ISEE 3 Observations of Traveling Compression Regions in the Earth’s Magnetotail

J. A. SLAVIN,\textsuperscript{1} M. F. SMITH,\textsuperscript{1} E. L. MAZUR,\textsuperscript{2} D. N. BAKER,\textsuperscript{1} E. W. HONES, JR.,\textsuperscript{3} T. IYEMORI,\textsuperscript{4} AND E. W. GREENSTADT\textsuperscript{5}

A traveling compression region (TCR) is a several-minute long compression of the lobe magnetic field produced by a plasmoid as it moves down the tail. They are generally followed by a longer interval of southward tilting magnetic fields. This study reports the first comprehensive survey of TCRs in the distant magnetotail. A total of 116 TCRs were identified in the ISEE 3 magnetic field observations. Of this population, 37 TCRs were observed to be separated by 30 min or more from any other TCR and are termed “isolated” events. “Paired” events are defined as two TCRs separated by less than 30 min. There were 36 such TCRs corresponding to 18 paired events. “Multiple” events were also observed in which more than two TCRs occurred in a series without a gap between TCRs of more than 30 min. The 11 multiple events identified in this study had an average of about four traveling compression regions each for a total of 43 TCRs. The mean amplitude, $\Delta B/B$, and duration, $\Delta T$, for all TCRs were found to be 7.6% and 158 s, respectively. TCRs occurring as isolated events were the largest ($\Delta B/B = 8.8\%$ and $\Delta T = 218$ s) and those associated with multiple events were the smallest ($\Delta B/B = 5.6\%$ and $\Delta T = 84$ s). The mean duration of the period of southward tilting $B_z$ following isolated TCRs was 12.3 min. This time interval was found to be quite similar to the average spacing between TCRs in paired and multiple events, 11.2 and 10.2 min, respectively. TCR amplitude and duration were found to be independent of location within the tail lobes suggesting that the plasmoids which cause the TCRs maintain approximately constant volume and shape as they move down the tail. Mean plasmoid dimensions estimated from TCR duration and amplitude under the assumption of a quasi-rigid magnetopause are $35 R_E$ (length) $\times 15 R_E$ (width) $\times 15 R_E$ (height). Utilizing auroral kilometric radiation, the Al index, Pi 2 pulsations at two ground stations, and energetic particle data from three geosynchronous spacecraft, it is found that over 91% of the TCR events identified in this study followed substorm onsets or intensifications. The number of TCR events identified in this study are consistent with their release in association with a new substorm onset every 4-6 hrs. The results of this study strongly suggest that the release of plasmoids down the tail near the time of expansion phase onset is an integral step in the substorm process and an important element in the substorm energy budget.

\section*{Introduction}

One of the major achievements of the space physics community over the previous two decades is the observational determination that auroral substorms are, in fact, just the low-altitude manifestation of magnetosphere-wide disturbances. The most comprehensive and best supported description of the changes taking place in the magnetotail during substorms is the “plasmoid” model of Hones [1976, 1977]. The essential elements of the plasmoid model are displayed in Figures 1a–1d [Baker et al., 1987]. The sequence begins in Figure 1a with the tail near the end of the substorm growth phase [McPherron, 1970]. Magnetic reconnection at the dayside magnetopause following an earlier southward turning of the interplanetary magnetic field (IMF) has enhanced the lobe magnetic flux content by perhaps a factor of 2 [Holzer et al., 1986]. The high beta plasma sheet region separating the oppositely directed magnetic fields in the lobes (shaded) has decreased in thickness as the magnetic pressure in the lobes increased during the growth phase [Hones et al., 1984a; Baumjohann et al., 1992].

In Figure 1b a neutral line has formed in the near-tail region of the plasma sheet. Earthward of this neutral line the plasma sheet bulk flow is sunward as newly closed field lines contract toward the Earth. Tailward of the neutral line the flow is accelerated in the antisunward direction in response to Lorentz forces associated with disconnected lobe field lines and large-scale plasma pressure gradients. At the point where the last of the closed field lines threading the plasma sheet have undergone reconnection, the rate of reconnection has been hypothesized to grow “explosively” [Coroniti, 1983] as lobe flux tubes begin to disconnect from the Earth. In the plasmoid model, this is the point where the magnetic flux added to the lobes during the growth phase is dissipated. It is the energy liberated as reconnection closes previously open field lines that powers the substorm expansion phase. These expansion phase phenomena include high-speed plasma sheet flows and heating, energetic particle acceleration, ring current enhancement, ionospheric joule heating, auroral particle precipitation, and optical emissions. As the expansion phase progresses, charged particles precipitate into the upper atmosphere at higher and higher latitudes as tail reconnection involves lobe flux tubes originating deeper and deeper in the lobes, and the auroral bulge expands poleward.

Figure 1c emphasizes the magnetic island, or plasmoid, formed when the downstream plasma sheet was disconnected from the Earth just prior to expansion phase onset. Magnetic forces within the plasmoid reduce the dimensions

\textsuperscript{1}NASA Goddard Space Flight Center, Laboratory for Extraterrestrial Physics, Greenbelt, Maryland.
\textsuperscript{2}Hughes STX Incorporated, Lanham, Maryland.
\textsuperscript{3}Los Alamos National Laboratory, Los Alamos, New Mexico.
\textsuperscript{4}Center for Geomagnetic and Space Magnetism, Kyoto University, Kyoto, Japan.
\textsuperscript{5}TRW Space Sciences Department, Redondo Beach, California.

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neutral line has slowed. The plasmoid moves tailward under the influence of the overall tailward plasma pressure gradient, the Lorentz forces associated with the disconnected lobe flux tubes draped about the earthward side of the plasmoid, and the tailward momentum of the plasma sheet particles accreted during plasmoid formation. During the recovery phase of the substorm, the inner neutral line retreats tailward to become the new “distant” neutral line. In this manner the tail relaxes toward its initial state as the plasma sheet refills and the magnetic fields in the tail resume their presubstorm configuration.

Numerical MHD simulations [e.g., Birn and Hones, 1981; Lee et al., 1985; Scholer and Roth, 1987; Otto et al., 1990; Hesse and Birn, 1991] have reproduced the basic chain of events in Figure 1 and have lent credence to the conceptual framework originated by Schindler [1974] and Hones [1976, 1977]. However, only modest progress has been made in predicting, from first principles, the locations and merging rates for the reconnection neutral lines within the three-dimensional magnetotail.

The signatures which have been used to identify plasmoids in the ISEE 3 observations are (1) fast, anti-sunward flow in the central plasma sheet [Hones et al., 1984b; Baker et al., 1987], (2) north-then-south tilting of the plasma sheet magnetic field [Hones et al., 1984b; Baker et al., 1987; Richardson et al., 1987] often with a region of strong “core” field in the center of the field rotation [Slavin et al., 1989; Moldwin and Hughes, 1992], and (3) energetic charged particles with isotropic pitch angle distributions in the plasma rest frame [Scholer et al., 1984; Gloeckler et al., 1984; Richardson et al., 1987].

Studies of plasmoids identified using these various criteria have shown that (1) plasmoids have typical length scales of 10-60 $R_E$ along the X axis [Hones et al., 1984b; Scholer et al., 1984; Richardson et al., 1987; Moldwin and Hughes, 1992], (2) they move tailward with speeds typically 2-3 times that of the solar wind [Baker et al., 1987; Richardson et al., 1987], and (3) the observation of plasmoids in the tail is highly correlated with substorm activity near the Earth [Baker et al., 1984, 1987; Slavin et al., 1989; Moldwin and Hughes, 1993]. All of these results argue strongly for the basic validity of the magnetospheric substorm model depicted in Figure 1.

**Traveling Compression Regions**

Soon after the ISEE 3 Geotail observations became available, short duration intervals of enhanced lobe magnetic fields accompanied by north-then-south tilting of the vector field were reported by Slavin et al. [1984]. They named them “traveling compression regions,” or TCRs, because they were observed following the onset of substorms and the time delays increased with growing distance down the tail (that is, the compressions appeared to “travel” down the tail). These events were actually first noted by Maezawa [1975] in the Explorer 33 distant tail observations taken at lunar distances but were not studied in any great detail at that time.

Slavin et al. [1984] suggested that TCRs are the signature of lobe field lines draping about plasmoids moving rapidly down the tail. They based their interpretation on the uniqueness of the magnetic field signature (see Figure 2), the similarities between the temporal duration and estimates of tailward velocity for TCRs and plasmoids, and the very
distinct interval of southward $B_z$ which persists following the compression region (see Figure 3). Additional support for TCRs being produced by plasmoids has been provided by Murphy et al. [1987] and Owen and Slavin [1993]. In these studies the ISEE 3 energetic ion observations were used remotely to sense the plasma sheet during TCR encounters. The results were found to be consistent with the passage of a bulge in the plasma sheet coincident with the TCR compression signature.

