Physical nature of near-Earth magnetotail reconnection events

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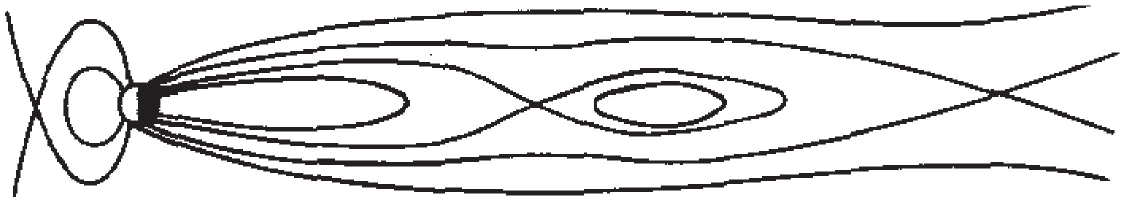
ABSTRACT. An important (and controversial) part of substorm development is the process known as near-Earth X-line formation, onset of magnetotail reconnection, plasmoid formation/ejection, and other names. The phenomenology of the associated changes in magnetic field, plasma flow, and energetic particle populations is reasonably well established from observations, but the underlying physical process itself is poorly understood. Outstanding open questions include: (1) What do we mean by reconnection when it is assumed to originate in the region of closed magnetic field lines? (2) What is the global magnetic topology of a plasmoid? of a magnetic flux rope? are they related? (3) Can the conventionally drawn two-dimensional plasmoid (with field lines that trivially close on themselves) be generalized to three dimensions? (4) How do we represent a magnetic topology that is intrinsically three-dimensional, has no plane of symmetry, and in general has only null points but no null lines? These questions involve fundamental issues about the meaning of magnetic topology and its role in reconnection.

(near-Earth X-line, magnetotail reconnection, plasmoid, . . .)



Will discuss

- What is the configuration/topology of the three-dimensional magnetic field in these events, and how does it evolve?
  (what is it?)

Will not discuss

- What process brings about the configuration and its changes — instability, non-equilibrium, fast-scale dynamics? originating in the magnetotail, nightside magnetosphere, ionosphere?
  (what causes it?)
- Is this magnetic reconnection? according to which definition?
  (what do we call it?)

- Topology ≡ study of properties invariant under arbitrary continuous deformations. (In physical problems, deformations may be subject to physical constraints, hence not completely arbitrary.)
- Magnetic field lines constitute a continuum: between any two field lines there is always another field line.
- $\nabla \cdot \mathbf{B} = 0$ implies a magnetic field line has no beginning or end; it does not imply the field line must close on itself (field lines that close on themselves are a set of measure zero).
- Distinction between "open" and "closed" field lines therefore refers to topology only in a restricted sense: deformations are constrained by the assumption that field lines have "feet" on specified distinct surfaces (e.g., Earth and somewhere in interplanetary space) — real distinction is between connections to different surfaces. (Restriction not unreasonable: when followed indefinitely, field lines lose physical meaning if not terminated by artificial cuts.)
- Every field line at the interface between "open" and "closed" goes ultimately in a different direction, depending on infinitesimal displacement; it must therefore pass through a magnetic field null point somewhere.

