Energy conversion in planetary magnetospheres

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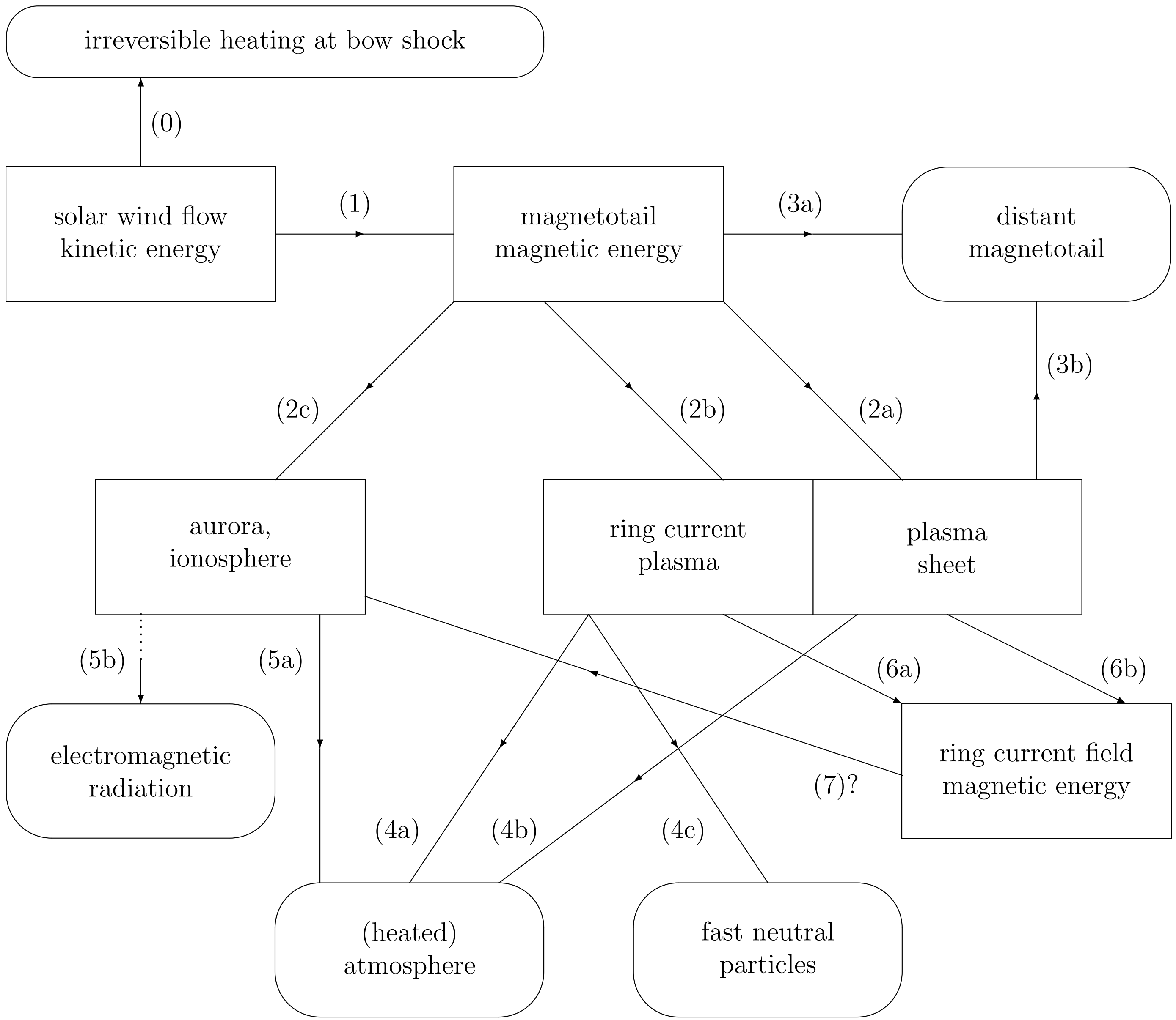
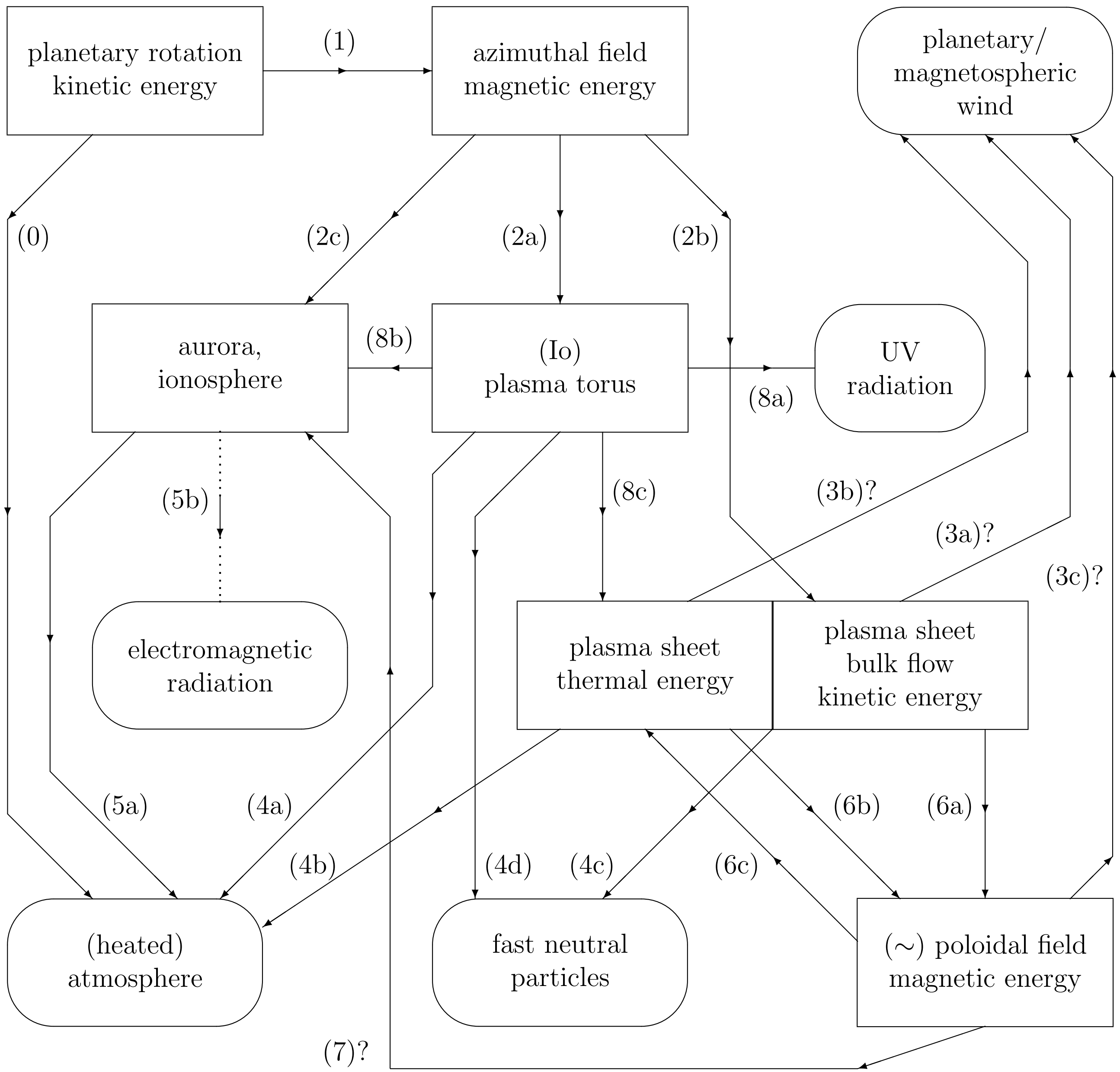
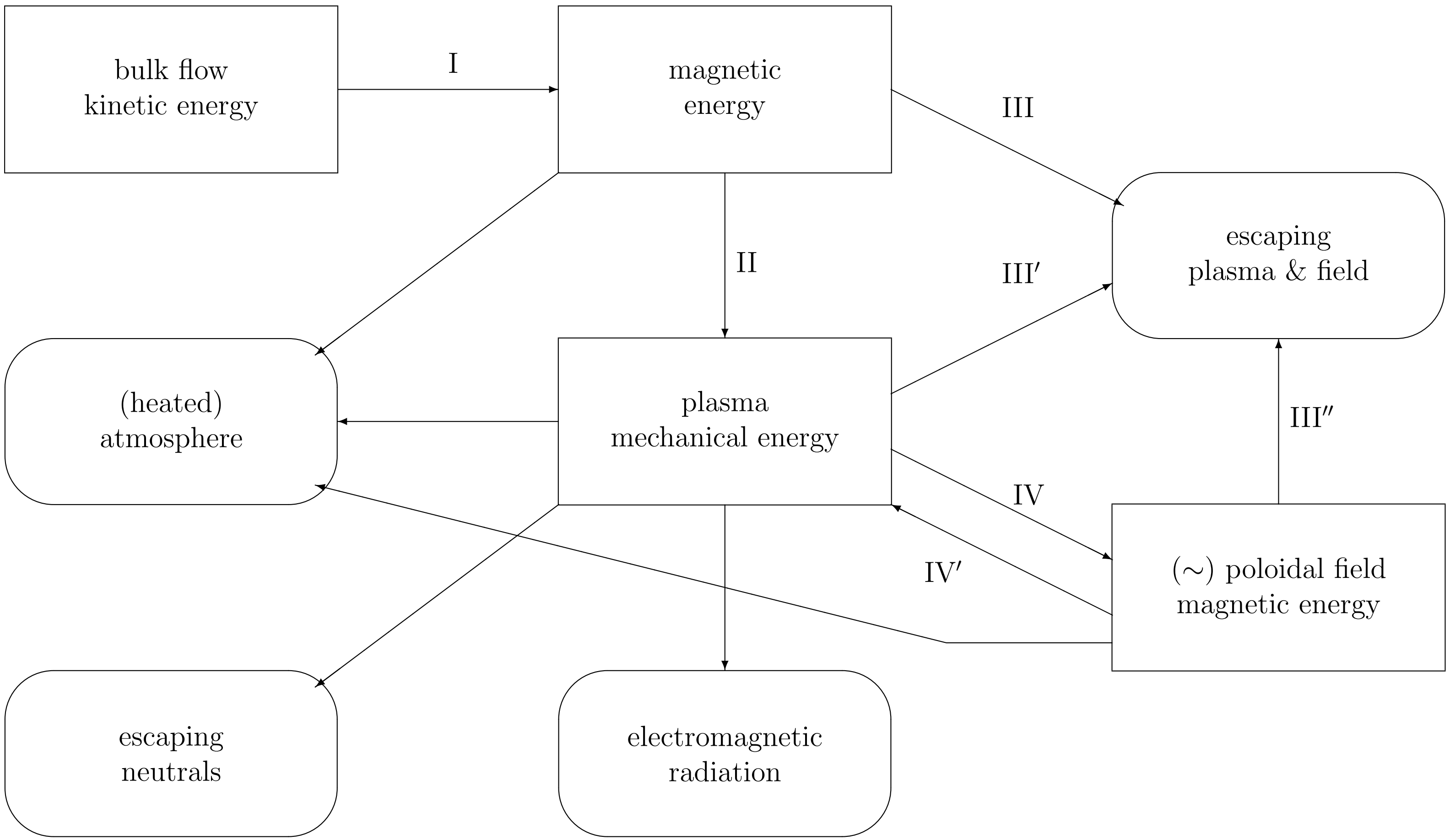

irreversible heating at bow shock
(0)
solar wind flow
kinetic energy
(1)
magnetotail
magnetic energy
(3a)
distant
magnetotail
(3b)
(2c)
(2b)
(2a)
aurora,
ionosphere
ring current
plasma
plasma
sheet
(5b)
(5a)
(6a)
(6b)
electromagnetic
radiation
ring current field
magnetic energy
(7)?
(4a)
(4b)
(4c)
(heated)
atmosphere
fast neutral
particles



planetary rotation kinetic energy
(1)
azimuthal field magnetic energy
planetary/ magnetospheric wind
(0)
(2c)
(2a)
(2b)
aurora, ionosphere
(8b)
(Io) plasma torus
UV radiation
(8a)
(5b)
(8c)
(3b)?
(3a)?
(3c)?
electromagnetic radiation
plasma sheet thermal energy
plasma sheet bulk flow kinetic energy
(5a)
(4a)
(6b)
(6a)
(4b)
(4d)
(4c)
(6c)
(heated) atmosphere
fast neutral particles
(∼) poloidal field magnetic energy
(7)?


bulk flow
kinetic energy
I
magnetic
energy
III
escaping
plasma & field
II
III′
(heated)
atmosphere
plasma
mechanical energy
III″
IV
IV′
(∼) poloidal field
magnetic energy
escaping
neutrals
electromagnetic
radiation

