Section 11 – The Solar Wind-Magnetosphere interaction – Non-Steady State

4C65/SS109/4680 Space Plasma and Magnetospheric Physics

Sect. 11 – The Solar Wind-Magnetosphere interaction – Non-Steady State

- In reality, the solar wind and IMF are far from steady in time (density, velocity variations, field strength and direction changes;
- We know reconnection occurs preferentially for southward IMF
  - Thus coupling of SW energy into the magnetosphere is time dependent:
    - Energy storage and release cycles
    - Time-variable magnetospheric convection

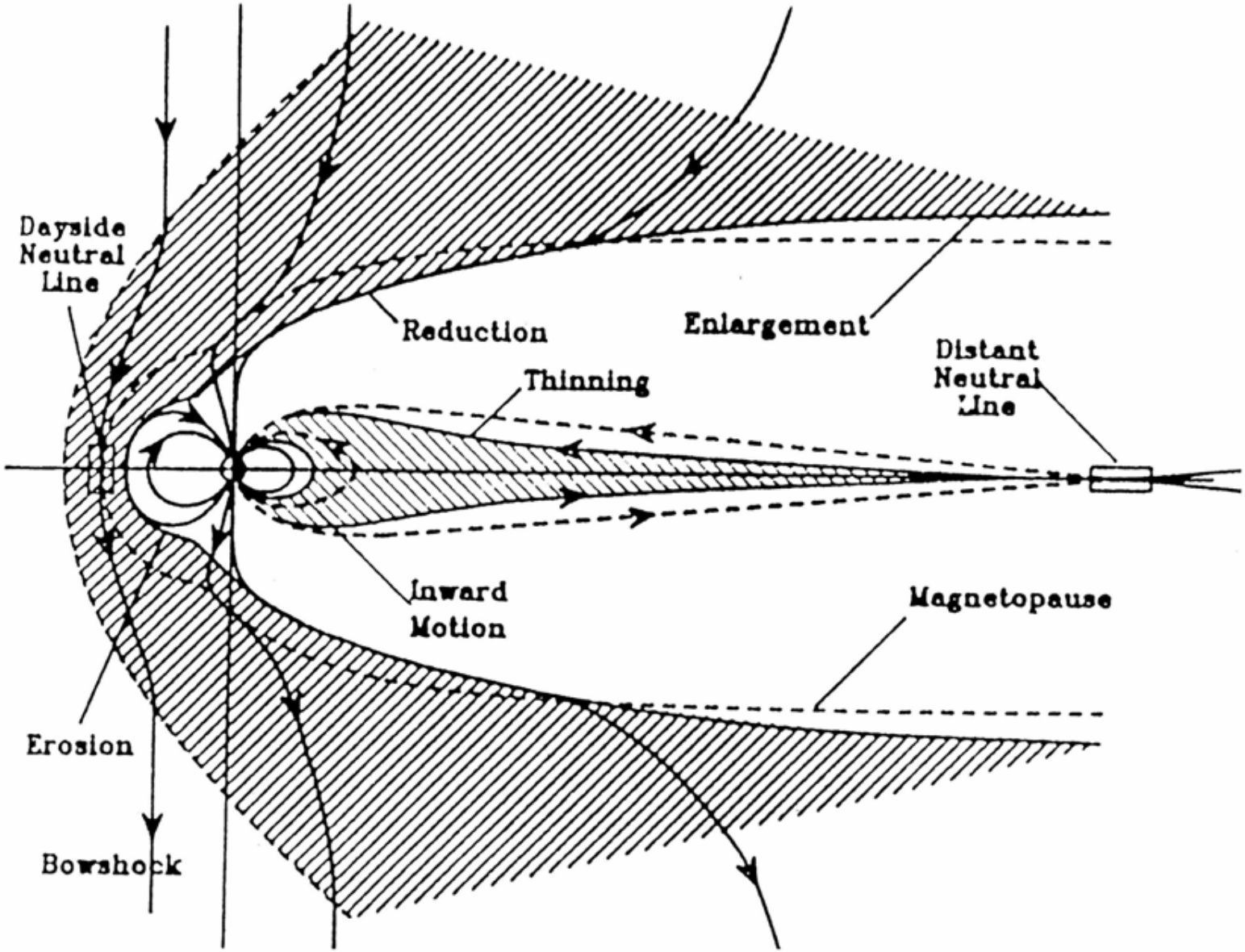
→ Magnetospheric Substorms

Substorm Phases 1

- Growth Phase (southward IMF, energy storage phase)
  - Enhanced dayside reconnection rate (> nightside reconnection rate at distant (~100 R_E) neutral line);
  - Net magnetic flux added to tail (and ∴ polar cap);
    - Tail thickens, lobe magnetic field strength increases;
    - Plasma sheet is compressed and thins;
    - Central cross tail current intensifies

