Space and Astrophysical Plasmas

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Plasmas in Nature

- Magnetic fields in cosmic plasmas

  Giovanelli (1947, 1948), Hoyle (1949)

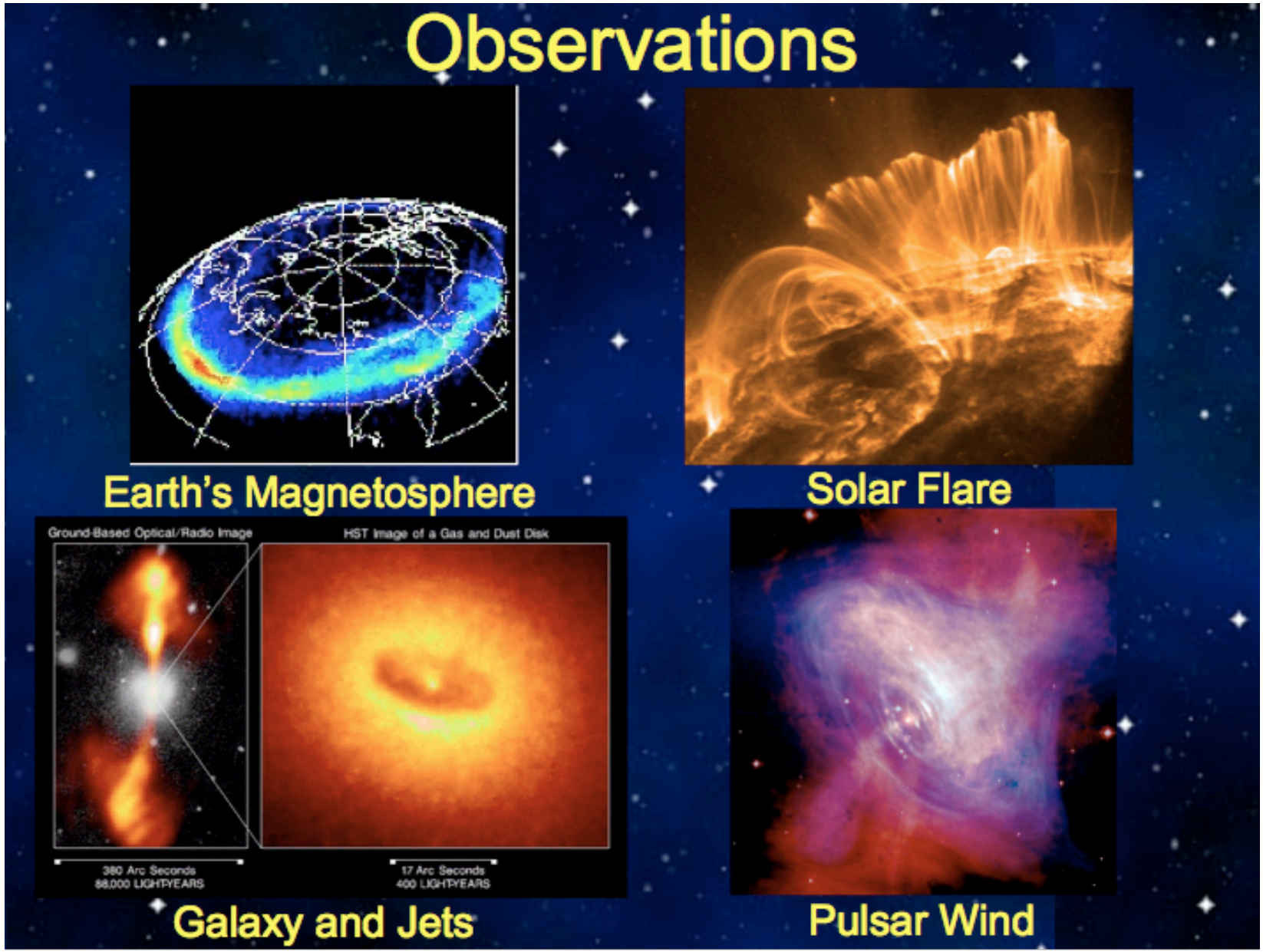
  Dungey (1961)
- Collisionless plasmas : reconnection, turbulence particle acceleration, and shocks
- Plasma universe (Alfven, 1986)

  visual , x-ray and γ-ray (> 10^2 eV), and infra-red
- Magnetospheric substorms, solar flares, pulsars, magnetars, terrestial γ-ray flashes, . .

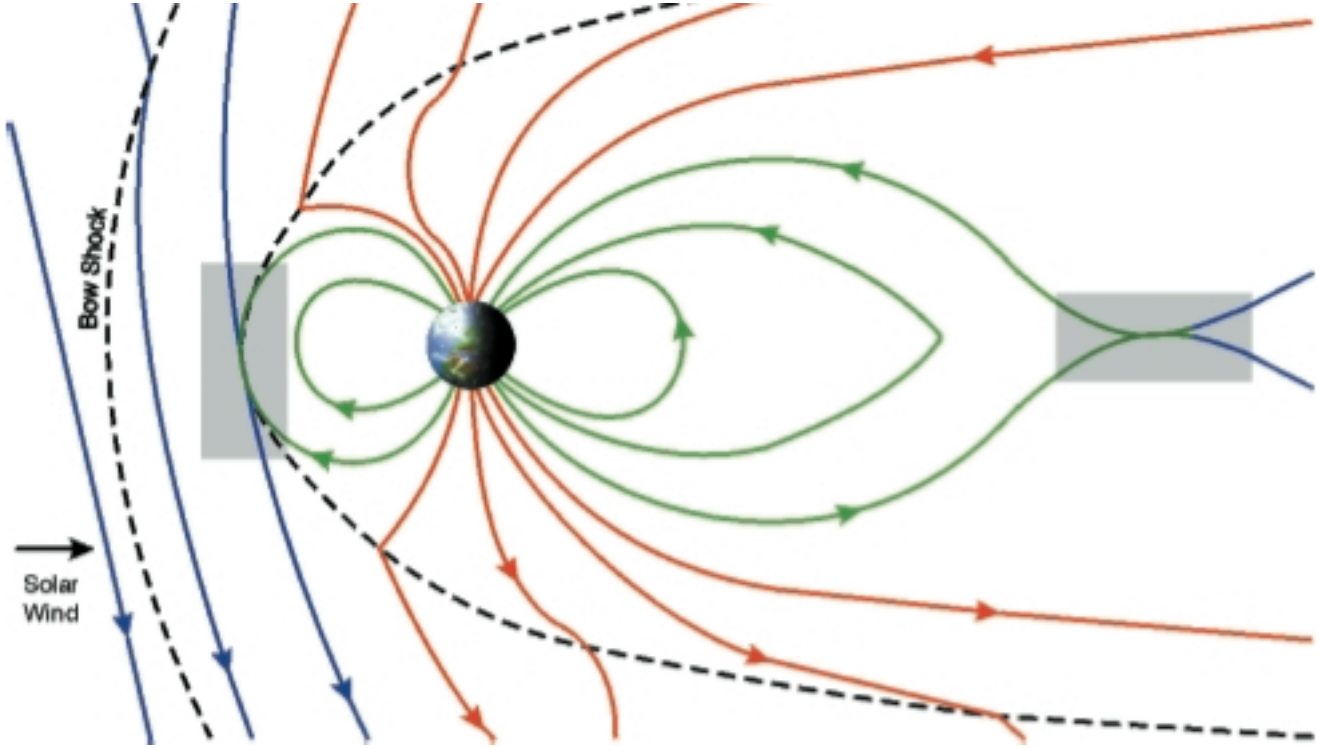
Themes:

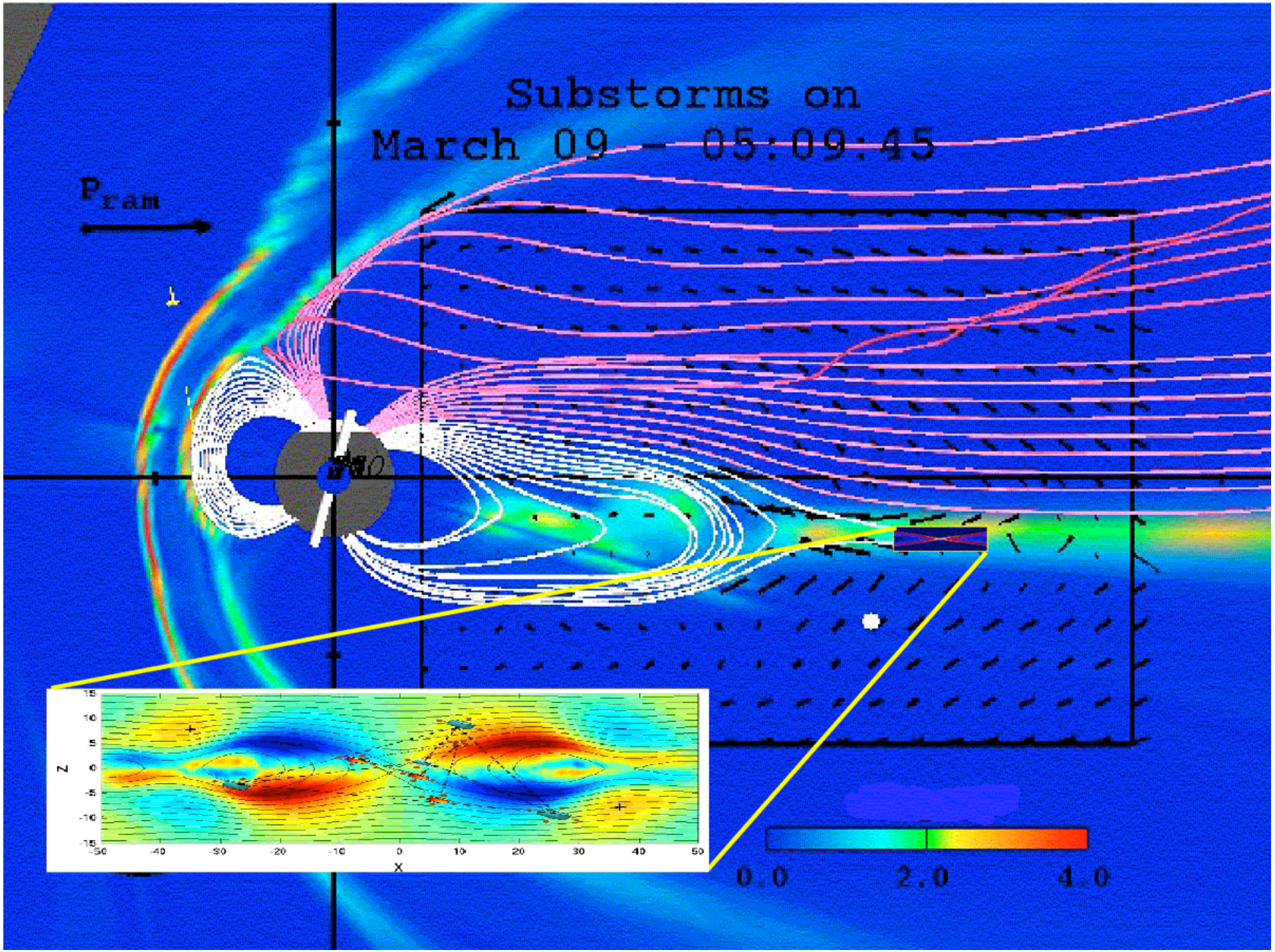
- Collisionless magnetic reconnection
- Space Weather - Magnetosphere
- Nonlinear dynamics and complexity
- Exospheres of planets
- Radiation Belt Dynamics