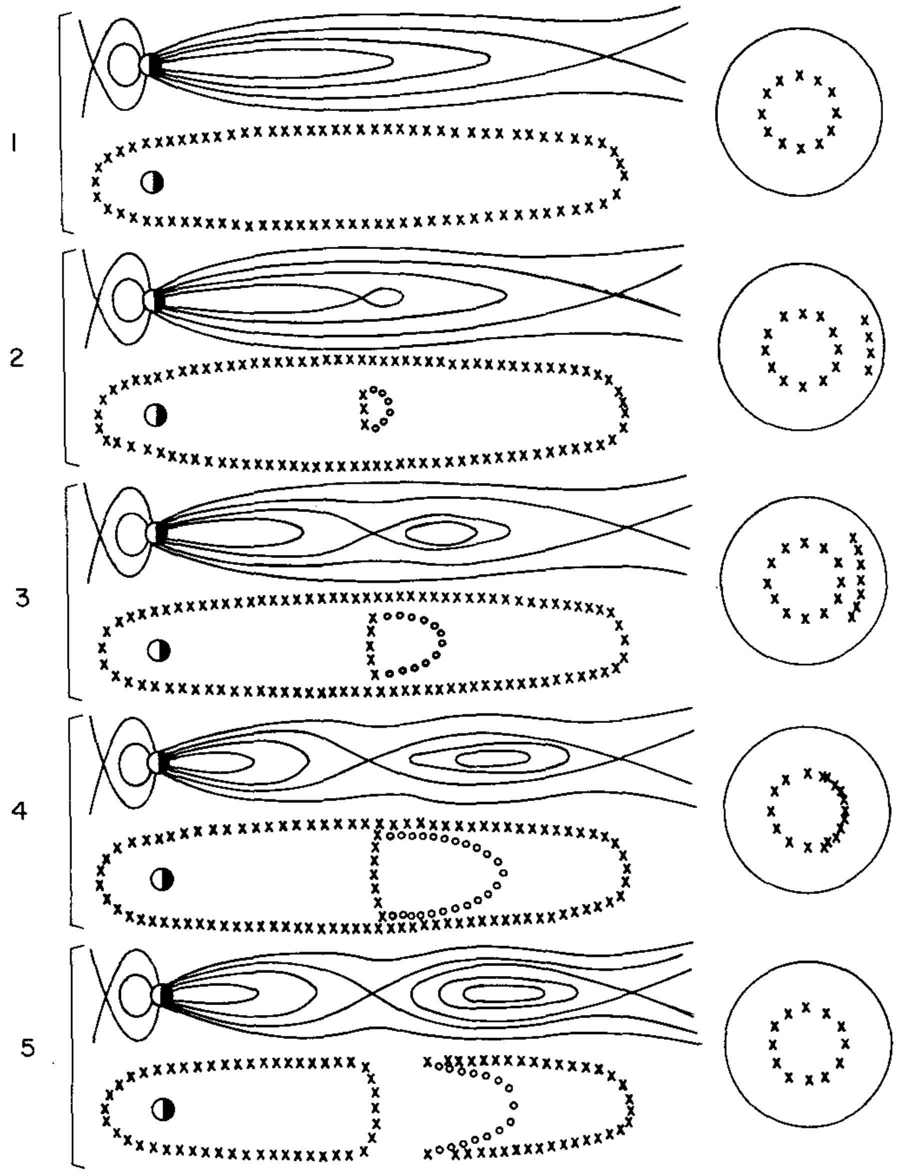


Figure 1: **Possible changes of the magnetic field topology: Earth.**

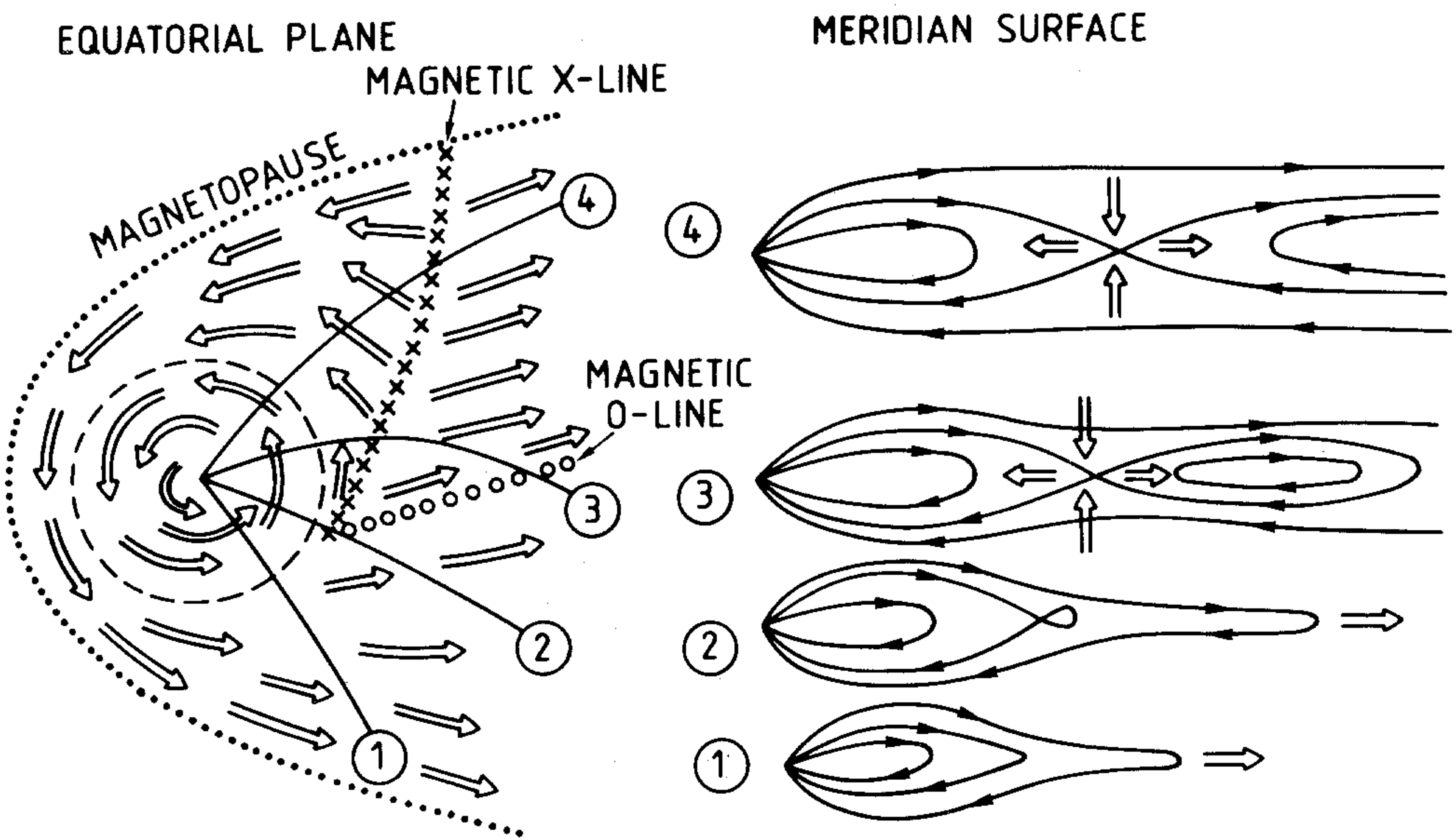
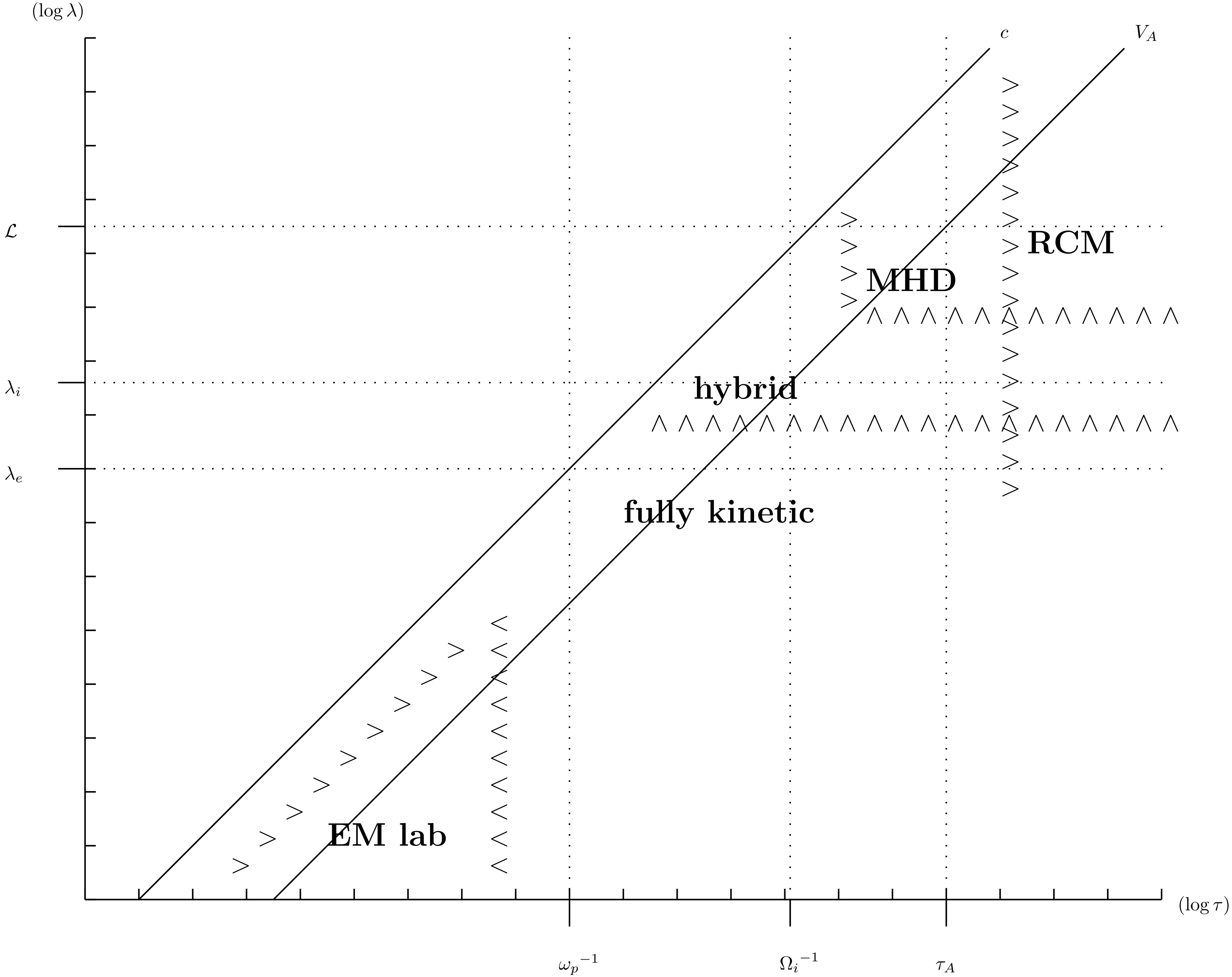


Figure 2: **Qualitative sketch of planetary wind flow and magnetic topology.**


(log λ)
$\mathcal{L}$
λ_i
λ_e
c
V_A
RCM
MHD
hybrid
fully kinetic
EM lab
$\omega_p{}^{-1}$
$\Omega_i{}^{-1}$
τ_A
(log τ)

ABSTRACT. Events corresponding to, analogous to, or similar to magnetospheric substorms have been discussed in connection with a number of objects other than Earth. They include: solar flares and coronal mass ejections at the Sun; events claimed to be scaled versions of terrestrial substorms, in the magnetosphere of Mercury; events similar in some ways to terrestrial substorms, in the magnetospheres of Jupiter, Saturn, and (possibly) Uranus. A systematic intercomparison is encumbered by the variety of observational aspects to a substorm, coupled with the lack of an universally agreed upon definition as well as of a consensus on the essential physical process. The main phenomena of a magnetospheric substorm at Earth can be subsumed under three groups: (1) enhanced energy dissipation (auroral emissions, energetic charged particles), occurring on a dynamical time scale (comparable to or shorter than wave travel times), accompanied by (2) changes of the magnetic field configuration, from stretched-out to more nearly dipolar, (3) fast (order of Alfvén speed or more) plasma bulk flows in the magnetotail. Observations of similar phenomena in other systems will be reviewed. If these substorm or substorm-like events are all regarded as different manifestations of an underlying universal process, the essential steps of the process would seem to be the following: (a) mechanical stresses deform the magnetic field into a configuration of increased energy, (b) the magnetic configuration becomes unsustainable and changes quickly, releasing the energy. The various systems may differ in the mechanical stresses, which are reasonably well understood for planetary magnetospheres but still very uncertain for solar processes. They may also differ in what makes the configuration unsustainable (for planetary magnetospheres, possibly related to the need for return of magnetic flux) and particularly in what sets off the quick change, both highly controversial.

