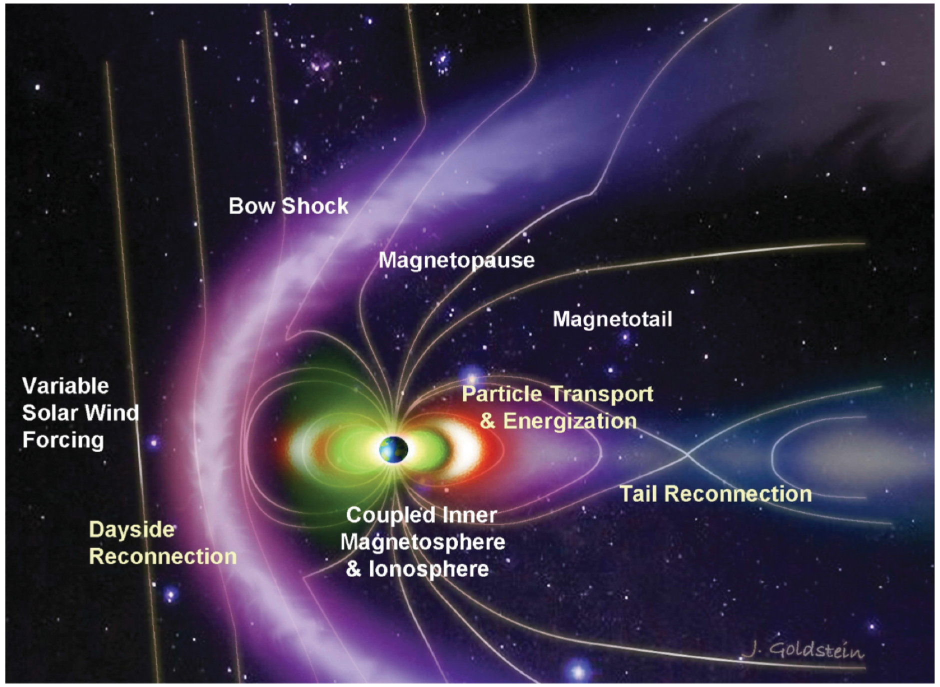
Introduction

Geomagnetic Storms: Classical Views & Developing Views

Delores Knipp

NASA Heliophysics Summer School 2020



Courtesy SWRI and J. Goldstein

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Smead Aerospace
UNIVERSITY OF COLORADO BOULDER
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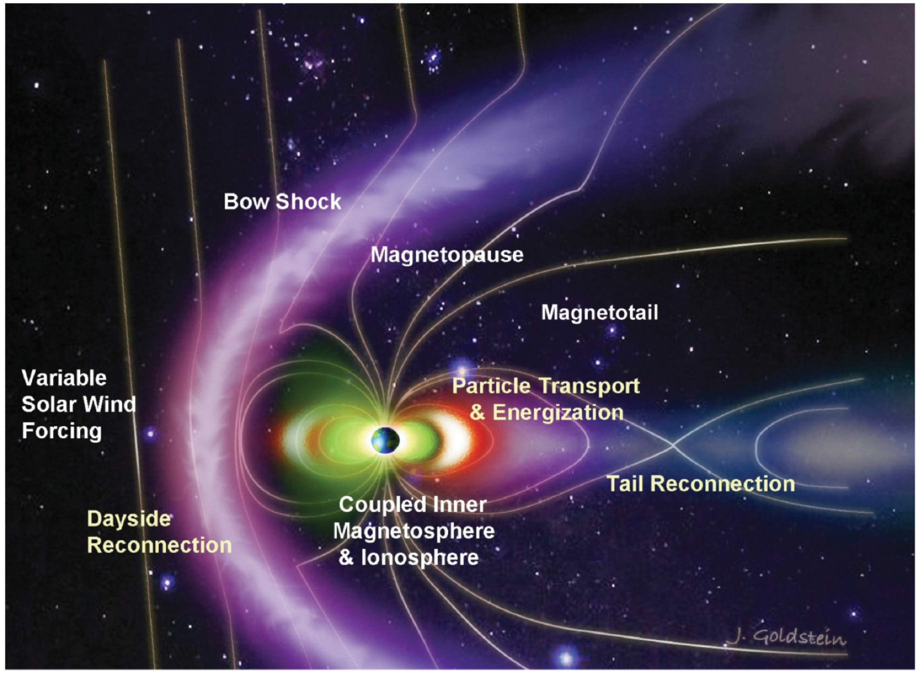
Introduction

Outline

- Definitions, Relations, Motivation
  - Places and Space (overview)
  - Physical Effects
  - Indices and Categories



- Geomagnetic Storms
  - Topology,
  - ‘Drivers’
  - Processes

- Historical Event--Variations on the Theme

Definitions, Relations, Motivations

Definition: **A geomagnetic storm is a multi-hour/day disturbance in the magnetized volume surrounding Earth due to enhanced dissipation of solar wind energy via strong magnetospheric convection and bursty flows**

Related to:

Heliospheric Disturbances	Geospheric Storms
Episodic restructuring of the solar magnetic field -Interplanetary Coronal Mass Ejecta (ICME) Shock-Sheath and/or 'Magnetic Cloud' Large-scale solar wind structures passing Earth -Coronal holes	Enhanced magnetic activity & particles -**Geomagnetic (space) storms** - (Auroral) Substorms -Ionospheric storms -Thermospheric storms

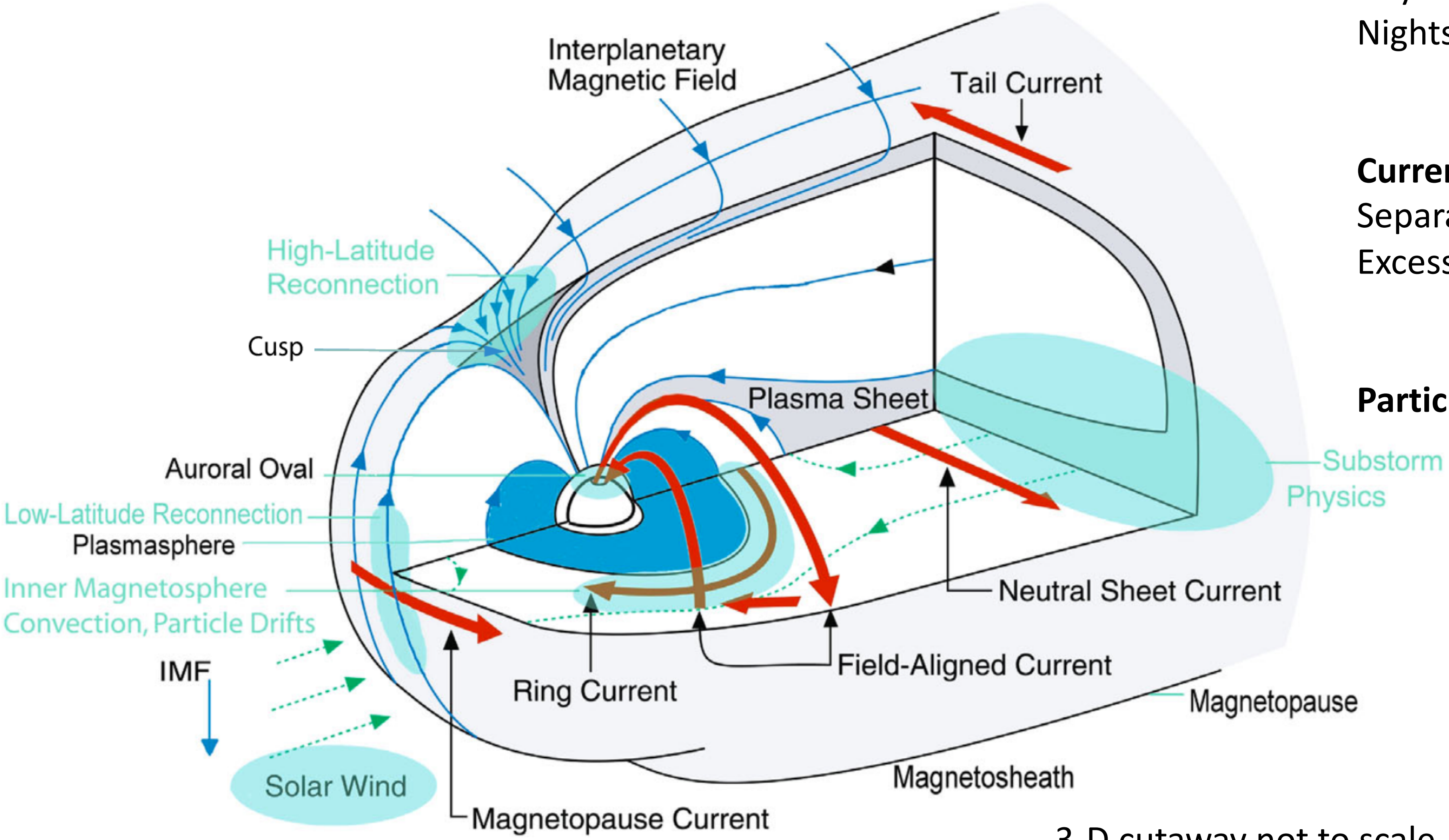
Inspired by G. Prölss, 2003

Motivations:

Understand space weather impacts on humans and engineered systems

Study system science of geospace disturbances and their 'drivers'

