OBSERVATIONS IN THE EARTH'S MAGNETOTAIL RELATING TO MAGNETIC MERGING*

(Invited Paper)

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Abstract. For more than a decade there has been growing conviction that the burst of energy from a solar flare is first stored in magnetic fields and is then released rapidly by magnetic field annihilation (magnetic merging). There has also been recognition that magnetic merging may be responsible for the energy release manifested in auroral phenomena at the Earth. The most substantial evidence that magnetic merging does indeed occur in the Earth's magnetosphere and causes the auroral phenomena is provided by recent observations, in the magnetotail, of very rapid ($\sim$500 km s^{-1}) tailward, then earthward, flow of plasma during magnetospheric substorms. The observations, made with the Vela and IMP satellites, reveal also that the component of the tail magnetic field perpendicular to the tail neutral sheet changes polarity at the time of the reversal of plasma flow. These features are interpreted as indicative of passage of a magnetic neutral line, at which magnetic merging is proceeding, past the observing satellite. This paper describes an example of such observations made with IMP 6. It is anticipated that such systematic measurements of the plasma, energetic particles and magnetic field in the neighborhood of the passing neutral line on many such occasions will provide a general understanding of the magnetic merging process which can then be applied to studies of solar flares and other astrophysical phenomena.

1. Introduction

The thought that magnetic field reconnection, or magnetic merging, plays a part in geophysical phenomena originated nearly as long ago as did the idea (Giovanelli, 1947, 1948) that this process is involved in the sudden release of energy that characteracterizes a solar flare. Hoyle (1949) suggested that if an interplanetary magnetic field (IMF) exists perhaps there would be magnetic neutral lines at the interface between the Earth's field and the IMF. The particles that precipitate into the Earth's polar atmosphere, producing the auroras, might thus derive their energy from merging of the magnetic fields along these neutral lines. When it was found (Coleman *et al.*, 1960) that an IMF actually does exist in the outward flowing solar wind, Dungey (1961) revived and extended Hoyle's idea, proposing that magnetic merging with the IMF occurs at the sunward surface of the Earth's field when the IMF has a southward component (i.e., opposite to the direction of the Earth's field there). A domain of 'open' field lines is thus produced; i.e., interplanetary field lines whose feet are attached to the Earth's polar regions. Swept onward by the solar wind, open field lines from opposite poles of the Earth can later reconnect with each other on the down-wind side of the Earth to become closed magnetic field lines once again, connected at both ends to the Earth.

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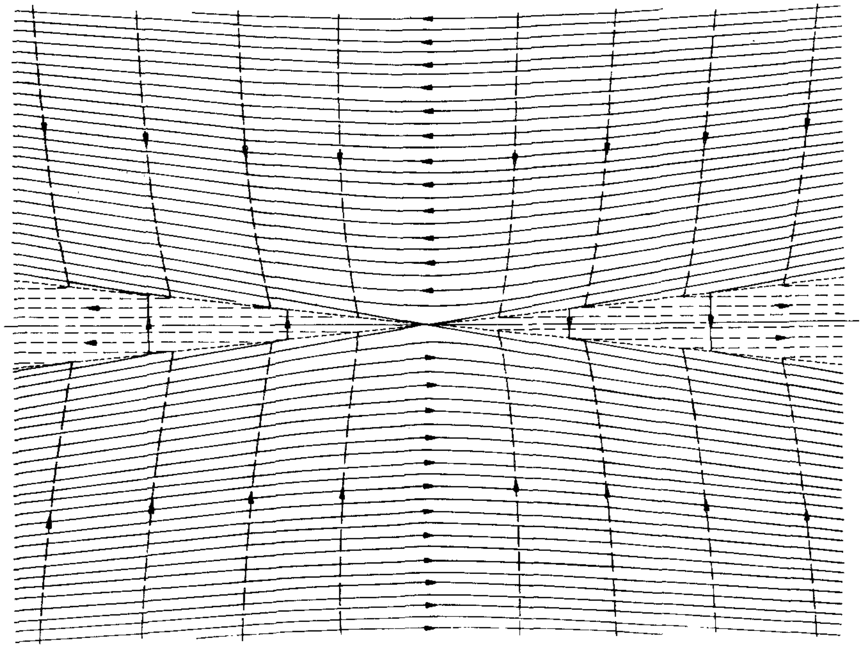

Fig. 1. Magnetic field lines (solid lines) and plasma flow streamlines (dashed lines) in Petschek's model. (From Vasyliunas, 1975).

