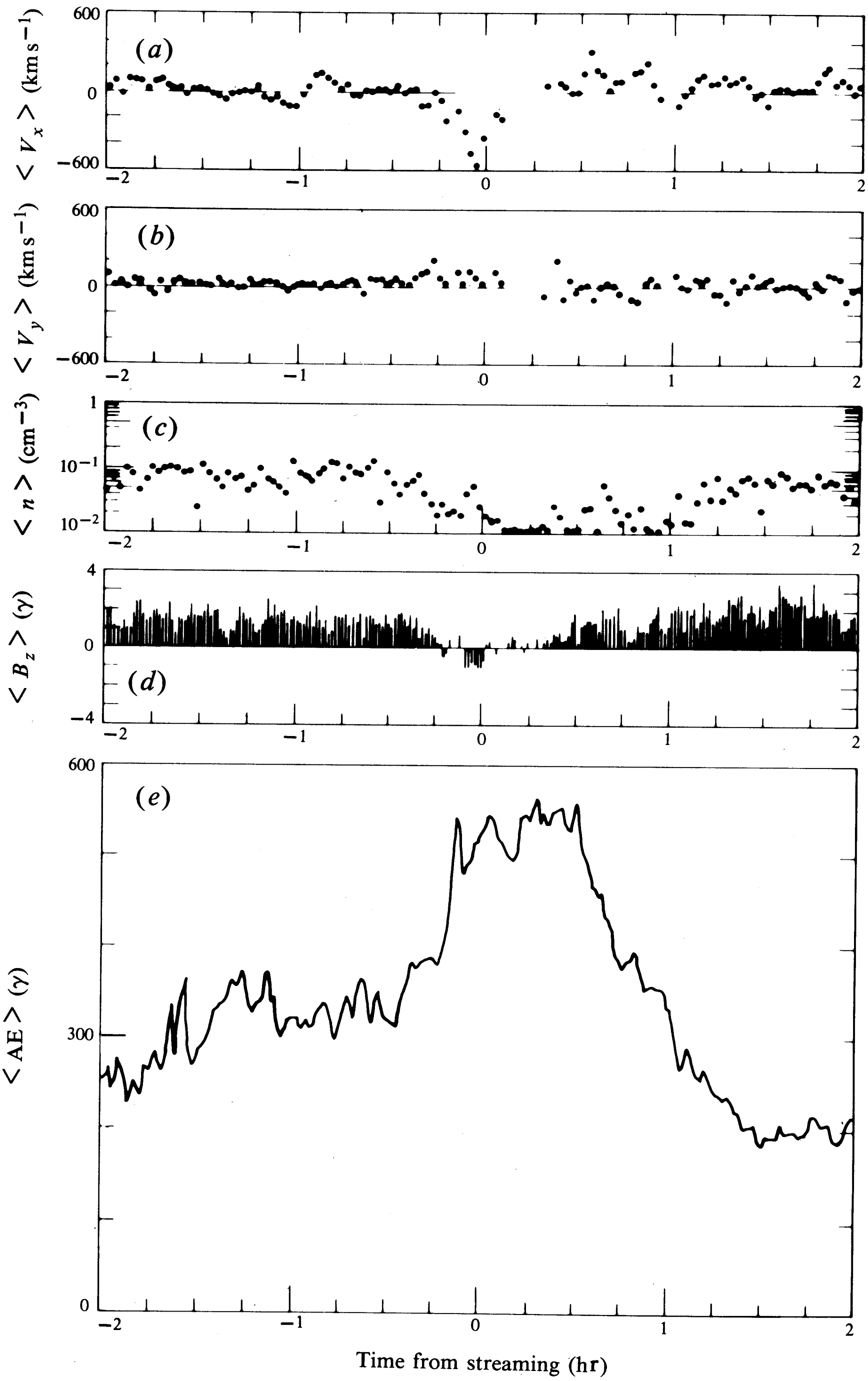

Fig. 8. Superposed epoch analysis of (*a*) the *x* component of the plasma flow velocity (positive *x* is earthward); (*b*) the *y* component of plasma flow velocity (positive *y* is duskward); (*c*) the plasma density; (*d*) the *z* component of the magnetic field; and (*e*) the AE index. Plotted values are the median over 16 events. Zero epoch time $T = 0$ is determined by the first observation of intense streaming of >200 keV electrons. [From Bieber *et al.* (1982).]

