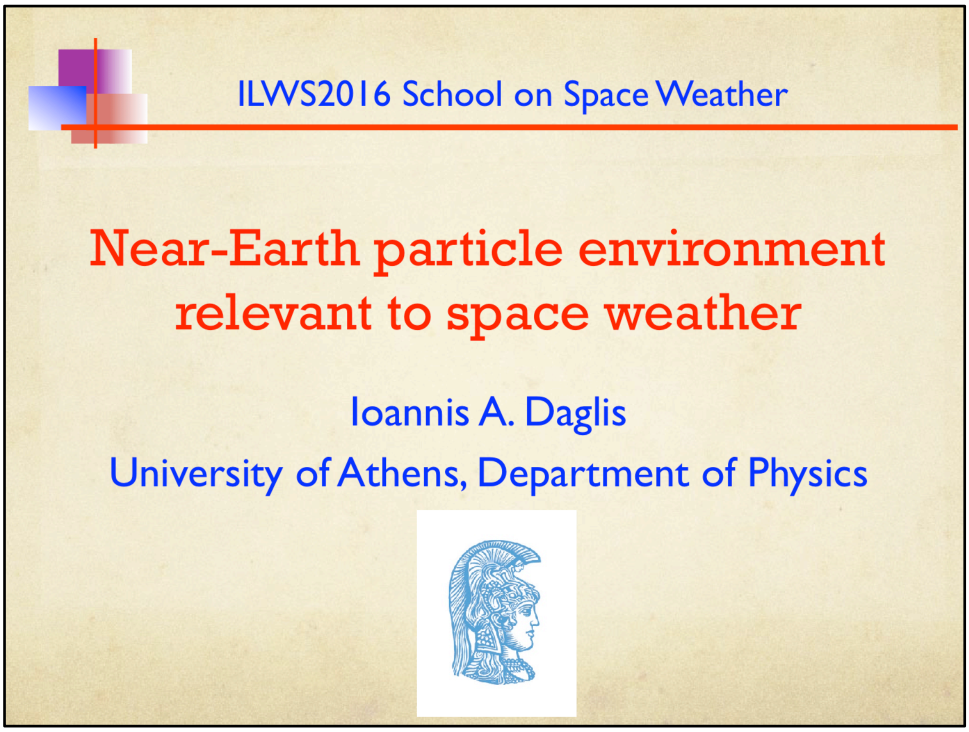


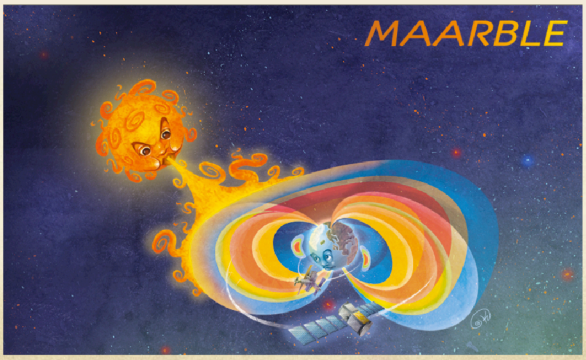
Thanks to organizers

The particles:

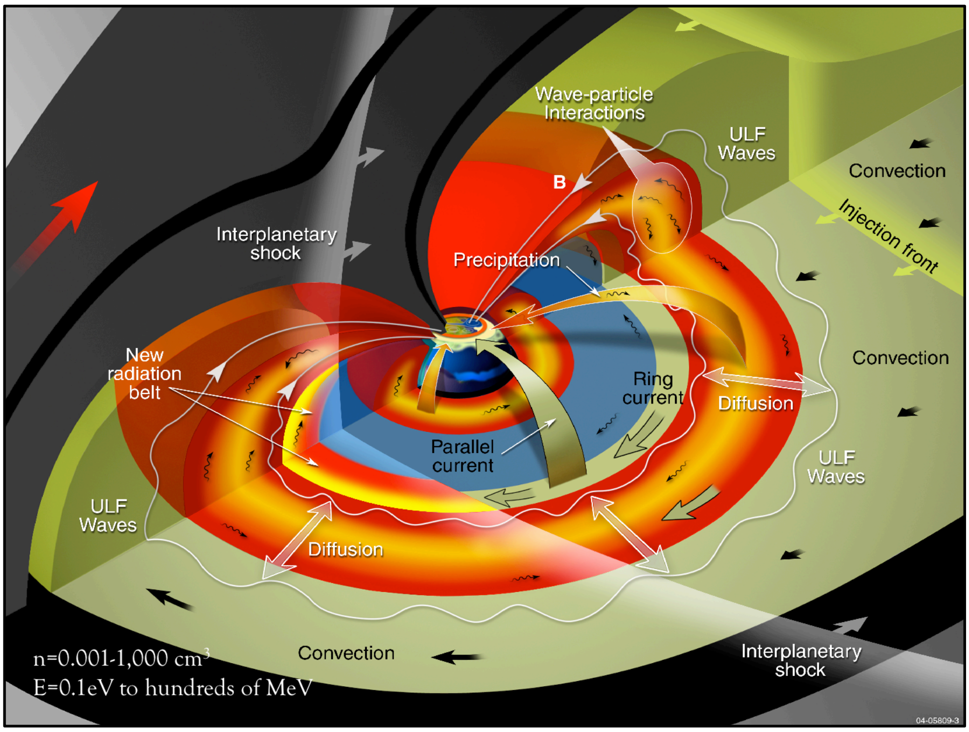
Ring Current, Radiation Belts, Plasmasphere

Space weather phenomenon connecting them:

Space storm (aka geospace magnetic storm)



Aka geomagnetic storm, space storm, magnetic storm

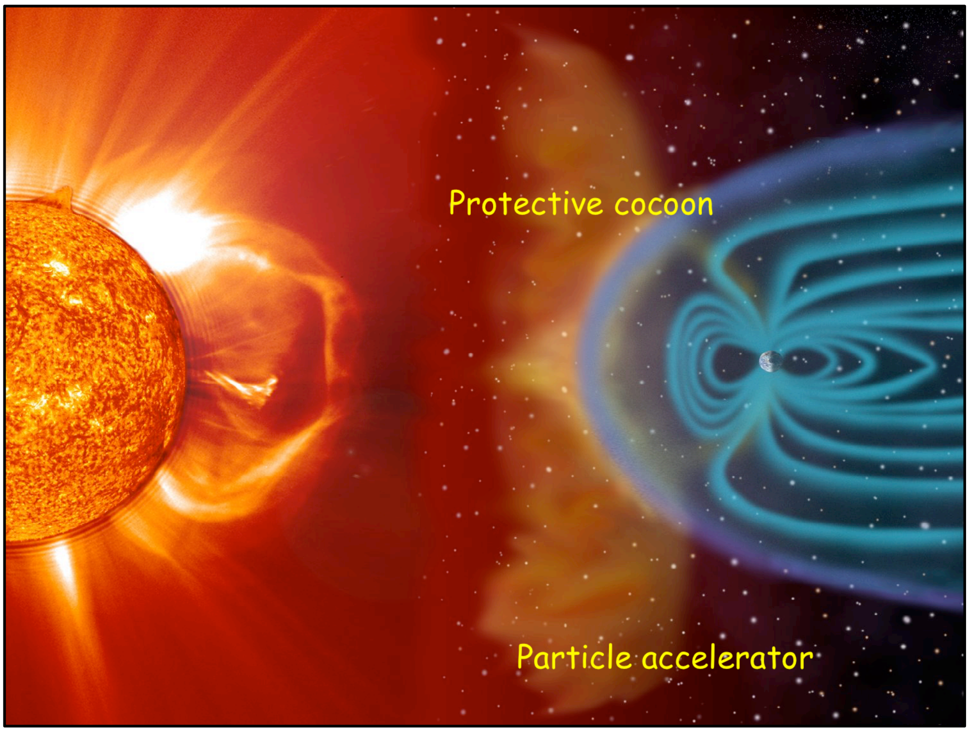


Huge span of 9 orders of magnitude in energy and 6 orders of magnitude in density.
Air molecules in the atmosphere only have about 0.03 eV, Protons in the inner belt: a couple of hundreds of million eV

This raises the most fundamental question in space research - **how come a few particles get so much?**

Mass: ~10^5 kg (100 tons) PEANUTS … 100 cars … The thin Atmosphere: ~10^{18}, i.e. one million millions the mass of msph.

