Outer Magnetosphere near Midnight at Quiet and Disturbed Times

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Ogo 5 magnetic-field and energetic-electron (E > 50 keV) data are used to study both the quiet-time, steady-state configuration of the outer magnetosphere or near tail region near midnight and the disturbed time changes of this configuration. The nighttime cusp is found to be a distinct feature within the plasma sheet at quiet times but indistinguishable from the plasma sheet at disturbed times. The sequence of thinning and expansion of the plasma sheet in this region in association with the substorms is studied. The response of the plasma sheet in the near tail at ~10 Rs is found to be similar to that in the more distant tail at >20 Rs. Finally, the nature of field-aligned currents flowing on the plasma-sheet boundary is investigated. Assuming infinite current sheets, the sheet current density at Ogo 5 is found to be approximately 10^-3 amp m^-1. At ionospheric altitudes in the auroral zone, these currents scale to 10^-1 amp m^-1, in good agreement with low-altitude measurements. These currents in space often appear in double or multiple sheets.

The sequence of events that occurs during a magnetospheric substorm is gradually becoming clear as a result of recent studies. However, attempts to define this sequence are hampered by the apparent variability of the signature in the tail [Hones et al., 1971a], difficulties in assigning the exact onset time for the various phases of a substorm from ground-based data, and the different velocities of propagation of the effects parallel and perpendicular to the neutral sheet [Akasofu et al., 1970; Meng et al., 1970].

Most studies of data obtained in the tail beyond distances of 15 Rs show that the plasma sheet thins during the growth phase or an early phase of the substorm and expands with a variable delay after the ground onset of the expansion phase [Fairfield and Ness, 1970; Hones et al., 1971b; Meng et al., 1971]. In addition, Aubry and McPherron [1971] have shown that at 30 Rs a plasma-sheet expansion can be triggered by a reversal of the interplanetary field from southward to northward.

The purpose of the present study is to improve our understanding of the region between 8 and 12 Rs on the basis of measurements made with the UCLA triaxial fluxgate magnetometer and the UCLA electron spectrometer on Ogo 5. In conjunction with these data, we shall use solar-wind magnetic-field measurements obtained by the Ames Research Center magnetometers on Explorers 33 and 35.

First, we shall study the topology of this near tail region at quiet times. We shall show that the 'nighttime cusp,' defined by Anderson and Ness [1966] as a region of magnetic field depressed relative to the dipole field in which there is a substantial level of energetic-electron flux, is a separate feature inside the plasma sheet. Since Ogo 5 did not have a working low-energy plasma probe during the interval covered in this study, we will use the magnetic-field strength and the flux of >50-keV electrons to locate the plasma sheet. The appearance of energetic electrons coincident with entry into a region of depressed and fluctuating magnetic field in the magnetotail has been used routinely as the signature of independent of any indication of substorm activity in ground records.
entry into the plasma sheet [Bame et al., 1967; Meng and Anderson, 1971]. This method of identifying the plasma sheet is supported by the observations of Montgomery [1968], who found that energetic electrons in the magnetotail are always accompanied by low-energy electrons.

Second, we shall analyze the changes in configuration of this region due to substorms. When substorms occur, high fluxes of energetic electrons are observed throughout the plasma sheet, and we then have no way to identify the nighttime cusp as a separate feature. Accordingly, the changes of configuration at all radial distances during substorms will be described as plasma-sheet changes.

The sequence of shrinking-expansion is well documented in the far tail. However, only two near-earth sequences have been studied in detail [Russell et al., 1971a; McPherron et al., 1972]. In this paper, we shall examine further examples of this behavior and then use the magnetic-field changes to infer the evolution of the current patterns in the tail.

Finally, we shall describe the sheets of field-aligned currents that are almost always observed on the border of the expanding plasma sheet in the near tail region. We shall show that the amplitude of these field-aligned currents is consistent with those observed in the auroral zone [Armstrong and Zmuda, 1970; Cloutier et al., 1970].