    Duration ~ 1 hour

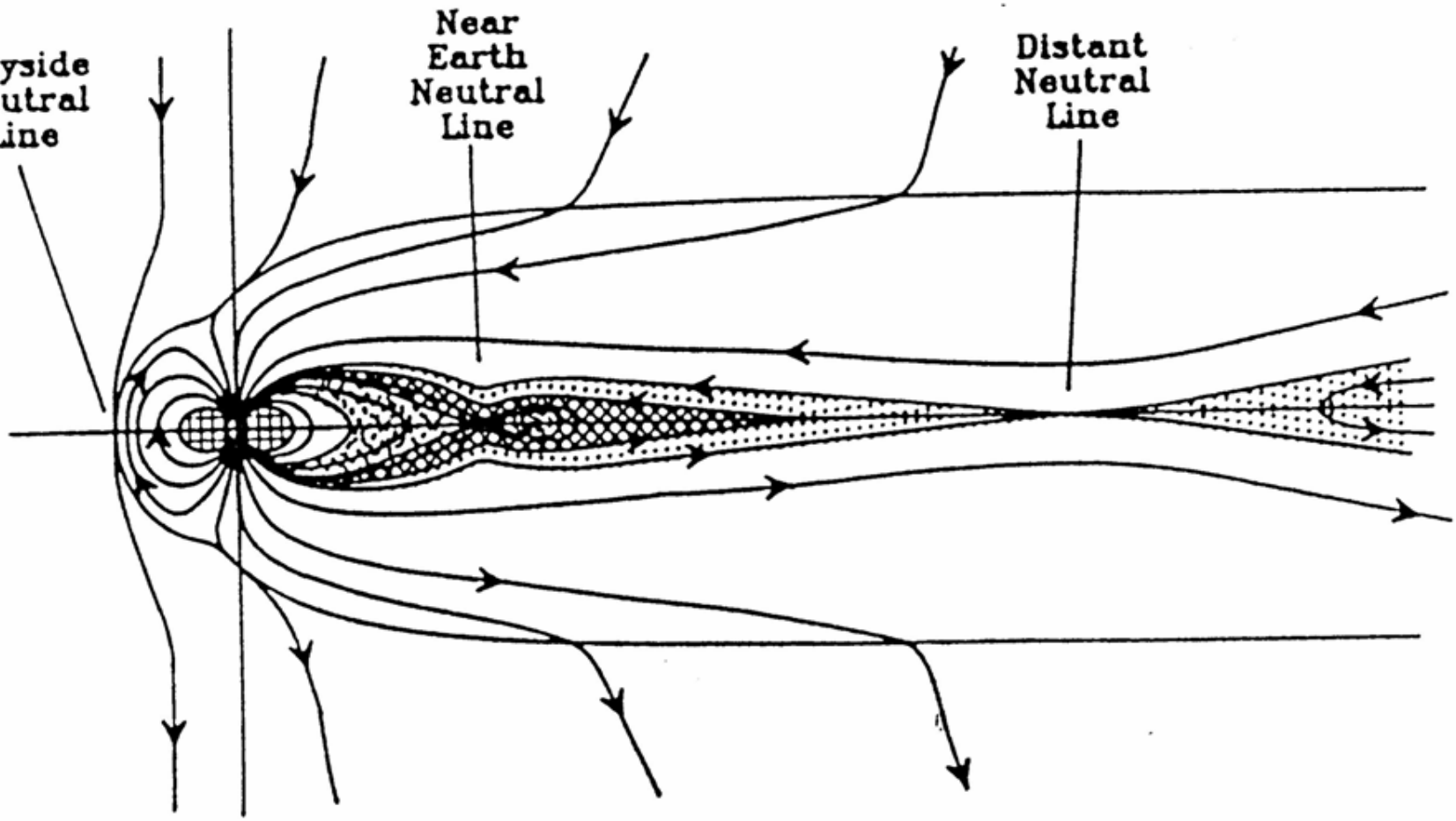
Substorm Growth Phase



Substorm Phases 2

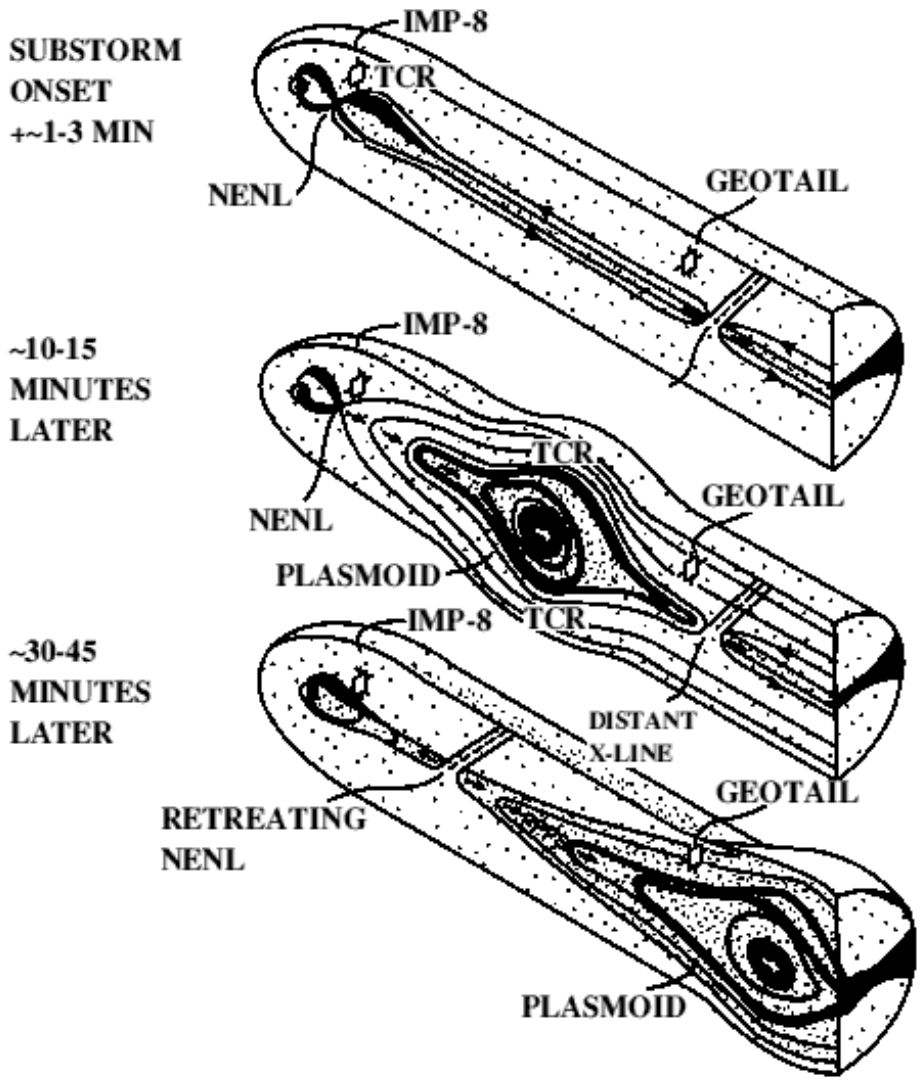
- Expansion Phase (explosive energy release phase)
  - Fast reconnection at new, near-Earth (~20-30 R_E) neutral line (NENL);
  - Stretched field lines are closed
    - Tail flux content reduced, lobe field strength decreases
    - Field lines become more dipolar
    - Substorm current wedge diverts cross-tail current through ionosphere
  - Magnetic energy converted to plasma kinetic energy;
    - Fast plasma flows away from NENL on both sides;
    - Particles injected into ring current region (violates 3rd adiabatic invariant)
  - Duration 30-60 minutes