Half an eV equals to the energy of a particle on Sun's surface (T=5,800 K, 1 eV = 11,600 K).
0.67 eV: The energy needed by a proton or neutron to escape the Earth's gravity.
40,000 eV: Energy required by an electron to penetrate a thin-wall Geiger counter like that of Explorer 1.



Magnetosphere: a protective cocoon for the Earth. Let me emphasize that however intense a solar flare may be, there is pretty much no effect in Geospace if the magnetospheric magnetic field is not … by a … There is much too often a misconception about the way the Sun influences dynamic processes in Geospace.

<u>The release of energy from the sun is necessary, but not enough</u>.

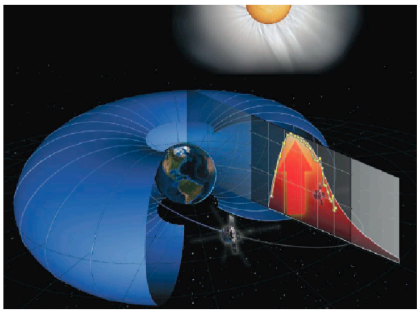
Now the fun and interesting fact is that Geospace is also a rather efficient cosmic accelerator. And because of this, it is the cradle of disaster.

SPACE PHYSICS

The Savage Radiation of the Van Allen Belts Is Homegrown

Back in 1958, Explorer 1, the first U.S. satellite, sent back unsettling news: Nearby space was pervaded by radiation intense enough to blind their instruments. The Van Allen radiation belts, extending from about 1000 kilometers to 60,000 kilometers from Earth, have been zapping unlucky satellites—and puzzling space physicists—ever since. Now, at last, researchers have figured out where the electrons that fill the Van Allen belts get their killer energy. A pair of probes launched last year has traced how energy streaming from the sun can boost electrons in the heart of the belts to speeds greater than 99% of the speed of light.

Researchers "have found the key

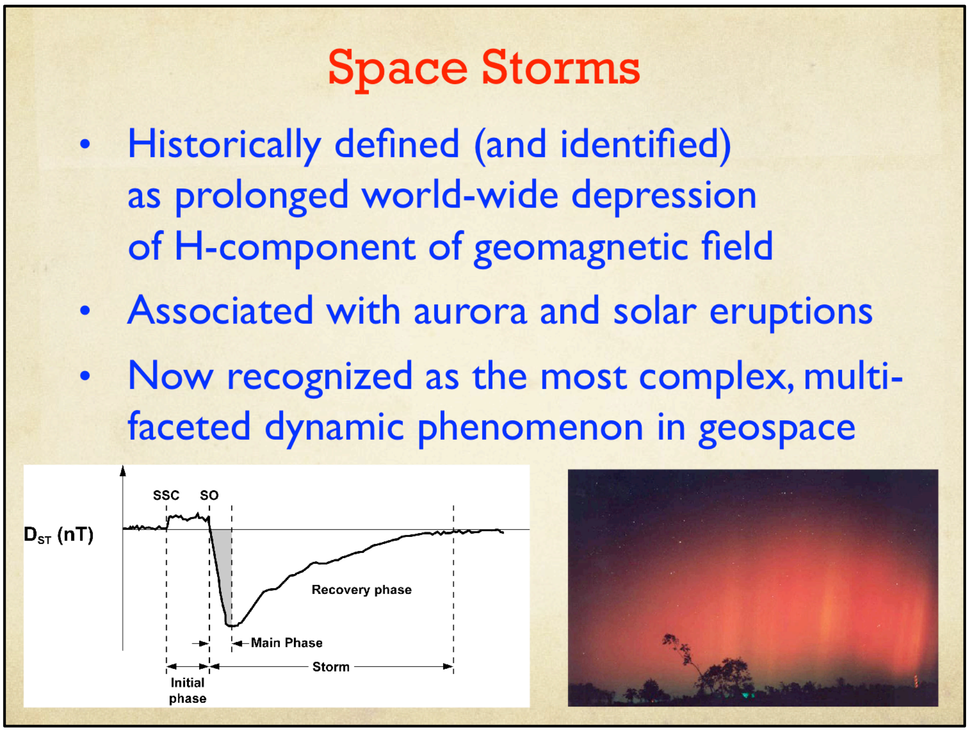


Inner turmoil. Electron energies (yellow curve) detected by two new spacecraft peak inside the radiation belts (including the magnetically defined blue torus) as expected for in situ acceleration (gray curve).