Magnetic Reconnection

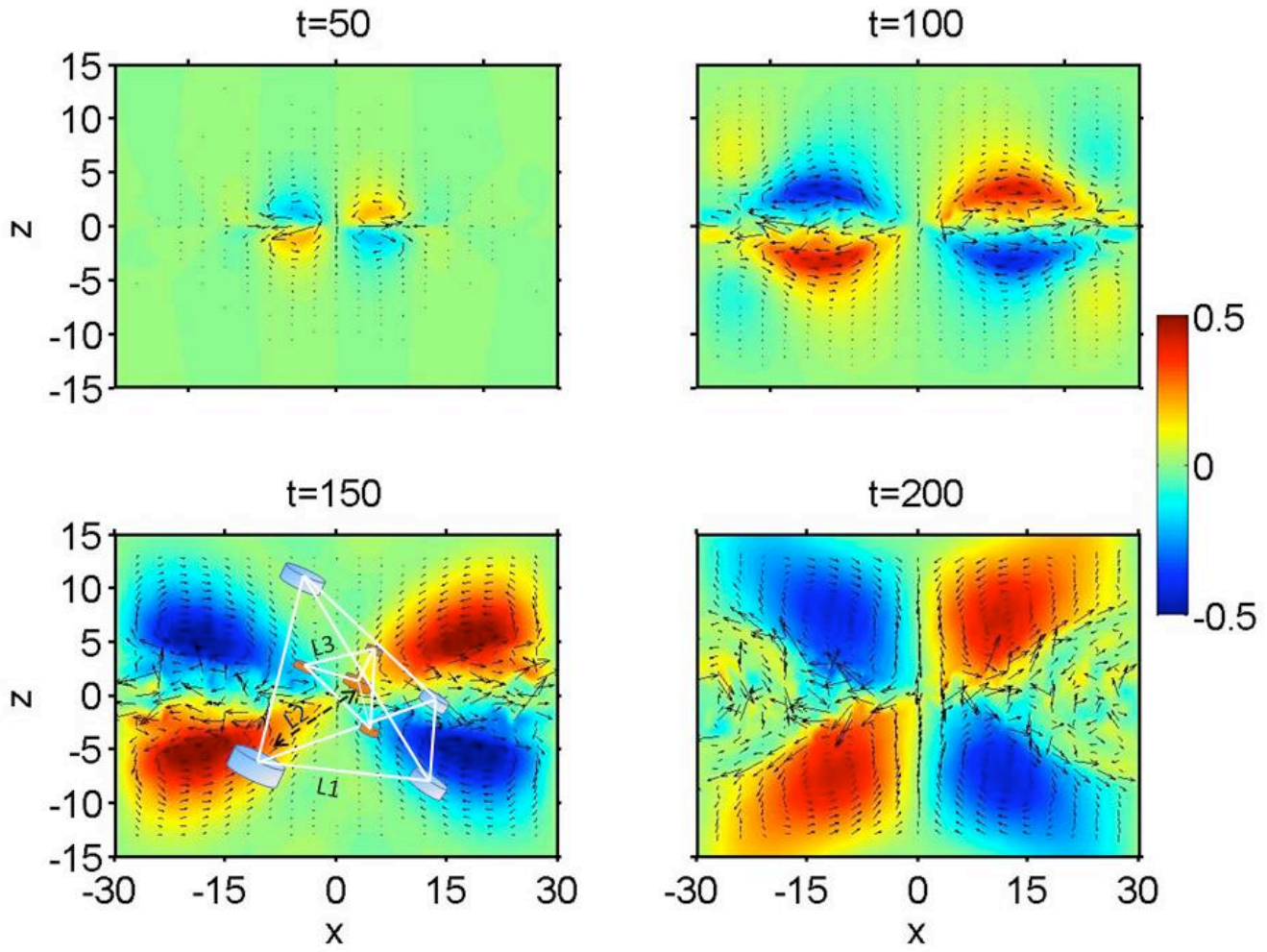


Magnetic Reconnection :
Magnetosphere




Substorms on
March 09 – 05:09:45
P ram
Z
X
0.0
2.0
4.0

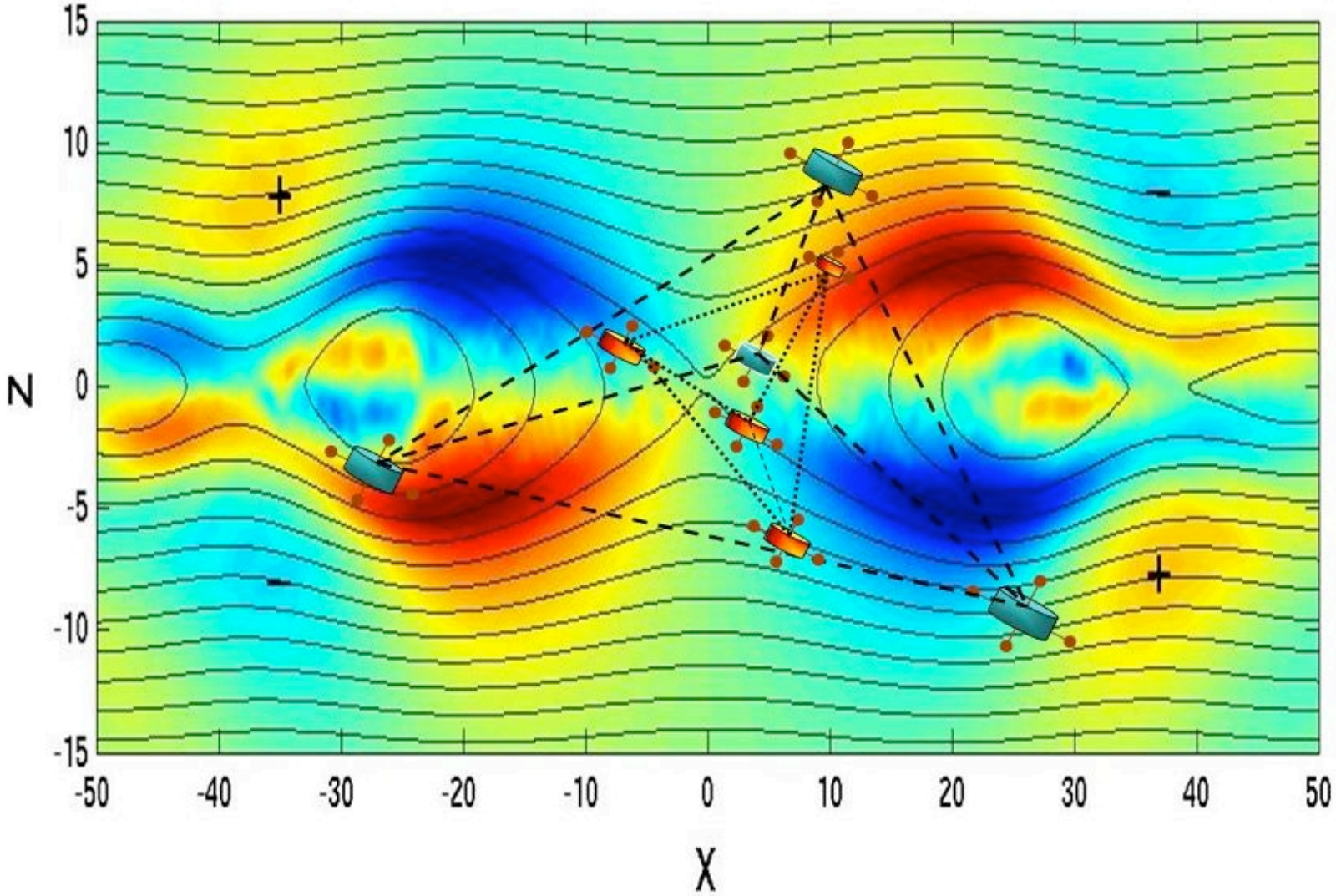
Reconnection at Electron scale



Quadrupole structure of magnetic field

(L3=100 km, d_e= 10 km)

