The Magnetosphere as a System

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- **Envision the magnetosphere as a system of interacting particle populations.**
- **Look at some system properties.**
- **Look at some system tools.**

Open-Access Review:

Borovsky & Valdivia, The Earth's Magnetosphere: A Systems Science Overview and Assessment. ***Surveys of Geophysics, 39*****, 817, 2018.**

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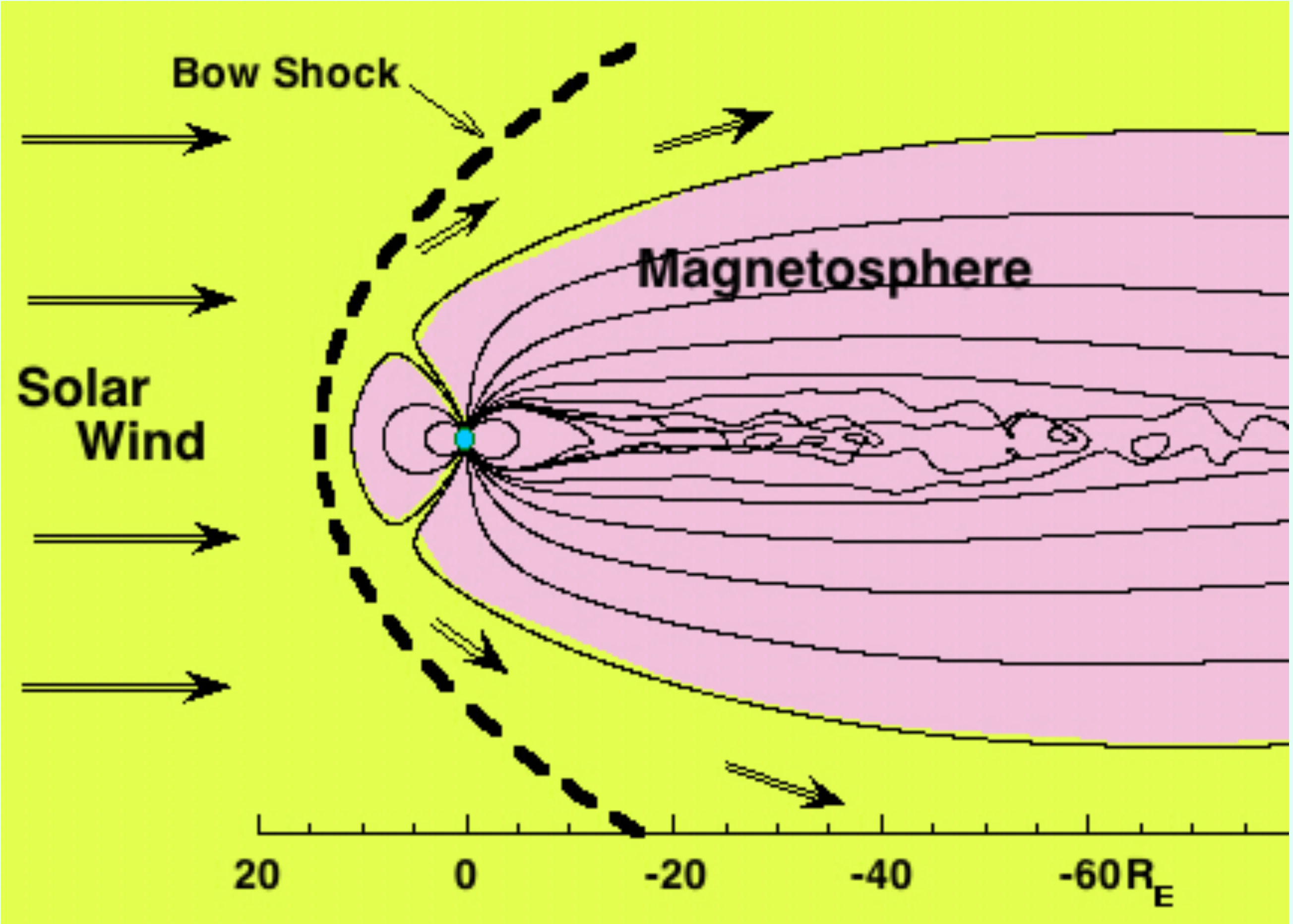
The Solar Wind and the Magnetosphere

The solar wind interacts with the outer portions of the Earth's dipole, where the dipole field strength is weak: B ∝ r^{-3}.