The uniqueness of the interpretation of the TCR magnetic field signature as being due to the draping and compression of lobe field lines about a bulge in the plasma sheet is examined in Figure 2. This figure compares the lobe magnetic field signature caused by a local bulging of the plasma sheet with those produced by finite duration regions of high and low external solar wind pressure. As shown in the upper two panels, a lobe field compression can be produced by an external increase in solar wind pressure and a north-then-south tilting can be caused by an interval of low pressure. However, only the internal bulging of the plasma sheet such as that caused by a plasmoid produces both the north-then-south field tilting and compression signatures observed during TCR events.

Originally, it was suggested that TCR compression signatures were ultimately due to the increase in the diameter of the tail required to accommodate the tailward moving plasmoid. This increase would cause the magnetopause to locally flare outward and increase the normal component of the solar wind ram pressure at the magnetopause. It was this enhanced inward pressure which was thought to compress the lobe magnetic field against the plasmoid [Slavin et al., 1984]. However, at that time it was not fully appreciated that plasmoids generally travel down the tail at speeds well in excess of that of the solar wind. This scenario for compressing the lobe field between a plasmoid and a flared magnetopause may still be correct to some extent, but the solar wind ram pressure in the frame of the plasmoid will usually be sunward, not antisunward as was initially suggested.

In addition, it should be noted that the fast mode magnetosonic speed in the downstream magnetosheath is generally below 100 km s$^{-1}$ and hence much lower than the antisunward speed of plasmoids. For this reason it may be the case that the TCR is ultimately due to the magnetosheath plasma not being able to move outward fast enough to fully respond to the outward pressure of the compressed magnetic fields in the lobes generated by the plasmoid moving rapidly tailward. In this case the bulge in the diameter of the tail associated with the tailward moving plasmoid might be significantly reduced in size from that depicted in Figure 1 with the magnetopause more closely resembling a quasi-rigid boundary over the short time a plasmoid takes to pass a given point.

Indeed, recent theoretical models [Bird, 1992; Young and Hameiri, 1992] produce plasmoid-associated compressions in the lobe magnetic field without necessarily requiring any variation in magnetopause diameter as the plasmoid moves down the tail. The results of these theoretical models and the physical considerations discussed earlier indicate that the changes in the lobes of the tail, the magnetopause, and the adjacent magnetosheath associated with traveling compression regions are still not fully understood.

![Diagram of magnetic field configurations](image)

**Fig. 2.** The lobe magnetic field must drape about the plasmoids formed during substorms as shown in the bottom drawing. The north-then-south tilting and compression of the lobe field as the plasmoid moves downstream are quite distinct from the signatures associated with short duration increases or decreases in external solar wind pressure as depicted in the top and middle drawings.

**TCR Survey Methodology**

The purpose of this study is to conduct a comprehensive survey of traveling compression region properties as determined by the ISEE 3 magnetotail measurements. In this respect it is complementary to similar efforts to ascertain the number and nature of plasmoids contained in the ISEE 3 data set [e.g., Moldwin and Hughes, 1992, 1993]. Summary data plots (i.e., 6 hours/frame) of the measurements returned by the Jet Propulsion Laboratory vector heliometer [Flanders et al., 1978] were visually inspected for the correlated north-then-south tilting of the $B_z$ component and compression of the lobe magnetic field used to define TCRs [Slavin et al., 1984, 1990, 1992]. High-resolution plots (i.e., 1 hour/frame) of both the magnetic field and plasma moments returned by the Los Alamos National Laboratory (LANL) plasma analyzer [Bame et al., 1978] were then prepared for candidate events identified in the coarser summary plots. In this study we have used only TCRs identified in these higher resolution magnetic field plots and confirmed by the plasma data to have been observed while ISEE 3 was located in the lobes of the tail [see Bame et al., 1983].

Four examples of TCRs in the high-resolution ISEE 3 magnetic field measurements illustrating the required signatures are presented in Figure 3. In the interest of comparability, all four TCR examples are taken from ISEE 3 observations at distances of $x = -70$ to $-80$ $R_E$. The relatively strong, smooth background magnetic field in these events is typical of the lobe regions of the magnetotail [Slavin et al., 1985]. The critical features identifying these events as TCRs are (1) the north-then-south variation of the $B_z$ component of the magnetic field with the inflection point at the peak in the
compression of the total field, (2) the similarity in the durations of the north–south $B_z$ variation and the compression required for this to be a field-draping signature, and (3) the persistent interval of $B_z$ southward following the field compression [Slavin et al., 1984, 1990, 1992]. The $B_z$ variation of the field (not shown; see Figures 4 and 5) closely follows that of the total field magnitude in the lobe regions. The variation in the $B_y$ component (also not shown; see Figures 4 and 5) is generally much smaller than that observed for $B_z$ and may be either east–then–west or west–then–east. It has been suggested that the sense of the $B_z$ variation may be an indication of whether the bulk of the plasmoid passed to the east or west of the spacecraft [Slavin et al., 1989].

Plasmoids are created by reconnection involving the closed field lines existing within the plasma sheet. As discussed earlier, they are believed to be ejected following substorm expansion phase onset when the last closed field line has been reconnected, and merging between the two opposite magnetic polarity lobes commences. The reconnection between the lobe fields results in the transport of newly closed magnetic flux earthward and newly disconnected “interplanetary” field lines tailward. The high-speed antisunward flows in the plasma sheet carrying these recently disconnected field lines tailward following plasmoids will not be observable by ISEE 3 when it is in the lobes although they are observed when the spacecraft is in the plasma sheet [e.g., Baker et al., 1987; Slavin et al., 1987]). However, a southward tilting to the lobe field may be observed due to the fact that these disconnected field lines must close across the midplane of the tail. The fact that such southward $B_z$ fields are generally observed following TCRs has been offered as strong evidence that the compression regions are in fact associated with the downtail motion of plasmoids [Slavin et al., 1984].

The events in Figure 3 were selected to show the large variation in the period of southward $B_z$ ranging from several minutes (the middle panels) to 40–50 min (the top and bottom panels), albeit these long intervals are very unusual. If this interpretation is correct, then the eventual northward turning of $B_z$ corresponds to the passage of the near-Earth neutral line as it retreats tailward during the recovery phase of the substorm as indicated in Figure 3.

High-resolution plots of the type shown in Figure 3 were also used to determine TCR duration $\Delta T$ and amplitude $\Delta B/B$. To avoid subjective decisions regarding the beginning and ending times of the individual events, it was decided to use the interval between the peak northward and southward excursions in $B_z$, which are well determined, as a measure of TCR temporal duration. The amplitude of the TCRs were measured against a total field baseline constructed by linearly interpolating between the lobe field intensity before and after the event. Experimentation with this procedure indicated that traveling compression regions with durations between about 30 s and 30 min and amplitudes in excess of 1% of the lobe field magnitude should have been identified with high reliability by the methods used in this study.

**Case Studies and Event Classification**

In the manner described above a total of 116 TCRs were identified in the ISEE 3 data set. Rather than being spaced uniformly in time throughout the period of observation, they were found to be distributed among 37 “isolated” TCR events, 18 “paired” events and 11 “multiple” events. Each type of TCR event is defined below, and examples are presented for both the middle and distant tail regions. Analyses of their frequency of occurrence, spatial distribution, amplitude, duration, magnetic structure and orientation, substorm association, and downtail velocity are presented in later sections.

**Examples of TCRs in the Middle Tail: $X = -60$ to $-100 R_E$**

An example of two isolated TCRs observed on April 11, 1983, at $X = -79 R_E$ are displayed in Figure 4a. For the purposes of this study TCRs which are separated in time by 30 min or more are classified as “isolated.” Despite their modest amplitude, $\Delta B/B \approx 5\%$ and 10\%, respectively, the several-minute long TCRs at 0212 and 0300 UT are readily identified against the steady lobe fields. Note that the inflection point in the north–then–south variation in $B_z$ is coincident with the peak in field magnitude and that they are both followed by an interval of southward $B_z$. As indicated by the vertical dashed lines, each of the TCRs is preceded by sharp increases in the $AL$ index with time delays of 11 and 7 min, respectively. The increase in $AL$ at 0201 UT is accompanied by the observation of a Pi 2 on the ground (Wingst) at 0159 UT. Similarly, the identification of the 0253 UT $AL$ increase as a substorm onset is supported by the observation of an
geosynchronous energetic particle injection event at 0258 UT.

