General Review on Reconnection: Concept and Theory

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The concept now known as magnetic field line reconnection or simply magnetic reconnection evolved from suggestions by R. G. Giovanelli (1947, 1948) that electrons in solar flares could be accelerated to high energies by non-MHD processes in zero magnetic fields at the interface between oppositely directed sunspot fields.

Concept further developed by Fred Hoyle (1949) (*external examiner of Giovanelli's Ph.D. thesis*), who also suggested that a similar process could explain energetic electrons in the terrestrial aurora.

Model for both aurora and flares further developed by J. W. Dungey (1953) (*Ph.D. student of Fred Hoyle*).

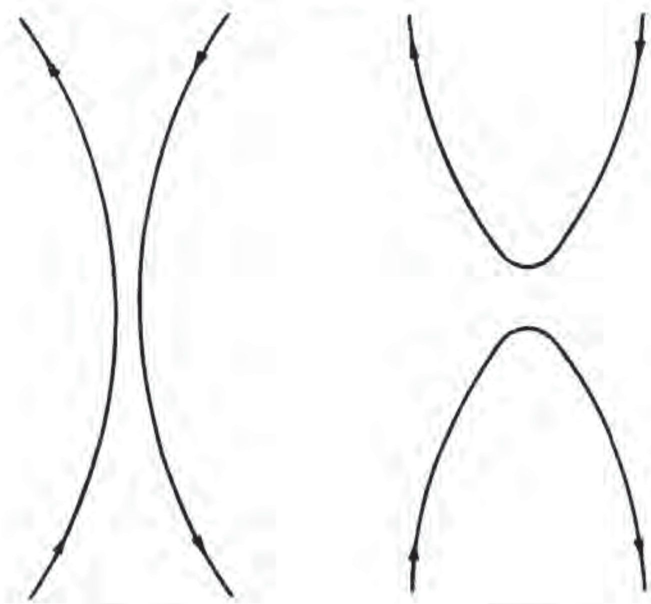
The term "reconnection" does not occur in these early papers, although Dungey (1953) clearly presents the picture implied by the term.

Why “reconnection” ?

J. W. Dungey
(*Phil. Mag.* 44, 725 – 738, 1953):

“The lines of force in fig. 2 (a) can be regarded as being broken and rejoined to form those shown in fig. 2 (b).”

Fig. 2

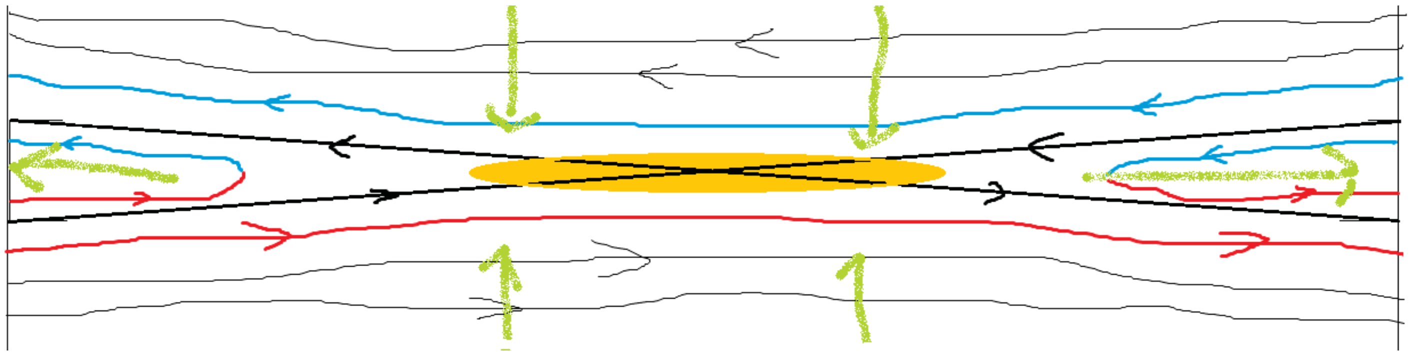


(a) (b)

In subsequent papers
“broken and rejoined” becomes “cut and reconnected”.

The phrase “ ... reconnection of the lines of force” appears in
E. N. Parker (*J. Geophys. Res.* 62, 509 – 520, 1957).