The solar wind compresses the dayside magnetosphere and draws the nightside magnetosphere out into a long "magnetotail".



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The Solar Wind Drives the Magnetosphere

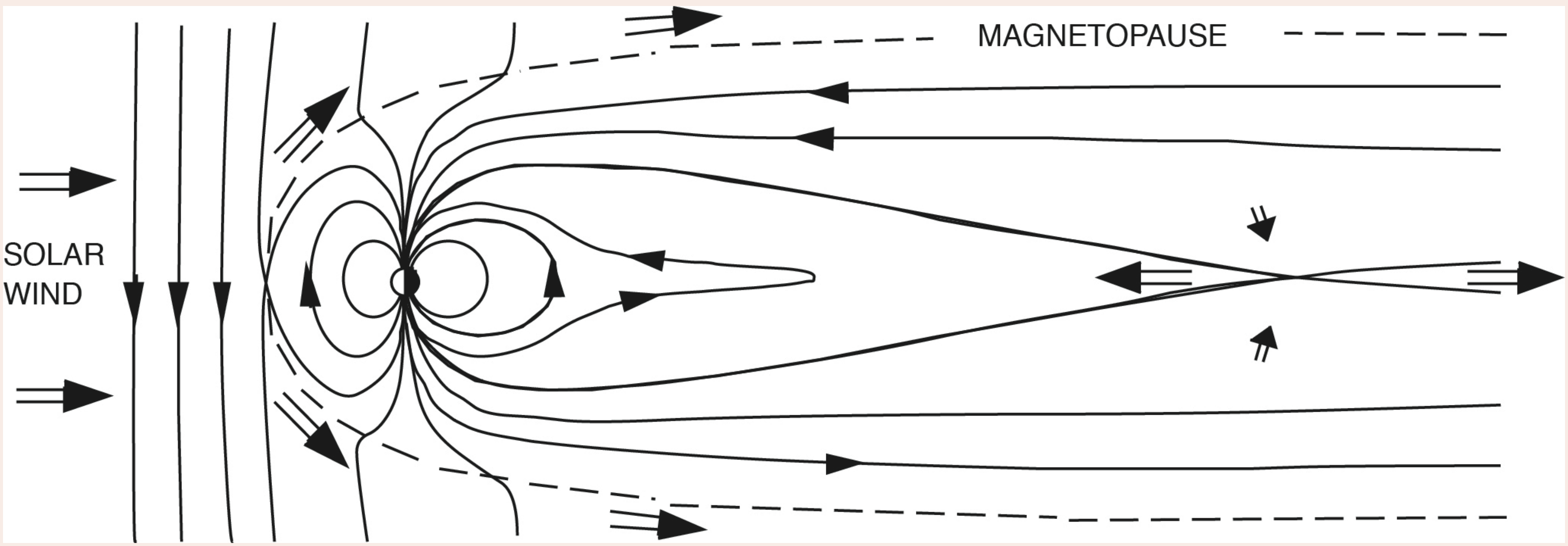
Reconnection is the dominant mechanism by which the solar-wind drives the magnetosphere.

1. Reconnection on the dayside connects the solar wind to the magnetosphere.

2. The moving solar wind drags magnetic flux into the magnetotail.

3. Reconnection in the tail disconnects the solar wind and allows magnetic flux to convect from the nightside to the dayside.

Reconnection allows plasma to enter and it drives magnetospheric and ionospheric convection.



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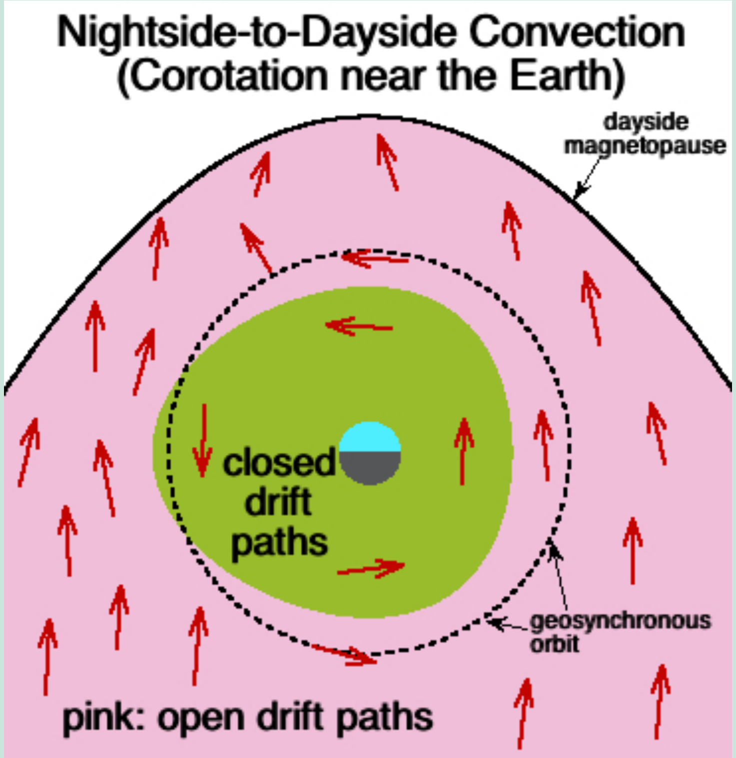
Magnetospheric Convection (Steady & Impulsive)