An example of a paired TCR event, that is, two TCRs separated by less than 30 min, is displayed in Figure 4b. The choice of 30 min is motivated both by our observations of TCR groupings and a desire to study the relationship of TCRs to substorm expansion phase. When numerous TCRs are observed in the ISEE 3 observations, they are frequently seen to be separated by less than 30 min in time (see Figure 11). With respect to substorm time scales, 30 min is a typical duration for the expansion phase. For this event ISEE 3 was located at a downstream distance of \( X = -73 \, R_E \). The two TCRs are easily identified by the north-then-south \( B_z \) signatures which accompany the pulses of enhanced field strength, \( \Delta B/B \approx 17\% \) and 3\%, respectively. The two TCRs are separated by 19 min in time, and \( B_z \) is southward during the entire intervening time as well as for about 10 min following the second compression region. As will be examined in more detail later, it is typical of these events that the first TCR of the pair is larger than the second. This paired event is preceded by a sharp increase in the \( AL \) index 7 min before the peak in the first TCR as indicated in the figure. The association between substorm onset and the 1321 UT increase in \( AL \) is supported by the observation of a geosyn-

![Figure 4b](image)

Three hours of ISEE 3 magnetic field observations (3-s averages) taken in the north lobe of the tail are displayed in GSM coordinates. A pair of TCRs are marked with vertical dashed lines. In the bottom panel the absolute value of the \( AL \) index (1-min resolution) is shown and the sudden enhancement which preceded the pair of TCRs is indicated with a dashed line.

chronic orbit energetic particle injection at 1325 UT and the observation of a Pi 2 event on the ground (Wingst) at 1319 (not shown). Finally, the gradual increase in lobe field strength prior to the observation of the TCR and the lower field intensity afterward are common features of these events. Although quite variable in magnitude and temporal extent, this systematic variation is indicative of the “loading” and “unloading” of the lobes with magnetic flux during the growth and expansion phases, respectively, of substorms [see Fairfield, 1986; Slavin et al., 1992].

Figure 4c displays measurements taken on April 10, 1983, containing a large isolated TCR at 1259 followed by a multiple TCR event starting at 1354 UT. All of these events were observed when ISEE 3 was at a distance of \( X = -78 \, R_E \). Once again, the initial TCR in the multiple event is the largest in amplitude with each subsequent TCR being closer in time to the previous one and smaller in amplitude. As with the other examples, the individual TCRs are followed by southward \( B_z \) magnetic fields.

The isolated TCR followed a small increase in the \( AL \) index with a time delay of 6 min. The 1253 UT onset of this small substorm is further supported by the observation of an energetic particle injection event at geosynchronous orbit and the observation of Pi 2 waves on the ground at 1252 (Memambetsu). The multiple TCR event is associated with a
very clear growth phase enhancement of the lobe magnetic field which began about 15 min before Pi 2 events are seen on the ground (Memambetsu starting at 1340 UT), and there is a sudden increase in the $AL$ index. Nearly coincident with substorm onset in the $AL$ index, the strength of the lobe magnetic field starts to relax back toward its pregrowth phase level. It is during this relaxation of the tail fields that three TCRs are observed at ISEE 3 with the first TCR following onset with a time lag of 6 min. Delay times of 4 min and 14 min, respectively, are derived from the geosynchronous orbit energetic particle injection and ground-based Pi 2 observations. Although there are multiple peaks in the $AL$ index, there is no clear association between the subsequent TCRs in this multiple event and fine structure in the $AL$ index.

It should be noted, however, that this multiple event is very unusual in that the initial TCR is not observed at the peak of the lobe field increase that marks the end of the growth phase and the beginning of the expansion phase as is typically the case (for example, see the events discussed by Slavin et al. [1990, 1992]). This is unexpected because plasmoids, as closed magnetic structures, should transport no net magnetic flux out of the tail. It is only after the ejection of the plasmoid that magnetic flux can be removed from the lobes by the tailward plasma flows with embedded southward $B_z$. A possible explanation for the initial TCR in the multiple event in Figure 4c occurring after the lobe field has started to decline is that an unobserved plasmoid was released earlier near the time when the lobe field peaked. This could happen, for example, if the plasmoid had formed at distances comparable to that of ISEE 3 (that is, one $x$-type neutral line earthward of the spacecraft at $X = -78 R_E$ and one tailward), then a well-defined TCR signature would not have been detected. In fact, the southward turning of $B_z$ after 1345 is consistent with this scenario and may correspond to the earthward half of the initial plasmoid. The TCR signature can be observed only if the plasmoid forms between the Earth and ISEE 3 and then moves tailward past the spacecraft.

Examples of TCRs in the Distant Tail: $X < -200 R_E$

An example of an isolated TCR observed when ISEE 3 was in the distant tail on February 2, 1983, at $X = -220 R_E$ is displayed in Figure 5a. The TCR is observed at 2303 UT, approximately 28 min after a particularly sharp jump in an increasing $AL$ index and 30 min after a Pi 2 event observed on the ground (Wingst). At these geocentric distances, the solar wind moves the tail rapidly over large lateral displacements as it responds like a “wind sock” to changes in upstream flow direction. The result is that ISEE 3 does not often spend long periods, i.e., hours, in a single region of the tail. In addition, the plasma sheet boundary layer expands in thickness as the spacecraft position recedes from the average distant neutral line position near $X = -100$ to $-120 R_E$ [Zwickl et al., 1984; Slavin et al., 1985]. Large-amplitude magnetosonic waves driven by streaming energetic ions in this region [Tsurutani et al., 1983] contribute greatly to the increased variance of the magnetic field observed as ISEE 3 moves down the tail. These waves are clearly present in the magnetic field observations displayed in Figure 5a between 2100 and 2150 and again after 2340 UT. In at least some instances these waves can be sufficiently large in amplitude so as to obscure TCR signatures.

A further example of TCRs in the very distant ISEE 3 observations is shown in Figure 5b. The TCRs in this paired event on July 29, 1983, passed over the spacecraft at 0919 and 0927 UT, respectively. They were preceded by clear spike in the $AL$ index at 0857 and a Pi 2 at 0847 (Memambetsu) yielding delay times of 22 to 32 min between the enhancement of substorm activity and the observation of the TCRs in the distant tail. Again, note the increased variance of the tail magnetic fields at these distances against which the TCR perturbations must be identified. Indeed, no multiple events with their smaller-amplitude TCRs were identified in the very distant tail, possibly, because of the increased wind-sock motion decreasing the number of long intervals in the lobes and decreased signal-to-noise ratio for their detection when the spacecraft is in the plasma sheet boundary layer.

**Spatial Distribution of TCR Events**

The trajectory of ISEE 3 during the Geotail Mission is displayed in Figure 6a. Projections of the orbit onto all three of the GSM planes are shown for two contiguous time intervals, October 1982 to May 1983, and June–November 1983. As can be determined from inspection of Figure 6a,
the spatial coverage of the tail between about the apogee of IMP 8, approximately \( X = -40 R_E \), and the most distant ISEE 3 apogee, \( X = -238 R_E \), was relatively comprehensive (see discussions by Sibeck et al. [1985] and Fairfield [1992]). However, it is very important to note that the spacecraft spent long intervals of time well above or below the midplane of the tail making encounters with TCRs more probable than encounters with the plasma sheet or plasmoids.

Figure 6b shows the locations of the 116 TCRs identified in this study. Comparison with the ISEE 3 trajectory plot indicates that TCRs were seen essentially everywhere the spacecraft went presumably as a result of the wind sock response of the tail to changing solar wind flow direction. However, the distribution in the GSM \( Z' - Y' \) plane shows that there is a tendency for the TCRs to be observed more frequently when ISEE 3 was above or below the average location of the plasma sheet. The prime designation on the coordinates indicate that they have been rotated by 4° to remove the average effects of solar wind aberration (i.e., mean tail axis is parallel to \( X' \)). Similar plots for plasmoids [Moldwin and Hughes, 1992] appear to show the inverse correlation with the plasmoids being observed most frequently near the midplane of the tail. The distribution of

Fig. 5b. Three hours of ISEE-3 magnetic field observations (3-s averages) taken in the north lobe of the tail are displayed in GSM coordinates. A pair of TCRs are marked with vertical dashed lines. In the bottom panel the absolute value of the \( AL \) index is shown, and the sudden enhancement preceding the TCRs is indicated with a dashed line.

TCRs along the \( Y' \) axis indicates that most are observed in the central portion of the tail, i.e., over a region \( 10-20 R_E \) wide. It is in this central region of the distant tail that reconnection signatures, such as \( B_z \) southward and high-speed tailward flow, are most commonly observed [Slavin et al., 1985, 1987].