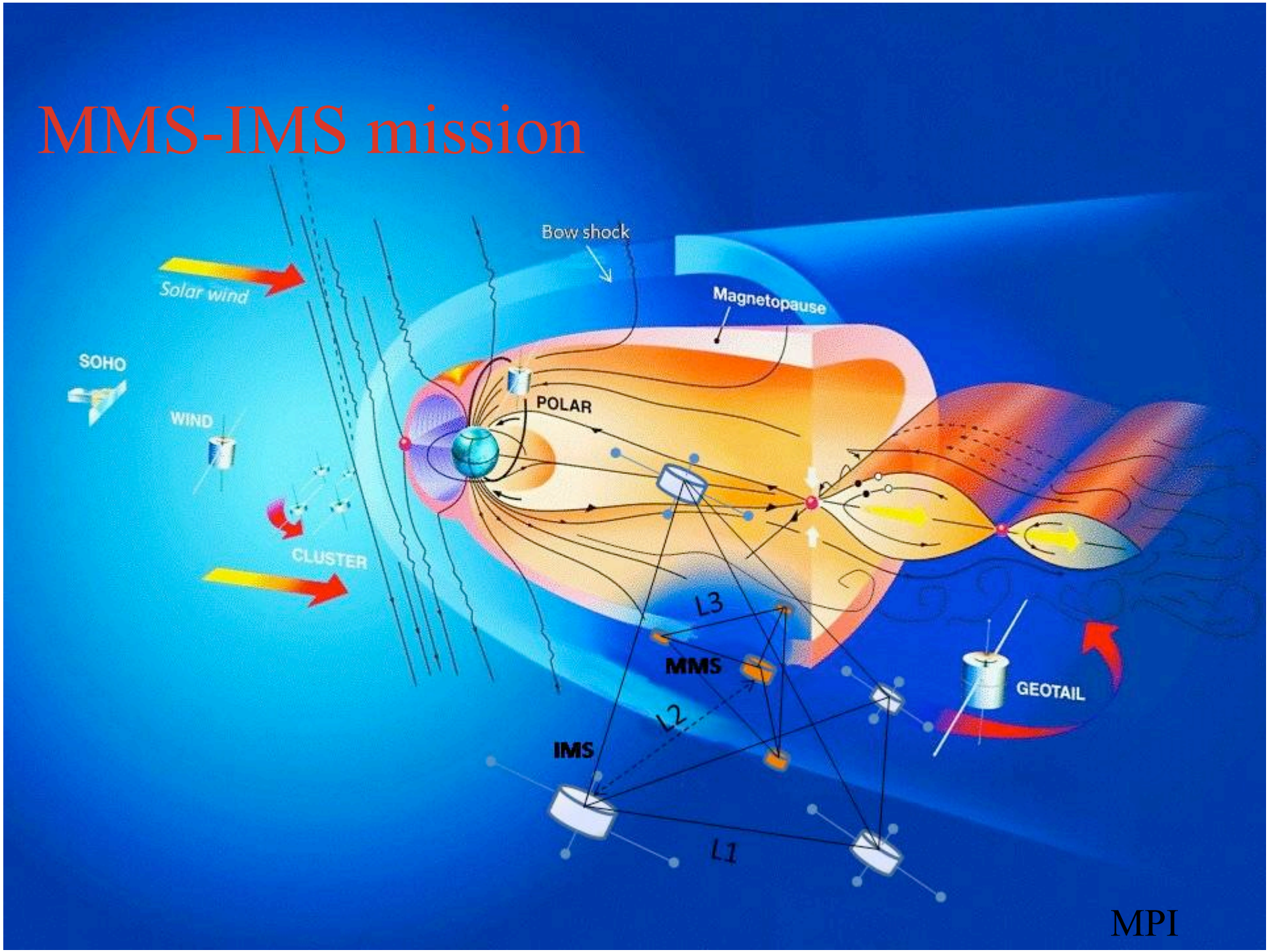
Reconnection at Electron scale



Nested quadrupole structure of magnetic field

(L3=100 km, d_e= 10 km)

MMS-IMS mission

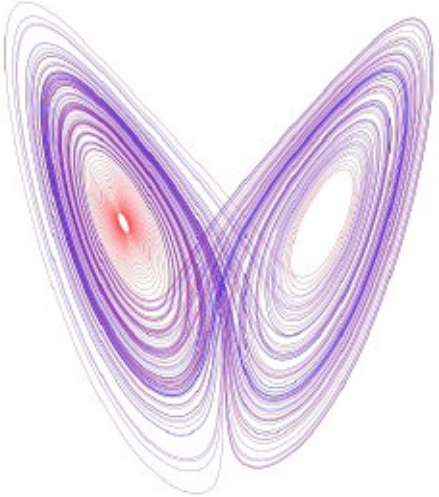


MPI

Nonlinear Dynamics and Complexity

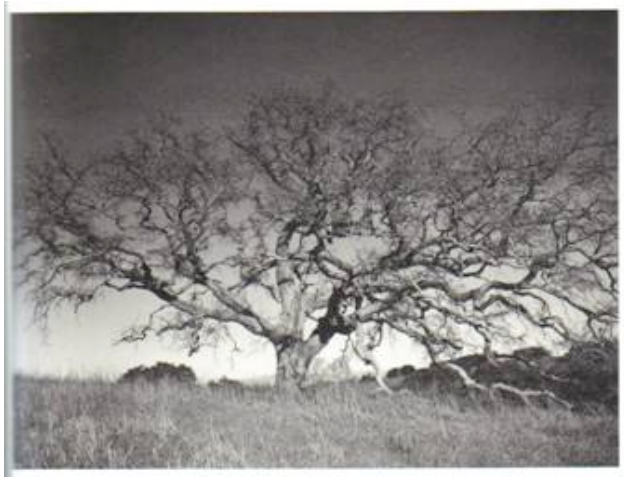
Dynamics (Lorenz, 1963)

- Deterministic dynamics
- Chaos
- Quantitative results
- Weak connection with data



Structure (Mandelbrot, 1977)

- Real objects in nature
  (Trees, clouds, coastline, etc.)
- Fractals
- Multifractals



Dynamics + Structure

Reconstruction of Dynamics

"Geometry from a time series"

(Packard et al., PRL, 1980)

Embedding theorem (Takens, 1981)

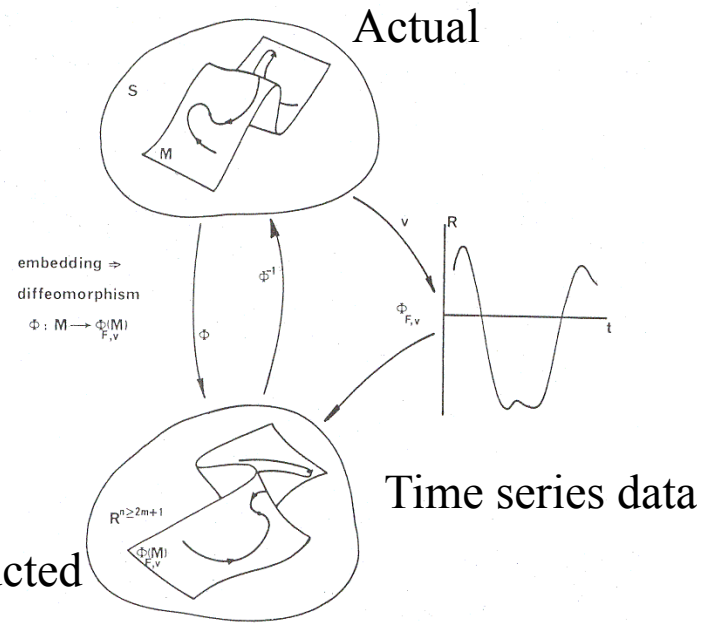
Time series data: $x(t)$

Time-delay embedding:

$$x_k(t_i) = x(t_i + (k\text{-}1)\tau)$$

Reconstructed space:

$$X_i = \{x_1(t_i), x_2(t_i), x_3(t_i), ..\}$$



(Broomhead and King, Phys. A, 1986)

Correlation Dimension

$$C(r) = \sum \Theta(r - |X_i - X_j|) \sim r^{\nu}$$

(Grassberger & Procaccia, PRL, 1983)

Nonlinear Dynamical Modeling – Space Weather

- Solar wind-magnetosphere system modeled as an input-output nonlinear system.