- Transports plasma
- Adiabatically heats plasmas
- Sets up current systems
- Drives internal processes;

  Creates unstable particle distribution functions

  Drives plasma waves

  Wave-particle interactions (energization and atmospheric loss)

  Ionospheric outflows of ions and electrons
- Exhausts plasma to the dayside magnetopause

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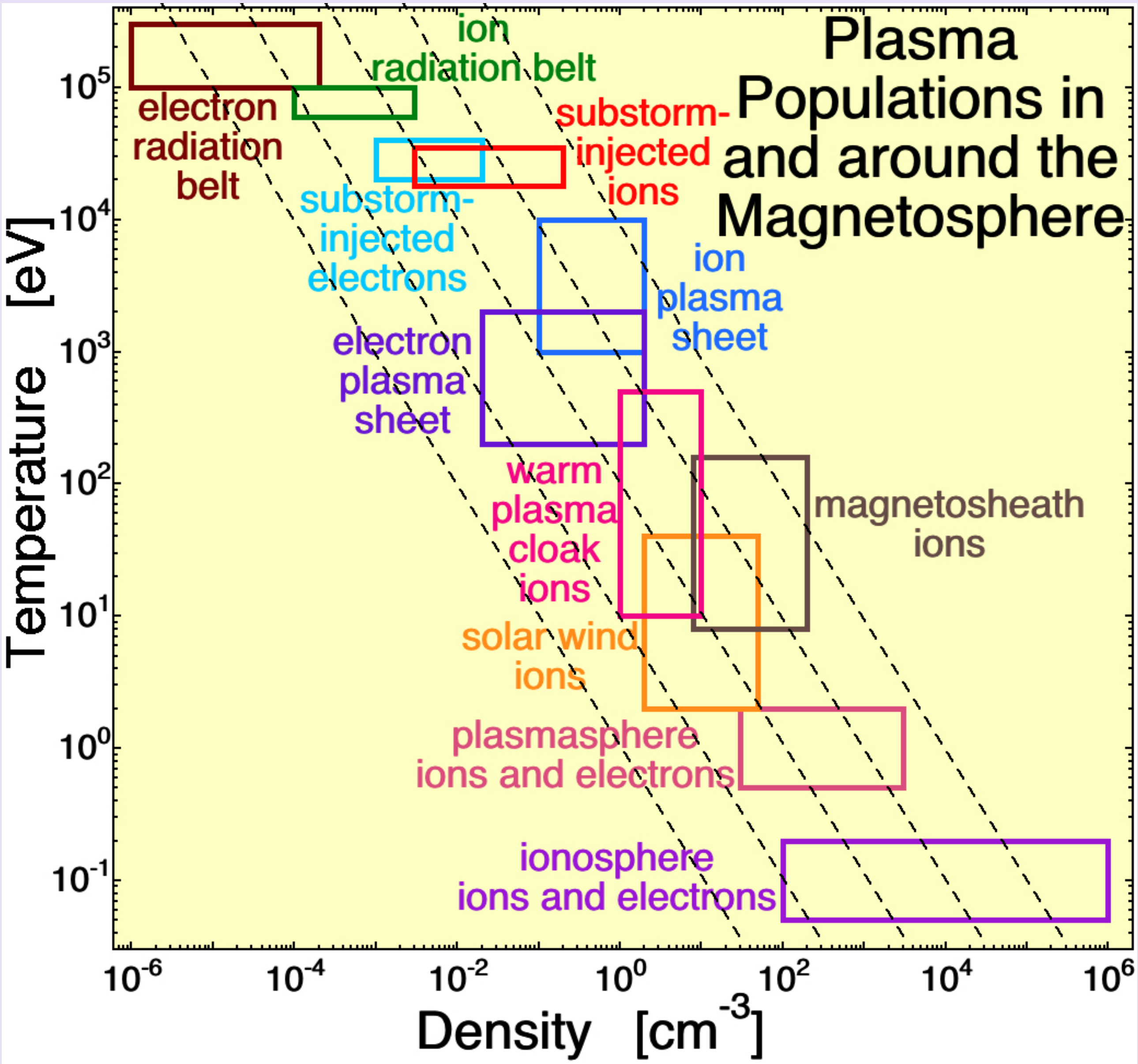
The Major Plasmas