We now turn to an actual data set to examine these signatures; this is shown in Fig. 8. Shown are the results of a superposed epoch analysis of plasma, magnetic field and energetic electron parameters measured by the IMP 8 satellite in the magnetotail and by associated geomagnetic activity, the data having been acquired during 16 individual substorms. The zero epoch time ($T = 0$) is determined in each event by the first observation of intense tailward streaming of >200 keV electrons. We take the (average) substorm onset time to be at $T = -10$ min, the time of the rapid increase of the geomagnetic index AE (panel 2 of Fig. 7). We see that tailward plasma flow (negative V_x) starts then, and about 5 min later B_z turns southward (negative) (panels 6 and 7 of Fig. 7). At $T = 0$ the energetic electrons start streaming tailward and by $T = 5$ min the plasma density n has dropped below the measurement threshold (panels 7 and 8). From $T = 5$ to 30 min the plasma density is low and the satellite is, on average, outside the plasma sheet (panel 9). At $T \approx 30$ min AE starts decreasing (the poleward leap of the electrojet), the plasma density increases, V_x is positive (earthward) the B_z becomes strongly positive (panel 10) as the plasma sheet recovers. Note that the satellite first passes through the separatrix layer as it enters the recovering plasma sheet. Earthward of the neutral line the separatrix layer is not as easily identified as when tailward because it does not represent a topology different from the rest of the earthward plasma sheet, i.e. they are both regions of closed field lines (class 1). Yet, the separatrix layer is usually identifiable as a region of earthward streaming ions.

(b) Observations in the Distant Tail

We now shift our observation point from the near tail where the plasmoid is disconnected from Earth to the distant tail where its later approach and passage can be clearly seen. During 1983 the satellite ISEE 3 twice travelled far out through the magnetotail and back to Earth, each time spending a month or more at distances of $\sim 200 R_E$. The identification of passing plasmoids was made soon after the data from these distant orbits began to be processed (Hones *et al.* 1984*a*; Scholer *et al.* 1984; Siscoe *et al.* 1984). It was found that the magnetotail at these distances remains a coherent structure with a plasma sheet and lobes, as seen in Fig. 6, but that it 'waves around' due probably to changes in the direction of flow of the solar wind. Thus ISEE 3, when at large distances, was outside the magnetotail about as often as it was within it. When inside the tail, ISEE 3 was usually in the lobe, suggesting that the plasma sheet at those distances is usually quite thin. However, it was soon found that plasma sheet appearances often occurred about 20–30 min after a substorm began at Earth (Hones *et al.* 1984*a*). At those times the plasma sheet contained hot plasma flowing rapidly (500–1000 km s^{-1}) tailward; most importantly, it was found that the first indication such an event was about to occur was the appearance of tailward streaming energetic (~ 100 keV) electrons several minutes before the hot plasma appeared and while the magnetic field was still lobe-like, i.e. strong and directed steadily earthward or tailward. When the hot plasma was seen (when the plasma sheet enveloped ISEE 3), the energetic electrons became isotropic (Scholer *et al.* 1984). These electron signatures can be recognized as first the arrival of the separatrix layer overlaying an advancing plasmoid, and then the arrival of the plasmoid itself with its closed magnetic loop structure. Another feature of the plasmoid's arrival is a brief northward turning of the magnetic field, followed by a usually more prolonged southward field.

There were occasions when a plasmoid passed and ISEE 3 did not actually enter it, but remained in the lobe. Then, only a north-then-south deflection of the lobe magnetic field was observed (Siscoe *et al.* 1984). In some cases when ISEE 3 was outside the tail as a plasmoid approached, it was temporarily enveloped by the tail and then left shortly after the plasmoid passed (Hones *et al.* 1984*a*).