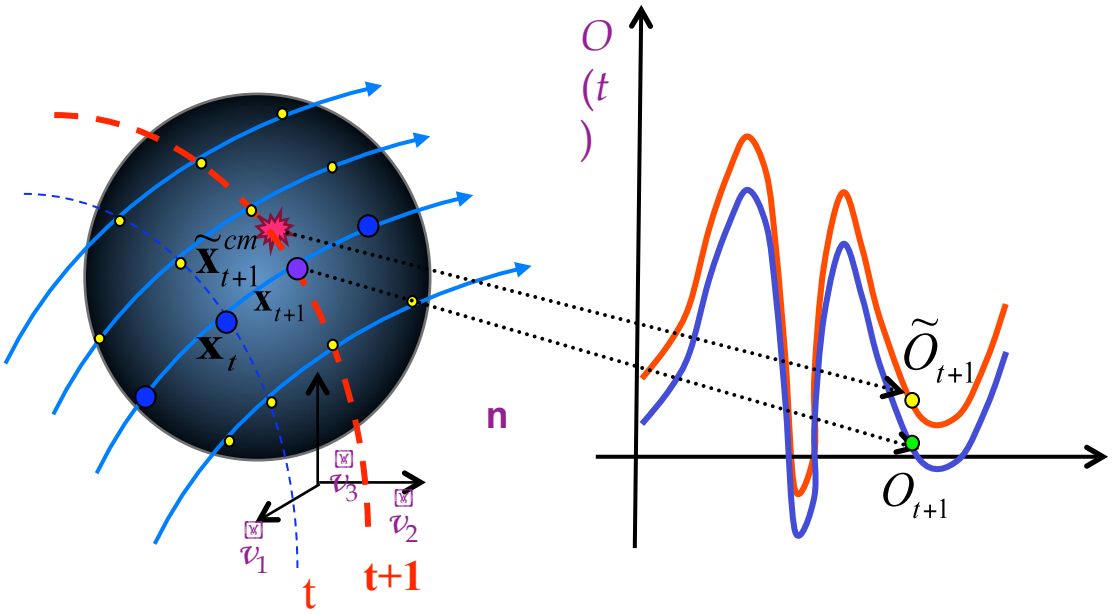
  INPUT: VBz

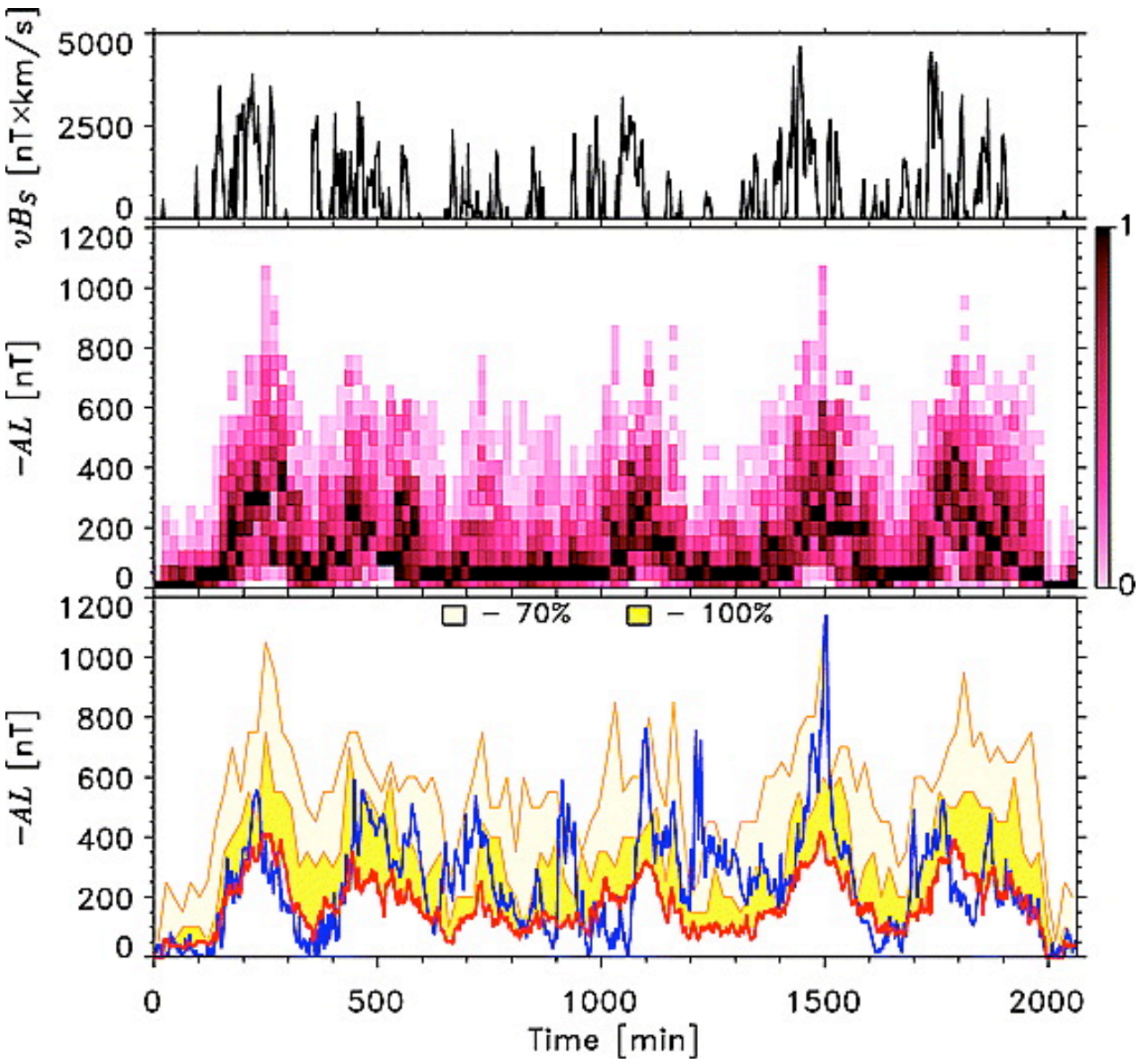
  OUTPUT: AL

  Trajectory matrix :

$$X = N^{-1/2}\begin{bmatrix} I_1(t_1) & I_2(t_1) & \cdots & I_{m/2}(t_1) & O_1(t_1) & O_2(t_1) & \cdots & O_{m/2}(t_1) \\ I_1(t_2) & I_2(t_2) & \cdots & I_{m/2}(t_2) & O_1(t_2) & O_2(t_2) & \cdots & O_{m/2}(t_2) \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ I_1(t_N) & I_2(t_N) & \cdots & I_{m/2}(t_N) & O_1(t_N) & O_2(t_N) & \cdots & O_{m/2}(t_N) \end{bmatrix}_{N\times m}$$