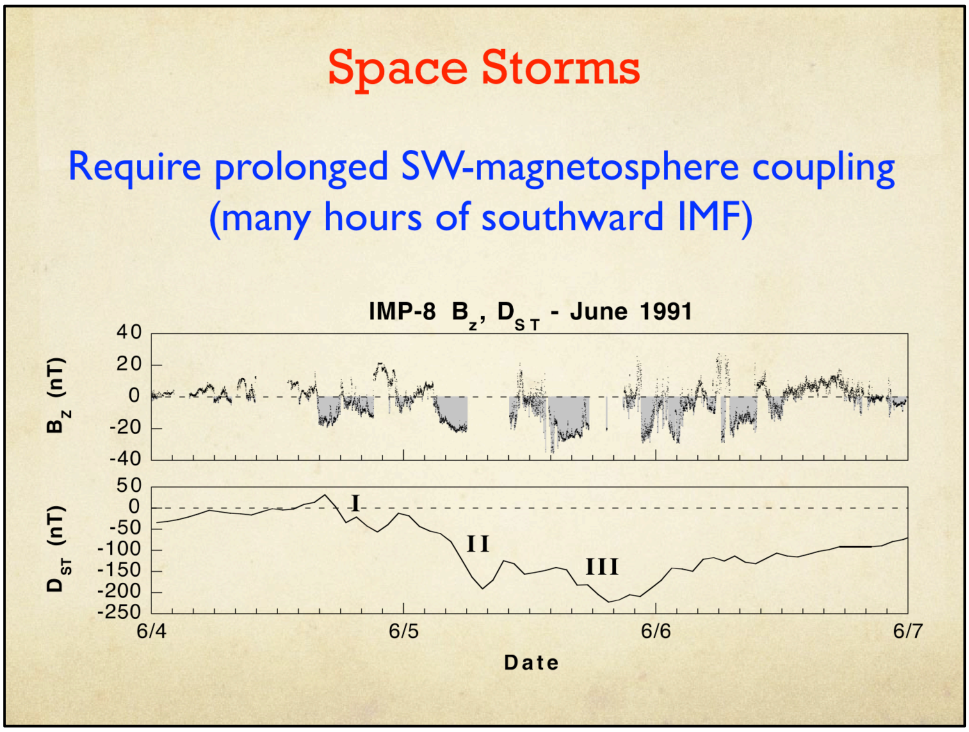
the outer belt, as some theories predicted, the data showed that energy surged among low-energy electrons already in the belts, Reeves says. Powerful electromagnetic waves in the solar wind were almost certainly transferring their energy to the resident electrons, boosting them to speeds at which they can fry a satellite's electronics.

It's still unclear which of a half dozen kinds of waves is the primary driver. But the most likely energy source, Reeves says, is so-called chorus waves, so named because, when converted to sound, their natural frequencies resemble a dawn chorus of birds. Chorus waves that are in sync with electrons spiraling

