Flux Transfer Events Are Made in Pairs

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The launch of the ISEE-1 and 2 high-altitude apogee, highly elliptical orbiter allowed the motion and structure of the magnetopause to be studied for the first time. A major finding was the formation of magnetic flux ropes that appeared to be the transfer of "quanta" of magnetic flux from the magnetopause to the polar caps. An example of this phenomenon is shown in Figure 1, that shows two "flux transfer events." These two events contain hot electrons. A possible interpretation of these electrons is that the electrons are trapped in closed magnetic field lines. However, not all FTEs contain trapped electrons, so the trapped particle explanation was not pursued.

The launch of the 4 spacecraft Magnetospheric Multiscale Mission (MMS) has enabled a much more detailed investigation of the solar wind interaction with the magnetosphere, including determining the force balance in these structures and their energetic particle content. Figure 2 shows two examples of Flux Transfer Events. In these ropes, the twisted magnetic field balances the outward pressure of the magnetic pressure plus thermal particle pressure. The sketch shows the magnetic structure of such a rope. R direction is along the axis of the rope identified as the direction of constant pressure. The rope on the left has a strong flux of energetic electrons and is classified as type A. The rope on the right has few energetic electrons and is labeled type B.

Cong Zhao, in his PhD thesis, identified the FTEs seen by MMS and found a very unexpected result. The number of type A and type B were the same within statistical error in every way they were studied: location, size, IMF orientation, etc. The only explanation that could account for this observation that was probable was that every FTE formation event produced two flux ropes: one connected to both polar regions and trapping magnetospheric electrons, and one not connected to the magnetosphere at all. This conclusion is consistent with a production mechanism that in turn is quite probable, that the FTEs are produced by entanglement of reconnected magnetic flux tubes. The tangled field lines liberate themselves through reconnection that simplifies the magnetic structure. A manuscript explaining how this process works has been submitted to *Geophysical Research Letters.*

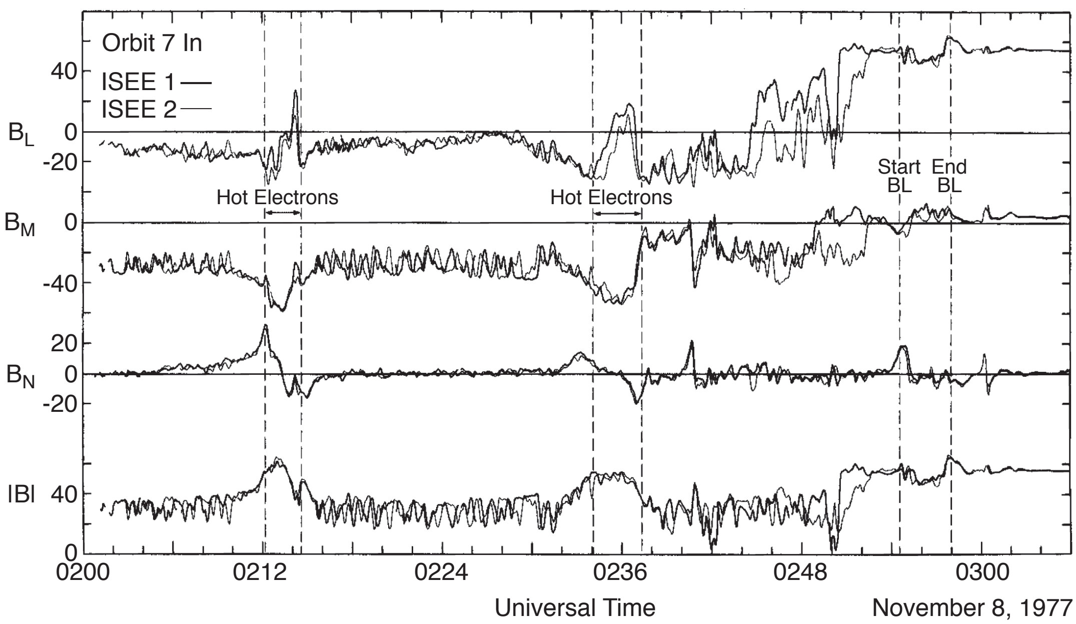

Figure 1. The time series of the magnetic field measurements by ISEE-1 that showed the magnetic field and energetic electrons at the Earth magnetopause, indicating that the magnetic flux ropes were formed at the magnetopause when the interplanetary field was southward and that these ropes could carry energetic magnetospheric electrons. (Russell and Elphic, 1979)