Place and Spaces Overview



3-D cutaway not to scale

Reconnection Processes
Dayside
Nightside

Currents
Separate magnetic domains
Excess charged particle pressure

Particle populations
Cold
Warm
Hot
Relativistic

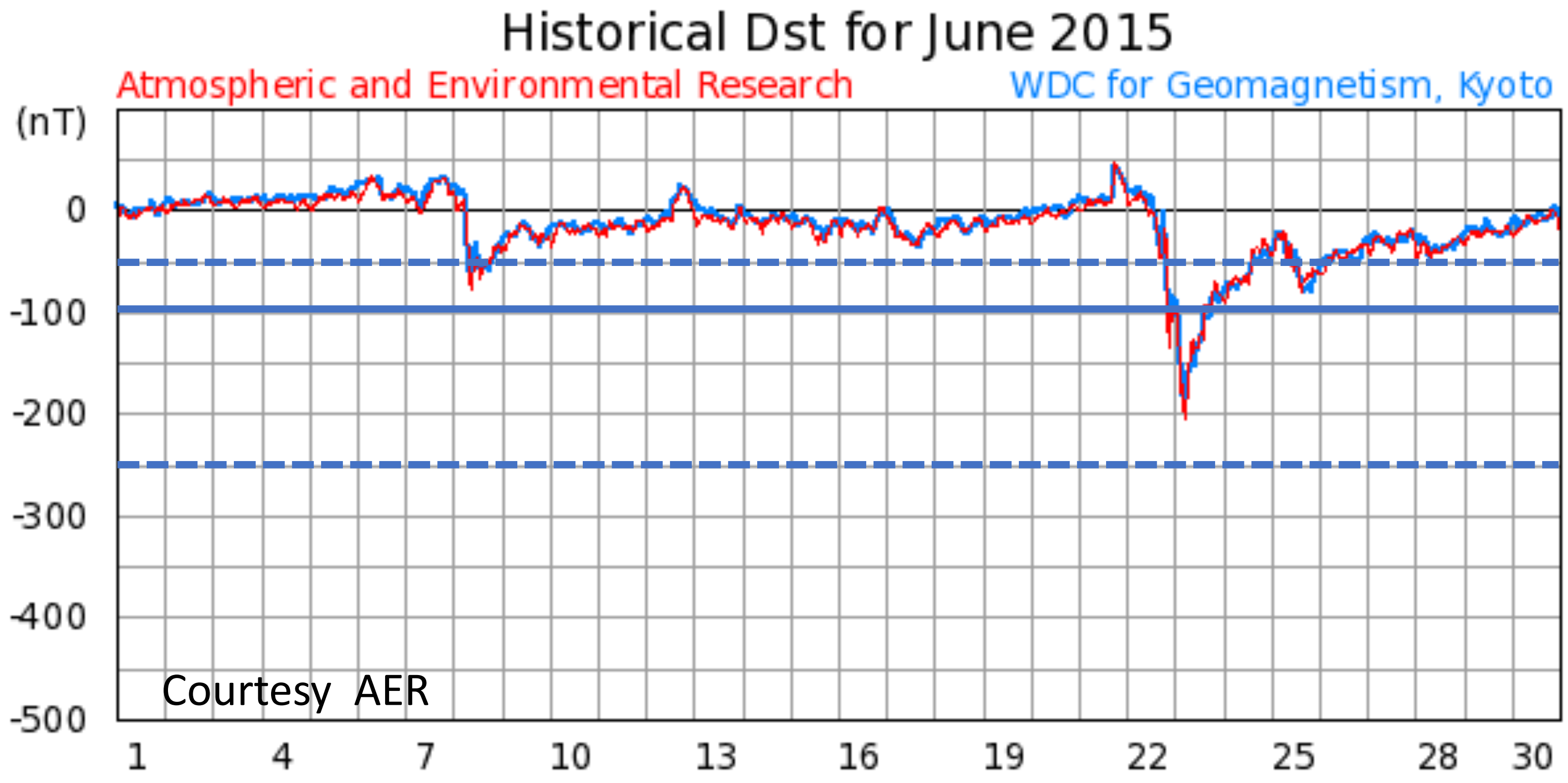
Physical Effects of Geomagnetic Storms

Global in Nature:

- Magnetic disturbances measured on the Earth's surface (and in space),
  - Ground disturbance was original defining storm feature [*von Humboldt* , 1808].
  - Allows for thresholding by measurements/indices
- Acceleration of charged particles in geospace,
  - Radiation belts;
  - Plasmasheet leading to enhanced Ring Current
  - Ring Current reduction of Earth's surface field at mid and low latitude
  - Ionospheric outflow to plasmasheet
- Impressive aurora displays, often at sub-auroral latitudes
- Intensification of electric currents in space and on the ground,
- Reshaping of the plasmasphere
- Strong wave-particle interactions
- Enhanced coupling to Earth's ionosphere and thermosphere (I-T)
- Feedback between most elements of the system

In part from Daglis et al. 2003, doi:10.1029/2002JA009722

Magnetic disturbances measured on the Earth's surface and in space



Surface magnetic field depression due to a band of ions, at a distance of 3 - 8 R_E that circulate around the Earth as part of the Ring Current. Most of the energy is carried by 10-200 keV ions, although electrons circulating the opposite direction may contribute. Other current systems may contribute to the Dst Index

Reduction of the Earth’s low-latitude surface magnetic field measured as the Disturbance storm time (Dst) Index in units of nT for two geomagnetic storms in June 2015.

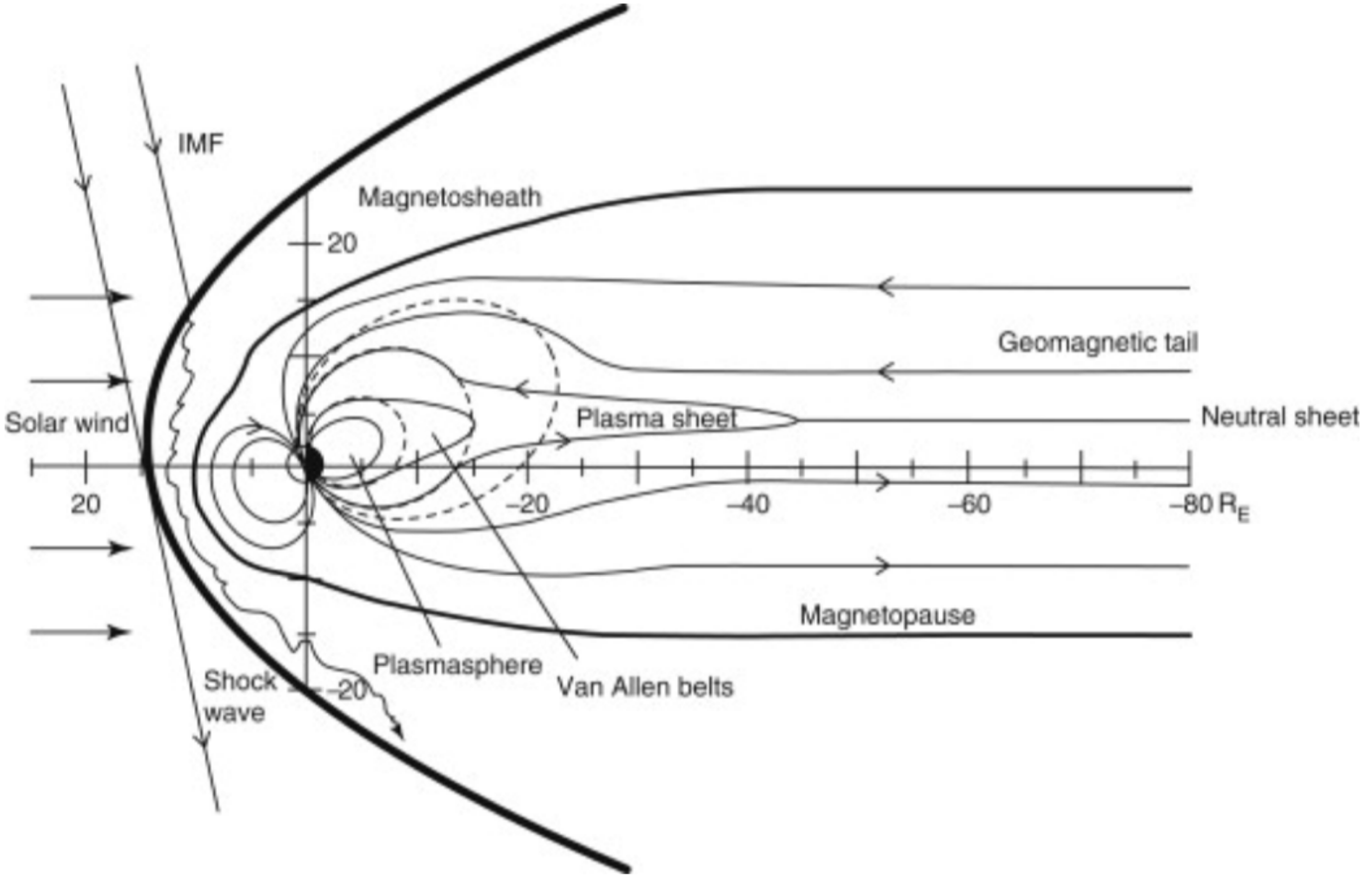
Blue --hourly index from Kyoto World Data Center

Red -- similar index derived from low earth orbiting (LEO) spacecraft

Initial Phase = + Enhancement
Main Phase = Sharp decrease
Recovery Phase = Long return to baseline value

Basics of Magnetosphere Topology & Particle Populations

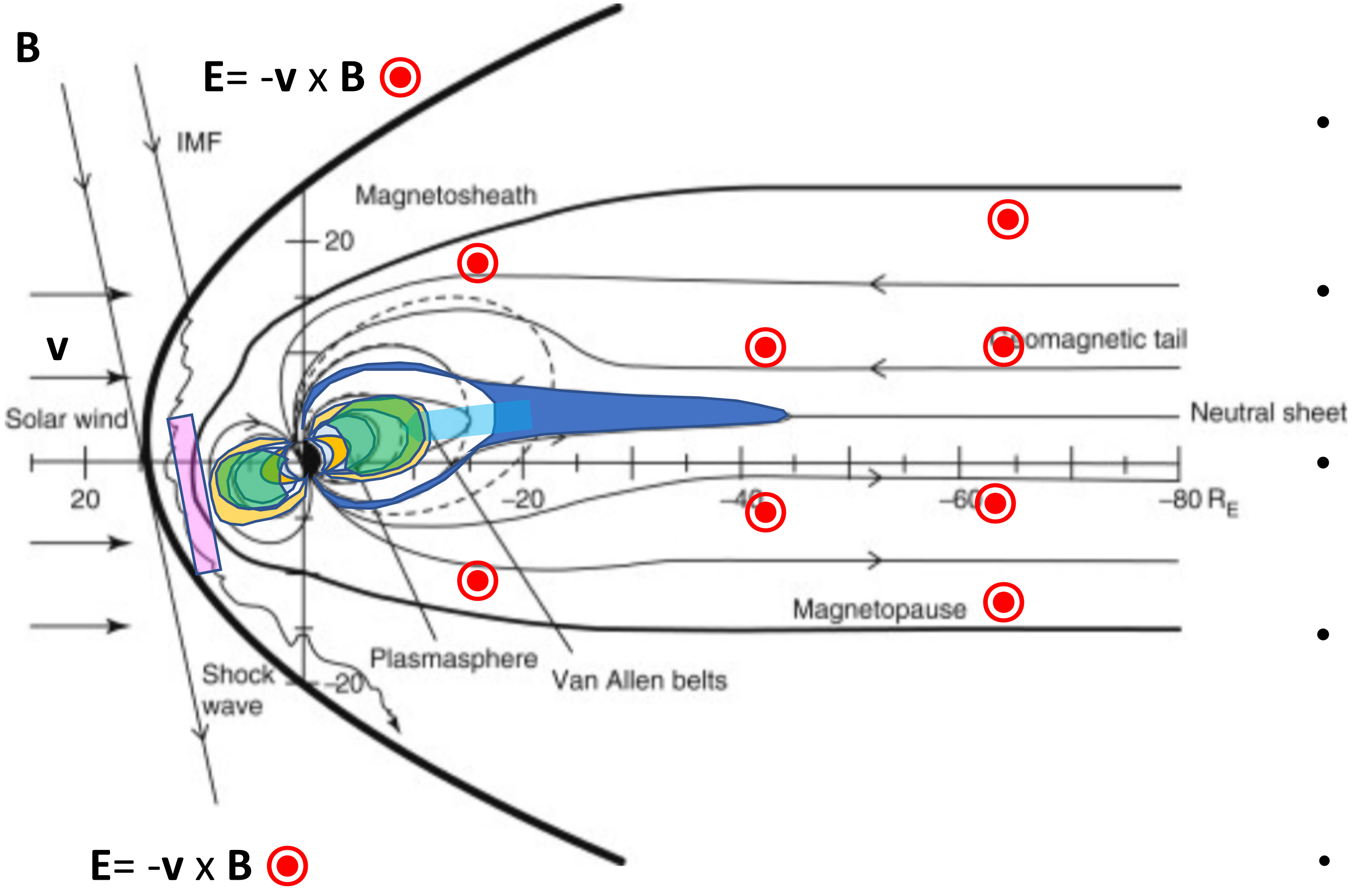
Region of geospace dominated by
Earth's magnetic field