ICS9-5 *Substorm as a common process in the universe*

1. **Is the substorm a common process in the universe?**

2. **What is a substorm?**

   (a) **Defining phenomenon?** *(observed)*

   (b) **Defining process?** *(conceptual)*

There does not seem to be a generally accepted clear definition of the magnetospheric substorm, either as phenomenon or as process — in contrast to the magnetic storm, for which there is a clear definition as phenomenon.

***What constitutes a magnetospheric substorm?* I**

Phenomena at Earth:

1. **• Geomagnetic disturbances**
   ("polar elementary storm", magnetic bay...)

   • Auroral breakup and and follow-on developments
   (surge, expansion...)

2. **• Rapid enhancement of energetic charged particle intensities**
   ("injection" events, beams...)

3. **• Enhancement of magnetotail magnetic field, followed by reduction**

   • Strong bulk flow of plasma in the magnetotail, predominantly away from Earth at larger distances

(...can be expanded into unending detail...)

What constitutes a magnetospheric substorm? II

Processes at Earth:

- **[1] enhanced energy input and dissipation**
- **[2] change of magnetic field configuration**
  - **from highly stretched (increased flux in magnetotail, reduced flux in nightside equatorial region)**
  - **to more nearly dipolar (increased flux on the nightside)**
  - **accompanied (most probably) by changes of magnetic topology**
- **occurring on dynamical time scales (comparable to or shorter than wave travel times)**

Main points of controversy:

- **reason for [2]**
- **temporal and causal relationships between [1] and [2]**

(...can be expanded into unending detail...)

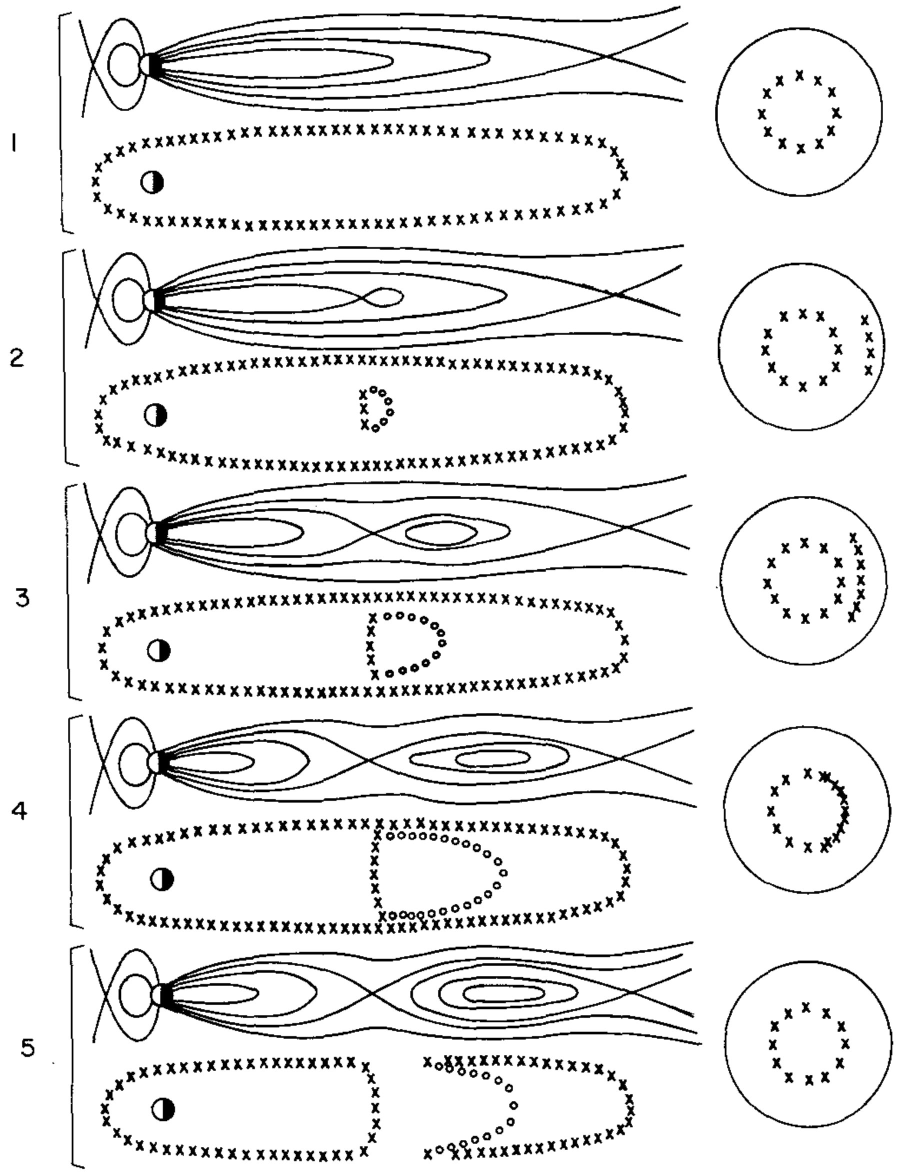


Figure 3: **Possible changes of the magnetic field topology during substorms.**

Solar flares and terrestrial magnetospheric substorms

- **solar flare defined by localized explosive energy release (electromagnetic radiation)**
- **magnetic field configuration complex, known to a limited extent, often only by inference**
- **the concept and much of the early theory of magnetic field line reconnection developed initially from the hypothesis that the magnetic field is the only plausible source of energy for solar flares**
- **the concept and the theory later taken over and applied to the terrestrial magnetosphere, first to the configuration (open magnetosphere), then to energy dissipation generally, and finally to substorm**
- **CME may be defined by explosive enhancement of outflow (in some respects an enormously upscaled flare)**

Substorms in planetary magnetospheres?

