Multiple Flux Ropes in the Earth's Magnetotail

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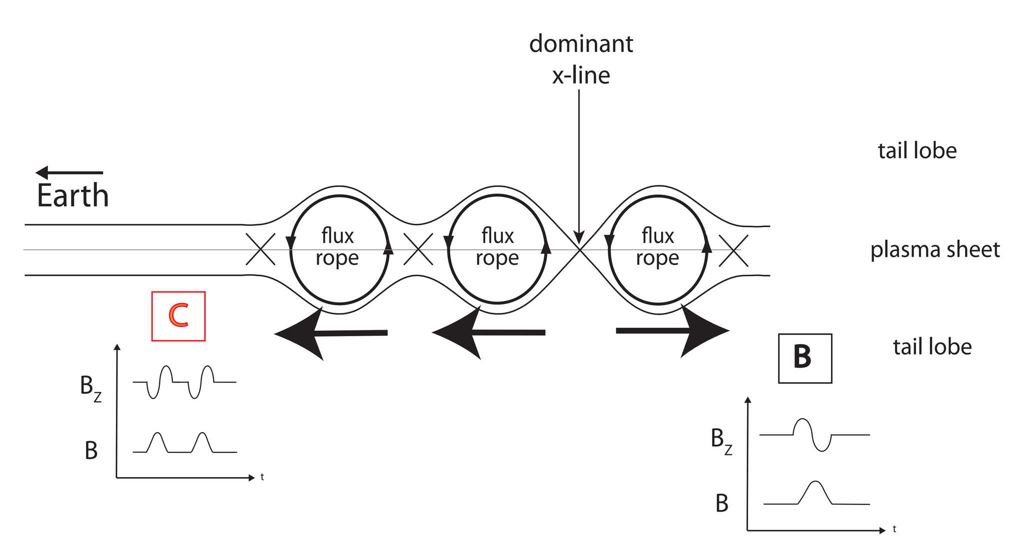
SCIENCE QUESTIONS

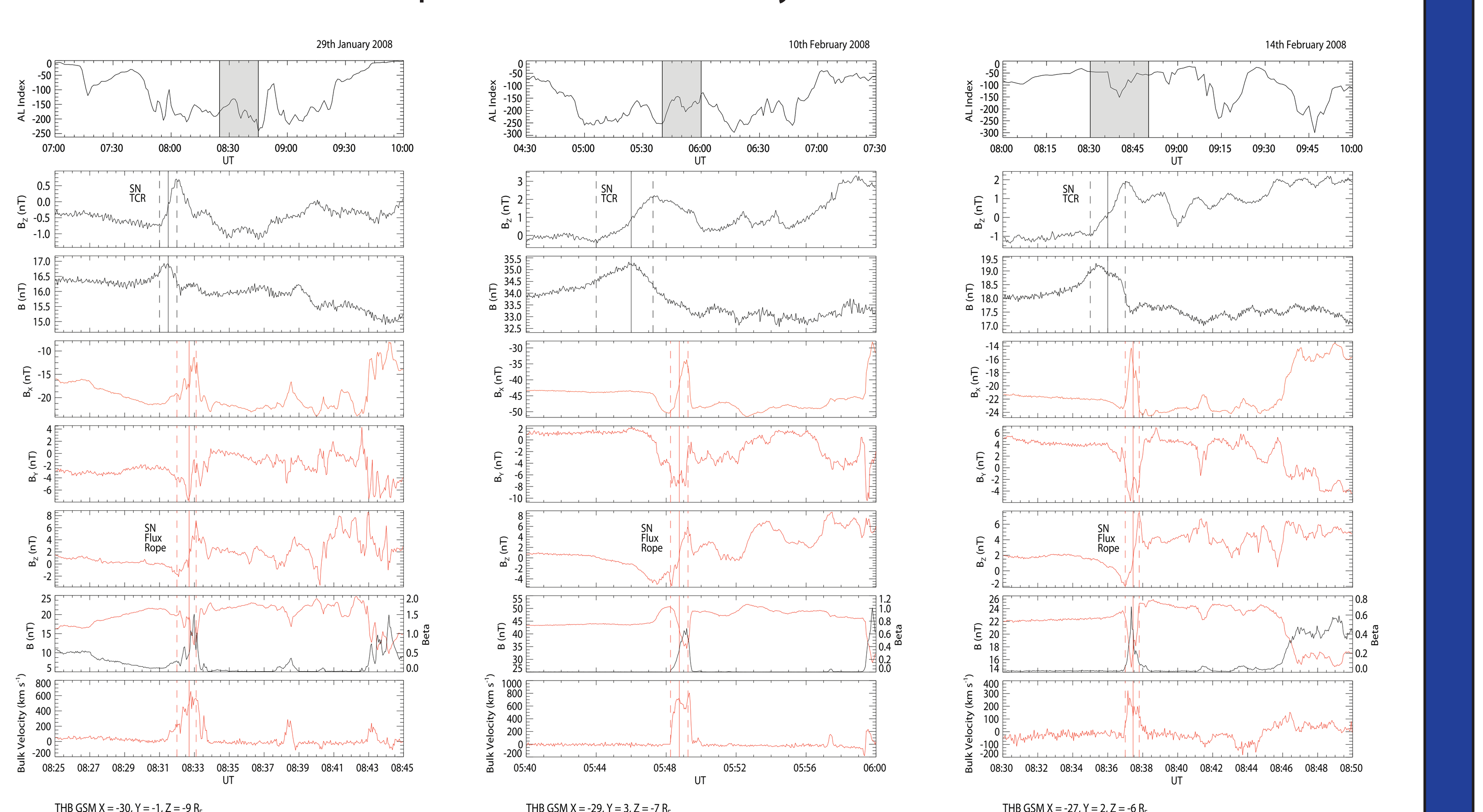
- What is the average location of x-line formation, and how does this change over a solar cycle?
- What solar wind and internal magnetospheric properties determine the number of x-lines that form?
- What is the reconnection rate at each x-line?
- How far across the tail do the x-lines extend?
- Can neighbouring flux ropes coalesce?
- What can flux rope/TCR observations tell us about the nature of substorms?

1. FLUX ROPE FORMATION

- Transport of magnetic flux from the dayside to the tail lobes causes an increase in tail lobe pressure
- Instabilities in the thin tail current sheet lead to multiple reconnection sites
- Flux ropes form between the pairs of x-lines
- The first x-line to reconnect lobe field lines experiences a huge increase in reconnection rate and outflow speed
- Flux ropes on either side of this dominant x-line are then swept Earthward or tailward
- Flux ropes locally increase the plasma sheet thickness, compressing the lobes and generating travelling compression regions (TCRs)
- The magnetic signature of a flux rope/TCR is a bipolar B_z coinciding with an enhancement in B
- Observations of FRs/TCRs moving in opposite directions by a pair of spacecraft can be used to determine the dominant x-line location



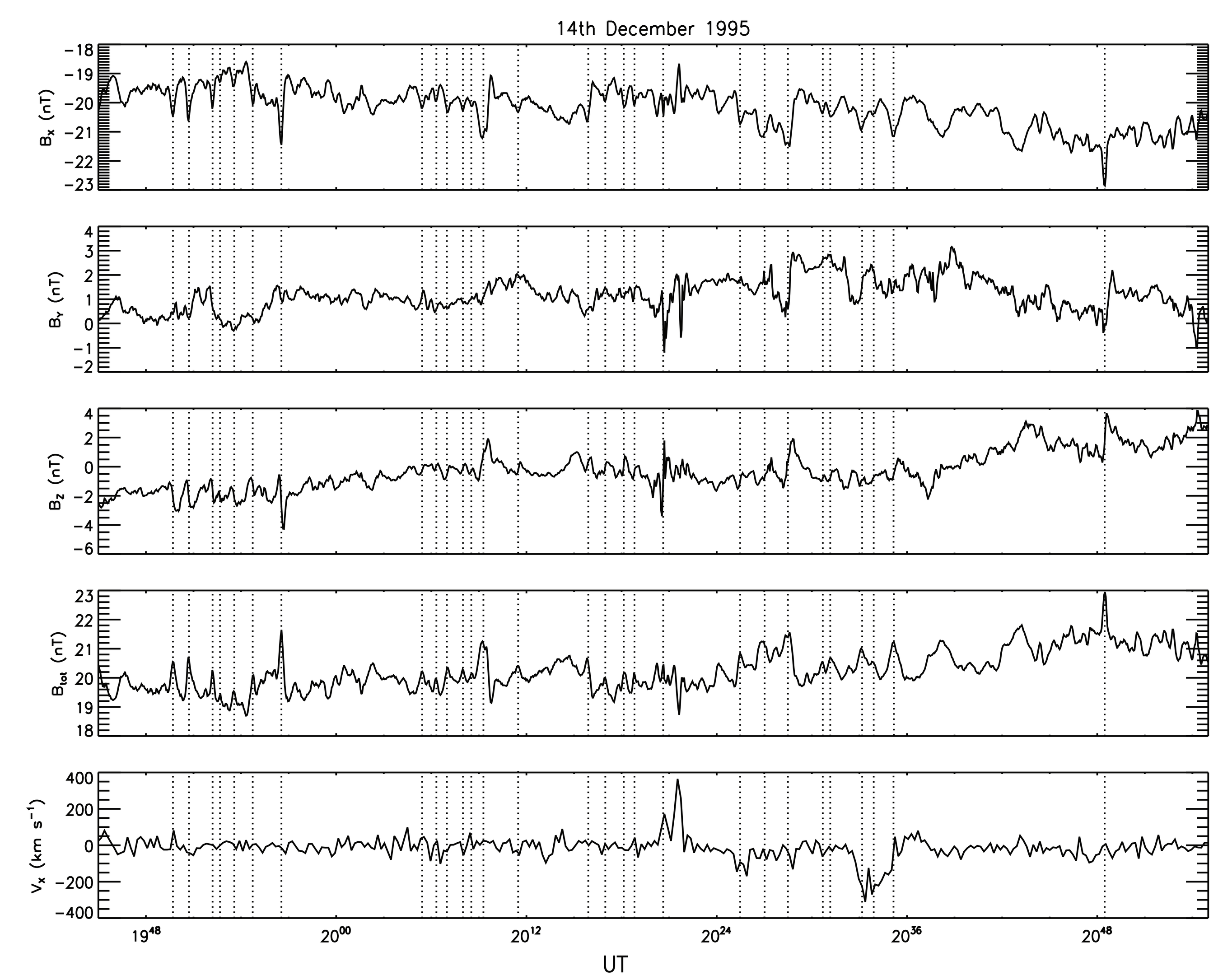
2. CASE STUDIES: Flux ropes/TCRs observed by THEMIS B and C



- In each case TH B observes an Earthward-moving (SN) TCR, while TH C observes an SN flux rope
- Timing analysis yields the velocity of the flux ropes, assuming that they are aligned in the dawn-dusk direction (1000, 590 and 670 km/s)
- TH C observed Earthward bulk flow velocity associated with the FRs (600, 700 and 350 km/s)
- Observations of the same FR/TCR at both spacecraft are extremely rare, given their approximate alignment every 4 days
- When the spacecraft are separated by >2 R_E in GSM Y, the structures are generally not seen at both
- The flux ropes may only extend 1-2 R_E across the tail

3. GEOTAIL CASE STUDY: 14th December 1995

- Geotail was located at GSM [XYZ] = [-29,-2,-4] R_E between 19:30 and 21:00 UT on 14th December 1995
- Five 'groups' of FRs/TCRs are observed during this time interval; the first set are 7 NS (tailward-moving) TCRs, followed six minutes later by 7 SN (Earthward-moving) TCRs. The subsequent three groups are all SN.
- The location of the dominant x-line has retreated over the spacecraft during the six minute interval between the first two groups.

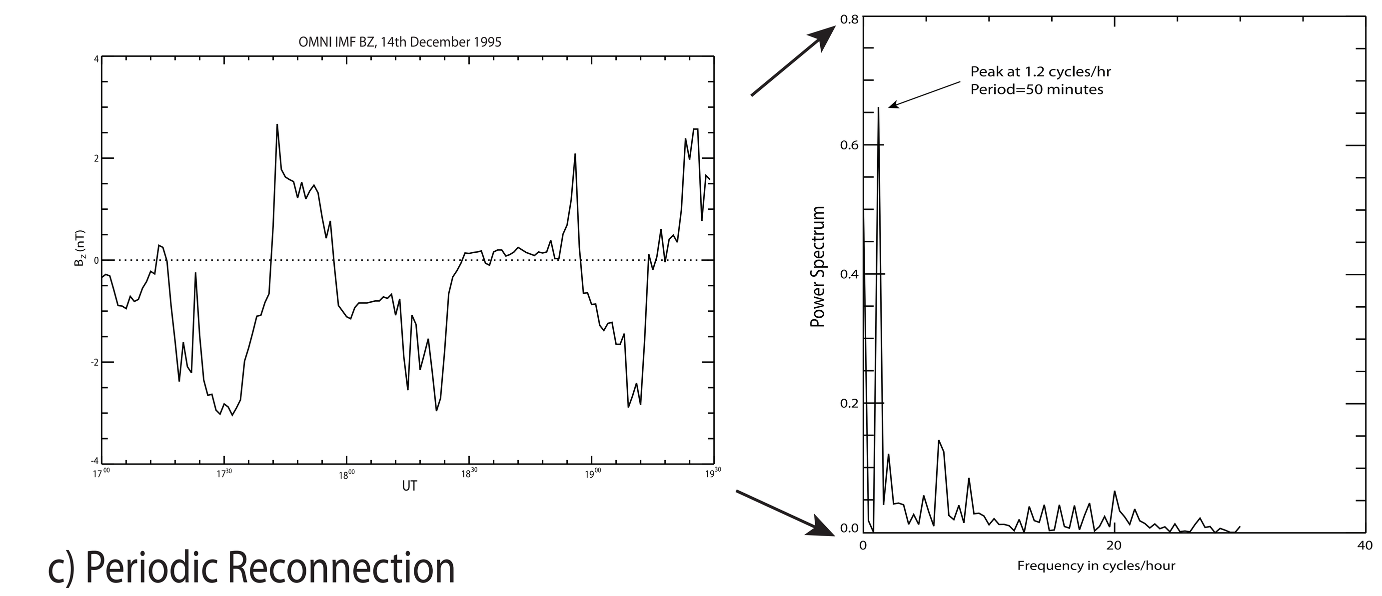


a) How many x-lines?

- We assume that each flux rope is formed by a pair of x-lines and consider the first group above.
- Taking a flux rope diameter of ~3R_E (average for this location in the tail), and no subsequent flux rope growth, 8 simultaneous x-lines producing the first 7 TCRs would span a distance of >20 R_E downtail. This is unlikely, as Geotail is located at X=-29 R_E.
- The most likely scenario is that a small number of x-lines are continually forming and ejecting FRs (one, or a pair) throughout each interval.