The manner in which magnetic fields merge at the boundary between two regions of plasma containing oppositely directed field lines has been the subject of a number of theoretical studies. In studies by Sweet (1958) and Parker (1963) the merging was assumed to proceed by diffusion, i.e., the magnetic field energy is dissipated solely due to the finite conductivity of the plasma. Petschek (1964) pointed out that standing magneto-hydrodynamic waves would be generated at the boundary and would greatly enhance the rate of merging. In any case the plasma moves toward the boundary from both sides, enters a 'diffusion region' (also called a magnetic neutral line) and is ejected from it in both directions along the boundary. The process is illustrated in Figure 1 which is a representation of Petschek's description of the merging process. The theory indicates that the plasma is ejected from the diffusion region along the boundary at speeds near the Alfvén speed, V_A, characteristic of the conditions outside the boundary. It is to be noted (Figure 1) that the magnetic field lines threading the ejected plasma are normal to the boundary and have opposite polarity on the two sides of the diffusion region.

This paper describes observations of plasma and magnetic field in the tail of the Earth's magnetosphere (the magnetotail) which have revealed these two predicted features of magnetic merging (rapid plasma flow in both directions along the boundary and reversal of the field components normal to the boundary) occurring in association with magnetospheric substorms. These observations constitute a very substantial confirmation that magnetic merging does indeed occur in the magnetotail and that it serves to convert stored magnetic energy to kinetic energy of auroral particles.

2. Observations

2.1 Substorm behavior of the magnetotail plasma sheet

The discovery of the two direct consequences of magnetic merging noted above was made possible in part because of a remarkable behavior of the magnetotail plasma sheet during magnetospheric substorms. Recognition of this behavior developed from several years of plasma sheet observations with the Vela satellites. Figure 2 depicts the noon-midnight meridian plane of the magnetosphere. The plasma sheet lies along the midplane of the magnetotail and carries the current which causes the magnetic field reversal across the midplane. The plasma sheet extends all the way across the tail and is usually $\geqslant 6$ Earth radii (R_E) thick. (One Earth radius = 6370 km.)

The Vela satellites are in circular orbits of radius $\sim 18 R_E$ that are inclined at an

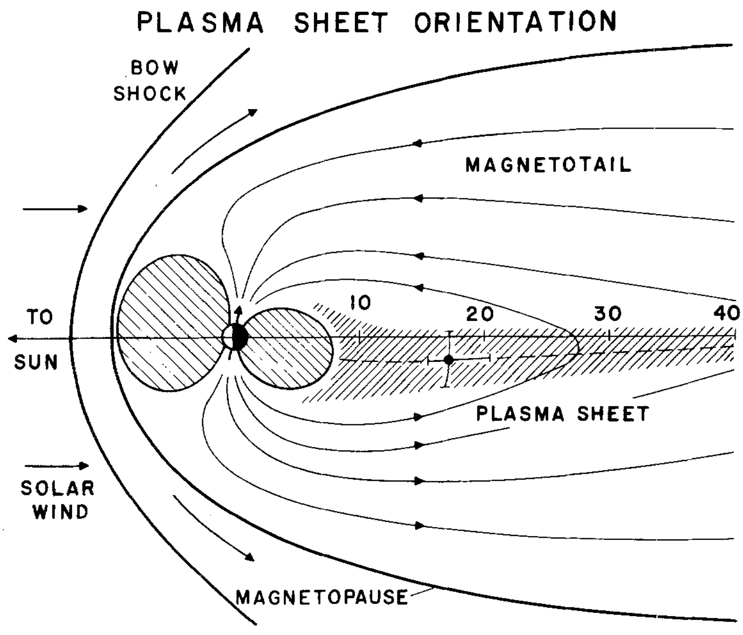

Fig. 2. Noon-midnight meridian plane of the Earth's magnetosphere. The bow shock and magnetopause are shown with arrows indicating the path of solar wind flow through the shock and around the magnetosphere. Within the magnetotail magnetic field lines point away from the Earth in the southern half and toward the Earth in the northern half. The plasma sheet is indicated by the long hatched region running off the figure to the right. Its earthward edge is shown reaching in to the region of the trapped radiation belts. The dashed line through the plasma sheet represents the magnetic 'neutral sheet', a region where a rather sharp reversal of the tail magnetic field is sometimes observed. The sheet is not strictly neutral because a finite but small (a few times 10^{-6} G) field is usually observed during its crossings. (From Bame *et al.*, 1967.)