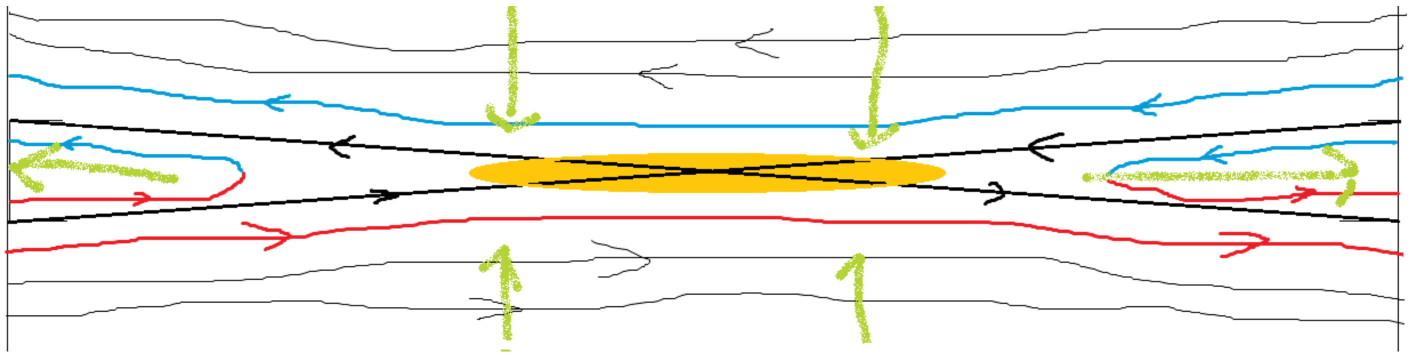
What is the physical meaning (*if any*) of reconnection ?



1. *(literal meaning)* Two distinct field lines (e.g., blue and red) approach each other (green arrows) and, when they make contact, are cut and reconnected. Reonnection (I) occurs at the point of contact, which is a magnetic null.

   This presumes that a given field line maintains its identity as it is displaced. There is, however, nothing in Maxwell's equations that could define a field line as being the same at different times.

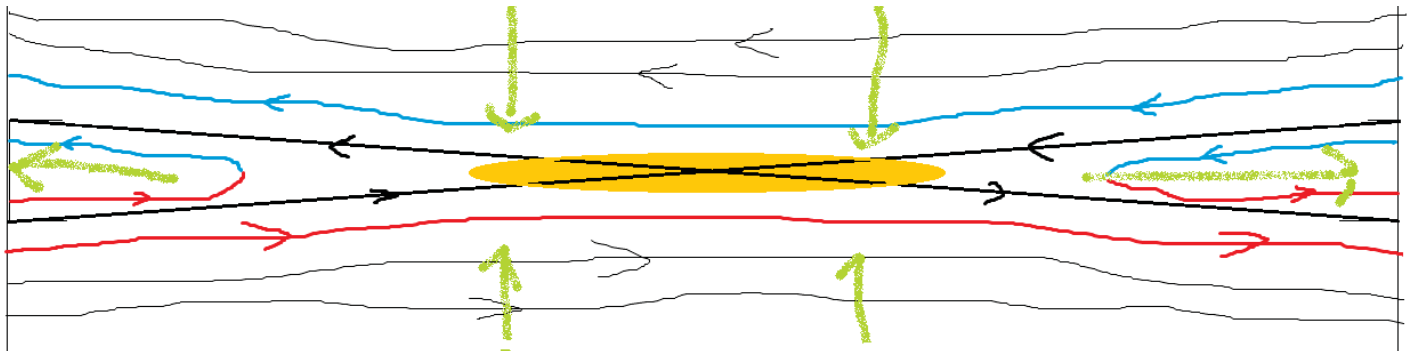
   (Motion of field lines can be prescribed arbitrarily by specifying a velocity on any surface that is crossed by the field lines once.)



2. If MHD approximation holds, plasma elements which are at one time connected by a single magnetic field line remain at subsequent times connected by a single (not "the same") field line.

   Reconnection (II) occurs when MHD approximation breaks down within a segment of a field line (e.g., in the vicinity of a magnetic null, *orange shading in figure*) and plasma elements on the two sides of the segment no longer remain connected — "generalized reconnection" [Schindler, Hesse, and Birn (*J. Geophys. Res.* 93, 5547–5557, 1988)]. *(Why "reconnection" and not simply, e.g., "variable connection"?)*

   May occur even without magnetic nulls or oppositely directed fields, e.g., across thin current sheets or highly resistive layers.