The occurrence rates for TCRs as a function of downtail distance are examined in more detail in Figure 7. The top panel graphs the number of TCRs versus GSM \( |X'| \) with bins of \( 10 R_E \) width. As shown, the number of TCRs observed decreases quickly inside of the orbit of the Moon (60 \( R_E \)) and exhibits peaks at 70-80 \( R_E \) and 220-240 \( R_E \). There is also a dearth of TCRs at \( X' = 140-180 R_E \). However, examination of the ISEE 3 trajectory, displayed in Figure 6a, shows that when the spacecraft was a distances of \( X = -140 \) to \(-180 R_E \), it was generally very near the low latitude flanks of the tail. The second panel displays the total amount of time ISEE 3 spent in the lobes of the tail as a function of \( |X'| \). Note the peaks in tail lobe dwell time at \( X' = -70 \) to \(-80 R_E \) and beyond \( -200 R_E \) associated with ISEE 3 apogee intervals. The third panel of the figure displays the rate at which TCRs were observed, i.e., the data in the top panel have been divided by the amount of time the spacecraft spent in each \( X' \) bin. The result is a clear decrease in the number of TCRs observed earthward of \( X' = -60 R_E \) and a broad maximum in the \( X' = -60 \) to \(-130 R_E \) region. The decrease in the rate at which TCRs are observed closer to
signatures can be observed. Alternatively, there may be some factor(s) relating to how the lobe field drape over the plasmoid which makes the TCR signature more difficult to detect in the very distant tail where, on average, flaring of the magnetopause has ceased, and more of the tail field is disconnected from the Earth.

The finding that TCRs often occur in groups of two or more suggests that individual substorms frequently produce more than one TCR. For the purpose of comparing substorm occurrence rates with those of TCRs, it is of interest to display not the rate at which the individual TCRs are observed, but the rate at which isolated, paired and multiple “events” occur. This is done in the bottom panel of Figure 7. The resulting distribution versus distance down the tail is very similar to the previous panel, but with the disparity in the rate of occurrence between the middle and distant tail somewhat reduced. If it is assumed that each of these isolated, paired, or multiple TCR events are caused by

the Earth is in good agreement with the 0.05 TCRs/hour at
$X = -30$ to $-40 \, R_E$ determined using IMP 8 magnetic field
observations by Slavin et al. [1990]. There is also a small
decline in the rate of TCR production beyond $X = -100 \, R_E$. The reason for this is unclear. As mentioned earlier, this
effect may be due to the presence of large amplitude waves
in the distant plasma sheet boundary layer obscuring the
TCR signatures. In this case, the spacecraft would have to
be located farther from the plasma sheet before clear TCR

Fig. 6a. Orthogonal views of the ISEE 3 trajectory in GSM
coordinates are displayed for the October 1982 to November 1983,
interval covered by the Geotail Mission. For reference, the magne-
topause surface from Howe and Binsack [1972] is also shown.

Fig. 6b. The locations of the TCR events identified in this study
are displayed in aberrated GSM coordinates along with the magne-
topause model of Howe and Binsack [1972].
plasmoid(s) released during a single storm, then the implied substorm occurrence rate in the bottom panel is once every 4–6 hours. This result is in good agreement with typical substorm occurrence rates [e.g., Akasofu, 1964].

TCR Amplitude and Duration

Two properties of TCRs which can be directly measured are the amplitude and duration of these magnetic field perturbations. For all 116 TCRs the lobe magnetic field intensity before and after the event has been used to define a baseline relative to which its total amplitude can be determined. In Figure 8a various histograms displaying TCR perturbation amplitude are presented. In the left-hand column the top panel shows a histogram of amplitude for the TCRs corresponding to isolated events. The mean amplitude is 8.8% with a standard deviation of 5.4%. The second and third panels display the amplitudes for TCRs in the paired and multiple events. The average amplitude of the paired events, 8.7%, is very similar to that of the isolated TCRs, but the mean amplitude of the multiple events, 5.6%, is significantly less. The histogram in the bottom panel shows TCR perturbation amplitude for all 116 TCRs irrespective of the type of event to which they corresponded with a resulting mean amplitude of 7.6%.

The decrease in mean amplitude of the TCR perturbation as the number of TCRs per event increases suggests that the north-south dimensions of plasmoids in the multiple events are much less than in the isolated events. Accordingly, it might be the thought that the total volume, and hence mass, of the plasmoids released during the multiple events is less than during isolated events. However, the right-hand column of Figure 8a displays the integrated amplitude of all the TCRs within each event. The top panel on the right-hand side is identical to the top panel on the left-hand side since isolated events contain only a single TCR. For the second panel the amplitudes of the two TCRs in each paired event have been added to produce 18 events with a mean summed amplitude of 17.4%. Similarly, the third panel on the right-hand side shows that the mean summed amplitude of the 11 multiple TCR events is 22%. The conclusion drawn from Figure 8a is that while the amplitude of individual TCR decreases as one goes from isolated to paired to multiple events, the sum over all of the TCRs in each event goes up. Accordingly, insofar as TCR amplitude is proportional to the vertical dimensions of the underlying plasmoid, this result suggests that the total plasmoid volume and mass are larger for events with multiple plasmoids, albeit the individual plasmoids are smaller.

It has been noted in the case studies that when more than one TCR occurs in a series, e.g., a paired or multiple event, then the amplitude of the TCRs tends to decrease with each succeeding TCR. The top panel of Figure 8b examines this

Fig. 8a. The left-hand panels display histograms of the amplitude, $\Delta B / B$ (%), of the TCRs in the isolated, paired, and multiple events. The right-hand panels display the integrated amplitude for the TCRs in the isolated, paired, and multiple events.

Fig. 7. The top panel displays the number of TCRs observed by ISEE 3 as a function of GSM X'. The second panel gives the total amount of time ISEE 3 spent in the lobe regions of the tail as a function of downstream distance. The third panel displays the number of TCRs observed per hour ISEE 3 spent in the lobes. The bottom panel shows the number of isolated, paired, and multiple TCR “events” per hour of lobe observations.
Fig. 8b. In the top panel the amplitude of TCRs in multiple events, normalized to the initial TCR in each case, is plotted against their numerical order within the event (e.g., first, second, third, etc.). Note that in multiple TCR events the initial TCR has the greatest amplitude, the second TCR is, on average, the second largest in amplitude, and so forth. The lower panel plots the average amplitude for all of the TCRs in a given event against the total number of TCRs in the event. As shown, the greater the number of TCRs in a given event, the smaller the average amplitude of the TCRs.

issue by normalizing the amplitudes of TCRs in the 11 multiple events identified in this study to the amplitude of the first TCR in each event. The normalized amplitudes of the first, second, third, etc., TCRs in each of the multiple TCR events have then been averaged together and plotted along with a standard error in the mean shown as a vertical bar. The results in the top panel confirm that the amplitudes of the individual TCRs decrease as one goes from the first to succeeding TCRs in multiple events.

By comparison, the bottom panel of Figure 8b displays the average amplitude of the TCR perturbation for isolated, paired, and multiple events as a function of the number of TCRs in each event. The results confirm and extend the conclusion drawn from Figure 8a that the mean amplitude of the TCR perturbations in these events decreases as the total number of TCRs in a given event increases.

If the dimensions of plasmoids are relatively stable following their release down the tail, as has been suggested by both theoretical [Hesse and Birn, 1991] and observational [Moldwin and Hughes, 1992] studies, then the amplitude of the TCR perturbations would be expected to be independent of the downtail distance at which they are observed. The top panel of Figure 8c displays the mean amplitude for all 116 TCRs, averaged over 5 $R_E$ bins as a function of distance down the tail. As indicated by the flat slope of the linear least squares fit to the data, TCR amplitude is nearly constant down the tail. Examination of TCR perturbation amplitude versus the $Y'$ and $Z'$ location of ISEE 3 produces similar flat responses as shown in the bottom two panels of Figure 8c. Hence the TCR observations collected during this study suggest that plasmoids do not change significantly in their north-south dimensions following their formation and release down the tail.

As with many space plasma phenomena, the determination of the beginning and ending times for these events is not precise. The endpoints of the TCR compression and tilting signatures smoothly blend into the background field of the lobes with no sharp boundaries. For this study the duration of the TCR is defined as the interval between the peak northward and southward tilting of the GSM Z field component. While underestimating the duration of the underlying plasmoid bulge by about a factor of 2, TCR duration defined in this manner is highly reproducible and allows for ready intercomparison between different TCRs.

Figure 8a displays histograms of TCR duration, $\Delta T$, during isolated, paired, and multiple events. As shown in the left-hand column, the mean TCR duration decreases from just under 3.5 min for isolated TCRs to around 2.5 min for TCRs in paired events to under 1.5 min for multiple events. However, the right-hand column displaying the summed durations for TCRs during such events indicates that the integrated duration of the multiple and paired events greatly exceeded that of the isolated events. These results, like those for TCR amplitude, suggest that isolated plasmoids are...
on average the largest in volume and mass, but the summed values of the plasmoids occurring during paired and multiple events are greater still.