angle of ~60° with respect to the ecliptic plane. The satellites carry plasma probes that measure the energy spectra of electrons and of protons in the range ~10 eV < E < 30 keV. They also carry other particle detectors that measure the fluxes of electrons and protons above several higher energy thresholds. The plasma sheet is observed by the Vela satellites on each of their passes through the tail. Within it the plasma density is ~0.1 to 1.0 cm^{-3}. The plasma electrons and protons typically have nearly Maxwellian spectra peaked at a few hundred eV and at a few keV, respectively. The flux of energetic electrons (e.g., $E_e > 40$ keV) can be below the thresholds of the detectors during very quiet geomagnetic conditions but is often quite intense during active conditions. Energetic protons (e.g., $E_p \geq 0.3$ MeV) are observed much less frequently and only in association with strong geomagnetic activity (Hones *et al.*, 1976b). Outside the plasma sheet, in the 'lobes' of the magnetotail, plasma density is very low (~10^{-2} cm^{-3}) and energetic particles are not observed.

Early studies with the Vela satellites showed that the plasma sheet becomes very thin during substorms (Hones *et al.*, 1967). The magnetospheric substorm was first recognized as a distinct element of magnetospheric behavior by Akasofu (1964) who made a detailed examination of its manifestations in the auroras (i.e., the 'auroral substorm') at the Earth. An auroral substorm that occurred on 1968, September 14, is illustrated in Figure 3. A bright arc of emission appeared south of College, Alaska at 0930–0931 UT (2330–2331 150° WMT). The bright auroras moved rapidly poleward, reaching far north of College by 0937 UT. Thereafter bright auroral emission persisted over the entire visible sky until 1010 UT. At 1016 UT (picture not shown here) the sky above College suddenly started to become clear of auroras and auroras brightened substantially on the far northern horizon. This was the 'poleward leap' of the auroral activity that has recently come to be recognized as a distinct and identifiable feature that occurs late in many substorms (Hones *et al.*, 1973).

Westward electric currents flow in or near the bright auroral emission and these cause negative deflections of the horizontal component of the magnetic field measured at the Earth under the auroras. Such a deflection, called a 'negative bay' was measured at College during the September 14 substorm (bottom panel of Figure 4). The negative bay started at 0930 UT and reached its peak just before 1000 UT. It was recovering rapidly at 1016 UT.

The top panel of Figure 4 depicts the intensity of the flux of electrons ($E_e \geq 40$ keV) measured at Vela 4A which was in the plasma sheet when the substorm began. A brief spike of electron flux began at precisely 0930 UT. Several minutes later the flux dropped rapidly and fell below the instrument threshold. This was the 'thinning' of the plasma sheet that is characteristically observed at the onset of a substorm, as was noted above. At 1016 UT the electron flux began a rapid rise and soon reached intensities 10 times as great as those encountered before the substorm. The essential features of the plasma sheet's behavior during this substorm on 1968, September 14 can be summarized as

