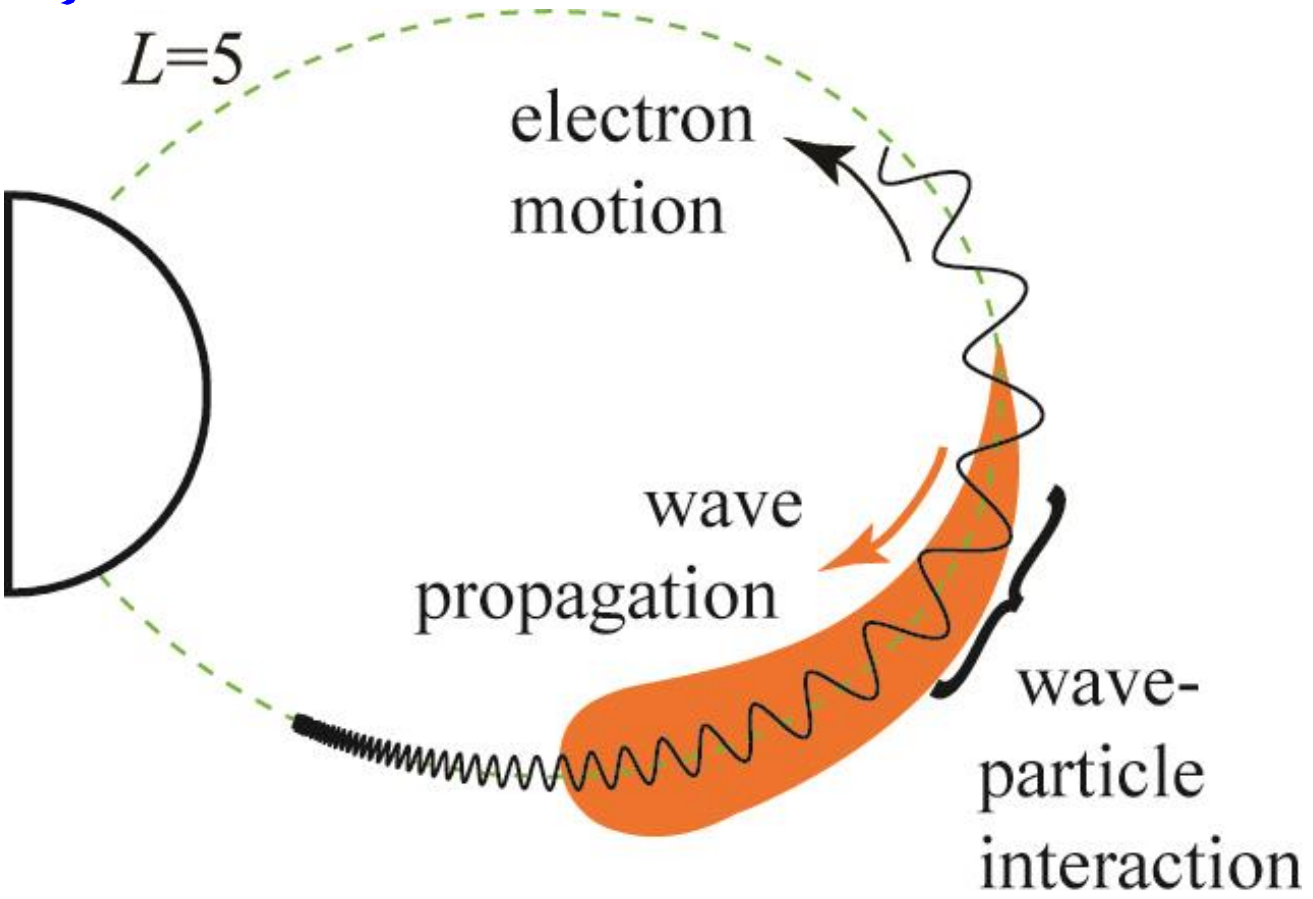
Space Physics Master's Course
Lecture 7
Space Magnetic Storms



Recommended Reading

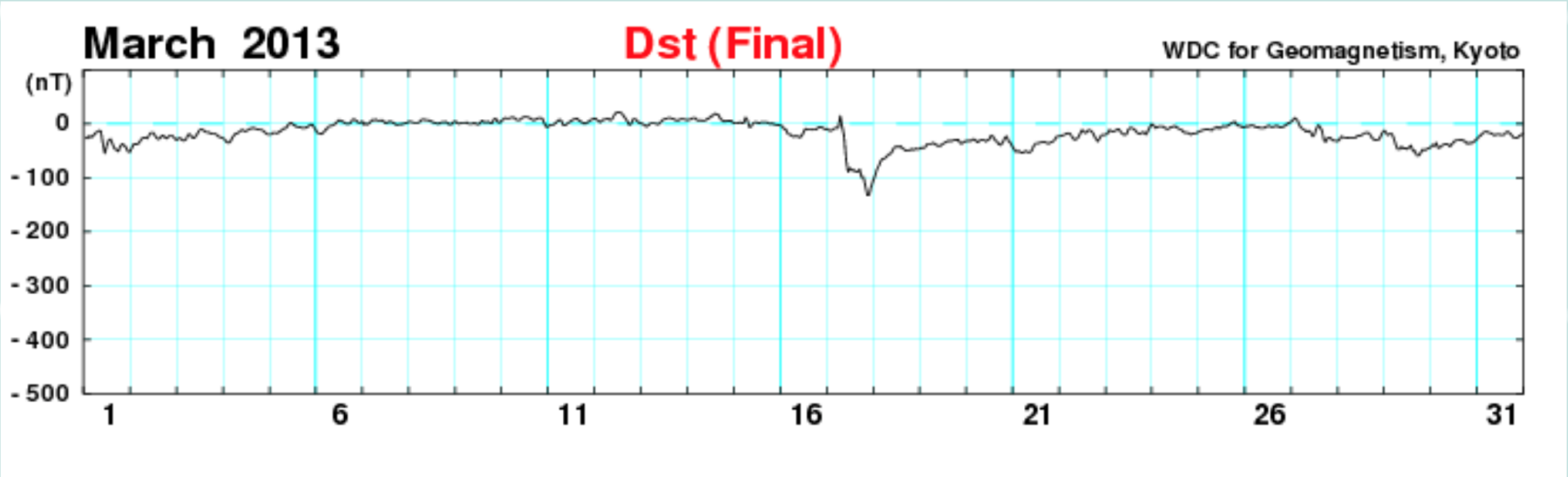
Διαστημική Φυσική: Δαγκλής, Κατσαβριάς, Γεωργίου, Σέργης. Κεφάλαιο 8

(https://repository.kallipos.gr/handle/11419/11507)

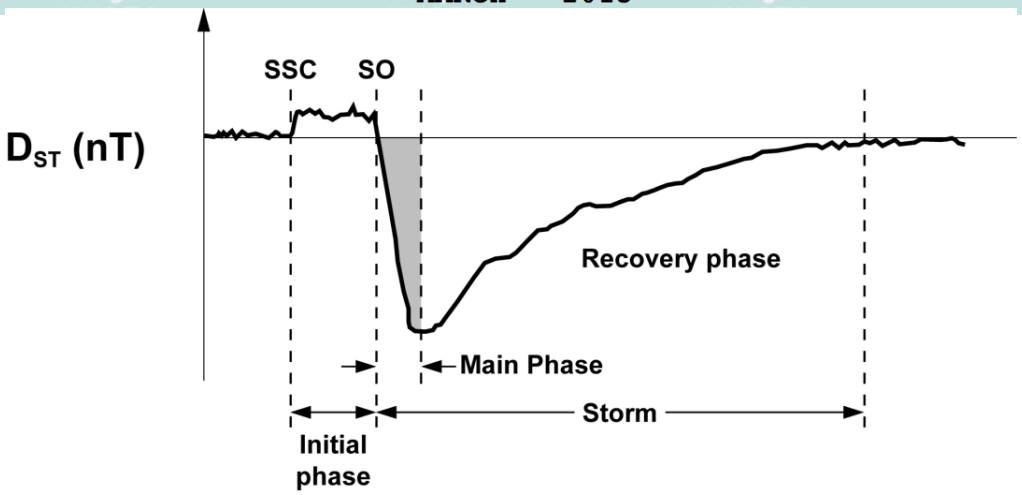
Storms and radiation belts: Reeves and Daglis

https://eclass.uoa.gr/modules/document/file.php/PHYS367/Βιβλιογραφία/Chapter%203%20Reeves%20and%20Daglis.pdf