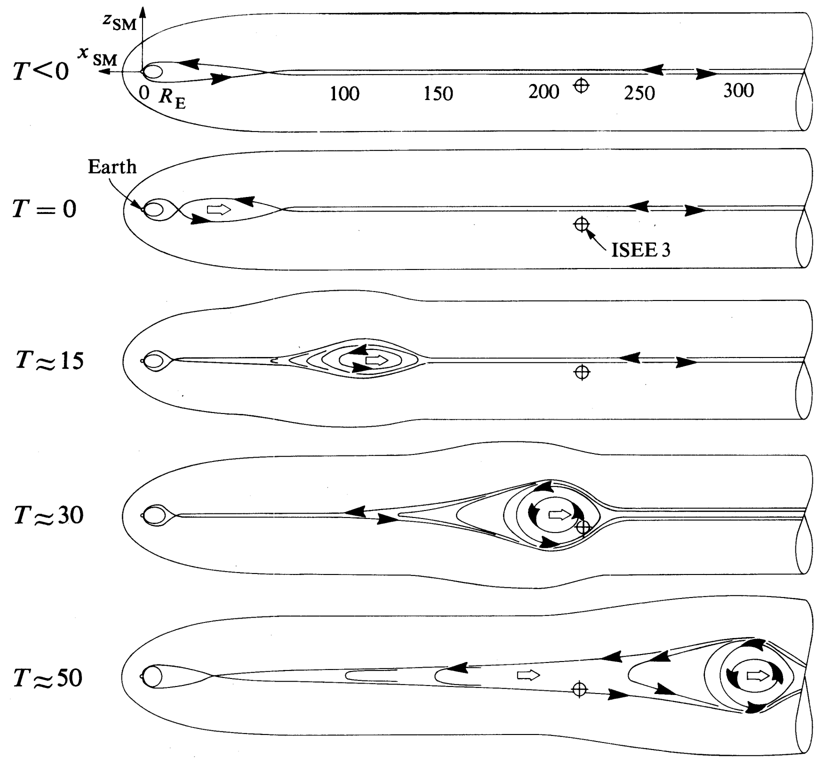

Fig. 9. Model depicting the severance of (a longitudinal sector of) the plasma sheet at the onset of the substorm expansive phase ($T = 0$) and its departure along the tail as a closed magnetic structure, i.e. a plasmoid. Solid arrows indicate the magnetic field direction and open arrows the plasma flow. [From Hones *et al.* (1984*a*).]

The interpretation given to these observations is represented in Fig. 9. At $T < 0$ the closed plasma sheet extends to a distant neutral line around $100 R_E$. At $T = 0$ the plasma sheet is disconnected near the Earth and by $T \approx 30$ min it envelopes ISEE 3. By then, the plasmoid has expanded to a large size because of the reduced magnetic pressure of the distant lobes. This large object moving along the tail axis creates a bulge in the accompanying tail diameter. Also, the plasmoid is followed (and pulled tailward) by a large region of later reconnected lobe (now interplanetary) field lines, referred to as the 'post-plasmoid plasma sheet'.

In Fig. 10 we show the results of a study of a single plasmoid passage at ISEE 3, illustrating the signatures discussed above. The plasmoid resulted from a substorm that began at 0250 UT. At the time of these measurements ISEE 3 was $217 R_E$ downstream from Earth. In Fig. 10 we notice several abrupt parameter changes: (1) a sudden appearance of energetic electron flux, streaming in the tailward direction,

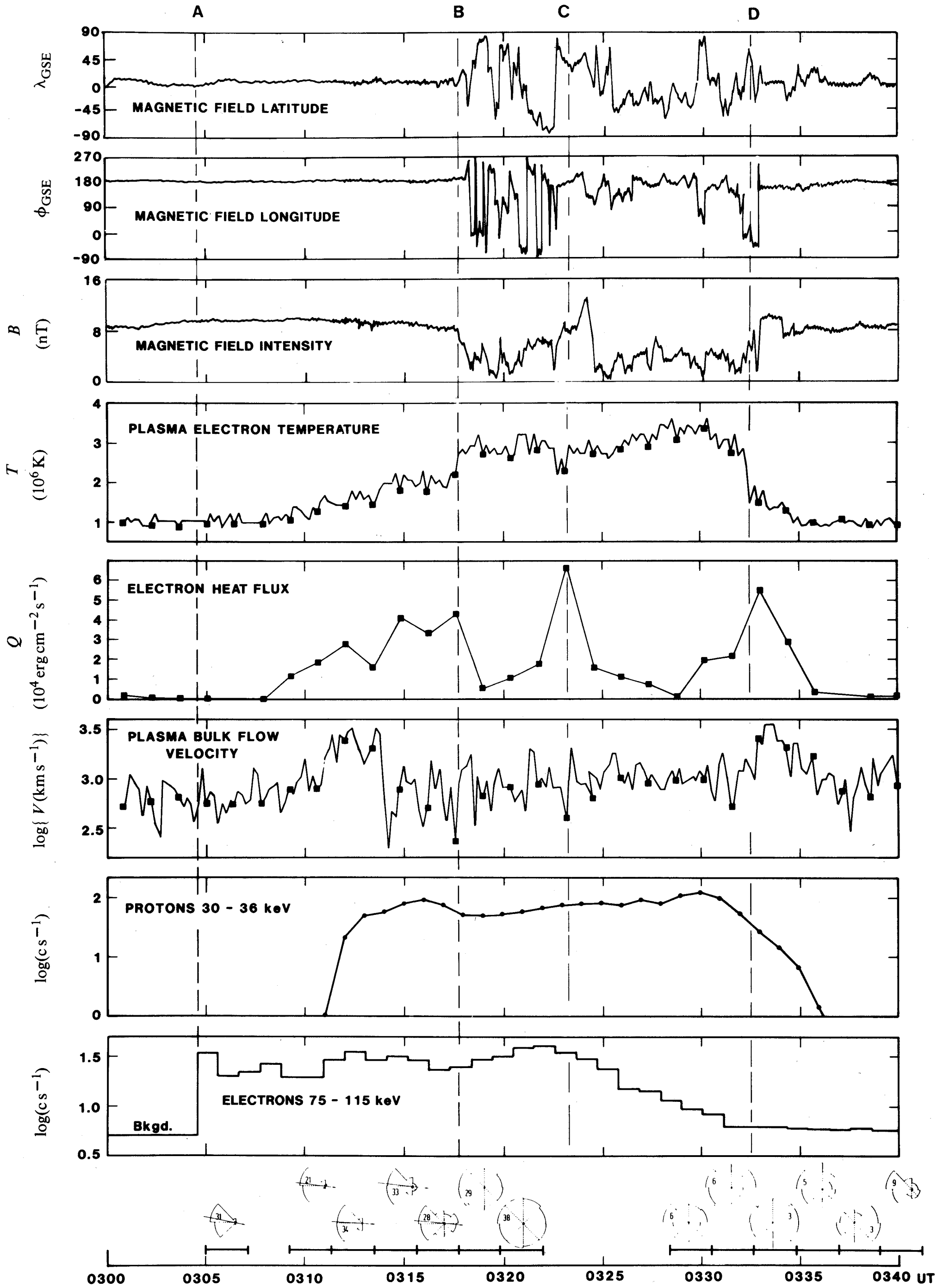

Fig. 10. Data from the ISEE 3 satellite showing the passage of a plasmoid at $r = 217 R_E$ on February 16, 1983. At bottom are azimuthal angular distributions of the 75–115 keV electrons with lines indicating the 128 s time intervals over which they were measured. Leftward pointing sectors (as in the first distribution for example) designate tailward streaming electrons. The letters A–D at the top mark important transitions that are indicated in Fig. 11.