2-D Schematic, ~scaled
Noon-Midnight Meridian
Parks (2015)

- Magnetic cell that
  - Mostly excludes the solar wind plasma
  - Surrounded by sheath of 'shocked' solar wind
  - Bowshock slows the incoming flow to subsonic
    - Heats and randomized solar wind plasma
  - Compressed on dayside, with extended tail
    - Deformed dipole field within about 6-10 R_E
    - Tail stretches several hundred R_E anti-sunward
  - Bounded by a 3-D current sheet
    - Dynamic (and not shown in this schematic)
  - If magnetic flux in solar wind is completely 'frozen-in', then no mixing of solar wind and geomagnetic field
    - System is closed
  - Otherwise: Reconnection
    - System is open

Topology:
Southward Interplanetary Magnetic Field (IMF)

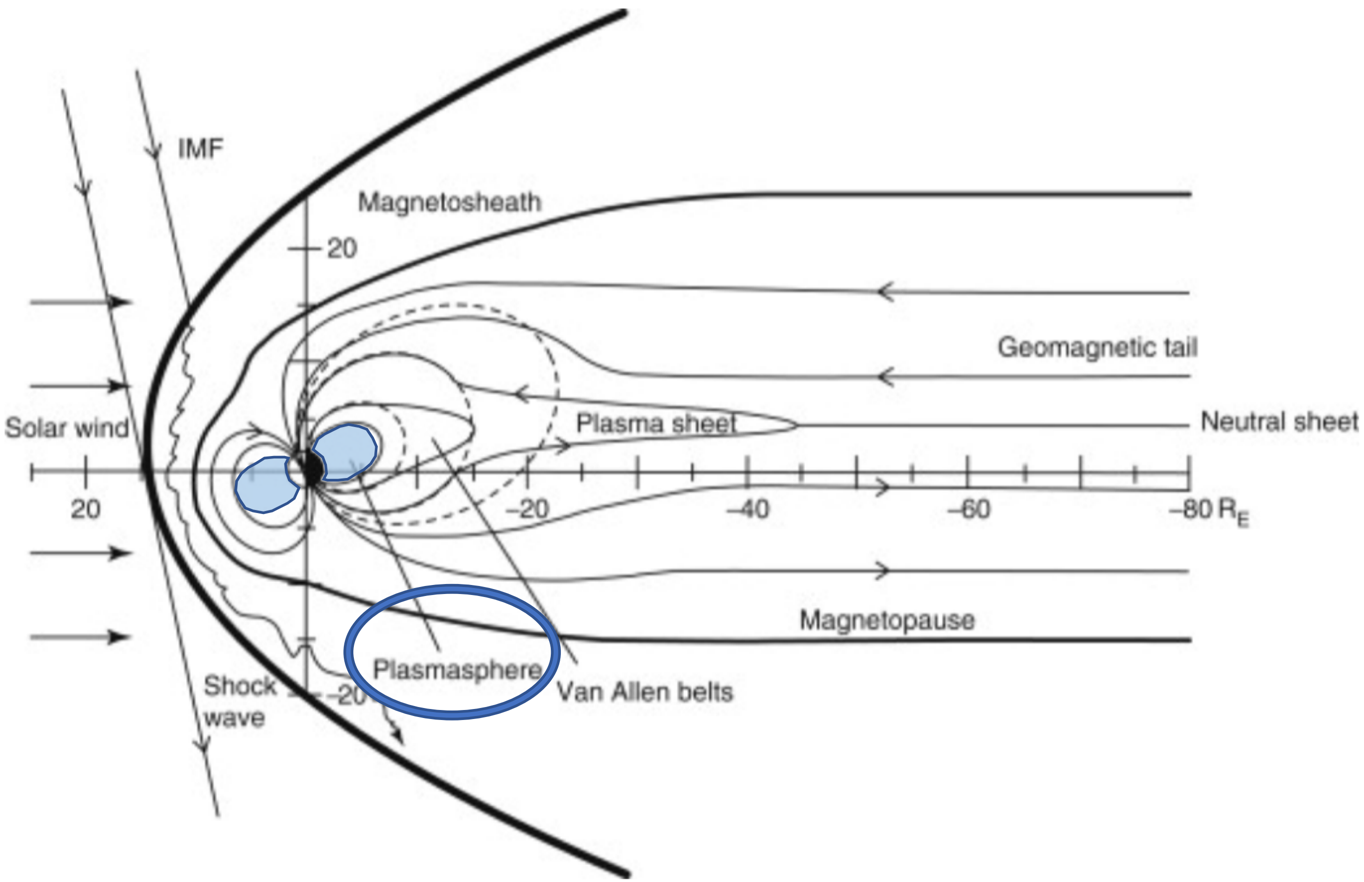


2-D Schematic, ~scaled
Noon-Midnight Meridian

- Dayside **magnetic merging** opens Earth's geomagnetic field
- The **convection electric field** (**E**) is enhanced by southward IMF and fast solar wind.
- Some particles can be captured from the solar wind (10%)
- Particle populations strongly influenced by solar wind energy deposition
- Plasma motion subject to convection electric field(s)
  - Drift
  - Organize into currents

Basics of Magnetosphere Topology & Particle Populations

Region of geospace hosting charged particles



2-D Schematic, ~scaled
Noon-Midnight Meridian

– Magnetic cell that
  - Contains particles from different sources
    - Solar wind, the ionosphere and cosmic rays via the atmosphere

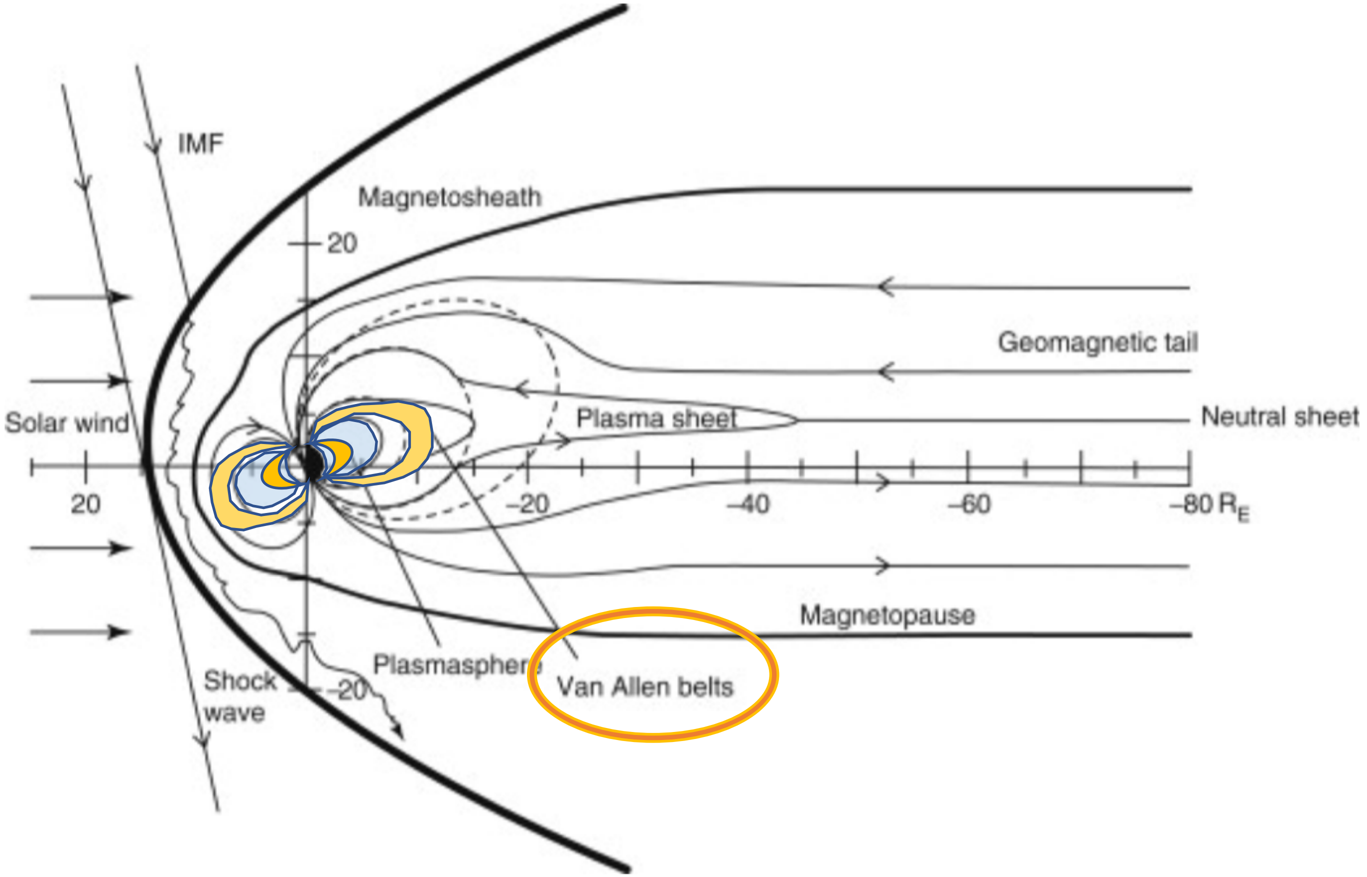
– Particle populations organized by energy & location
  - Subject to significant storm-time variations