Substorm Expansion Phase



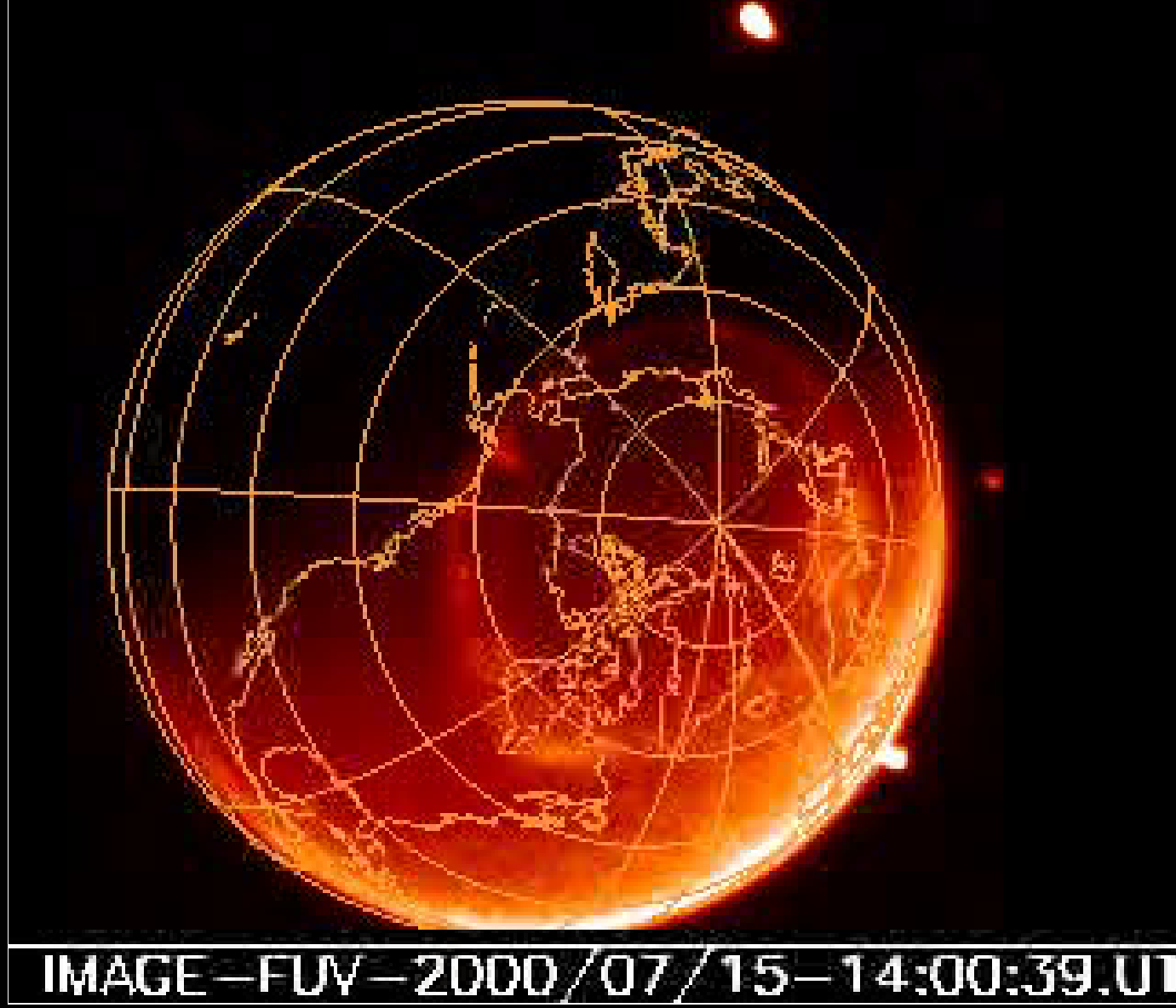
- <u>Expansion Phase</u> (explosive energy release phase) cont.
  - Between neutral lines, a closed loop of magnetic flux is created. This is called a *PLASMOID*.
    - Eventually disconnected from Earth and expelled tailward, removing flux and plasma (and therefore energy) from the tail.