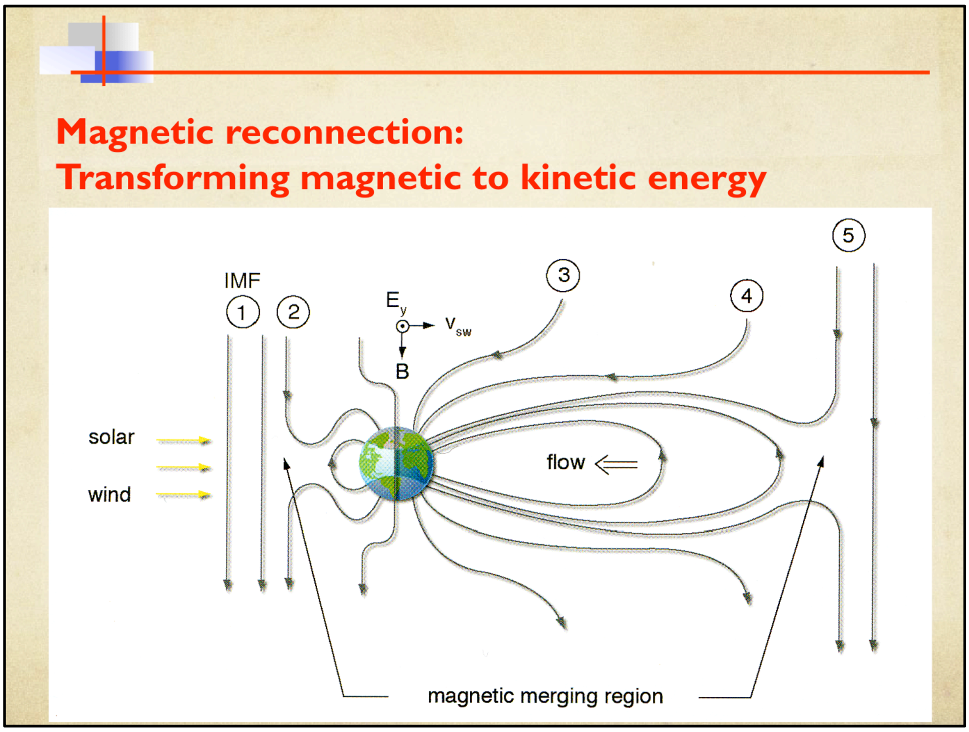
Science, 2013



Global Geomagnetic Field Depression which can be explained through the diamagnetic effect of a giant (ring) current flowing around the Earth.



Energy requirement: many hours of southward IMF, leading to extensive magnetic reconnection and increase of magnetic flux in the terrestrial magnetosphere. Usually associated with CMEs.



The fundamental process: Magnetic Reconnection on the Sun and in Geospace.

Space Storms

Not to be confused with Solar Storms,
(aka Solar Radiation Storms)
which are episodes of intense acceleration
of solar particles to very high energies
(Solar Energetic Particles – SEPs)
by solar flares and/or CMEs.

particles from the solar corona

Space Storms

Not to be confused with Solar Storms,
(aka Solar Radiation Storms)
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Solar Storms and Space Storms **are not identical!**

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Solar Storms and Space Storms **are not identical!**
Solar Storms **do not cause** Space Storms!

(frequent mistake of public outreach articles)

NOAA categorizes Solar Radiation Storms using the NOAA Space Weather Scale on a scale from S1 - S5. The scale is based on measurements of energetic protons taken by the GOES satellite in geosynchronous orbit. The start of a Solar Radiation Storm is defined as the time when the flux of protons at energies ≥ 10 MeV equals or exceeds 10 proton flux units (1 pfu = 1 particle*cm-2*s-1*ster-1). The end of a Solar Radiation Storm is defined as the last time when the flux of ≥ 10 MeV protons is measured at or above 10 pfu. This definition allows multiple injections from flares and interplanetary shocks to be encompassed by a single Solar Radiation Storm. A Solar Radiation Storm can persist for time periods ranging from hours to days.