- **Plasmasphere, cold,**
  - Corotating plasma from the ionosphere

Topology

Basics of Magnetosphere Topology & Particle Populations

Region of geospace hosting charged particles



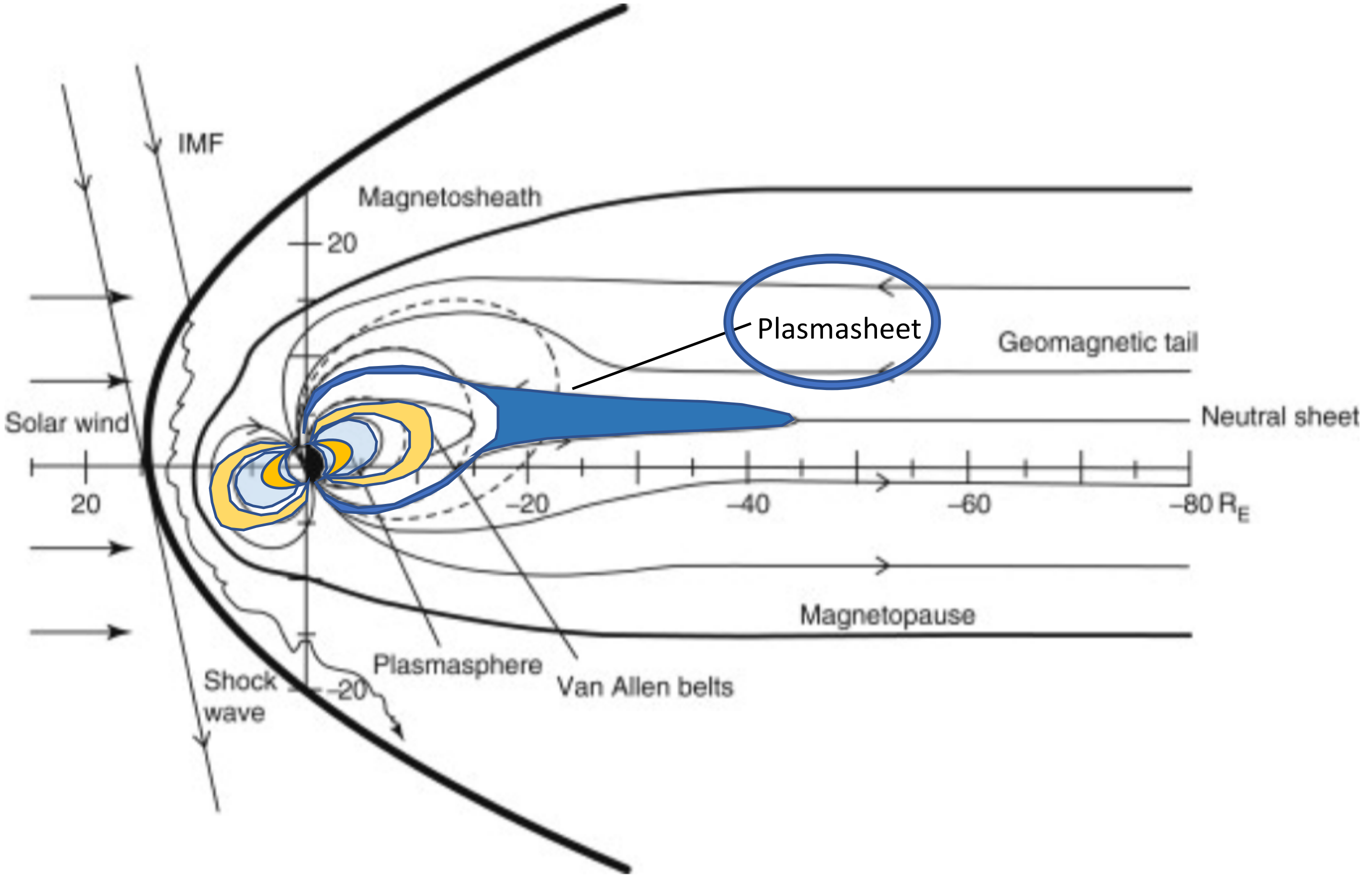
2-D Schematic, ~scaled
Noon-Midnight Meridian

- Magnetic cell that
  - Contains particles from different sources
    - Solar wind, the ionosphere and cosmic rays via the atmosphere

- Particle populations organized by energy & location
  - Subject to significant storm-time variations
- Plasmasphere, cold,
  - Corotating plasma from the ionosphere
- **Radiation belts, hot**
  - Outer Belt energy density in high energy electrons
  - Inner Belt energy density in high energy ions
    - Some contribution by high energy electrons

Basics of Magnetosphere Topology & Particle Populations

Region of geospace hosting charged particles



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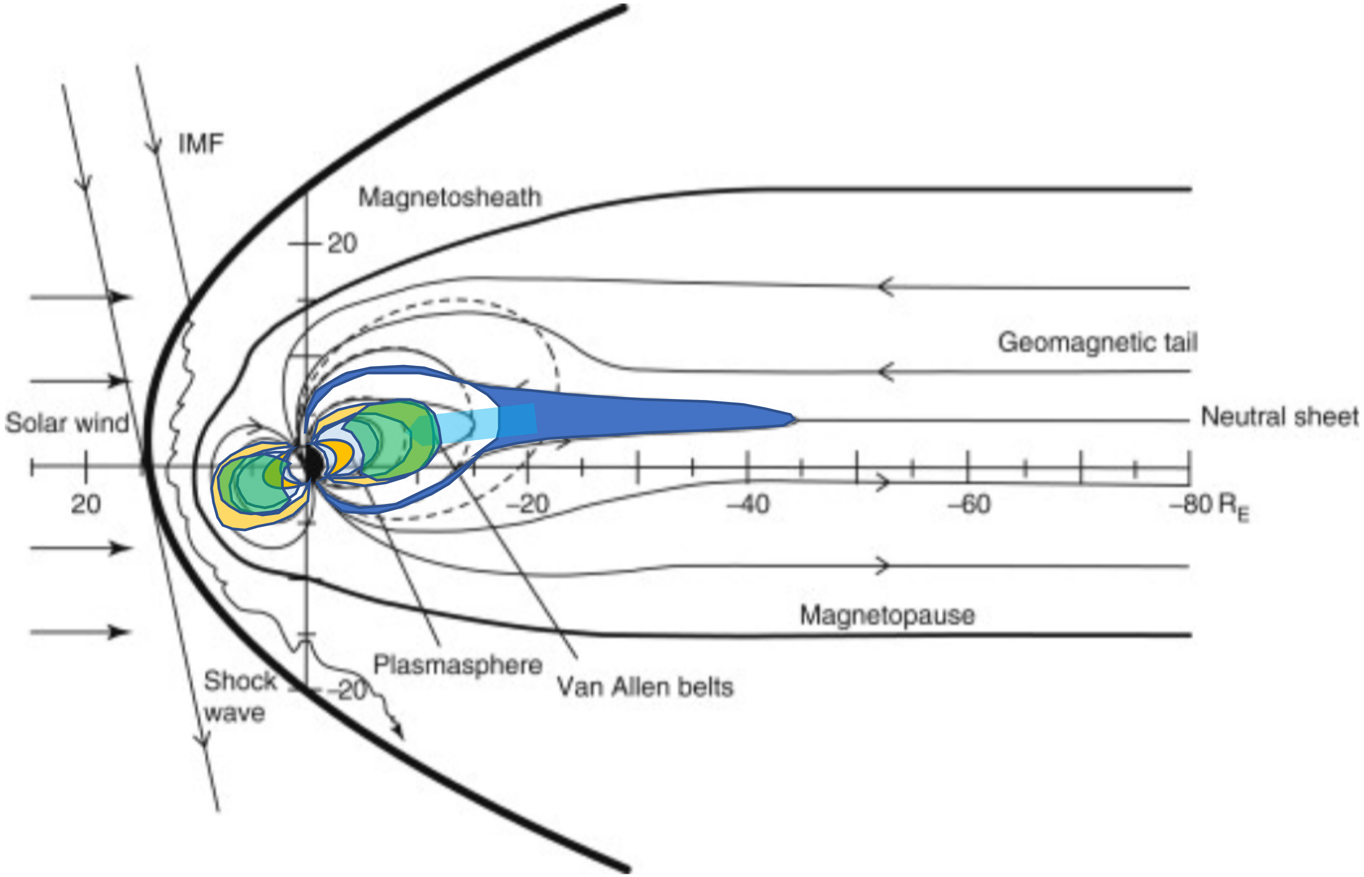
Noon-Midnight Meridian

– Magnetic cell that
- Contains particles from different sources
  - Solar wind, the ionosphere and cosmic rays via the atmosphere

– Particle populations organized by energy & location
  - Subject to significant storm-time variations
- Plasmasphere, cold,
  - Corotating plasma from the ionosphere
- Radiation belts, hot
  - Outer Belt energy density in high energy electrons
  - Inner Belt energy density in high energy ions
    - Some contribution by high energy electrons
- **Plasmasheet, medium**
  - Replenished by the solar wind
  - Storm time contribution by the ionosphere
  - Feeds aurora, radiation belts and ring current

Basics of Magnetosphere Topology & Particle Populations

Region of geospace hosting charged particles

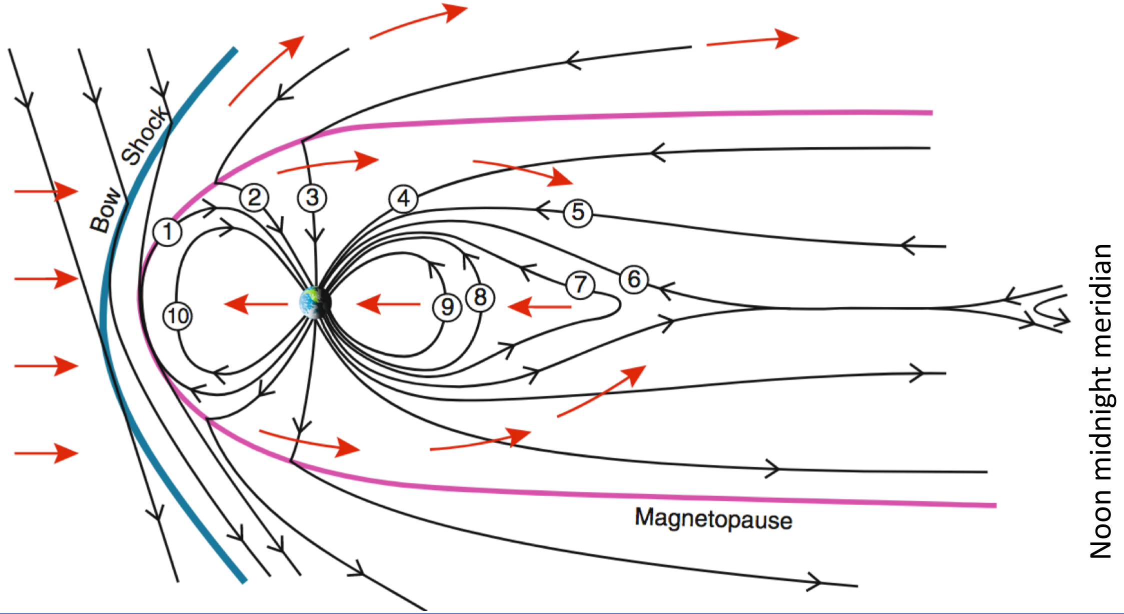


2-D Schematic, ~scaled
Noon-Midnight Meridian

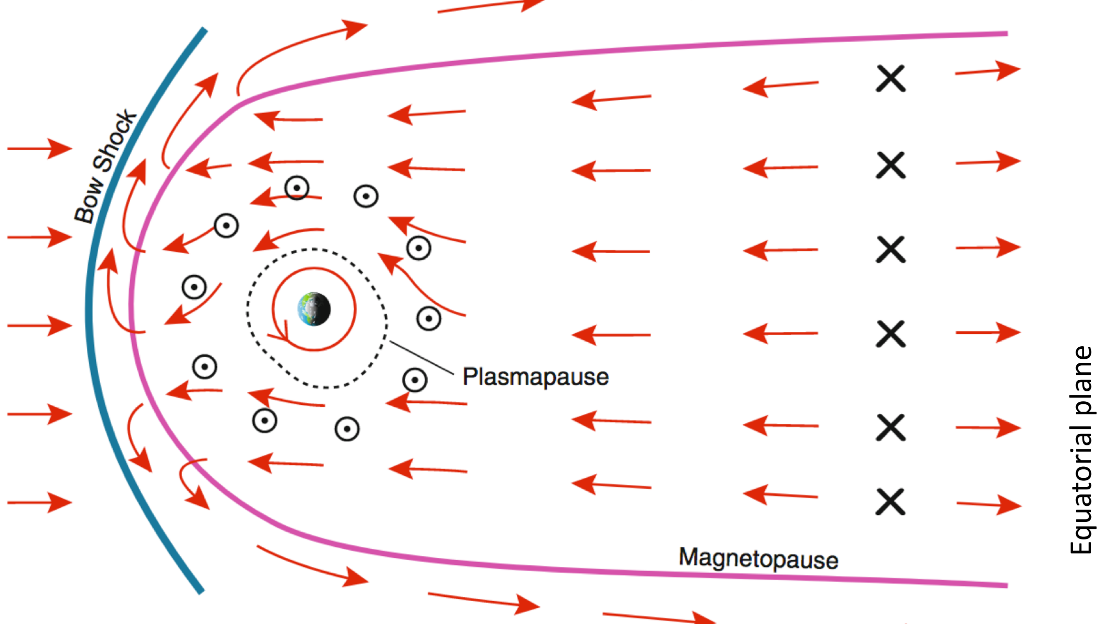
- Magnetic cell that
  - Contains particles from different sources
    - Solar wind, the ionosphere and cosmic rays via the atmosphere