3. Thick field lines in the figure lie in the separatrix surfaces, separating regions containing topologically different magnetic field lines (in the figure, differently connected to the edges; more generally, e.g., “open”and “closed” field lines in the magnetosphere).

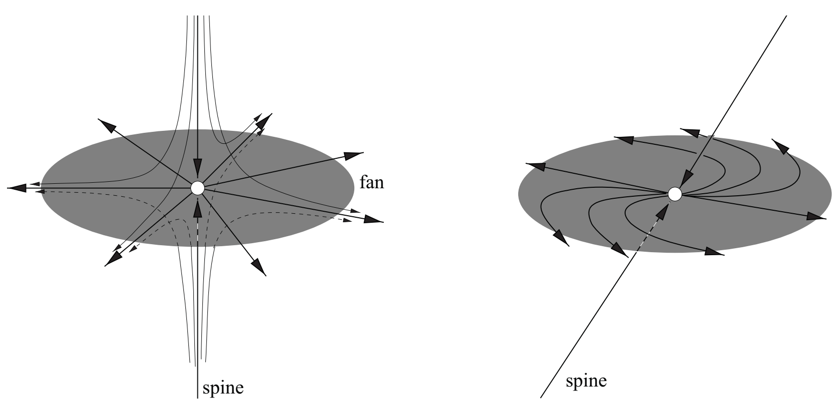
Reconnection (III) occurs when magnetic flux is transported across separatrix surfaces.
Magnetic flux transport governed by

$$\partial \mathbf{B}/\partial t + \nabla \cdot (\mathsf{I} \times c\mathbf{E}) = \mathbf{0}$$

(Faraday’s law rewritten in standard conservation form).

Across topological boundaries,
flux transport rate/unit area = electric field tangent to the boundary.

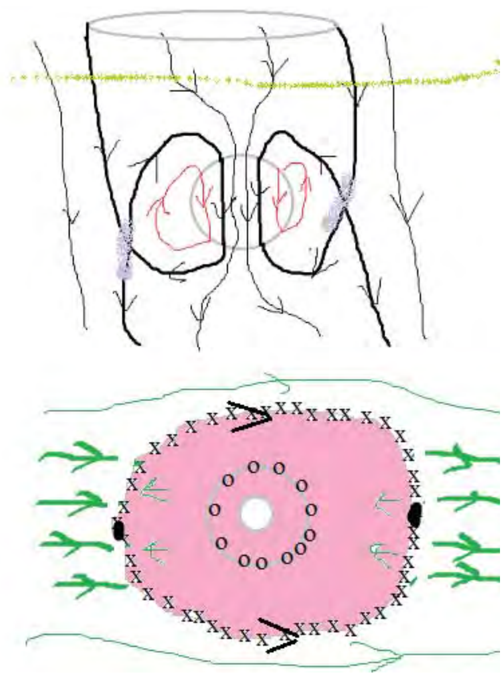
- Magnetic field lines constitute a continuum: between any two field lines there is always another field line. ***(Not modeled in numerical simulations.)***
- If there is an interface separating different classes of field lines, (e.g., “open” and “closed”) every field line at the interface goes ultimately in a different direction, depending on infinitesimal displacement; it must therefore pass through a magnetic field null point somewhere (not a null line — they do not exist except in two dimensions or other special symmetries).
- At a generic null point, there is a “fan” surface formed by field lines radiating from (or toward) the null point, plus a single “spine” line pointing toward (or away from) the null point.



(figure from D. W. Longcope, ***Living Rev. Solar. Phys.*** 2, 7, 2005)

Simple model: dipole plus constant southward and slightly antisunward field, plus quasi-spherical magnetopause