Plasmoid Formation and Ejection



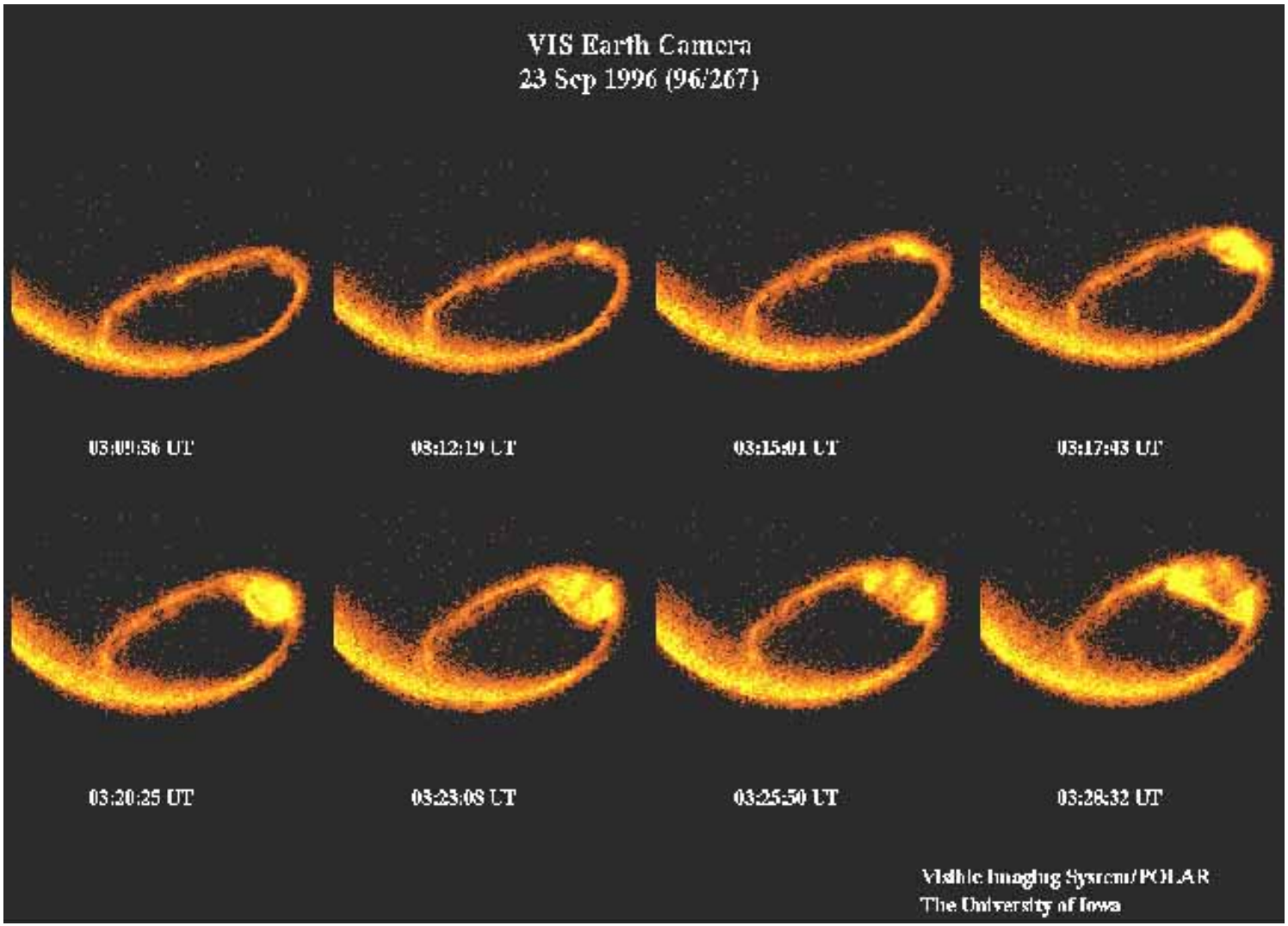
Expansion Phase (explosive energy release phase) cont.

Aurora from space movie:

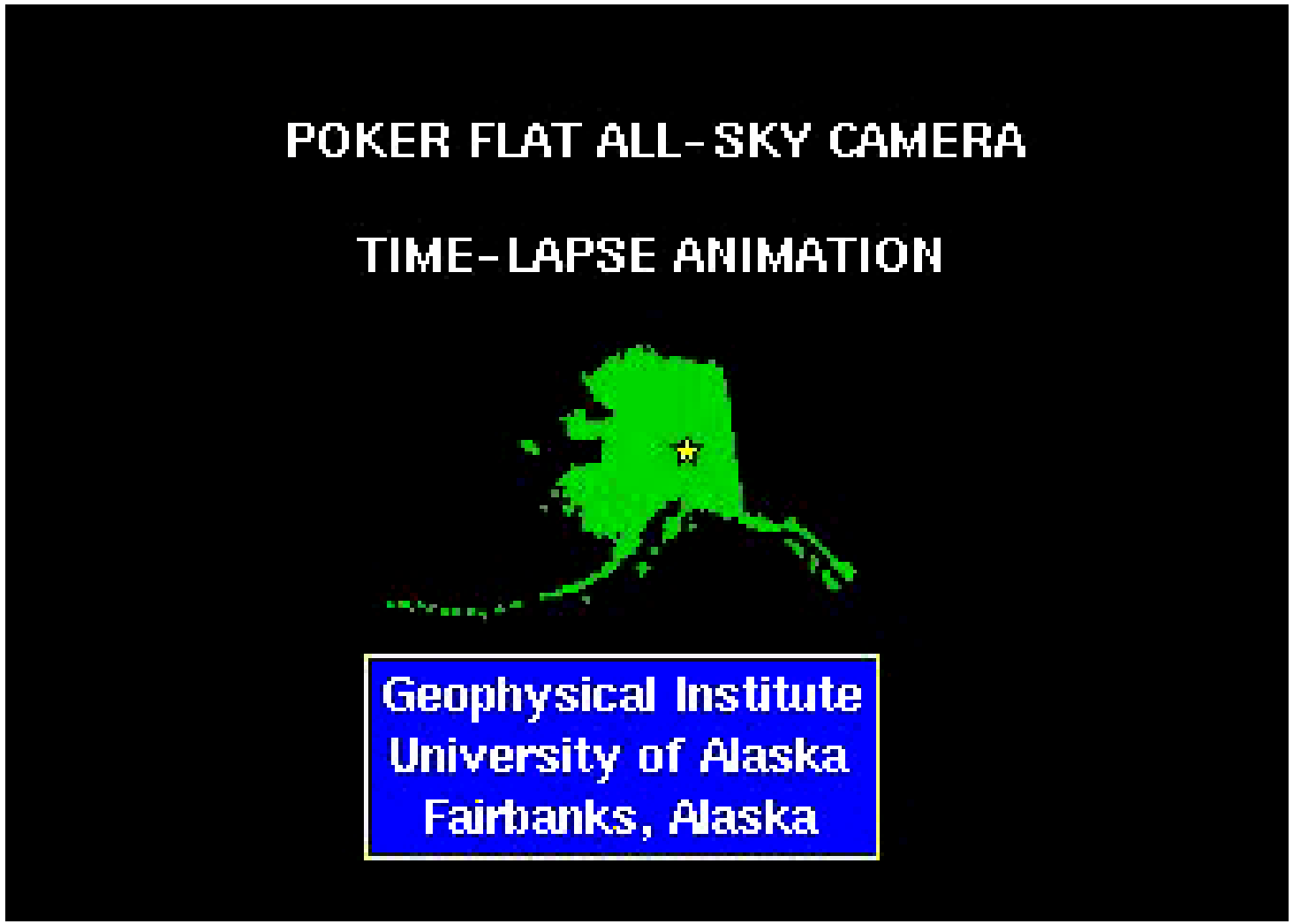


- Currents diverted into ionosphere (substorm electrojets – see later)
  - Causes Joule heating of the ionosphere – energy dumped into ionosphere
  - Associated with major auroral activity (aurorae brighten and expand poleward and westward)

Substorm Auroral Activity from Space

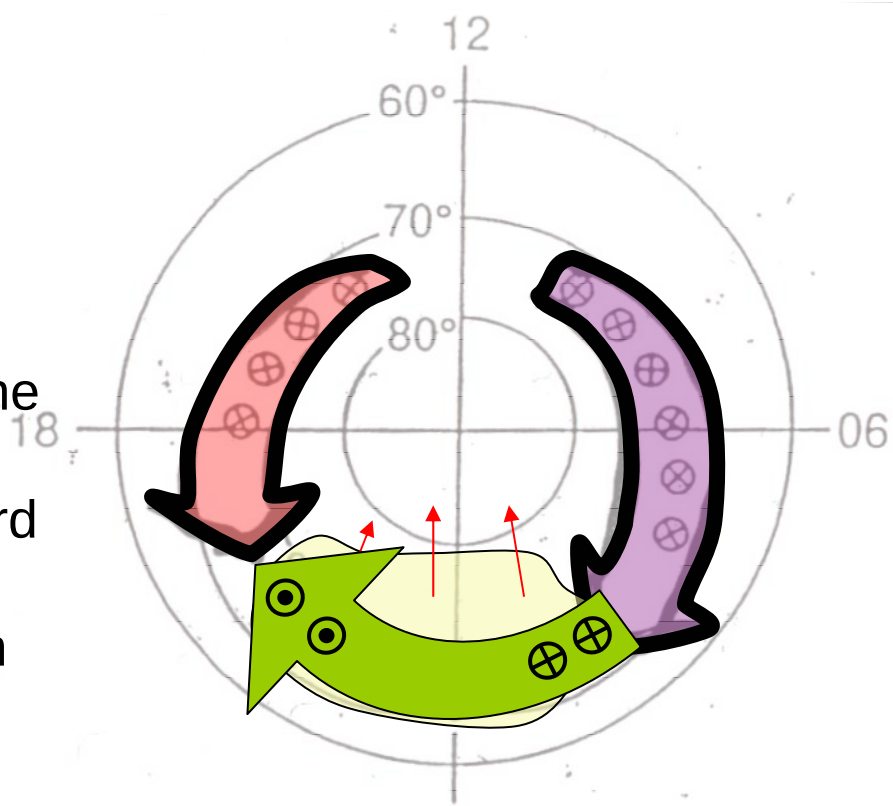


The Dynamic Aurora (Movie)