- Particle populations organized by energy & location
  - Subject to significant storm-time variations
- Plasmasphere, cold, and dense
  - Corotating plasma from the ionosphere
- Radiation belts, hot and tenuous
  - Outer Belt energy density in high energy electrons
  - Inner Belt energy density in high energy ions
    - Some contribution by high energy electrons
- Plasmasheet, warm and variable
  - Replenished by the solar wind
  - Storm time contribution by the ionosphere
  - Feeds aurora, radiation belts and ring current
- **Ring Current, cool-medium and highly variable**
  - Contributes to magnetic field variation at Earth

(Sub)Storm Reconnection-Driven Magnetospheric Dynamics



Courtesy of F. Bagenal, LASP



- ‘Dungey substorm cycle’
  - Merging allows solar wind **E** penetration
- The numbers show the time sequence for a flux tube being reconnected at the dayside magnetopause and linking through the magnetosphere.
- $\mathbf{E} = -\mathbf{v}_{sw} \times \mathbf{B}_{sw}$ is the dawn-to-dusk direction
- The direction of the equatorial-magnetosphere particle drift is earthward
  - Streamlines are for ‘cool’ plasma
- Dungey cycle is rarely steady-state
  - Characterized by magnetotail instability
  - Some particles /channels gain excess energy
- **Substorm and Storm and dynamics**

Sub-Storm Cycle Including Plasmoids And Aurora

- Far ends of the same magnetic instability
- Several recurrences in a geomagnetic storm

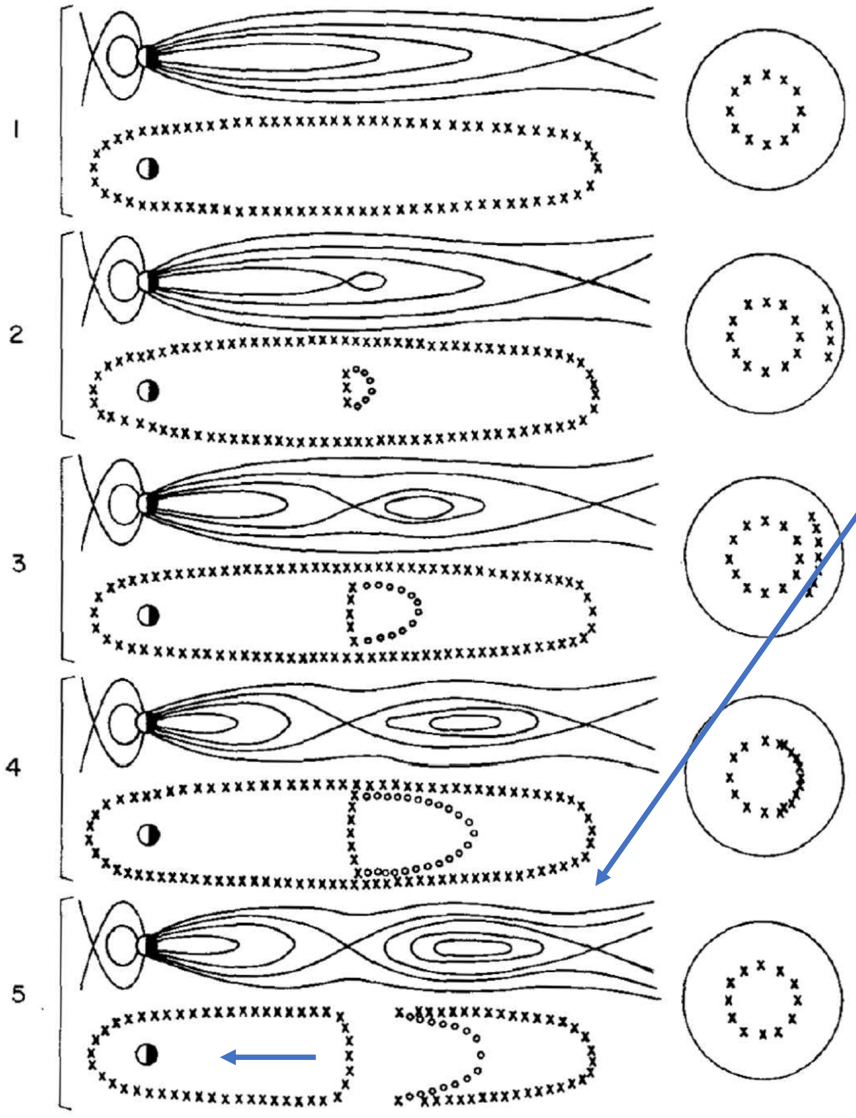
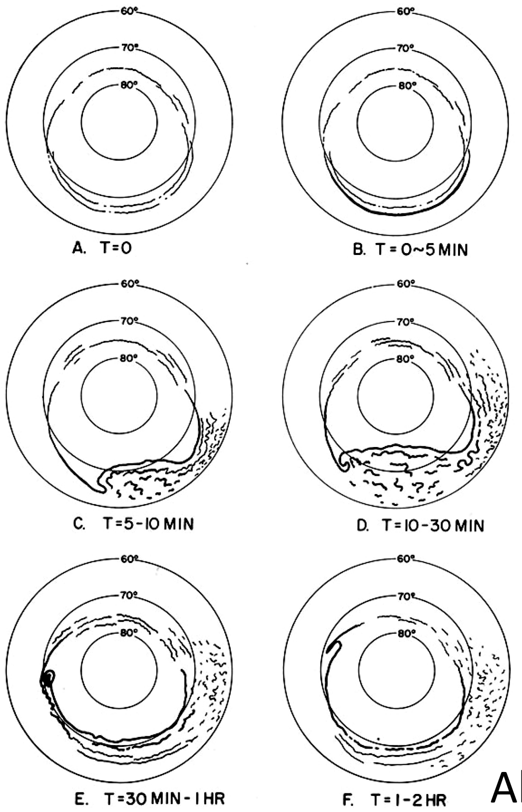
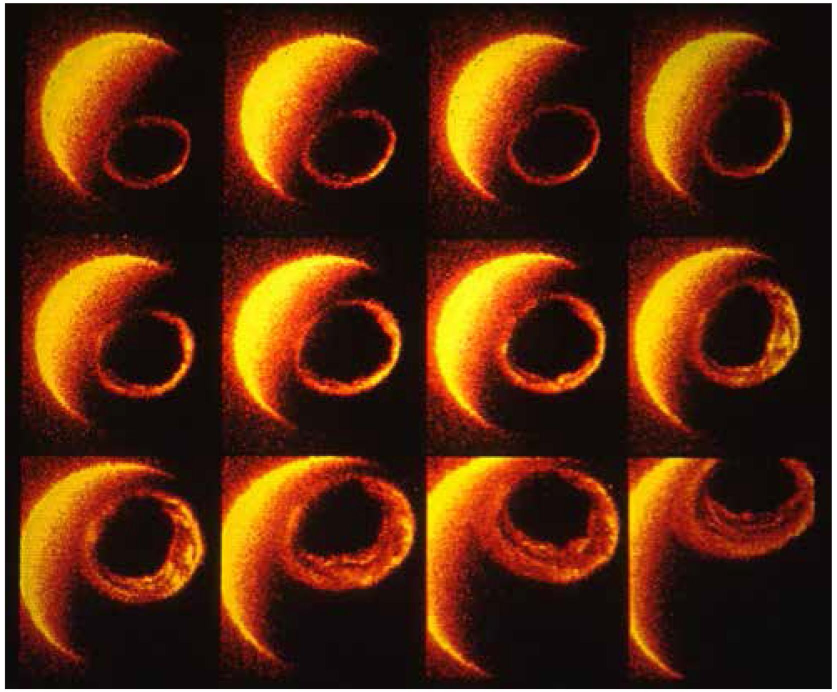