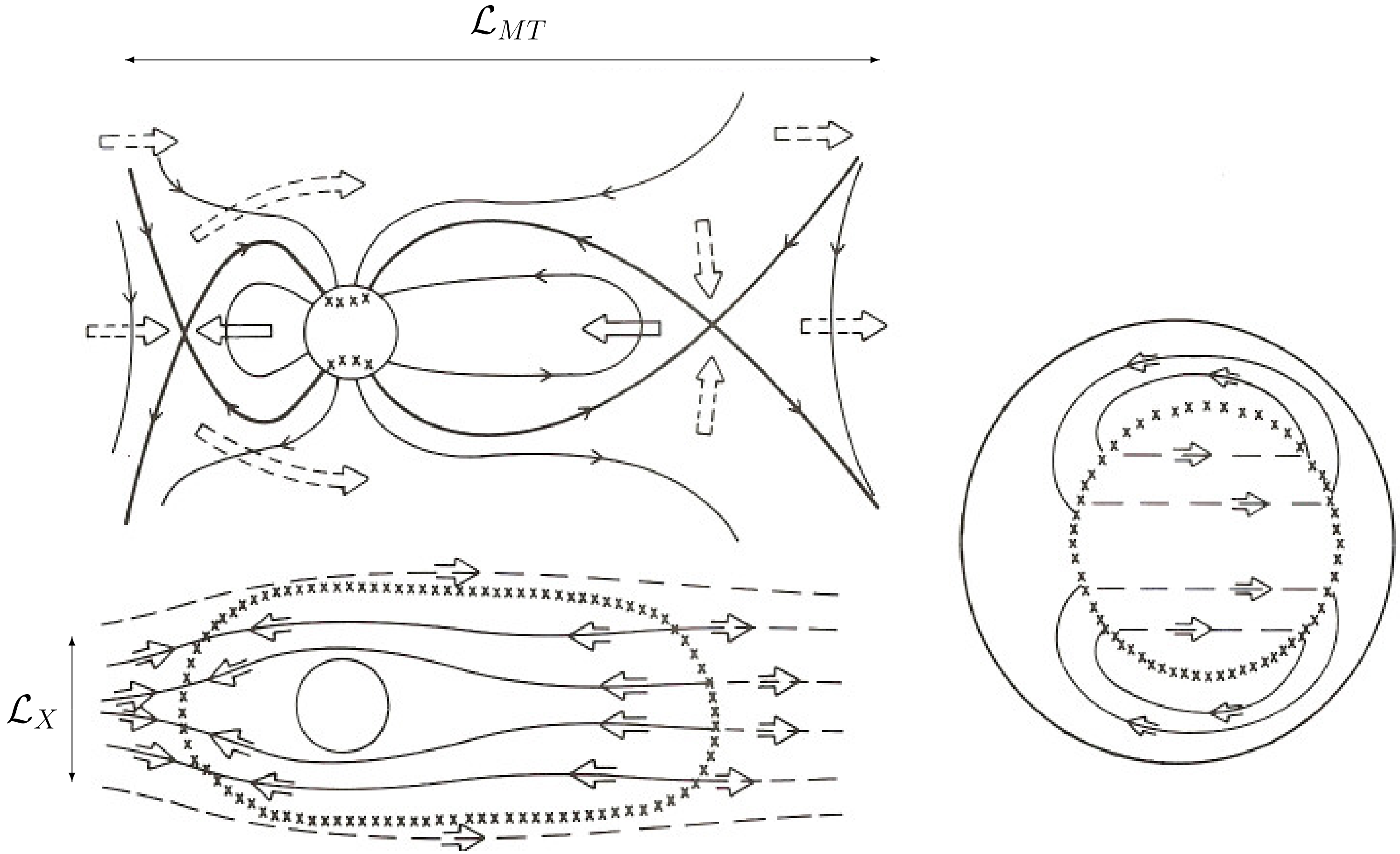


Fig. 1. Schematic topological view of magnetically open magnetosphere. Upper left: noon-midnight meridian plane. Lower left: equatorial plane. Right: projection on ionosphere. (Lines: plasma flow streamlines, x's: (projection of) magnetic X-line = interplanetary/open/closed field line boundary = polar cap boundary.)

Topology of simple open magnetosphere with dayside and nightside reconnection (Dungey model) well understood in principle (but not in detail and not quantitatively)

thanks in part to simple model of uniform field plus tilted dipole (e.g., Frankenthal et al., final report AFCRL-64-433 ASE-509, 1964; Cowley, Radio Sci. 8, 903–913, 1973)

- Open/closed and interplanetary/open boundary field lines pass through X-line that forms ring around Earth (stretched tailward).
- Reconnection occurs at "dayside" and "nightside" segments of X-line.
- The X-line contains two magnetic null points, connected by singular ("separator") magnetic field lines. Only for special symmetries (including north-south symmetry, with magnetic field at the equator normal to the equator everywhere) is the X-line a magnetic neutral line.
- (In the real magnetosphere, the X-line is most likely imbedded in current sheets, and location of null points has no global significance.)

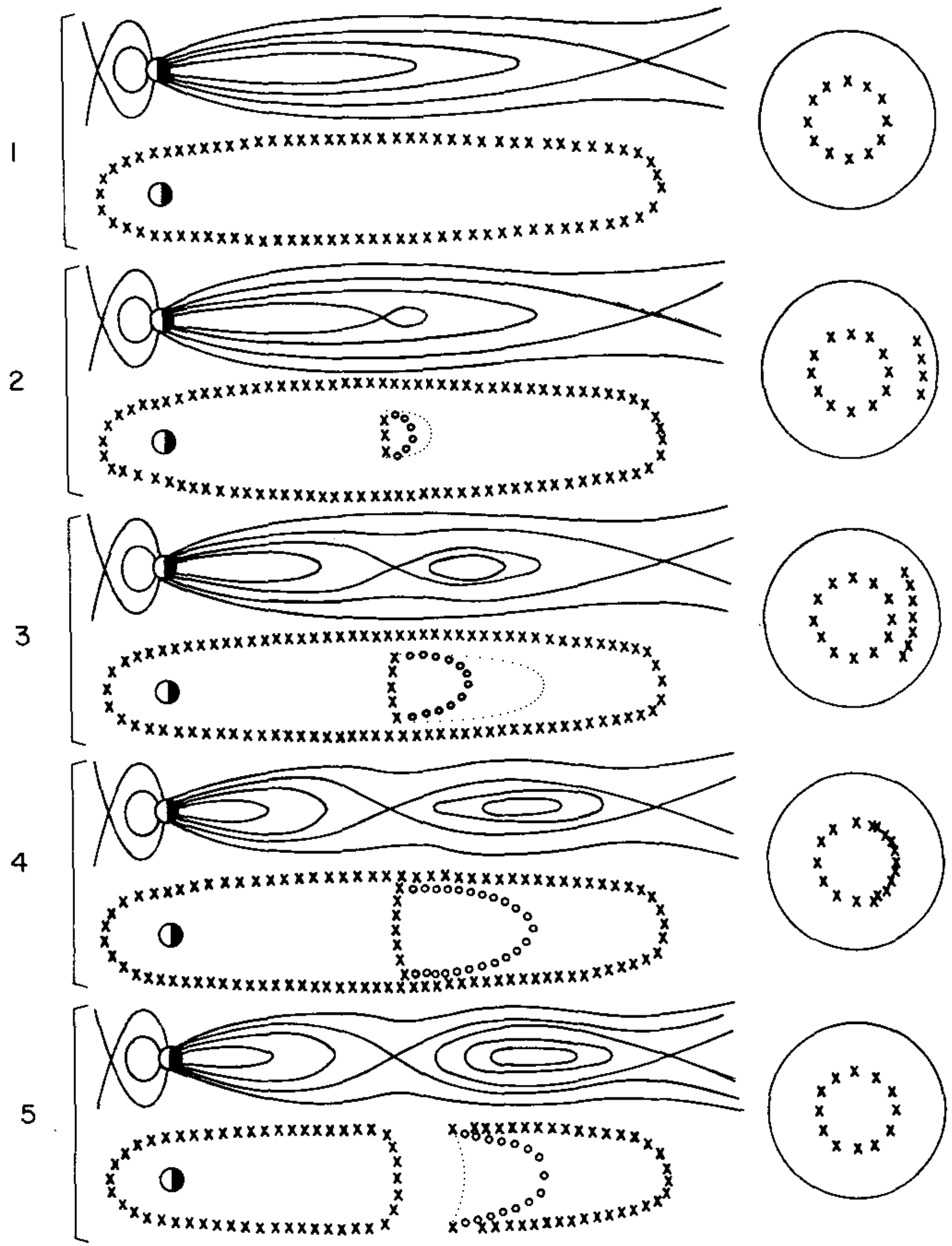


Fig. 2. Possible changes of the magnetic field topology during substorms. Each of the five panels is in the same format as [Fig. 1] (Vasyliūnas, 1976).

Added dotted lines: boundaries of plasmoid in equatorial plane.

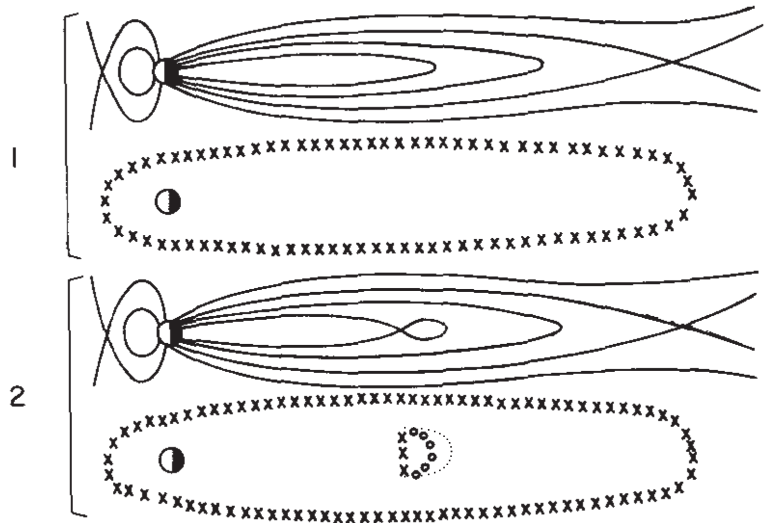
(Further discussion, with historical and critical remarks: Vasyliūnas, Space Sci. Rev. 158, 91–118, doi:10.1007/s11214-010-9696-1, 2011.)

- To my knowledge, this was the first attempt to visualize what happens in three dimensions (not followed much: the greatly embelished adaptation of this figure by Hones, which became very popular and has been cited almost exclusively, shows the meridian panels only, completely ignoring the three-dimensional aspects).
- Original motivation (not published, unrelated to substorms): If the nightside reconnection (flux return) region of the open magnetosphere is carried antisunward (e.g., by plasma-mantle flow) indefinitely, does anything occur that prevents the magnetotail from increasing in length without limit ("disconnects" the distant magnetotail)?
- The plasmoid in Fig. 2 is conceived as an intrinsically three-dimensional structure, consisting of magnetic field lines that connect neither to the Earth nor to the interplanetary medium.

- Is such a structure topologically possible?
- If not, how is the "disconnection" of the magnetotail effected? In particular, how does the three-dimensional configuration of the magnetic field change between panels 1 and 2 of Fig. 2?

Are the topological distinctions in Fig. 2 destroyed by adding a constant magnetic field component in the third dimension?

The physical process that produces the change of the configuration from panel 1 to panel 2 and onwards affects all components of **B**, hence B_y cannot be prescribed independently for all panels but only for panel 1 (initial state, no topology change yet), after which it evolves together with B_z and B_x. Adding an initial constant B_y gives a magnetic field in panel 1 with field lines which appear skewed between north and south (out of the $x - z$ plane).



When viewed in appropriately tilted coordinates (noon-midnight meridian rotated around the tail axis), however, field lines in panel 1 are coplanar north and south, with no out-of-plane component; the configuration is identical to that in Fig. 2 with no B_y, except that the central current sheet is no longer perpendicular to the plane but is tilted east-west. With panel 1 essentially the same, there is no apparent reason why the subsequent evolution should be qualitatively different.

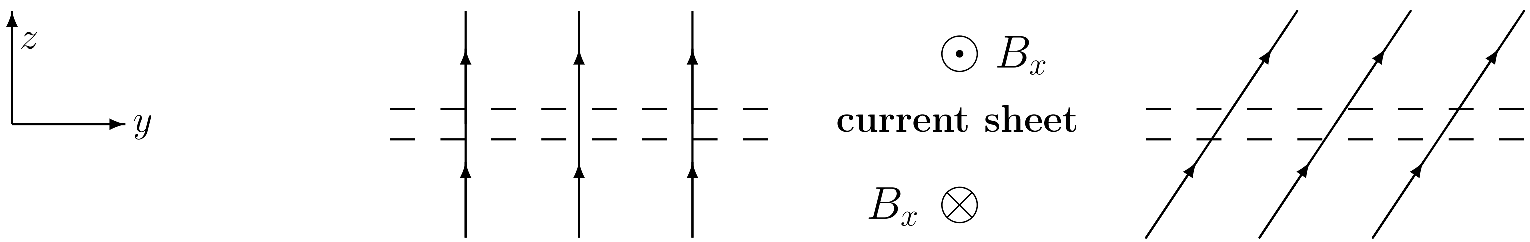


Figure 2 is drawn with the implicit (symmetry) assumption that field lines lie in the meridian plane (at least at noon/midnight). General surfaces containing field lines can be constructed from the Euler potential representation of the magnetic field:

$$\mathbf{B} = \nabla\alpha \times \nabla\beta \ . \tag{1}$$

$\alpha = constant$ and $\beta = constant$ define surfaces on which field lines lie; the intersection of $\alpha = c_1$ and $\beta = c_2$ surfaces is one particular field line. (As is well known, α and β are not unique and are not single-valued except over a limited domain.)

Can Figure 2 be generalized by reinterpreting the meridian plane as a constant β surface, field lines on it being intersections with α surfaces?

Problem: if neighboring α and β surfaces differing by finite $\Delta\alpha$ and $\Delta\beta$ are presumed separated by finite (nonzero) space intervals everywhere, the reinterpreted Fig. 2 contains a magnetic neutral line and a non-zero-measure set of field lines that close on themselves. This indicates that some implicit symmetry condition has been assumed.

In a completely general three-dimensional configuration, without any symmetry assumptions, at the magnetic null points either the α or the β surfaces (or possibly both) must run together and become singular (Fig. 3).

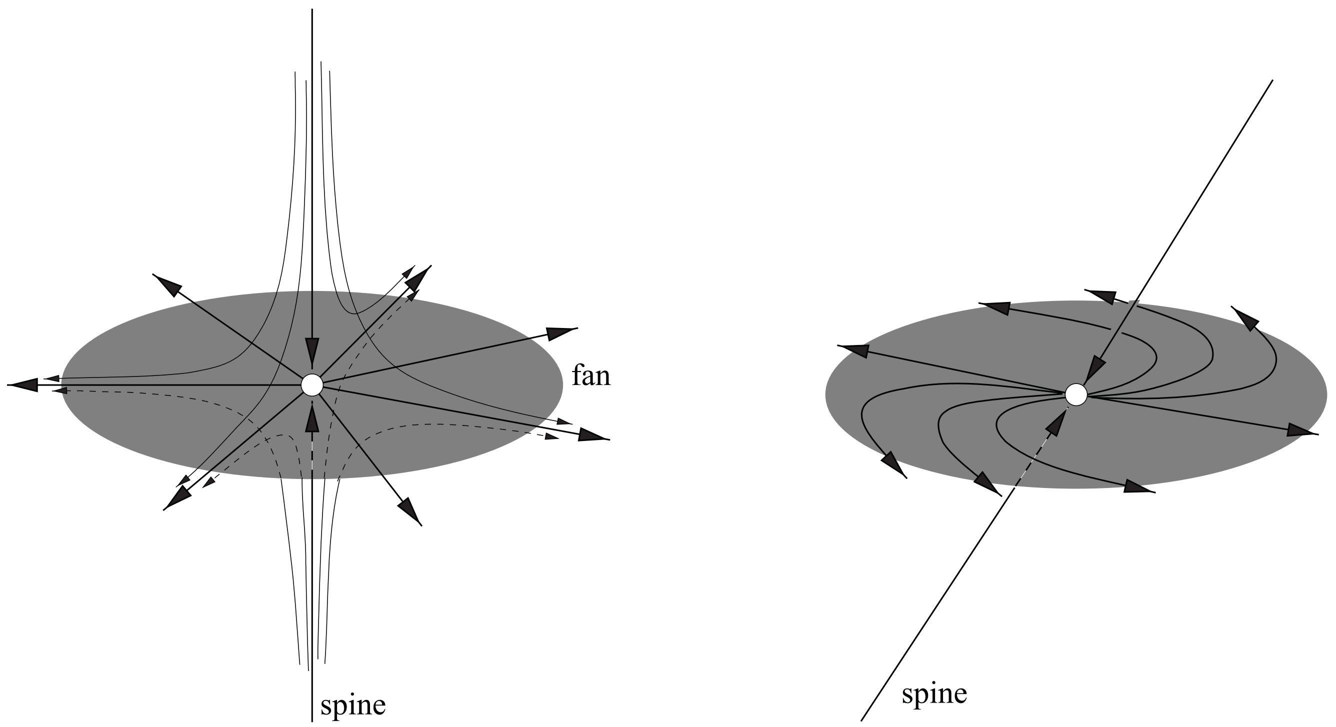


Fig. 3. Sketch of field lines near null point (*white circle*); left $\mathbf{J} = 0$, right $\mathbf{J} \neq 0$ (from D. W. Longcope, *Living Rev. Solar. Phys.* **2, 7, 2005).**

The "fan" surface (*shaded*) may be taken as constant α, field lines in it being intersections with constant β (gives some idea how complex the α–β surfaces must be to represent a magnetic null).