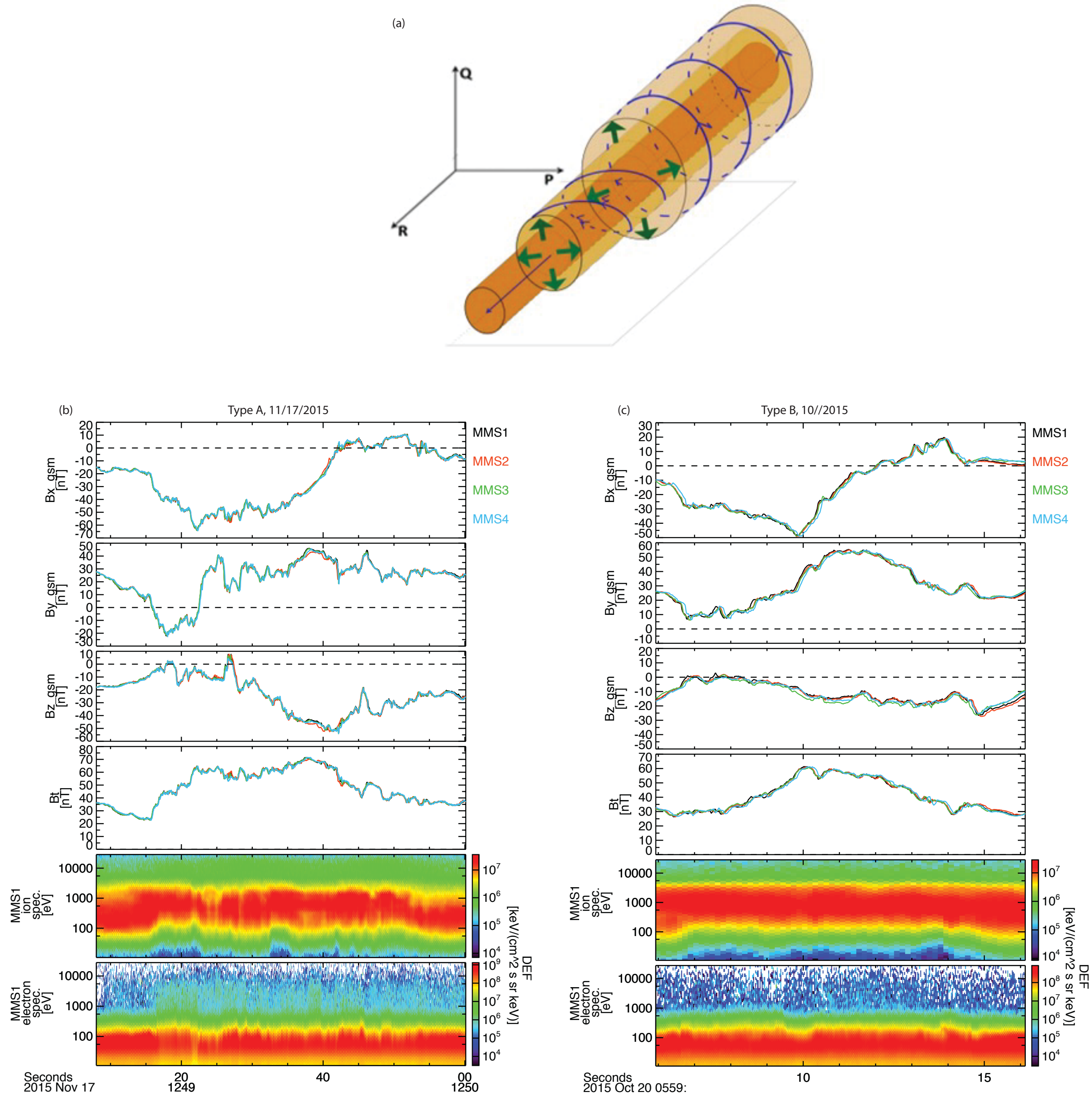

Figure 2. (a) Sketch of the internal structure of a magnetic flux rope, whose magnetic and plasma pressure forces combine to create an equilibrium of forces. Curvature force presses inward, and pressure gradient force presses outward; purple lines surrounding the rope represent the magnetic field lines; green arrows indicate the magnetic pressure. The rope coordinate system is defined as follows: R points to the rope axial direction along which the pressure gradient is minimum; Q is defined by the transverse crossing, the direction is obtained by four-spacecraft timing; P completes the right-hand coordinates; **(b), (c)**: Time series of magnetic field and plasma and particle data during two intervals. During the first interval, energetic electrons are present (Type A), but in the second interval, they are not (Type B). This indicates that the first flux rope is connected to the magnetosphere with trapped electrons inside, and during the second interval, the flux

rope does not contain any electrons and thus seems not to connect with the radiation belts.

References

Russell, C. T. & Elphic, R.C. (1979), ISEE Observations of Flux Transfer Events at the Dayside Magnetopause, *Geophys. Res. Lett.* 6, 33-36.

Zhao, C. (2019), Statistical Study on Two Types of Flux Transfer Events, Dissertation submitted in partial fulfillment for the degree Doctor of Philosophy in Geophysics and Space Physics, UCLA.