As with TCR amplitude, Figure 9b indicates that the duration of these events does not display a significant dependence on GSM \( X' \), \( Y' \), or \( Z' \) position within the tail. This supports the conclusion reached by previous studies that plasmoids evolve little after formation and maintain an approximately constant volume as they move down the tail. Finally, Figure 10 examines the relationship between TCR perturbation amplitude, and duration. As shown, these two quantities are not closely correlated. However, the amplitude of the compression regions tends to increase as TCR duration grows. This result suggests while the underlying plasmoids vary significantly in shape, the longer plasmoids tend to be larger in the north-south direction.

**Principal Axes Analysis**

Further insight into the structure of TCRs can be gained from examining the magnetic field in principal axes coordinates [Sonnerup and Cahill, 1967]. In this system the \( B_1 \) axis is defined to be along the direction of maximum variance for the magnetic field during the time interval of interest. The other two axes, \( B_2 \) and \( B_3 \), are oriented along the intermediate and minimum variance directions, respectively. Figure 11 displays 2 min of ISEE 3 magnetic field measurements (3-s averages) in principal axes coordinates for the TCR which was observed at 0300 on April 11, 1983 (see Figure 4a). The directions of the principal axes (i.e., the eigenvectors).

![Fig. 9b. TCR duration is averaged into 5 \( R_E \)-wide bins and plotted against aberrated GSM \( X \), \( Y \), and \( Z \) location. Least squares linear fits to the data indicate that TCR duration varies little with where they are observed in the lobes.](image)

![Fig. 10. Amplitude is plotted against duration for all 116 TCRs identified in this study. The least squares best fit line has a slope of 0.02 and a correlation coefficient of 0.4.](image)

![Fig. 9a. The left-hand panels display histograms of the duration, \( \Delta T \)(s), of the individual TCRs for isolated, paired, and multiple events. The right-hand panels display the integrated durations of the TCRs in the isolated, paired, and multiple events.](image)
Fig. 11. ISEE 3 magnetic field observations (3-s averages) are displayed in principal axes coordinates for a typical TCR beginning at 0259 UT on April 11, 1983. The eigenvector and eigenvalue for each principal axis is displayed in parentheses for each panel. Note that the minimum variance direction is well defined and nearly aligned with the GSM Y axis. In contrast, the maximum variance direction is close to the GSM Z direction. Hodograms of the field variation are displayed in the bottom panels.

tors) in GSE coordinates are given in each of the panels as are the eigenvalues. Note the large ratios of maximum to intermediate and intermediate to minimum eigenvalues indicating that the eigenvectors are well defined. As shown, the minimum variance direction for this TCR is essentially along the GSE Y axis. The intermediate and maximum variance directions were largely along the GSE X and Z axes, respectively. Hodograms at the bottom of Figure 11 provide views of the TCR magnetic field variation in two orthogonal planes. The beginning and end of the traces are marked with "B" and "E", respectively. As shown, the field variation was limited to a simple planar tilting of the magnetic field which is confined to the B2-B1 plane. Viewed in this coordinate system, the very simple nature of the TCR signature is apparent with the magnetic field draping about the plasmoid. There is no evidence for the more complicated minimum variance frame signatures which would be associated with complex magnetic structures such as flux ropes [see Slavin et al., 1989].

In order to determine the generality of this result, principal axes have been determined for all of the TCRs identified in this study. The minimum variance unit vectors for all of these TCRs have been projected into the solar wind abberated GSE Z'-Y' and Y'-X' planes and are displayed in Figure 12. As shown, the minimum variance directions for most of these TCRs are transverse to the central axis of the tail and generally parallel to the plane of the cross-tail current layer. Of the 116 events, 69 have minimum variance directions within 45° of the Y' axis, while only 18 and 15, respectively, lie within 45° of the X' and Z' directions. Again, these results are generally consistent with traveling compression regions being simple lobe field-drapping signatures as originally suggested by Slavin et al. [1984].

TCR SUBSTORM ASSOCIATION

As pointed out earlier, it was the frequent association between TCRs and substorm activity that led to their being identified as the lobe signature of tailward moving plasmoids. Later studies such as Slavin et al. [1989] have supported this close tie between the observation of a substorm onset or intensification and the observation a short time later of a TCR in the distant tail. Recently, Slavin et al. [1992] have reported upon ISEE 3 observations taken during a one-and-a-half day interval during which 15 substorm onsets and/or intensifications all produced TCRs and/or
plasmoids. This section presents some additional case studies which utilize a variety of substorm phenomena as indicators of expansion phase onset and concludes with comprehensive statistical analyses of the substorm-TCR relationship.

Case Studies

An example of a well-defined substorm onset followed by the observation of a TCR at ISEE 3 on October 23, 1982, is shown in Figure 13a. There is a sharp turn-on at 1526 UT of auroral kilometric radiation (AKR) evident in the ISEE 3 100-kHz electric field measurements displayed in the top panel. This was accompanied by a sudden increase in the AL index in the bottom panel and PI 2 pulsations on the ground (Memambetsu). There is a 10- to 15-min delay until a dispersive energetic electron injection is observed near dawn by the geosynchronous spacecraft 1981-025 [e.g., Baker et al., 1984]. The time delay between the substorm onset at 1526 and the arrival of the TCR at ISEE 3 at $X = -86 R_E$ is 15 min.

Figure 13b presents another example of the substorm-TCR association. On December 26, 1982, there was a clear substorm onset signature in the 100-kHz AKR measurements at 0601. On this occasion, geosynchronous spacecraft 1982-019 was near local midnight, and an only slightly dispersive energetic electron injection was observed 7 min later. Similarly, the response in the AL index was also somewhat delayed, most probably because of the relative locations of the westward electrojet and the standard ground stations. For this event, no PI 2 waves were observed at the Membsu (Japan) or Wingst (Germany) stations used in this study. The time delay between the earliest substorm onset in auroral kilometric radiation (AKR) and the arrival of the TCR at ISEE 3 at $X = -69 R_E$ is 11 min. This particular TCR is also interesting in that it had a very unusual, almost sawtooth compression signature. As suggested by the small bump halfway down the compression ramp, this event may

Fig. 12. The minimum variance vectors determined for all of the TCRs identified in this study are projected in the abberated GSM $Y$-$Z$ and $X$-$Y$ planes. Note the strong tendency for the minimum variance direction to lie generally parallel to the abberated GSM $Y$ axis.

Fig. 13a. The top panel displays ISEE 3 100-kHz electric field observations of AKR. The second panel shows an energetic electron ($E > 30–200$ keV) injection at geosynchronous spacecraft 1982-025. A single TCR is observed at ISEE 3 ($X = -86 R_E$) 15 min later as shown in the measurements of lobe magnetic field intensity displayed in the third panel. The bottom panel shows the absolute value of the AL index. In this example the AKR and AL onsets are nearly coincident while the dawn location of the geosynchronous spacecraft introduces a time delay in the arrival of injected energetic particles.
Fig. 13b. A second example of the correlation between the arrival of TCRs at ISEE 3 and observations of substorm onset closer to the Earth following the same format as Figure 13a. In this case, the substorm onset in the AKR and AL observations are also nearly coincident, but with only a small delay in energetic particle arrival time because of the more favorable geosynchronous spacecraft position at 0130 UT. A single TCR is observed at ISEE 3 11 min later.

Fig. 13c. A third example of the correlation between the arrival of a TCR at ISEE 3 and observations of substorm onset closer to the Earth follows the same format as the preceding figures. The delay between the arrival of a pair of TCRs at ISEE 3 at $X = -73$ $R_E$ and the earliest indicators of substorm onset is 7.5 min.
have been caused by a so-called "double-loop" plasmoid [Richardson et al., 1987] with two unresolved, nearly contiguous bulge signatures moving down the tail together. Finally, Figure 13c provides a more complete view of the substorm which gave rise to the pair of TCRs examined earlier in Figure 4b. As shown, there is a near coincidence between the rise of AKR against a moderate solar background and the initiation of a strong increase in AL at 1321 UT. This substorm onset identification is supported by the observation of a Pi 2 event on the ground (Memambetsu) at 1319. Geosynchronous spacecraft 1981-025 was 4.5 hours past local midnight and observed a dispersive energetic electron injection event beginning at 1325. The time delay between the AKR-AL onset and the arrival of the first TCR at ISEE 3 at X = -73 R_E is 7.5 min.