b) What IMF conditions led to the formation of so many x-lines?

- OMNI data from 3 hours prior to the Geotail observations are shown below
- The event occurred during a small substorm, with AL index reaching ~-250 nT
- The IMF B_z component fluctuated between negative and positive values, with a period of 50 minutes
- It has been suggested that pulsed SW driving with a period of ~ 45 minutes results in enhanced cross polar cap potentials, corresponding to enhanced reconnection rates at the dayside or in the tail



c) Periodic Reconnection

- Five 'groups' of FRs/TCRs were observed 5-15 minutes apart. Previous studies (e.g. Slavin et al., 2003) have also observed groups of flux ropes separated by 10-15 minutes.
- Studies of bursty bulk flows have suggested that 15 minutes may be the characteristic timescale for reconnection events in the tail (e.g. Angelopoulos et al., 1994)
- Auroral brightenings and PI2 pulsations were also observed to recur on a 10 minute timescale in a case study by Kepko et al. (2008).

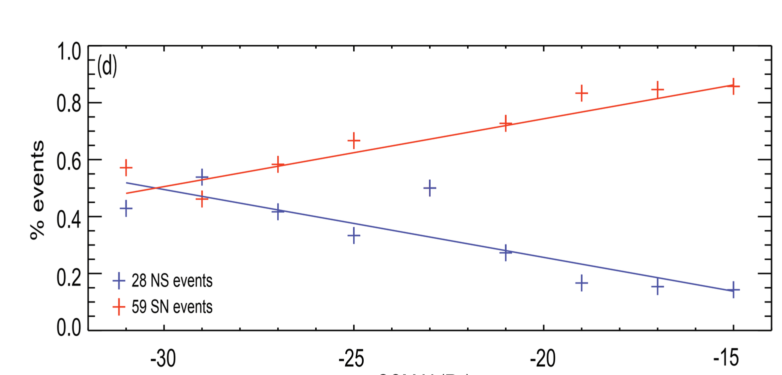
d) Reconnection rate at each x-line

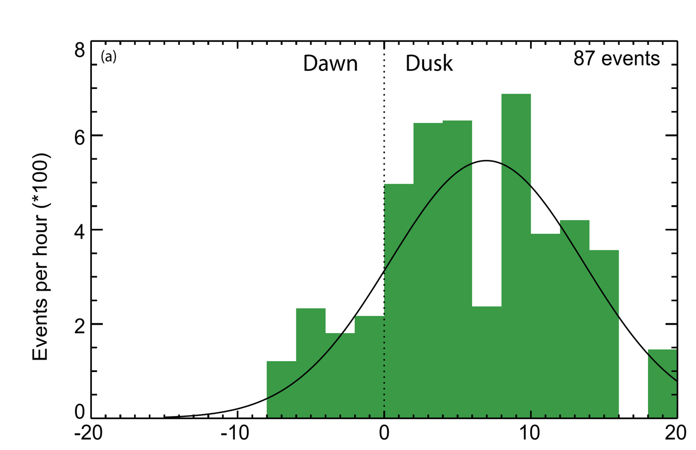
- Statistical studies of TCRs from 1995/96, 2000/01 and 2008/09 using Geotail and THEMIS data have shown that the average amplitude of single FR/TCRs is higher than that of multiples
- The first, or last TCR in a chain is frequently found to be the largest in amplitude (see case study)
- Observing the amplitude of multiple FR/TCRs can tell us the relative reconnection rate at each x-line:

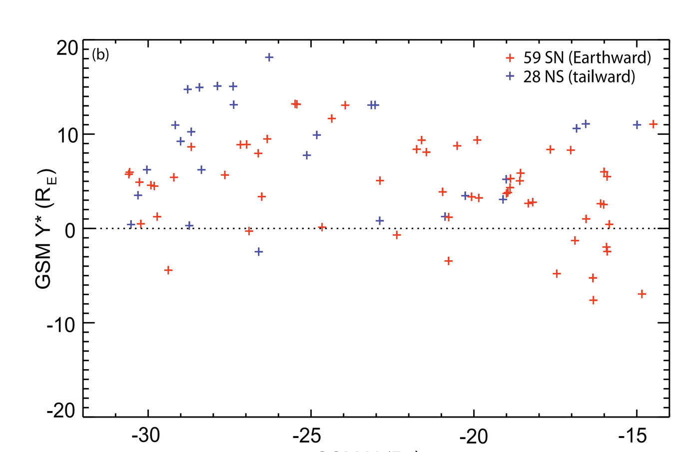
a) The reconnection rate at the outermost x-lines will be higher as the outflow is only suppressed on one side, which generates larger flux ropes at either end of a chain (e.g. Nakamura et al., 2010)
b) Simulations have shown that if an x-line between two FRs is no longer active, the FRs can merge to produce a single, larger FR.

4. STATISTICAL STUDY: average location of the x-line

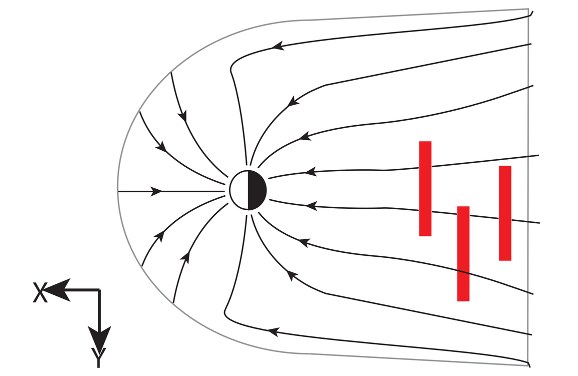
- 87 reconnection events (individual or groups of FRs/TCRs) were identified in THEMIS B and C second tail season magnetic field data
- The relative number of SN and NS FRs/TCRs at a given distance downtail gives the probability of the x-line forming Earthward or tailward of this location
- The average downtail distance of the x-line during solar minimum is ~30 R_E







- FRs/TCRs were more frequently observed on the dusk side of the tail than the dawn side.
- This is in agreement with other reconnection-related phenomena such as BBFs and auroral brightenings.
- The THEMIS orbits are such that the outmost spacecraft line up in the tail once every 4 days, however there are only a few rare cases where flux ropes are observed by both spacecraft
- Bursty bulk flows are confined to narrow channels (e.g. Angelopoulos et al., 1994)
- We suggest that each x-line only spans a few R_E in GSM Y



5. CONCLUSIONS

1. Multi-spacecraft observations of flux ropes enable the location of the NENL to be determined

2. Several observations of the same FR/TCR have been made with the outer pair of THEMIS spacecraft, although such observations are rare. This is thought to be due to the narrow extent of x-lines in GSM Y.

3. Five reconnection intervals were identified in Geotail data during 75 minutes of data.
   - The reconnection site retreated over the spacecraft location
   - Multiple x-lines formed continuously throughout each interval to produce so many FRs
   - This high level of tail reconnection may be caused by periodic driving at the dayside MP
   - The largest FRs are generally formed at each end of a chain, in line with model predictions

4. The average location of the reconnection site during solar minimum was found to be GSM [X,Y]=[-30,5] R_E.
   - This is towards the tailward end of previous estimates, perhaps because of low dayside driving during this period
   - X-lines are displaced towards dusk in line with other reconnection-related phenomena observed in the tail and on the ground. They only span a fraction of the full width of the tail.

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