- Local-linear filter prediction [*Vassiliadis et al., JGR,* 1995]
- Mean-field model [*Ukhorskiy et al.,* 2002, 2004]
- Weighted mean-field model [*Chen al.,* 2007, 2008]





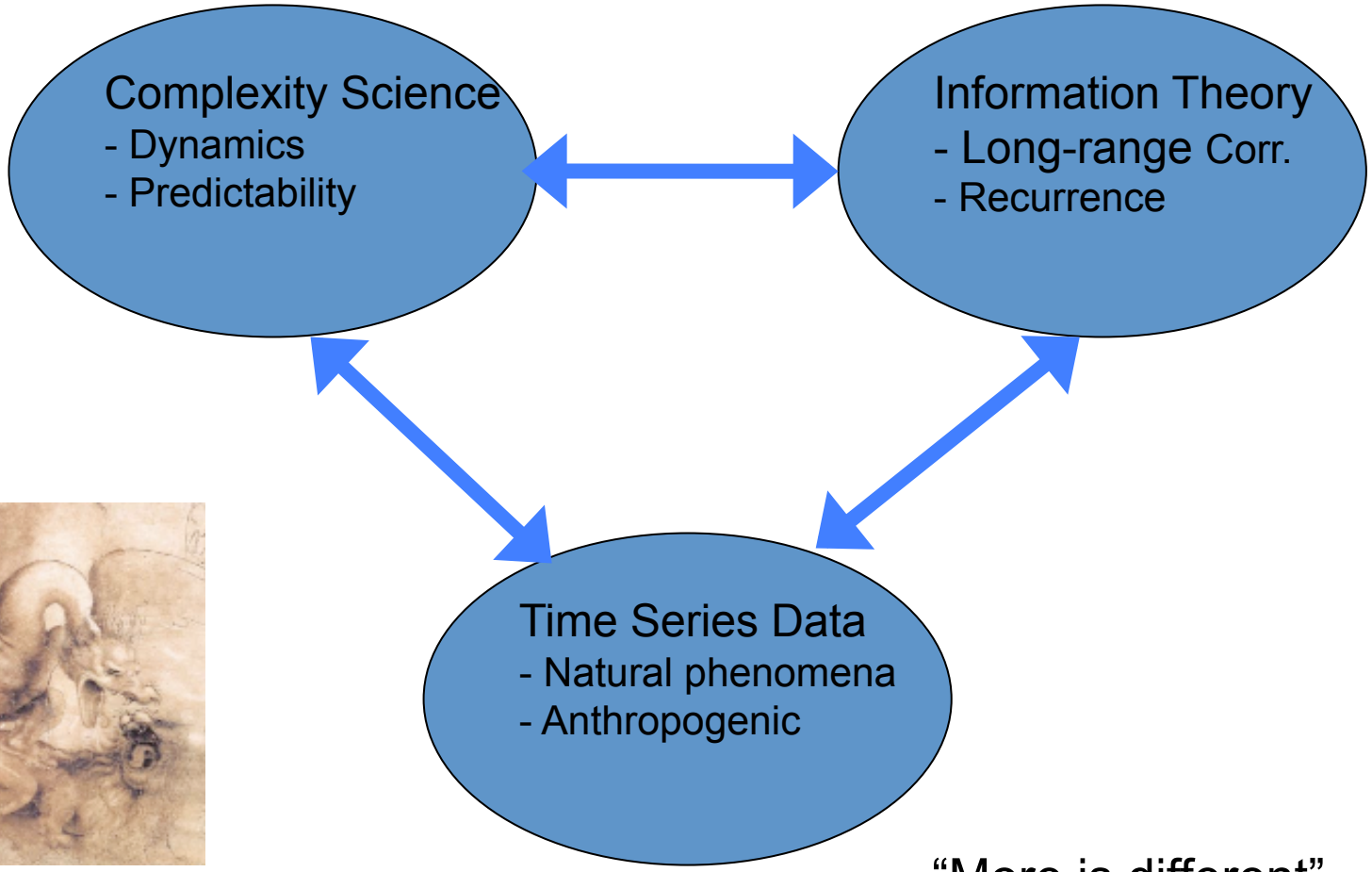
Space Weather Forecasting:

Dynamical prediction - Mean-field model

Deviations (multiscale) -

Conditional probabilities

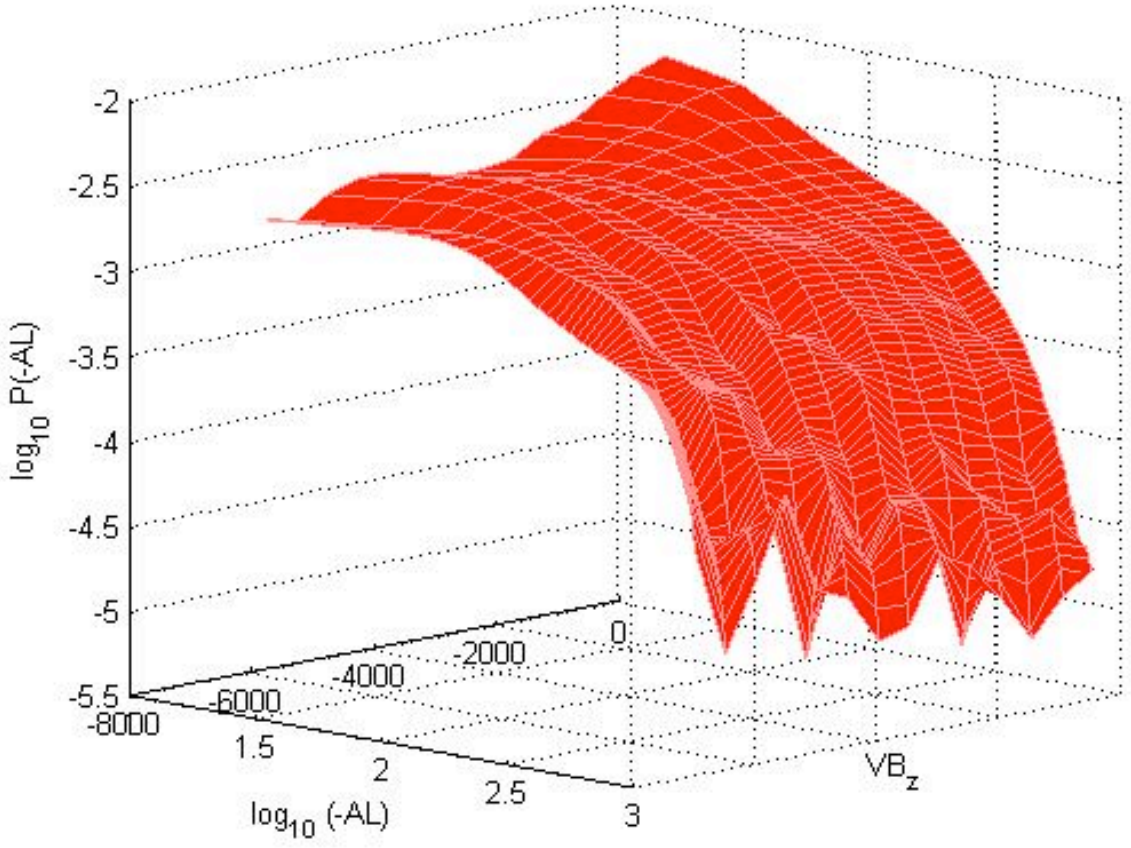
Extreme Events:
Data-derived Modeling Framework