Statistical Analyses

To examine the association between TCRs and substorm activity in more detail, the AKR emissions measured at ISEE 3, the AL index, the Pi 2 observations at the Memambetsu and Wingst ground stations, and LANL energetic charged particle measurements from three geosynchronous spacecraft have been surveyed to identify clear substorm onsets or intensifications prior to all of the isolated, paired, and multiple TCR events identified in this study. An attempt was made to associate individual TCRs in paired and multiple events with finer structure variations in these substorm indices, but the results were not definitive. Accordingly, all delay times used for the paired and multiple events correspond to the delays between the substorm onset indicator and the arrival of the initial TCR of the event.

For the isolated TCR events, onset/intensification signatures were found in one or more of the substorm indicators for 34 of 37 events. The results for the paired and multiple TCR events were 15 of 18 and 11 of 11, respectively. Overall, 60 of the total 66 events, or 91% were preceded by well-defined substorm onset/intensification signatures. Given the limitations of the various substorm indicators, a 91% success ratio is consistent with essentially all TCRs being associated with substorms.

In Figure 14a the delay times between the onset of substorm activity in AKR power and the arrival of the TCR at ISEE 3 are plotted versus GSM X'. In the case of the paired and multiple TCR events the delay is based upon the arrival of the first TCR in the series. Of the 66 total events, clear onsets or intensifications were observed for 32. However, this success ratio of 50% may have been limited by the fact that the ISEE 3 100-kHz electric field data were available only in the form of low-resolution daily survey plots on microfiche. It is probable that only the stronger substorm onsets could be discerned from these plots. Previous studies with access to digital AKR data records had much higher success ratios [e.g., Slavin et al., 1992]. This bias toward stronger substorms may also be reflected in the high mean downtail speed of 1173 km s^{-1} derived from the best fit to the delays in Figure 14a. The linear fit is obviously uncertain (i.e., a correlation coefficient of only 0.6) with the horizontal axis intercept in front of the Earth, but the flat slope is clearly indicative of a high tailward velocity.

Figure 14b displays the time delays between substorm onset and the arrival of the TCR at ISEE 3 based upon the AL index. As shown, such onsets or intensifications (for examples, see Figures 4a–4c and 5a and 5b) were identified for 55 of the 66 isolated, paired, and multiple TCR events. Although there is still considerable scatter, the correlation coefficient for this larger set of points is quite good, 0.8. As shown, the delay times grow from approximately 10 min at X' = -80 R_E to 40 min at X' = -230 R_E. A linear least squares fit to the points produced a mean tailward speed of 583 km s^{-1}. This speed is in good agreement with those determined in previous plasmoid studies [e.g., Richardson et al., 1987].

As shown in Figure 14c, Pi 2 pulsations at Memambetsu and Wingst were found for only 36 of the 66 events. The reason for this lower success ratio than was the case for AL is probably the use of records from only two ground stations. However, despite the smaller number of points the best fit to the time delay data yields an average tailward speed of 794 km s^{-1} in general agreement with the AL and AKR results.

Figure 14d presents the time delays determined from the geosynchronous energetic particle injection observations. Substorm injections were identified for 44 of the 66 TCR events, i.e., 67%. Again, the time delays were smallest close to the Earth and largest at the greatest distances with values similar to those determined using AL and Pi 2 observations. The mean tailward speed determined from the linear best fit to the points is 649 km s^{-1}, consistent with the results obtained with the other substorm indicators. Overall, the association between substorm activity and TCRs appears to be well defined and highly reproducible independent of the choice of substorm indicator.

In order to examine these delays and determine how the different substorm indicators relate to each other, Figure 15 displays histograms of the delays for TCRs observed at -100 < X' < -60 R_E. As shown, the mean delays are in close agreement. The mean values range from 13.8 min for AKR to 11.0 min for energetic electron injections at geosynchronous orbit. The fact that AKR is the earliest indicator of substorm onset is consistent with AKR propagating at a speed essentially equal to that of light. The field-aligned currents which drive the westward electrojet measured by the AL index and Pi 2 pulsations all propagate at hydromag-
Fig. 14b. Delay times between substorm onsets or intensifications in the AL index and the observation of TCRs as a function of ISEE 3's downtail distance.

Fig. 14d. Delay time between substorm injection events at geosynchronous spacecraft and the observation of TCRs as a function of ISEE 3's downtail distance.

magnetic wave speeds which are very high in the inner nightside magnetosphere. Energetic charged particles injected near local midnight orbit can take many minutes to drift to the location of one of the three geosynchronous spacecraft used in this study [e.g., Reeves et al., 1991]. In fact, temporal differences between substorm onset, typically observed in the AL index and energetic particle injections, are often larger than observed here [e.g., Kamide and McAlpine, 1974].

Finally, the substorm intensity associated with the three categories of TCR events has been examined by producing histograms of the AL index corresponding to the times the events arrived at ISEE 3. As shown in the top panel of Figure 16, the mean absolute value of AL for the isolated events is 301 nT with a standard deviation of 208 nT. For the paired events the mean level of substorm activity is slightly less at 257 nT. The substorm activity associated with multiple TCR events, however, is significantly higher at 449 nT. Hence it appears that isolated and paired TCRs, despite the larger amplitudes and durations of their individual TCRs, tend to be associated with smaller substorms. Multiple TCR events, on the other hand, are generally observed during more intense substorms.

Fig. 14c. Delay times between substorm onsets determined from the observation of Pi 2 pulsation events at Memambetsu (Japan) and Wingst (Germany) and the observation of TCRs as a function of ISEE 3's downtail distance.

Fig. 15. Histograms of delay time between onset or intensification in the various substorm indicators and the arrival of TCRs at ISEE 3 are displayed for $-100 R_E < X' < -60 R_E$.
DISCUSSION

The results of this first comprehensive survey of traveling compression regions in the distant magnetotail are important in several respects. First, they provide strong support for the original interpretation that TCRs are in fact large-scale compressions of the lobes caused by the rapid downtail motion of plasmoids. Second, the amplitude and duration of TCRs provide some information on the three-dimensional shape and volume of the plasmoid bulge. A determination of plasmoid volume also allows an estimate of the amount of energy dissipated in plasmoid formation and acceleration down the tail to be made. Third, the close association between substorm expansion phase onset and TCRs provides strong support for the plasmoid model of magnetotail dynamics. Below these TCR-related issues and applications are considered in more detail.

TCR Structure

Principal axes analyses performed on the magnetic field have confirmed that the TCR magnetic field variations are very simple and highly reproducible. The compression and north-then-south tilting of the field correspond to a pinching of the lobe flux tubes between the plasmoid bulge and the outer boundary of the tail. The finding that TCR amplitude is not dependent upon the GSM Y or Z location of the spacecraft supports the simple model in which the TCR compression is relatively uniform across the lobes in planes transverse to the X axis. Furthermore, the constancy of TCR amplitude as a function of X suggests that plasmoids do not grow or dissipate significantly as they move down the tail. The good agreement between the in situ observations of plasmoid velocity and those derived from TCR observations using the time-of-flight technique indicates that plasmoid velocity must be relatively constant following release. Similar conclusions have been reached by recent studies of plasmoids [Moldwin and Hughes, 1992].

Plasmoid Dimensions

Both the duration and amplitude of a TCR contain information on the dimensions of the underlying plasmoid bulge. The duration of the compression region in time can obviously be directly converted to length with a knowledge of the speed with which it passed over the spacecraft. The mean duration between the peaks in the north-then-south Bz draping signature determined in this study ranged from 218 s for isolated TCRs to only 84 s for TCRs occurring during multiple events. Assuming 700 km s^{-1} as a representative downtail speed based upon the results in Figure 14, the corresponding distance between the Bz extremes in the TCR-draping signatures range from 10 to 25 RE for multiple and isolated events, respectively. However, as discussed earlier, the distance between the extrema in the Bz signature is estimated to be only about half of the full TCR length. The total TCR dimension along the X axis is therefore approximately 20–50 RE. Accordingly, the mean plasmoid length derived from the TCR observations is approximately 35 RE.

There is, however, an important caveat in relating this length scale to plasmoid dimensions. First, TCRs can only be used to remotely sense the plasmoid bulge and not necessarily the entire region magnetically connected to the plasmoid. For example, if the bulge region were limited to just the central 75% of the magnetic island, then the length estimates based upon the TCR observations would be in error by 25%. In fact, the in situ plasmoid studies do generally yield longer lengths for plasmoids than those derived here from TCRs. For example, Richardson et al. [1987] found a mean single loop plasmoid length of 59 RE with a standard deviation of 24 RE. In this case, the inference would be that the bulge sensed by the TCR is, indeed, only about half of the total length of the plasmoid. However, determination of plasmoid length from in situ measurements is not without uncertainties. The plasmoid boundary cannot always be determined with great precision from the plasma and energetic particle measurements. In addition, there are important differences among the operational definitions used to identify plasmoids. The study by Moldwin and Hughes [1992], for example, used a largely magnetic field-based definition of what constitutes a plasmoid which differed significantly from the previous investigations. In marked contrast with previous studies, they obtained a mean length of only 17 RE. The 35 RE derived from the TCR observations in this study is intermediate between the extremes produced by the in situ plasmoid studies.