Missing:

LLBL

Mantle

Chex-protons

Cold e⁻ outflows

Remnant layer

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Envisioning the System

Complex System (*definitions are diverse*)

- Components are not homogeneous
- Components have multi-level structure
- Complicated interactions
- Some interactions are nonlinear

PSP = Plasmasphere (and plume)
ERB = Electron Radiation Belt
IRB = Ion Radiation Belt
IPS = Ion Plasma Sheet
EPS = Electron Plasma Sheet
SIE = Substorm-Injected Electrons
LLBL = Low-latitude boundary layer

Earth's Magnetosphere

Subsystems are the diverse particle populations

Populations are co-located (so they easily interact)

Dipole inside of the plasmapause and inside the plume

PSP, ERB, IRB, IPS, Ionosphere

Dipole outside of the plasmapause and plume

EPS, ERB, IRB, IPS, Cloak, SIE, Ionosphere

Magnetotail

IPS, EPS, Mantle, LLBL, Ionosphere

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Interacting Particle Populations

Coupling Mechanism	Driven by	Lives in	Affects
Chorus	SIE	EPS	ERB
EMIC	IPS	PSP	ERB
ULF	MSH,IPS	Cloak,IPS	ERB,IRB
Nightside Alfven	IPS	IPS	Ionosphere,ERB
Hiss	SIE?	PSP	ERB
Magnetosonic	IPS	IPS,Cloak	ERB
Diamagnetism	IPS	IPS	ERB,IRB,SIE

SIE = Substorm-Injected Electrons
PSP = Plasmasphere (and plume)
MSH = Magnetosheath

IPS = Ion Plasma Sheet
EPS = Electron Plasma Sheet
IRB = Ion Radiation Belt
ERB = Electron Radiation Belt

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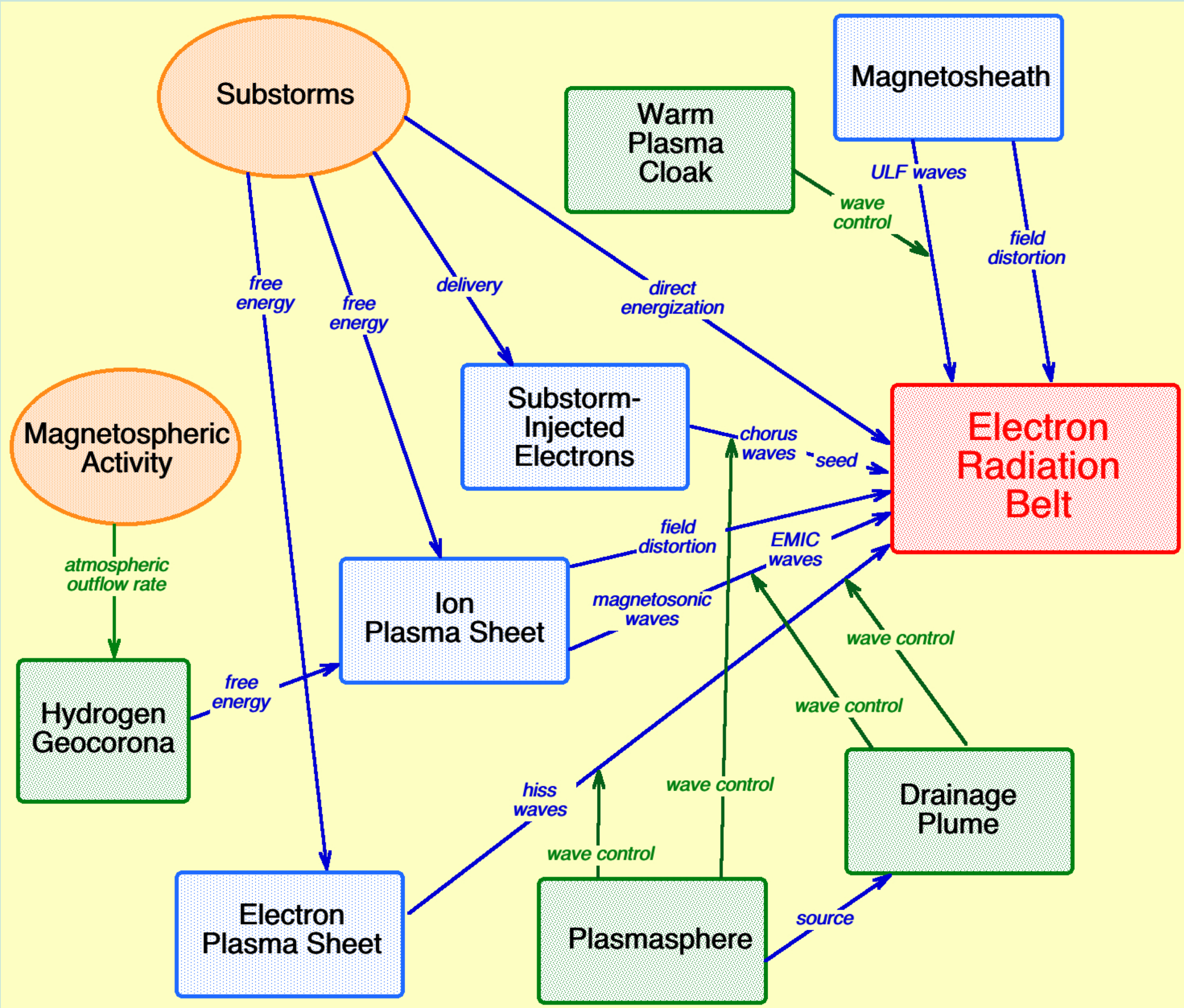
Complicated Interactions



