GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 23, 2208, doi:10.1029/2003GL018438, 2003

Cluster four spacecraft measurements of small traveling compression regions in the near-tail

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Received 17 August 2003; revised 14 October 2003; accepted 5 November 2003; published 9 December 2003.

[1] Cluster observations taken during a substorm on September 19, 2001 have revealed the presence of small traveling compression regions (TCRs) in the near tail. These measurements are used to determine directly the speed and direction of TCR propagation and the amplitude of the underlying bulge in the plasma sheet. The time-of-flight speeds derived from the arrival times of the magnetic perturbations at the different Cluster s/c yielded a mean speed of 413 km/s. For 2 of the TCRs s/c 1, 2 and 4 were located sufficiently close to the plasma sheet that they were immersed in the central plasma sheet plasma as the TCR swept over s/c 3. In this manner the Cluster measurements directly demonstrated that these small TCRs are caused by moving bulges in the plasma sheet-lobe interface. In summary, our analysis of the Cluster measurements has directly demonstrated the existence of moving bulges in the north-south thickness of the plasma sheet, most probably due to the formation of flux ropes, and their role in producing traveling compression regions. *INDEX TERMS:* 2744 Magnetospheric Physics: Magnetotail; 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2764 Magnetospheric Physics: Plasma sheet; 2788 Magnetospheric Physics: Storms and substorms. **Citation:** Slavin, J. A., et al., Cluster four spacecraft measurements of small traveling compression regions in the near-tail, *Geophys. Res. Lett.*, *30*(23), 2208, doi:10.1029/2003GL018438, 2003.

1. Introduction

[2] Traveling compression regions (TCRs) are intensifications of the lobe magnetic field thought to be caused by localized bulges in the plasma sheet due to the formation and rapid movement of magnetic flux ropes [*Slavin et al.*, 1984]. The magnetic fields in the lobes are pinched between the bulging of the plasma sheet and the magnetopause and constrained to drape closely about the bulge in the plasma sheet - lobe interface. The earthward or tailward motion of these bulges then causes the accompanying region of lobe compression also to "travel". If they move tailward (earthward) then the sense of the B_z perturbation is north-then-south (south-then-north).

[3] TCRs have been studied extensively using the deep tail ISEE 3, IMP 8 and Geotail measurements [*Shirai et al.*, 2001; *Taguchi et al.*, 1998; *Slavin et al.*, 1993; *Owen and Slavin*, 1992]. At those distances they have been used primarily to remotely sense the motion and dimensions of plasmoid-type flux ropes as they rapidly move tailward at speeds of 600 to 1000 km/s. However, *Moldwin et al.* [2001; 1994] have reported TCRs in the IMP 8 data that are inferred to be moving earthward based upon the sense of the B_z perturbation, i.e., south-the-north as opposed to the north-then-south variation usually observed in the distant tail. The direction and speed of TCRs inferred from all of these single spacecraft studies is based upon the sense of the draped field perturbation and statistical estimates that assumed the time of release for the underlying plasmoid-type flux ropes coincided with substorm onset [*Taguchi et al.*, 1997; *Slavin et al.*, 1993].

[4] Here we examine a series of 6 TCRs observed by Cluster during a substorm that took place on September 19, 2001. These are the first reported instances of TCRs in the very near tail, $X \sim -19\ R_e$, and their existence supports recent studies indicating that small scale flux ropes frequently form in the plasma sheet as a result of multiple x-line reconnection [*Slavin et al.*, 2003a, 2003b]. The measurements from Cluster also allow us, for the first time, to directly ascertain the speed and direction of the movement of the TCRs. Finally, for 2 of the events, the tetrahedral geometry of the Cluster s/c make it possible to observe simultaneously both the plasma sheet bulge and the TCR so that the amplitude of the traveling bulge in the plasma sheet - lobe interface may be estimated.