- **reports of substorms or substorm-like events in magnetospheres of other planets are based primarily on observations of the magnetic field that indicate a change from tail-like to more dipolar configuration**
- **interpretation of observed enhancements of the intensity of energetic charged particles is ambiguous — in particular, "injection" events interpreted as indicative sometimes of substorms, sometimes of interchange motions**
- **qualitative similarity to observations at Earth is often taken as conclusive indication of an event analogous to the terrestrial substorm (without asking for confirming evidence)**
- **description of changes of magnetic field topology adapted from the terrestrial model, replacing the solar wind stress on open field lines by stress from (rotationally driven) outflow of plasma**

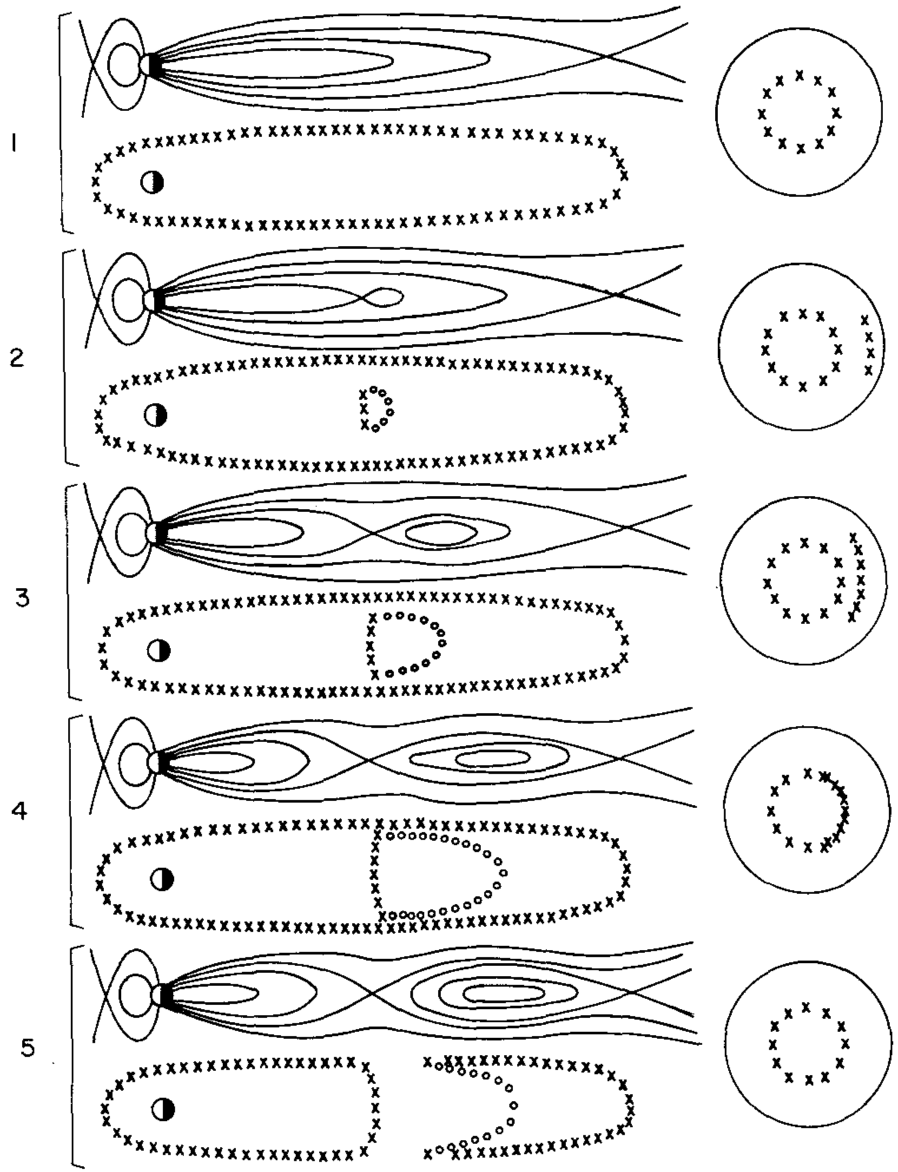


Figure 4: **Possible changes of the magnetic field topology: Earth.**

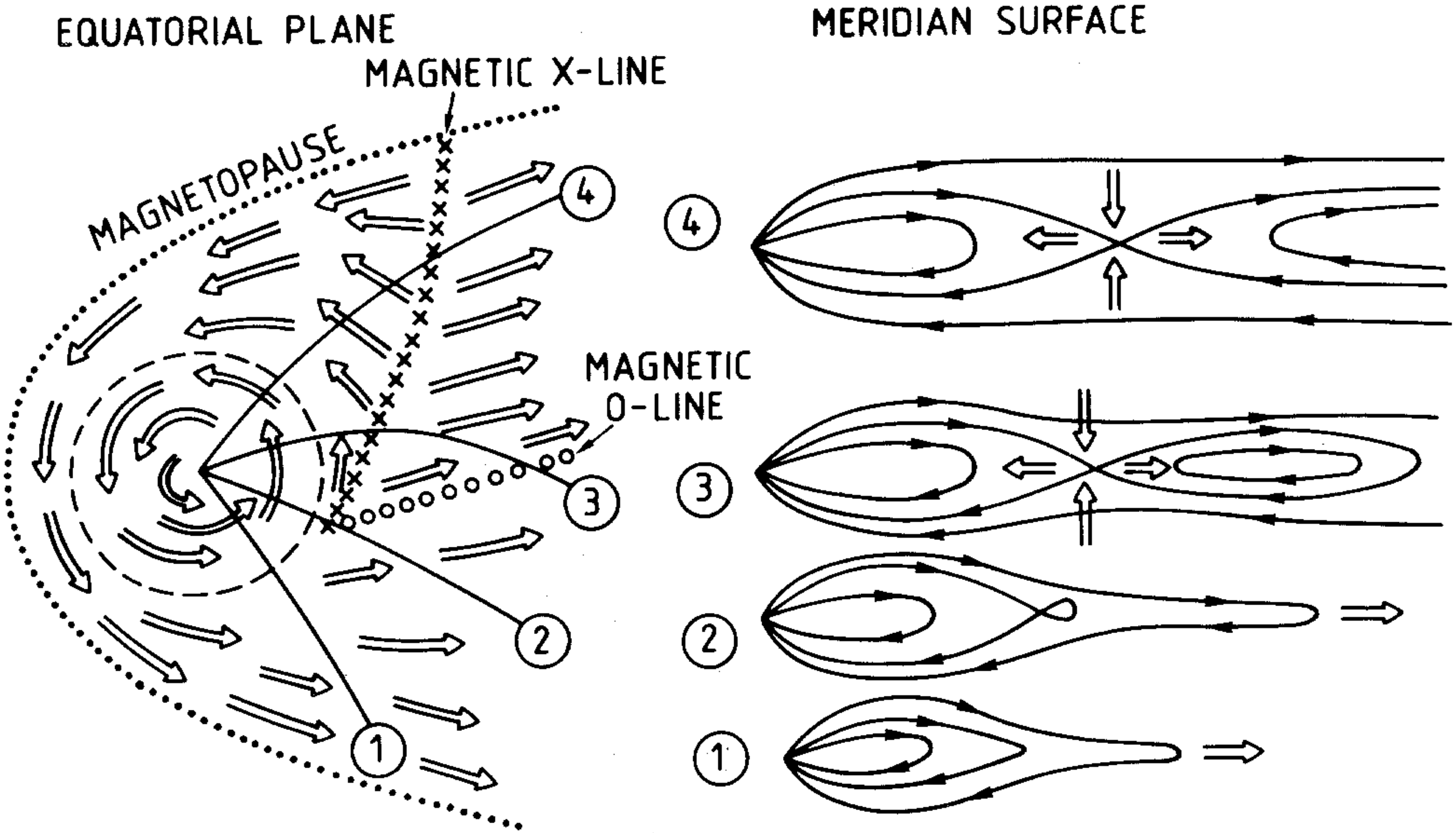


Figure 5: **Qualitative sketch of planetary wind flow and magnetic topology.**

An underlying universal process?

- **Step 1: mechanical stresses deform the magnetic field into a configuration of increased energy.**
- **Step 2: the magnetic configuration becomes unsustainable and changes quickly, releasing the energy.**
- **(Both steps are in general associated with magnetic topological changes.)**
- **In most cases, the mechanical stress is related to plasma flow, which transports magnetic flux and, with field lines attached to a massive body, increases the magnetic energy.**
- **Why the magnetic configuration becomes unsustainable and what causes the quick change remain highly disputed questions; many possibilities can be imagined, and there may not be a universal answer.**
- **A potentially universal aspect is magnetic flux return: inability to return the flux smoothly (albeit for many possible reasons) seems to play a role (for Earth at least).**

Conclusions **(I)**

- **The solar flare is the prototype of an explosive energy release, interpreted as originating from stored magnetic energy and thereby providing the initial theoretical framework for understanding the substorm.**
- **Solar events (flares and coronal mass ejections) and magnetospheric substorms may differ considerably, however, in the specifics of the magnetic field configuration.**
- **Events in which magnetic field, plasma, and energetic charged particle intensities change similarly to what is observed at Earth during substorms occur in the magnetospheres of Mercury, Jupiter, and Saturn. That these are close analogs of the terrestrial substorm, differing only in scale (and for Jupiter and Saturn also in the dominant role of rotation instead of solar wind flow) is a plausible (although for the most part not yet confirmed) hypothesis.**

Conclusions (II)

- **A universal framework for all these events can be envisaged as a two-step process, first building up and then quickly releasing the energy in the magnetic field. The first step is reasonably well understood, in principle if not in detail. For the second step, there are so many possibilities and the range of views even in the single case of Earth so extreme, that the chances of identifying a universal process — if one exists — are at present remote.**