OVERVIEW AND RECENT ADVANCES IN FLUX ROPE AND INTERLINKED FLUX TUBE STUDIES IN MAGNETOSPHERIC ENVIRONMENTS

[An incomprehensive review]

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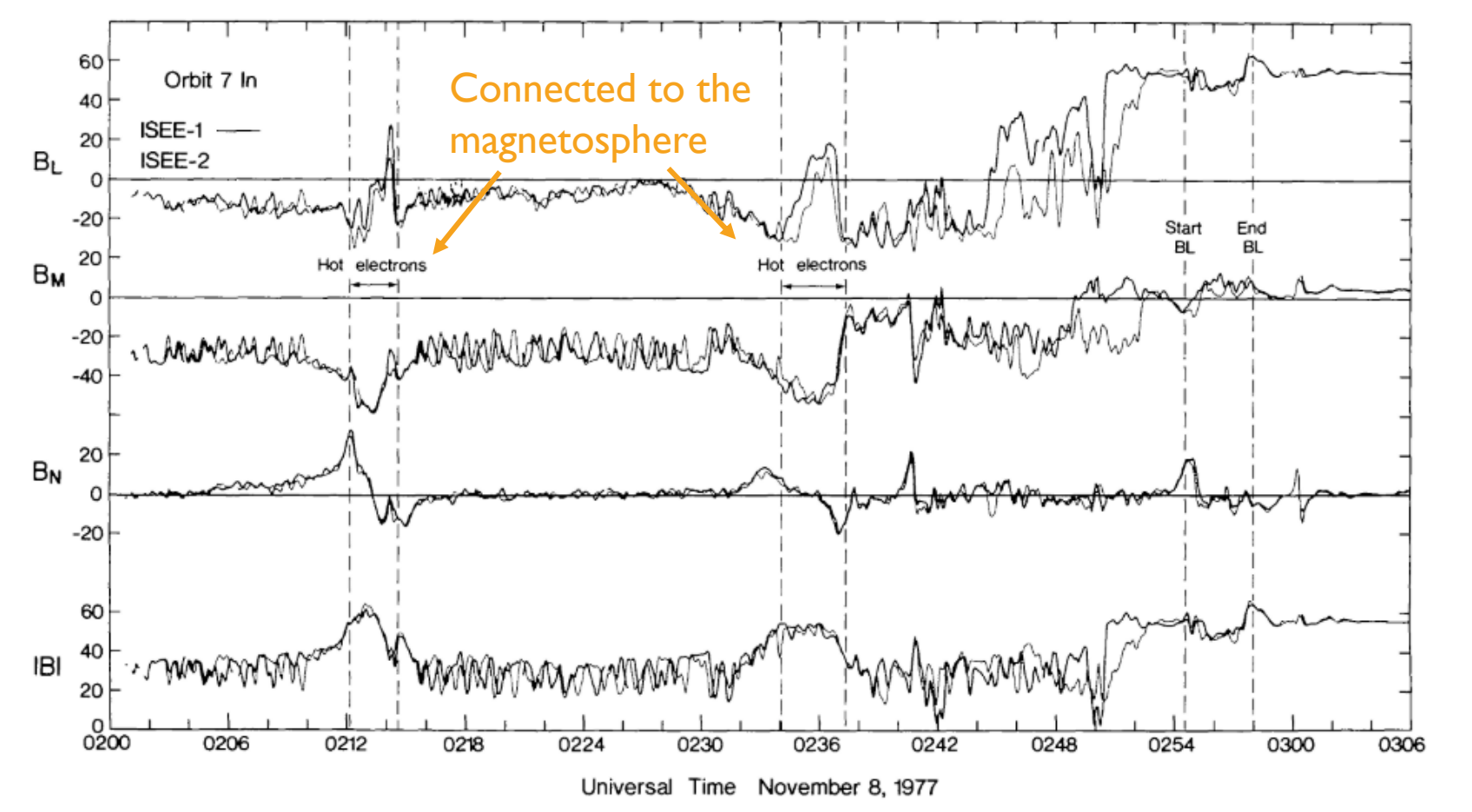
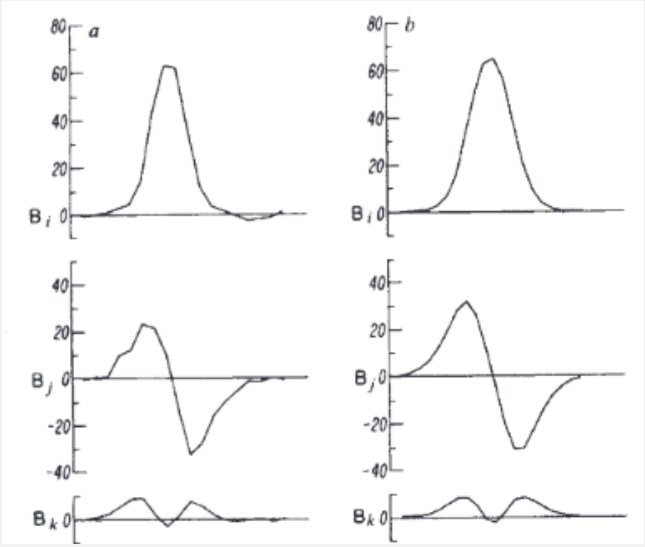
BRIEF HISTORY OF FLUX TRANSFER EVENTS