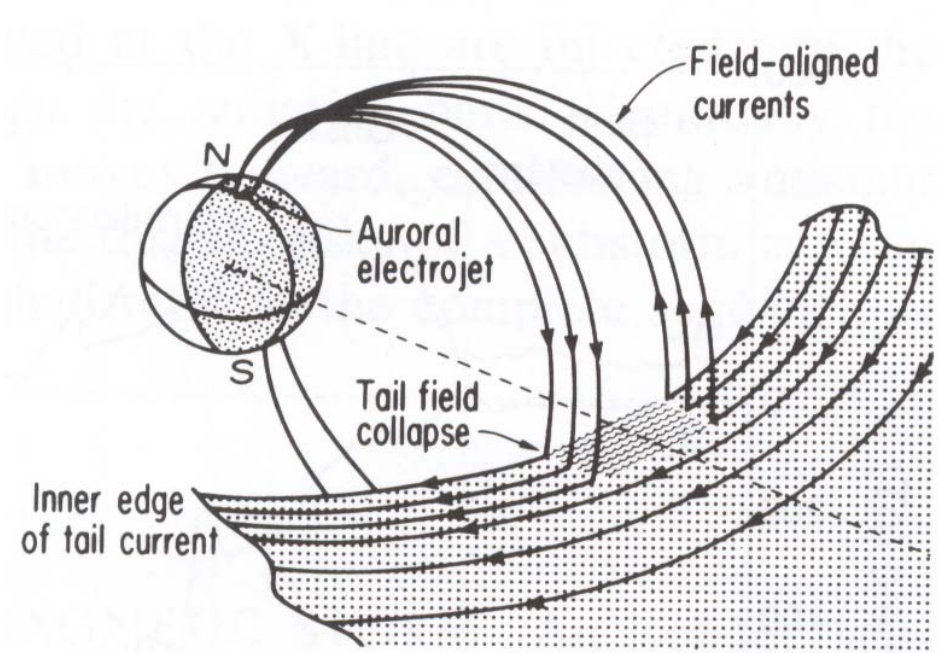
The Substorm Current Wedge

- During substorms, *all* convection-related currents (Region 1, 2, etc.) are enhanced.
- However, a new current system also appears – the 'substorm current wedge'
- In ionosphere - 'substorm electrojet':
  - Increased conductivity created by enhanced particle precipitation associated with the enhanced, expanding aurora;
  - A new current flows westward around midnight polar cap
  - Ionospheric part of substorm current wedge;



The Substorm Current Wedge (cont.)

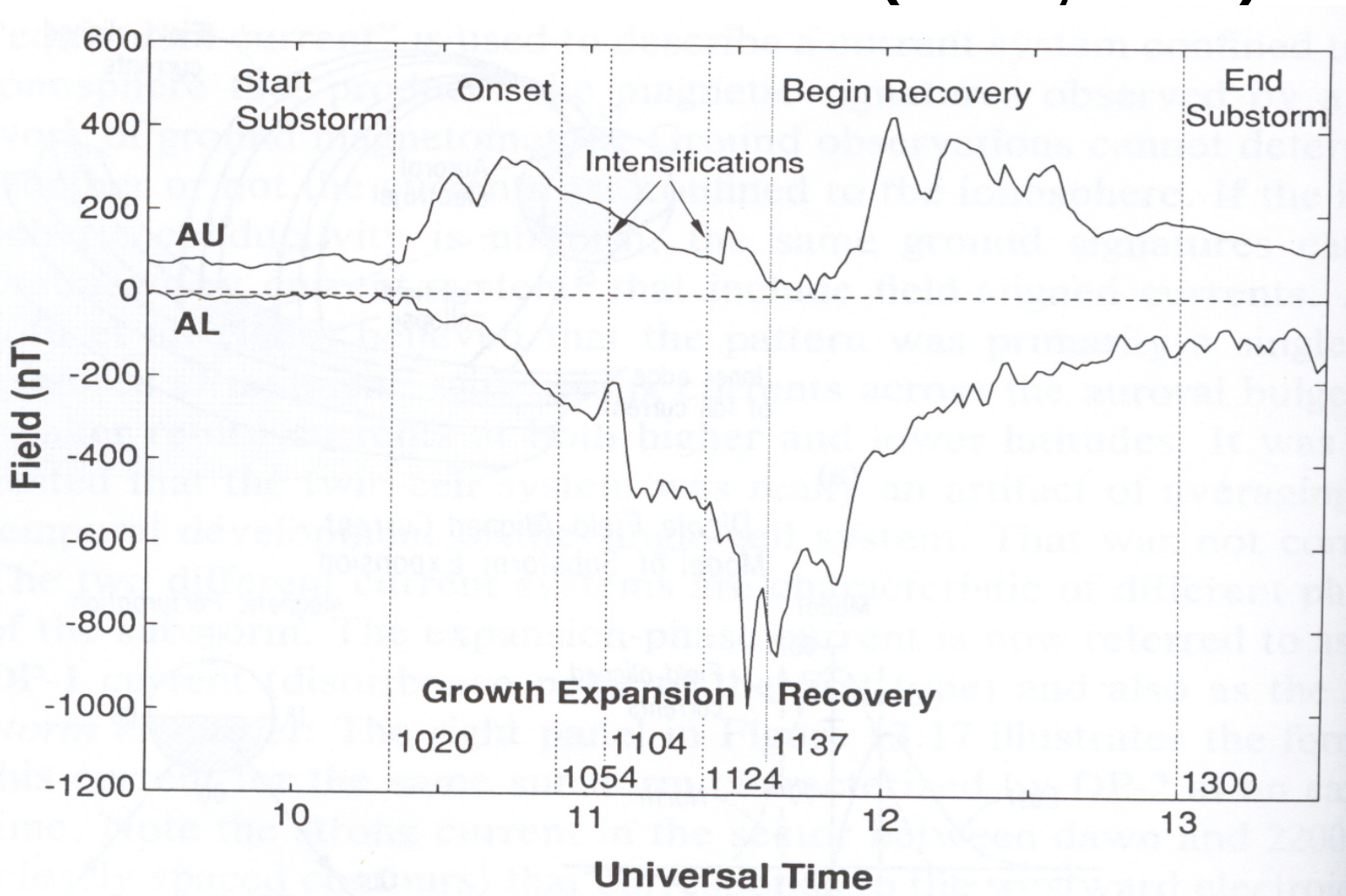
- Auroral electrojet is closed by field aligned currents connecting it to the cross tail current
  - FACs flow down field lines on post-midnight side of tail, back up on pre-midnight side
- Current flows across tail in opposite direction to cross tail current sheet
  - Cancels the cross tail current in tail centre;
  - 'current disruption' (reduction) allows field dipolarization (curl B = μ_o j)