Solar-wind driving has not been indicated here.

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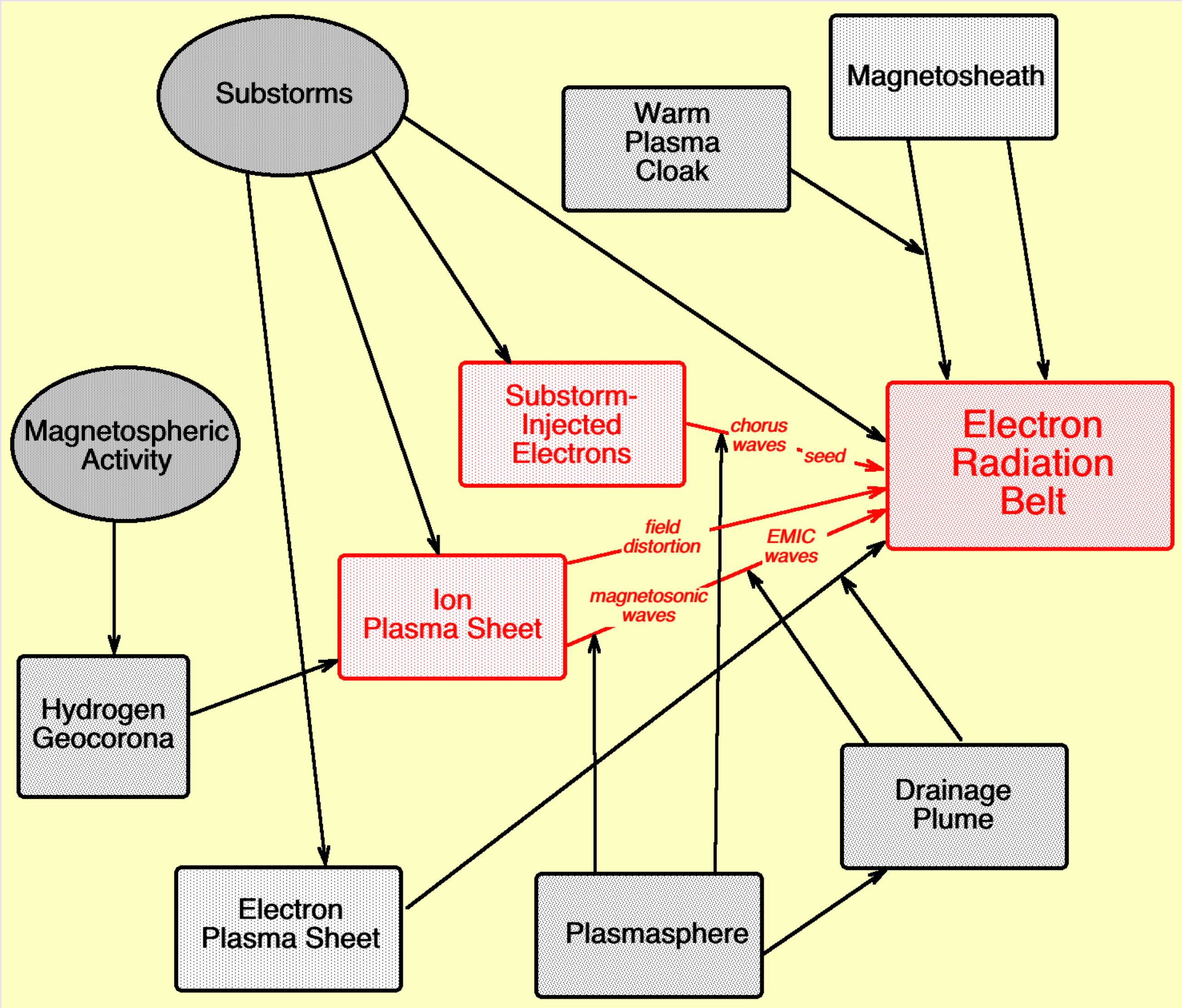
Example of Nonlinear Interacting Populations