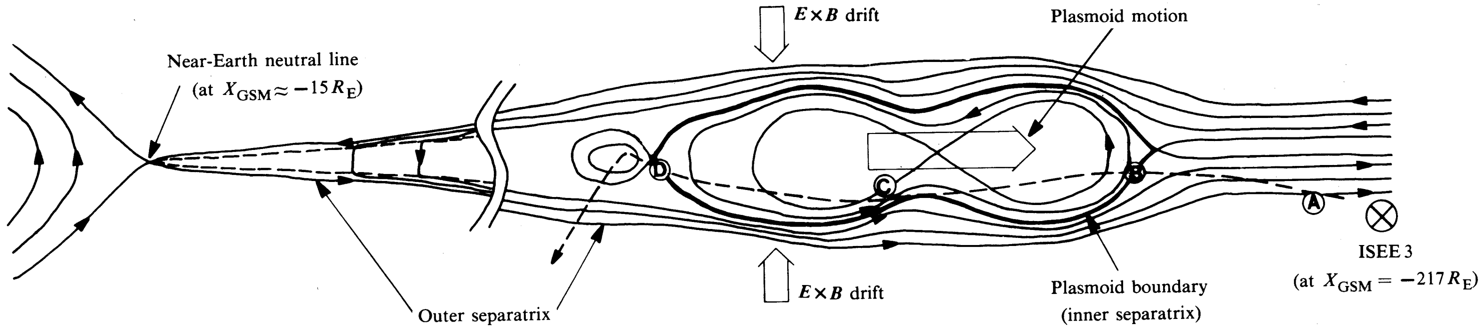

Fig. 11. Schematic diagram of the plasmoid of February 16, 1983 and its surrounding separatrix layer. The dashed curve is the inferred path of ISEE 3 through the structure, crossing the separatrix at A, entering the plasmoid at B, encountering an indentation of the plasmoid (or a waving of the plasma sheet) at C, leaving the plasmoid at D, and soon after crossing the separatrix again. [From Hones *et al.* (1984 *b*).]

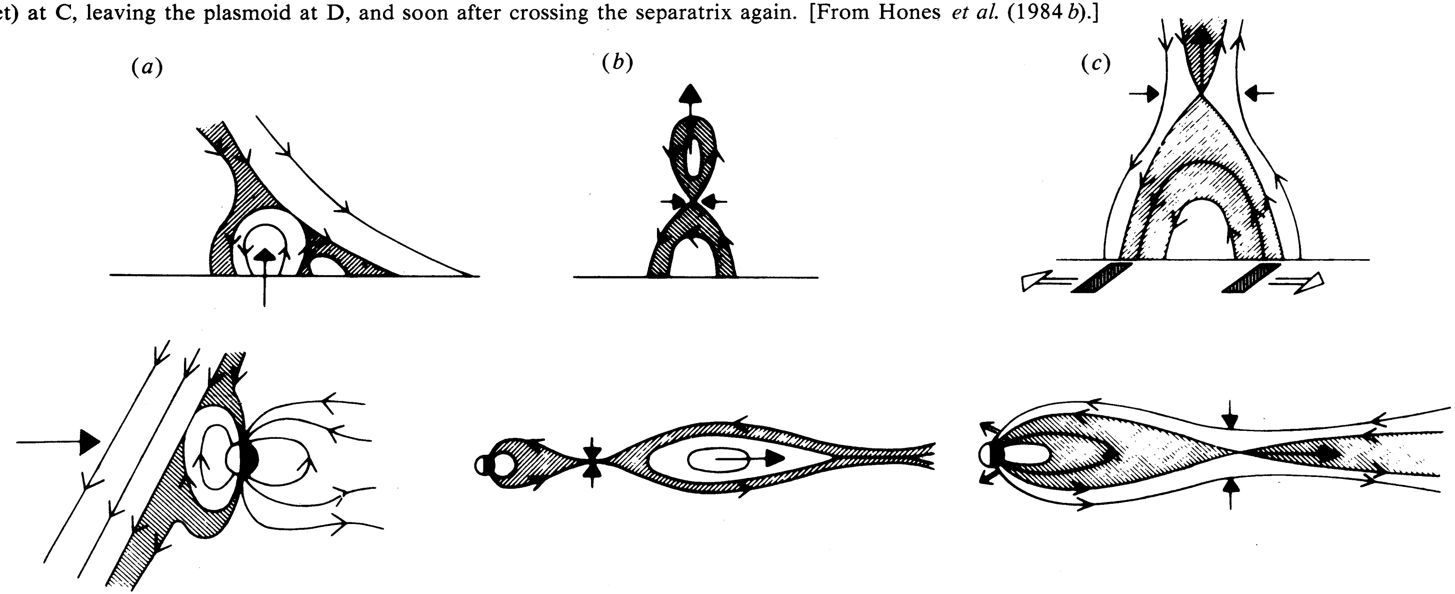

Fig. 12. Apparent similarities between a solar flare (*top*) and the magnetosphere (*bottom*) (see Section 4). [From Priest (1984).]