Fig. 6.5

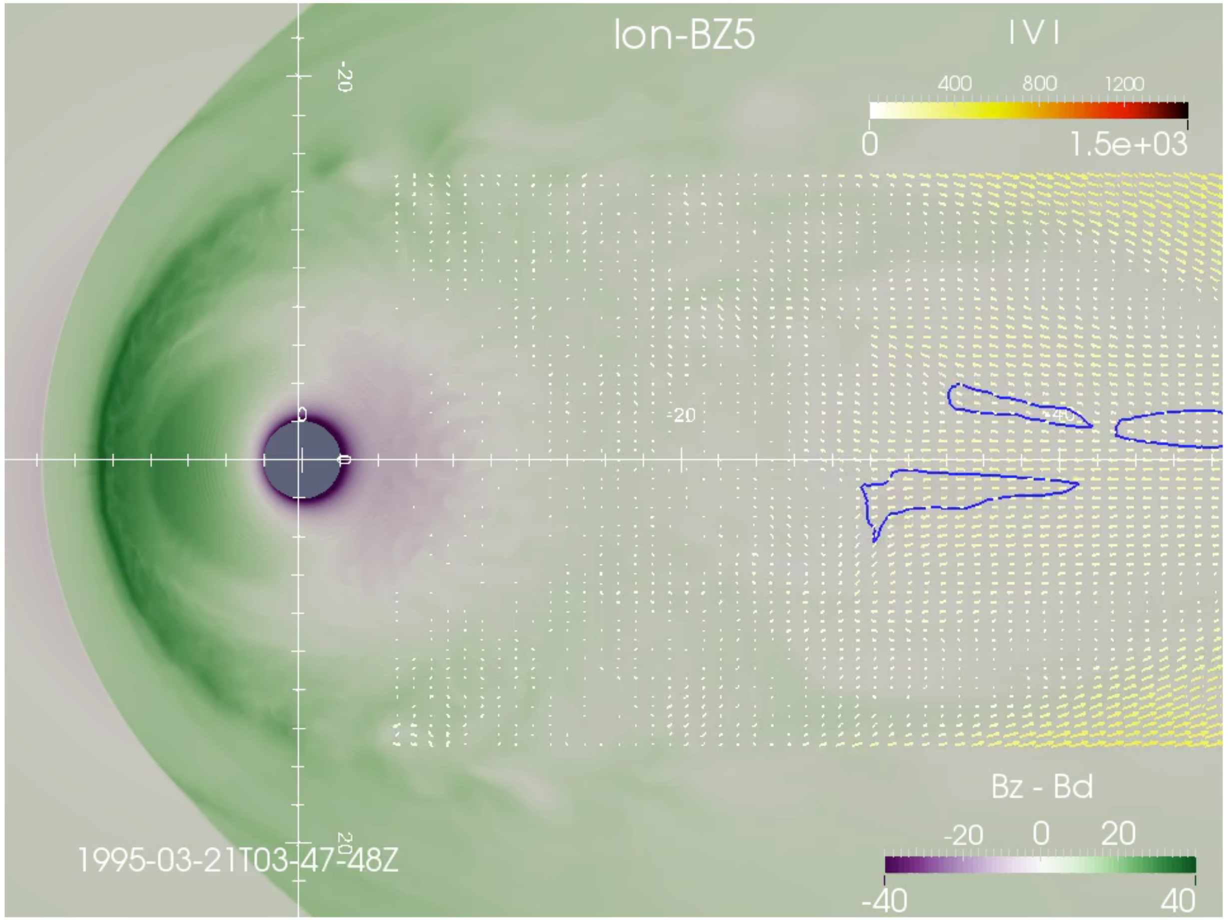




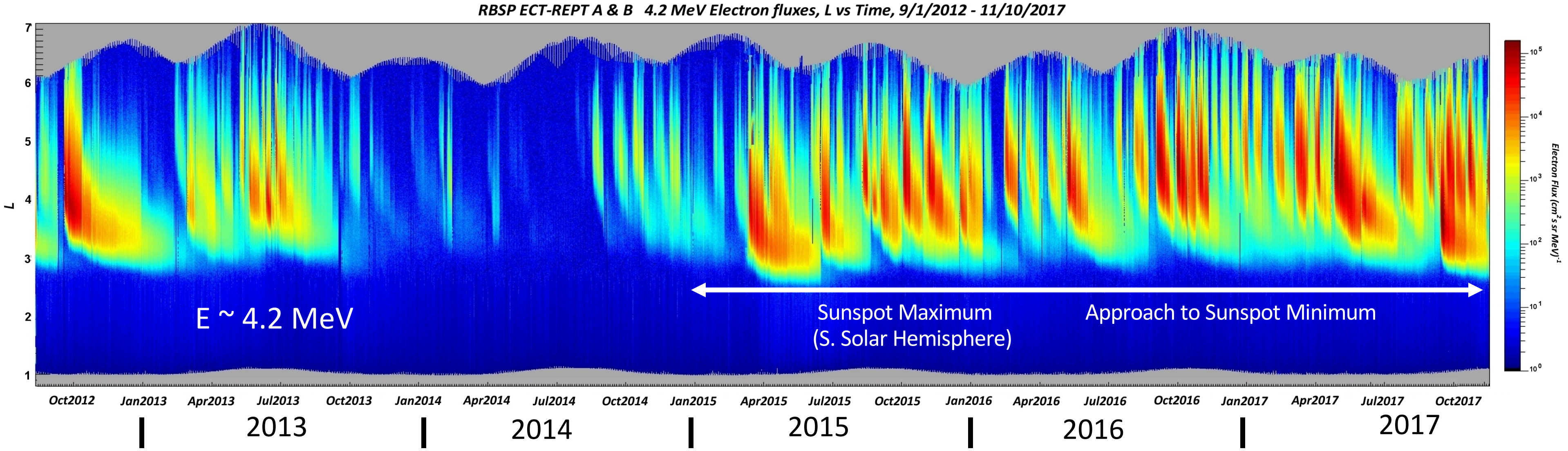
Akasofu (2015) Eos

Large substorm: 10^{16} J dissipated at rate 10^{11} W during expansion phase

Movie: Convection vs Bursty Bulk Flows



Radiation Belt Multi-MeV Electrons Over Multi-Year Span



Courtesy
Dan
Baker
LASP

Acceleration and loss over significant fraction of Solar Cycle 24 for E ~ 4.2 MeV electrons

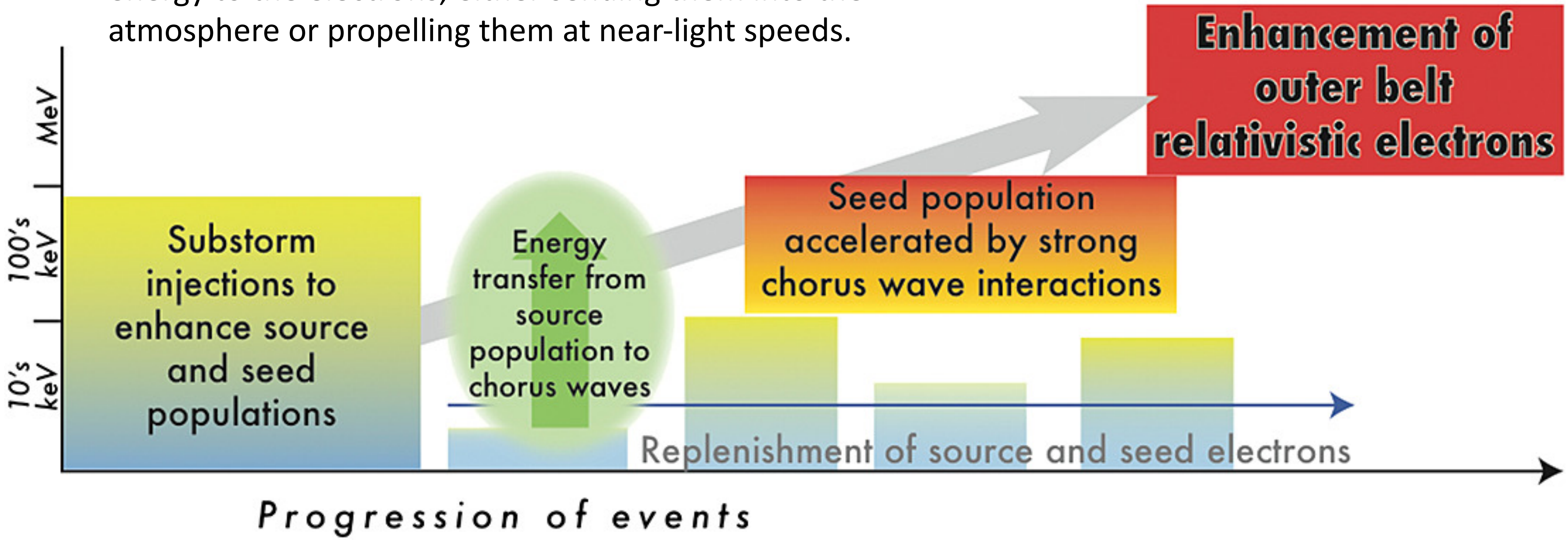
Li et al. (2015) found three main contributions to efficient acceleration events:

(1) prolonged southward Bz,
(2) high solar wind speed,
(3) low solar wind dynamic pressure.

the study also showed that intense chorus waves are present for far longer periods during the efficient enhancements.

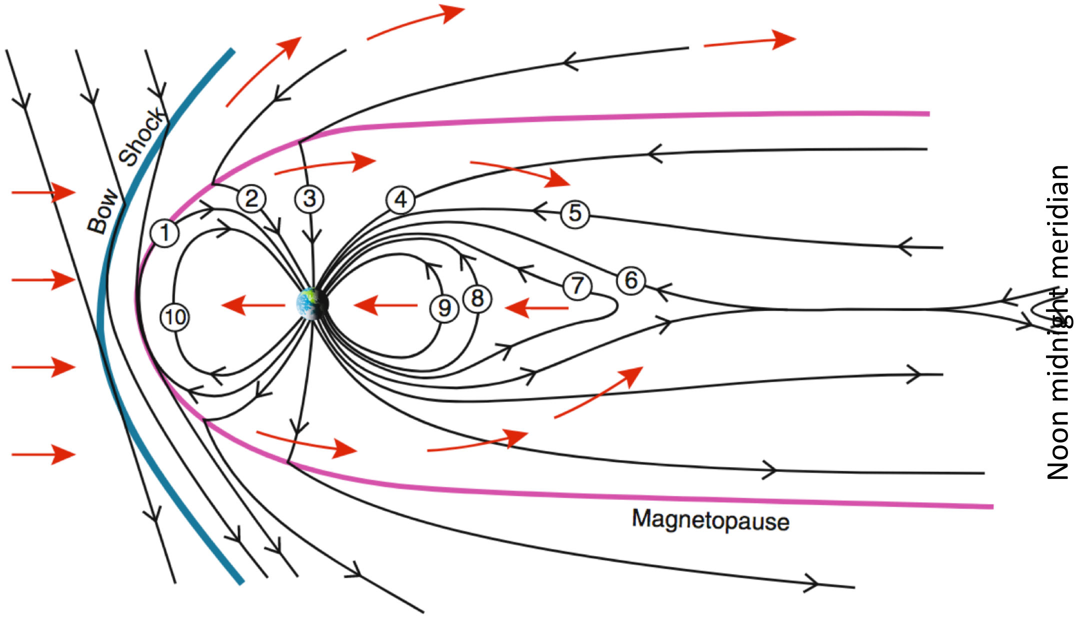
The storm-substorm path to outer radiation belt enhancements

Low-frequency chorus waves resonate and exchange energy with electrons trapped in the radiation belts. Excited by the low-energy population, the waves then give energy to the electrons, either sending them into the atmosphere or propelling them at near-light speeds.



Jaynes et al. (2015)

Forming the Storm time Ring Current

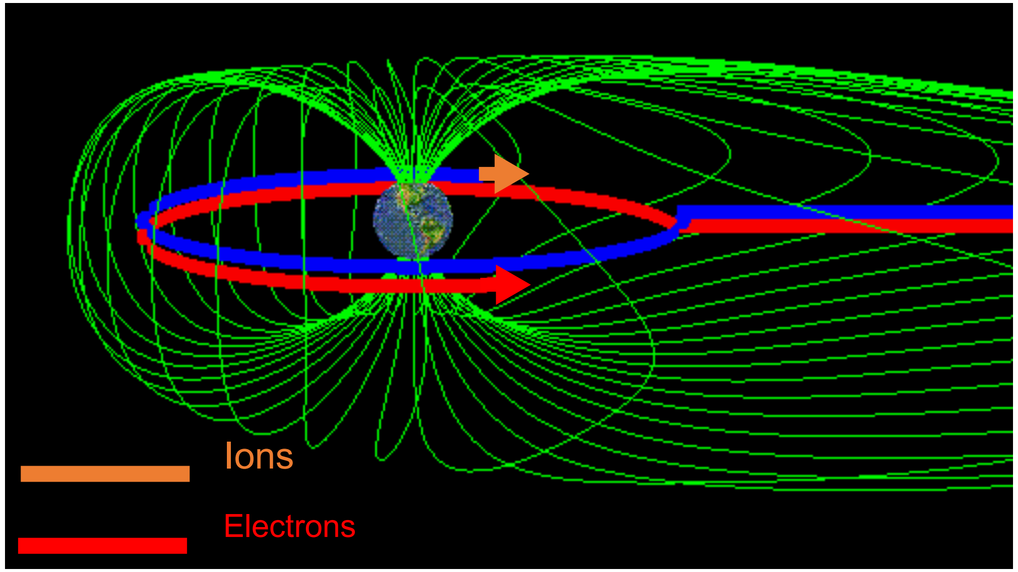


The field depression quantified by Dst is the result of plasma pressure that inflates the dipole field. Essentially a magnetic storm is the addition of a large amount of plasma energy to the dipolar field region of the magnetosphere.