"Here be no dragons"
D. Ruelle, Nature, 2001

"More is different"
P. Anderson, Science, 1972

Conditional Probability Functions: Statistical Physical Approach

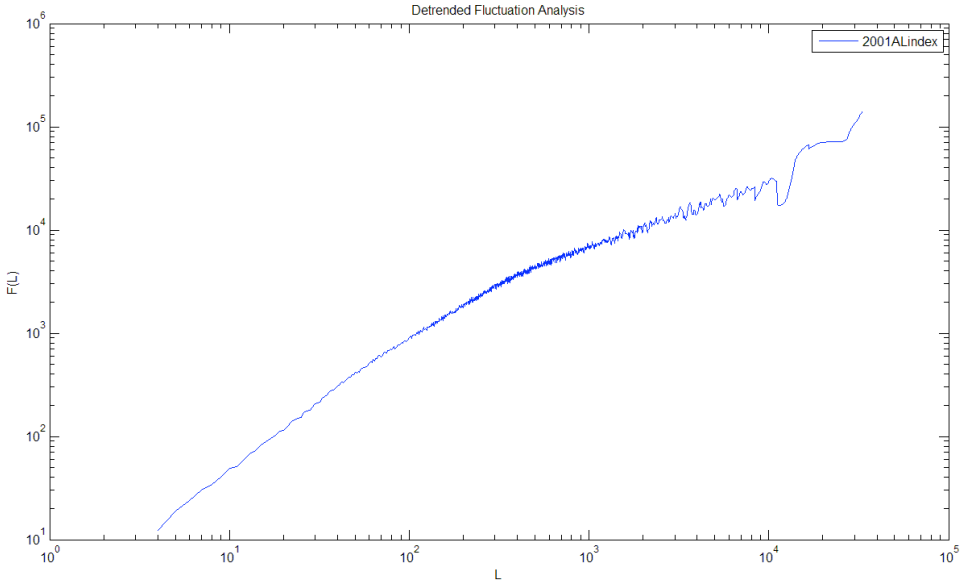


Multiscale phenomenon

Long-range Correlations – Extreme Events

- Measure of inherent behavior
- Characterizes underlying statistical processes
- Clustering of events
- Origins of Extreme events

Detrended Fluctuation Analysis



Substorms

Scaling index = 0.44 (Auto correlation function)

0.96 (Mutual information function)

- Uncorrelated beyond ~ 10 hrs

Nonlinear Dynamics and Complexity

- Two approaches:
  - Nonlinear dynamics (Data-derived modelng)
  - Statistical Physics (Non-equilibrium)

- Improved data-derived modeling:

  Weighted mean-field approach – forecasting global behavior

- Multiscale nature of the magnetosphere

  Conditional (Bayesian) probabilities

- Long-term Correlations

  AL index closer to uncorrelated behavior

- Modeling of extreme events

Planetary Exospheres:

Moon, Mercury, Mars, asteroids, .

Lunar horizon glow, swirls, mini-magnetospheres ..

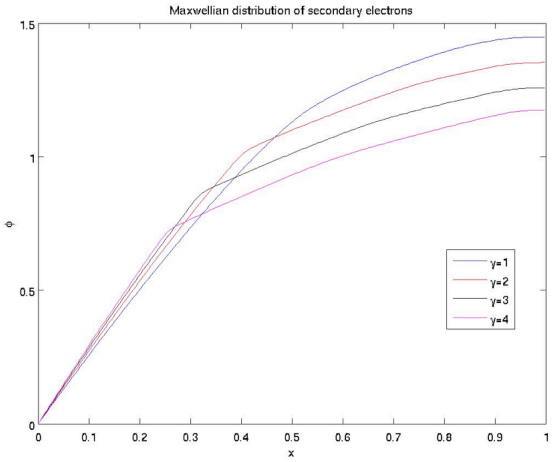
Charging of regolith

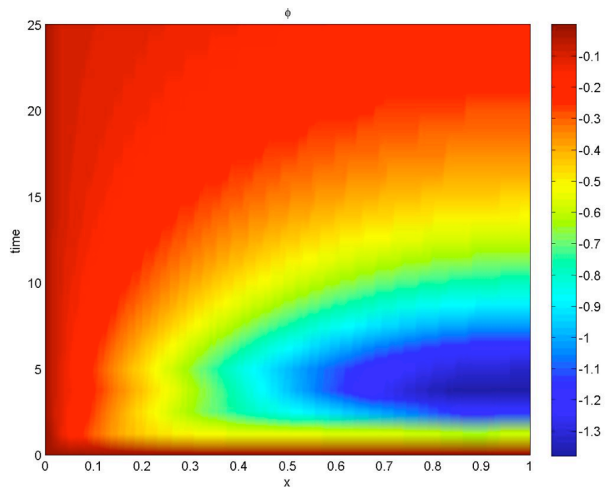
$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}(nv) = 0,$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} = \frac{qE}{m} - \nu H(x - L)v,$$

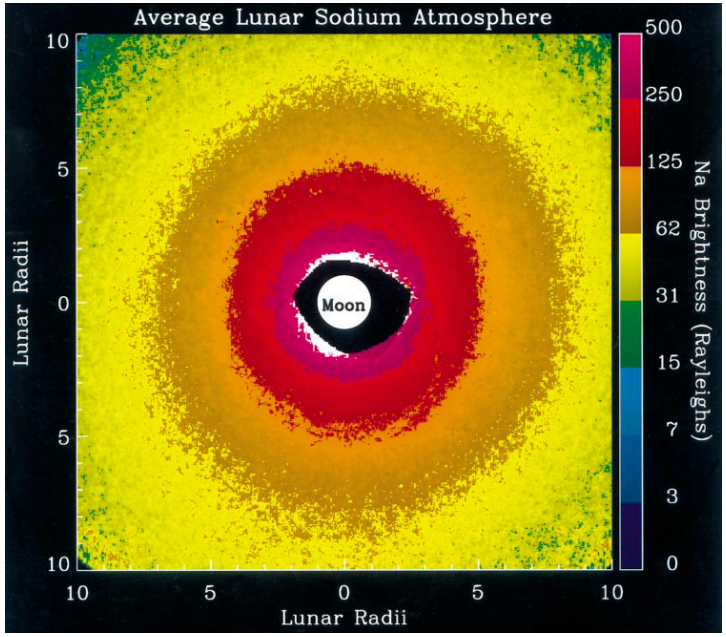
$$\frac{\partial E}{\partial x} = 4\pi n(q + e\gamma n_s),$$