Russell & Elphic (1978) – **Detached flux rope structures near MP**

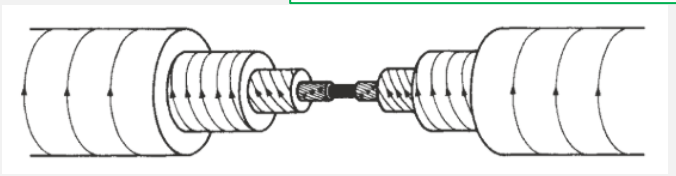


Helical flux rope structures



in-situ model

$$B_\varphi = B(\rho) \times \cos(\alpha(\rho))$$
$$B_Z = B(\rho) \times \sin(\alpha(\rho))$$
$$B(\rho) = B_0 \times \exp(-\rho^2/l_B^2)$$
$$\alpha(\rho) = \pi/2 \times (1 - \exp(-\rho^2/l_A^2))$$

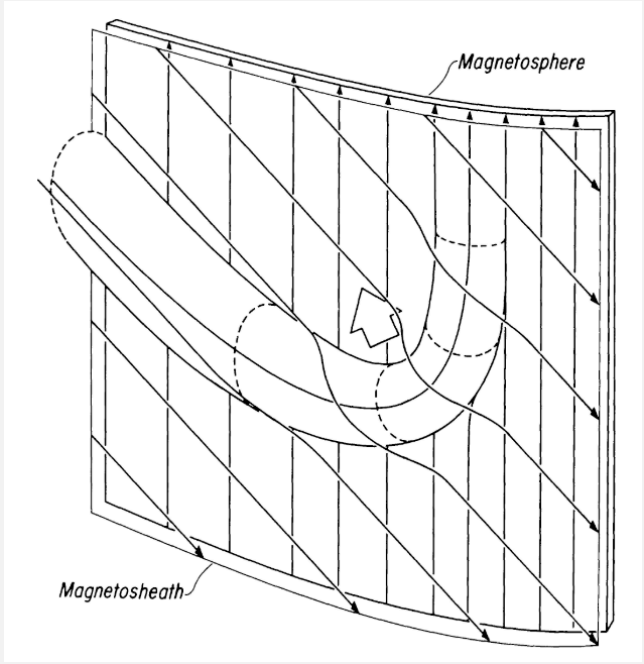


- Results of "patchy" reconnection
- "Bursts" of particles at the entries to the magnetopause flux tubes