**Topology of the Near Tail Region at Quiet Times**

Figures 1 (left) and 2 show examples of the variation of the energetic electron flux ($E > 50$ kev) and the magnetic field for passes through the near tail region during intervals of low magnetic activity. At the top of each figure, the position of the satellite is indicated in GSM. $Z'$ is the distance from the expected position of the neutral sheet [Russell and Brody, 1967]. $AB$ is the observed field magnitude minus the reference multipole field magnitude [Cain et al., 1967], and $\delta$ is the rms amplitude of waves with frequencies greater than 0.07 Hz. $B_z$ (GSM) is the vertical component of the tail field, and solar-wind $B_z$ (GSM) is the vertical component of the interplanetary magnetic field measured on Explorer. This quantity is not given in Figure 2, because at this time the Ames magnetometer on Explorer 33 was in the error mode, and we know only that the solar-wind magnetic field had a fluctuating vertical component that was only occasionally southward.

**August 25, 1968**. The satellite was very close to the expected position of the neutral sheet on August 25, 1968, and the small value of $\Delta B$ shown in Figure 1 (left) is typical of the plasma sheet. The solar-wind magnetic field was northward and geomagnetic activity was very low. During this interval, the $Kp$ index was 0+ and there was no evidence of any substorm activity on ground-based magnetic records. Before 1300 UT at distances beyond $X = -13 R_s$, there was no flux of energetic electrons above the minimum detectable flux of $10^7$ cm$^{-2}$ sec$^{-1}$ ster$^{-1}$ except for a small burst at about 1200 UT. The isolated spikes in the electron flux at low levels of flux are the nonphysical result of the method of data acquisition. A minimum number of counts, dependent on telemetry rate, must be accumulated in a detector before a signal is registered. The average flux is then plotted at the midpoint of the time interval. The flux before the sharp rise at 1400, for example, averages $2 \times 10^5$ cm$^{-2}$ sec$^{-1}$ ster$^{-1}$, but has not been smoothed so that the time of the sharp increase can be accurately specified. The difference in the appearance of the same level of flux in Figure 1 at 1115 (1-kbit/sec telemetry rate) and at 1330 (8 kbit/sec) results from the different telemetry rates. At approximately 1400 UT, Ogo 5, already in the region of negative $\Delta B$, entered a region of high flux of energetic electrons which we consider to be the nighttime cusp.

**August 20, 1968**. As is stated above, the solar-wind magnetic-field orientation on August 20 (Figure 2) was fluctuating but mainly northward. The $Kp$ index ranged from 1+ to 2, and evidence for two extremely weak substorms was found in the ground records. The onsets of the expansion phases for these two substorms determined from the low-latitude magnetograms occurred at the times indicated by the vertical dashed lines. The first substorm at 0825 was very weak but produced an expansion of the plasma sheet that engulfed Ogo 5: in consequence, at about 0825 UT the spacecraft went from the tail main lobe ($\Delta B \sim 20 \gamma$ and electron flux $<10^7$) to the plasma sheet ($\Delta B \sim 10 \gamma$ and electron flux $\sim 10^7$). This substorm was not preceded by the usual significant increase in the
magnitude of the field in the lobe. The lack of increase is consistent with its weak signature in ground records. From 0830 to 0945 UT, Ogo 5 remained in the plasma sheet and $\Delta B$ remained constant. At about 0945, Ogo 5 entered a region of greater magnetic-field depression, and within ten minutes recorded a large increase in the flux of energetic electrons. Again we consider this region of increased particle flux, not associated with any substorm effect, to be the nighttime cusp.

**Summary.** In these two examples, we see rather sharp changes in particle fluxes that are not associated with either substorm effects or crossings into the plasma sheet. In both cases, Ogo 5 was already inside the plasma sheet when these regions were encountered. Thus we must conclude that at quiet times the nighttime cusp is a well-defined region separate from the plasma sheet. This is not to say that low fluxes of energetic electrons do not exist within the plasma sheet at quiet times, but only that they
are distinct from the high fluxes observed within the nighttime cusp.

Changes in the Near Tail Region Configuration at Disturbed Times

August 17, 1968. The data for August 17, a very disturbed day, have been plotted next to the data for August 25, a very quiet day, for contrast (Figure 1). The orbit of Ogo 5 was roughly the same on August 17 as on August 25, but the particle and field behaviors differ markedly. The Kp index ranged from 3+ to 6— during the interval, and three strong substorm expansions were detected in ground magnetograms. The interplanetary field was predominantly southward throughout this interval.