Up to this point there has been no experimental determination of the north-south dimensions of plasmoids. The average radius of the distant magnetotail and the half thickness of the plasma sheet have been estimated using statistical techniques to be approximately 24 and 3.4 RE, respectively [Fairfield, 1992]. The spatial distribution of TCRs in Figure 6b shows that despite dense coverage of the equato-

![Fig. 16. Histograms of the absolute value of AL at the time of arrival of isolated (top panel), paired (middle panel) and multiple (bottom panel) TCR events. Note that the number of TCRs increased as the level of substorm intensity grows.](image-url)
where $h$ is the increase in plasma sheet half thickness due to
the plasmoid bulge and $B_{TCR}$ is the compressed field ob-
erved at the peak of the TCR. The factor of 0.3 multiplied
times $h$ assumes that the east-west extent of plasmoids is
approximately $15 \ R_E$ as suggested by the spatial distribution
of TCRs in Figure 6b. Given that plasmoids must be
narrower than the total width of the tail, this estimate is
probably no more uncertain than about a factor of 2. Using
the mean TCR perturbation amplitude of 8% obtained in a
previous section yields $B_{TCR} = 10 \ nT$. Solving equation (2)
for the increase in effective plasma sheet half height pro-
duces $h = 4 \ R_E$. The total height of the plasmoid is then the
thickness of the plasma sheet, $7 \ R_E$, plus $2h$ for a total of $15
R_E$. This value is comparable to the estimated east-west
plasmoid dimension inferred from the TCR spatial distri-
bution and is slightly less than half of the plasmoid length
derived from the measured durations of TCRs.

As stated earlier, this value for the north-south extent of
plasmoids will be a lower limit to the extent that the
magnetopause is indeed able to bulge outward and relieve
the lobe compression as the plasmoid passes. The validity of
the quasi-rigid magnetopause approximation can be investi-
gated by considering the situation where the magnetopause
is assumed to move outward by just $5 \ R_E$, for example. This
outward motion would have to take place during a period of
time equal to half a TCR duration, or about 80 s (see Figure
9a). The outward speed of the magnetopause must therefore
be $5 \ R_E \ 80 \ s^{-1}$ or $400 \ km \ s^{-1}$. This speed is about a factor
of 3 less than the magnetosonic speed in the lobes, but at
least 5 times larger than the typical magnetosonic speed in
the magnetosheath (i.e., an interesting bow shock would be
expected to form around the expanding segment of the
magnetopause). Furthermore, for a typical magnetosheath
density of 8 protons \ cm$^{-3}$, the ram pressure experienced by
the lobe magnetic fields during the super-magnetosonic
expansion of the tail diameter would be $2 \times 10^{-6} \ dyn \ cm^{-2}$.
The magnetic field strength inside of the lobes required to
balance this ram pressure would be about 70 nT! In fact, a
displacement of the magnetopause by only $1 \ R_E$ in $80 \ s$
would require a ram pressure-equivalent lobe field of $15 \ nT$
which is 50% larger than what is observed on average for
TCRs. Hence the modest amplitude of TCRs appears to
argue strongly against plasmoids causing any large increases
in tail diameter as they move quickly down the tail. Furth-
more, while more detailed theoretical models of the plas-
moid-lobe-magnetosheath interaction are needed, the
assumption of a quasi-rigid magnetopause (on TCR time
scales) in estimating the north-south dimensions of
plasmoids may be quite reasonable.

Although theoretical modeling of the lobe magnetic fields
and adjacent magnetosheath will be necessary before the
TCR signatures can be deconvolved in a more rigorous
manner, the results presented above suggest mean plasmoid
dimensions of $35 \ R_E$ (length) $\times 15 \ R_E$ (width) $\times 15 \ R_E$
(height). The uncertainties in these mean dimensions are
difficult to evaluate, but they are probably no worse than
a factor of 2. It is significant to note that, as displayed in
Figure 17, these dimensions are far more suggestive of a slab
of plasma sheet material which has been disconnected from
the Earth over a broad local time sector than a cylindrical $O$
type neutral line or the Venus-type flux rope geometries.
sometimes assumed for plasmoids. This result appears to be in reasonable agreement with the results of in situ analyses of internal plasmoid magnetic fields [Slavin et al., 1989] and global MHD modeling [e.g., Kageyama et al., 1992].

**Plasmoid Energy**

On the basis of mean dimensions of $35 \times 15 \times 15 R_E$, the typical volume enclosed by a plasmoid may be estimated by assuming that it resembles an ellipsoid of revolution about the $X'$ direction

$$\text{vol} = \frac{4}{3} \pi (ab^2) = 4100 R_E^3 = 1.1 \times 10^{24} \text{ m}^3$$

(3)

where $a$ is the semimajor axis, $17.5 R_E$, and $b$ is the semiminor axis, $7.5 R_E$. Assuming a typical plasmoid ion density of $0.15 \text{ cm}^{-3}$ [Moldwin and Hughes, 1992] and a mean ion mass of 1 amu yields a typical plasmoid mass of

$$M = (1.5 \times 10^5)(1.67 \times 10^{-27}) \text{ vol} = 2.8 \times 10^2 \text{ kg}$$

(4)

The magnetic and thermal energies lost down the tail with the plasmoid are

$$E_{\text{magnetic}} = \left( \frac{B^2}{8\pi} \right) \text{ vol} = 1.6 \times 10^{13} \text{ J}$$

(5)

$$E_{\text{thermal}} = (5 n_e k_B T_e) \text{ vol} = 2.3 \times 10^{14} \text{ J}$$

(6)

where mean magnetic field intensities, 6 nT, and thermal energy densities, $0.5 \text{ K cm}^{-3}$, have been taken from Baker et al. [1987] and Moldwin and Hughes [1992], respectively, and an ion to electron temperature ratio of 5 [Slavin et al., 1985] has been used. The order of magnitude difference between the thermal and magnetic energy densities emphasizes the high beta nature of the region internal to plasmoids [Baker et al., 1990; Slavin et al., 1989].

The energy dissipated in accelerating the plasmoid up to a mean speed of $700 \text{ km s}^{-1}$ can also be readily calculated:

$$E_{\text{kinetic}} = \frac{1}{2} MV^2 = 7 \times 10^{14} \text{ J}$$

(7)

Clearly, the bulk of the energy dissipated in the creation and expulsion of plasmoids goes into the downtail acceleration of the plasma contained within the plasmoid as has been suggested by various numerical simulations [Hesse and Birn, 1991]. Taken together, these energies are comparable to the total amounts typically dissipated in ionospheric joule heating during substorms [Wei et al., 1985]. Accordingly, there may be an approximate equipartition between the energy dissipated in the inner magnetosphere and ionosphere and the energy lost down the tail to antisunward flows and plasmoids. A more precise analysis of the relative role of plasmoid ejection and high speed flow down the tail in the energy budget of substorms will probably have to await the more comprehensive data sets to be collected by the Geotail Mission.

**Substorm Association**

A strong association between substorm onset or intensification and the observation of traveling compression regions in the distant tail has been demonstrated through the use of both case studies and statistical analyses. The spatial distributions displayed in Figure 6b and Figures 14a–14d show that TCRs start to be seen in large numbers at a downstream distance of about $60 R_E$ with the implication that they form and are released near this distance. The existence of the TCRs themselves indicate that a segment of the plasma sheet has grown in north-south extent and been released down the tail at high speeds. While detailed fields and particles measurements from future missions will probably be required to determine with certainty the degree to which the magnetic fields in a plasmoid close on themselves or are open to the outside environment [Hughes and Sibeck, 1987], the ISEE 3 TCR observations are consistent with the basic predictions of the plasmoid model.

The large southward fields that are generally observed following the passage of a TCR (for example, Figures 3) constitute strong evidence for the continued reconnection of open lobe field lines after the release of the plasmoid, another key prediction of the plasmoid model. Following the passage of the plasmoid at ISEE 3 southward $B_z$ in the plasma sheet and in the adjacent regions of the lobes will be observed as newly reconnected lobe flux tubes convect tailward. This will continue until the near-Earth X line weakens and moves tailward of the spacecraft. At this point, $B_z$ becomes positive at ISEE 3. In particular, the duration of the southward tilting of the lobe magnetic field following TCRs should provide a measure of how much time passes between the initiation of reconnection between lobe field lines, i.e., the time of substorm onset and plasmoid release, and the retreat of the near-Earth neutral line past ISEE 3.