(Russell & Elphic, 1979)

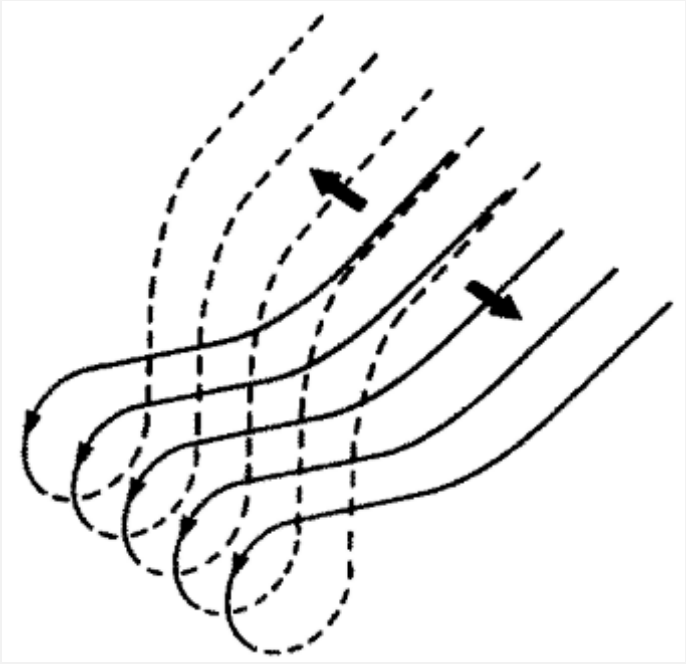
GENERATION MECHANISMS OF FLUX TRANSFER EVENTS

Elbow-shape flux rope model
(Russell & Elphic, 1978)



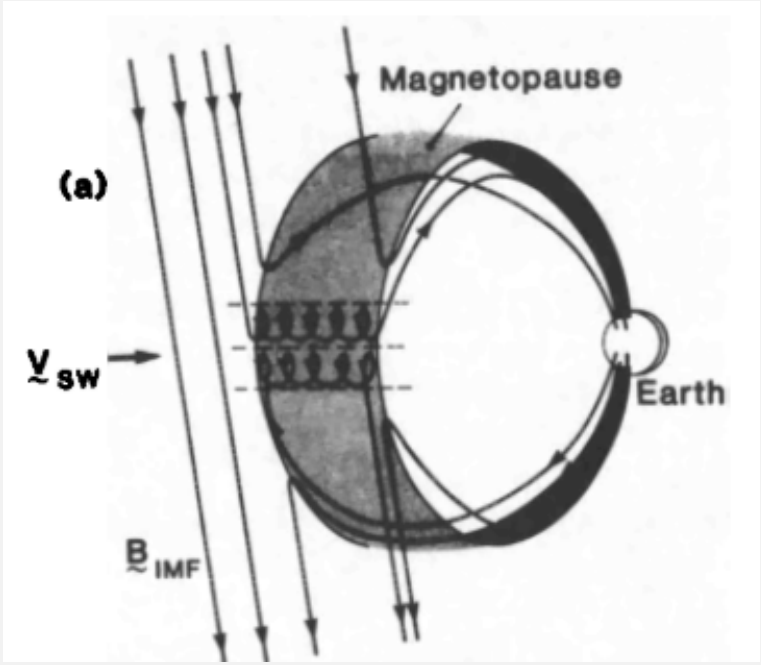
- Patchy reconnection at a spatially limited reconnection site

Single X-line reconnection model
(Southwood et al. 1987; Scholer, 1988)



- Bursty reconnection at a single X-line. A flow shear causes the field to skew. A magnetic shear leads to a core field.