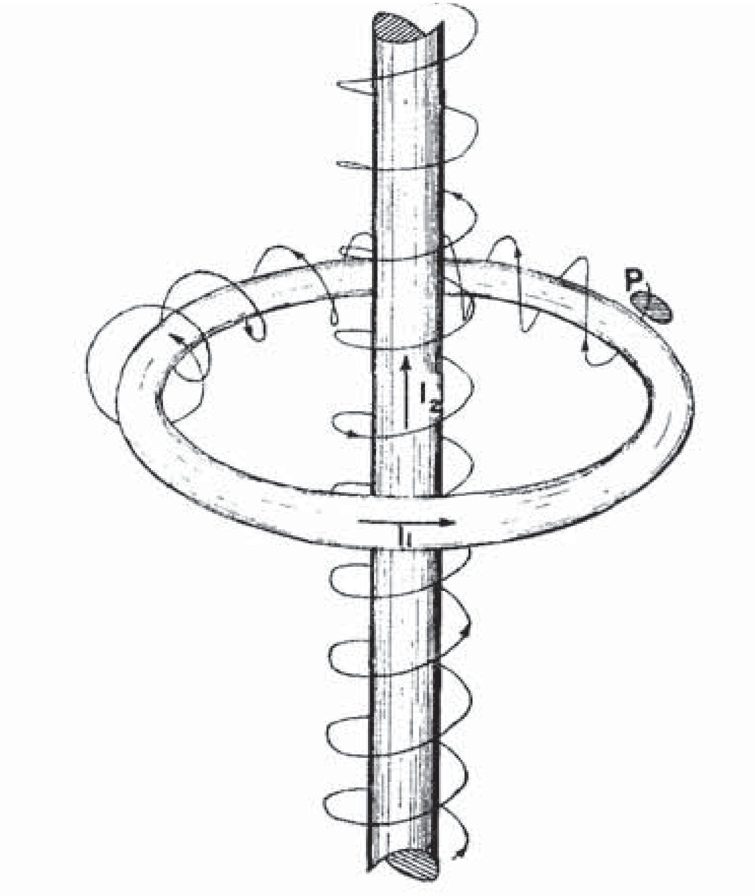
The region shown in Fig. 2 with field lines closing on themselves (the "plasmoid" or "magnetic island") is often described as a flux rope if $B_y \neq 0$; sometimes this is presented as an interpretation alternative to the plasmoid model.

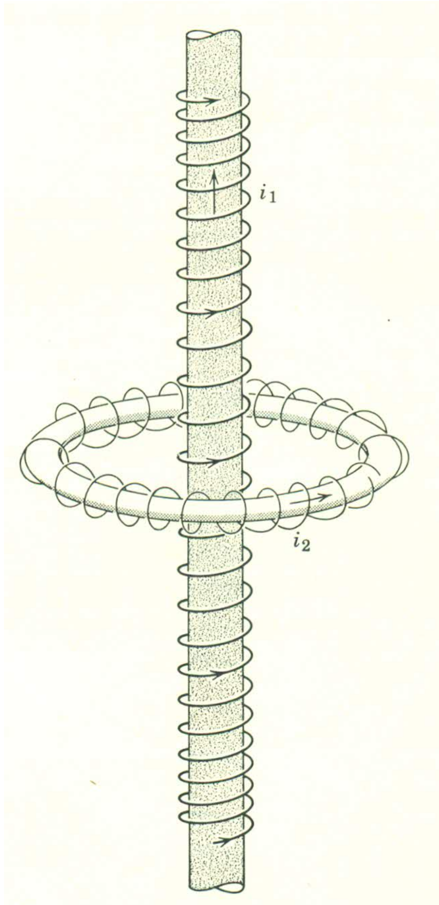
- A flux rope embodies an implicit symmetry condition, just as much as Fig. 2 relabeled with α and β: the surfaces are still presumed separated by finite (nonzero) space intervals everywhere, only in a nested axial geometry instead of planar.
- At least as generally represented, a flux rope with non-zero core field has a null line of $(\nabla \times \mathbf{B}) \times \mathbf{B}$, further assumed to coincide with a magnetic field line. These are very special symmetry conditions.
- A flux rope is created by twisting a magnetic flux tube, which by itself does not change the magnetic topology.

Summary

1. There is considerable evidence that increase of closed magnetic flux in the nightside magnetosphere and decrease of open flux in the magnetotail at substorm expansion events occurs not by simple enhancement of reconnection at the distant open-magnetosphere X-line but by a new reconnection process that is initiated (by whatever cause) on closed field lines.
2. Although there numerous theoretical ideas and models for such a process, we still lack a basic picture of how the topological changes of the magnetic field proceed. Existing representations for the most part embody special symmetries and assume topological features that may or may not exist in general.
3. What is needed is a simple conceptual model of the magnetic field, akin to the uniform-field-plus-tilted-dipole model for the Dungey magnetosphere, which would just display the general existence of the topological changes (but otherwise need not satisfy any particular constraints).

(end of presentation)





O-type null line (e.g., core of uniform-current ring solenoid) + tilted uniform field gives two O-type null points but there is no core field line emanating from them (field line from any point on the core goes away from core immediately).