at ~0304 : 30 UT; (2) a sudden increase of the 30–36 keV proton flux at ~0311 UT following a more gradual increase of plasma electron heat flux and plasma electron temperature that started at ~0308 UT; (3) a jump of the plasma electron temperature coincident with a decrease of heat flux and magnetic field strength at ~0317 : 40 UT (also at about this time the energetic electron flux ceases its strong tailward streaming and becomes much more isotropic); and (4) the inverse signatures of increasing B, increasing heat flux and decreasing electron temperature at ~0332 : 30 UT. The energetic electron flux has disappeared after the measurement from 0339 : 03 UT to 0341 : 11 UT, which showed a low flux streaming tailward.

This whole sequence of signatures is easily understood in the context of a tailward moving plasmoid, which is depicted in Fig. 11. Letters A–D along the suggested path of ISEE 3 mark transitions similarly lettered in Fig. 10.

4. Discussion

In this paper we have discussed briefly evidence for magnetic reconnection and plasmoid formation on the Sun (in flares and possibly at other times as well) and, at greater length, the evidence that these processes occur in the Earth's magnetotail during substorms. The evidence for their occurrence on the Sun is substantial; that for their occurrence in the magnetotail is even stronger. There are obvious analogies between the reconnection scenario for the Sun and that for the magnetotail. Fig. 12 illustrates three of these analogies: (*a*) Emerging flux reconnection on the Sun seems similar to dayside reconnection, a matter to which we have given little attention here (but see Fig. 1). (*b*) Two ribbon flares bear some similarity to substorms, with an X line forming below a rising filament in one case and earthward of the escaping plasmoid in the other. (*c*) In the flare main phase the Hα ribbons move apart and the X line rises, similar to the aurora's poleward leap (Hones 1985) and the tailward retreat of the neutral line which are regarded as the terminal phase of a substorm.

However, we must be careful not to take these analogies too seriously because there are important differences in geometry and in parameter regime, and different physical effects are present. The build-up to flares and substorms appears to be quite different. That for flares is imposed by convective motion of the photosphere at the feet of the field lines which will eventually reconnect. That in the magnetosphere is imposed from outside, i.e. by the action of the solar wind pulling magnetic flux into the magnetotail. Furthermore, vorticity appears to play an important role on the Sun in applying the magnetic stress that is ultimately relieved by reconnection (see e.g. Priest 1984). Twisted fields seem to be less important in the magnetosphere.

Nevertheless, it is possible that there could be a useful carry over of information and ideas between these two research areas. Perhaps it is most likely that information from magnetotail observations, where detailed *in situ* measurements are possible, can be applied in flare studies. For example, the ISEE 3 observations of plasmoids in the far tail have focused attention on the existence and characteristics of the separatrix layer. Is it possible that separatrix layers may be identified in remote observations of the corona, such as those of Fig. 4, or be found enveloping the plasmoid structures when they are encountered in interplanetary space? It is quite clear that close interaction between these two fields will be beneficial to both.

Acknowledgment

This work was performed under the auspices of the U.S. Department of Energy.

References

Bame, S. J., Asbridge, J. R., Feldman, W. C., Gosling, J. T., and Zwickl, R. D. (1981). *Geophys. Res. Lett.* **8**, 173.

Bavassano, B., Mariani, F., and Villante, U. (1974). *Space Res.* **14**, 403.

Bieber, J. W., Stone, E. C., Hones, E. W., Jr, Baker, D. N., and Bame, S. J. (1982). *Geophys. Res. Lett.* **9**, 664.

Burlaga, L. F., and Behannon, K. W. (1982). *Sol. Phys.* **81**, 181.

Dungey, J. W. (1953). *Philos. Mag.* **44**, 725.

Dungey, J. W. (1961). *Phys. Rev. Lett.* **6**, 47.

Giovanelli, R. G. (1946). *Nature* **158**, 81.

Gosling, J. T., Hildner, E., MacQueen, R. M., Munro, R. H., Poland, A. I., and Ross, C. L. (1974). *J. Geophys. Res.* **79**, 4581.