Multiple X-line model
(Lee & Fu, 1985)

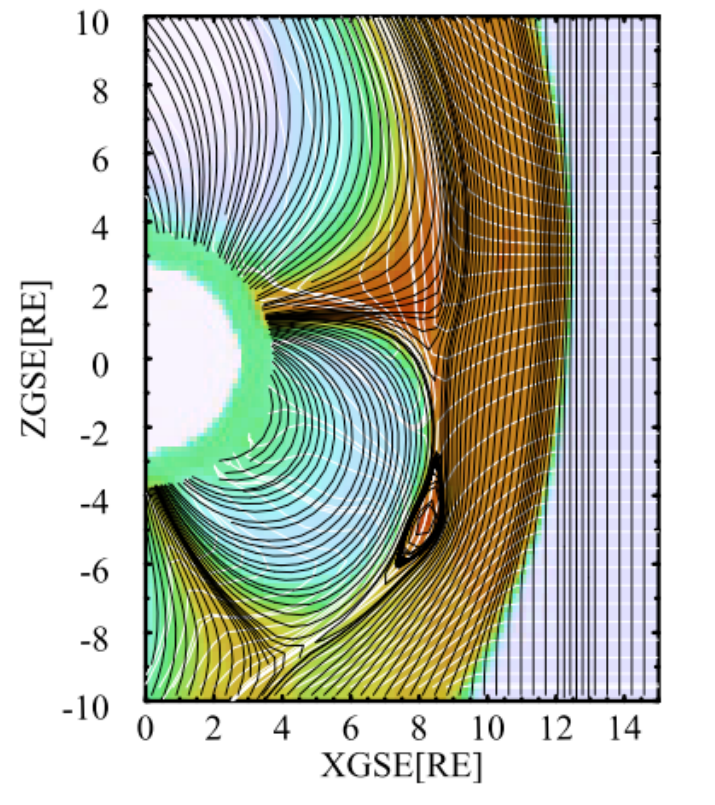


- Simultaneous reconnection at multiple reconnection sites. The IMF B_Y component gives the core field of a helical flux rope.

MULTIPLE X-LINE MODEL AND OBSERVATIONAL EVIDENCE

Multiple X-line model: dipole-tilt effect

(Raeder, 2006)



- Sequential generation of new X-lines due to non-colocation of X-line and non-stagnation flow lines

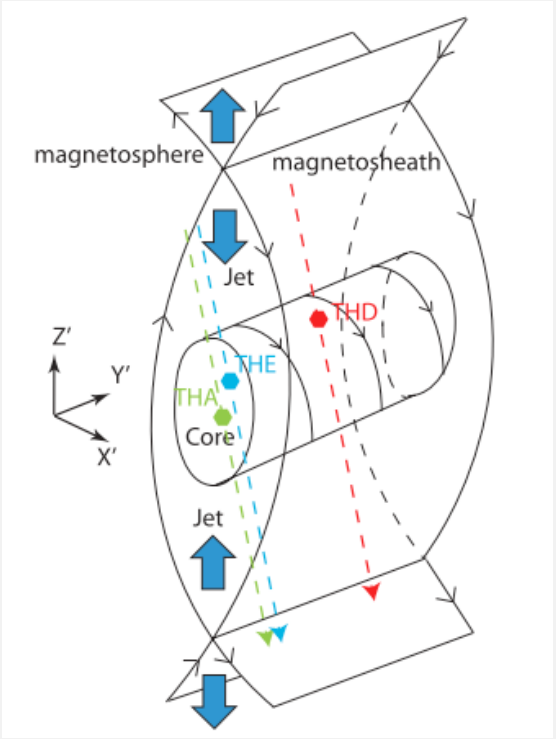
Observational evidence by Hasegawa et al. (2010)

- Two oppositely-directed ion jets converging towards the southward-moving FTE observed by THEMIS

Direct evidence of a 3-D magnetic flux rope flanked by two active reconnection X lines by Øieroset et al. (2011)