The August 17 data illustrate clearly why the nighttime cusp cannot be distinguished from the plasma sheet at such disturbed times. There were large fluxes to much greater radial distances, and these fluxes were quite variable. Some of these fluctuations were associated with
the thinning and subsequent expansion of the plasma sheet, but others were not. Each of the three onsets of expansion phases that we have identified from the ground-based magnetograms was simultaneous, within the error inherent in reading the ground data, with the plasma-sheet expansion as identified from the decrease of $\Delta B$ and with the large increase in electron flux. Also, there were no obvious triggers for these substorms in the interplanetary field data.

August 15, 1968. The data obtained by Ogo 5 on August 15 (Figure 3) have been extensively examined in other papers [McPherron et al., 1972; Kivelson et al., 1972; West et al., 1972; Buck et al., 1972]. We repeat these data here as a further example of near tail behavior at disturbed times. During this interval, $Kp$ was 4, and the interplanetary field was alternately oriented northward and southward. There were two well-defined onsets of substorm expansion phases, at 0430 and 0714 UT.

As in the preceding example, very large fluxes of electrons appeared as soon as the satellite was engulfed by the expanding plasma sheet, both at a radial distance of 11.5 $R_E$ (0430 UT) and at 7.9 $R_E$ (0714 UT), and we cannot define the nighttime cusp as a separate entity. At 0430 UT, Ogo 5, about 3 $R_E$ above the expected

Fig. 3. Variation versus universal time of the 20-sec average of the $>50$-kev electron flux and the 1-min average of the magnetic field for a disturbed day (August 15, 1968). The parameters are the same as in Figure 1. The scale for the top panel is the logarithm of the particle flux.
neutral-sheet position, was engulfed in the expanding plasma sheet with a delay of about 16 min after the substorm onset.

**Summary.** At disturbed times, the plasma sheet in the near tail is filled with large fluxes of energetic electrons. These fluxes can have very large apparent temporal variations, which are at least partly due to the thinning and expansion of the plasma sheet. At these times, the nighttime cusp as a separate entity inside the plasma sheet cannot be defined. The expansion of the plasma sheet, which can be identified both by the sudden increase of the electron flux and by the sudden decrease in the magnitude of the magnetic field, usually begins simultaneously with the onset of the expansion phase as determined from ground-based magnetograms. Time delays observed when the satellite is not near the neutral sheet can be interpreted in terms of finite expansion velocities perpendicular to the neutral sheet.

**Near Tail Current Pattern at Quiet Time**

In the preceding sections, we discussed the variations in the energetic-electron flux and magnetic-field strength as an aid to understanding the steady-state configuration of the near tail and the changes in this configuration occurring as a result of substorms. The variations in the vector components of the magnetic field during these passes can also aid in this understanding.

**Perturbation Field for a Model Current Pattern**

To visualize how the variation in the vector components of the magnetic field can be used, let us examine a qualitative model of the field due to a nightside current pattern shown on the right of Figure 4. This current pattern comprises a thin tail current sheet producing a perturbation field $\Delta B_1$ and a field-aligned current sheet $J_1$ flowing on a magnetic shell and producing a perturbation field $\Delta B_2$. Since we are interested in the magnetic effects only close to midnight and to the equatorial plane, at about $10 R_E$, we need not consider the effects of the return currents on the magnetopause.

To represent the magnetic-field perturbations that would be observed on the satellite as it moved in the current system described, we use a dipole meridian coordinate system. In this

![Fig. 4. Top right: a cross section of the nighttime magnetosphere showing the qualitative variation of the perturbation field measured due to an idealized current system along a typical inbound Ogo 5 orbit. Lower right: schematic definition of dipole reference system used to analyze perturbations. Left: example of the evolution of the perturbation field expected on this typical pass. $\Delta B$ is plotted in the dipole meridian reference system.](image-url)
system, the \( Z \) axis is parallel to the dipole axis and northward; the \( X \) axis is in the magnetic meridian containing the point of observation and is outward; and the \( Y \) axis is azimuthal and positive eastward. This is sketched in the lower right-hand panel of Figure 4. The evolution of the tip of the perturbation vector recorded by Ogo 5 inbound on the dashed line orbit is sketched on the left-hand side of this figure in both the \( X-Y \) plane and the \( X-Z \) plane for our typical orbit. The \( X-Z \) variation is mainly a rotation due to the neutral-sheet current, while the \( X-Y \) variation shows the change in \( \Delta B_x \) due to the neutral-sheet current and the change in \( \Delta B_y \) due to the field-aligned current sheet.