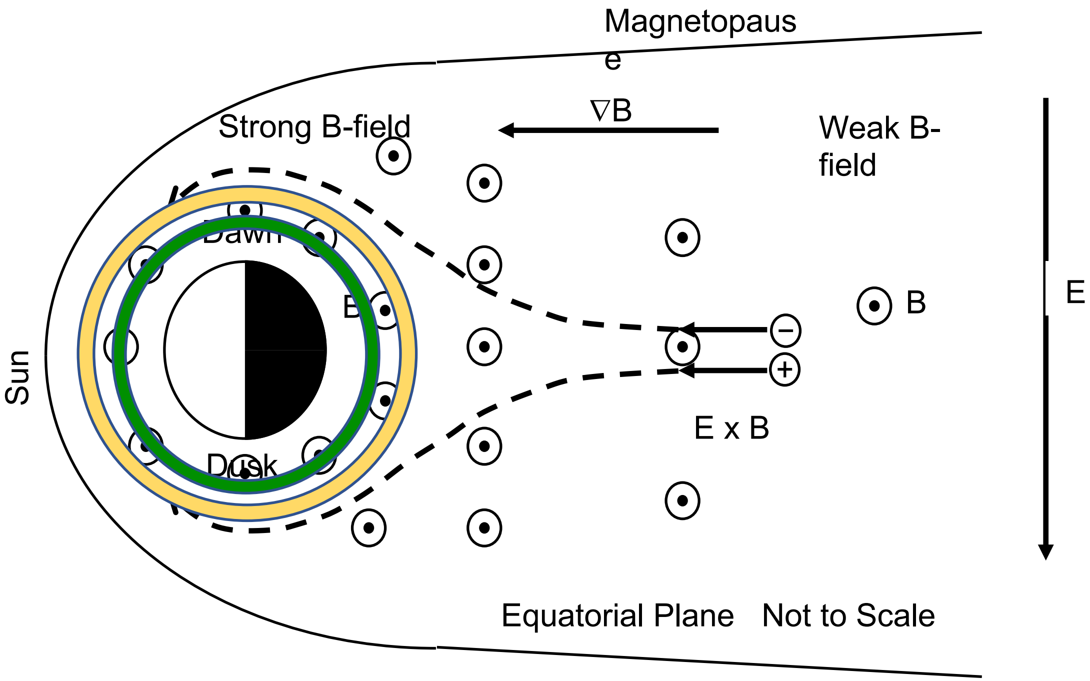
- Energetic particles from the magnetotail diverts around Earth
  - E x B Drift
  - Di-poloarization fronts from substorms
- Ring Current is a transient collection of particles
- 10^4-10^5 eV
- Associated with geomagnetic storms
- Enhancements last a few days
  - Energy required for a 100 nT low-latitude field depression: ~5 x10^{15} J
  - Dessler-Parker-Sckopke theorem

$$\boldsymbol{\mu}|_B \cdot \mathbf{b}(0) = 2U_\mathrm{K} \qquad (6.2)$$

Plasmasheet Convection: Warm/Hot Particles



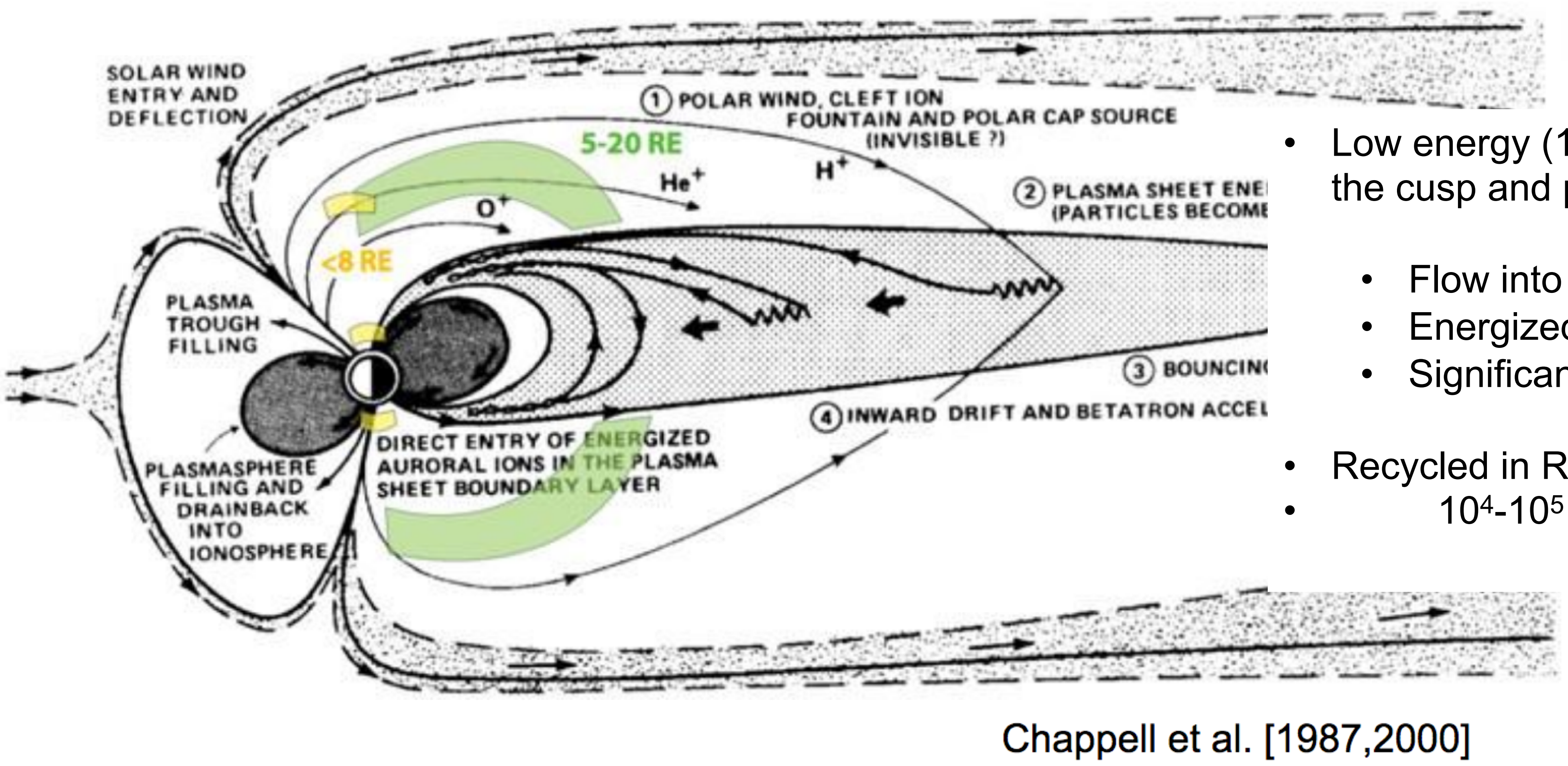
Noon midnight meridian



Equatorial plane

- Warm plasma E x B drift toward Earth and comes under the influence of grad B and curvature drift.
- Some particles become trapped or semi-trapped
- Most cool particles drift toward the magneto-nose and enter the magnetosheath where they might be recycled during reconnection
- Electrons move anti-clockwise around Earth
- Ions move clockwise around Earth
- Together these motions form a circular current system around Earth—the Ring Current
- The solar wind **E** thus adds energy into magnetospheric particles
- During storm time, preferentially into ring current ions

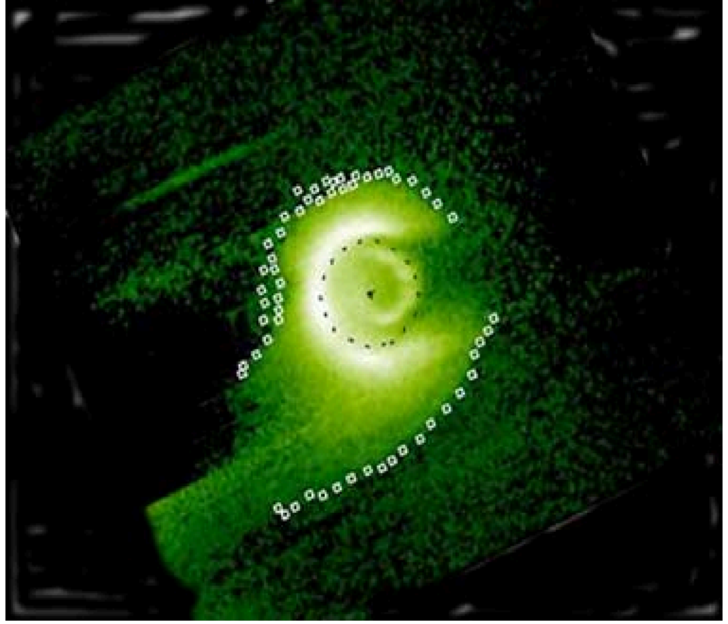
Forming the Storm time Ring Current

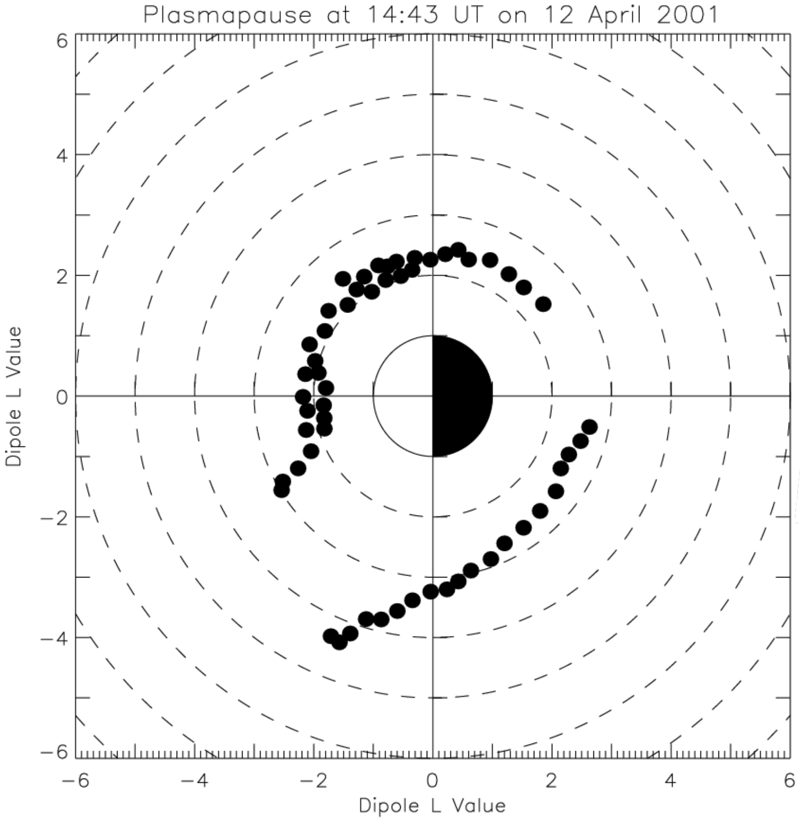


- Low energy (1-3eV) particles from the cusp and polar cap
  - Flow into plasmasheet
  - Energized by inward drift
  - Significant O+ in some storms
- Recycled in Ring Current
- 10^4-10^5 eV