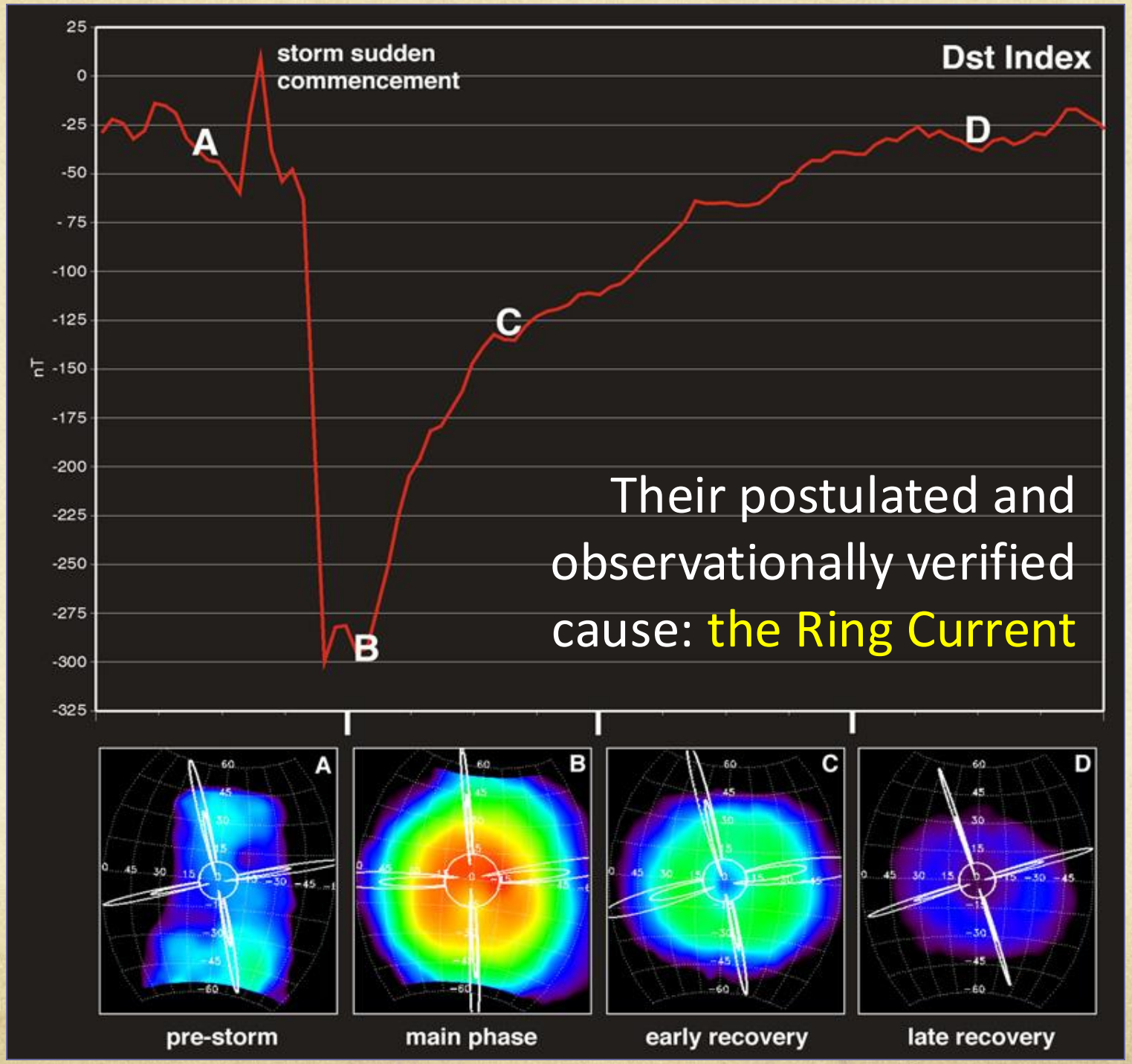
Kyoto Word Data Center for Geomagnetism



WDC for Geomagnetism, Kyoto
Hourly Equatorial Dst Values (FINAL)
MARCH 2013

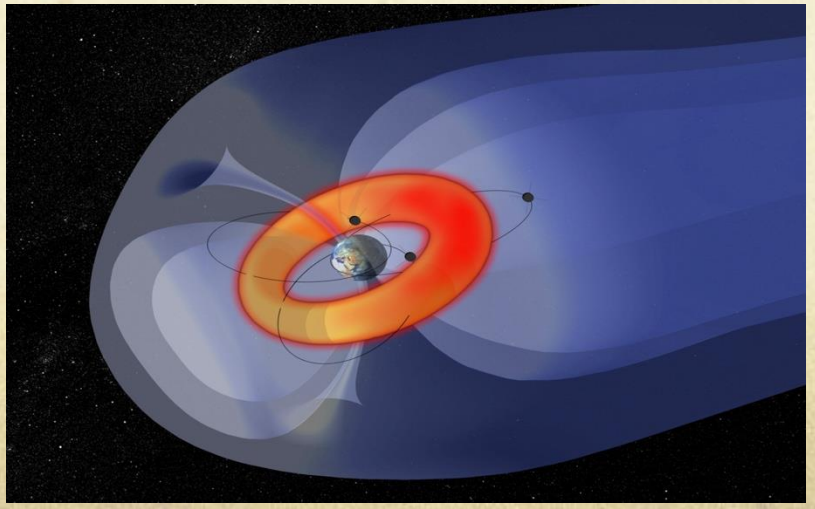


Magnetic Storms

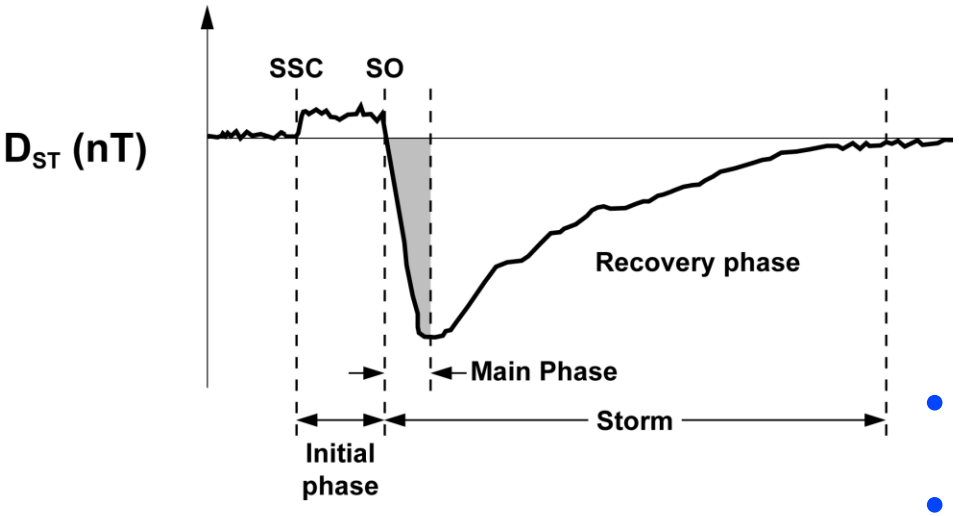


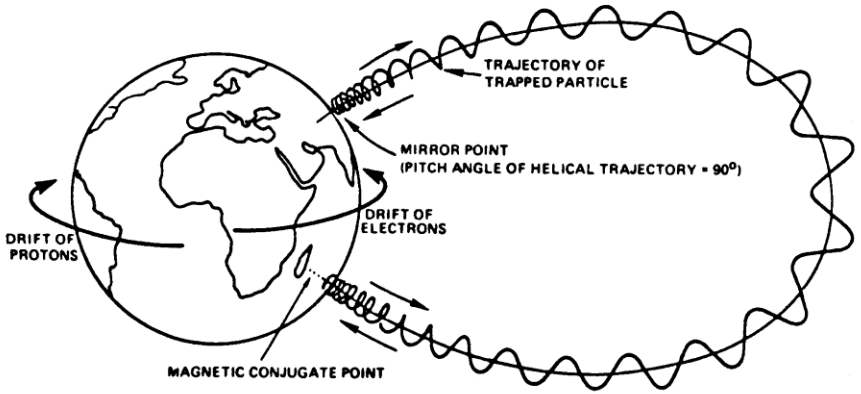
Ring Current

- Carried mainly by ions (H^+, O^+, N^+, He^{++}, He^+) in the energy range ~1 keV to a few 100s keV
- Bulk of energy within 50-100 keV
- Spatial extent: ~2-8 R_E (geocentric)
- Maximum intensity at ~3-5 R_E (geocentric)



Geomagnetic Storm: Ring Current Evolution





- **Composition: e^-, H^+, He^+, O^+, N^+, He^{++}**
- **Energy Range: ~ 1 keV < E < 300 keV**
- **Location: ~ 2 < L < 8**
- **Energy Density: ~ 10 - 1000 keV/cm^3**

THE INTERRELATIONSHIP OF MAGNETOSPHERIC PROCESSES

VYTENIS M. VASYLIUNAS

Dept. of Physics and Center for Space Research, Massachusetts Institute of Technology, Cambridge, Mass., U.S.A.

"One Ring to rule them all . . ."
J. R. R. TOLKIEN

1. Introduction

Convection of plasma in the magnetosphere is one of the major aspects of magnetospheric dynamics. Attempts during the past 10 yr to understand this complicated phenomenon have led to a sequence of theoretical models of constantly increasing sophistication (see, for example, Axford (1969)). Most of these models have been

Vasyliunas, in *Earth's Magnetospheric Processes*, 1972

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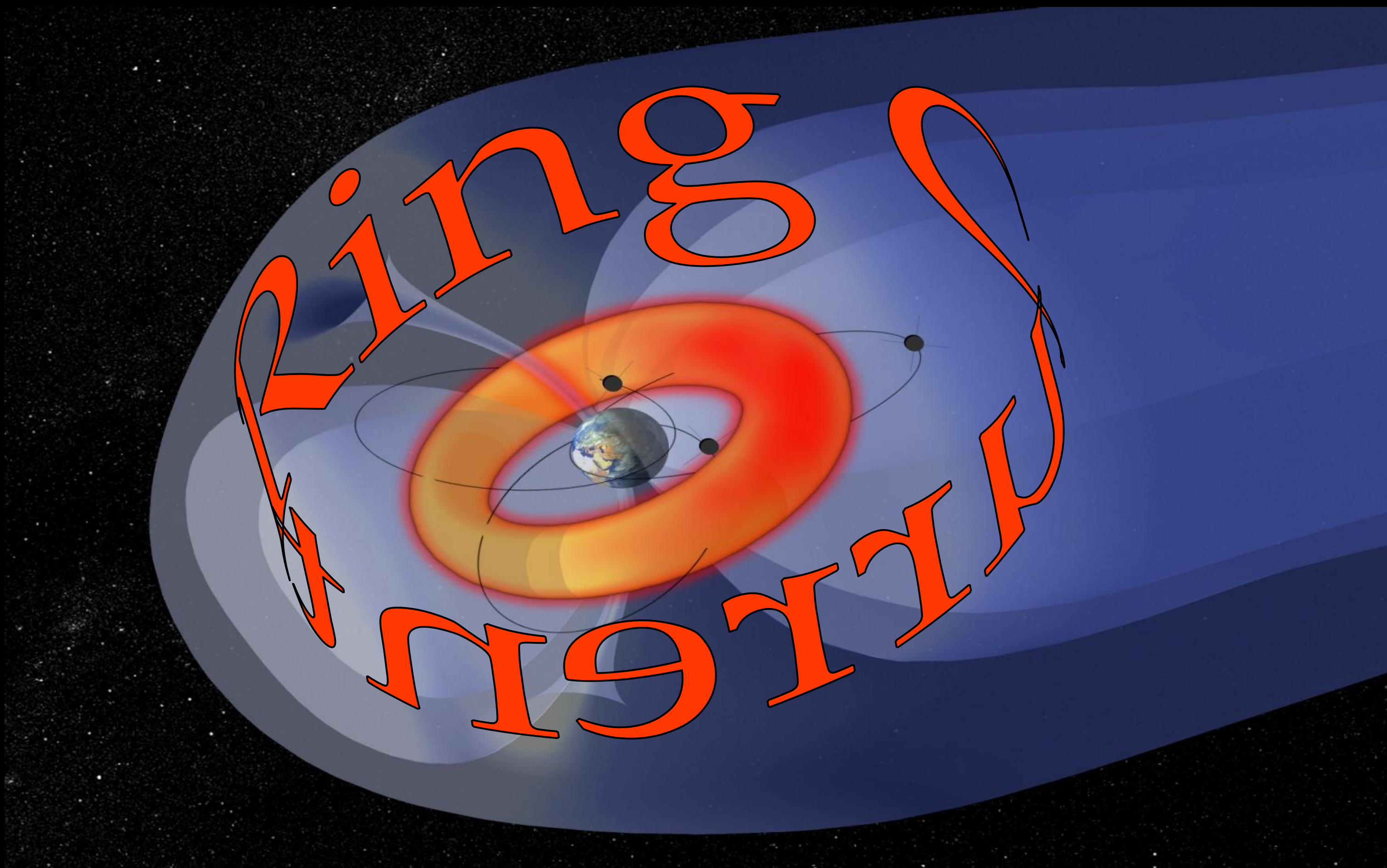

Ring Current


One Ring to rule them All


One Ring to rule them All

The ring current was the first space particle population theoretically predicted, in an effort to explain the occurrence of magnetic storms.

The radiation belts were the first space particle population to be actually discovered.