Gosling, J. T., Pizzo, V., and Bame, S. J. (1973). *J. Geophys. Res.* **78**, 2001.

Hones, E. W., Jr (1979*a*). *Space Sci. Rev.* **23**, 393.

Hones, E. W., Jr (1979*b*). *In* 'Dynamics of the Magnetosphere' (Ed. S. I. Akasofu), p. 545 (Reidel: Dordrecht).

Hones, E. W., Jr (1985). *J. Geophys. Res.* **90**, 5333.

Hones, E. W., Jr, Asbridge, J. R., Bame, S. J., and Singer, S. (1973). *J. Geophys. Res.* **78**, 109.

Hones, E. W., Jr, Baker, D. N., Bame, S. J., Feldman, W. C., Gosling, J. T., McComas, D. J., Zwickl, R. D., Slavin, J. A., Smith, E. J., and Tsurutani, B. T. (1984*a*). *Geophys. Res. Lett.* **11**, 5.

Hones, E. W., Jr, Birn, J., Baker, D. N., Bame, S. J., Feldman, W. C., McComas, D. J., Zwickl, R. D., Slavin, J. A., Smith, E. J., and Tsurutani, B. T. (1984*b*). *Geophys. Res. Lett.* **11**, 1046.

Hones, E. W., Jr, Pytte, T., and West, H. I., Jr (1984*c*). *J. Geophys. Res.* **89**, 5471.

Hones, E. W., Jr, and Schindler, K. (1979). *J. Geophys. Res.* **84**, 7155.

Hoyle, F. (1949). 'Some Recent Researches in Solar Physics' (Cambridge Univ. Press).

Illing, R. M. E., and Hundhausen, A. J. (1983). *J. Geophys. Res.* **88**, 10210.

Kopp, R. A., and Pneuman, G. W. (1976). *Sol. Phys.* **50**, 85.

MacQueen, R. M. (1980). *Phil. Trans. R. Soc. London* A **297**, 605.

Montgomery, M. D., Asbridge, J. R., Bame, S. J., and Feldman, W. C. (1974). *J. Geophys. Res.* **79**, 3103.

Palmer, I. D., Allum, F. R., and Singer, S. (1978). *J. Geophys. Res.* **83**, 75.

Parker, E. N. (1957). *J. Geophys. Res.* **62**, 509.

Petschek, H. E. (1964). *In* 'The Physics of Solar Flares', NASA Special Publn SP-50 (Ed. W. N. Hess), p. 425 (NASA: Washington, DC).

Pilipp, W. G., and Morfill, G. (1978). *J. Geophys. Res.* **83**, 5670.

Priest, E. R. (1984). *In* 'Magnetic Reconnection in Space and Laboratory Plasmas' (Ed. E. W. Hones, Jr), p. 63 (AGU: Washington, D.C.).

Pytte, T., McPherron, R. L., Kivelson, M. G., West, H. I., Jr, and Hones, E. W., Jr (1978). *J. Geophys. Res.* **83**, 5256.

Scholer, M., Gloeckler, G., Klecker, B., Ipavich, F. M., Hovestadt, D., and Smith, E. J. (1984). *J. Geophys. Res.* **89**, 6717.

Siscoe, G. L., Sibeck, D. G., Slavin, J. A., Smith, E. J., Tsurutani, B. T., and Jones, D. E. (1984). *In* 'Magnetic Reconnection in Space and Laboratory Plasmas' (Ed. E. W. Hones, Jr), p. 240 (AGU: Washington, D.C.).

Sweet, P. A. (1958). *In* 'Electromagnetic Phenomena in Cosmical Physics' (Ed. B. Lehnert), p. 123 (Cambridge Univ. Press).

Vasyliunas, V. M. (1975). *Rev. Geophys. Space Phys.* **13**, 303.

Walker, R. C., Villante, U., and Lazarus, A. J. (1975). *J. Geophys. Res.* **80**, 1238.

Zwickl, R. D., Baker, D. N., Bame, S. J., Feldman, W. C., Gosling, J. T., Hones, E. W., Jr, McComas, D. J., Tsurutani, B. T., and Slavin, J. A. (1984). *J. Geophys. Res.* **89**, 11007.

Manuscript received 11 March, accepted 12 July 1985