2. September 19, 2001 TCRs

[5] As reported by *Borälv et al.*, [Correlation between Ground-based Observations of Substorm Signatures and Magnetotail Dynamics, submitted to Annales Geophysicae, 2003] the onset of a small substorm took place at 20:39 on Sept. 19, 2001. Several subsequent intensifications were detected at ~21:09, 21:15, and 21:51 before the recovery phase was initiated around 22:15. Figure 1 shows a series of 5 TCRs with south-then-north (SN) B_z variations were observed by Cluster at 20:57:20, 21:08:58, 21:23:32,

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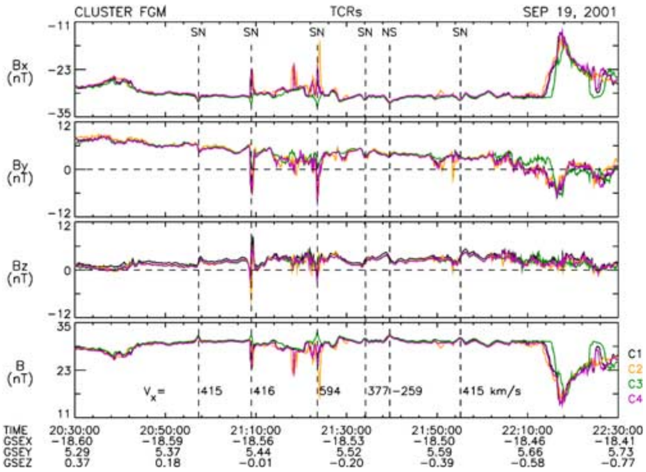

Figure 1. Cluster FGM observations of a series of TCRs recorded on September 19, 2001.

21:34:06, and 21:55:10. As will be discussed later, for two of these events only s/c 3 (i.e., the green trace) remained in the lobe region to detect the TCR. These compression regions should all be moving earthward based upon the sense of the B_z perturbation. The single north-then-south (NS) TCR presumably associated with a tailward moving plasma sheet bulge occurred at 21:39:35. As will be described in a later section, these propagation directions are confirmed by the V_x speeds determined by the time of arrival of the compressions at the 4 s/c (see bottom of Figure 1). As suggested by Boralv et al., these TCRs indicate that tail reconnection was taking place throughout this substorm in support of the near-Earth neutral line model of substorms.

[6] An expanded view of the Cluster FGM magnetic field measurements [*Balogh et al.*, 1997] for the first TCR centered on ∼20:57:20 is displayed in Figure 2. Color codes shown in the lower right-hand side of the figure indicate the magnetic field profiles observed by the different spacecraft. From the intensity and polarity of B_x we can see that all 4 s/c were located in the southern lobe of the magnetotail. The vertical dashed line marking the peak compression in B_x occurs near the center of the ΔB_z and ΔB_y variations. The SN sense of the B_z perturbation suggests that this TCR was associated with an earthward moving plasma sheet bulge. Similar magnetic field draping arguments applied to the GSM X-Y plane would indicate that the west-east B_y perturbation is due to the peak of the plasma sheet bulge having passed to the east [see *Slavin et al.*, 1993]. Finally, comparison of the most tailward s/c, #4 (magenta trace), and the most earthward s/c, #1 (black trace), does indeed show that the TCR was observed first at the more tailward s/c 4 and then propagated to the most earthward s/c 1.

[7] The duration of the compression was approximately 40 sec, based upon the extremes in B_z, and the intensity of the compression was about 1.8 nT or $\Delta B/B \sim 6\%$. The range of durations and compression ratios for the other 5 TCRs observed during this substorm ran from 26 to 72 sec and 4 to 8% with an average for all six of 49 sec and 6%, respectively. For comparison the mean values determined by IMP 8 and ISEE 3 at distances of $X \sim -30$ to -38 R_e and $X < -60$ R_e were 8% and 80–110 sec and 8% and 158 sec, respectively [*Taguchi et al.*, 1998; *Slavin et al.*, 1993].

3. TCR Propagation Speed and Direction

[8] Magnetic field measurements from the four Cluster s/c allow the direction and propagation speed of the TCRs to be determined using "time of flight" (TOF) calculations. Although the 4 s/c will take slightly different paths through the compression region, they will all record B magnitude profiles with the peak marking the center line of the plasma sheet bulge and the surrounding compression region. And, fortuitously, s/c 1 and 4 were nearly aligned in the GSM X direction with a separation of 1664 km. For comparison, the separations in the GSM Y and Z directions between s/c 1 and 4 were only ∼400 and 300 km, respectively. Accordingly, the direction and TOF speed of the TCRs can be determined by performing lag correlations between the magnetic field intensity measured at s/c 1 and 4 to determine the time required for the TCR to pass from one spacecraft to the other so that:

$$\mathbf{V_x} = (X_1 - X_4)/\Delta T_{14} \tag{1}$$

[9] For the 4 TCRs during which all 4 Cluster remained in the lobe region the lag time analysis yielded well defined, single peaks with correlation coefficients greater than 0.9. The magnitude of the time delays between s/c 1 and 4 ranged from 4.0 to 6.4 sec. In agreement with the interpretation of the sense of the ΔB_z variation, the lag time delays

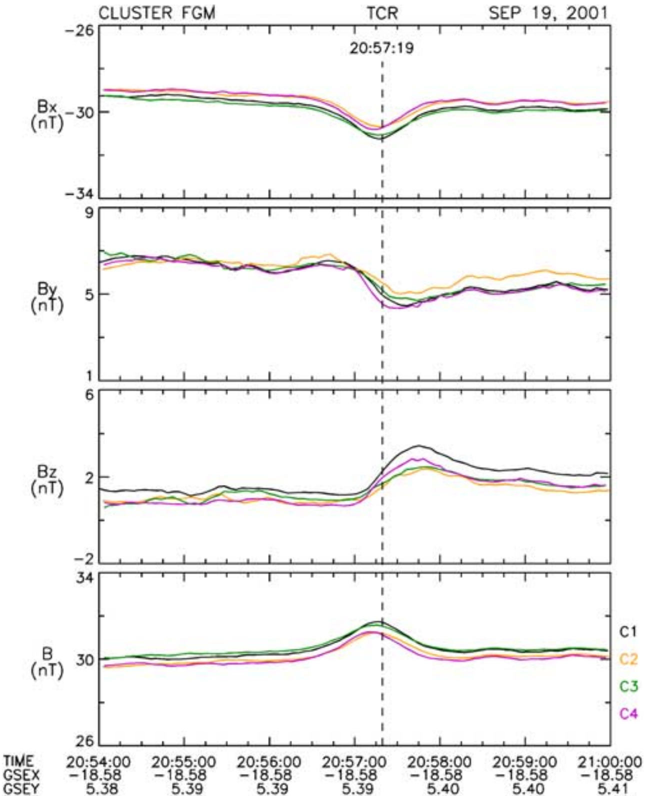

Figure 2. Cluster FGM observations of an individual SN TCR.

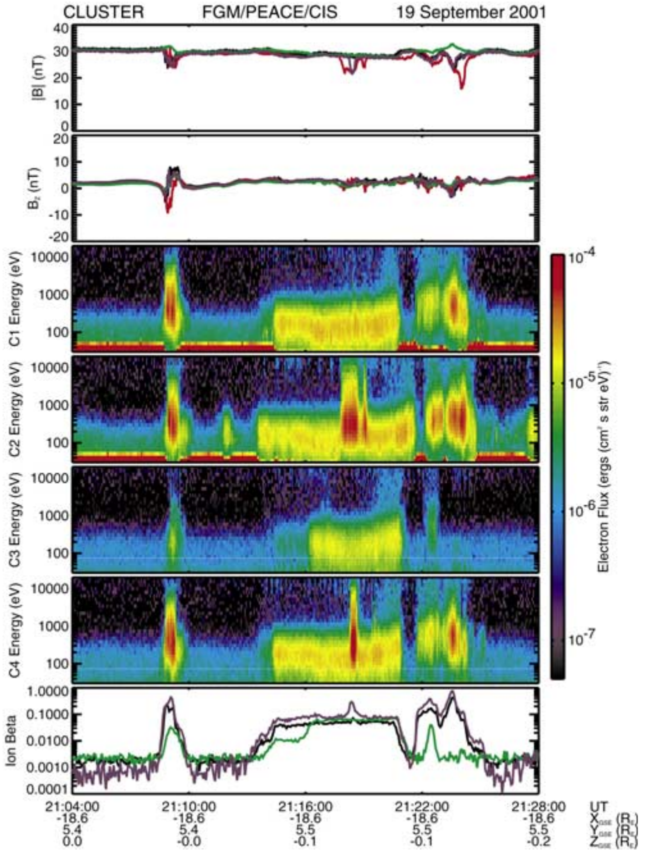

Figure 3. Cluster FGM, PEACE and CIS measurements during an interval containing two TCRs.

were positive, indicating earthward motion, for all of the SN TCRs and negative for the single NS TCR. The TCR speeds were 415 km/s, 377 km/s, −259 km/s and 415 km/s, respectively. For the two TCR events shown in Figure 3 three of the s/c entered the plasma sheet bulge. For these events we repeated this analysis using the B_z profiles and also found well defined lag correlations (>0.9). However, the higher variance in the B_z profiles resulted in the lag times being at least weakly dependent upon the start and stop time of the interval selected for analysis. For this reason the lag times determined using the field magnitude are preferred. The corresponding speeds determined using B_z for these two events were similar to those found earlier for the other TCRs; 416 km/s and 594 km/s. The speeds determined in the manner are indicated at the bottom of Figure 1 and yielded a mean speed of 413 km/s.

4. Plasma Sheet Bulge Amplitude

[10] For a single spacecraft, the only method for inferring the amplitude of the underlying bulge in the plasma sheet that creates the TCR is to invoke conservation of magnetic flux and compute the fractional reduction in the cross sectional area of the lobes necessary to produce the observed compression ratio [*Slavin et al.*, 1993]. Application of those arguments to these near-tail TCRs produces estimates for the increase in the total thickness of the plasma sheet in the bulge region of ∼1–3 R_e. However, this technique is quite sensitive to the assumed dimensions of the tail and the thickness of the plasma sheet both of which are highly time variable in the near-tail.

[11] Fortunately, the Cluster mission, again, provides us with a more direct approach. Figure 3 displays magnetic field and plasma data for the second and third TCRs. They differ from the other TCRs in that s/c 3 (green trace) remained in the lobe while the plasma sheet bulge engulfed s/c 1, 2 and 4. The diamagnetic nature of the magnetic field decreases at the three northern-most s/c is confirmed by the CIS plasma ion and PEACE plasma electron measurements [*Réme et al.*, 2001; *Johnstone et al.*, 1997]. In the bottom panel of Figure 3, the CIS ion moments are used to compute plasma ion beta at s/c 1, 3 and 4 (no CIS data is available from s/c 2). As shown, the plasma beta parameter shows that s/c 1 and 4 did indeed move from the plasma sheet boundary layer into the plasma sheet bulge where beta values reached ∼0.1 to 1. For s/c 3 ion beta also increases slightly for the first TCR in Figure 3, but not at all for the second. The PEACE spectrograms show the appearance of relatively high fluxes of hot plasma sheet electrons coincident with the decreases in the magnetic field at s/c 1, 2, and 4. S/c 3, on the other hand, just grazes the plasma sheet for the first TCR with low fluxes of hot electrons appearing coincident with the TCR perturbations while there is no evidence of enhanced electron flux for the second event.

[12] Figure 4 provides a schematic depiction of a small plasma sheet bulge due to the earthward motion of a flux rope relative to the actual locations of the Cluster s/c in the GSM X-Z plane. As shown, the Cluster s/c span a distance in the Z direction of ∼0.5 R_e. The Cluster measurements in Figure 3 indicated that the northern most s/c were located very near the plasma sheet both before and after the TCR at s/c 3, but they were easily engulfed during the TCR itself. Similarly, s/c 3 appears to have just remained outside the plasma sheet bulge; albeit, in the case of the first TCR the

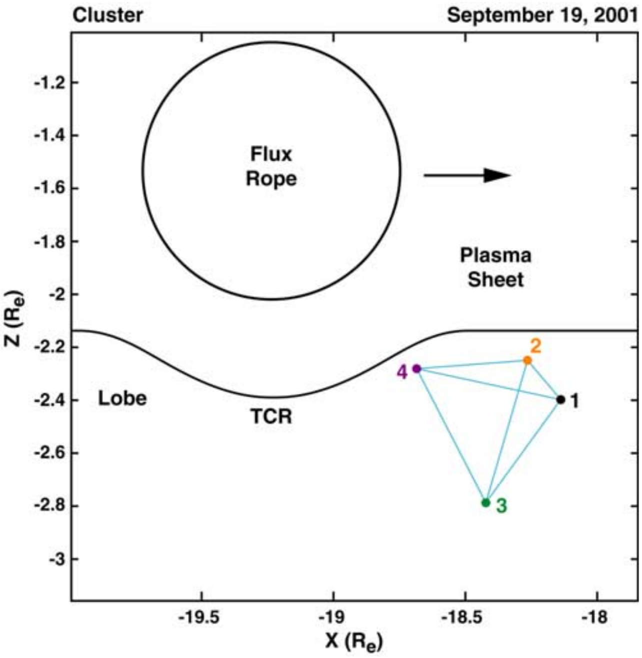

Figure 4. Schematic view of the bulge in the plasma sheet caused by the earthward motion of a small flux rope.

ion and electron flux enhancements indicate that the outermost layers of the plasma sheet were encountered. Accordingly, the sum of the plasma measurements made during these two events suggest that the amplitude of the bulges in the plasma sheet causing the TCRs at s/c 3 were comparable to the $\sim$0.5 R_e span of the cluster tetrahedron in the Z direction. Hence, the estimated total increase in the thickness of the plasma sheet associated with these TCRs is $\sim$1.0 R_e.

5. Summary

[13] The TCRs observed by Cluster in the near-tail differ from those observed in the more distant tail by IMP 8, ISEE 3 and Geotail in several respects. First, the vast majority of the TCRs, i.e., 5 out of 6, move earthward as opposed to tailward. Second, the mean duration of the Cluster TCRs was just $\sim$50 sec versus the $\sim$160 sec determined by ISEE 3 at $X < -60$ R_e. The Cluster 4 s/c observations demonstrate directly, for the first time, that SN and NS TCRs propagate earthward and tailward, respectively. The time-of-flight speed derived from the arrival times of the TCRs at the different Cluster s/c yielded a mean speed of 413 km/s. This is considerably slower than the 600–800 km/s values typical of plasmoids and TCRs in the distant tail (i.e., $X < -100$ R_e) [*Ieda et al.*, 1998]. Finally, for 2 of the events Cluster observed both the TCR and the underlying bulge in the plasma sheet. Analysis of the 4 s/c measurements yielded an estimated total increase in plasma sheet thickness associated with the bulge of $\sim$1 R_e.

[14] These Cluster TCR observations are of special interest because of the recent Geotail results indicating that small flux ropes with diameters of a few earth radii are common in the near-tail plasma sheet at distances of $X > -30$ R_e [*Slavin et al.*, 2003a, 2003b]. Those studies found that earthward of $X \sim -25$ R_e, the mean location of the near-earth neutral line [*Nagai et al.*, 1998], plasma sheet flux ropes are generally immersed within earthward directed bursty bulk flows (BBFs). They are referred to as “BBF-type” flux ropes in contrast with the “plasmoid-type” seen predominantly beyond that distance [*Ieda et al.*, 2001; 1998]. *Slavin et al.* [2003a, 2003b] proposed that the small near-tail flux ropes form as a result of simultaneous reconnection at a series of X-lines. The dimensions, compression ratios, predominant earthward propagation speeds of the near-tail TCRs observed by Cluster all appear to be consistent with the earthward passage of the small flux ropes discovered earlier by Geotail. The relationship between these small flux ropes and the brief TCRs they generate and the much larger plasmoid-type flux ropes and longer duration TCRs found in the distant tail remains to be understood. [see *Slavin et al.*, 2003a].

[15] **Acknowledgments.** The computational assistance provided by Carmen Liebrecht is gratefully acknowledged. The work by one of the authors (IR) was supported by the Deutches Zentrum fur Luft und Raumfart under contact 50OC0103.

References

Balogh, A., et al., Cluster Magnetometer Team, The Cluster Magnetic Fields Investigation, *Space Sci. Rev.*, *79*, 65, 1997.

Ieda, A., S. Machida, T. Mukai, Y. Saito, T. Yamamoto, A. Nishida, T. Terasawa, and S. Kokubun, Statistical analysis of plasmoid evolution with GEOTAIL observations, *J. Geophys. Res.*, *103*, 4435, 1998.

Ieda, A., D. H. Fairfield, T. Mukai, Y. Saito, S. Kokubun, K. Liou, C.-I. Meng, G. K. Parks, and M. J. Brittnacher, Plasmoid ejection and auroral brightenings, *J. Geophys. Res.*, *106*, 3845, 2001.

Johnstone, A. D., et al., PEACE: A plasma electron and current experiment, *Space Sci. Rev.*, *79*, 351, 1997.

Moldwin, M. B., and W. J. Hughes, Observations of earthward and tailward propagating flux rope plasmoids: Expanding the plasmoid model of geomagnetic substorms, *J. Geophys. Res.*, *99*, 183, 1994.

Moldwin, M. B., M. Collier, J. A. Slavin, and A. Szabo, On the Origin of Reverse Polarity TCRs: Wind and IMP 8 Observations, *Geophys. Res. Lett.*, *28*, 1925, 2001.

Nagai, T., M. Fujimoto, Y. Saito, S. Machida, T. Terasawa, R. Nakamura, T. Yamamoto, T. Mukai, A. Nishida, and S. Kokubun, Structure and Dynamics of magnetic reconnection for substorm onsets with GEOTAIL observations, *J. Geophys. Res.*, *103*, 4419, 1998.

Owen, C. J., and J. A. Slavin, Energetic ion events associated with traveling compression regions, *Proc. Int'l Conf. Substorms*, *Eur. Space Agency, Spec. Publ. 335*, pp. 365–370, 1992.

Rème, H., et al., First multi-spacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster Ion Spectrometry (CIS) experiment, *Ann. Geophys.*, *19*, 1303–1354, 2001.

Shirai, H., T. K. Takada, Y. Kamide, and T. Mukai, Enhancements of lobe ion density and velocity associated with plasmoids, *J. Geophys. Res.*, *106*, 29,935, 2001.

Slavin, J. A., E. J. Smith, B. T. Tsurutani, D. G. Sibeck, H. J. Singer, D. N. Baker, J. T. Gosling, E. W. Hones, and F. L. Scarf, Substorm Associated Traveling Compression Regions in the Distant Tail: ISEE-3 Geotail Observations, *Geophys. Res. Lett.*, *11*, 657, 1984.

Slavin, J. A., M. F. Smith, E. L. Mazur, D. N. Baker, T. Iyemori, and E. W. Greenstadt, ISEE-3 Observations of Traveling Compression Regions in the Earth's Magnetotail, *J. Geophys. Res.*, *98*, 15,425, 1993.

Slavin, J. A., R. P. Lepping, J. Gjerloev, D. H. Fairfield, M. Hesse, C. J. Owen, M. B. Moldwin, T. Nagai, A. Ieda, and T. Mukai, Geotail Observations of Magnetic Flux Ropes in the Plasma Sheet, *J. Geophys. Res.*, *108*(A1), 1015, doi:10.1029/2002JA009557, 2003a.

Slavin, J. A., R. P. Lepping, J. Gjerloev, D. H. Fairfield, M. H. Acuna, M. L. Goldstein, A. Balogh, M. Dunlop, M. G. Kivelson, K. Khurana, A. Fazakerley, C. J. Owen, H. Reme, and J. M. Bosqued, Cluster measurements of electric current density within a flux rope in the plasma sheet, *Geophys. Res. Lett.*, *30*(7), 1362, doi:10.1029/2002GL016411, 2003b.

Taguchi, S., J. A. Slavin, M. Kiyohara, M. Nose, R. P. Lepping, and G. Reeves, Temporal relationship between mid-tail TCRs and substorm onset: Evidence for near-Earth neutral line formation in the late growth phase, *J. Geophys. Res.*, *103*, 26,607, 1997.

Taguchi, S., J. A. Slavin, and R. P. Lepping, Traveling compression regions in the mid-tail: 15 years of IMP 8 observations, *J. Geophys. Res.*, *103*, 17,641, 1998.

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