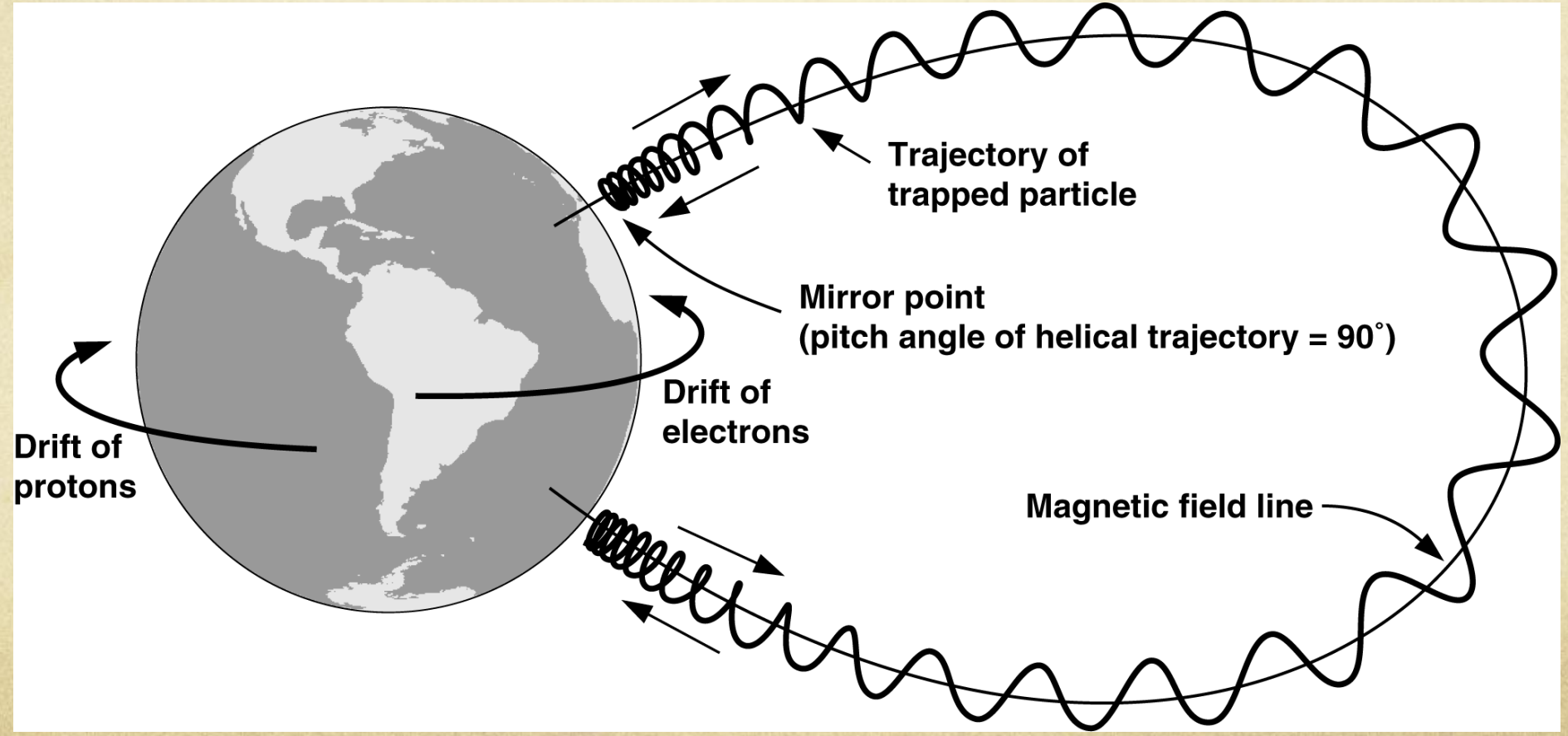
Their main difference is their energy level.

Van Allen Radiation Belts

Same principle as RC:

a combination of gyro, bounce and drift motions

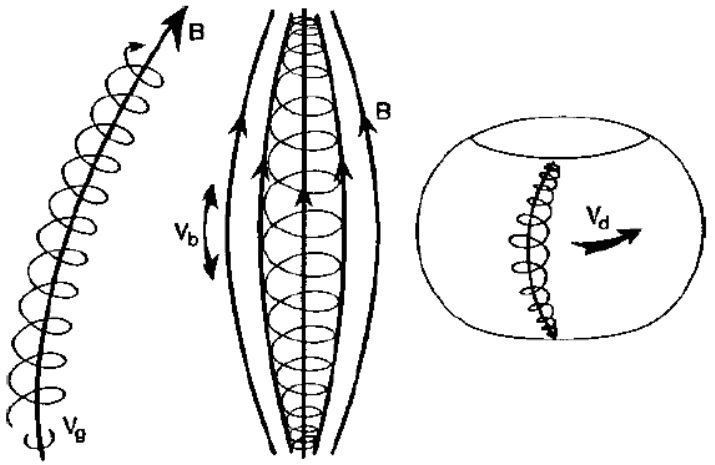
corresponding to three invariants



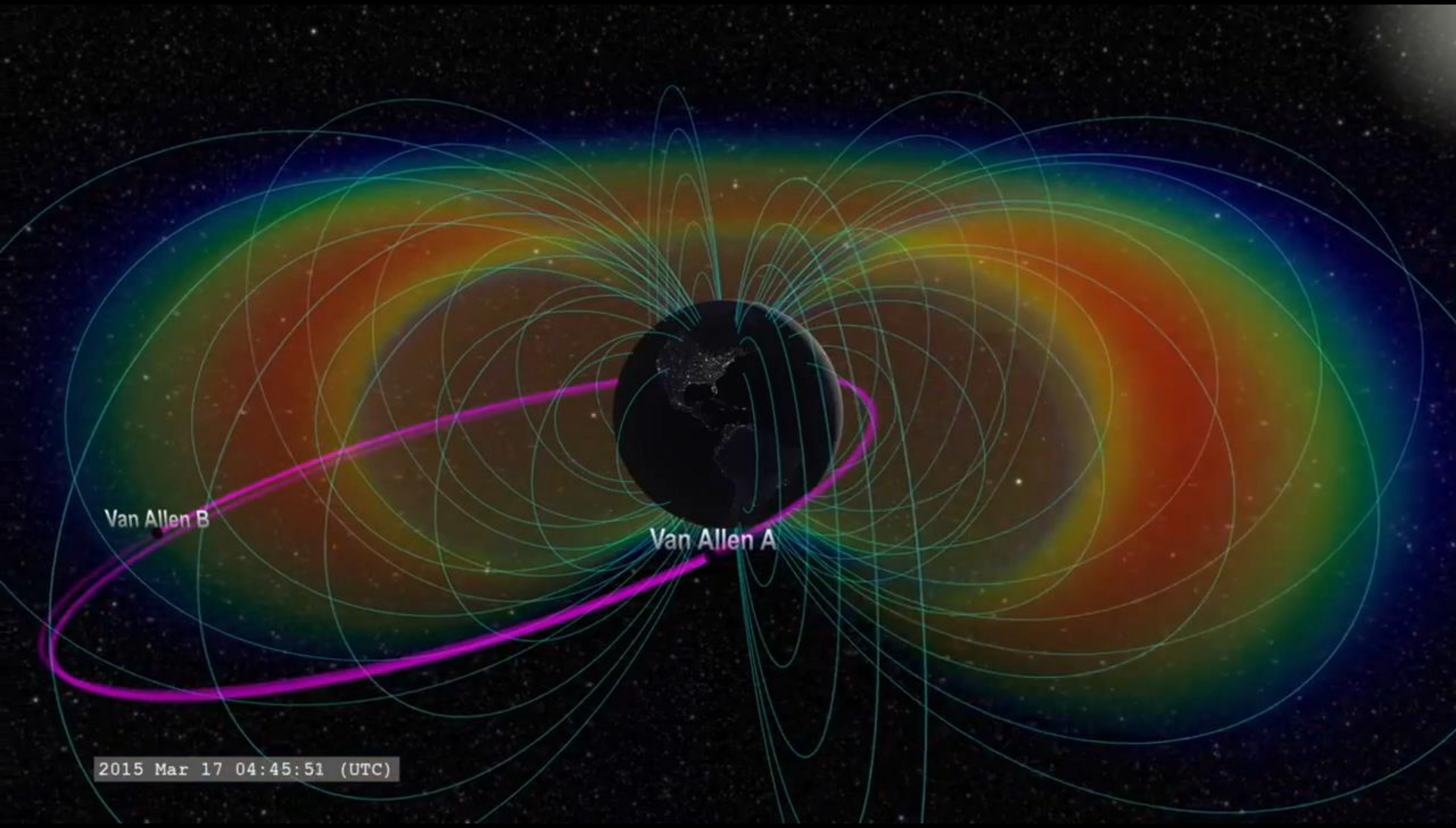
Periodic motion

- Energetic particles undergo three types of periodic motion:
  - They gyrate around the magnetic field
  - They bounce between the mirror points
  - They drift around the Earth
- Associated adiabatic invariant

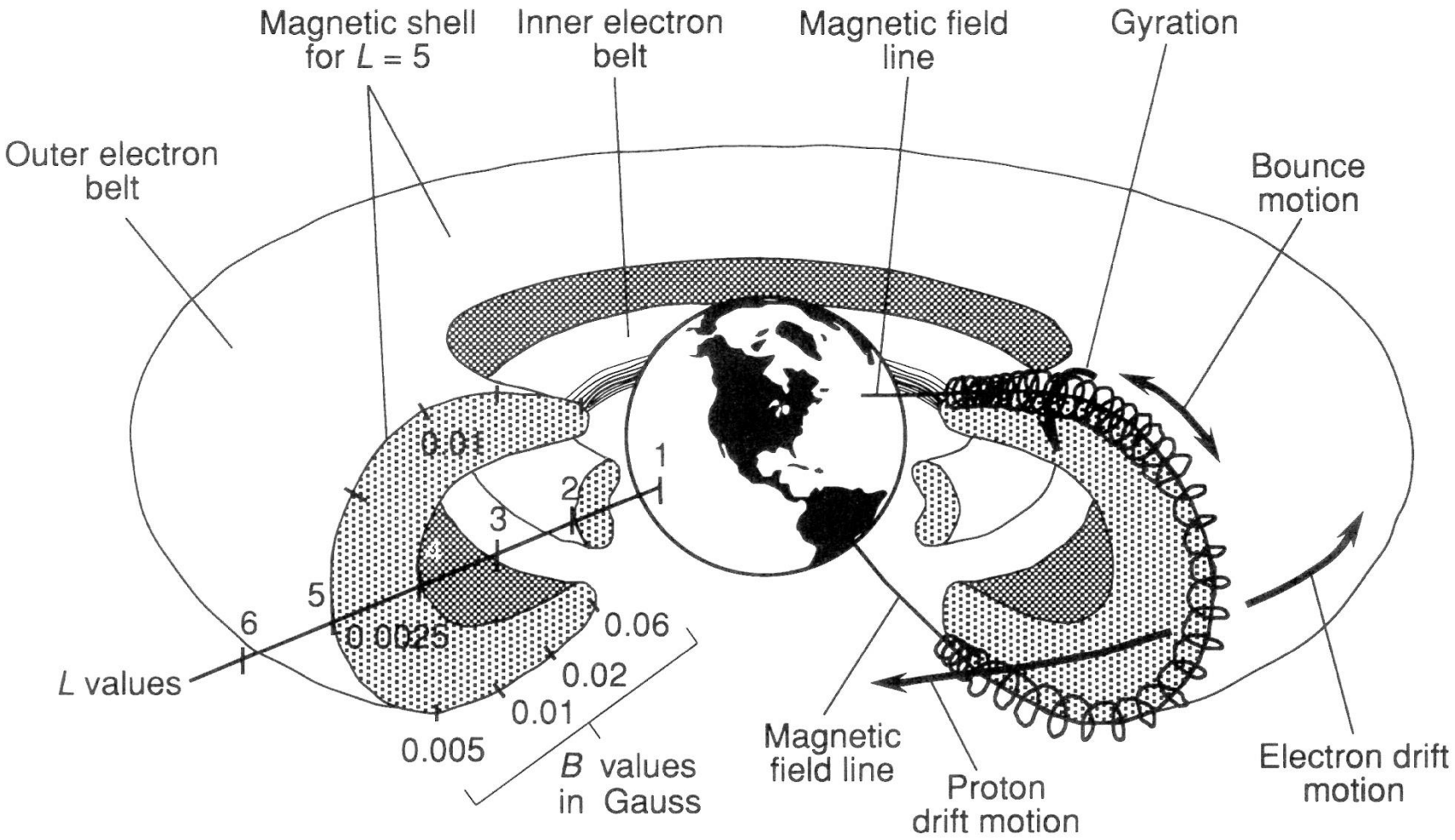
1 MeV electron, $\alpha = 45°$, $L = 4.5$



	gyro motion	bounce motion	drift motion
f	10 kHz	3 Hz	1 mHz
T	0.1 ms	0.36 s	15 min
	$\mu = \frac{p_\perp^2}{2mB}$	$J = \int_{bounce} p_\parallel ds$	$\Phi = \int_{drift} BdS$


Van Allen B
Van Allen A
2015 Mar 17 04:45:51 (UTC)