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Integro-Differential Correlations of Interacting Populations

For the energization and the loss of the radiation belt (as measured by the flux F):

$$dF/dt = +\text{chorus intensity} \quad \Rightarrow \quad F = \int \text{chorus } dt$$

$$dF/dt = -\text{EMIC intensity} \quad \Rightarrow \quad F = -\int \text{EMIC } dt$$

An "evolutionary algorithm" yields:

$$F_{1.2MeV} \approx 0.595 \int^{53hr} F_{130keV}\, dt - 0.258 \int^{11hr} P_{ips}\, dt$$

$$F_{1.2} \leftrightarrow \int F_{130}, P_{ips} \qquad r_{corr} = 0.820$$

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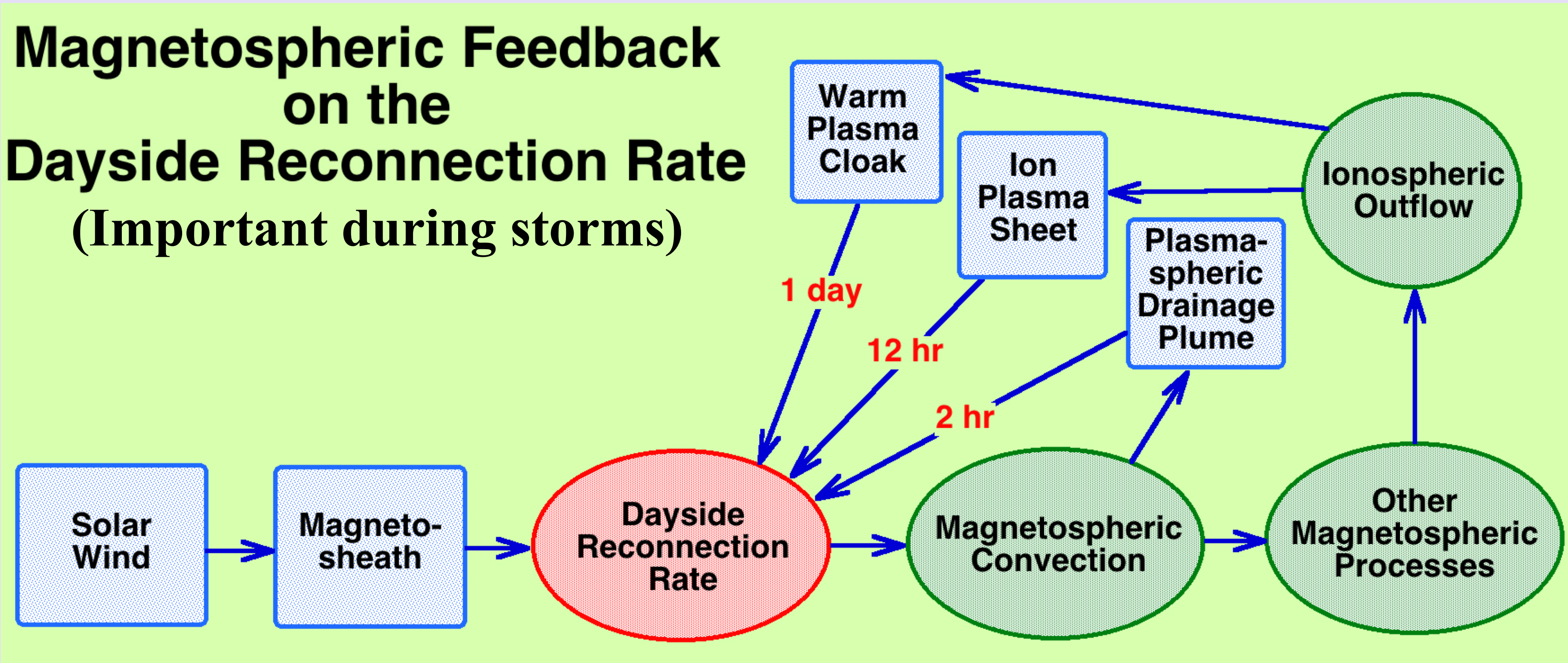
Feedback Loops