$$n_s = \int_{E_c}^{\infty} f(E)dE$$

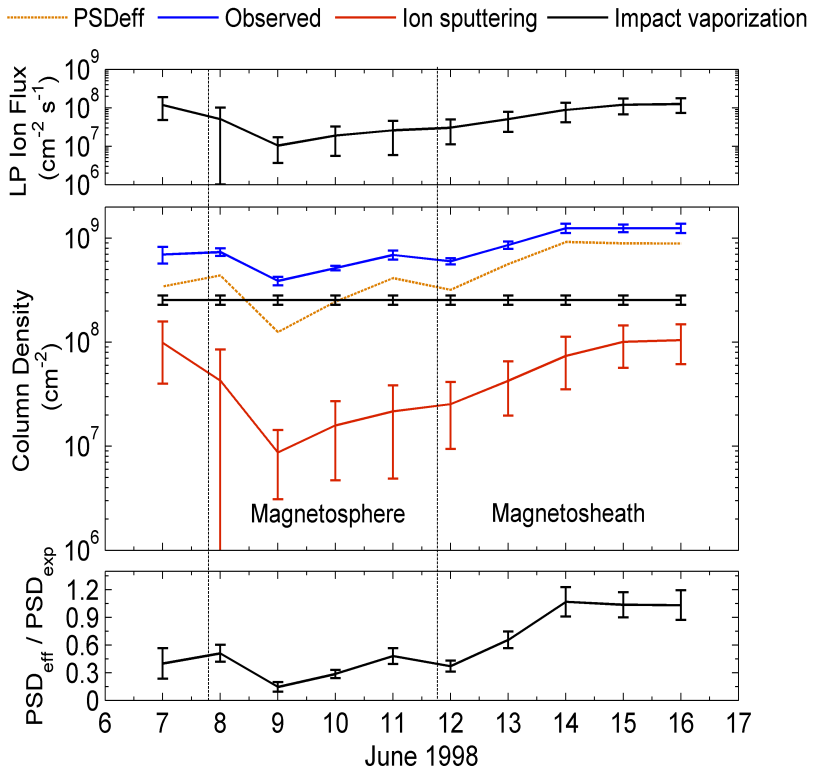




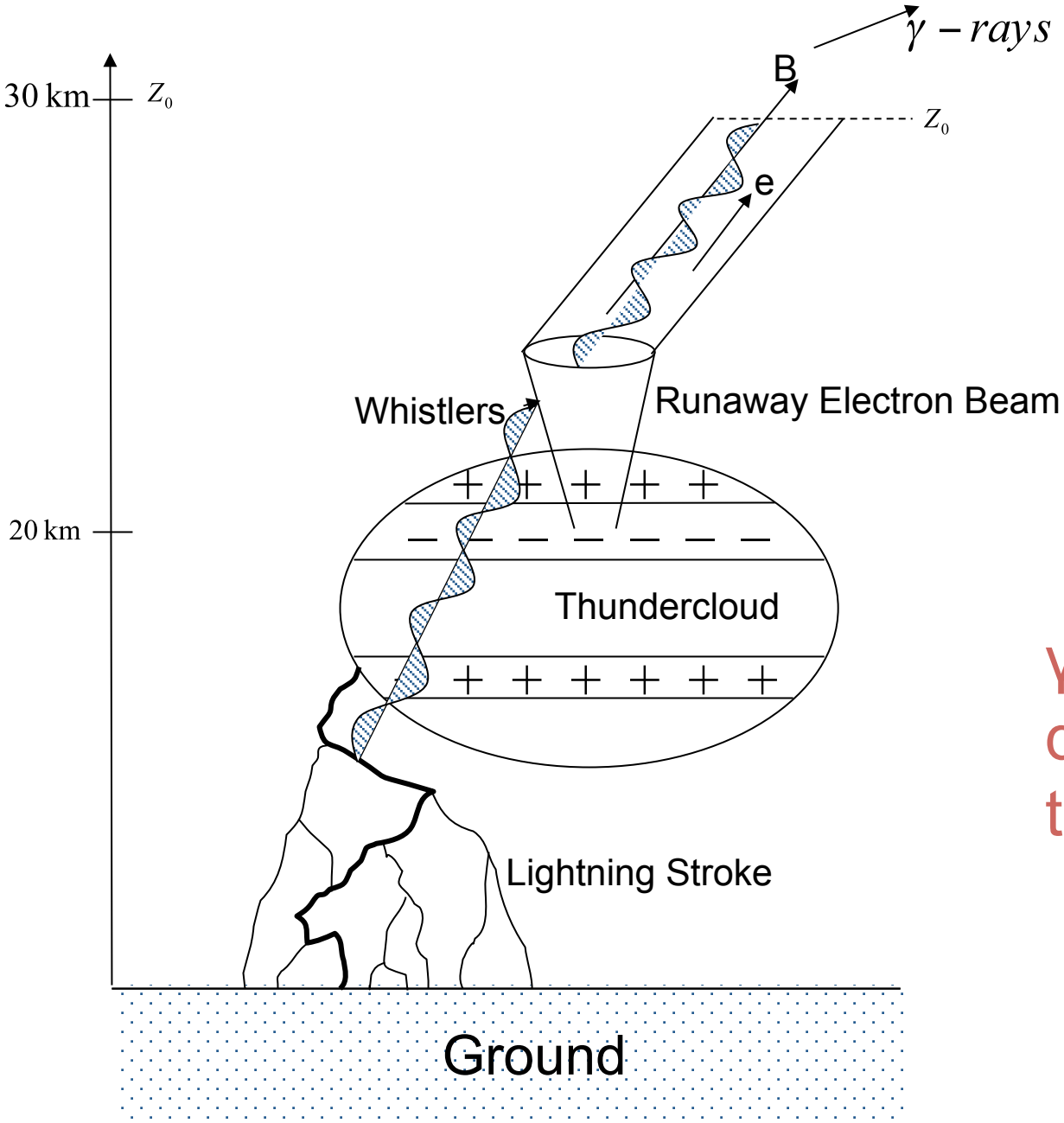
Lunar Na composition



Mendillo, 1999



Sarantos et al. Geophys. Res. Lett. 2008



γ-ray flashes during thunderstorms

MURI
Dennis Papadopoulos PI

FUNDAMENTAL PHYSICS ISSUES ON RADIATION BELT DYNAMICS AND REMEDIATION

PARTICIPATING UNIVERSITIES

UNIVERSITY OF MARYLAND, COLLEGE PARK

STANFORD UNIVERSITY

UNIVERSITY OF CALIFORNIA, LOS ANGELES

DARTMOUTH COLLEGE

VIRGINIA TECH

Space and Astrophysical Plasma Processes

- Theory
- Modeling
- Simulations

- First principles
- Dynamical systems