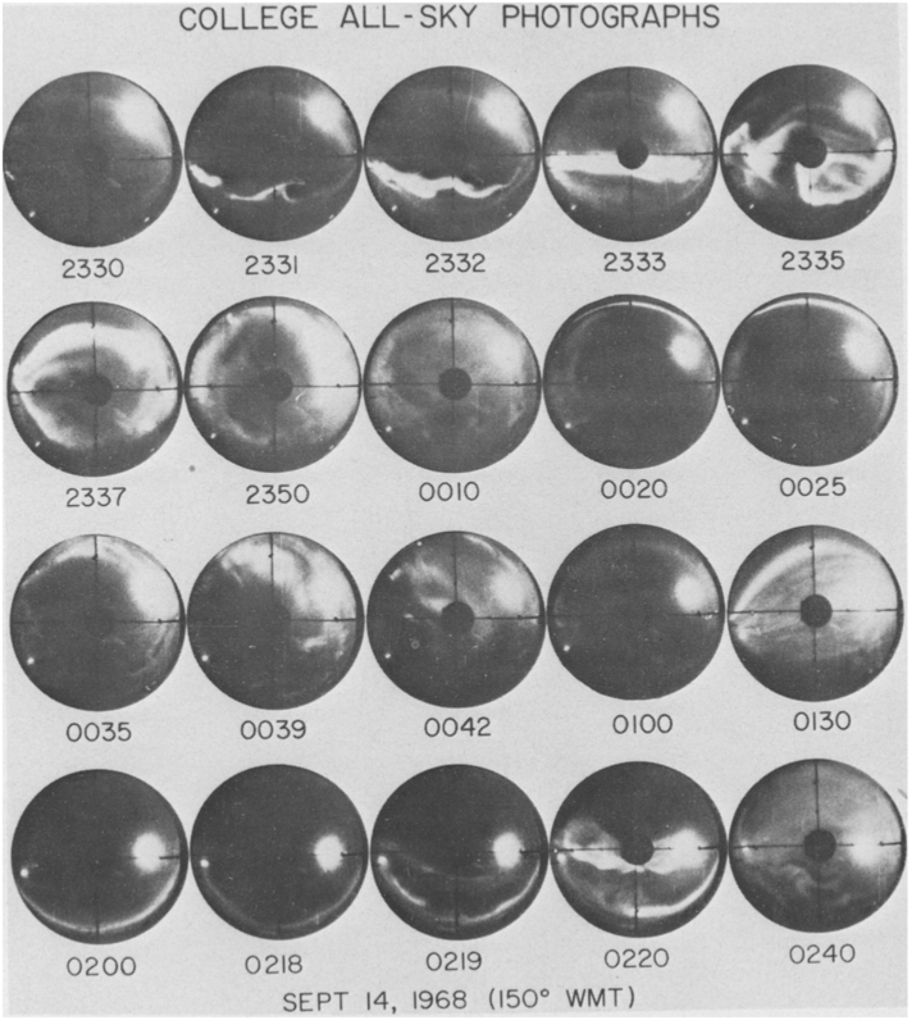

Fig. 3. All-sky camera pictures taken from College, Alaska on 1968, September 14. Magnetic north is at the top. Magnetic west is to the left. Times shown are 150° west meridian time. (From Hones *et al.*, 1971.)

follows:

(a) A brief enhancement of electron flux started coincident with the substorm's onset, i.e., with the brightening of auroras and the sudden deepening of a magnetic bay.

(b) The electron flux then soon dropped to background levels and remained low for about one-half hour while intense auroras and magnetic activity prevailed in the auroral zone.

(c) The electron flux increased suddenly to high levels coincident with a poleward leap of the auroras and with the recovery of the magnetic bay.

The Vela satellites rotate with a period of ~64 s and 16 proton spectra

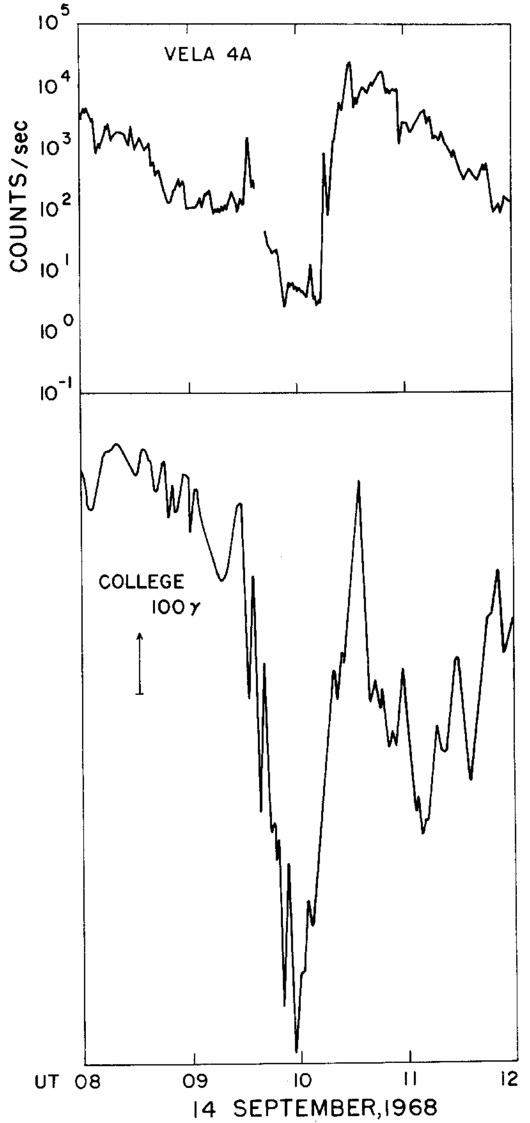

Fig. 4. Top: response of a solid state detector on Vela 4A to energetic electrons ($36 < E_e < 260$ keV) in the plasma sheet. Bottom: horizontal component of the magnetic field at College, Alaska (magnetic latitude = 64.6°). Magnetic local midnight at College is ~1200 UT. (From Akasofu *et al.*, 1971.)

are taken during each rotation by the plasma probes. These measurements reveal that strong anisotropy of the plasma proton flux develops, having one flux peak per rotation, as the plasma sheet thins. The phasing of this flux peak with appropriate Sun signals shows that the anisotropy results from a rapid bulk flow of protons tailward past the satellite. When the plasma reappears the proton flux is again anisotropic but the phasing shows that there is then a bulk flow sunward. On occasions when a Vela satellite is very near the tail's midplane during a substorm, the plasma does not disappear entirely during thinning. Rather, the satellite remains in a thin residual plasma sheet throughout the substorm, in which plasma flows continually tailward. On such occasions a reversal of the plasma flow to the sunward direction is seen, together with an enhancement of plasma and energetic electron intensity, as the plasma sheet recovers late in the substorm.