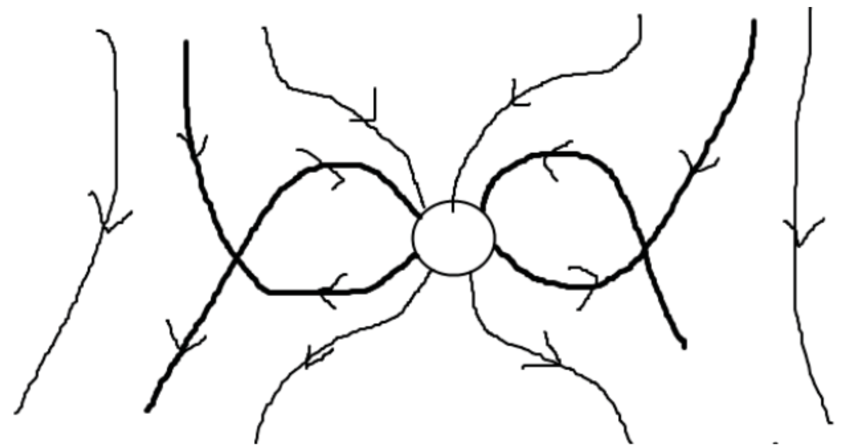
- Separatrix surfaces consisting of open/closed and interplanetary/open boundary field lines intersect at an X-line that forms a ring (stretched tailward) around planet.
- Reconnection occurs at inflow ("dayside") and outflow ("nightside") segments of X-line.
- The X-line contains two magnetic null points, connected by singular ("separator") magnetic field lines. Only for special symmetries is the X-line a magnetic neutral line.
- With no symmetry, every field line on the separatrix surfaces connects to one of the null points on the X-line.

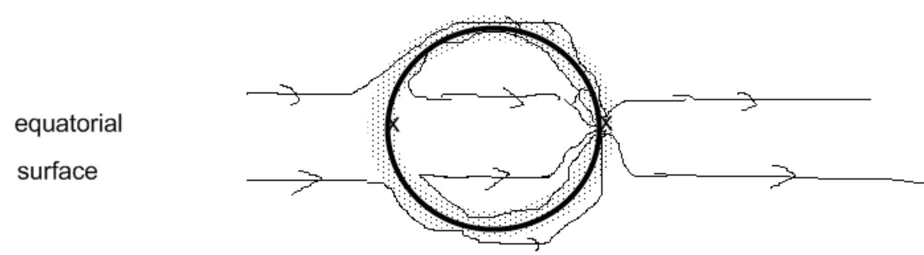


(Top) meridian plane projection (*purple* null-point fan orientation) *(Bottom)* quasi-equatorial cut

- Real magnetosphere: X-lines most likely imbedded in current sheets, and location of null points (*there may be more than one pair*) has no global significance.

- Reconnection process, with its singularities of the magnetic field (null points, X-lines,etc.), is often contained within a non-MHD current sheet (Syrovatskii, Dungey, Crooker, & many others).
- Magnetic flux transport can occur anywhere at the current sheet, governed by the transverse electric field, regardless of what the field lines are doing inside the sheet.
- If one insists on describing flux transfer in terms of field lines, every field line transported across the open/closed boundary moves through one of the null points — at infinite speed (to accommodate finite amount transported through a point). Large "swinging" motions of field lines, unrelated to plasma flow, occur within non-MHD region.

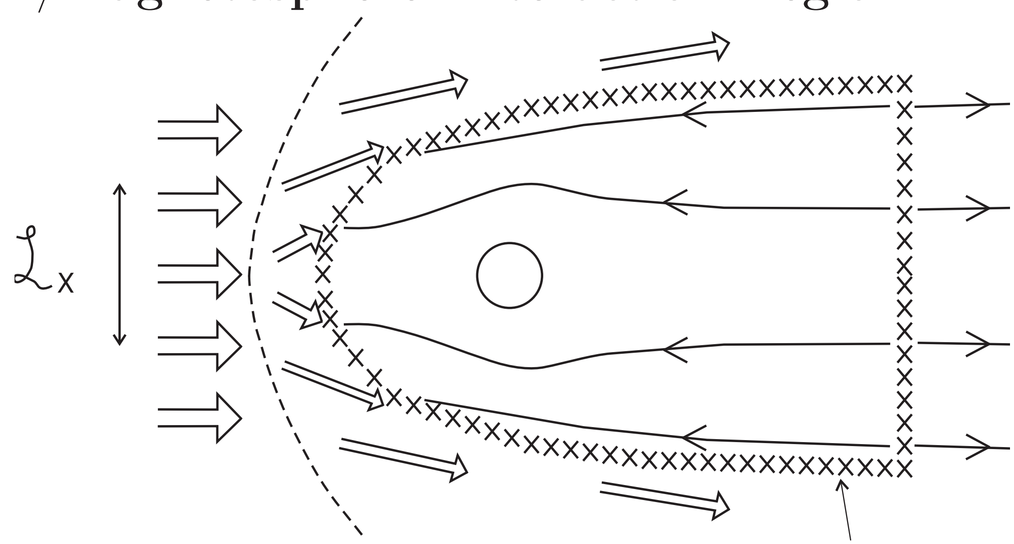


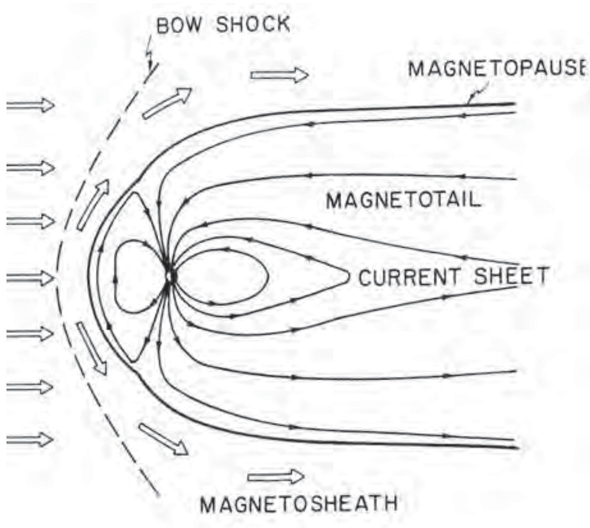


(inside circle: north polar cap)

- For thin current sheets, transverse electric field within the sheet $\approx$ transverse electric field outside.
- Relation between electric field and non-MHD properties of plasma within the current sheet widely studied, particularly in the vicinity of the null point ("diffusion region").
- Transverse electric field outside the current sheet strongly coupled to the plasma flow configuration in the exterior region.
- For dayside reconnection, the reconnection rate depends on how much of the solar-wind flow goes around the magnetosphere vs. how much enters the magnetosheath/magnetosphere interaction region.

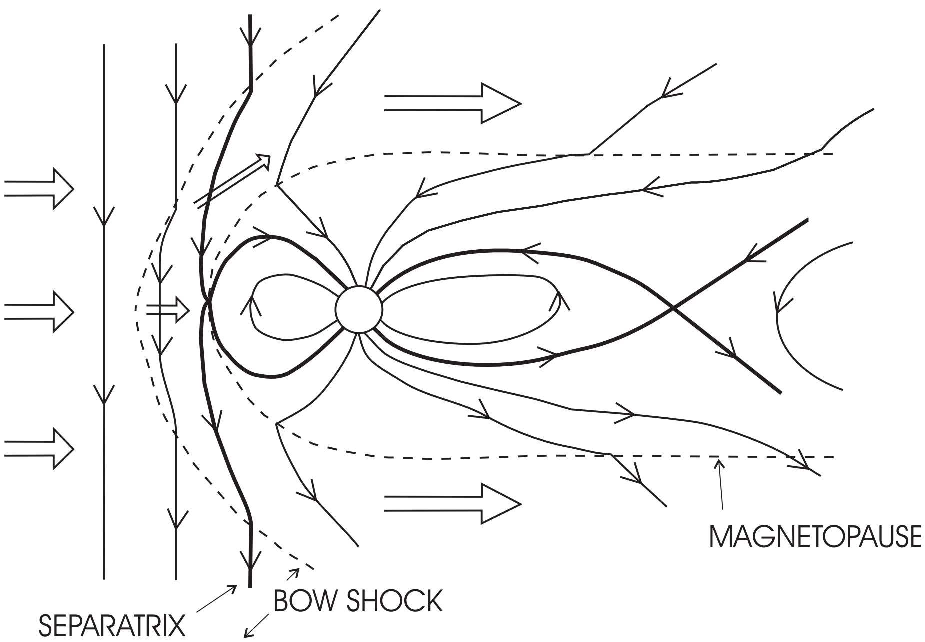
To what extent does the dayside reconnection rate depend on how much plasma entering from the magnetosheath can be accommodated in the diverted post-reconnection flow (***Axford conjecture***) vs. on non-MHD properties of the current sheet?





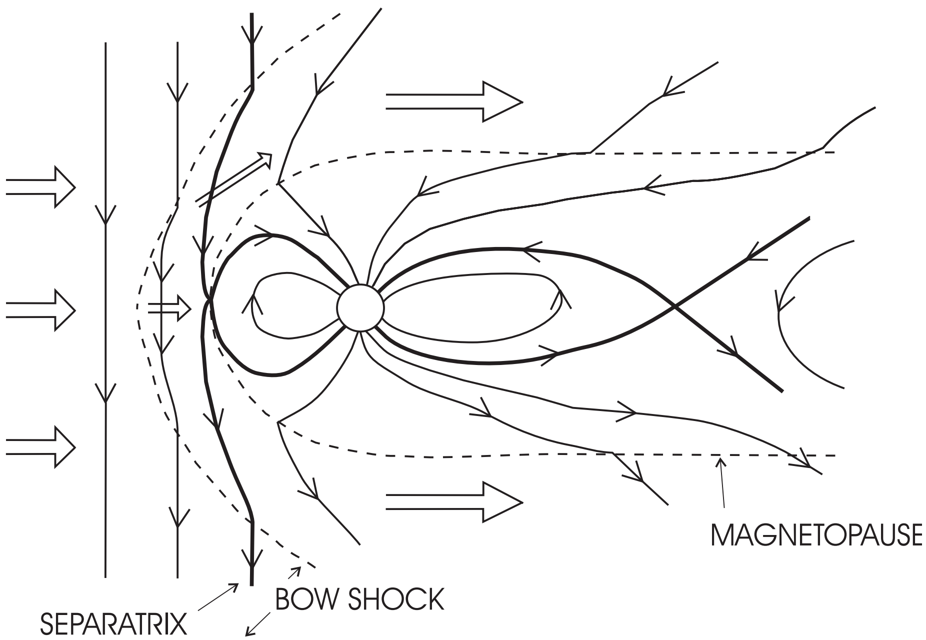
Closed magnetosphere (no reconnection)

- no streamlines or magnetic field lines cross between interior (geomagnetic field) and exterior (solar-wind field and flow)
- <u>magnetopause defined uniquely as the surface separating interior and exterior</u>



Open magnetosphere

- connection between geomagnetic and solar-wind magnetic field lines
- solar wind plasma flows (in part) through geomagnetic field lines
- magnetopause is crossed by magnetic field lines, may be crossed by streamlines (from either side)
- what is the magnetopause?

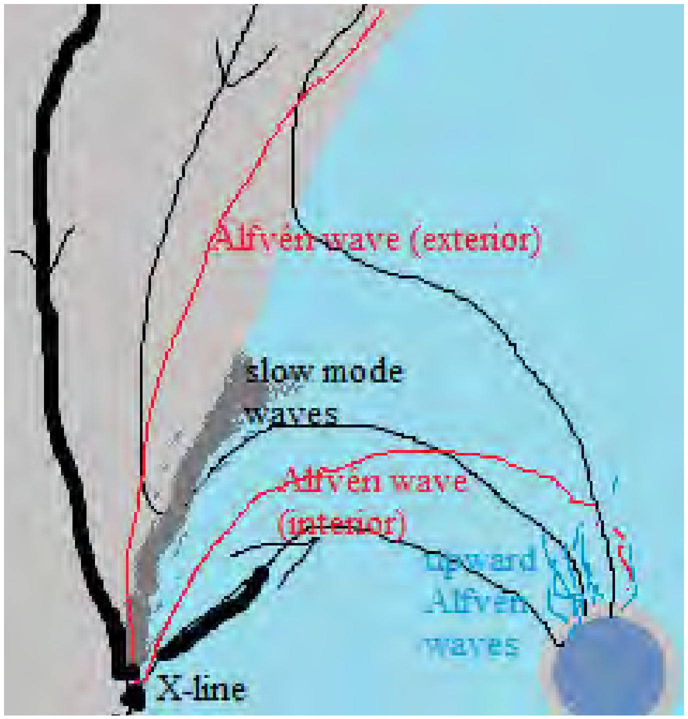


Open magnetosphere

- what is the magnetopause?
- In observations, the magnetopause is identified as a current sheet:
  - what is its physical nature?
  - what determines its location?
  - is it a single sheet or multiple sheets?

- Not related to the separatrix surface except in the immediate vicinity of the null points or the X-line.
- May be related to standing waves in the flow generated by the direct interaction (contact) between magnetosheath and magnetosphere plasmas and fields.

Standing waves attached to dayside X-line:



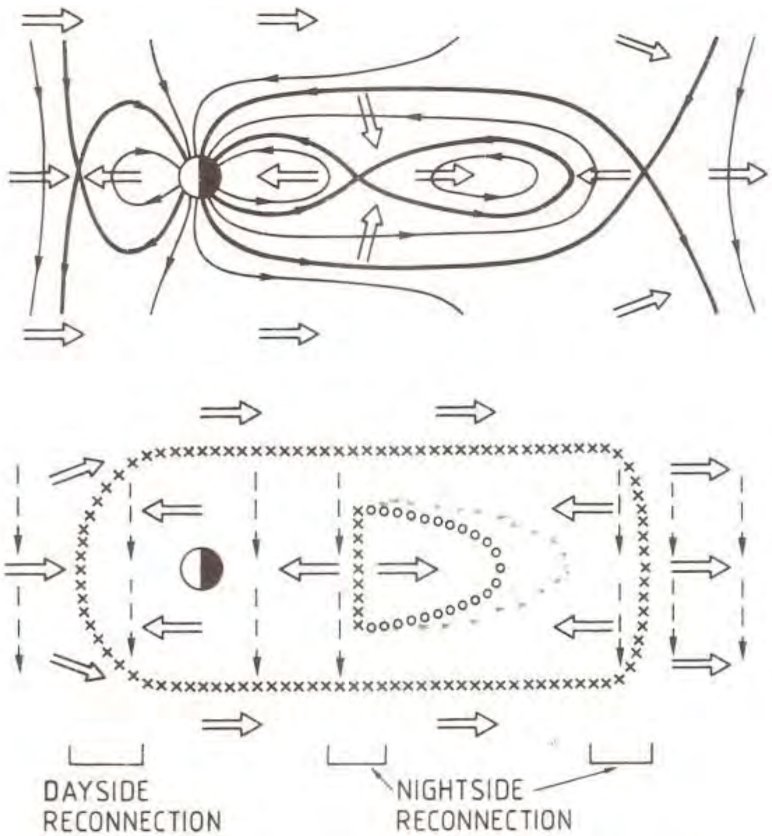
1. Alfvén wave (rotational discontinuity) propagating into magnetosheath side.
2. Slow mode wave (possibly two) on either side (possibly both) of discontinuity (4) *(below)*.
3. Alfvén wave (rotational discontinuity) propagating into magnetosphere side.

Non-wave (quasi-static) boundary:

4. Magnetosheath/magnetosphere plasma interface, nominally a contact discontinuity, possibly a diffuse structure merged with (2).

Alfvén wave (1), the outward-propagating rotational discontinuity, is often identified as <u>the</u> magnetopause.

Reconnection in Earth's magnetotail



Distinguish between distant tail reconnection and near-Earth reconnection.

- Distant-tail reconnection occurs on the nightside segment of the X-line ring, returns magnetic flux of the open magnetosphere.
- Near-Earth reconnection is associated with substorms, formation of "near-Earth" X-line, and plasmoids. Not clear if there is flux transport across magnetic topological boundaries (***what boundaries?***) or just a pronounced non-MHD regime (reconnection II).
- In three dimensions, magnetic field lines that close on themselves are a set of measure zero, and plasmoids as commonly drawn do not exist unless special symmetries are assumed. If a plasmoid is a magnetically detached region, its geometry in three dimensions must be more complicated than either the usually drawn quasi-spherical shape or a flux rope.

Conclusions

1. The concept of magnetic reconnection can be defined in several different ways (some only indirectly related to the word "reconnection").
2. Reconnection involves interplay between (1) large scale flows and their boundary conditions and (2) small-scale non-MHD effects. There are many questions about relations between the two.
3. Reconnection between interplanetary and terrestrial magnetic fields to form the open magnetosphere occurs both on dayside and on nightside (magnetic flux return) and has a topology that is understood in principle although not in detail. The topology of nightside reconnection associated with "near-Earth X-line" is poorly understood, if at all.
4. There is no clear theoretical concept of what the magnetopause is in a magnetically open magnetosphere.
5. The main effects of reconnection on the magnetospheric energy budget are indirect: enable conversion of solar-wind flow kinetic energy to magnetic energy stored in the magnetotail, and enable deep penetration of convection that creates the storm-time ring current. Direct conversion of magnetic to plasma energy by reconnection is secondary.

(end of presentation)