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Emergence

Emergence is the appearance of a behavior caused by the interactions of a system's components.

1. **The spatial patterns of pulsating aurora**
2. **Auroral arcs**
3. **The dynamic electron radiation belt**

What needs to happen to have an electron radiation belt?

(1) A dipolar region and a repeatedly unstable magnetotail

(2) Energetic substorm-injected electrons for the seed population

(3) Free energy in the electron plasma sheet to drive chorus

(4) Energization via wave-particle interactions

and

(5) ULF waves must act to redistribute the radiation-belt

(6) Hiss inside the plasmasphere to scatter into the atmosphere

(7) ULF waves acting during shadowing

(8) EMIC waves in the plume to scatter into the atmosphere.

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System Tool: Vector-Vector Correlation

S(t) = solar-wind state vector

S(t) contains n_{sw}, v_{sw}, B_{mag}, θ_{clock}, θ_{Bn}, M_A, TILT, δB, F10.7, I_{strahl}

M(t) = magnetospheric state vector

M(t) contains Kp, Dst, AL, AU, PCI, MBI, n_{ips}, T_{ips}, P_{ips}, F_{e130}, $F_{e1.2}$, mP_e, mP_i, ULF, t_{since}, ...

S(t) → **M**(t)

Method gives

1. Universal solar-wind driver functions
2. Collective modes of reaction of the magnetosphere
3. Composite scalar description of system activity
   a. High prediction accuracy
   b. Quasi-linearity (same description storm versus quiet)