The interpretation that has been made of this plasma sheet behavior during substorms is depicted in Figure 5. There may be a gradual thinning of the plasma sheet prior to the substorm's onset although this is still rather uncertain and no consistent evidence regarding plasma flow at this time has been found, as is indicated by the question marks in Figure 5a. At the substorm's onset ($T=0$, Figure 5b) a magnetic neutral line forms across the tail earthward of the Vela satellite (V) causing rapid thinning of the plasma sheet and onset of rapid flow of

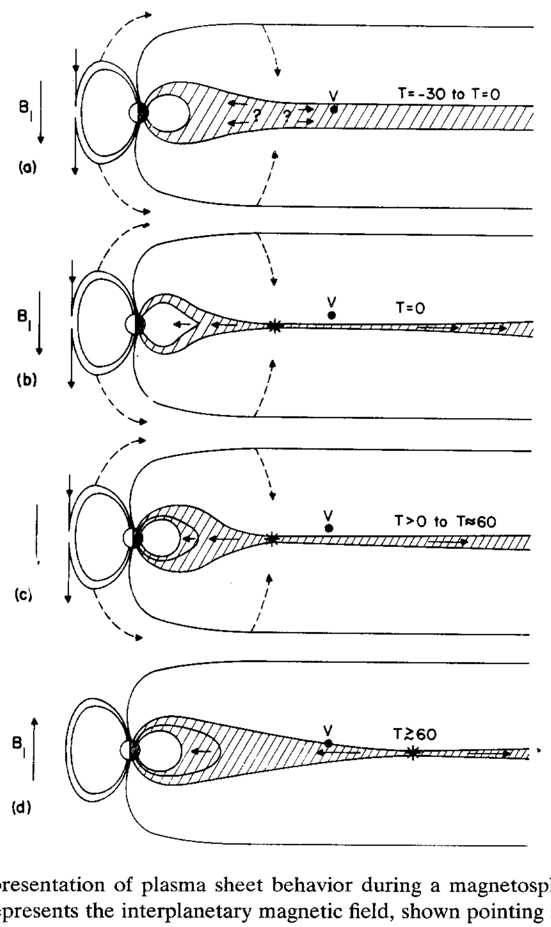

Fig. 5. Schematic representation of plasma sheet behavior during a magnetospheric substorm. The Sun is to the left. B_I represents the interplanetary magnetic field, shown pointing southward (opposite to the Earth's field at the nose of the magnetosphere). Dashed arrows depict possible flow of plasma and magnetic field lines resulting from magnetic merging at the front of the magnetosphere as proposed by Dungey (1961). The plasma sheet is the hatched region. Plasma flow is indicated by arrows in the plasma sheet. A star indicates the magnetic neutral line. A Vela satellite is represented by the dot labeled V. (From Hones *et al.*, 1974.)

plasma tailward and sunward as shown by the arrows. Then, for an interval of tens of minutes to an hour (Figure 5c) the neutral line persists near the location of its formation, causing plasma to be continually ejected sunward and tailward. Only if a Vela satellite is in the region occupied by the thin residual plasma sheet will it sense the continuing tailward flow. Late in the substorm the neutral line suddenly moves far tailward past the satellite (Figure 5d). The thicker portion of the plasma sheet earthward of the neutral line then envelops the satellite and rapid earthward flow of plasma is detected. The arrow labeled B_I represents the IMF which is portrayed here as pointing southward. The possible merging of the magnetic field at the front of the magnetosphere and the subsequent flow of plasma and field lines into the tail, as proposed by Dungey (1961) are indicated in the diagrams.