In order to determine whether our model is realistic, we can look at the observed vector perturbation field for the two quiet days already studied.

**August 25, 1968.** We have plotted on the left in Figure 5 the 15-min averaged perturbation field for the same 7-hour interval on August 25 as is displayed in Figure 1. We observe the expected rotation in the \( X-Z \) plane, and we find that for this very quiet day the field produced by the tail-sheet current is very small (< 15 \( \gamma \)); some amplitude variation is superposed on the rotation predicted by our model.

**August 20, 1968.** For clarity, we consider 1-min averages of the perturbation field for only a 1-hour interval on August 20, 0945–1045 UT (Figure 6). Obviously the variability is larger than in Figure 5, but we still observe a rotation in the \( X-Z \) plane. The major difference between this pass and the one shown in Figure 5 is the sudden change in \( \Delta B_y \) occurring between 0947 and 0949 UT. We interpret this as due to the satellite's crossing of a shell of earthward-flowing field-aligned current and, from the data shown in Figure 2, we know that this current flows just beyond the outer boundary of the nighttime cusp as defined by the energetic electrons. On the right of Figure 6, in addition to the Ogo 5 orbit, we have sketched a cross section of the nightside outer magnetosphere consistent with our observations for August 20, 1968. The orientation of the magnetic field observed by Ogo 5 was in agreement with the model of Fairfield [1968], and our addition to this model is the separation into three different regions, as deduced from our data. The point marks the outer boundary of the nighttime cusp where the field-aligned current (flowing earthward) was recorded at 0947 UT. At 0825 at the border of the plasma sheet, fluctuations of \( \Delta B_y \) consistent with the crossing of a double current layer were also recorded (this part of the data is not shown).

**Summary.** At quiet times, the vector field shows the variation expected for a steady current flowing in the neutral sheet. In association with even very small magnetic perturbations, there can also be field-aligned currents flowing not only on the plasma-sheet boundary but also...
inside the plasma sheet. In our one example, this current appeared to flow just outside the boundary of the nighttime cusp.

Changes in the Current Pattern at Disturbed Time

August 17, 1968. In this section we examine the perturbation field for the interval 1900 UT to 2100 UT, August 17, 1968 (Figure 7), during the growth phase and expansion phase of a substorm (see right-hand side of Figure 1). The orbit of Ogo 5 plotted on the right of Figure 7 shows that, because of the large inclination of the dipole axis, Ogo 5 was below the equatorial plane and at a roughly constant distance from it throughout the period of interest. The plots on the left again connect the tips of the 1-min averaged perturbation fields. In addition, the projection in the meridian plane of the total field at 2019 and 2050 UT is shown. In contrast with the perturbation-field variations on August 20 and 25, which were space dependent, the data shown in Figure 7 represent mainly time-dependent variations. The increase of the perturbation field from 10 $\gamma$ to 50 $\gamma$ before 2040 UT during the exit from the thinning plasma sheet cannot be readily attributed to a unique current system. However, the successive values of the perturbation field vector at 1900, 2040, and 2100 UT are consistent with a strong increase of $|\Delta B_z|$ due to an increase of the cross-tail current before the onset of the substorm (at about 2045) and a sudden decrease after this onset. The sudden re-entry into the plasma sheet after 2049 is obviously associated with the crossing of a double sheet of field-aligned current (which produces successive $-15-\gamma$ and $+15-\gamma$ variations in $\Delta B_z$). In summary, on August 17 during the growth phase of the substorm we observe at about 10 $R_E$ a shrinking of the plasma-sheet region associated with a strong increase in the cross-tail current. After the onset of the substorm expansion phase, a double sheet of field-aligned current is observed on the boundary of the expanding plasma sheet.

August 15, 1969. For August 15, we examine in Figure 8 the perturbation field for the interval 0610-0728 UT, again during the growth
Fig. 7. *Left*: evolution of the 1-min average of the perturbation field vector in the dipole reference system on August 17, 1968, from 1900 to 2100 UT. Between 1900 and 1930 UT (dotted line), the trend only is indicated. *Right*: two projections of the Ogo 5 orbit are shown. The variation of orientation of the magnetic equatorial plane between 1900 and 2100 is shown by the dashed lines.

Fig. 8. *Left*: evolution of the 1-min average of the perturbation field vector in the dipole meridian reference system on August 15, 1968, from 0610 until 0728 UT. In the plane $\Delta B_x$, there is very little change between 0610 and 0659 and, to minimize confusion, the corresponding line has not been drawn. *Right*: two projections of the Ogo 5 orbit in GSM coordinates are shown.
phase and expansion phase of a substorm (see Figure 3). The orbit of Ogo 5, plotted on the right of Figure 8, shows that during this interval the spacecraft remained above the neutral sheet. The plots on the left connect the tips of the 1-min averaged perturbation fields. The projection in the meridian plane of the total field direction at 0630 and 0704 UT is also shown.

From 0630 until 0704 UT, at the beginning of the substorm growth phase, the perturbation field was in the meridian plane, nearly perpendicular to the total field, and increased by a factor of 2. This can be attributed to a corresponding increase in the amplitude of the tail-sheet current.

From 0704 until 0713 UT, a new perturbation field was superimposed on the original one; its projection in the meridian plane was nearly parallel to the total field. In addition, a large (15 γ) component perpendicular to the meridian plane appeared. These perturbations are consistent with the assumption that Ogo 5 entered the boundary of the shrinking plasma sheet. The current flowing in this boundary can be resolved into two components: a current parallel to the tail current, and a field-aligned current responsible for the 15-7 change of AB. At 0713, one observes a small but sharp drop in the perturbation field of the plasma-sheet boundary, followed at 0716 UT by a large and sudden decrease of the total perturbation field, including the AB due to the tail-sheet current and the AB due to the field-aligned current (decrease of AB after 0716 UT). The changes of the field around 0714 UT were so rapid that the 1-min averaging masks many important details. Figure 9 presents the variations of the particle flux averaged over 7-sec and 1-sec averages of the magnetic field (in GSM) between 0650 and 0750 UT. The purpose of the dashed vertical lines is to permit an easy correlation of the data at some critical times. A careful examination of both Figures 8 and 9 leads us to the following interpretation: at 0713, Ogo 5 was in the outer boundary of the plasma sheet or immediately outside it. The sharp changes beginning at 0714 were due to back and forth motions of this boundary (one can check that the variations of the field amplitude and the particle flux are then anticorrelated). A few seconds after 0716 UT, the tail current was partly switched off, resulting in a sudden increase in $B_z$ (GSM). At this time, Ogo 5 was again inside the boundary, and we observe a sudden decrease of the perturbation field normal to the dipole meridian (Figure 8). We cannot say, however, whether this decrease was caused by a real temporal decrease of the current or by a motion of the field-aligned current sheet away from the satellite. In contrast to the observations of August 17, those of August 15 give a very clear picture of the plasma-sheet behavior before the onset of the substorm expansion phase but are less readily interpreted after this onset.

As was stated above, this particular substorm has been studied elsewhere. In particular, the timing of the substorm and the shrinking-expansion of the plasma sheet were described in these studies. By examining in detail the perturbation fields, however, we have gained additional information on the substorm effects. In particular, we have been able to separate the effect of the increasing tail current before 0704 UT, the disappearance of the diamagnetic effect after 0704 when Ogo 5 was crossed by the shrinking boundary, the field-aligned current observed inside this boundary, and the very rapid motions of this boundary beginning at 0714, followed by the sharp decrease of the tail current at 0716 UT.

**Field-Aligned Currents**

In the preceding section, we have shown evidence for sheets of field-aligned current in the border of the plasma sheet or of the cusp region. The signature of these currents is a change in $\Delta B_y$ as observed on August 20 at 0947 (Figure 6), on August 17 at 2040–2050 (Figure 7), and on August 15 from 0704 till 0720 UT (Figure 8). We have looked for other examples of these field-aligned currents. Figure 10 is the projection in the equatorial GSM plane of the Ogo 5 positions at the time of a number of crossings of the boundary of the plasma sheet. All these crossings were associated with ground magnetic perturbations, although some of these perturbations were very small and could not be considered as fully developed substorms. For each crossing of the plasma-sheet border, we have computed from the change in $\Delta B_y$ the direction and amplitude of the field-aligned current. Table 1 summarizes our results. The numbers in the first column...
Fig. 9. Variation versus universal time of the 7-sec averages of the >50-kev electron flux and of the 1-sec average of the magnetic field (in GSM) for August 15, 1968, near the time of the substorm onset (~0714 UT).

refer to the positions indicated in Figure 10; $Z'$ is the distance from the expected position of the neutral sheet [Russell and Brody, 1967]. The quantity $b_r$ given in Table 1 is the absolute value of the largest change in $\Delta B_r$ during the crossing. The current $J$ is computed assuming an infinite plane sheet. Thus

$$J(\text{amp m}^{-1}) = \mu_0^{-1} b_r$$

$$= 8 \times 10^{-4} b_r \text{ (gammas)}$$

In order to compute the field-aligned sheet-current density $J_A$ that would be observed on these field lines at auroral altitudes, we must scale these values by a factor inversely proportional to the perpendicular distance to the dipole axis. The distance from the dipole axis $d$ of the point of each observation is given in Table 1. The distance from the dipole axis of the nightside auroral oval (65° invariant latitude) is 0.42 $R_s$. Thus our scaling law becomes

$$J_A = 2.4dJ$$

The resulting values of $J_A$ are given in Table 1. In the next column are tabulated brief descriptions of the nature of the crossings. Here 'onset' refers to the onset of the expansion phase.

The entries in the final column describe the type of current sheet encountered. These types are illustrated schematically in Figure 11. Only in cases where the identification was straightforward have we used the terms single sheet (SS) and double sheet (DS), which we have further classified according to the directions in
which currents flow, as indicated by the numbers 1 or 2 in Figure 11 and Table 1. Signatures that could have been interpreted as an oscillating single or double sheet or as a multiple sheet have been classified as multiple sheets.

We do not wish to give the impression that $b_r$ is zero everywhere except when we cross the plasma-sheet border. Slow variations of $\Delta B_r$ occur during large parts of the Ogo 5 orbit, and small-amplitude fluctuations of $B_r$ are also systematically observed inside the plasma sheet. We cannot relate these changes in $B_r$ to a specific current, because we do not know where the current is flowing. The analysis of the $B_r$ variations at the plasma-sheet border is very different. Their amplitude is large, and the source can be identified because we cross the current sheet itself. Moreover, the structure of a single or double sheet is at times rather clear. Although in some cases the temporal sequence of field changes is consistent with the existence of multiple current sheets, this in itself does not prove their existence any more than multiple magnetopause or shock crossings prove that there is more than one magnetopause or shock front. In fact, we do encounter apparent multiple plasma-sheet crossings on many orbits. However, when we do, the period of these crossings is much shorter (typically 1-2 min) than that of the current reversals, and thus we feel that such motions do not affect our conclusions appreciably. If a single current sheet oscillated in strength, the magnetic perturbations could be interpreted as due to multiple sheets. Although we cannot rule this out, and it undoubtedly does occur at times, we note that on August 15 the current was quite steady on two separate occasions for at least 20 min while the plasma sheet thinned and then expanded. Thus we feel that the cases described as multiple current sheets may well arise from striated currents in the magnetosphere.
From Table 1, we conclude that:

1. A double sheet (DS) or a multiple sheet (MS) of field-aligned current is observed nearly systematically at the border of the plasma sheet when it expands after a substorm onset. The exceptional case of August 15 is possibly due to the fact that Ogo 5 crossed only part of the current system.

2. The amplitude of the currents, projected into the auroral zone, is from 8 to 50 \( \times 10^{-8} \) amp m\(^{-1}\).

**DISCUSSION**

We have shown that at quiet times the nighttime cusp exists as an independent topological feature inside the plasma sheet in the nightside magnetosphere. At disturbed times, we cannot at present find a difference between the nighttime cusp and the plasma sheet, but we have shown that this region at about 10 \( R_E \) contracts before a substorm and expands suddenly at the onset of the substorm expansion phase. The observations of August 15 and 17 show that, during the growth phase of the substorm, the amplitude of the tail current sheet increases, the plasma sheet thins down, and large field-aligned current flows in this boundary. Something happens in this region just before the expansion onset. We could not interpret the details for August 17, but on August 15 very rapid motions of the boundary occurred two or three minutes before the sharp decrease of the tail-sheet current that is associated with the sudden expansion of the plasma sheet.