Van Allen Belts



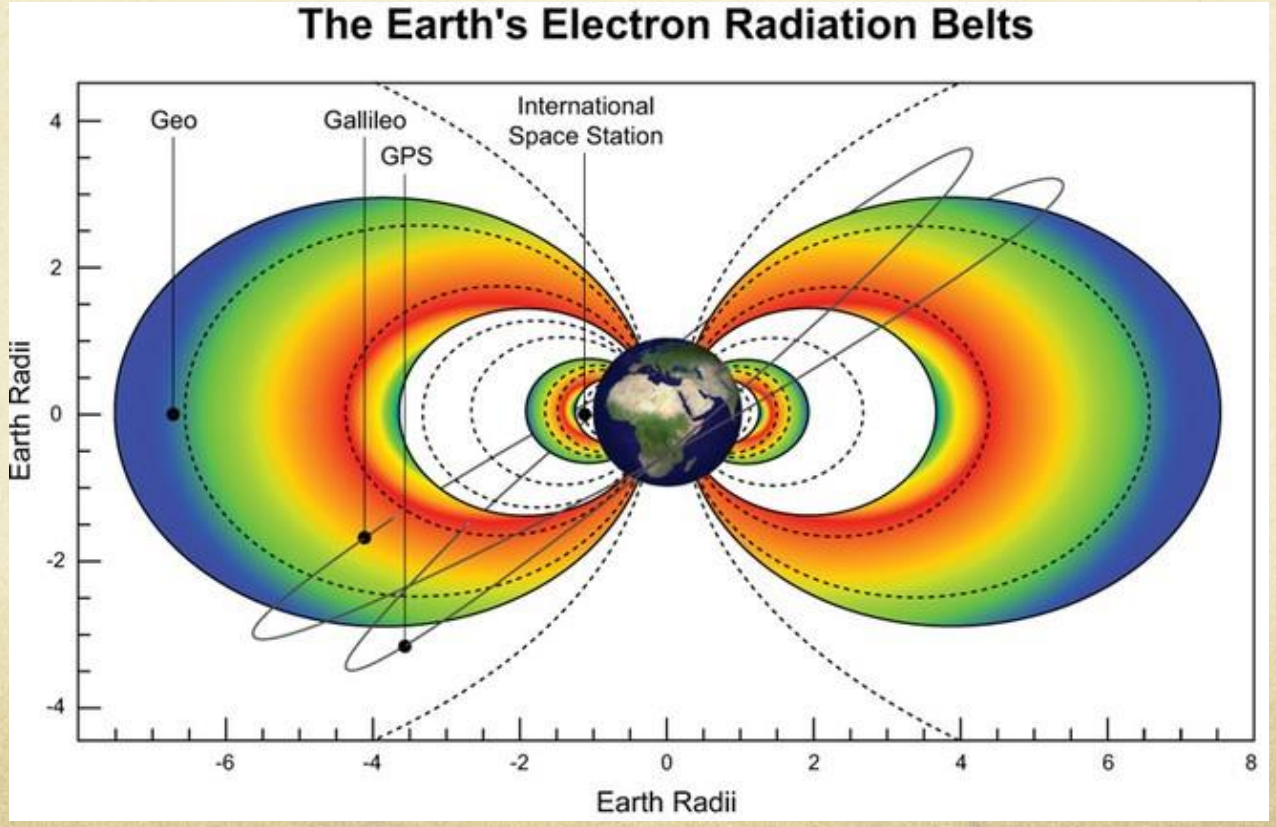
Mitchell [1994]

Van Allen Radiation Belts

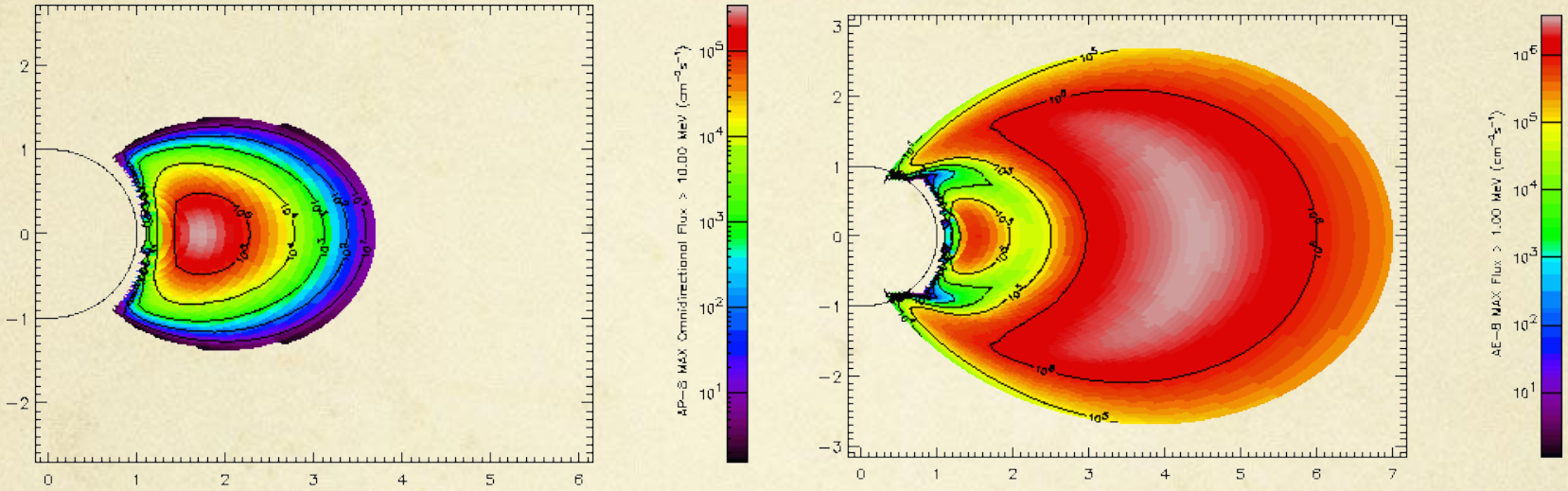
Distinguished by their (very) high energies:

100 keV – 10+ MeV (400 MeV)

and posing considerable threat to space assets



Van Allen Radiation Belts



Integral proton flux > 10 MeV
AP8 static model

Integral electron flux >1 MeV
AE8 static model

Ions:

- mainly protons
- confined to the inner zone
- energies 100's keV < E < 400 MeV

Electrons:

- two distinct populations: inner & outer zone
- energies 100 keV < E < 20 MeV
- steep power law: $E^{-(5-8)}$

The first artificial radiation belt

- Nicholas Christofilos, a Greek scientist who migrated in the US in 1953, had proposed in October 1957 that charged particles could be trapped around the Earth and that an artificial radiation belt, due to beta decay, could be created by exploding one or more small nuclear fission bombs at high altitude (~200 km)

The first artificial radiation belt

Christofilos' proposal evolved into Argus - the first active experiment in space, which was successfully performed in 1958

JOURNAL OF GEOPHYSICAL RESEARCH VOLUME 64, No. 8 August, 1959

The Argus Experiment*

N. C. CHRISTOFILOS

Lawrence Radiation Laboratory, University of California
Livermore, California

Abstract—A geophysical experiment on global scale was conducted last fall. Three small A-bombs were detonated beyond the atmosphere at a location in the south Atlantic. The purpose of the experiment was to study the trapping of the relativistic electrons (produced by the β-decay fission fragments) in the geomagnetic field. The released electrons are trapped by this field oscillating along the magnetic lines between two mirror points. In addition to this motion the electrons drift eastward, creating a thin electron shell around the earth. The lifetime and location of the thus-created global electron shell were measured by satellite- and rocket-borne instruments. Auroral luminescence was observed at the conjugate points. The electron shell exhibited remarkable stability during its lifetime. *No* motion of the shell or change in its thickness was detected.

This experiment was proposed by the writer a few weeks after the launching of the

The first artificial radiation belt

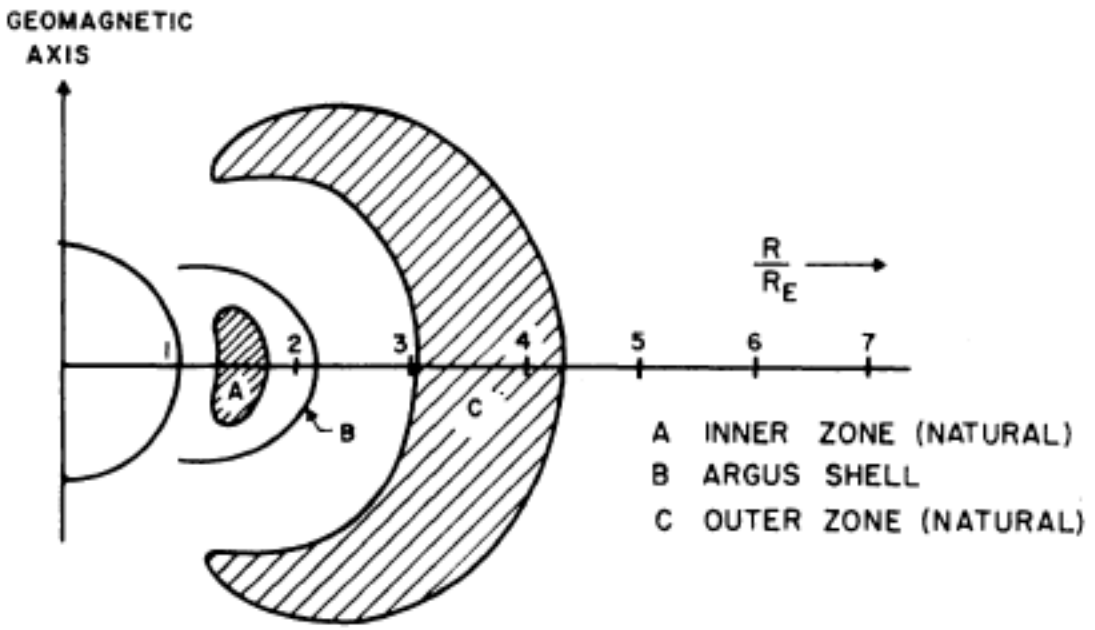
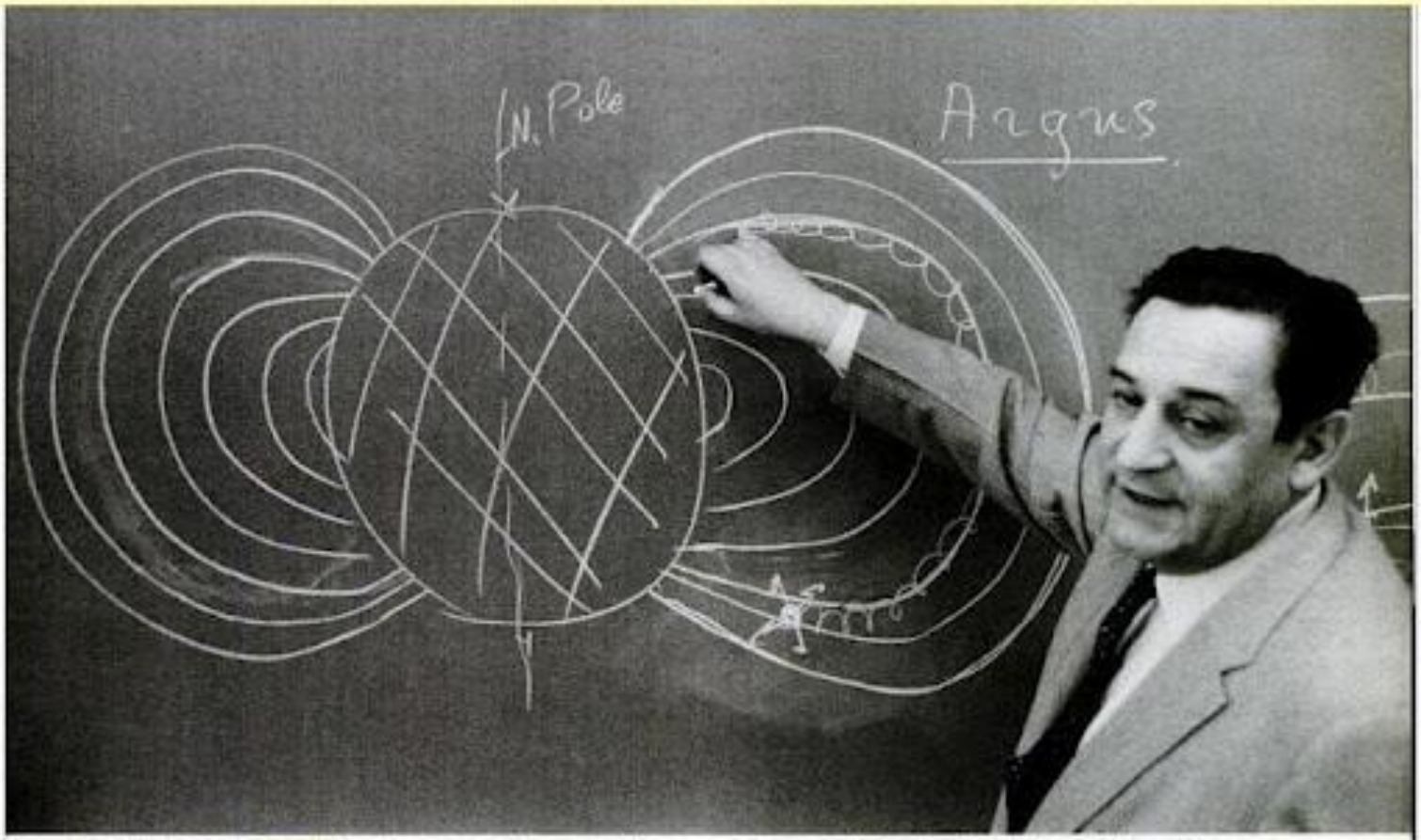