The interpretation of the observations portrayed in Figure 5 was made without benefit of simultaneous measurements of the magnetic field because the Vela satellites did not carry magnetometers. Recently, however, it has been possible to augment the picture provided by the Vela satellites using data from the Los Alamos plasma probe, the Goddard Space Flight Center magnetometer and the Berkeley energetic particle detector, all on the IMP 6 satellite. IMP 6 was in a highly elliptical orbit with apogee at $32R_E$. The satellite's spin axis was oriented perpendicular to the ecliptic plane. We shall next describe observations made with IMP 6 during a substorm on 1972 October 29.

2.2 IMP 6 Observations during a substorm on 1972, October 29

Figure 6 shows magnetic records from several stations in the northern auroral zone for 1972, October 29–30. The X (north-south) and Z (vertical) components of the field at the polar cap station, Baker Lake, are also shown. A substorm started at ~0600 UT, October 29, shown most clearly at Meanook, where the negative bay onset occurred at 0556 UT (plus or minus about 1 min). The bay reached a peak and immediately started to recover at 0632–0633 UT. The Z-component of the magnetic field at Baker Lake initially went positive, indicating that the westward ionospheric current (and likely, also, the auroras) lay to the south of the station. However at 0632–0633 the Z-component started a rapid negative excursion which indicates that the current moved rapidly poleward at that time (consistent with its departure from the lower latitude station, Meanook, starting at the same time).

The component, B_Z, of the magnetic field normal to the tail's midplane (approximately normal to the ecliptic plane) was continuously positive (i.e., northward) before ~0557 at which it began suddenly to go negative (Figure 7). IMP 6 was $31.1R_E$ from the Earth at solar magnetospheric longitude 160° (20 deg on the evening side of the midnight meridian) and was estimated to be $\sim 2.5R_E$ below the magnetotail neutral sheet. B_Z remained largely negative until ~0628 UT when it commenced to be mostly positive again. The total field intensity, B, increased suddenly to rather high values at ~0601–0602 UT after which it

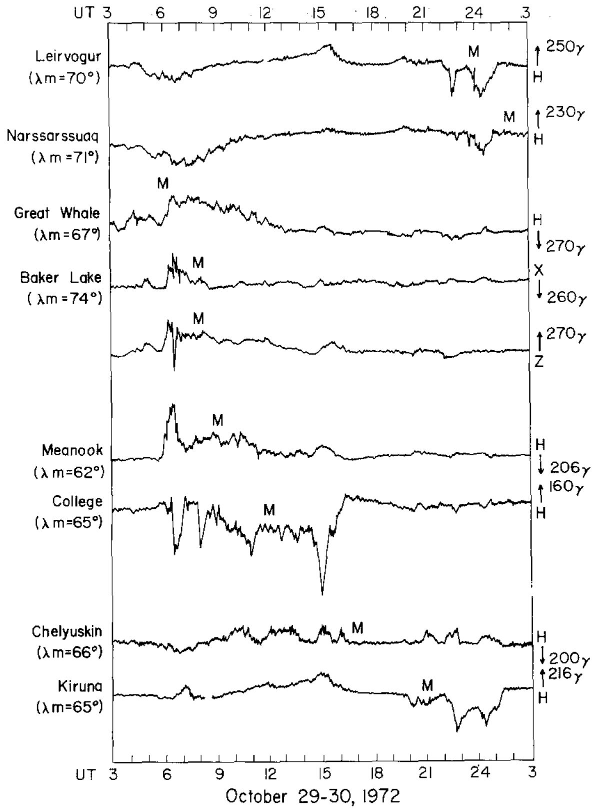

Fig. 6. Magnetic records from several stations on 1972, October 29–30. *M* indicates the UT of magnetic local midnight at each station. (From Hones *et al.*, 1976a.)

decreased, becoming highly variable and generally decreasing further after ~0610 UT. Energetic electron fluxes increased suddenly at 0556:30 UT and the energy spectrum became harder. The fluxes soon decreased, however, and reached very low levels at ~0603 UT. Thereafter the flux was highly variable and often quite low until ~0628–0629 when the fluxes began to increase soon reaching values substantially greater than those encountered before the substorm.

At ~0556:30 there was a substantial increase of the energy density of plasma electrons measured by the plasma probe (Figure 8). This was quickly followed by a decrease to very low values, reached at 0604 UT. Thereafter there was a general increase of the energy density. Plasma proton measurements revealed the onset of very rapid tailward flow of plasma at ~0556:30, continuing until just after 0600 at which time the proton flux fell to such low values that the flow could no longer be measured. When the flux again increased to measurable levels by ~0610–0615, the plasma was still flowing tailward. Reversal of the flow to sunward began ~0628 UT.