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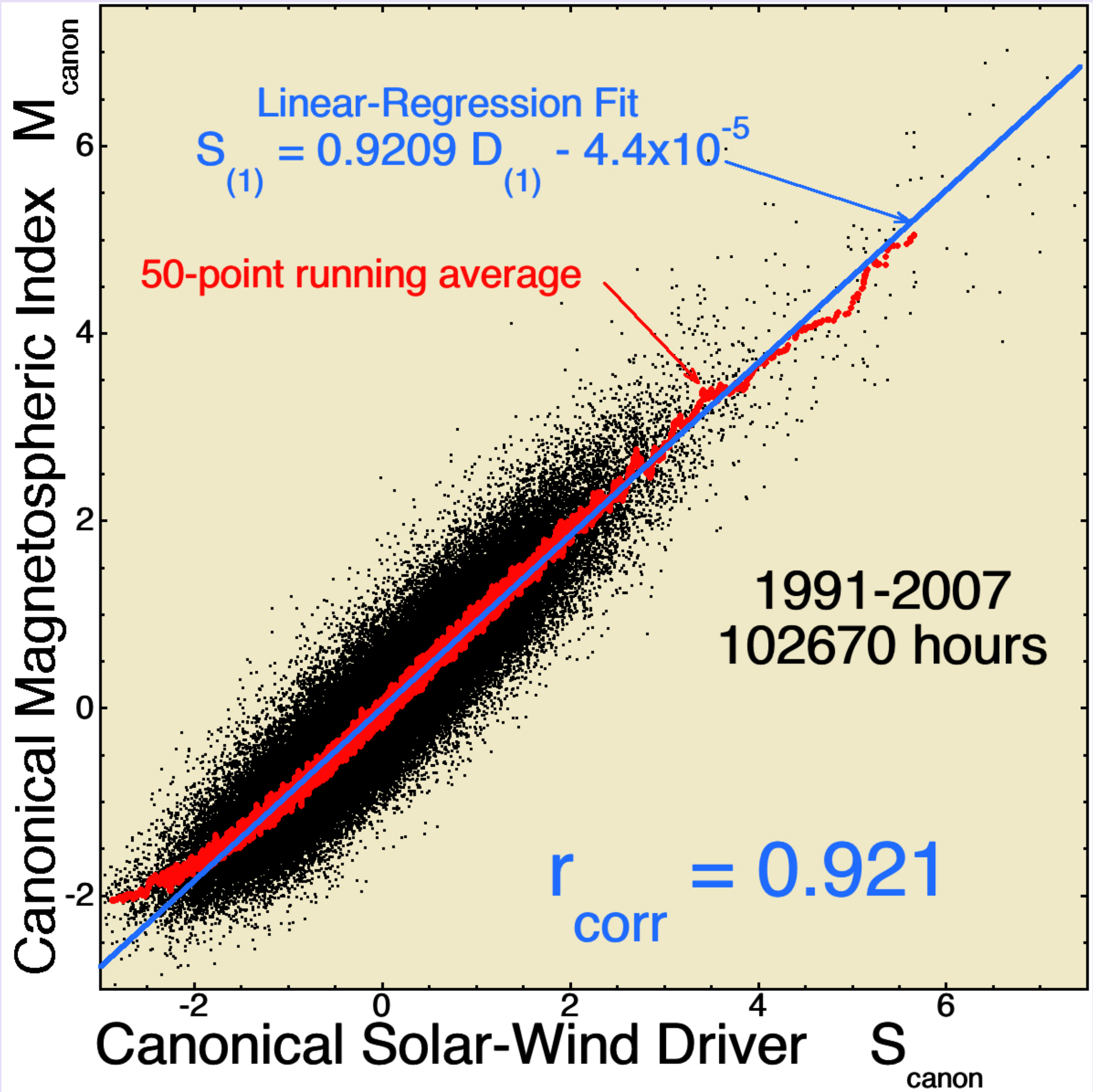

Canonical Magnetospheric Activity Index Versus Canonical Solar-Wind Driver

Note the linearity: Quiet time versus storm time

Robust:

Activity index

Universal driver

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Applicability of Systems Adjectives

Driven
Diverse
Interconnected
Interdependent
Open
Dissipative
Irreversible
Nonlinear
Turbulent
Feedback
Cyclic
Tipping point
Self-organized criticality
Adaptive
Emergence
Complex

See Borovsky+Valdivia, *Surveys Geophys.* [2018] for the arguments.

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Some Outstanding System-Level Questions

1. What are the mechanisms behind the sudden loss of the outer electron radiation belt?
2. What are the impacts of the various cold-ion and cold-electron populations of the magnetosphere?
3. What are the pathways of plasma transport into the magnetosphere?
4. How does polar-cap-potential saturation work?
5. What causes the 3-hr periodicity of substorm recurrence?
6. What are the controlling factors for ionospheric outflows?
7. How do we integrate the solar-wind-driven magnetosphere into "Earth Systems Science"?

$$\left.\begin{array}{l}\text{auroral precipitation}\\ \text{radiation-belt precipitation}\\ \text{SEP precipitation}\end{array}\right\} \Longrightarrow \left\{\begin{array}{l}\text{atmospheric chemistry}\\ \text{atmospheric electricity}\end{array}\right.$$

(This presentation is being recorded.)

Recommended Papers

Magnetospheric Tutorials:

Eastwood et al. (2015) What controls the structure and dynamics of the Earth's magnetosphere?, Space Sci Rev 188:251.

Lyon (2000) The solar wind-magnetosphere-ionosphere system, Science, 288:1987.

Otto (2005) The magnetosphere, Lecture Notes in Physics 656:133.

Siscoe (2011) Aspects of global coherence of magnetospheric behavior. J Atmos Solar Terr Phys 73:402.

Data Analysis Methods:

Sharma (2014) Complexity in nature and data-enabled science: The Earth's magnetosphere. AIP Conf Proc 1582:35.

Stepanova &Valdivia (2016) Contribution of Latin-American scientists to the study of the magnetosphere of Earth. A review. Adv Space Res, 58:1968.

Valdivia et al. (2005) The magnetosphere as a complex system. Adv Space Res, 35:961.

Valdivia et al. (2013) The magnetosphere as a complex system. Adv Space Res 51:1934.

Vassiliadis (2006) Systems theory for geospace plasma dynamics. Rev Geophys, 44:RG2002.

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