N.B. Increase in auroral activity and poleward/ westward expansion corresponds to current disruption spreading tailward

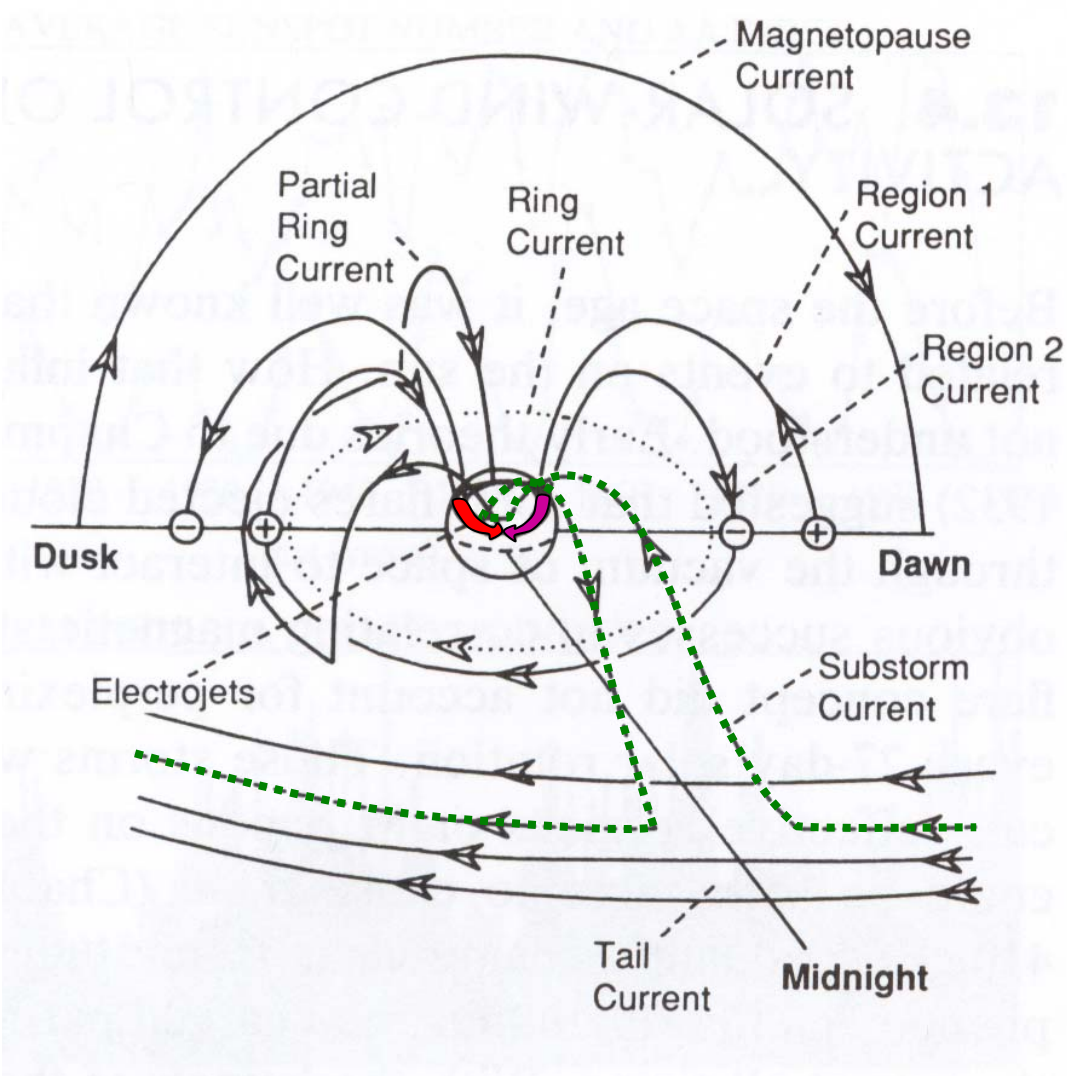
- Reconnection of field lines connected to higher latitudes

Auroral Indices (AU, AL)



- Magnetic deflections can be detected at auroral zone magnetometer stations – these provide a basis for ‘auroral activity indices’ which are used as a measure of the level of substorm activity.