Using the pre-TCR and post-TCR lobe magnetic field $B_z$ levels as a baseline, the interval of southward field after each of the isolated TCRs has been determined and plotted in the top panel of Figure 18. As indicated, the southward field
intervals range from a few minutes to nearly an hour with a mean of 12.3 min. In the interest of having a well-defined start time for the southward $B_z$ intervals, these measurements are made from the peak in the TCR field compression. Accordingly, they include 1–2 min of southward $B_z$ associated with the draping of the lobe field about the plasmoid as opposed to disconnected fields earthward of the plasmoid. Finally, although not displayed, the duration of the post-TCR interval of southward $B_z$ does not show a significant correlation with distance downstream, $X'$. 

Another important result of this study is that TCRs, and by inference plasmoïds, are often observed in groupings of two or more. If each plasmoid is created by the tailward retreat of a near-Earth neutral line and the formation of a new X line in the near-tail, then it might be expected that the spacing between successive plasmoïds would be similar to the duration of southward $B_z$ following isolated plasmoïds. As shown in the lower two panels of Figure 18, this is indeed the case with the temporal separation between successive peaks in the TCR signatures (P-P) for paired and multiple TCR events being 11.2 and 10.2 min, respectively. Again, these time intervals do not appear to be a function of downtail distance implying that $X$ lines retreat tailward at speeds comparable to that of plasmoïds. Furthermore, the mean dwell time for $X$ type neutral lines in the near tail appears to be about 10 min independent of the number of plasmoïds formed and released. If confirmed by later studies, this is an extremely important finding as a determination of the position, intensity, and motion of neutral lines as a function of substorm phase is essential to understanding tail dynamics. This mean value of about 10 min is about 3–6 times shorter than usually assumed or determined in previous substorm studies [e.g., Hones, 1977; Baker and Pulkinen, 1991].

Examination of substorm conditions associated with the 66 isolated, paired, and multiple TCR events identified in this study has shown that 91% were preceded by onset or intensification signatures in at least one of four indicators: AKR, the AL index, Pi 2 pulsations at two ground stations, and energetic particle injections at three geosynchronous spacecraft. Combined with similar results derived from earlier plasmoïd studies [e.g., Baker et al., 1984, 1987; Slavin et al., 1989; Moldwin and Hughes, 1993], there appears to be ample evidence to conclude that large segments of the cislunar plasma sheet become detached and move down the tail at high speeds following expansion phase onset.

Given the strong correlational association between substorms and TCRs demonstrated in this study, an important question to address is whether all substorms produce plasmoïds and TCRs or just a special subset. A rigorous answer to this question would require stationing a spacecraft continuously in the distant tail and observing the plasmoïds and/or TCRs produced by each substorm. Unfortunately, the large-amplitude motion of the distant tail in response to changes in the solar wind velocity vector generally does not allow spacecraft such as ISEE 3 to remain in the distant tail for long periods of time. Slavin et al. [1992] have recently reported upon an unusual interval when ISEE 3 remained in the tail for one-and-a-half days during which 15 substorms were detected on the ground and in the near tail. For each substorm one or more plasmoïds and/or TCRs were later observed at ISEE 3. Moldwin and Hughes [1993] have also reported a one-to-one correlation between isolated, large substorms and the later observation of a TCR or plasmoïd at ISEE 3.

Given the results of these recent studies, it is appropriate to inquire as to whether the frequency of occurrence statistics for TCRs reported here are consistent with all substorms releasing plasmoïds down the tail. TCR observations are particularly well suited for this purpose because this compression signature is observable across the full cross section of the lobes; about $3 \times 10^{16}$ m$^2$ from (1). By comparison, the mean cross section of plasmoïds in the Y-Z plane based upon the results of this study is a circle of radius of $7.5 R_E$ or $3.6 \times 10^{15}$ m$^2$. Accordingly, it would be expected that a spacecraft randomly situated in the distant tail would observe an order of magnitude more TCRs than plasmoïds. In reality, some TCRs must be obscured in the very distant tail by the large-amplitude waves driven by ion beams in the plasma sheet boundary layer [Tsurutani et al., 1985] or waves on the magnetopause. For this reason the order of magnitude estimate for the ratio of TCRs to plasmoïds should be treated as an upper limit. Indeed, a recent study which examined both plasmoïds and TCRs observed 5–10 traveling compression regions for each in situ encounter with a plasmoïd [Slavin et al., 1992].

On the basis of the 116 TCRs identified in this study, it would be expected from the arguments above that perhaps only 10–20 plasmoïds would have been observed during the course of the ISEE 3 mission. In fact, the early studies by Hones et al. [1984a, b], Scholer et al. [1984], and Richardson et al. [1987] dealt with only 14, 24, and 37 plasmoïds, respectively. The first attempt to survey all plasmoïds in the ISEE 3 data set [Moldwin and Hughes, 1992], however, identified a total of 366 plasmoïds. Their criteria were far less restrictive than the earlier studies and consisted primarily of bipolar variations (+/− or −/+ ) in either the $B_x$ or $B_z$ components of the magnetic field without requiring coincident observations of high-speed tailward flow or isotropic energetic electrons. However, if only the subset of their plasmoïds identified on the basis of north-then-south $B_z$ fields, then the total number drops from 366 to 147 events [Moldwin and Hughes, 1992], which is comparable to the number of TCRs, 116, found in this study. In any case, the results of this study and that by Moldwin and Hughes [1992] appear to be in some conflict as to the correct ratio of TCRs to plasmoïds which should be observed by a spacecraft in the distant tail. Although it must be remembered that this ratio should be at least a weak function of spacecraft trajectory and how much time is spent in the deep lobes as opposed to the central plasma sheet, comparison of the ISEE 3 results with those of the Geotail Mission in regards to this issue should be of considerable interest.

Finally, the TCR observations taken during substorms of differing intensities have yielded some new results with respect to plasmoid dimensions and how substorms lose energy down the tail. As depicted schematically in Figure 19, TCRs seen during isolated and paired events were determined to be larger in amplitude and duration than those during multiple events. The intensity of the AL index corresponding to these isolated events was seen to be significantly lower than during the multiple events. Hence while the magnetosphere dissipates larger quantities of energy during very intense substorms, it does so by ejecting multiple, smaller plasmoïds rather than through the formation and expulsion of a single large plasmoid.
CONCLUSIONS

These are the primary results from this comprehensive survey of traveling compression regions in the ISEE 3 magnetotail observations:

1. The magnetic structure and general properties of TCRs are consistent with their original interpretation as the signature of lobe field draped about the plasmoid bulge as it rapidly moves down the tail.

2. The frequency with which TCRs were detected per unit time ISEE 3 spent in the lobe region was relatively constant beyond $X' = -60$ to $-80 \, R_E$, suggesting that plasmoid formation typically takes place at or inside of this distance.

3. TCRs are observed not just in isolation (37 TCRs), but frequently in pairs (18 events for 36 TCRs) and multiple events (11 events containing 43 TCRs).

4. The frequency with which isolated, paired, and multiple TCR events were observed per unit time ISEE 3 spent in the lobes of the tail was consistent with all substorms producing one or more plasmoids at a rate of one substorm every 4–6 hours.

5. The average duration of southward $B_z$ following isolated TCRs is comparable to the time separation between successive TCRs in paired and multiple events, about 10 min. This result is interpreted as evidence that reconnection $X$ lines typically remain in the near tail for only about 10 min before retreating tailward at high speed. This interval is significantly shorter than the value of 30–60 min often assumed by substorm models.

6. TCR amplitude and duration do not change with distance down the tail, indicating that the size and shape of the underlying plasmoids do not change greatly after their initial formation and release.

7. The estimated typical dimensions of plasmoids based upon the observed TCR duration and amplitude are $35 \, R_E$ (length) $\times 15 \, R_E$ (width) $\times 15 \, R_E$ (height).

8. When compared with common indicators of substorm activity, over 91% of TCR events were found to be preceded by substorm onsets or intensifications with mean time delays ranging from 10 min at $X' = -80 \, R_E$ to 30 min at $X = -230 \, R_E$.

9. Stronger substorms tend to produce more than one TCR, but with their individual amplitudes and durations being less than for those occurring in isolation. Conversely, smaller substorms tend to produce only one or two TCRs, but they tend to be larger than those in multiple TCR events.

10. The total energy dissipated through the release of plasmoids down the tail appears to be comparable to the energy dissipated in the ionosphere during substorms through joule heating.

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E. W. Hones, Jr., Los Alamos National Laboratory, Mail Stop D438, Los Alamos, NM 87545.

T. Iyemori, Data Analysis Center for Geomagnetism and Space Magnetism, Faculty of Science, Kyoto University, Kyoto 606, Japan.

E. W. Greenstadt, TRW, Mail Station RI-2020, Redondo Beach, CA 90278.

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