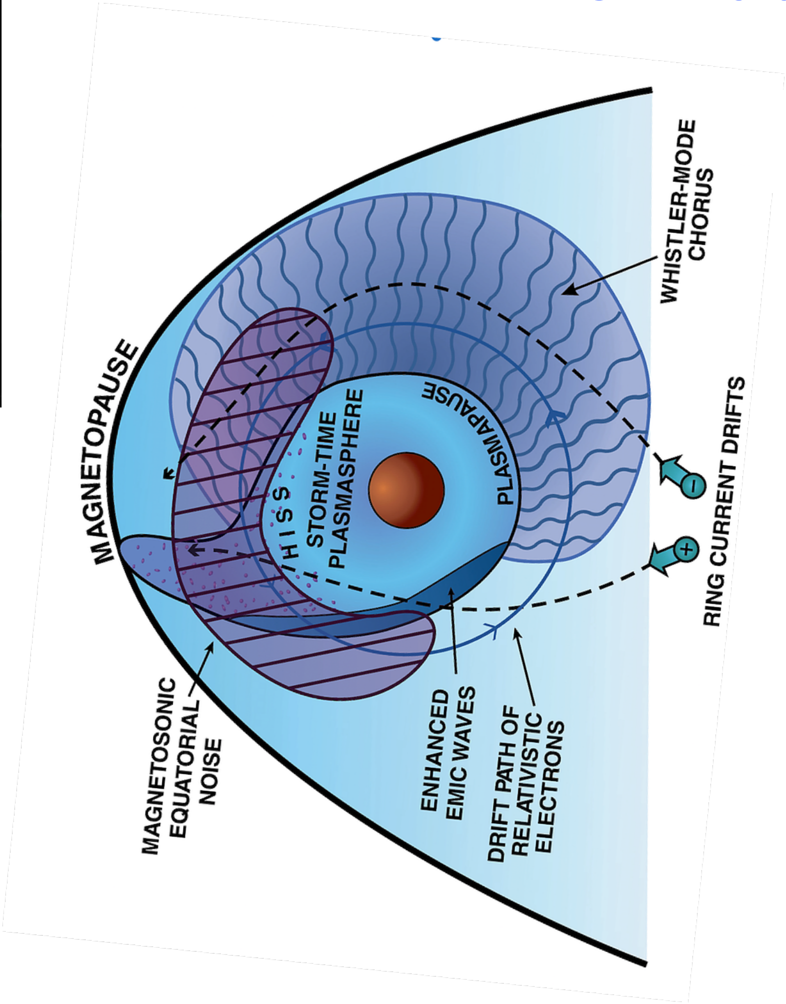
Chappell et al. (1987, 2000)

Disturbing the Plasmasphere and Inner Radiation Belt?





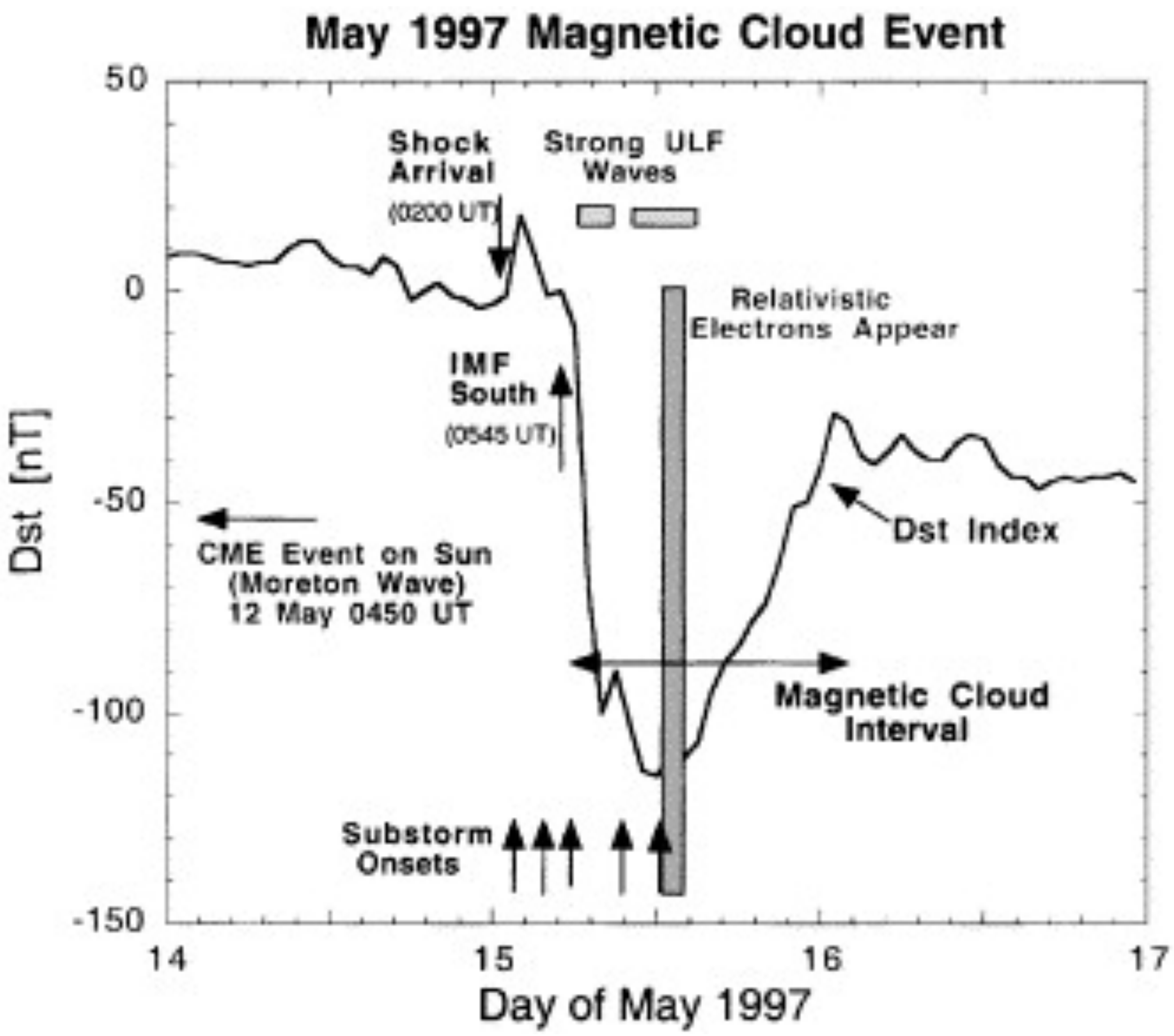
Yizengaw et al., 2008



Thorne et al, 2011

- Ring Current interaction with plasmasphere under large scale electric field
  - Compresses and shears plasmasphere
  - Draws cold plasmasphere material into dayside merging region
  - Reduces merging efficiency
  - Wave-particle interaction may accelerate electrons into the inner radiation belt for long term storage

Bringing Storms and substorms together



Solar wind disturbance arrives at Earth

Probably high speed solar wind (shock)

ICME with south field first

Prolonged interval of Bz –

Numerous substorms

Strong Ring Current-Intense Storm

Outer Radiation Belt enhanced

Likely followed by more high speed flow

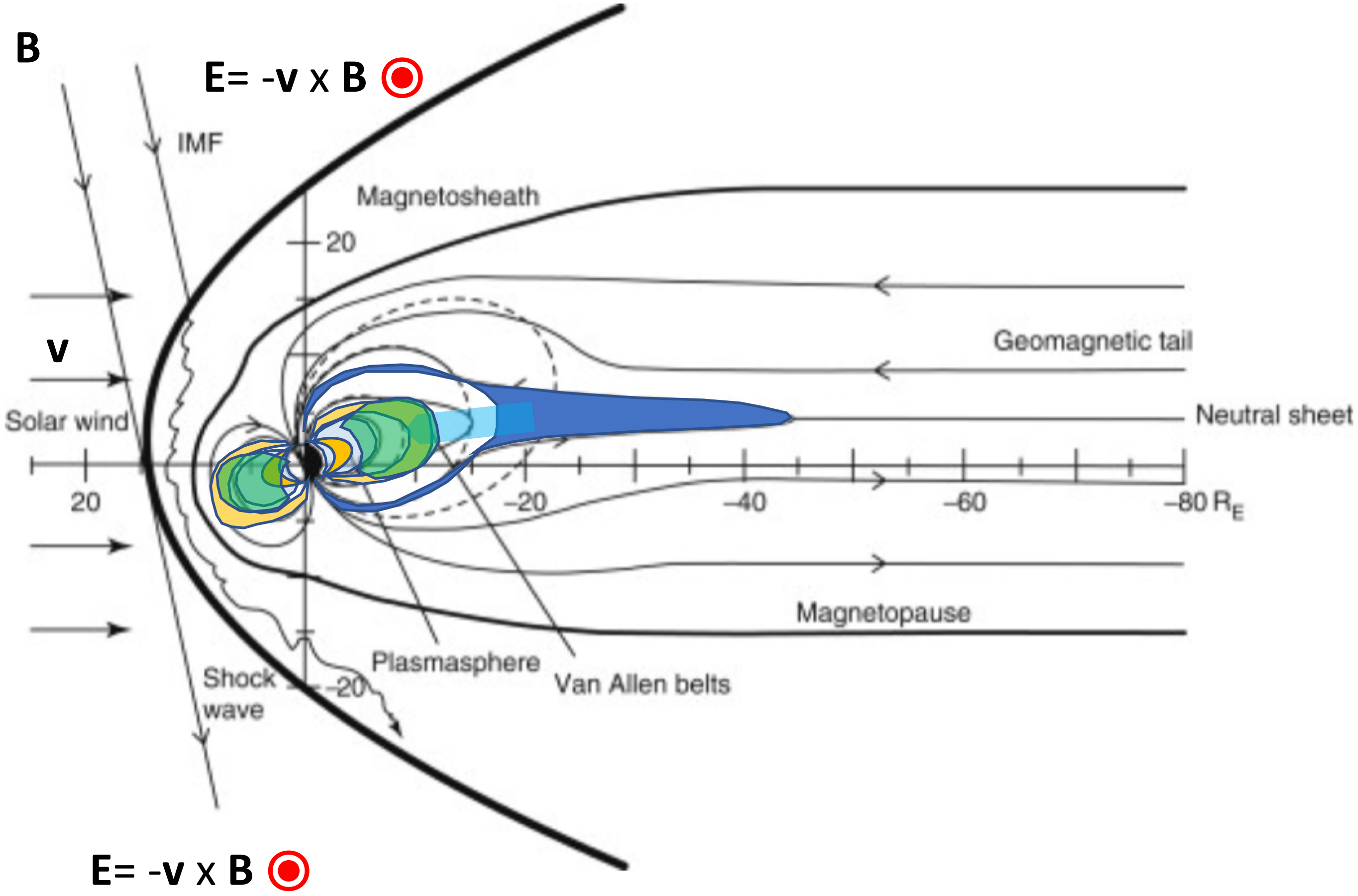
Indices and Measures

- Gonzalez and Tsurutani [6] found that a dawn-dusk convection electric field greater than 5 mV/m, which means 10 nT magnetic field and 420 km/s speed, lasting for at least 3 hours, is the minimum interplanetary condition for the occurrence of an intense geomagnetic storm, i.e. storm-time Dst index less than -100 nT.

- Storms result from strong, prolonged convection of plasma into the inner magnetosphere

Particle Populations and External/Internal Influences

Region of geospace hosting charged particles



2-D Schematic, ~scaled
Noon-Midnight Meridian

- Magnetosphere under influence of southward IMF
- Opened by dayside merging
  - Allowing influence of solar wind electric field
- Closed by nightside reconnection
  - Enhances convection and bursty flows
- Subject to significant storm-time variations
- Plasmasphere,
  - Compression and loss
- Radiation belts,
  - Suddenly Depleted
  - Re-established in 24-48 hours
  - Expanded in latitude and L-shell
- Plasmasheet
  - Thinned/Expanded
  - Dipolarized
- Ring Current, cool-medium and highly variable
  - Rapid enhancement
  - Slow decay