In the course of this study, we have found that there is usually geomagnetic activity on the ground at the times of plasma-sheet expansion. However, not all this activity could be classified as fully developed substorm activity.

We should also emphasize that we never observed a steady plasma-sheet boundary. All our observations relate to an expanding or thinning plasma sheet associated with some magnetic activity. This is probably because in the steady state the plasma-sheet boundary is diffuse and the satellite velocity is so small normal to this boundary that no sharp signature is apparent in the magnetic-field data. Furthermore, for the Ogo 5 orbit, during the interval required to cross the quiet-time plasma-sheet boundary, there is a high probability of a plasma-sheet expansion.

Our last and probably most significant result concerns the double or multiple sheets of field-aligned currents flowing on the expanding plasma sheet.

**TABLE 1.** Radial Distance, Strength, and Nature of the Field-Aligned Current Sheets Observed in the Near Tail

<table>
<thead>
<tr>
<th>No.*</th>
<th>Date</th>
<th>Time</th>
<th>( d, R_E )</th>
<th>( Z', R_E )</th>
<th>( b, \gamma )</th>
<th>( J_1 ), amp/m</th>
<th>( J_{41} ), amp/m</th>
<th>Nature of Crossing</th>
<th>Type of Current Sheet†</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>July 25</td>
<td>1005-1014</td>
<td>10.2</td>
<td>0.7</td>
<td>17</td>
<td>( 1.4 \times 10^{-3} )</td>
<td>( 34 \times 10^{-2} )</td>
<td>Quiet-time crossing</td>
<td>SS1</td>
</tr>
<tr>
<td>2</td>
<td>Aug. 9</td>
<td>2013-2040</td>
<td>15.3</td>
<td>1.3</td>
<td>10</td>
<td>( 0.8 \times 10^{-3} )</td>
<td>( 29 \times 10^{-2} )</td>
<td>Expansion after substorm onset</td>
<td>MS</td>
</tr>
<tr>
<td>3</td>
<td>Aug. 9</td>
<td>2251-2315</td>
<td>12.6</td>
<td>0.8</td>
<td>9</td>
<td>( 0.8 \times 10^{-3} )</td>
<td>( 22 \times 10^{-2} )</td>
<td>Expansion after substorm onset</td>
<td>MS</td>
</tr>
<tr>
<td>4</td>
<td>Aug. 15</td>
<td>0424-0449</td>
<td>11.5</td>
<td>2.3</td>
<td>23</td>
<td>( 1.8 \times 10^{-3} )</td>
<td>( 49 \times 10^{-2} )</td>
<td>Expansion after substorm onset</td>
<td>SS2</td>
</tr>
<tr>
<td>5</td>
<td>Aug. 15</td>
<td>0707-0717</td>
<td>8.0</td>
<td>0.2</td>
<td>13</td>
<td>( 1.1 \times 10^{-3} )</td>
<td>( 21 \times 10^{-3} )</td>
<td>Thinning followed by expansion</td>
<td>SS2</td>
</tr>
<tr>
<td>6</td>
<td>Aug. 17</td>
<td>2049-2051</td>
<td>9.0</td>
<td>-2.2</td>
<td>12</td>
<td>( 1.0 \times 10^{-3} )</td>
<td>( 21 \times 10^{-3} )</td>
<td>Expansion after substorm onset</td>
<td>DS1</td>
</tr>
<tr>
<td>7</td>
<td>Aug. 20</td>
<td>0817-0829</td>
<td>12.8</td>
<td>1.8</td>
<td>8</td>
<td>( 0.6 \times 10^{-2} )</td>
<td>( 18 \times 10^{-3} )</td>
<td>Expansion after substorm onset</td>
<td>DS2</td>
</tr>
<tr>
<td>8</td>
<td>Aug. 20</td>
<td>0947-0949</td>
<td>11.1</td>
<td>0.2</td>
<td>9</td>
<td>( 0.7 \times 10^{-3} )</td>
<td>( 18 \times 10^{-3} )</td>
<td>Crossing of cusp boundary</td>
<td>SS1</td>
</tr>
<tr>
<td>9</td>
<td>Aug. 28</td>
<td>0452-0501</td>
<td>11.3</td>
<td>2.1</td>
<td>13</td>
<td>( 1.1 \times 10^{-3} )</td>
<td>( 29 \times 10^{-2} )</td>
<td>Expansion after substorm onset</td>
<td>DS1</td>
</tr>
</tbody>
</table>