- Observed colliding plasma jets near the center of the flux rope

Paradigm shift towards the multiple X-line model

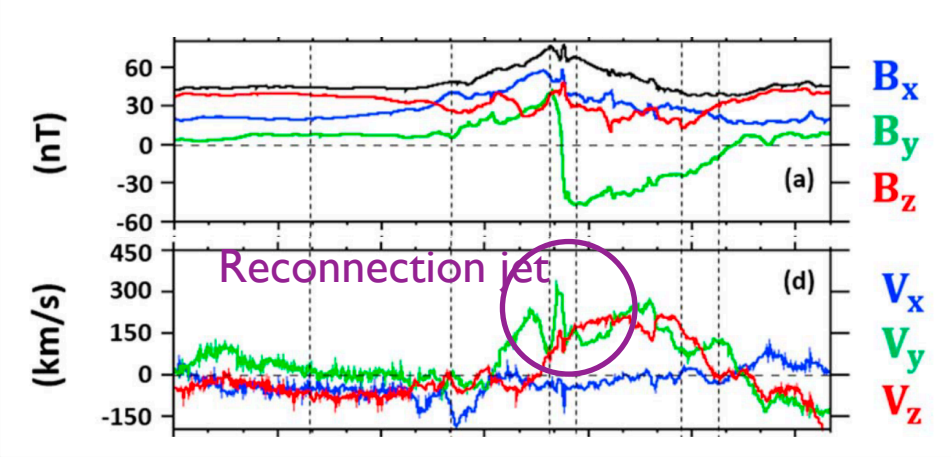


INTERLINKED FLUX TUBES

Interlinked flux tubes (IFTs) have been hypothesized from patchy reconnection (Otto, 1995). They have been observed by Cluster (Louarn et al., 2004) with similar signatures to FTEs but with complex plasma populations.

MMS observations of reconnection at FTE center

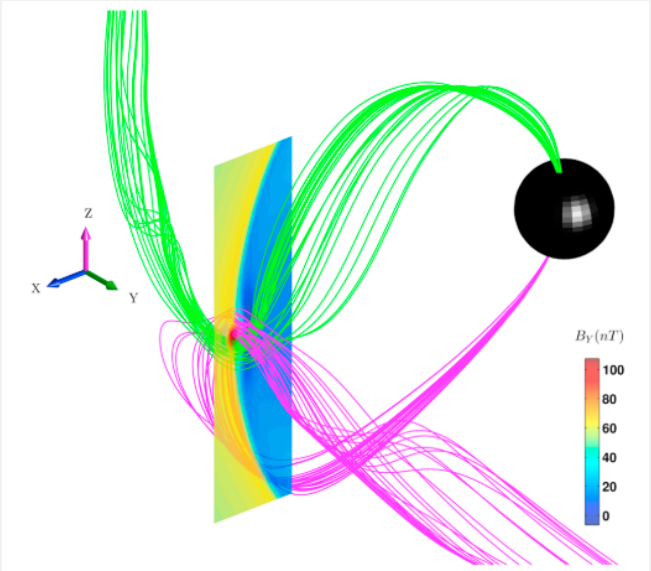
[Kacem et al. 2018; Øieroset et al. 2019]



- Bipolar magnetic variation but with a thin currrent sheet with clear signatures of magnetic reconnection

Global MHD simulations of IFTs

[Cardoso et al. 2013; Farinas-Perez et al. 2018]