In this substorm we have seen, again, the plasma sheet behavior described

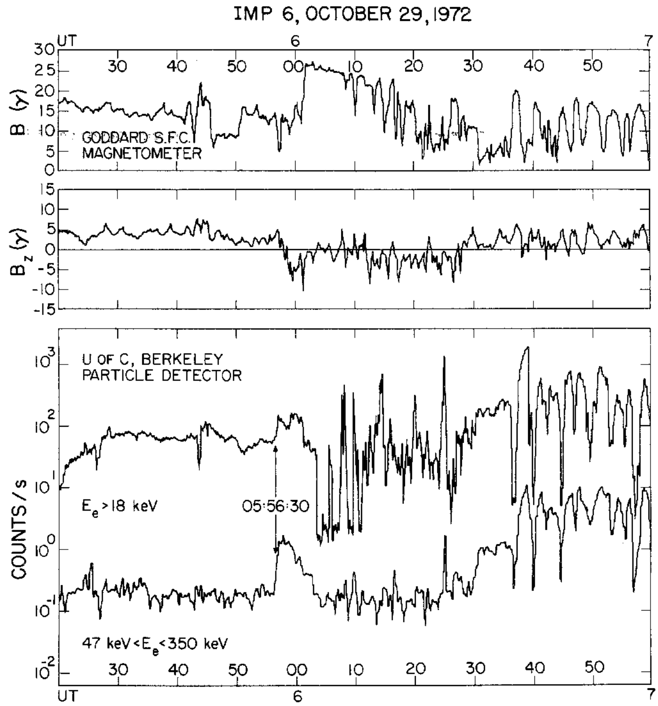

Fig. 7. Top two panels: Total magnetic field, B, and magnetic field component perpendicular to the tail's midplane, B_Z, measured with the Goddard Space Flight Center magnetometer on IMP 6, 1972, October 29. The magnitude of the field is given in gammas (γ). One gamma = 10^{-5} G. Bottom panel: Counting rates of two of the University of California, Berkeley energetic particle detectors on IMP 6.

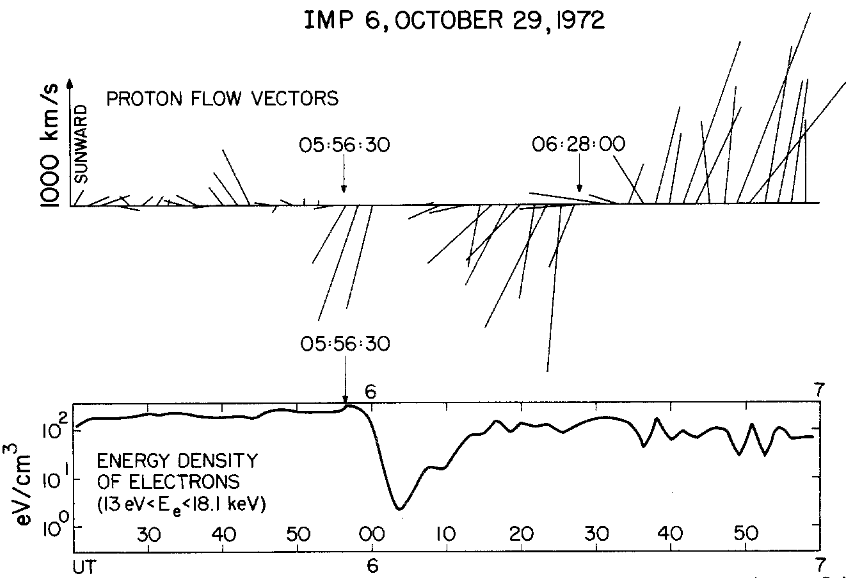

Fig. 8. Top: Flow vectors derived from proton measurements with the Los Alamos Scientific Laboratory plasma probe on IMP 6. Bottom: Energy density of plasma electrons measured with the plasma probe.

above for the 1968, September substorm. But here the simultaneous measurements of plasma, energetic particles and magnetic field have provided further insight:

(a) The spike of energetic electrons starting at 0556 30 UT was accompanied by a brief enhancement of plasma energy density and by the onset of tailward flow of plasma; these coincided closely with the southward turning of B_Z. The onsets of all three of these phenomena coincided (as closely as can be determined from the ground magnetic records) with the onset of the substorm at the ground.

(b) The thinning of the plasma sheet left IMP 6 outside the plasma sheet for several intervals between 0603 UT and 0611 UT (as shown by the deep drops of the >18 keV electrons (Figure 7). Thereafter, until ~0628 UT, IMP 6 was in tailward flowing plasma containing highly variable electron flux and predominantly southward B_Z.