FIG. 19.—The general relationship of the Argus shells to the structure of the natural radiation zones. See references 4 and 5.



EXPLAINING ARGUS, Christofilos shows how magnetic field encompasses the earth (center). When nuclear bomb is detonated (*symbol at lower right*) some of its radiation is trapped and travels along lines of magnetic force to point at opposite end of line. Then it spreads around the earth in a thin shell of electrons.

TRIUMPH IN SPACE FOR A 'CRAZY GREEK'

Theory of Boston-born maverick scientist led to sensational Project Argus

Magnetic storms = strong ring current

Storm-time RC build-up involves

massive acceleration of ions,

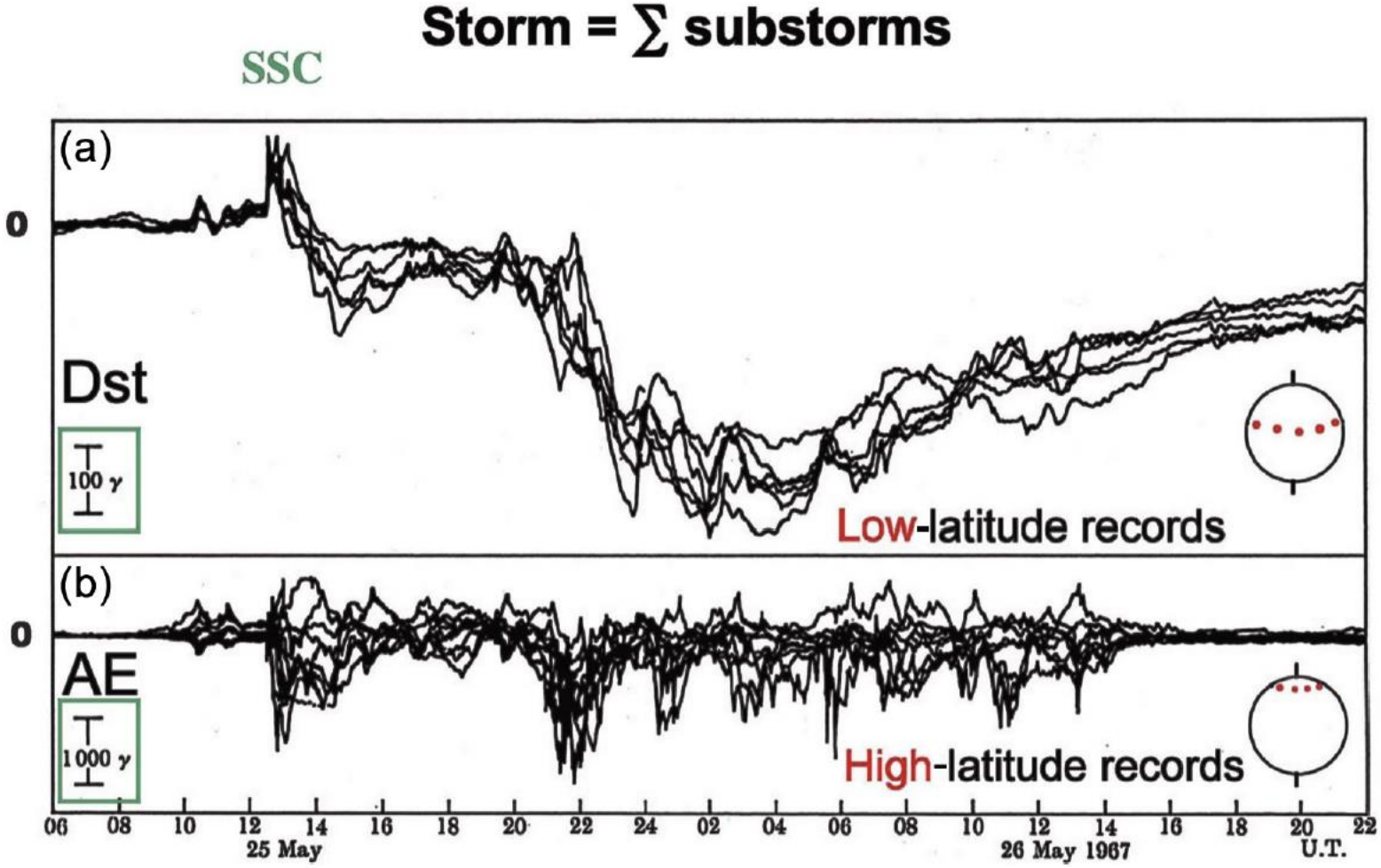
from a few keV to 100s keV.

Result of impulsive induced electric fields

or steady large-scale electric field?

(i.e. **substorms or convection?**)

The original Chapman-Akasofu storm-substorm concept



Rikubetsu 1994 (Kamide+, JGR1998)

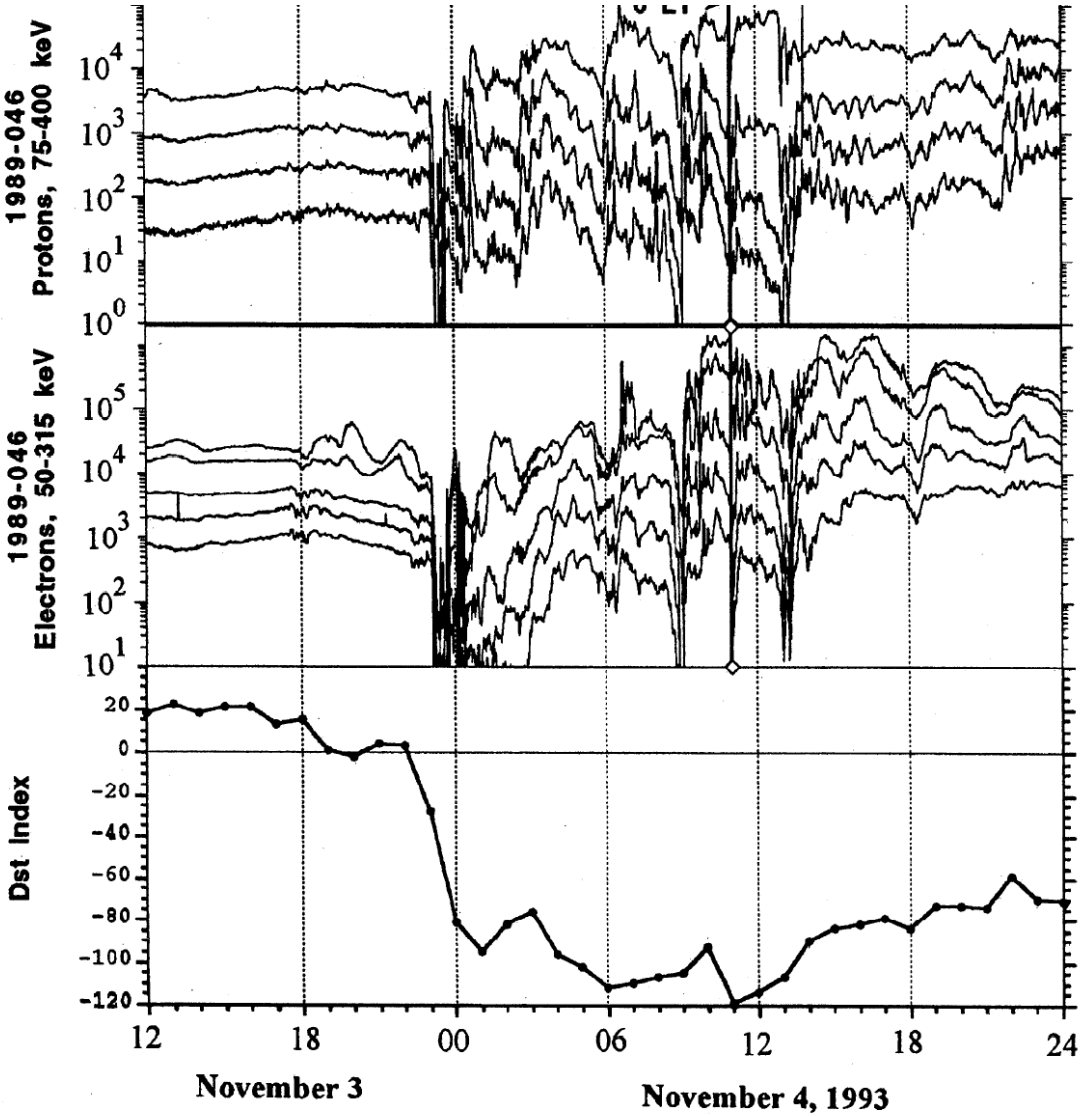
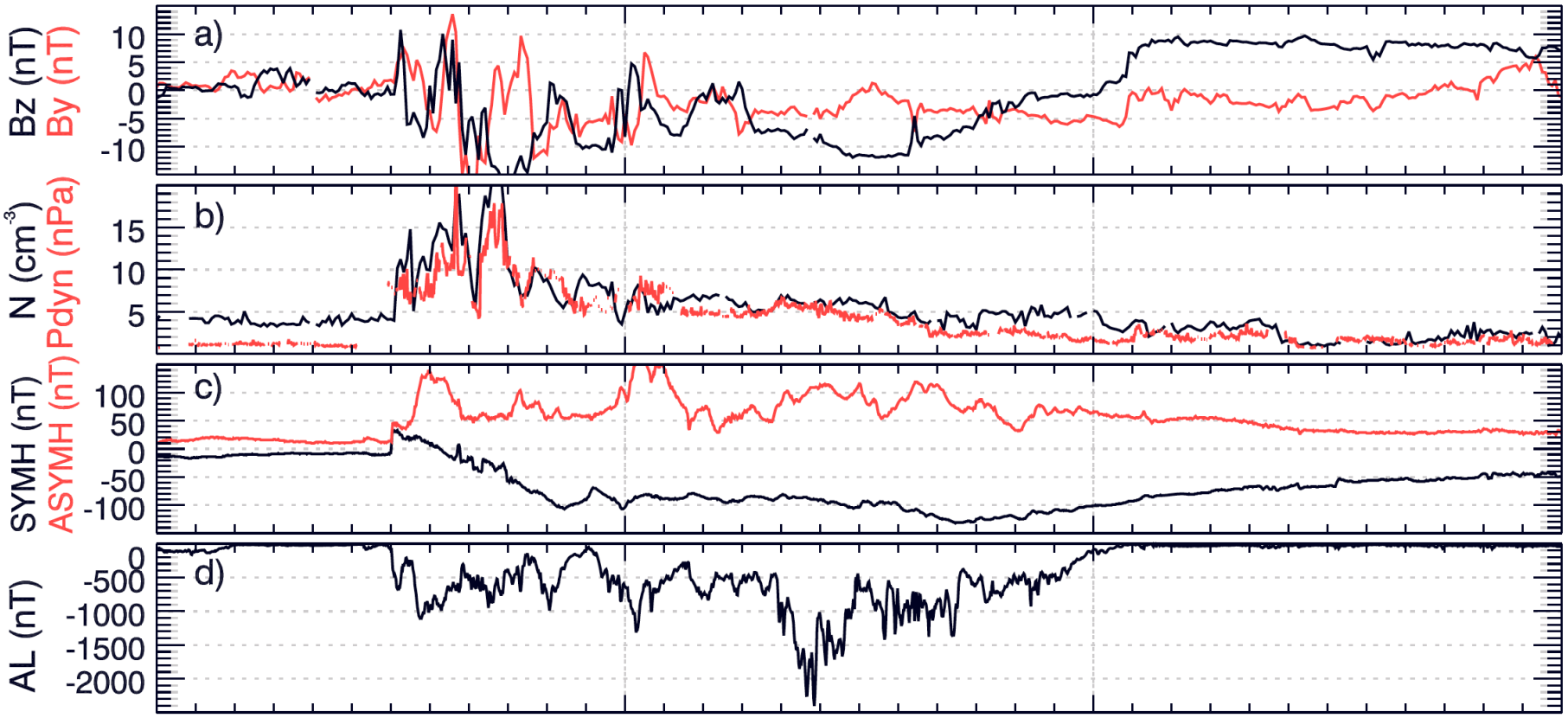