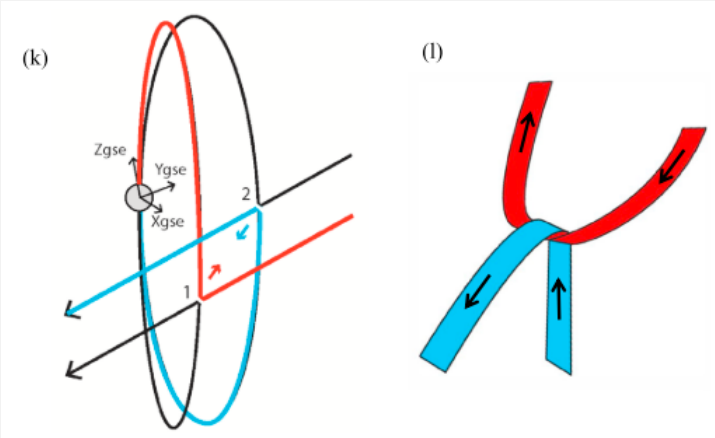


Southward IMF with strong B_Y component

- found an FTE that evolves into IFTs

FORMATION MECHANISMS OF IFTS

In-situ observation results



[Øieroset et al. 2019]

Reconnection at the thin current sheet between **converging jets**

Multiple X-line reconnection with strong guide fields ?

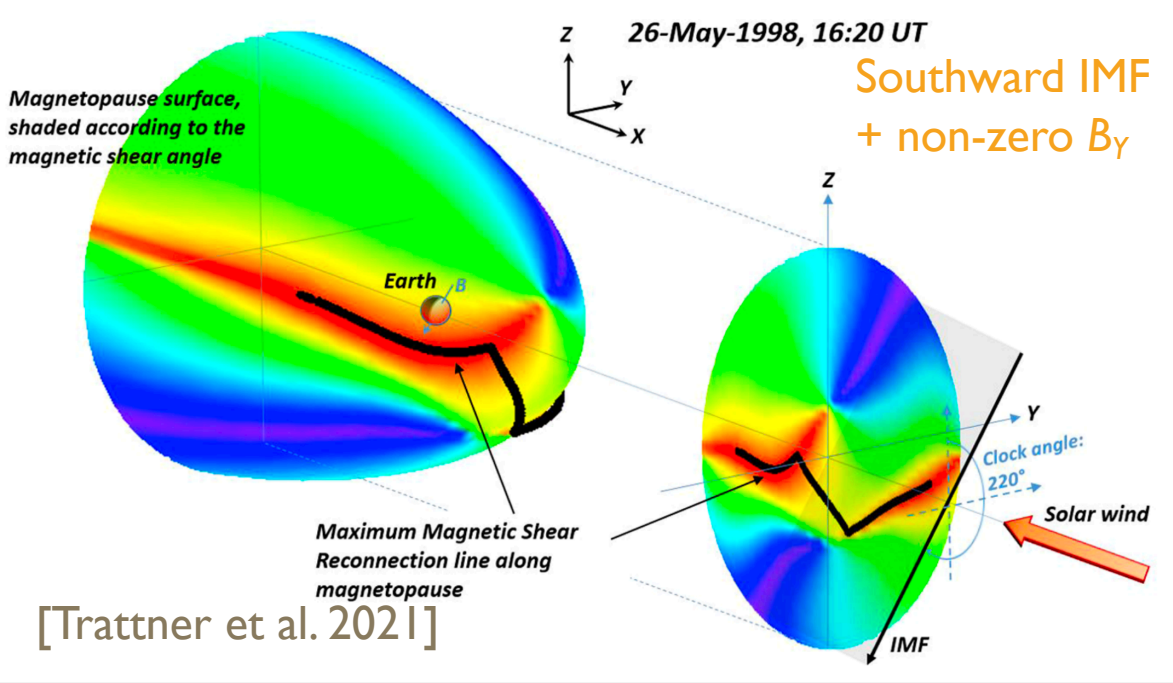
Global 3-D MHD simulation results

- Global MHD simulations by Farinas-Perez et al. (2018) reveal an IFT that originates as an IFT and an FTE that evolves to an IFT, possibly due to internal reconnection
- Guo et al. (2020) show that flux ropes can coalesce to form new ones with larger diameter under predominantly southward IMF conditions.
- However, when the IMF clock angle is small (<135°), the coalescence between flux ropes is not found (Guo et al. 2020). Effects of the strong guide field on reconnection?