* See Figure 10.
† See Figure 11.
plasma-sheet boundary right after the substorm onset. These currents, when projected into the auroral zone, vary from 8 to 50 × 10^-8 amp m^-2. Their structure in multiple sheets and their amplitudes are in agreement with the auroral field-aligned currents observed by Zmuda et al. [1970] (2.4 to 72 × 10^-8 amp m^-2), Cloutier et al. [1970] (26 × 10^-8 amp m^-2), Armstrong and Zmuda [1970] (64 × 10^-8 amp m^-2), and apparently give strong support to a model in which the poleward motion of the aurora is a direct projection onto the ionosphere of the expansion of the plasma sheet. We note, however, that this agreement may be to some extent fortuitous, for there does not exist a detailed analysis of an observation of the field-aligned currents flowing during the poleward expansion of an aurora. The arc studied by Cloutier et al. was slowly moving southward, and the currents studied by Armstrong and Zmuda were at 0900 LT and presumably associated with the polar cusp.

Hones et al. [1970] also have examined the association between auroral and plasma-sheet motion. They state that the observed relation between the speed with which the electrojet moves poleward and the expansion rate of the plasma sheet during the recovery phase of a substorm supports qualitatively the view that heated plasma is injected during a substorm. Plasma injection will change the configuration of the magnetic field. In terms of the change in the configuration of the tail actually observed coincident with plasma-sheet expansion, we propose an explicit interpretation of the observations of Hones et al. [1970]. Figure 12a shows the plasma sheet (shading) before the expansion limited by the line of force A. Figure 12b shows the plasma sheet after the expansion, limited by the line of force B, as was assumed implicitly by Hones et al. [1970]. Figure 12c shows the plasma sheet after the expansion, limited by the same line of force B, this time oriented properly to take account of the observed return to the dipole configuration. In the sequence 12a–12c, a satellite at 1 would see an expansion of the plasma sheet, and at the same time a satellite at 3 would see a thinning of the plasma sheet, while at 2 there would be almost no changes. In other words, if one wants to use the ‘conservation of flux’ argument to match the velocities in the auroral zone to the velocities in the tail, one has to take into account the fact that the orientation of the magnetic field in the plasma sheet can change by

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**Fig. 11.** Various field-aligned current systems encountered by Ogo 5 at the plasma-sheet boundary (see Table 1): SS, single sheet; DS, double sheet; MS, multiple sheet; the numbers 1 and 2 specify direction of current flow. By multiple sheet we mean a succession of more than two sheets with opposite currents; the example of a multiple sheet shown is only one of many possibilities.

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**Fig. 12.** Association between the plasma-sheet border and the auroral zone. The plasma sheet is limited before expansion by the line of force A and after expansion by the line of force B. If one assumes no change in the field orientation, going from A (top) to B (center) implies expansion everywhere. But if one takes account of the associated change in field orientation, going from A (top) to B (bottom) represents an expansion for a satellite at 1, no change for a satellite at 2, and a thinning for a satellite at 3.
nearly 90° during the plasma-sheet expansion.

The simple model in Figures 12a and 12c is consistent with the observation that, in association with a substorm expansion phase, the plasma sheet at 18 Rs can either suddenly expand or thin down [Hones et al., 1971a].

In summary, we have shown that during the growth phase of a substorm the amplitude of the tail current at about 10 Rs increases by as much as a factor of 2. This is associated in this region with a shrinking of the plasma sheet and an increase of the field-aligned currents on its boundary. The substorm onset on the ground appears to be simultaneous with a sharp decrease of the tail-sheet current and an expansion of the plasma sheet. Accordingly, this current decrease seems to begin in the cusp region and to propagate tailward. The sheets of field-aligned current flowing on the boundary of this expanding plasma sheet correspond closely in structure and amplitude to those observed flowing into auroral arcs.

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References