Figure 11. The response of geosynchronous energetic particles to the November 3-5, 1993, geomagnetic storm known as the "National Space Weather Event." The figure shows proton and electron fluxes from two geosynchronous satellites along with the *Dst* index for this period. Very strong injections of energetic particles are observed. However, a direct, quantitative relationship between geosynchronous injections and the development of *Dst* is difficult to establish.

March 2013 storm, Van Allen Probes



Gkioulidou+, JGR 2014

Rikubetsu 1994 (Kamide+, JGR1998)

Substorms or convection?

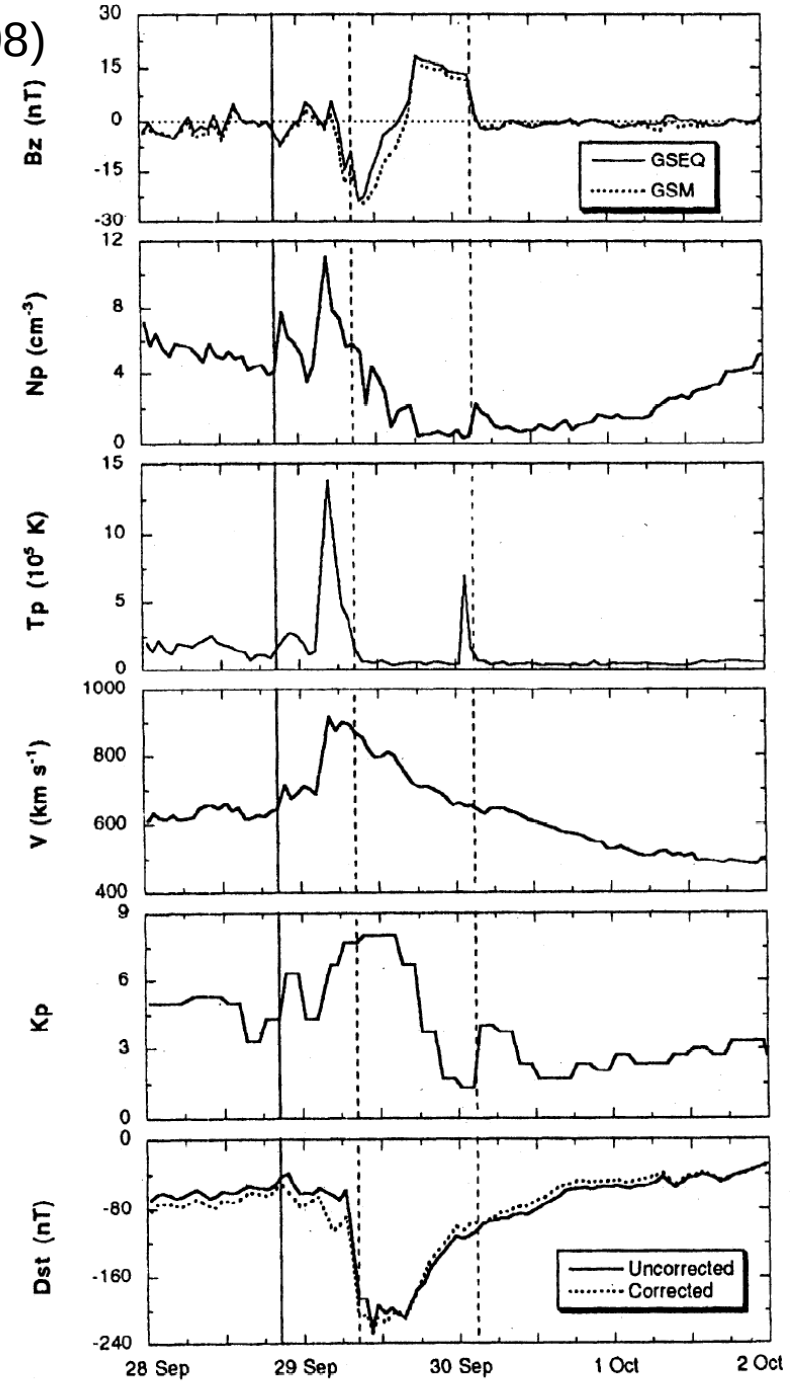


Figure 5. Interplanetary and geomagnetic data for a shock-ICME

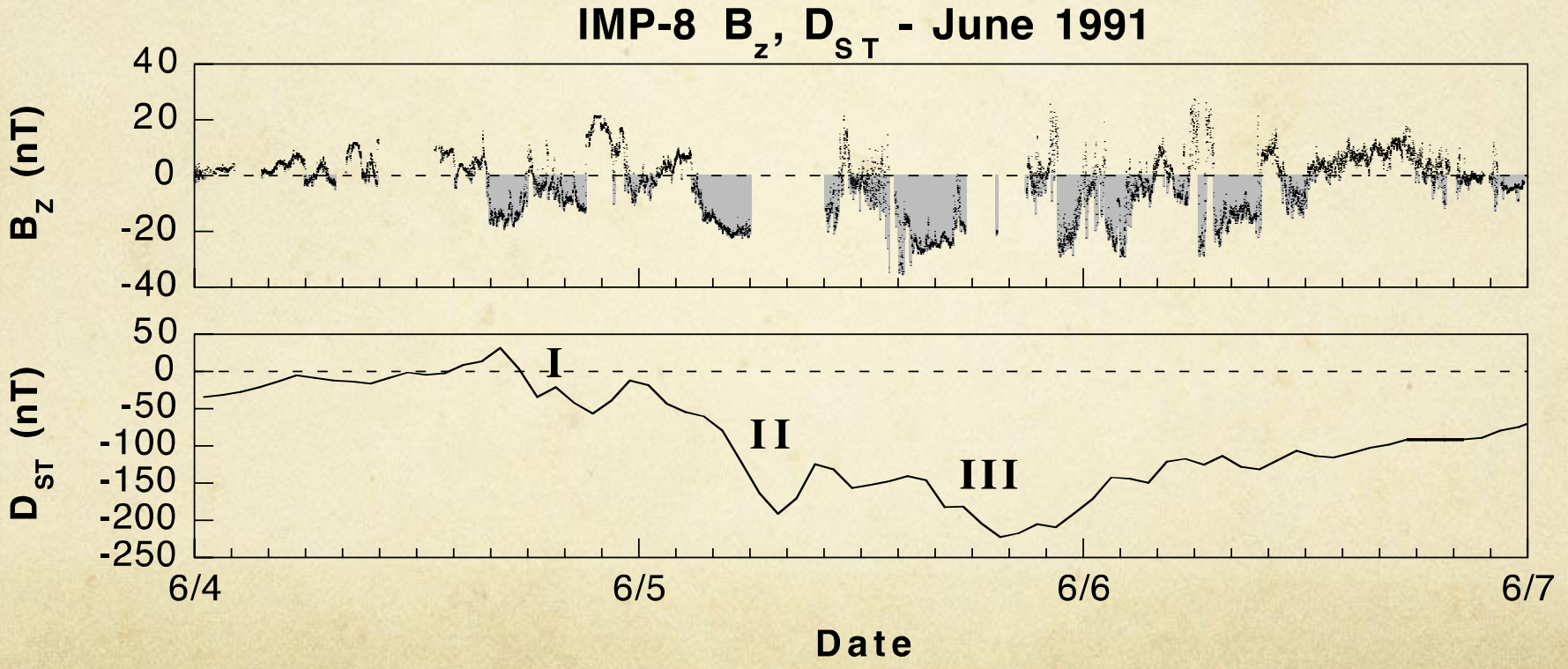
Substorms or convection?

Modeling efforts showed that
adiabatic acceleration associated with
earthward convection of ions under the
influence of the large-scale electric field
is sufficient to produce
the storm-time ring current

and therefore substorms are redundant.

Magnetic Storms

Require prolonged SW-magnetosphere coupling (many hours of large IMF B_s / E_y)



Daglis et al., PSS 2007

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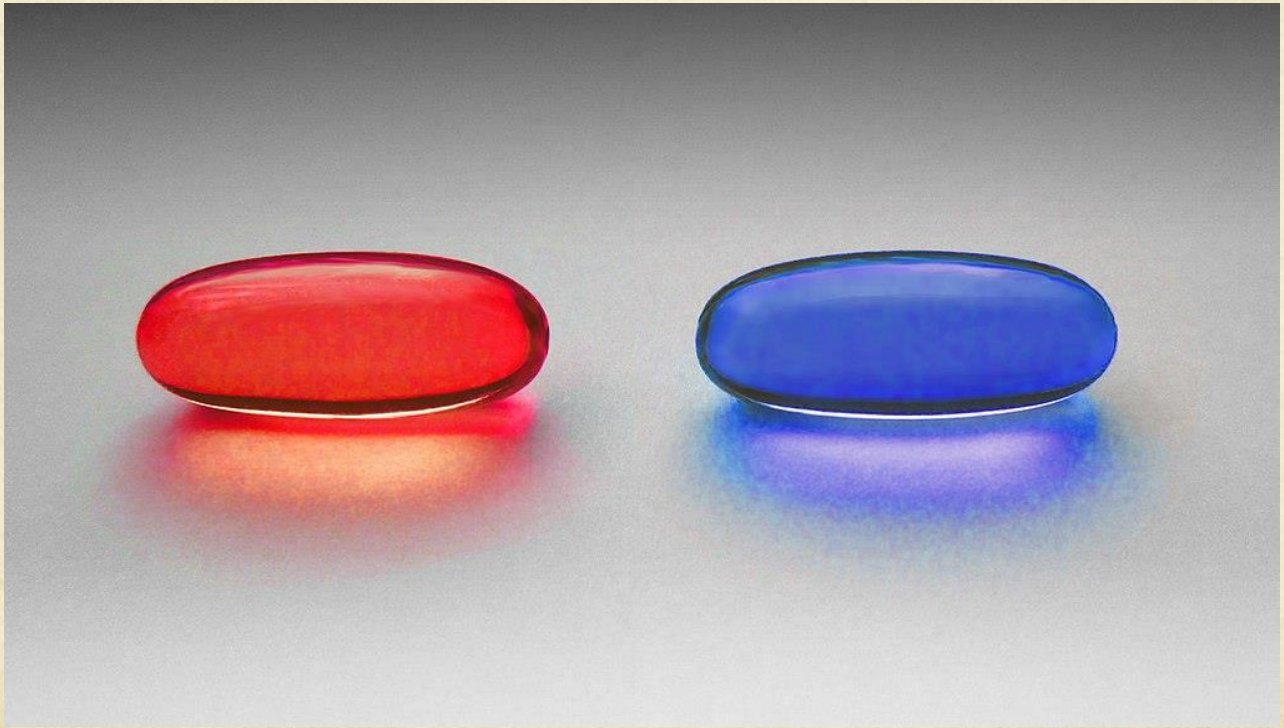
Substorms or convection?

Does reality confirm virtual reality?



The Matrix (1999)

Substorms or convection?

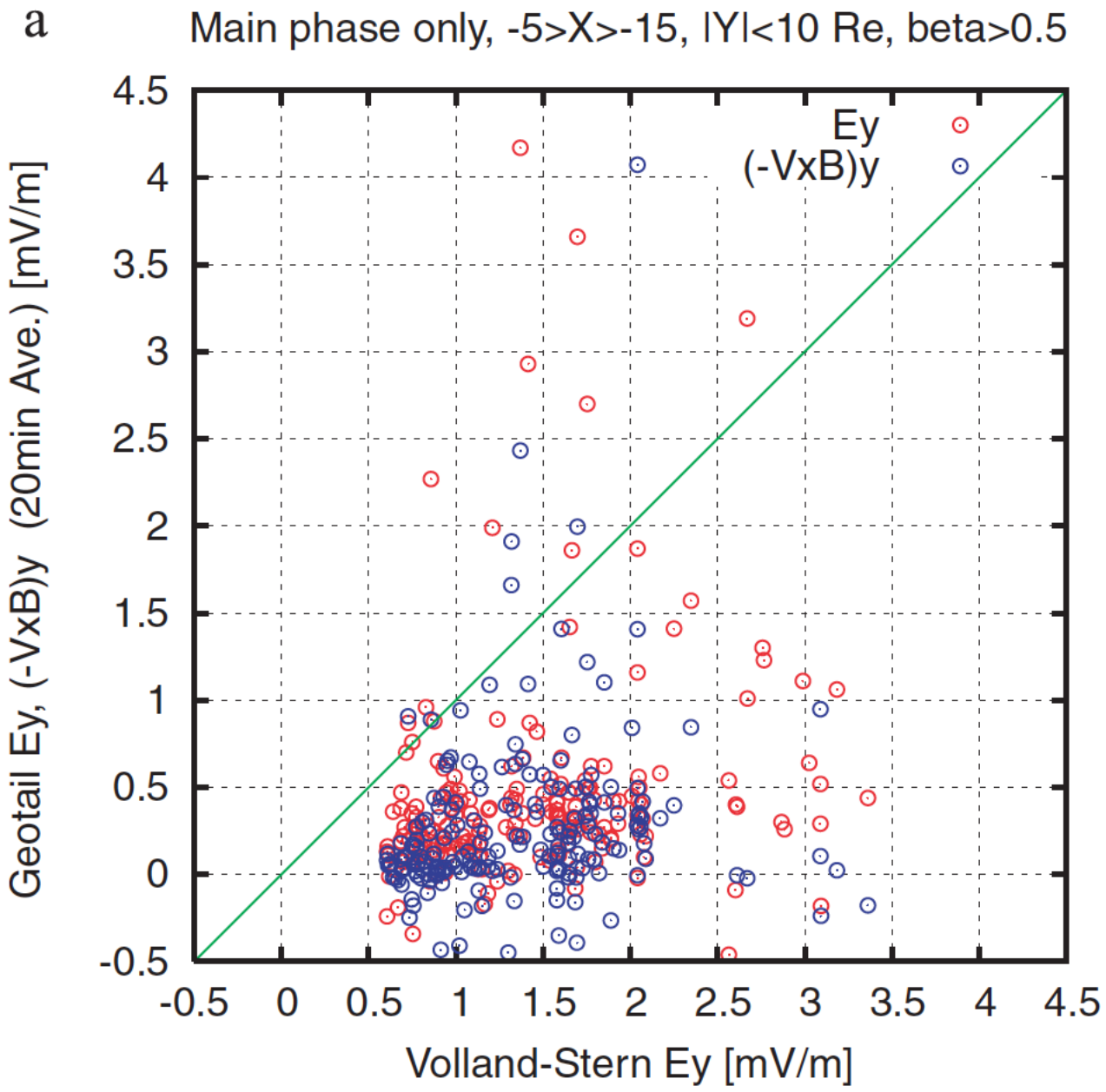
Basic assumption
of pro-convection, anti-substorm models:

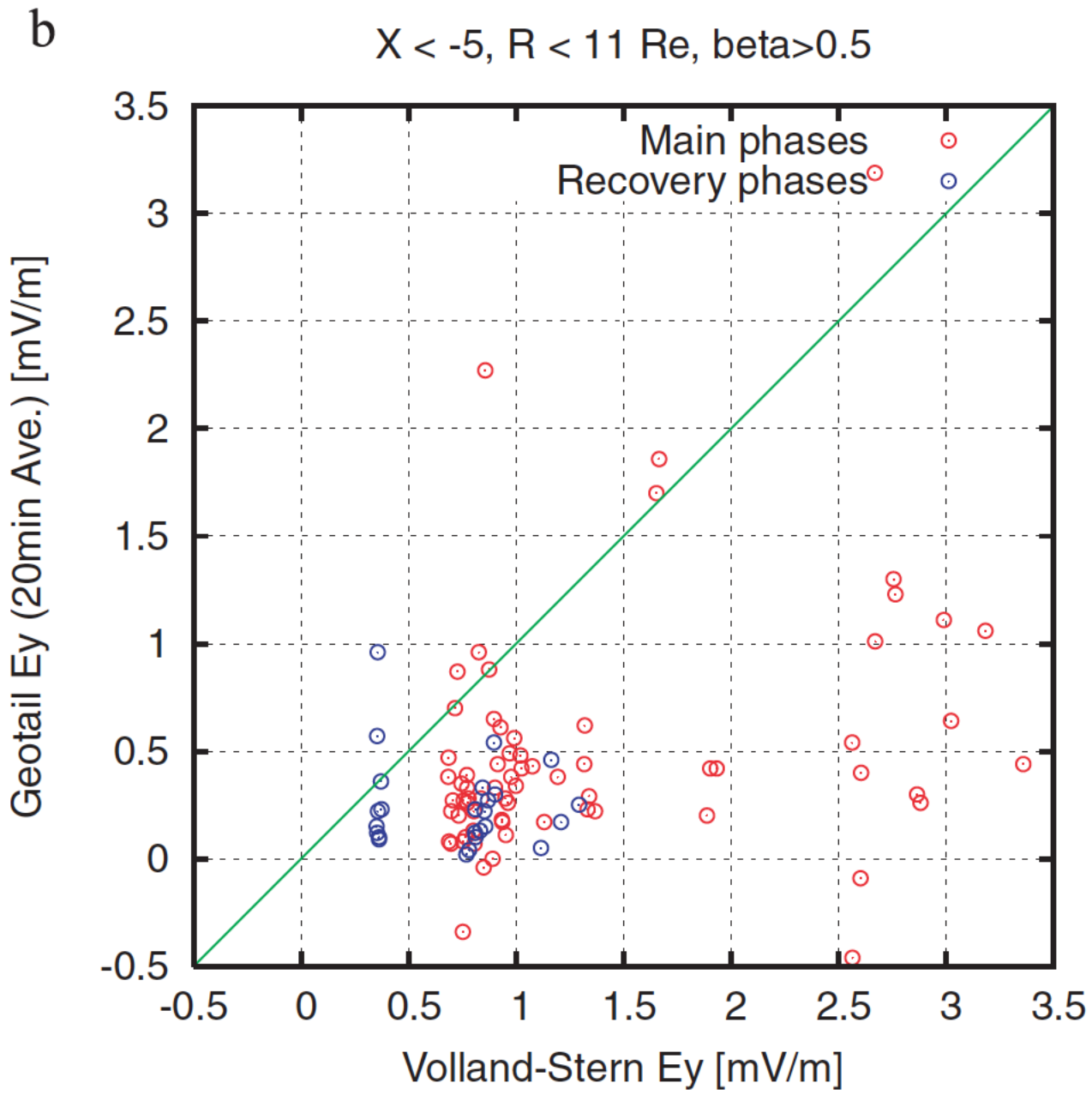
tail / plasma sheet **E** follows closely IMF E_y
and, therefore, is enhanced during storms

Substorms or convection?

Hori et al (JGR2005), 9 years Geotail data:

Large-scale electric field
in the near-Earth plasma sheet
is not enhanced
during storm main phase
and **does not** correlate well with IMF


a
Main phase only, -5>X>-15, |Y|<10 Re, beta>0.5
Ey
(-VxB)y
Geotail Ey, (-VxB)y (20min Ave.) [mV/m]
Volland-Stern Ey [mV/m]
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5


b
X < -5, R < 11 Re, beta>0.5
Main phases
Recovery phases
Geotail Ey (20min Ave.) [mV/m]
Volland-Stern Ey [mV/m]
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-0.5
0
0.5
1
1.5
2
2.5
3
3.5

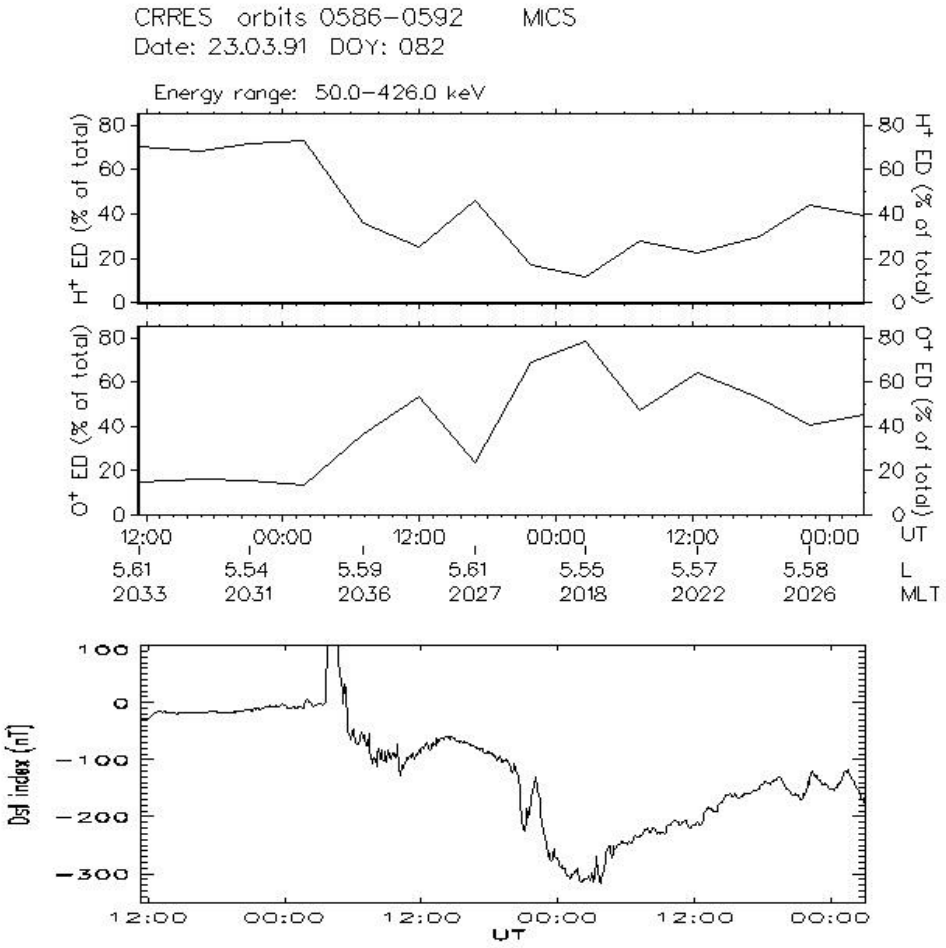
Substorms or convection?

Perfect results of models
are useless
if actual conditions
do not correspond
to the basic assumptions of the models

Substorms or ~~convection~~?

Perfect results of models
are **useless**
if actual conditions
do not correspond
to the basic assumptions of the models

Ring current during intense storms



Daglis, GM 1997

Substorms and O^+ acceleration/dominance

Preferential acceleration

and subsequent dominance of O^+

advocate substorm role

(Delcourt / Daglis / Metallinou / Nose)

Substorm influence

More recently, Van Allen Probes observed frequent, **small-scale** proton injections deep into the inner magnetosphere in the region L~4-6.

Gkioulidou [2014] estimated that their overall direct effect can account for **~30%** of the energy gain in the ring current region

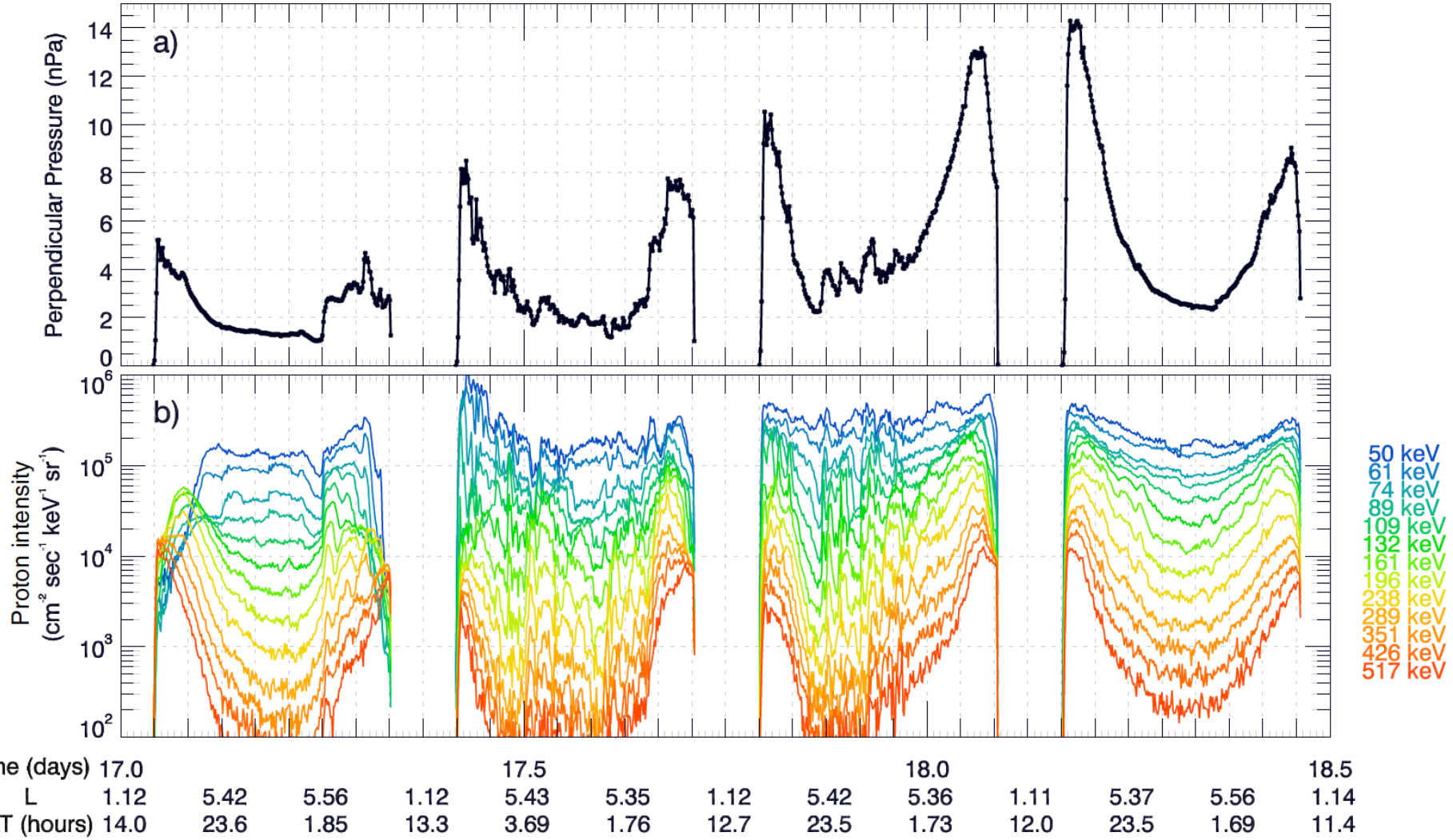
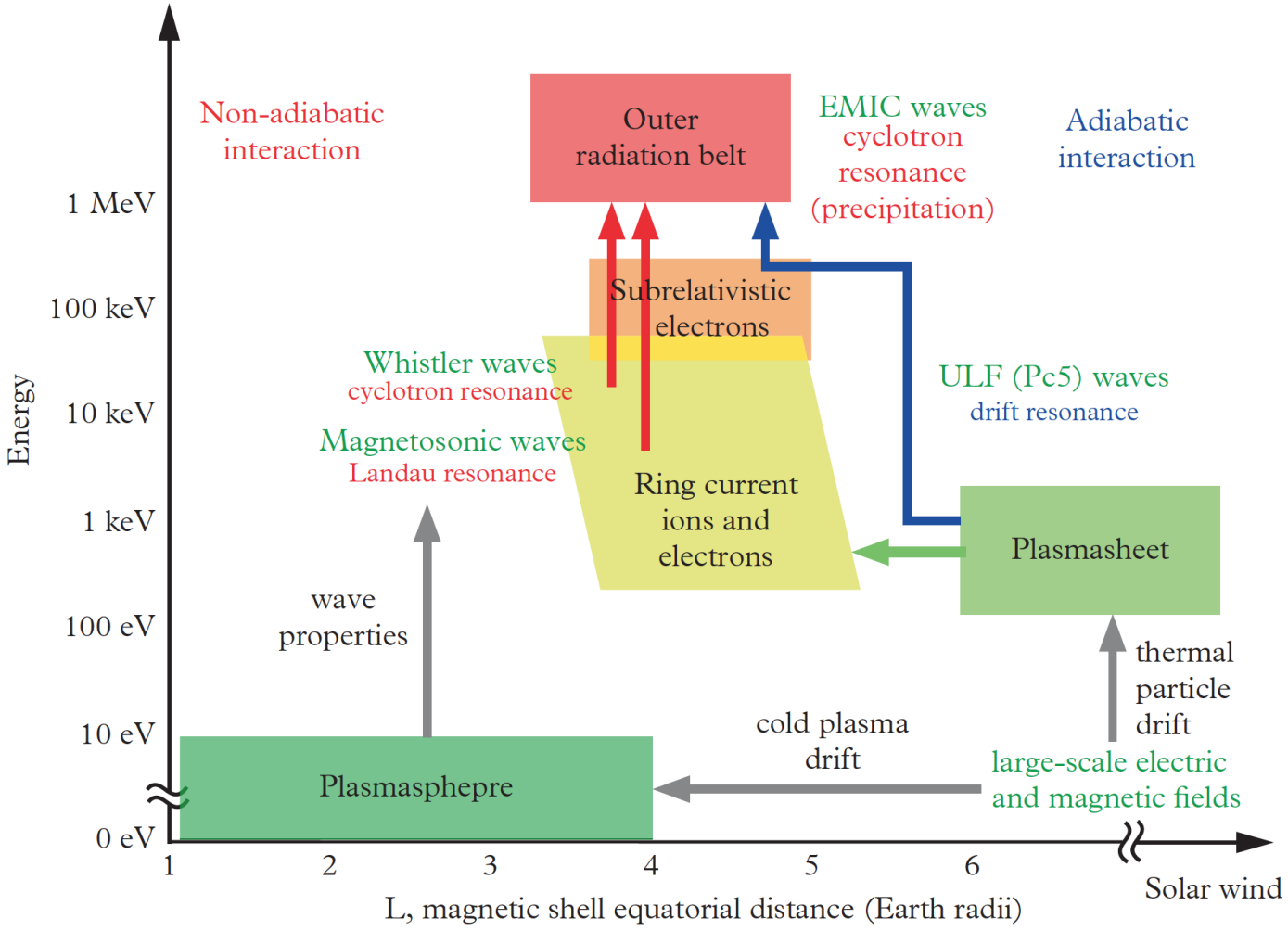


Figure 2. (a) Perpendicular pressure of 20 – 570 keV energy protons, and (b) intensities of 90 pitch angle protons for representative energy channels between 50 and 517 keV.

Gkioulidou+, JGR 2014



Takahashi and Miyoshi, 2016

Interaction of various waves
(in various ways)
with various particle populations
during storms/substorms

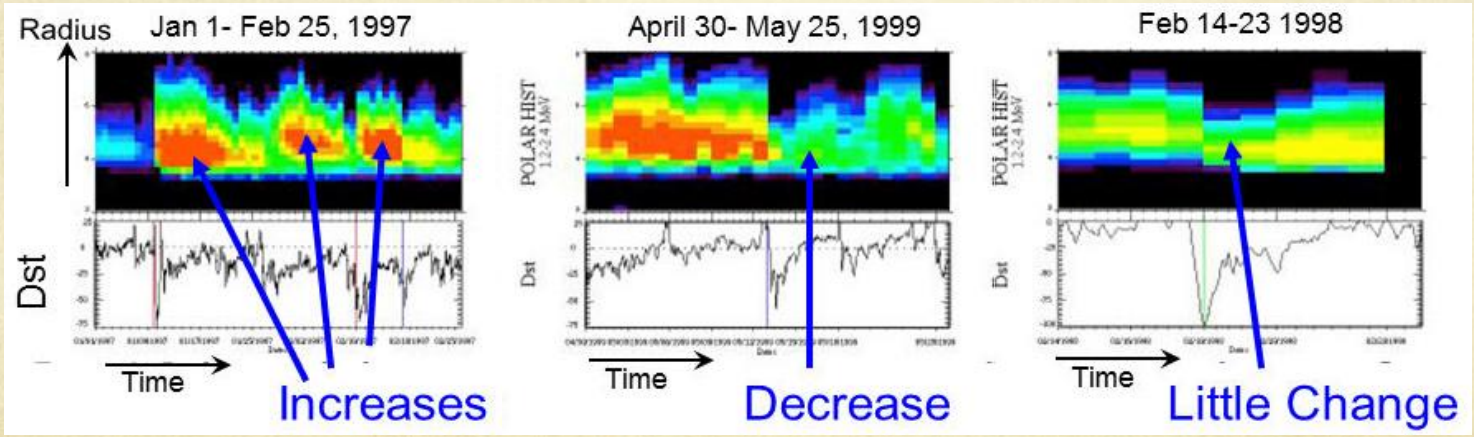
Storms and RBs

Magnetic storms
have a variable outcome
on relativistic electron fluxes

50% lead to **enhancement** of e^- fluxes

20% lead to **depletion** of e^- fluxes

30% do not affect e^- fluxes



Reeves+, GRL2003