DAYSIDE RECONNECTION AND FORMATION OF IFT

Empirical model of dayside reconnection

Continuous long reconnection X-line (i.e., maximum shear line) on the magnetopause [Trattner et al. 2007].

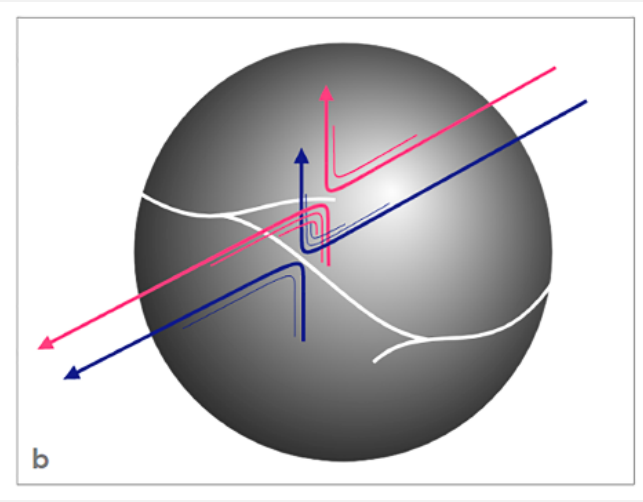


[Trattner et al. 2021]

Maximum Magnetic Shear model predicts reconnection at the elongated « component reconnection tilted X-line ».

From survey of reconnection inside FTEs (i.e., IFTs), Fargette et al. (2020) found that IFTs were predominantly preceded by IMF with strong B_Y.

Maximum Magnetic Shear model suggests a possible bifurcation of the maximum shear line.



[Fargette et al. 2020]

Are the interlinked flux tubes generated from the bifurcated maximum shear line?

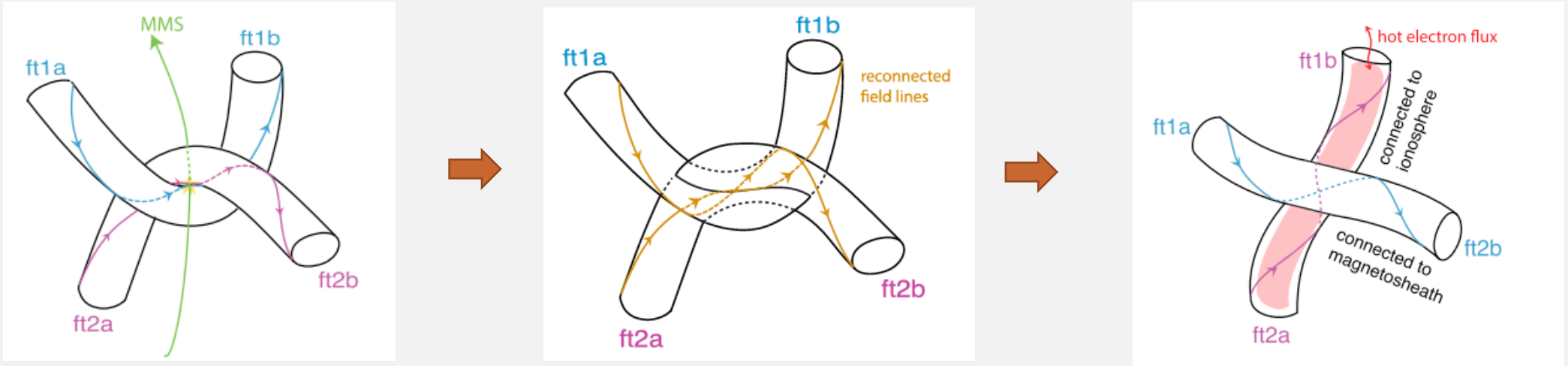
RELATION BETWEEN IFT AND FTE?