Combined Current Systems



- Schematic illustration of the connections between various current systems we have discussed in the course:
  - Ring Current;
  - Magnetopause current;
  - Tail Current;
  - Region 1 FACs
  - Region 2 FACs
  - Hall currents (electrojets)
  - Pedersen Currents
  - Substorm Current Wedge
  - Substorm electrojet

Substorm Phases 3

- Recovery Phase (relaxation phase)
  - Decrease in reconnection rate at NENL neutral line);
  - NENL migrates tailward (becomes new distant NL).
  - Auroral currents and activity weaken.
  - Magnetosphere returns to quiet, relaxed state.

  - Cycle repeats on average 3-4 times per day (depending on SW conditions), typically storing and releasing ~10^{16} J energy per cycle.

- NB – substorm research is a very active and hotly debated area – not everyone accepts the physical explanation we have discussed here!

Growth Phase		
Ground/Ionosphere	Geosynchronous	Magnetotail
• Dawn-dusk E-field in polar cap intensifies; • Polar cap expands equatorward; • Fading auroral features.	• B-field becomes more tail-like (stretched).	• Magnetopause flaring increases; • Lobe magnetic flux content increases; • Plasma sheet thins; • Tail current sheet intensifies; • Slow (if any) reconnection of closed flux at Near-Earth Neutral Line (NENL).
Expansion Phase		
Ground/Ionosphere	Geosynchronous	Magnetotail
• Equatorward auroral arc brightens; • W. (substorm) electrojet intensifies; • High latitude -ve bays/Mid-latitude +ve bays; • Magnetic pulsations (Pi2's); • Poleward expansion of pre-midnight auroral surge.	• Energetic particle injections; • B-field rapidly dipolarizes; • Substorm current wedge expands.	• Fast reconnection of open flux at NENL; • Lobe magnetic flux content decreases; • Field-aligned currents and auroral kilometric radiation (AKR) intensify; • Plasmoid pinched off and ejected downtail; • Travelling compressions of lobes associated with plasmoid release.
Recovery Phase		
Ground/Ionosphere	Geosynchronous	Magnetotail
• Auroral bulge fades and contracts.	• Current wedge weakens.	• NENL retreats downtail. • Plasma sheet thickens. • Tail currents and fields 'relax'.

Summary table of substorm effects in different regions of the magnetosphere during the 3 different phases

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Section 11- The Non-Steady State Magnetosphere

11.5 Magnetic Storms

We have seen that magnetic substorms have timescales of a few hours, and are driven by fluctuations in the IMF over those timescales. Prolonged periods of southward IMF and/or fast solar wind flows lead to major magnetic storms. These are often associated, for example, with the passage of a coronal mass ejection (CME) past the Earth – these take several days to pass by, during which time the solar wind flow speed is often relatively high. In addition, CMEs are often associated with magnetic clouds, or loops, which result in prolonged periods (~days) of southward then northward (or vice versa) IMF. Magnetic storms again have several characteristic phases:

Sudden Impulse/Storm Sudden Commencement

Storms associated with CMEs usually display SIs or SSCs. The arrival of a CME is associated with a sudden increase of the solar wind dynamic pressure, which acts to suddenly compress the entire magnetosphere. This results in a sudden impulse (SI) or increase in the magnetic field strength within the magnetosphere or as measured on the ground. This non-adiabatic compression of the field also appears allow the rapid escape of ring current particles. Since the presence of these particles acts to reduce the equatorial ground field strength, their loss also increases the surface field. The term sudden storm commencement (SSC) thus refers to a sudden increase of the field strength measured on the ground which occurs before the major decrease observed during the …….

Storm Main Phase

The prolonged southward IMF and fast SW flows act to transfer large amounts of energy into the magnetosphere. At least part of this energy (released perhaps during many rapidly recurring substorms and/or lots of particle injections) appears as an enhanced radiation belt/ring current particle population. The increase in ring current is observed on the ground as a reduction in the equatorial surface field strength which may persist for several days.

Decay/Recovery Phase

This begins once the IMF turns northward again, or the dynamic pressure of the SW reduces to more normal values. The enhanced ring current population slowly declines as particles are lost, either into the ionosphere following scattering into the loss-cone, or by charge exchange with the cold plasmasphere plasma. Thus the ring current declines such that the equatorial surface field strength returns to it normal, non-storm level. Again this phase can last ~days.

N.B.1 The equatorial magnetic field disturbance is routinely recorded at stations around the world and used as a measure of magnetic storm activity – this is known as the *Dst index*.

N.B.2 The radiation belt populations of relativistic electrons are significantly enhanced during the magnetic storm. The reason for this is not fully understood, and is a hot topic for research – particularly as these particles, often referred to as '*killer electrons*' are the ones that do most damage to satellites and their systems in orbit. A relatively new field which aims to understand how and when these phenomena occur and attempts to predict them (so that spacecraft can be put into 'safe modes') is known as '*Space Weather*'.

Magnetic Storms – Dst Index

- Depression of the equatorial surface magnetic field during a major magnetic storm: