Inner magnetosphere and space weather: Radiation Belts and Ring Current

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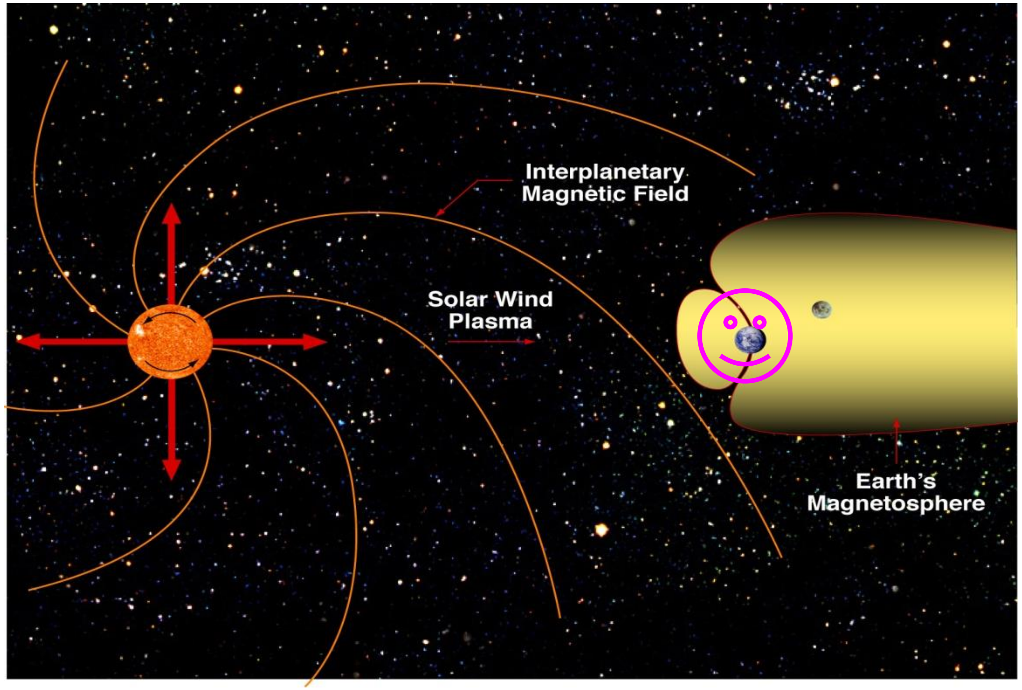
Inner magnetosphere: Size vs importance, Physics



Inner magnetosphere
has rather ***modest size***,
with about 10 Re radius,

BUT the ***significance***
of the occurring processes
is ENORMOUS

Although quite a significant progress has been made, inner magnetosphere is definitely ***worth of studying***

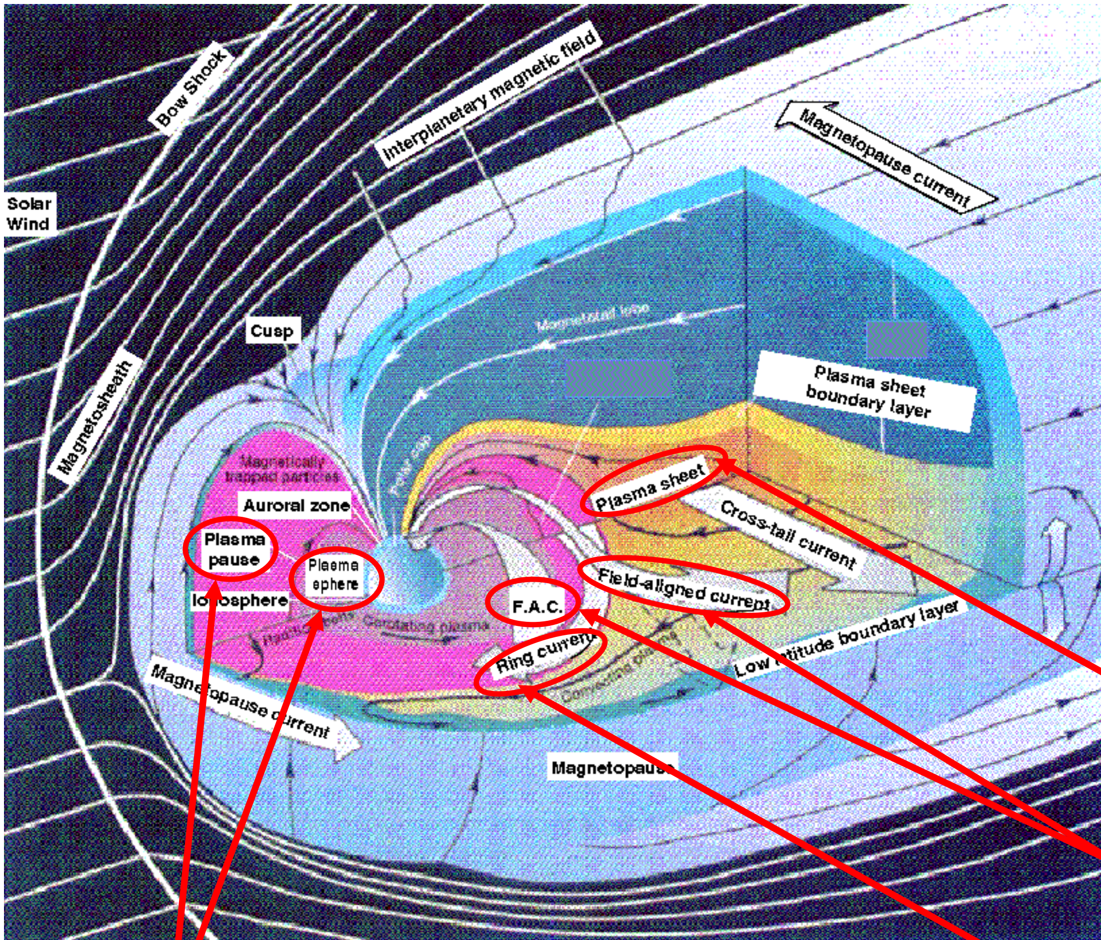
The Inner Magnetosphere

- Inner magnetosphere is where space weather matters
  - This is where we fly lots of commercial and military satellites
  - Even the calm times are full of dynamic processes
- There are 3 main plasma populations in the inner magnetosphere
  - coupled together
  - controlled by the electric and magnetic field
  - influenced by external source/driver terms
  - important for understanding space weather
  - modified during magnetic storms

Table 1. Characteristics of Inner Magnetospheric Plasma Populations

Population	Density	Temperature	Source	Composition	Driver	Importance
Plasmasphere	100s cm^{-3} to 1000s	<1 eV, maybe up to 10s of eV	Subauroral ionosphere	H^+, some He^+ and O^+	E field	Dominates mass density
Ring current	~few cm^{-3}, up to 10s	1–400 keV	Plasma sheet (SW and iono)	H^+, O^+ in storms	E and B fields	Dominates energy density
Radiation belts	$\ll 1$ cm^{-3}	100s of keV to MeV	Plasma sheet, SEPs, local acc.	Mostly e-, some H^+	B field	Dominates S/C damage

Dynamical inner magnetosphere: Overview



Plasma in magnetosphere:
mainly electrons and ions.

Sources of particles:
solar wind and ionosphere.

Plasma is grouped into different regions with different densities and temperatures.

Main regions:

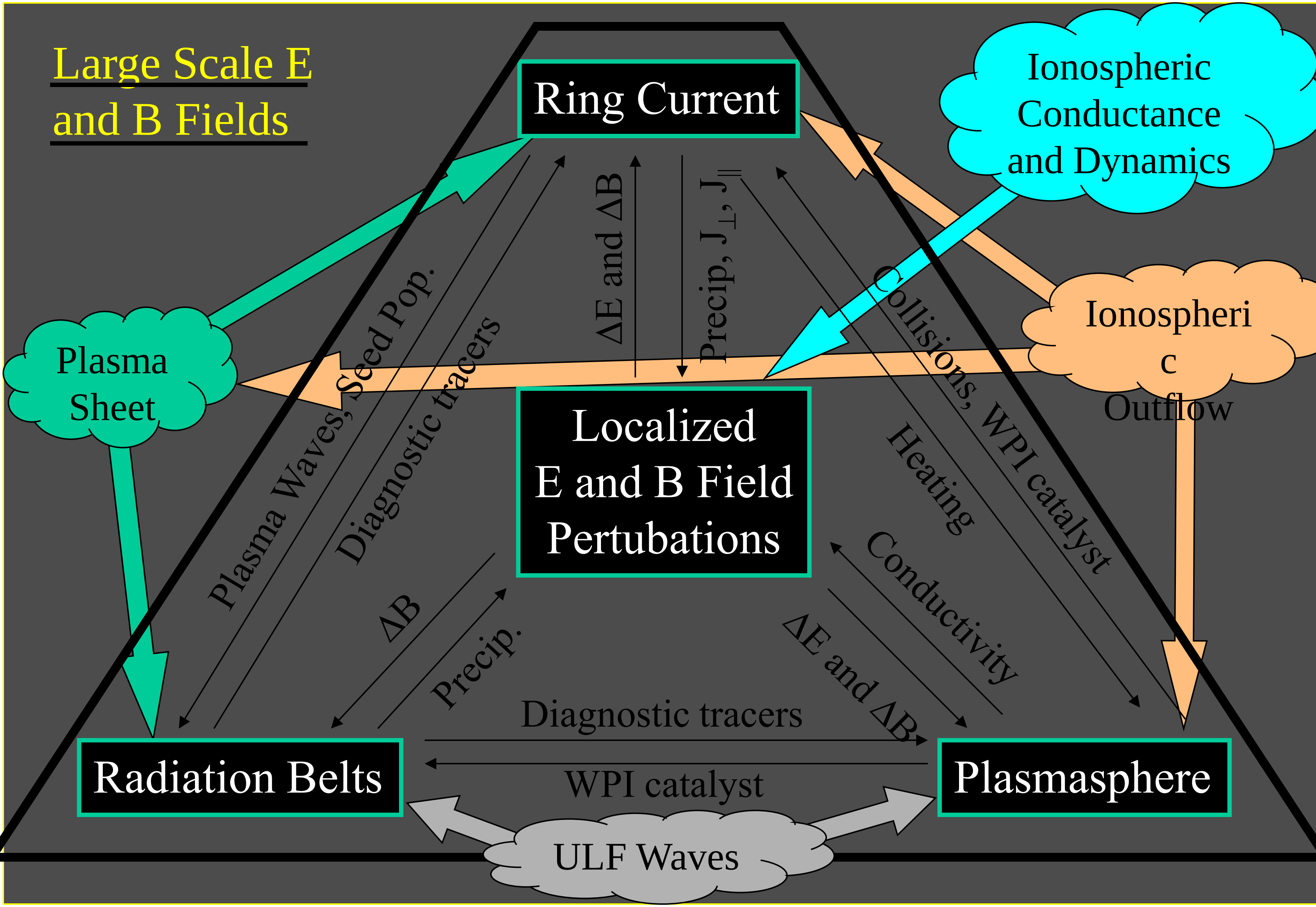
- near Earth plasma sheet
(7-10 Re, n = 0.1-1 cm^{-3}, T=5 keV)

- field-aligned currents (~ 10^6 A)

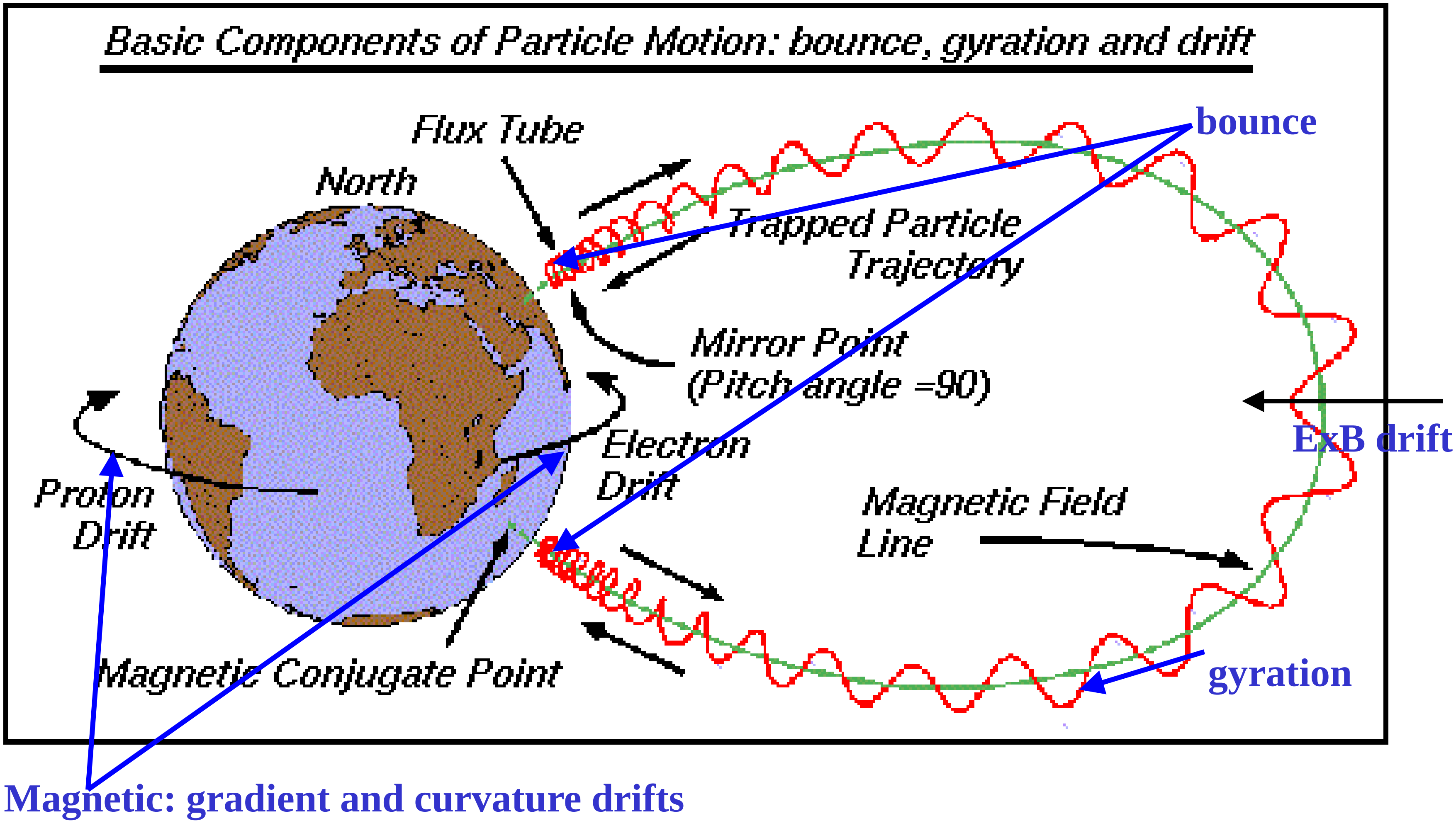
- ring current (20-300 keV)
- radiation belts (up to MeVs) (2-7 Re)

- plasmasphere (< 4 Re, 10^3 cm^{-3}, 1 eV)
- plasmapause (sharp at 4 Re, drop to 1 cm^{-3})

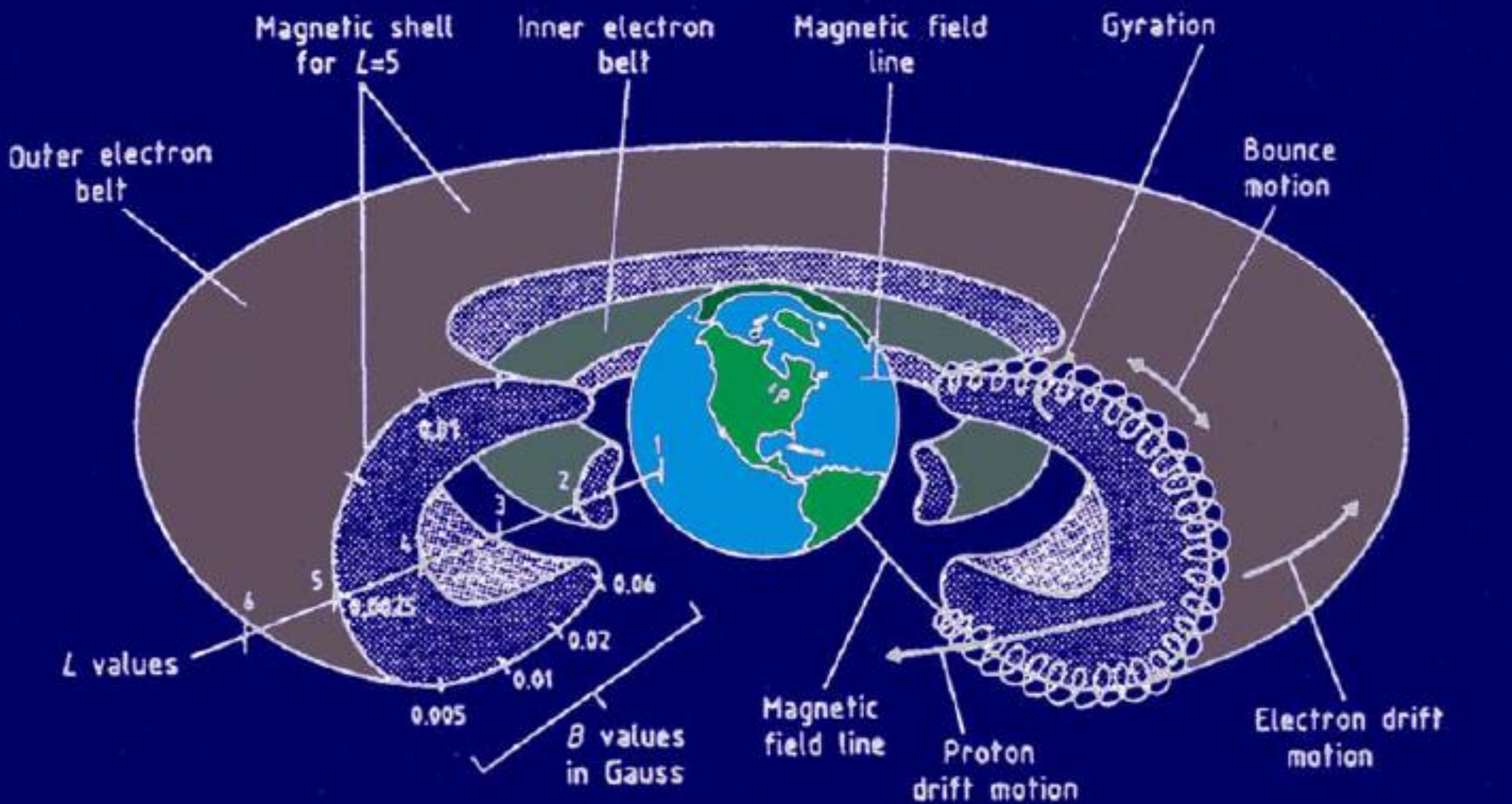
Inner Magnetospheric Coupling



Trapped particle motion

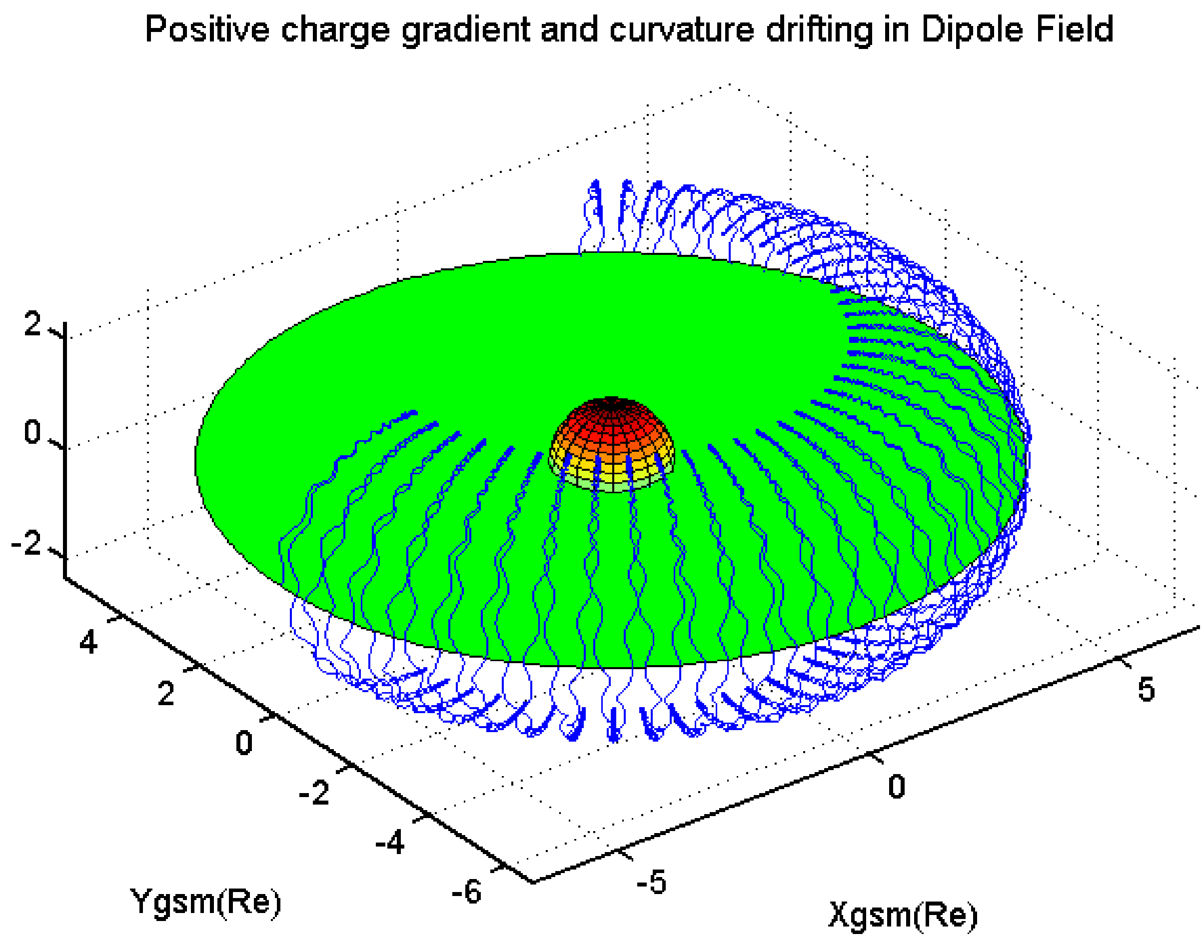


INNER MAGNETOSPHERE

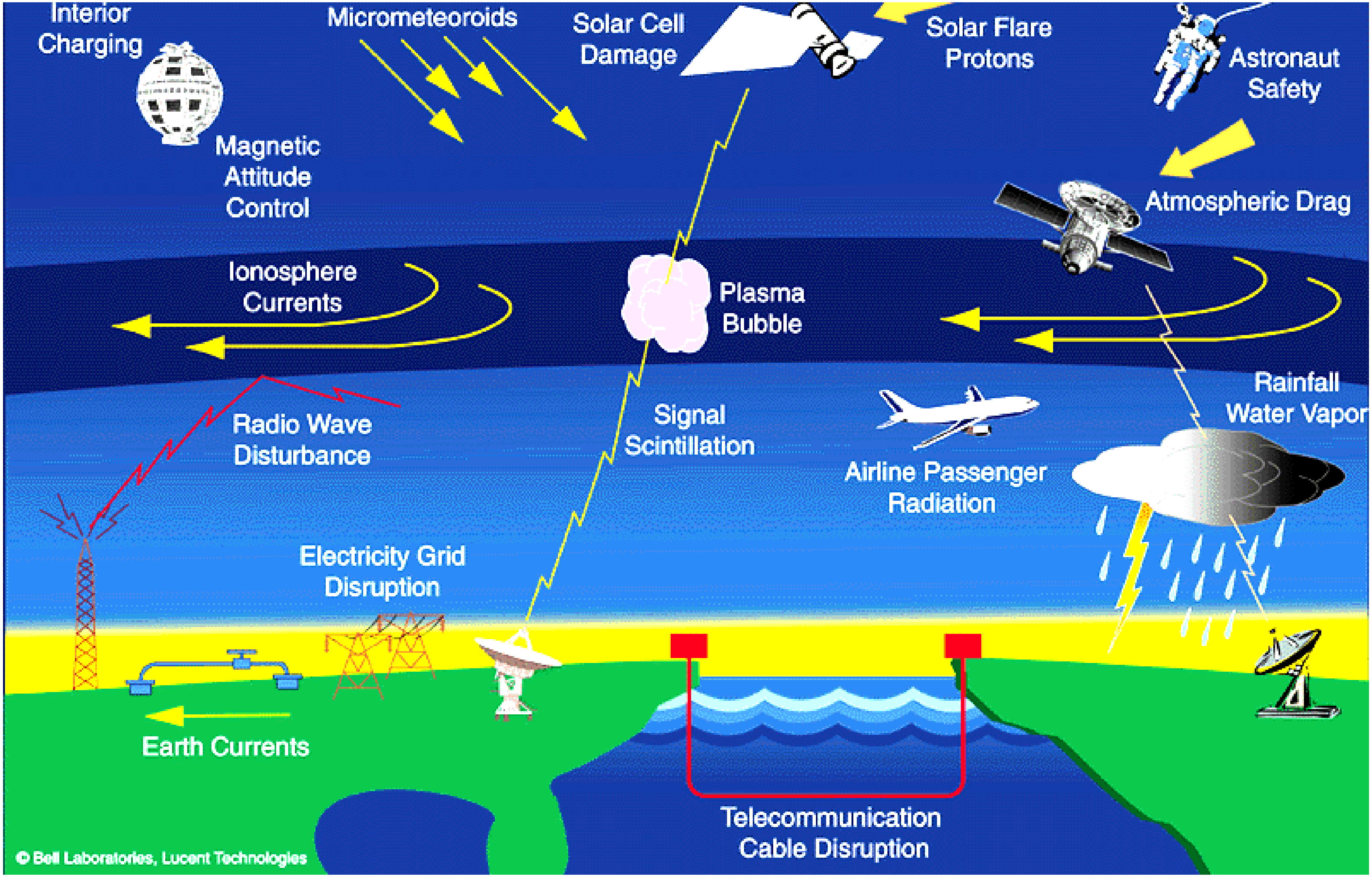


Sketch of a three-dimensional representation of the inner and outer radiation belts forming a ring current around Earth

Drift shells



Space weather effects

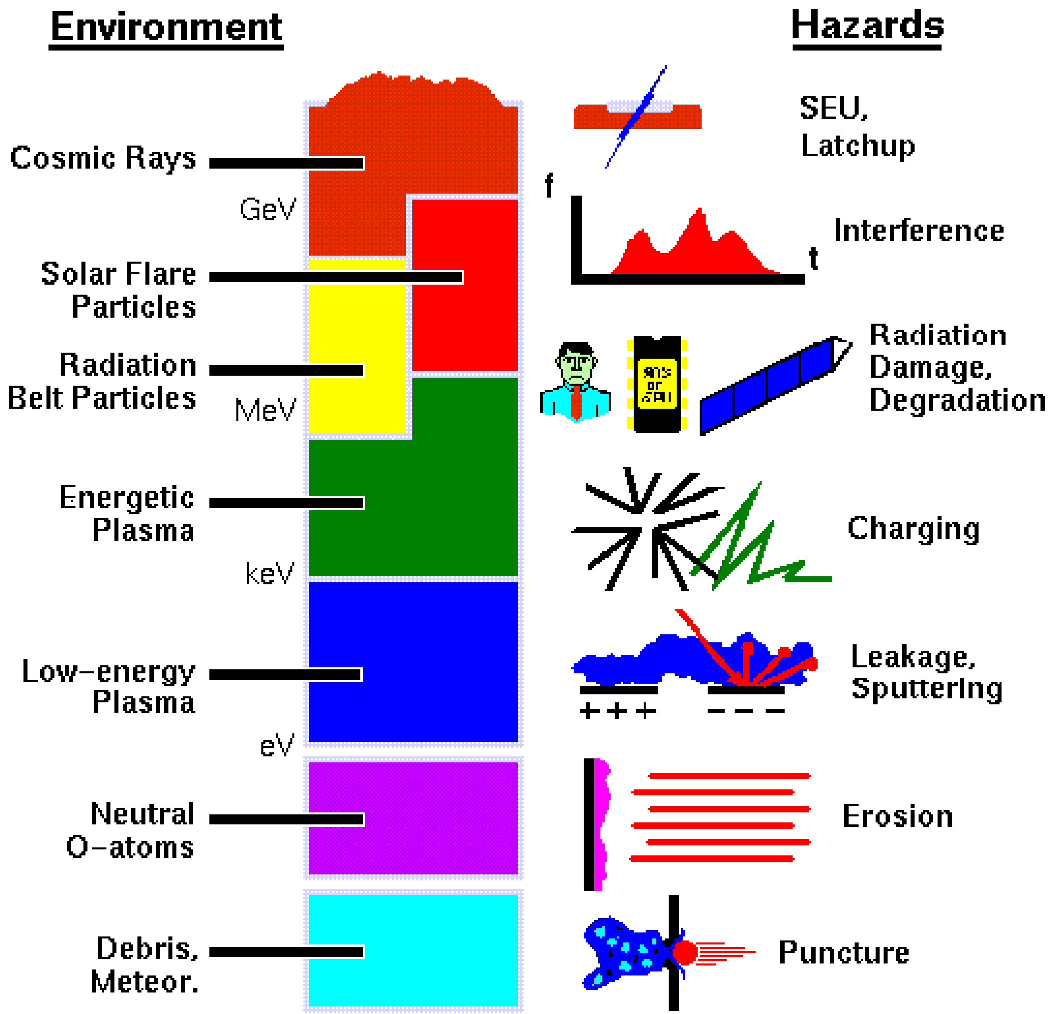


Space weather can age, damage or even kill satellites in orbit

- Neutrals
  - drag, orbit control
- Photons
  - surface ageing
  - background noise
- Plasmas
  - surface charging
  - electromagnetic noise
- Energetic particles
  - atom displacements
  - single event upsets
- Magnetic field
  - attitude control loss

Schematic of space effects

- Dependent on:
  - particle energy
  - particle mass
  - particle flux
  - total dosage
- Effects happen:
  - on the surface
  - deep within S/C
  - in electronics
  - in biological matter
- Also: orbit changes



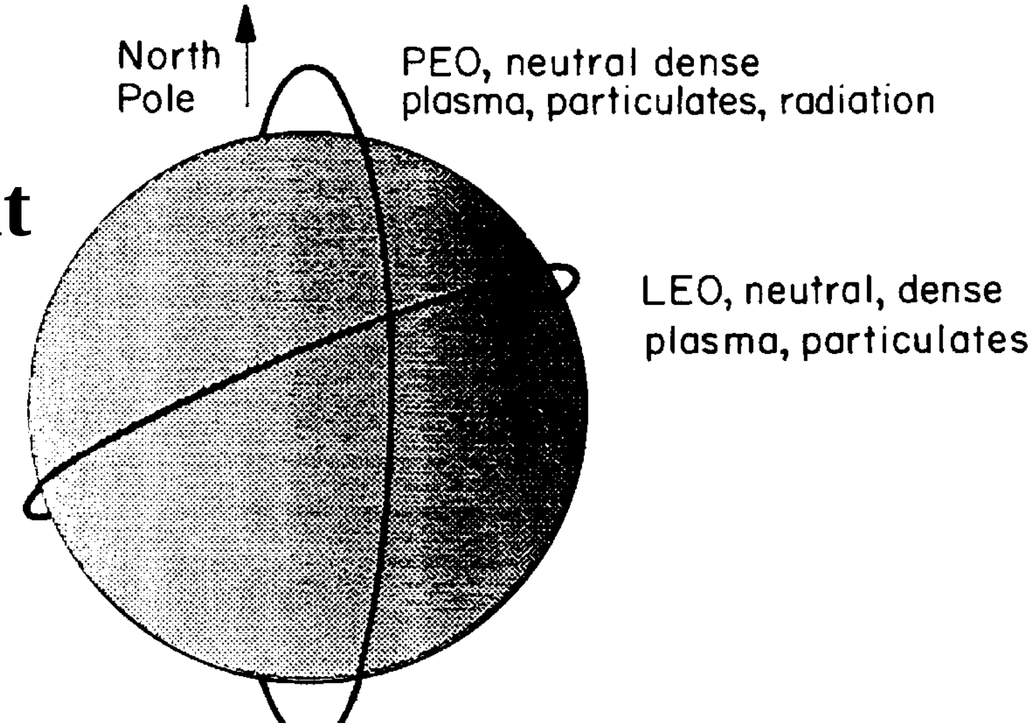
Space environment impacts S/C systems

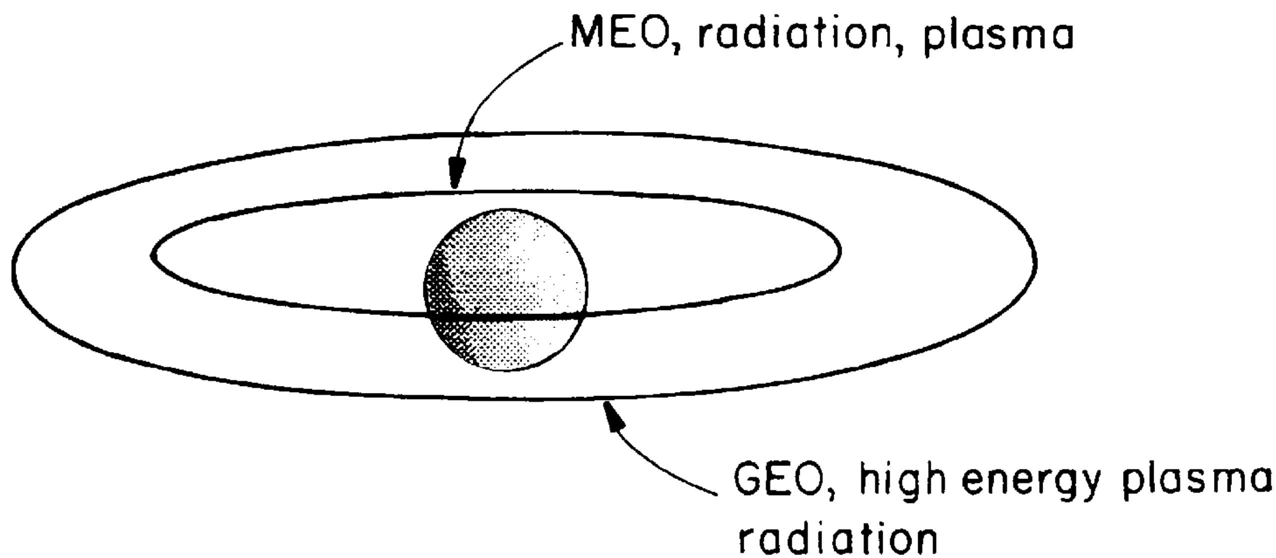
Spacecraft system	Neutrals	Plasma	Radiation	Particulates
Power	Change coverglass trasmittance	Shift ground, attract contaminants, arc damage	Degrade solar cell output, arc damage	Destroy solar cells
Propulsion	Source of contaminants & drag	Source of contaminants		Source of particulates
Attitude control	Torques, sensor degradation	Torques	Sensor degradation	
Structure	Erosion	Arc damage	Arc damage	Penetration
Thermal control	Change surface properties	Change surface properties	Change surface properties	
Avionics		EM Interference	Degradation	
Communications		EM Interference		
Payload	Sensor interference	Sensor interference	Avionics damage	Penetration

Classification of Orbits

Name	Altitude (km)	Inclination to Equator (deg)
Low Earth Orbit	100-1,000	< 65
Medium Earth Orbit	1,000-36,000	< 65
Polar Earth Orbit	>100	> 65
Geostationary Orbit	~ 36,000	~0
Interplanetary Orbit	Outside magnetosphere	N/A

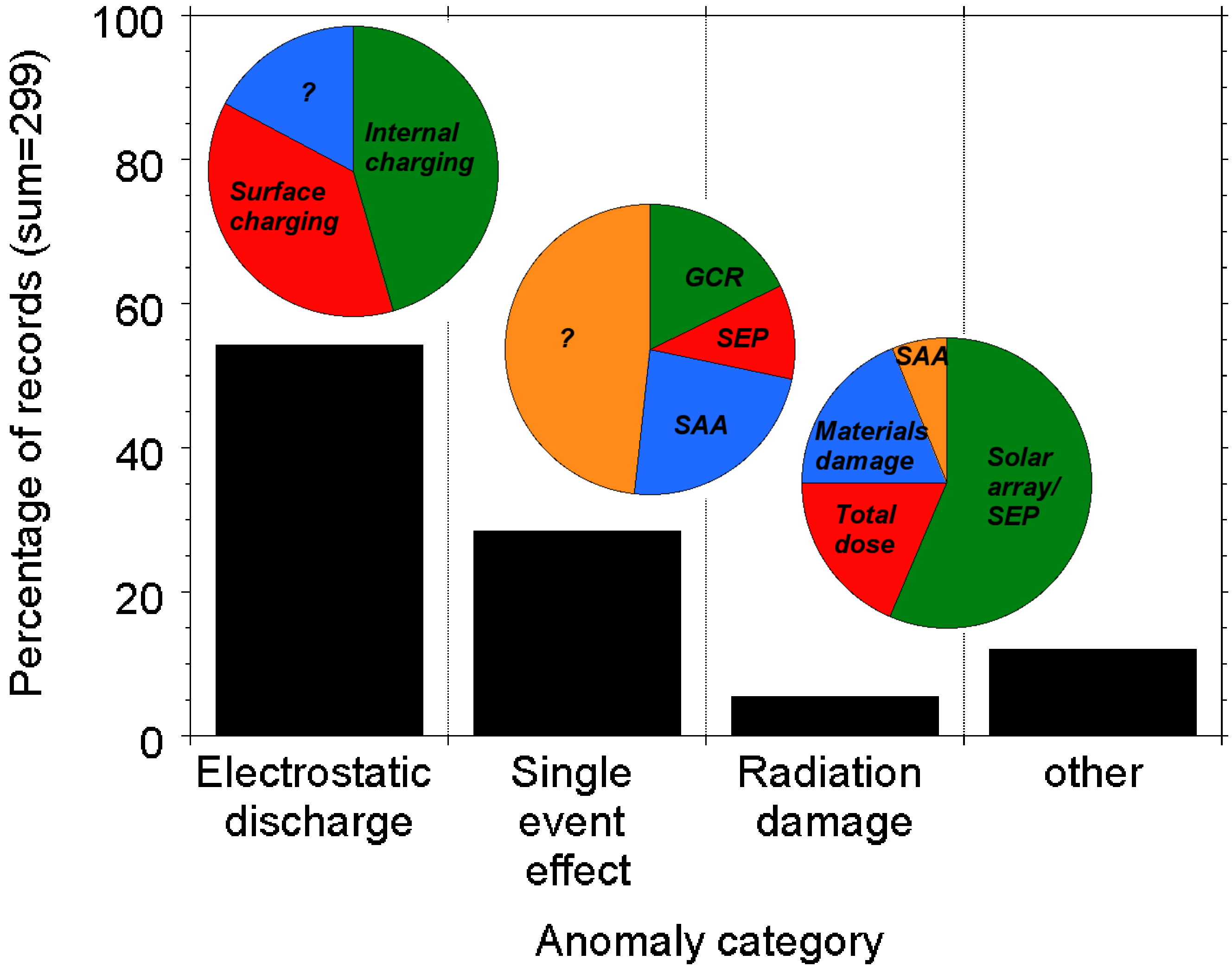
Different orbits experience different environments





Satellite system impacts

- Charging is actually a huge issue (>50%)

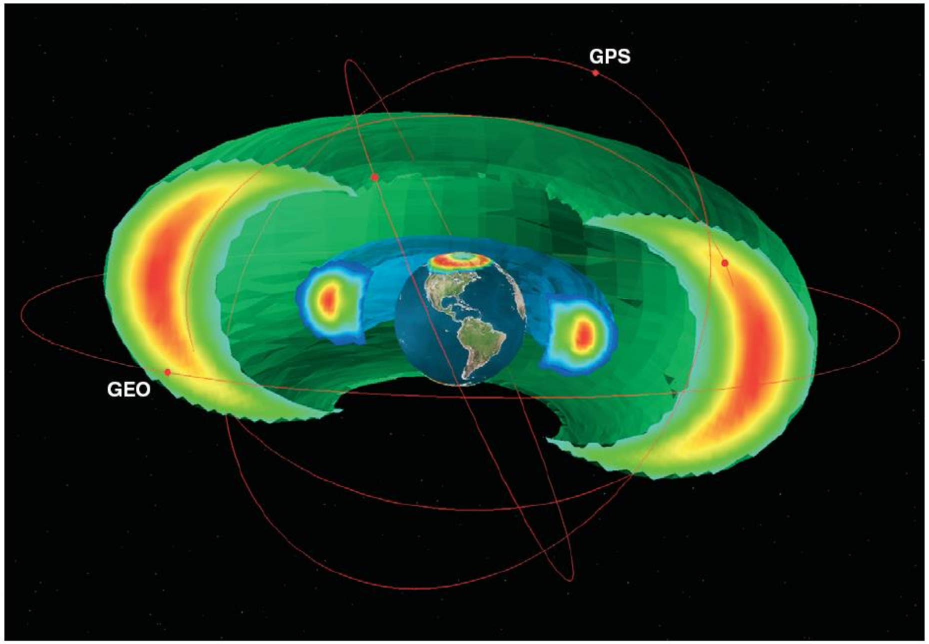


It is often difficult to prove that damage was due to space weather, but...

• 20.1. 1994	Damaged	Canadian Anik-1&2	communication
• 26.3. 1996	Damaged	Canadian Anik-1&2	communication
• 11.1. 1997	Lost	Telstar 401	communication
• 2-4.5. 1998	Lost	Equator-S Galaxy-4	scientific communication
• 6.-7.4. 2000	Degraded (solar panels aged in one day as much as usually during one year)	SOHO	scientific
• 10.11.2000	Degraded (solar panels lose 2% of power)	Cluster	scientific

- Incidents on commercial satellites poorly reported

Structure of radiation belts

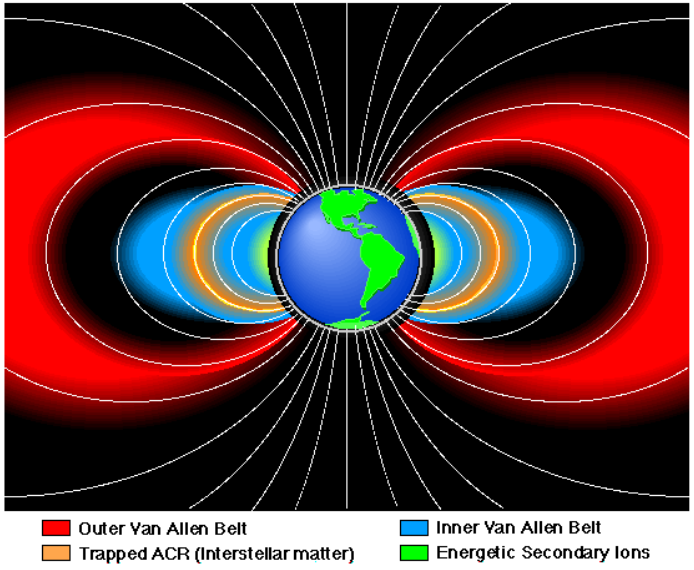


Radiation belts comprise energetic charged particles (from keV to MeV) trapped by the Earth's magnetic field.

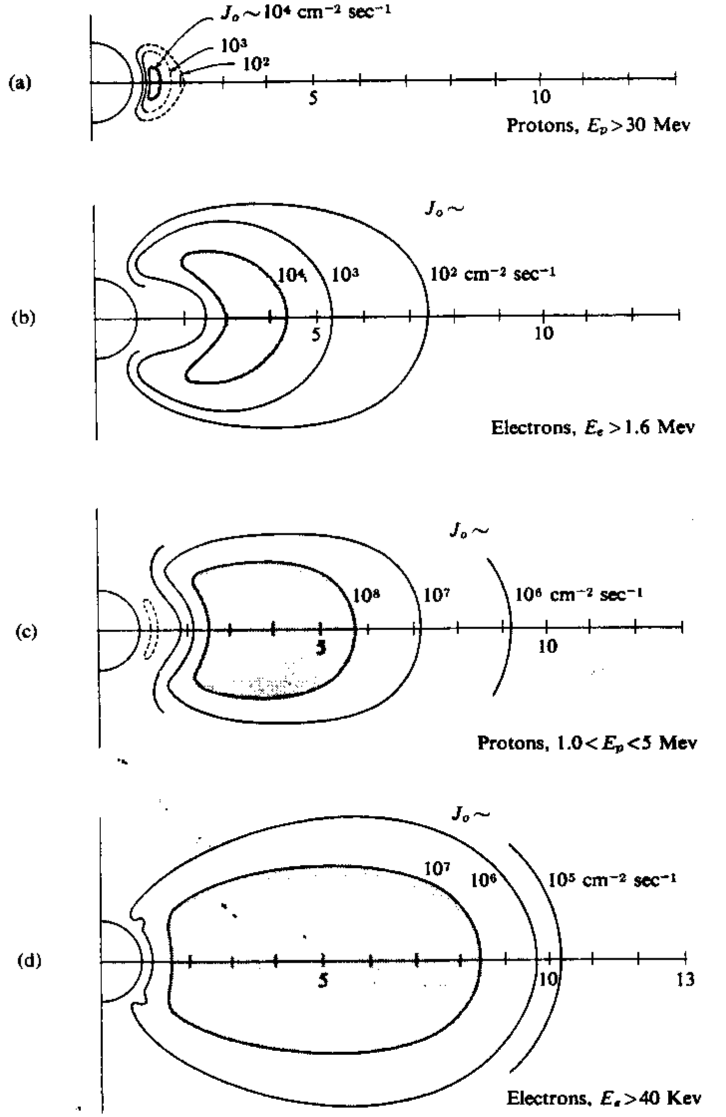
Inner belt region:
- located at L~1.5-2;
- contains electrons, protons, and ions;
- fairly stable population;
- subject to occasional perturbations due to geomagnetic storms,
- source of protons is the decay of cosmic ray induced albedo from the atmosphere.

Outer belt region:
- located at L~3-6;
- contains mostly electrons with up to 10 MeV;
- very dynamic;
- produced by injection and energization events following geomagnetic storms,

Slot region: lower radiation region between the belts



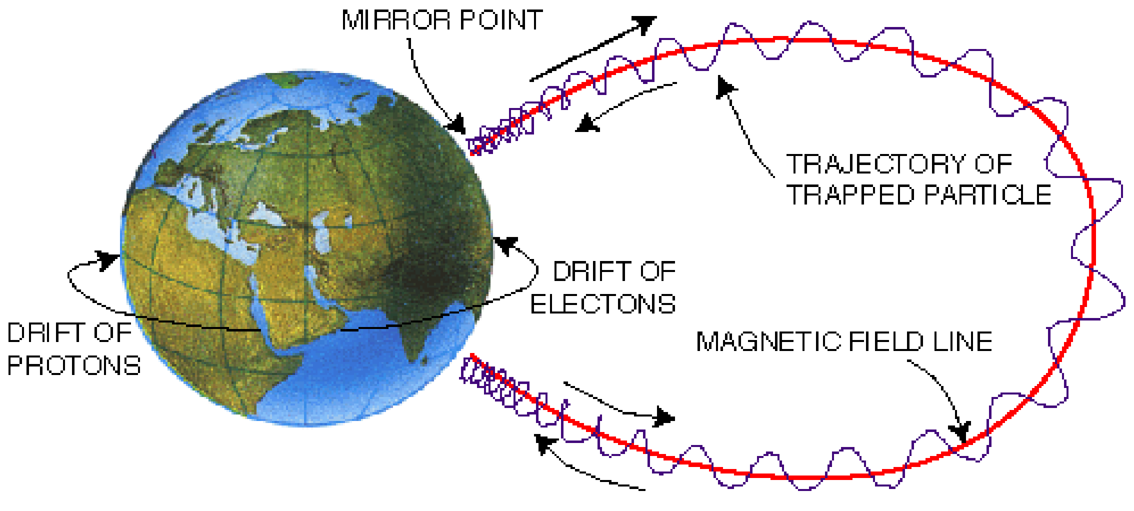
Approx. avg. contours of spatial distribution of trapped energetic protons & electrons

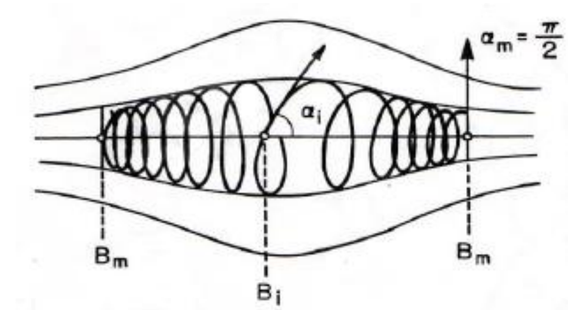


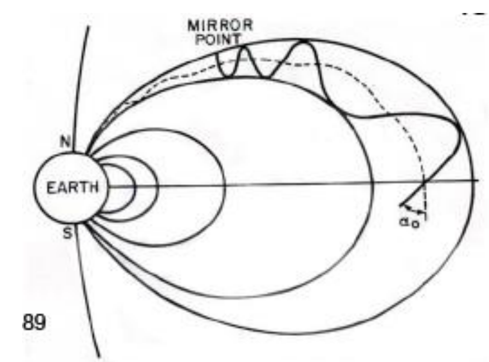
(Van Allen, 1968)

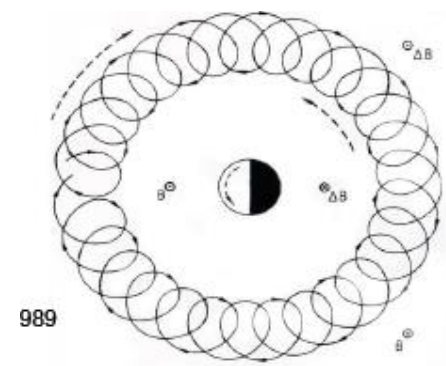
Particle motion in the radiation belts

Trapped particles execute 3 characteristic types of motion:







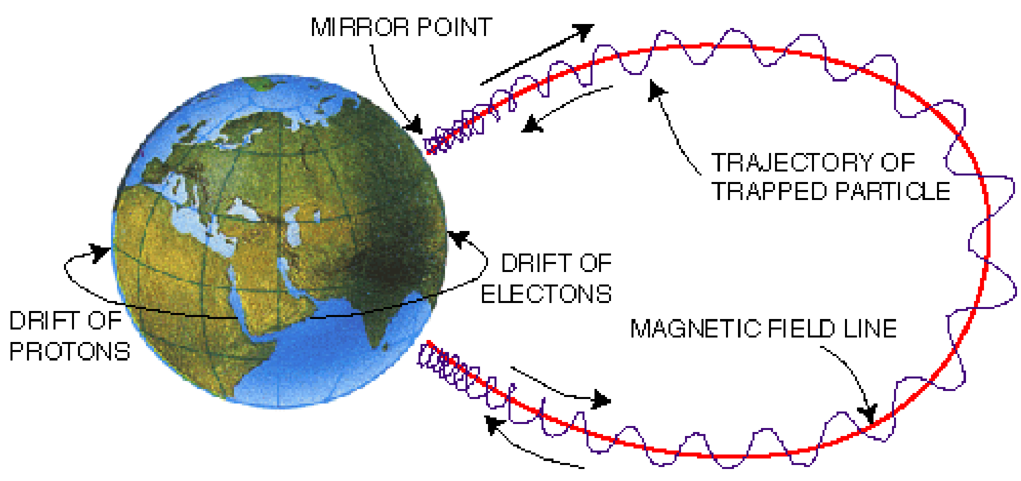


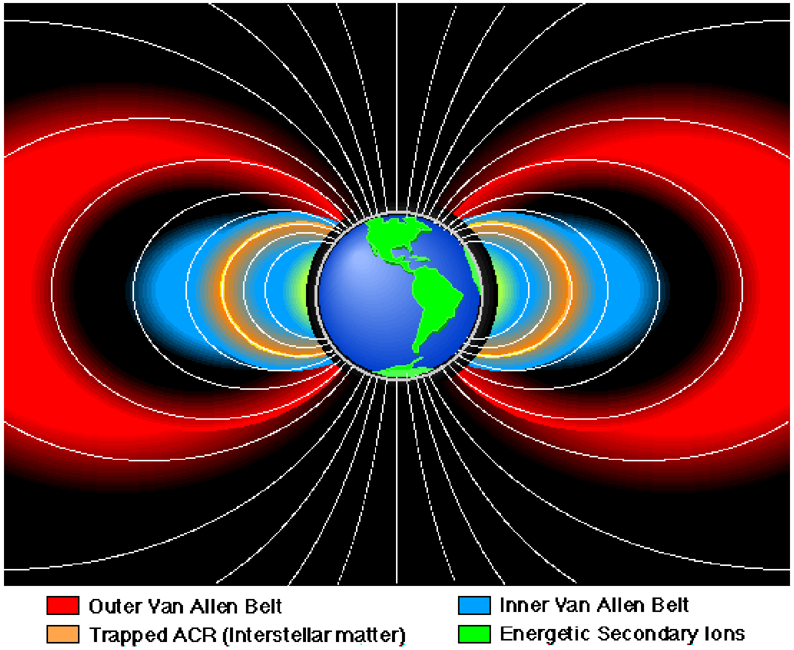
Characteristic time scales:

- Gyro: ~ millisecond
- Bounce: ~ 0.1-1.0 s
- Drift: ~ 1-10 minutes

Adiabatic invariants

Associated with each motion is a corresponding *adiabatic invariant:*
•Gyro: $M=p^2/2m_0B$
•Bounce: K
•Drift: L

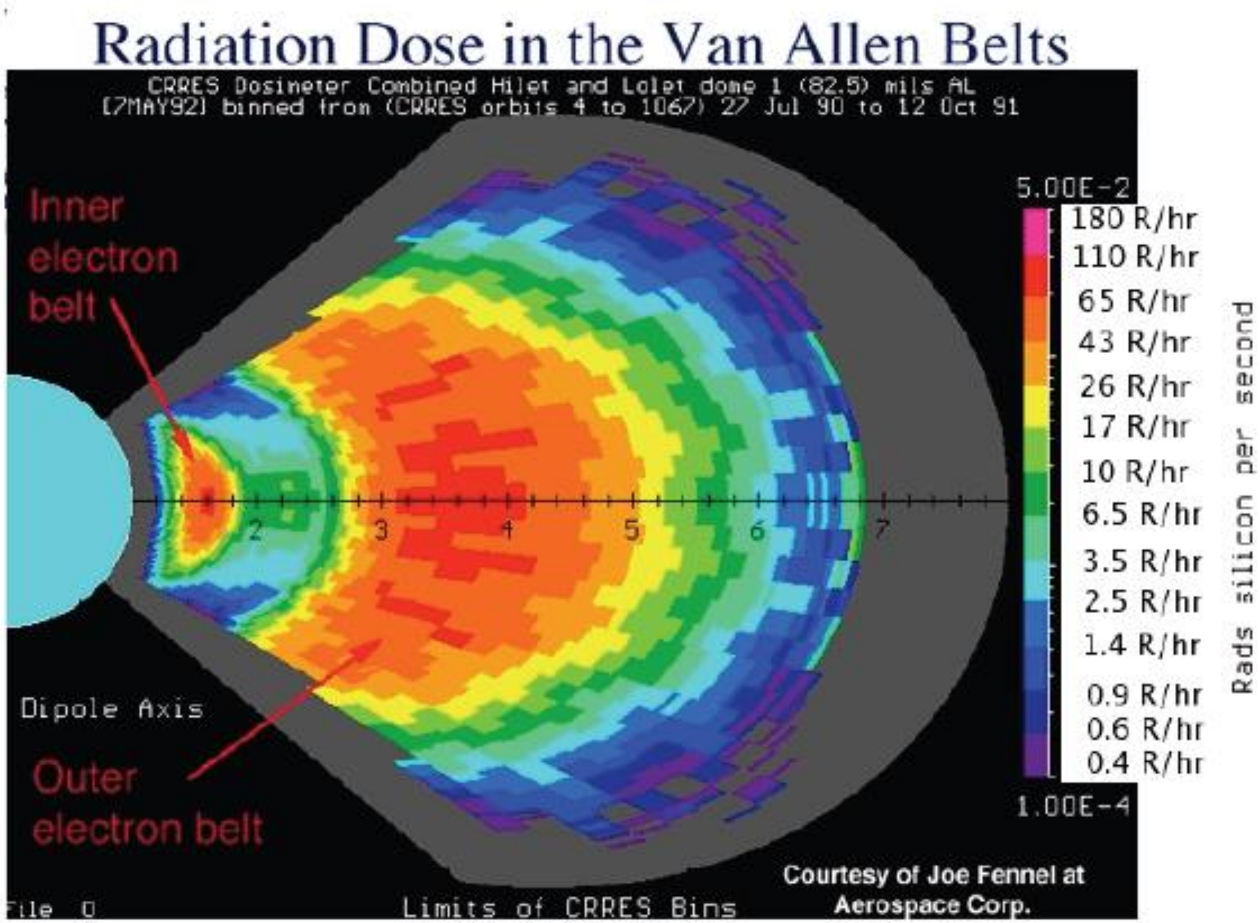




- M: perpendicular motion
- K: parallel motion
- L: radial distance of eq-crossing in a dipole field.

If the fields guiding the particle change slowly compared to the characteristic motion, the corresponding invariant is conserved.

Radiation fluxes from CRRES



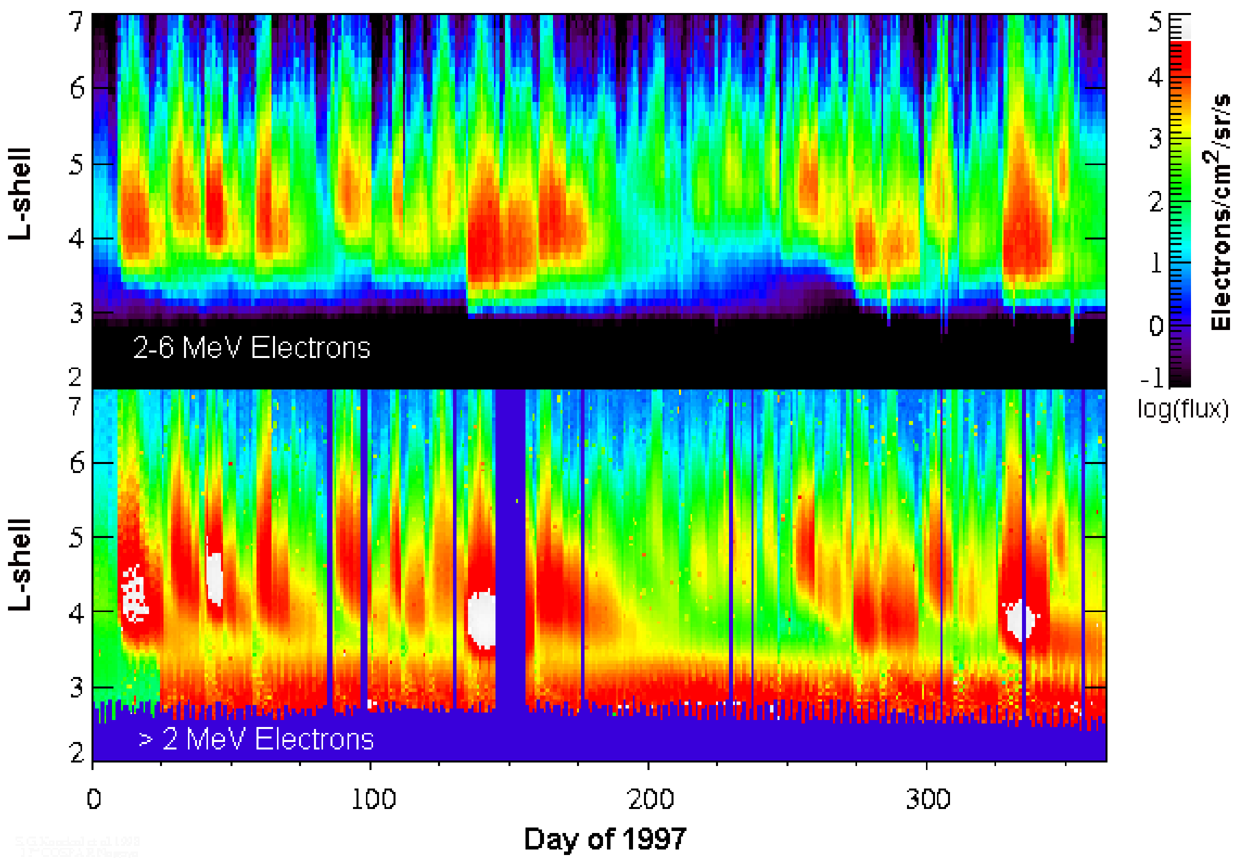
Fennel/Aerospace Corp., 2003

CRRES – Combined Release and Radiation Effects Satellite

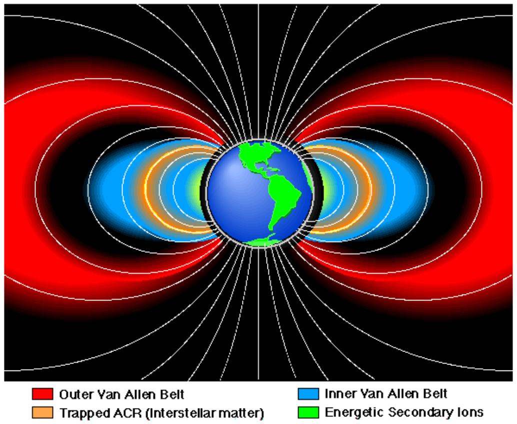
- radiation flux observations from CRRES, 1990-91
- Scale converted to rads/hour

Fluxes in the radiation belts

The radiation belts exhibit substantial variation in time:



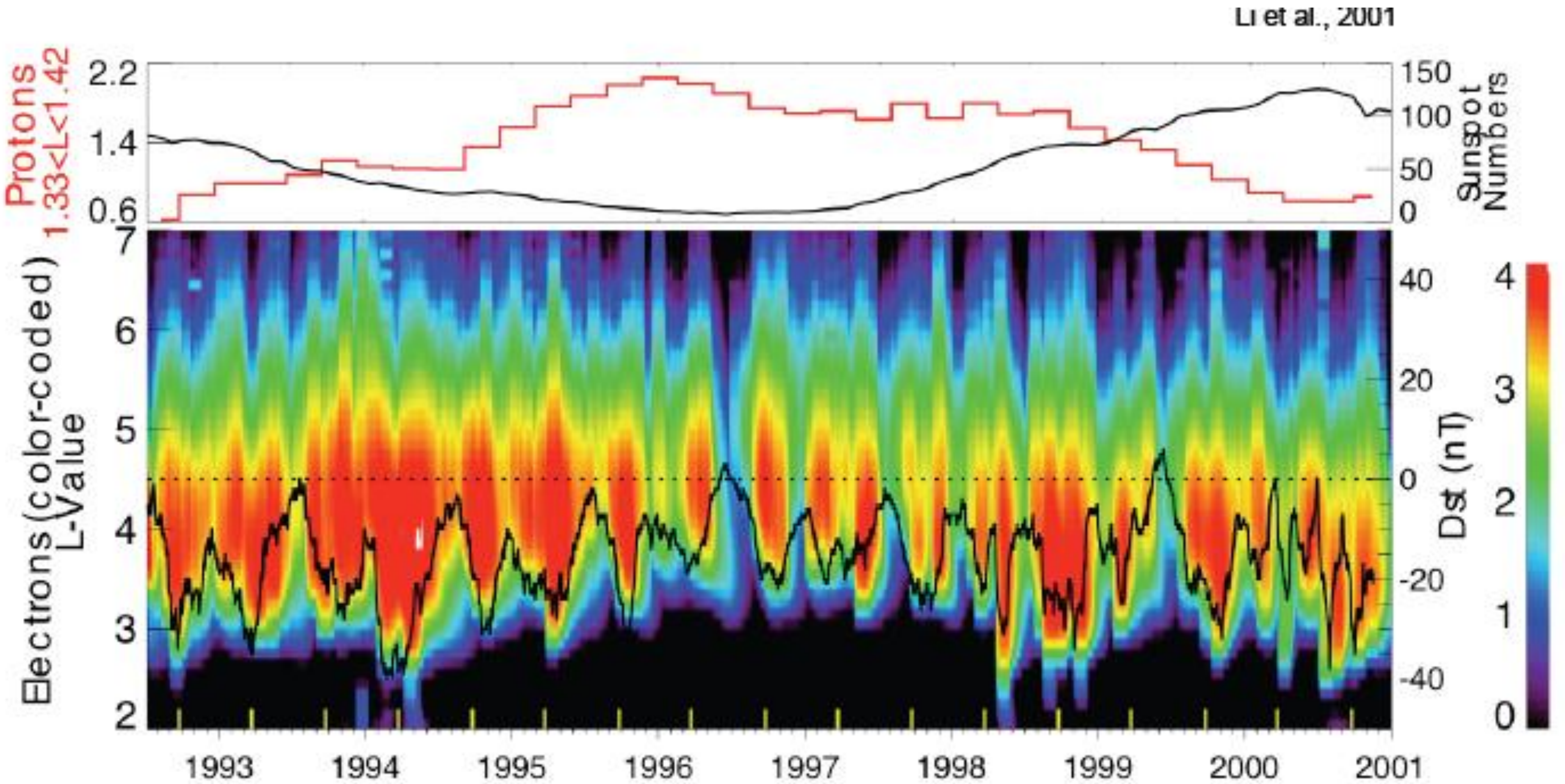
- Storm commencement: minutes
- Storm main phase: hours
- Storm recovery: days
- Solar rotation: 13-27 days
- Season: months
- Solar cycle: years



Long term dynamics from SAMPEX

SAMPEX - Solar Anomalous and Magnetospheric Particle Explorer

- SAMPEX observations over most of a solar cycle
- shows long-term dynamics in outer radiation belt



Why study the radiation belts?

- Because they're physically interesting!
- Relativistic electrons have been associated with spacecraft 'anomalies'.

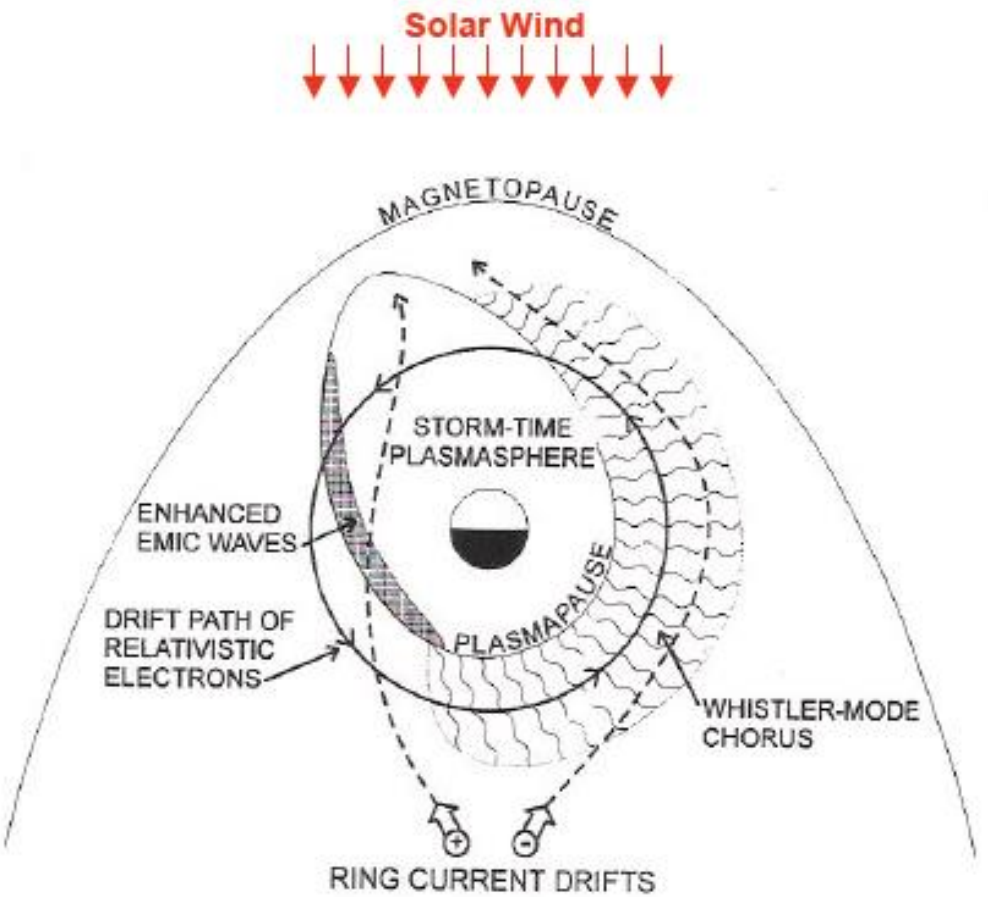
Want to try to describe and predict how radiation evolves in time at a given point in space.

Sources

- Solar wind particles enter via outer magnetosphere or from the plasma sheet.

- Cosmic ray albedo neutrons
  cosmic rays --> n --> H+ and e

- High altitude nuclear explosions can produce artificial radiation belts
  - several US, Soviet tests in 1958-1962 produced short-lived belts inside the inner belt



Summers et al., 1998

Accelerations mechanisms

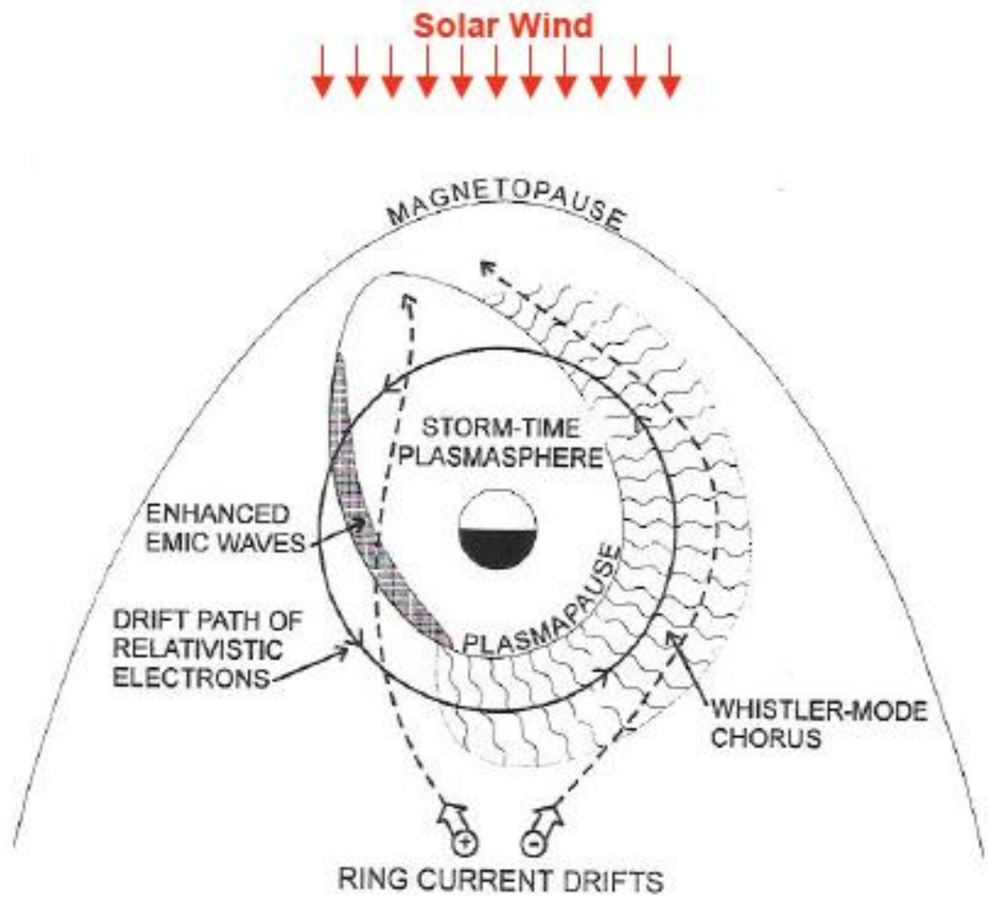
- Inward radial diffusion
  - [*Schulz and Lanzerotti, 1974*]
- Re-circulation model
  - [*Nishida, 1976; Fujimoto and Nishida, 1990*]
- Dayside compression (inductive E field)
  - [*Li et al., 1993; Hudson et al., 1997*]
- ULF enhanced radial diffusion
  - [*Hudson et al., 1999; Elkington et al., 1999*]
- Wave particle interactions
  - [*Temerin et al., 1994; Li et al., 1997; Horne and Thorne, 1998*; *Summers et al., 1998*]
- Cusp trapping and diffusion of energetic electrons
  - [*Sheldon, 1998*]
- Substorm injection
  - [*Kim et al., 2000; Fok et al., 2001*]
- ULF and whistler mode waves
  - [*Liu et al., 1999*]

Loss mechanisms

- Coulomb collisions:
  - with cold charged particles in plasmasphere, ionosphere

- Magnetopause shadowing:
  - loss of particles with orbits carrying them outside the magnetopause

- Scattering of particles by wave-particle interactions (PA diffusion)
  - into loss cone in phase space:
  - particles will collide with atmosphere



Summers et al., 1998

Summary on waves in radiation belts

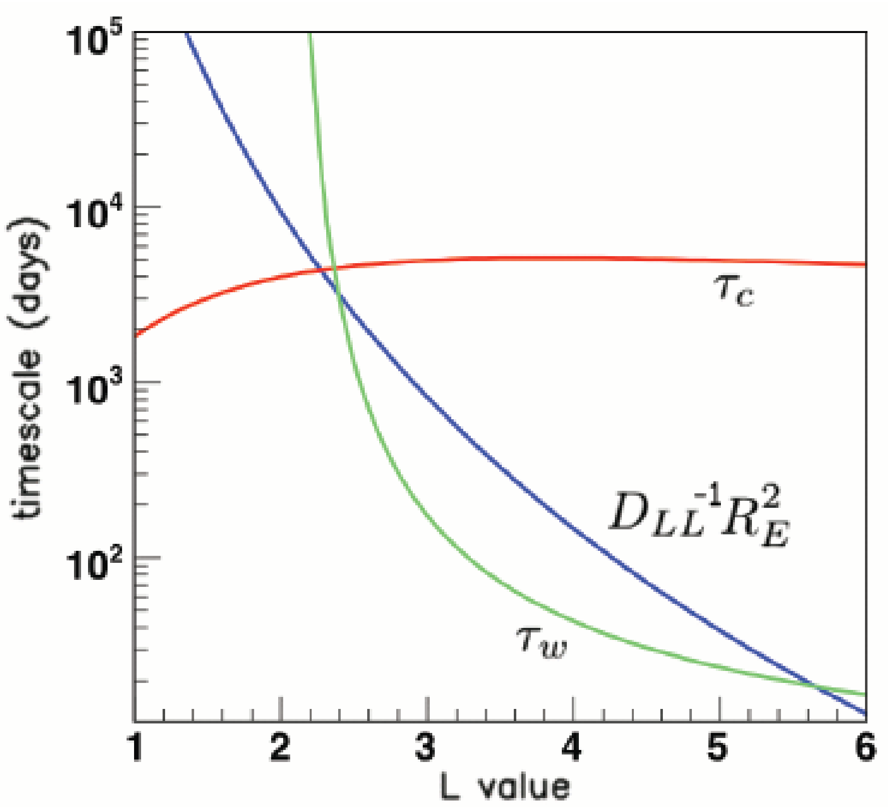
1) Several different waves are excited in the magnetosphere during geomagnetically active conditions and leading to non-adiabatic changes in the radiation belts.

2) EMIC waves, and whistler-mode chorus and hiss cause pitch-angle scattering and loss to the atmosphere. Net loss times for relativistic electrons can be less than a day during the main phase of a storm but much longer during the storm recovery.

3) Interactions with chorus emissions also leads to local acceleration and causes peaks in phase space density just outside the plasmapause.

4) ULF waves cause radial diffusion and associated particle energization during inward transport.

Why there are two electron belts

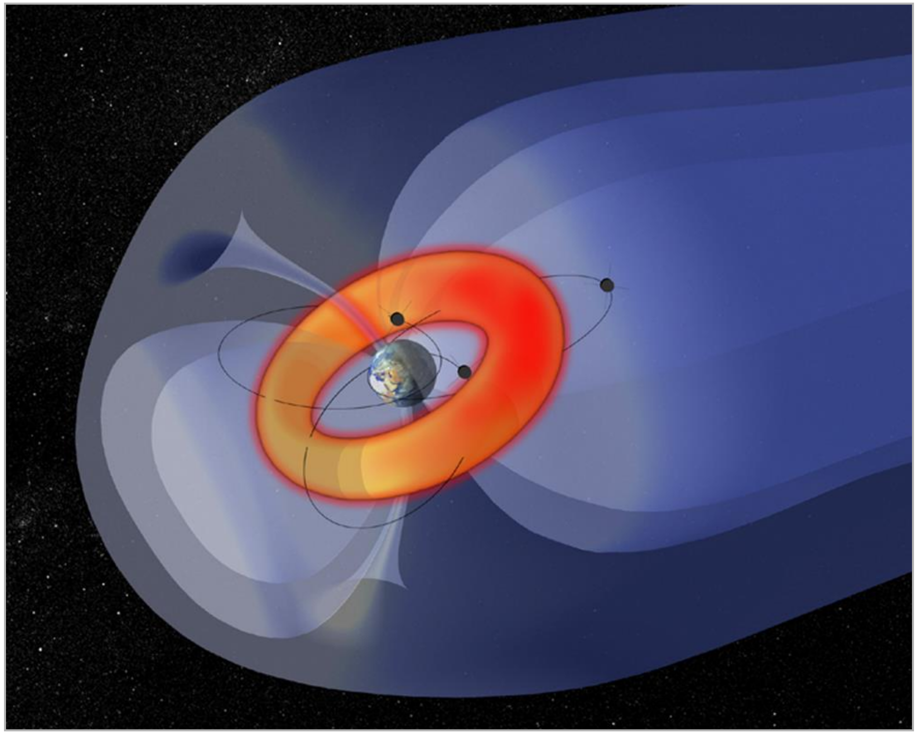


timescales for fixed μ=30 MeV/G *(after Lyons and Thorne, 1973)*

- D_{LL} drives inward diffusion, faster at large L
- whistler losses faster than replacement by diffusion in slot region
- those particles that reach low L have lifetimes of years

General structure of ring current

The symmetric ring current is one of the oldest concepts in magnetospheric physics:
A current of a ring shape flowing around the Earth was first introduced by *Stormer* (1907) and supported by *Schmidt* (1917). *Chapman and Ferraro* (1931, 1941) used a ring current concept for the model of a geomagnetic storm.



Ring current, simplified view:
- toroidal shaped electric current
- flowing westward around the Earth
- with variable density
- at geocentric distances between 2 and 9 Re.
- H+, O+, He+, e, 1-400 keV

Quiet time ring current:
of ~1-4 nA/m^2
Storm time ring current:
of ~7 nA/m^2

The first mission, which clarified the ring current energy and composition was AMPTE mission of the late 1980s.

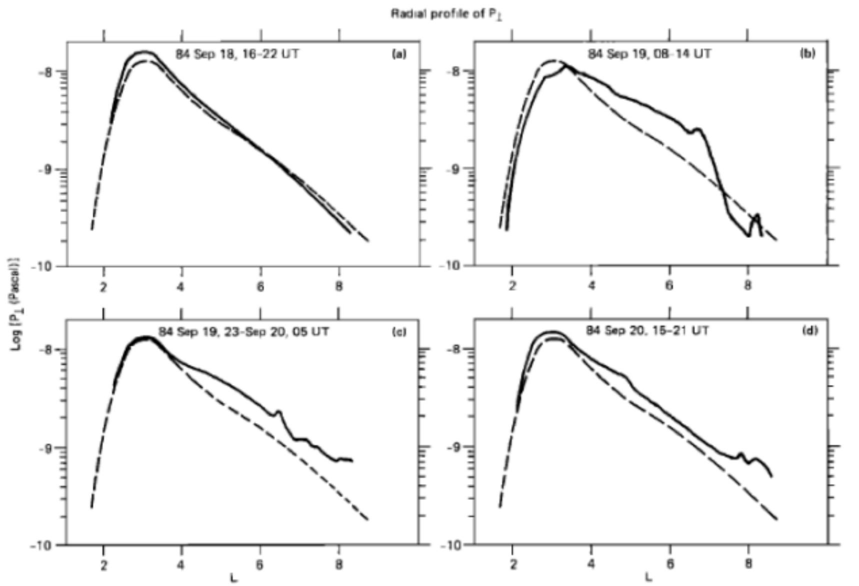
General structure of ring current: Observations

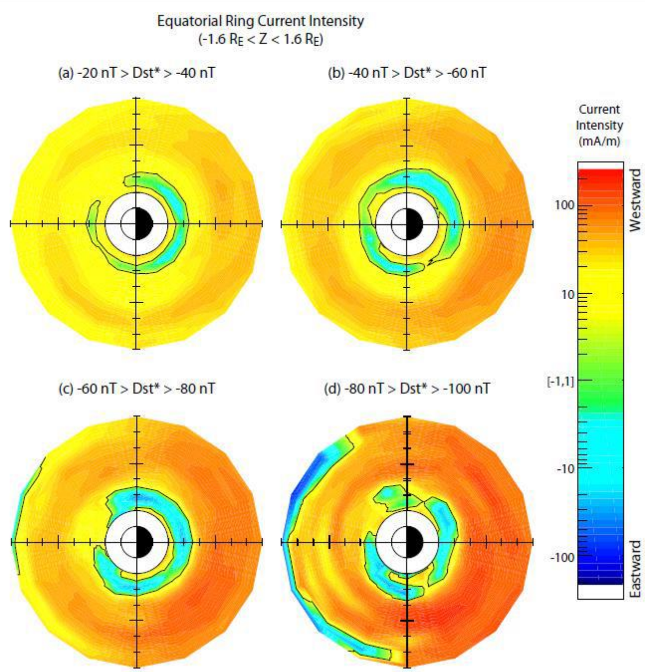
There have been numerous in-situ observations of the ring current:

- **particles measurements** giving plasma pressure and current estimated from it (*Frank*, 1967; *Smith and Hoffman*,1973; *Lui et al*., 1987; *Spence et al*., 1989; ***Lui and Hamilton* (1992);** *De Michelis et al*., 1997; *Milillo et al*., 2003; *Korth et al*., 2000; *Ebihara et al*., 2002; *Lui*, 2003);

- deriving the current from the **magnetic field measurements** (***Le et al*., 2004**; *Vallat et al*., 2005; *Ohtani et al*., 2007);

- **remote sensing of energetic neutral atoms** (ENAs) emitted from the ring current (information about ring current morphology, dynamics and composition) (*Roelof* , 1987; *Pollock et al*., 2001; *Mitchell et al*., 2003; *Brandt et al*., 2002a; *Buzulukova et al*., 2010; *Goldstein et al*., 2012).



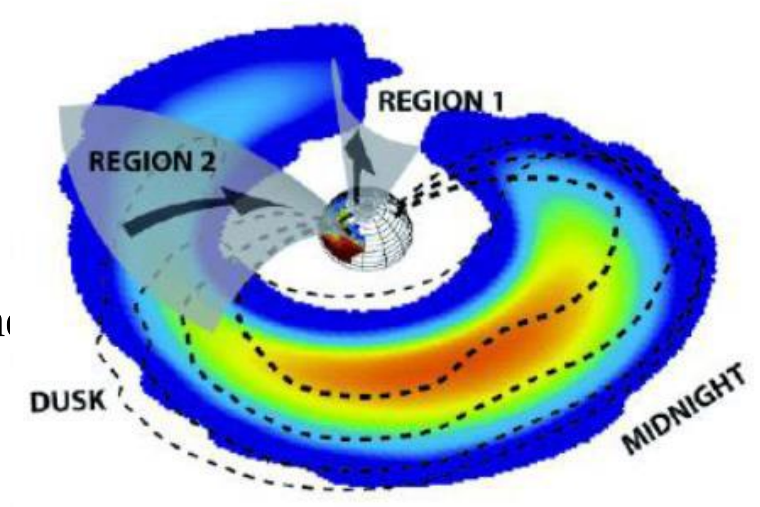


Ring current morphology

The ring current almost always is not a ring. The concept of the partial ring current and its closure to the ionosphere was early suggested by Alfven in 1950’s.

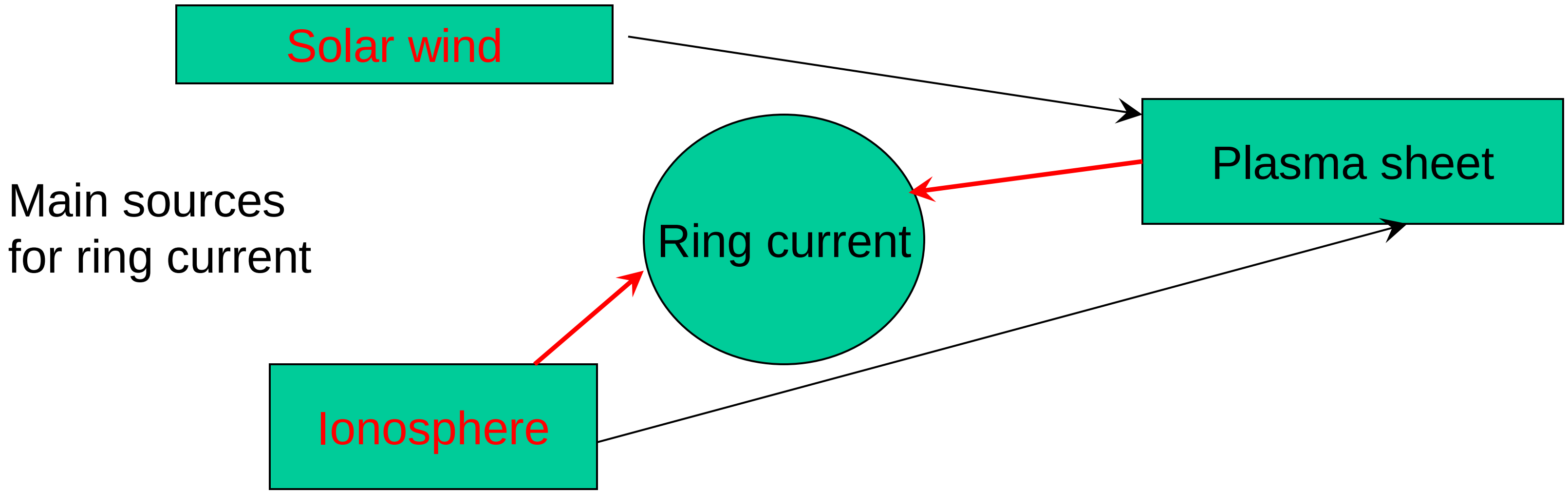
- Magnetosphere is **essentially asymmetric**, compressed by the solar wind dynamic pressure on the dayside, and stretched by the tail current on the night-side.
- **Plasma pressure** distribution during disturbed tim becomes **highly asymmetric** due to plasma transport and injection from the night-side plasma sheet to the inner magnetosphere.
- The resulting plasma distribution presents a gradient in the azimuthal direction resulting in the **spatial asymmetry of the ring current.**

The remnant of the perpendicular current must **flow along a field line** to complete a closure of the current



Current systems associated with the partial ring current as deduced from the ENA measurements (*Brandt et al*., 2008)

Sources of the ring current particles



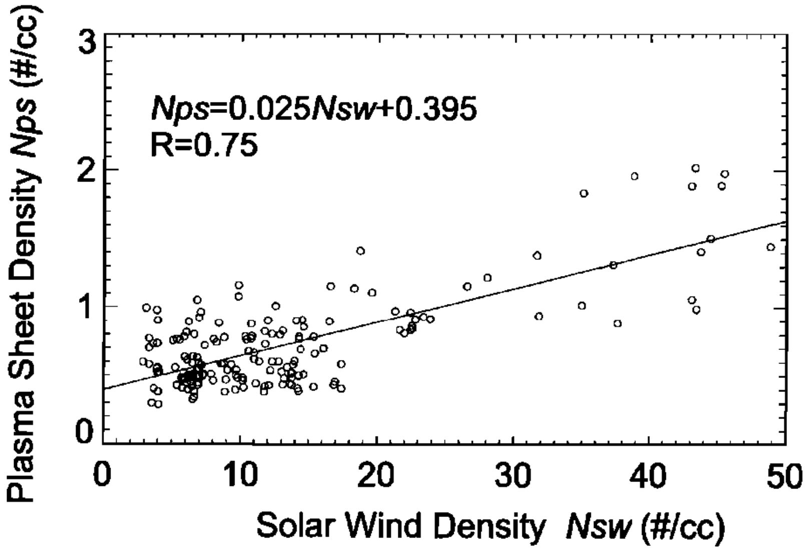
Origin of ion species:

- magnetospheric H+ ions: from ionosphere and solar wind (this complicates identification of the dominant source);
- majority of magnetospheric O+: ionosphere;
- He++: solar wind;
- He+: ionosphere.

Charge-exchange transforms solar wind higher charge state O ions to ionosphere-like lower charge state, solar wind He++ into He+ (provided by the ionosphere).

Solar wind entry to the magnetosphere

- through LLBL
- through high latitude plasma mantle
- through the cusp



Ebihara and Ejiri (2000)

Satellite observations:
Wind + **Geotail:**

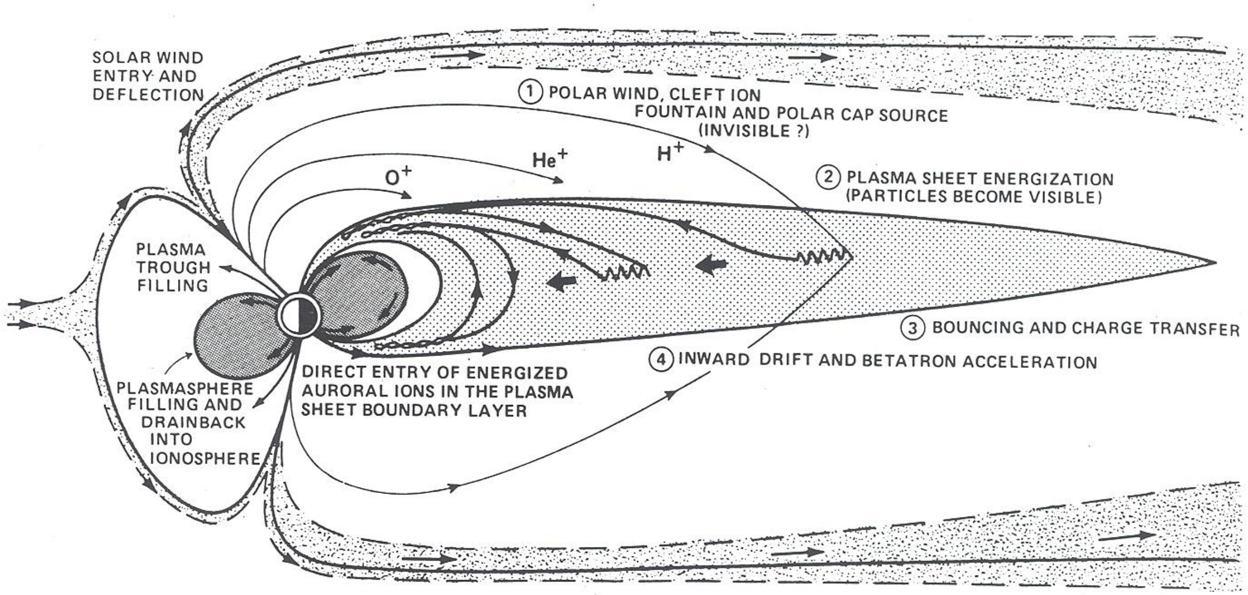
- for extended periods of northward IMF magnetotail < 15 RE is dominated by solar wind particles entering through the flanks (*Terasawa al., et 1997*);

- correlation between plasma sheet density (**Geotail**) at 9-11 Re and solar wind density (**WIND**)

Ionospheric outflow

Dominance of **ion outflow regions** depends on the magnetospheric conditions.

- dayside cleft,
- auroral region
- high-alt. polar wind,
- mid-lat. ionosphere.

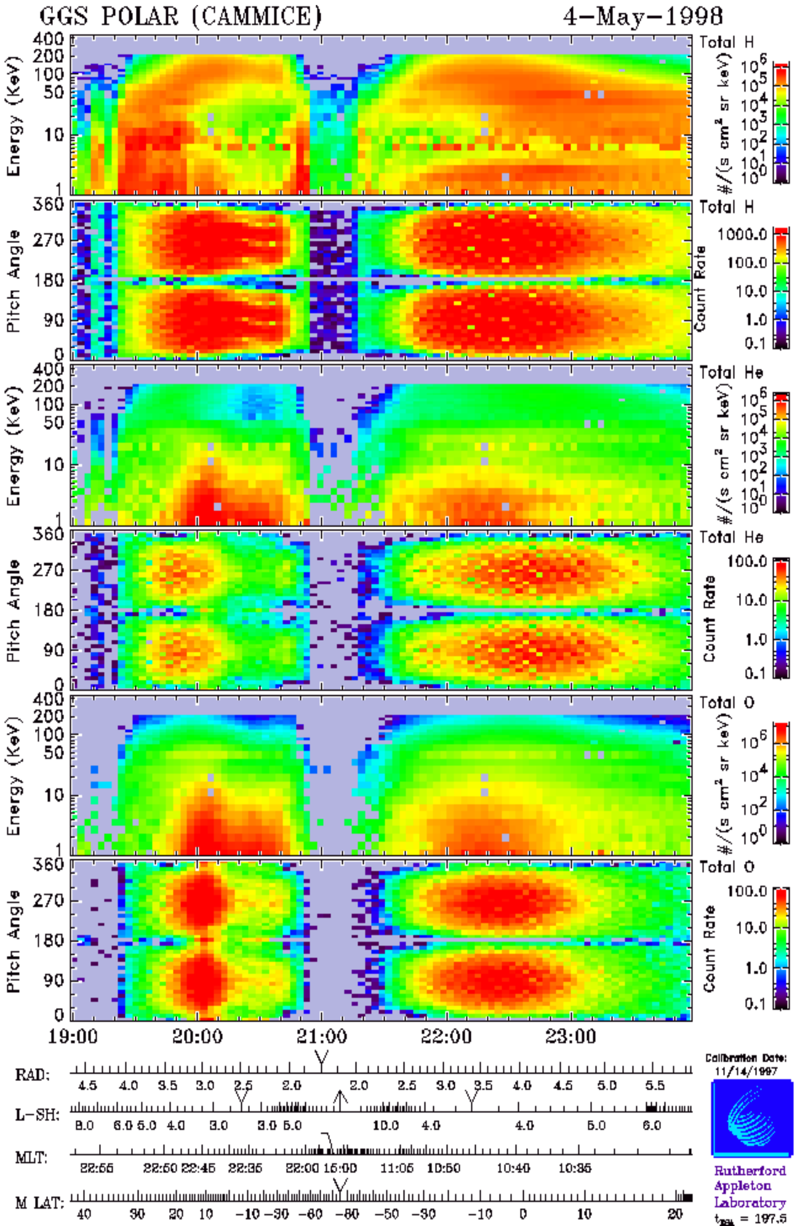


Chappel et al., 1987:

Ionospheric ions alone supply magnetospheric plasma sheet content

Efficient acceleration of ionospheric ions (from 1 eV to tens of keV) and associated extraction into the magnetosphere is under investigation.

Ring current energy density and total energy measured by Polar CAMMICE/MICS



Polar orbit, years 1996-1998

- 1.8x9 Re elliptical, 86 deg inclination,
- 18 hours period, apogee over north polar reg.,
- spin axis normal to orbit plane,
- ions (H+, He+, He++, O+,O++) of 1-200 keV

Energy density of ring current particles

$$w(L) = 2\pi\sqrt{2mq}\int_0^{\infty} dE\sqrt{E}\, j(E, L),$$

m - particle mass, q - particle charge state,
E - energy, j - measured particle flux

Total ring current energy

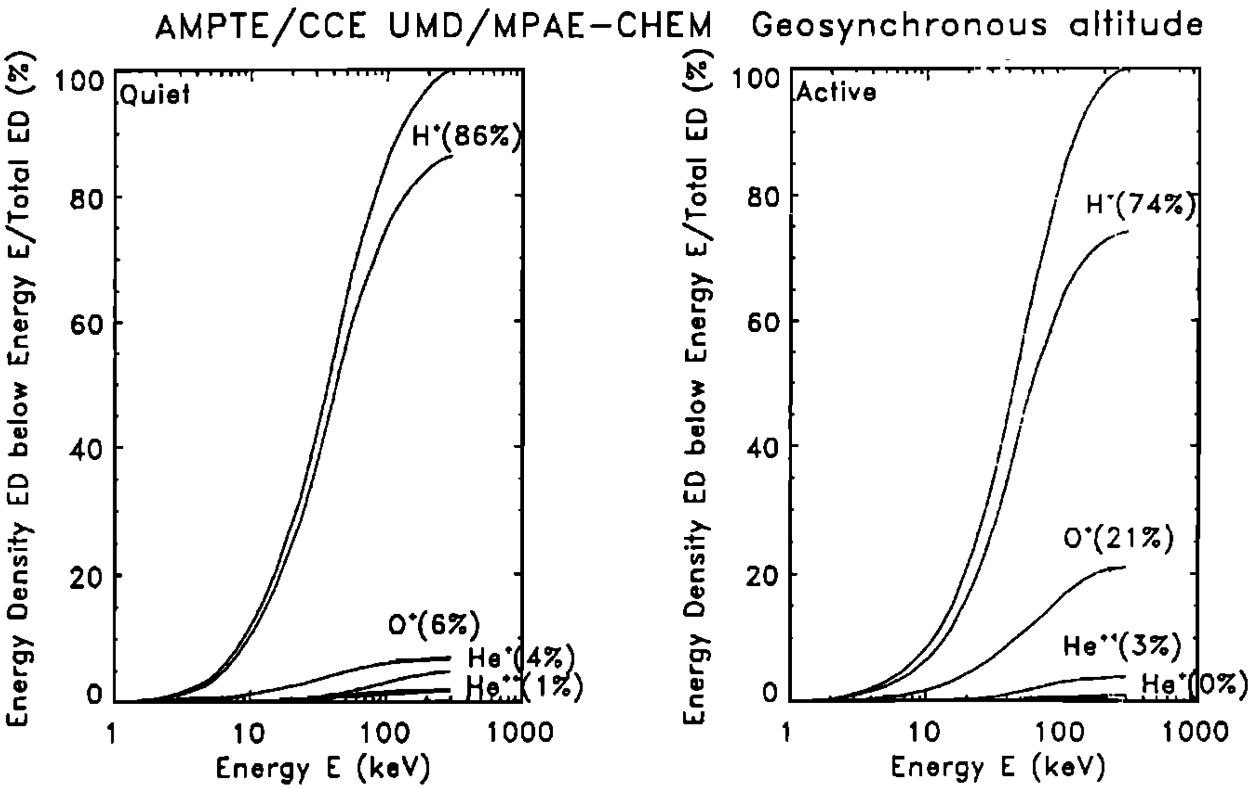
$$W_{RC} = \int_V w(L)\, dV,$$

$$dV = 2R_E^3 L^2 \sqrt{1-\frac{1}{L}}\left(\frac{1}{7L^3} + \frac{6}{35L^2} + \frac{8}{35L} + \frac{16}{35}\right) dL\, d\phi$$

ϕ - local time

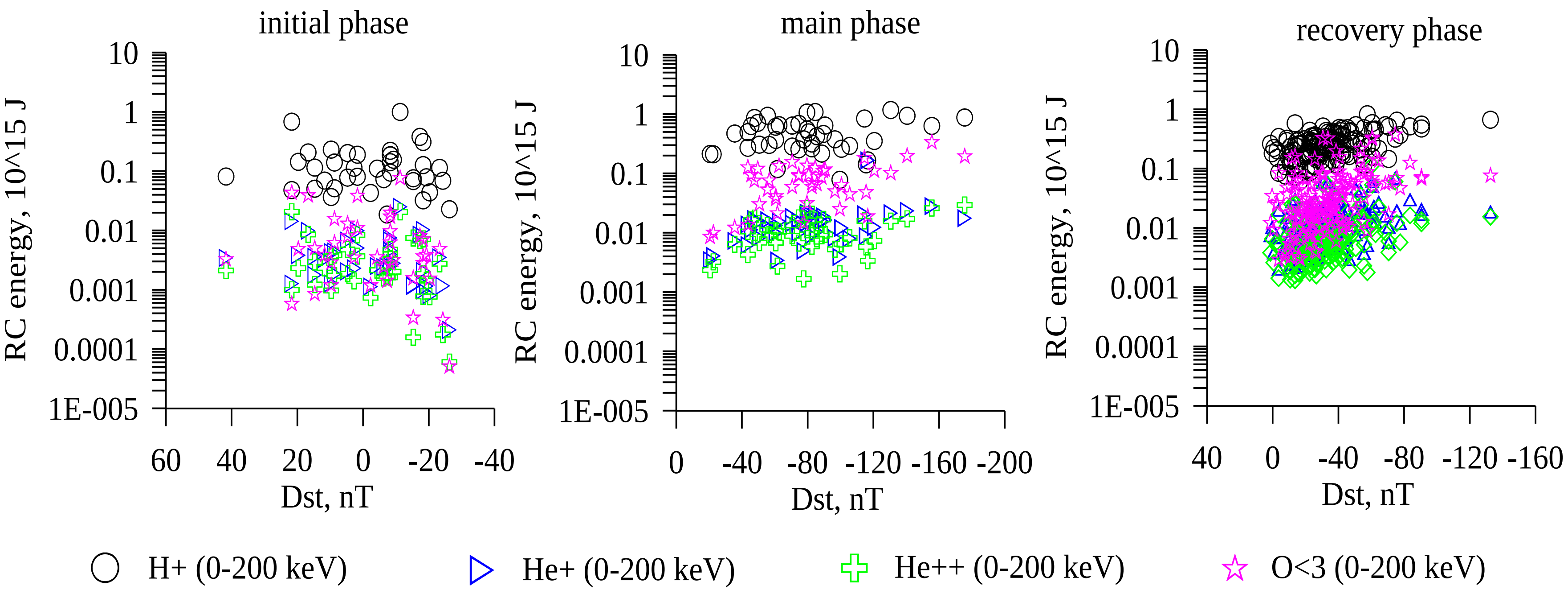
Ring current composition

Daglis et al., 1993



Quiet time ring current: dominated by protons, O + contribution is about 6%
Storm-time ring current: O + can contribute more than 50% during great storms

Contributions to ring current energy from ion species: Storm statistics

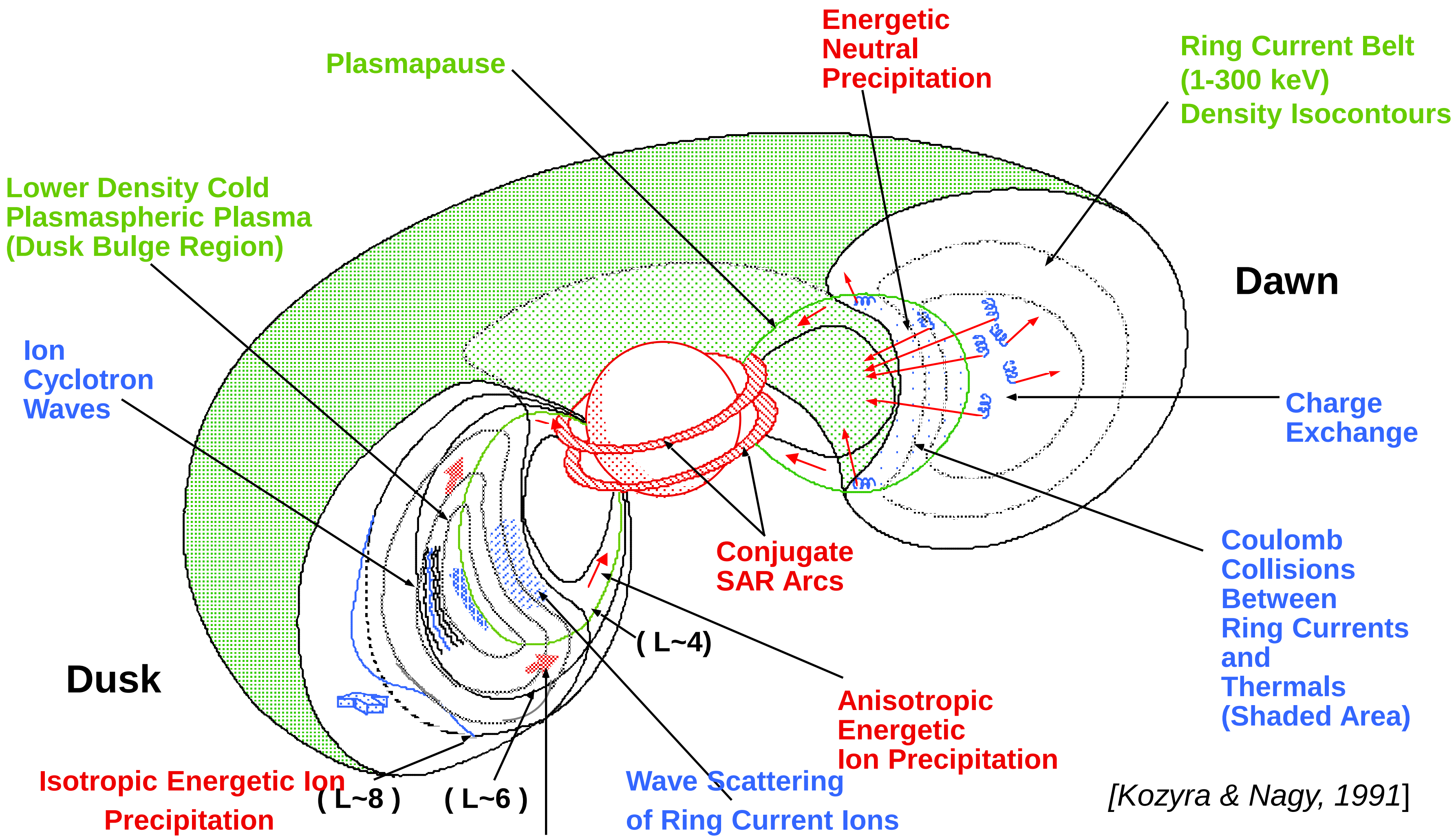


Initial phase: almost similar contributions (10^12 J) from ion species (He+,++, O+,++), no dependence on Dst

Main phase: larger contribution from He+ and He++ (10^13 J), O+,++ contribution increase up to several 10^14 J, increase with Dst decrease

Recovery phase: order of difference between He+,++ and O+,++ contributions (10^12-10^13 and 10^13-10^14), decrease with Dst increase

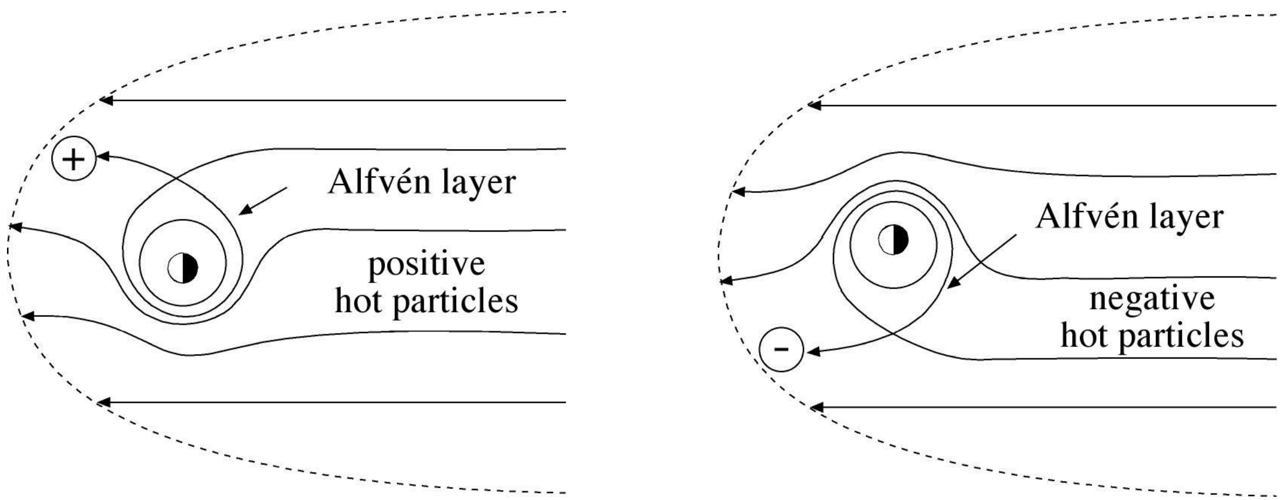
Ring Current Loss Processes



[*Kozyra & Nagy, 1991*]

Particle trapping and ring current

Electrons and ions move around the Earth in different directions, creation of ring current.



Trapping of particles

(1) Coupling between the solar wind and the magnetosphere intensifies,

(2) sunward convection increases,

(3) boundary separating the convective and co-rotational flow moves inward,

(4) freeing some of the plasma previously bound on "closed" trajectories ,

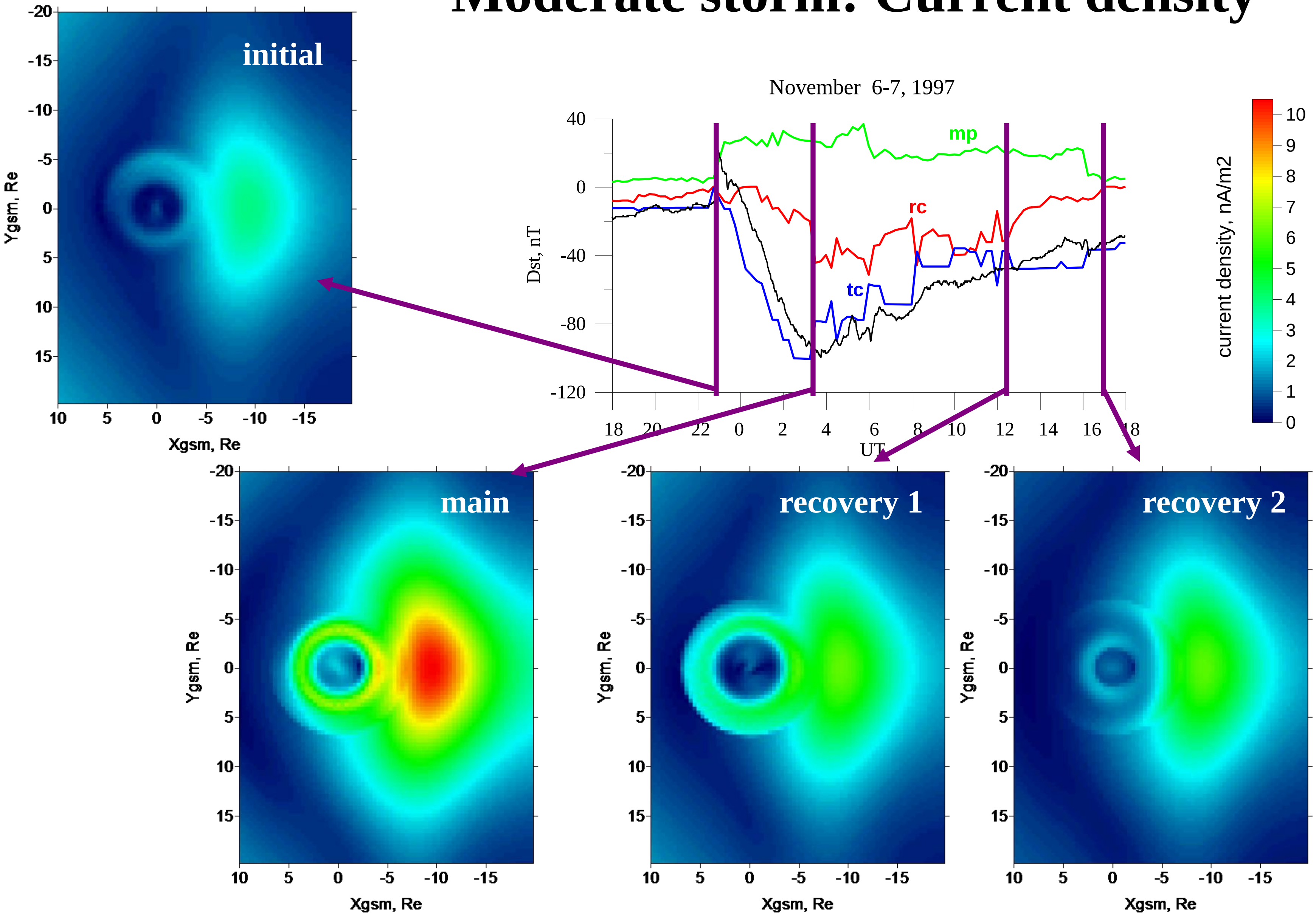
(5) That plasma follow "open" convective paths toward the dayside magnetopause.

(6) Weakening of convection

(7) region of near-Earth plasma that co-rotates with the Earth enlarges,

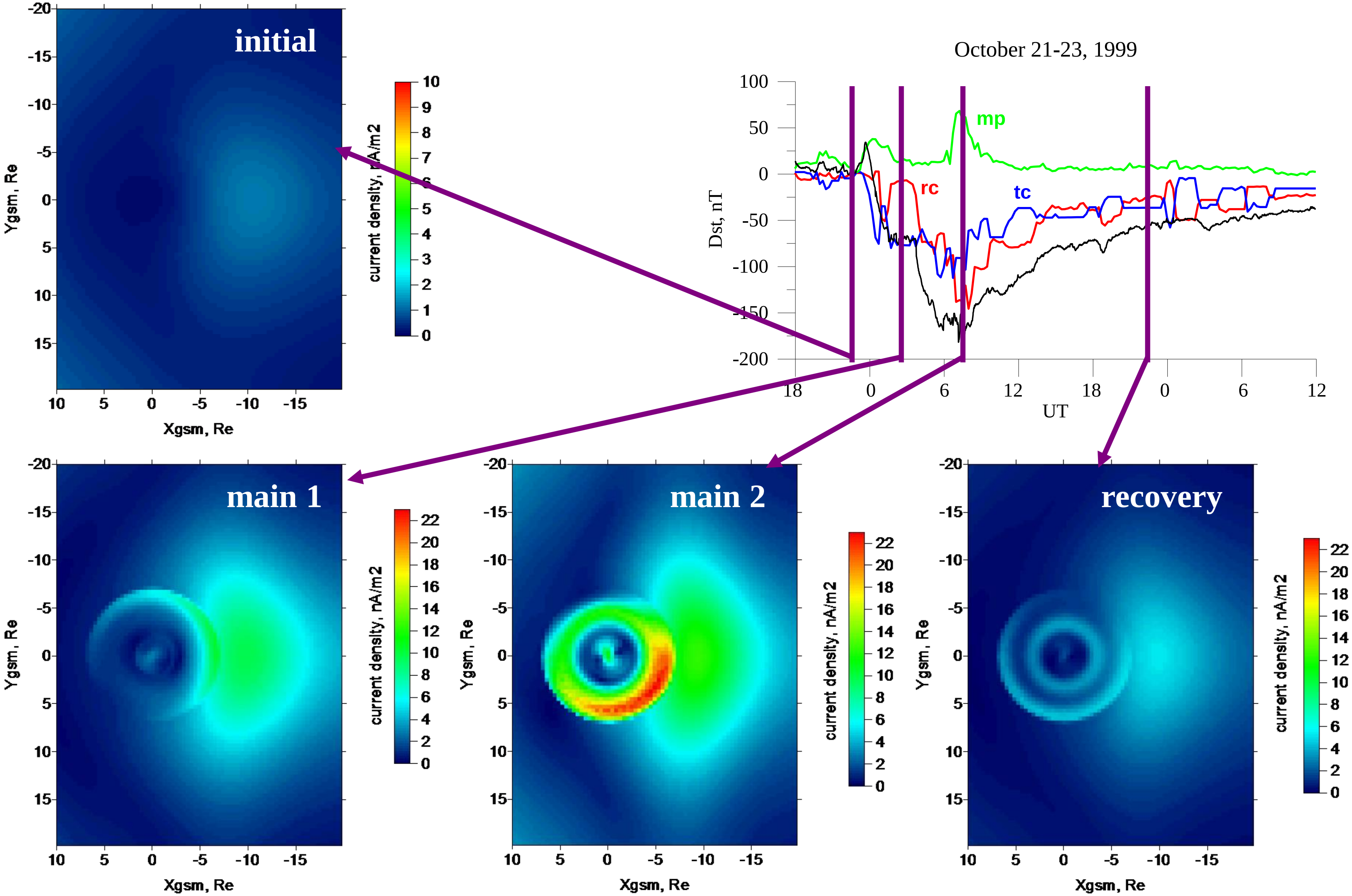
(8) magnetic field lines emptied of plasma during periods of high convection are refilled.

Moderate storm: Current density



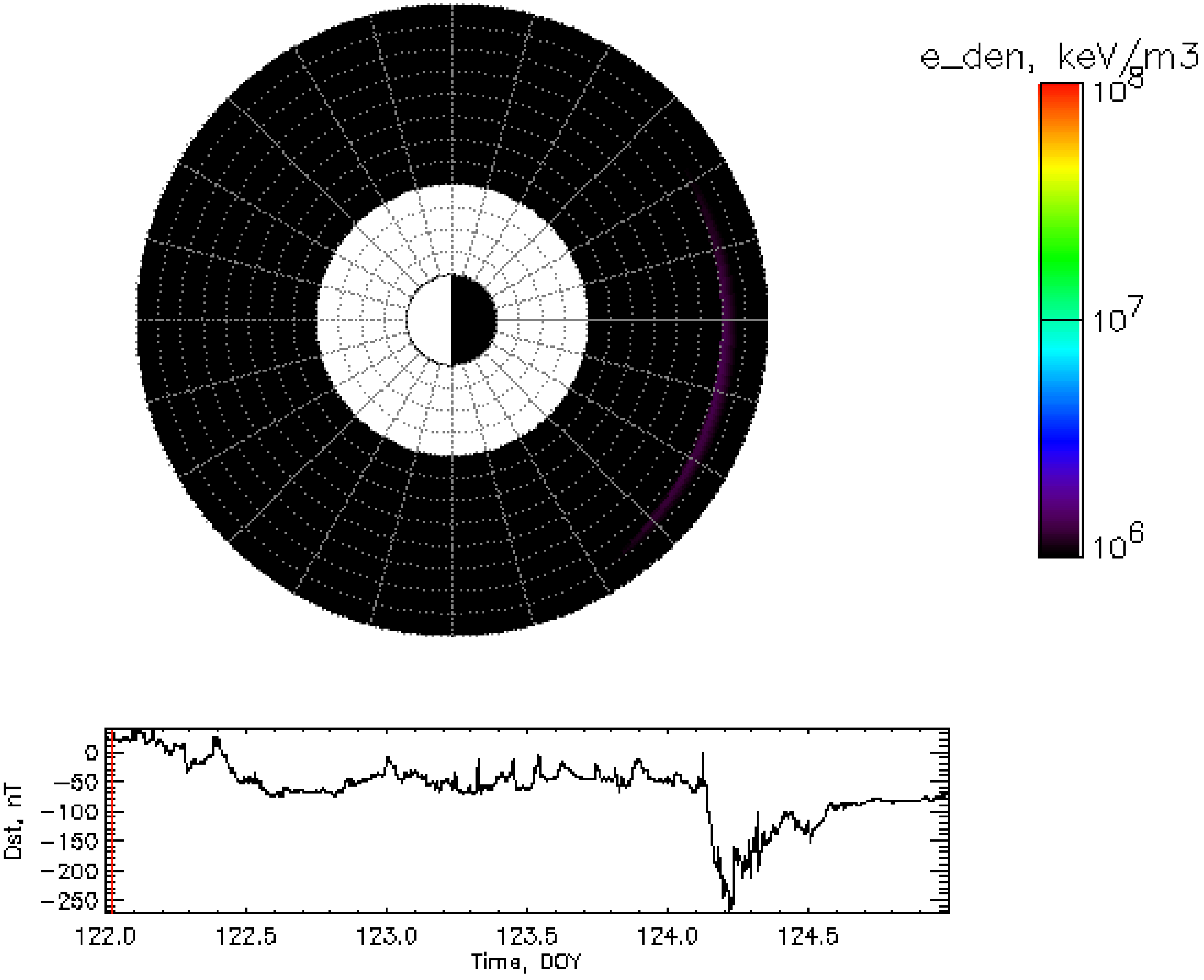
Event-oriented magnetic field model, From *Ganushkina et al.*, AnnGeo, 2010

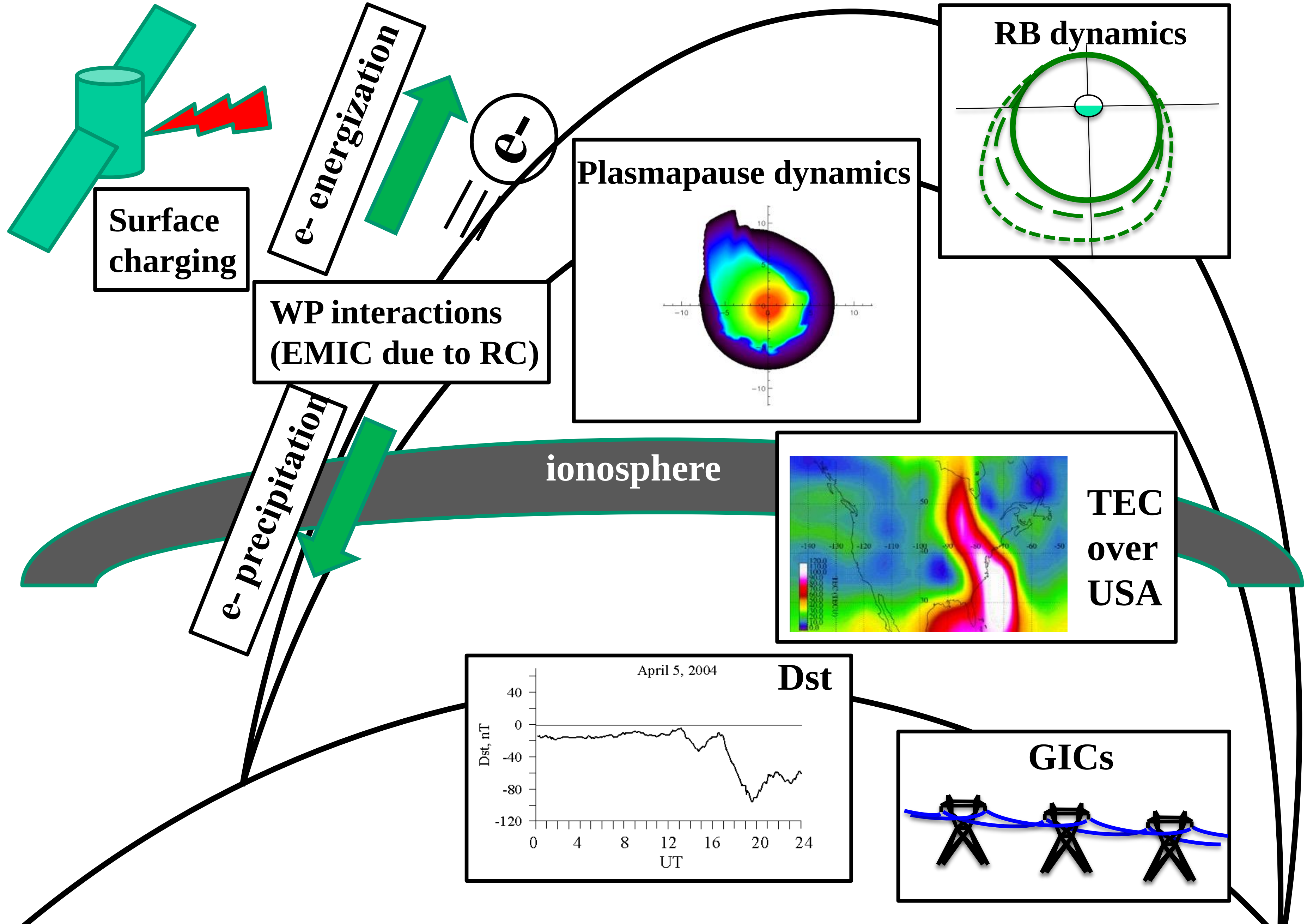
Intense storm: Current density



Event-oriented magnetic field model, From *Ganushkina et al.*, AnnGeo, 2010

Ring current development during storm on May 2-4, 1998: IMPTAM simulations (*Ganushkina et al.*, 2005)



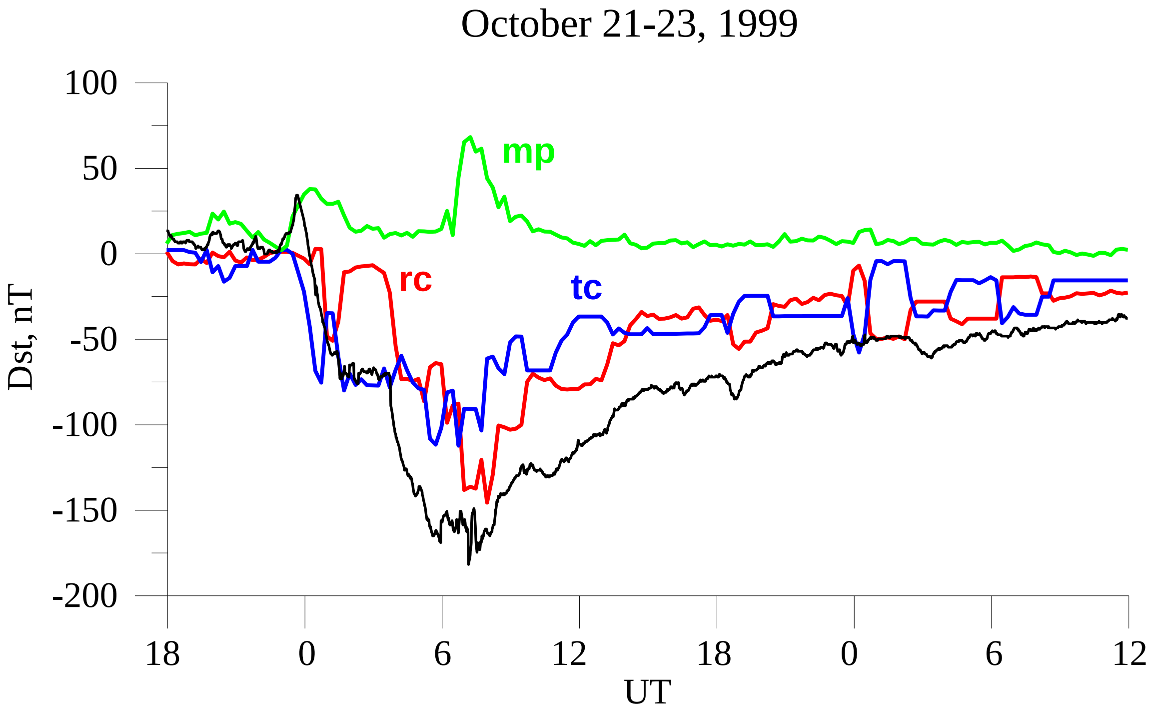


Space weather effects due to the ring current

Space weather effects due to the ring current (1)

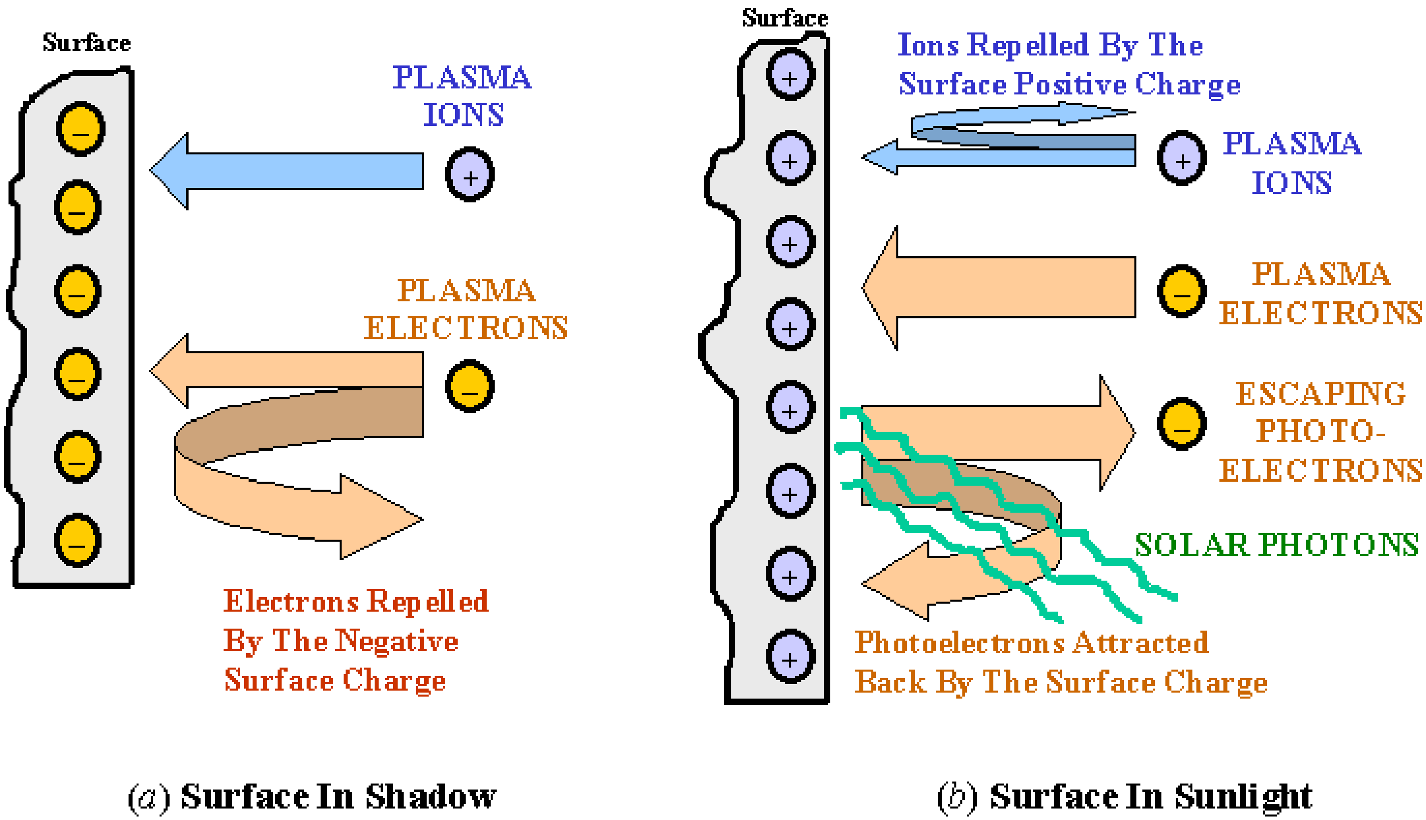
The space weather effects from the ring current particles with keV energy range cannot be considered as highly obvious as those from the "killer" electrons or from the solar energetic protons with energies of tens of MeVs but they are nevertheless quite significant.

- Ring current has a direct influence on the Dst-index computed from the ground-based magnetic field observations and which is an indicator of a storm activity.



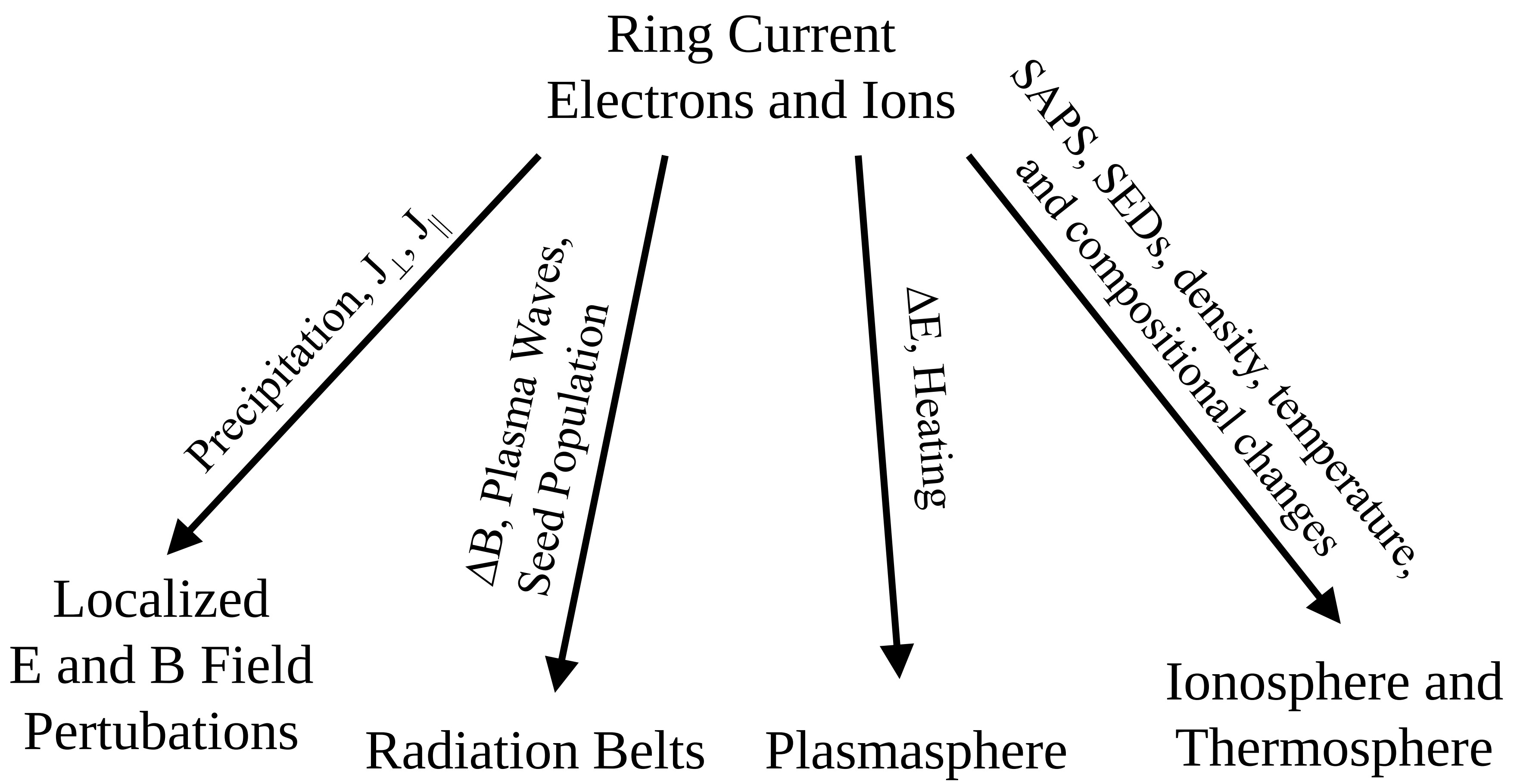
Space weather effects due to the ring current (2)

- Electrons with < 100 keV vary significantly with activity on the scale of minutes or shorter. They do not penetrate deep into the satellite materials but stay near the surface and can be responsible for surface charging effects which is a serious risk for satellites.



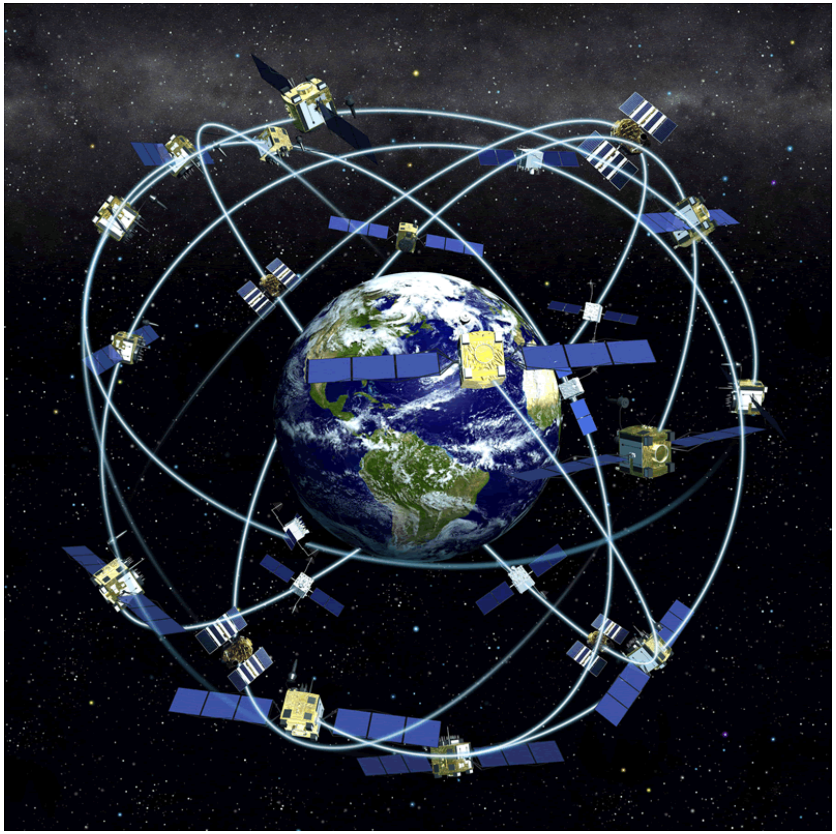
Space weather effects due to the ring current (3)

- Ring current dynamics is tied to both radiation belt losses and enhancements by affecting the efficiency of magnetopause shadowing and driving various wave-particle interactions. With the addition of the overlapping plasmasphere, the picture is more complicated.



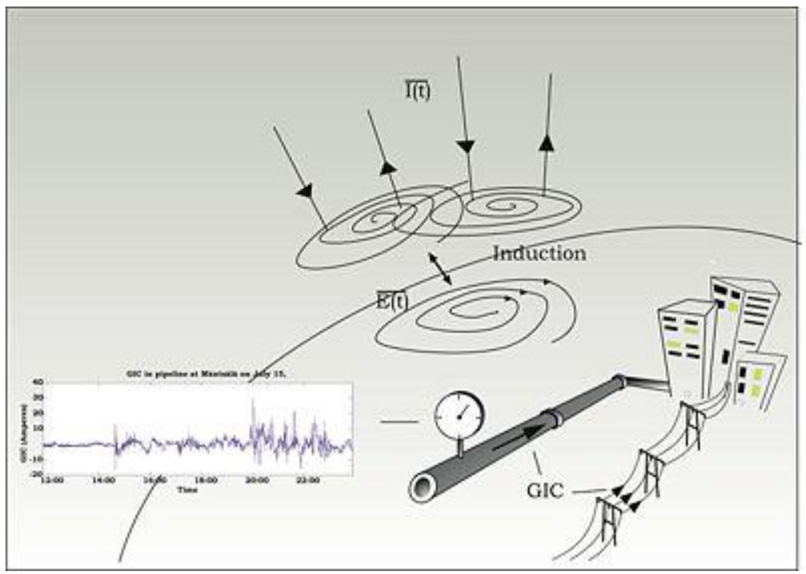
Space weather effects due to the ring current (4)

- The partial ring current closes through the ionosphere leading to the SAPS phenomenon of strong westward flows at midlatitudes. This rearranges the ionospheric density, creating SED plumes across the dayside middle and high latitude regions, extending even over the polar caps. These density enhancements adversely affect GPS signals, resulting in location errors of 50-100 meters during large events. Thermosphere is heated by the SAPS flows, leading to chemistry changes, and thermospheric winds ramp up to match the ionospheric flows during prolonged SAPS intervals.



Space weather effects due to the ring current (5)

- The ring current contributes to the Geomagnetically Induced Currents effects via its role in the generation of Region 2 FACs. The magnitude of GIC is determined by the horizontal geoelectric field which is mainly controlled by currents in the magnetosphere and ionosphere, and by the conductivity of the Earth. The large-scale electric currents in the ionosphere are coupled to the magnetosphere through field-aligned currents. The Region 2 currents which can be mapped to the ring current region are generated by the pressure gradient dynamics in the inner magnetosphere.



The dynamics of the ring current is a preeminent factor in space weather forecasting, thereby of critical importance to the health and safety of our spacecraft systems. The ring current does not interact independently and alone, it is tied to the greater system.