Are interlinked flux tubes generated from flux transfer events (after reconnection)? [Farinas-Perez et al. 2018]

Are flux transfer events generated from interlinked flux tubes (after reconnection)? [Russell & Qi, 2019]

Evolution of flux tube entanglement

[Russell & Qi, 2019; Qi et al. 2020]



This may explain the equal occurrence of flux ropes (a) filled with (b) devoid of hot electrons [Russell & Qi, 2019]

OUTSTANDING QUESTIONS

Formation and evolution of interlinked flux tubes and flux transfer event flux ropes

Nature of reconnection at the dayside magnetopause

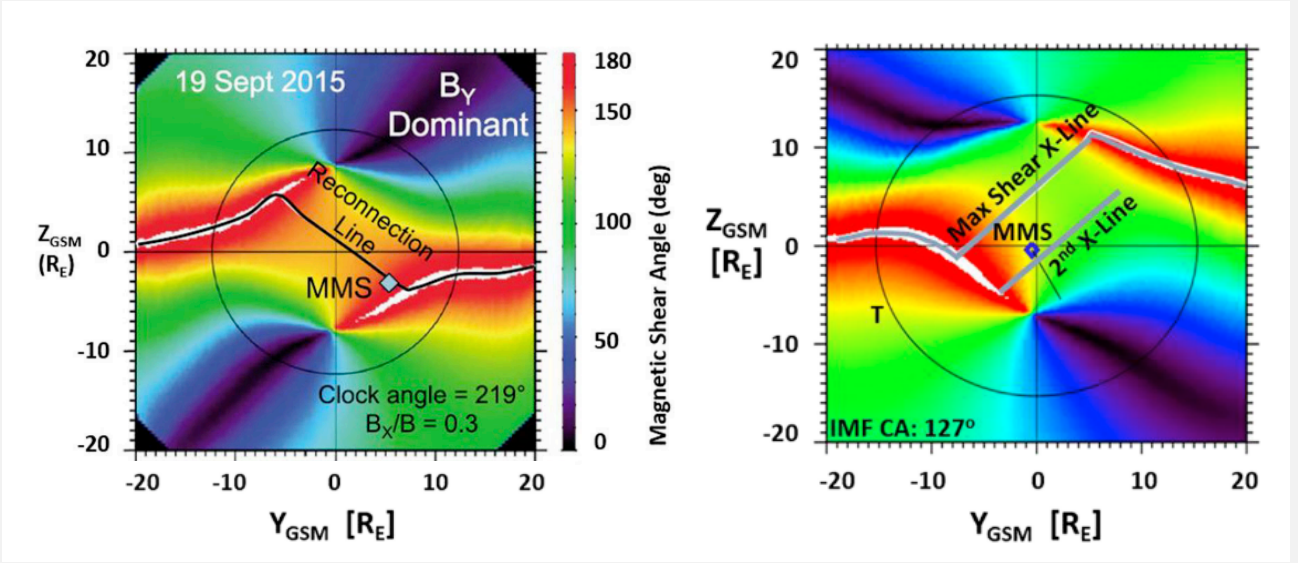
Component and anti-parallel reconnection

i.e., large-dipole tilt effect leading to a deflected Knee region [Trattner et al. 2018]

Simultaneous multiple X-line reconnection

see Fuselier et al. [2018]

Steady or transient reconnection



Space weather impacts

Do interlinked flux tubes transport fluxes (like flux transfer events) and how much do they transport? What are roles of IFTs in the magnetosphere-ionospheric coupling?

SUMMARY AND PERSPECTIVE

Overview and recent advances in flux transfer event and interlinked flux tube studies

Occurrence, formation, evolution of interlinked flux tubes and relation to flux transfer events

Nature of reconnection at the dayside magnetopause

- Multi-spacecraft with large spatial coverage studies
- Combined spacecraft and global simulation studies
- Coordination with ground observations (to assess space weather impacts)

Discussion and ideas are very welcome!