(c) The more enduring recovery of the energetic electron flux (i.e., the plasma sheet recovery) at ~0628 UT was accompanied by northward turning of B_Z and by reversal of plasma flow from tailward to sunward. These phenomena occurred about 4 min before the bay at Meanook began its recovery.

4. Discussion and Conclusions

The behavior of the magnetotail plasma sheet during magnetospheric substorms has been illustrated with two examples. The more detailed data sets available for the 1972, October 29 substorm permits us to conclude with considerable confidence that magnetic merging plays a dominant role in the substorm phenomenon.

Substorm onset is signalled by the formation of a neutral line at some near-Earth location in the plasma sheet. Tailward of the neutral line B_Z turns southward and a tailward rush of plasma begins. It is to be expected that earthward of the neutral line B_Z remains northward and that an earthward rush of plasma begins there. This earthward rush of plasma earthward of the neutral line at substorm onset has, indeed, been observed (Lui *et al.*, 1976). The initial spike of plasma and energetic electrons is a manifestation of the initial tailward surge of plasma. That it is, indeed, a *tailward* surge is illustrated by the flow vectors in the October 29 substorm (Figure 8). After this initial surge of plasma passes the satellite a residual plasma sheet remains which is probably quite thin and in which plasma continues to flow tailward. B_Z is southward in the thin residual plasma sheet and the fluid medium is evidently highly turbulent. Finally, late in the substorm (i.e., tens of minutes to an hour or more after its onset) the neutral line moves quickly tailward to a much more distant location (possibly beyond the Moon's orbit at $r \approx 60\ R_E$) after which earthward flowing plasma, northward B_Z and relatively steady high fluxes of energetic electrons are seen out to distances $\gtrsim 30 R_E$.

The total substorm behavior of the plasma sheet illustrated here, when viewed in the context of Figure 1, constitutes almost incontrovertible evidence for the occurrence of magnetic merging. This behavior permits us, in effect, to view alternately the regions tailward and earthward of the diffusion region in quick succession. The velocities of plasma flow along the plasma sheet range up to ~ 1000 km s^{-1}, approximately the Alfvén speed outside the plasma sheet, which is in accordance with the theoretical results of Petschek (1964). It is to be noted that the reversal of the magnetic field and the flow direction that takes place as the plasma sheet recovers is indicative that the neutral line or diffusion region is passing near the observing satellite. We anticipate that full analyses of the plasma, the magnetic field and other parameters in many such passages of the diffusion region will clarify our understanding of the merging process.

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Discussion

SHEELEY: What do you suppose causes the neutral line to move suddenly (or at all) tailward during substorm recovery?

HONES: The tailward movement of the neutral line occurs very suddenly and is accompanied, at the

Earth, by a very rapid 'poleward leap' of the bright auroras from typical auroral latitudes ($\approx 65°$) to low polar cap latitudes ($\approx 75°$). These phenomena present the appearance of a sudden change of the magnetosphere from one quasi-stable state to another, more stable state. Schindler has shown that the neutral line should initially form at the inner end of the tail where it meets the more solid dipole-like field of the inner magnetosphere. Perhaps this inner 'firm' region at the magnetic field builds outward during the expansive phase, causing the allowable location for neutral line location suddenly to change.

PRIEST: Your observations show a magnetic field in the magnetospheric current sheet which is rather 'turbulent'. How relevant then do you think the laminar collisionless models for a substorm trigger are? Is there any indication that the field becomes more turbulent after reconnection commences?

HONES: There is some indication that the field becomes more turbulent after reconnection commences, but this question has not been studied to the degree necessary to give a definitive answer. Nevertheless, it may be indicative that before a substorm the field may be sufficiently laminar for the models to be applicable.

KAHLER: We know that in solar flares the sizes of the events studied range from great flares to events so small that observers quibble over whether they are actually flares. We also know that some flares occur without an observed impulsive phase. Is there also a similar range of sizes in substorms and do some substorms lack particular phases?

HONES: There is a range of sizes of substorms. The manifestations (i.e., the auroras and associated currents) of the more intense substorms occur at lower latitudes (e.g., 60°–65°) on the Earth while the weaker substorms are manifested at higher latitudes (e.g., $\sim 70°$). Plasma flow measurements reveal that the neutral lines associated with the higher latitude substorms form at a greater distance in the tail (e.g., $>30 R_E$) than do those with the lower latitude substorms, which form at ~ 10–$15 R_E$. Both strong and weak substorms exhibit impulsive onsets.