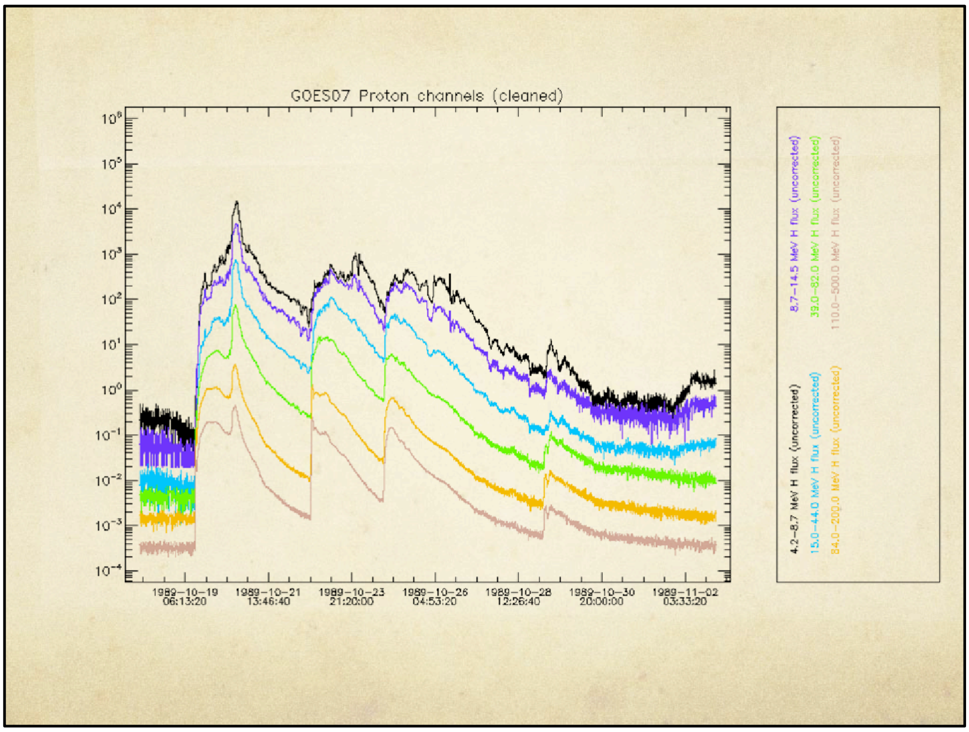
Solar radiation storms

Solar Energetic Particles (SEPs)

Flux of energetic ions >10 MeV

10 – 10^2 – 10^3 – 10^4 – 10^5

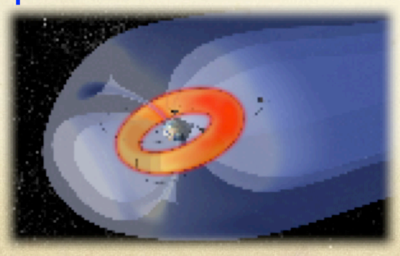
Minor – Moderate – Strong – Severe – Extreme

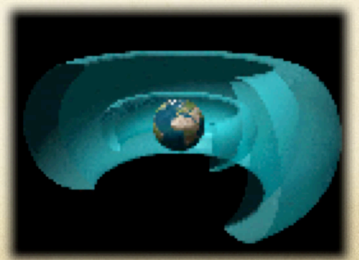


An example of a STRONG solar storm

Ring Current and Van Allen Belts

- RC: Carried mainly by ions (**H^+, O^+**, He^{++}, He^+) in the energy range ~10 keV to a few 100s keV. Spatial extent: 3-9 R_E
- RBs: protons (inner belt) and electrons (outer belt) in the energy range 100 keV to 20+/400+ MeV. Spatial extent:

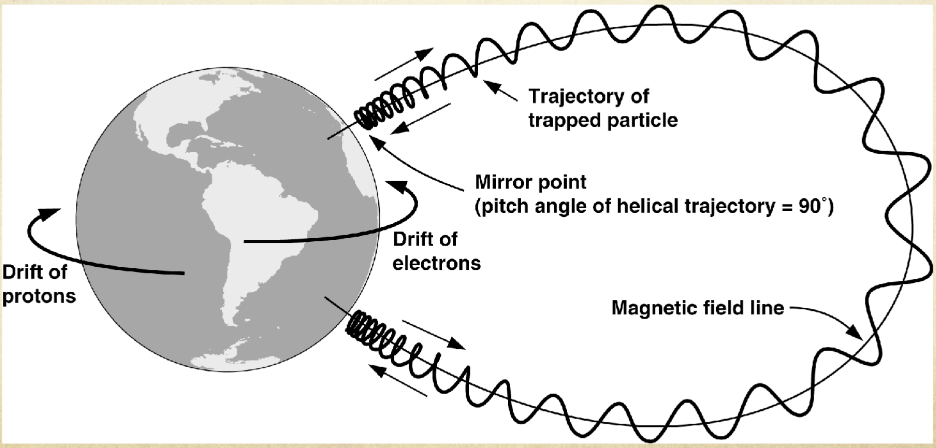




RC: of both solar and terrestrial origin. Total intensity of several Mega Amperes.
Bulk of energy within 50-100 keV. Maximum intensity at 3-5 R_E (geocentric)

RC and RBs

Same principle as RC:
combination of gyro, bounce and drift motions
corresponding to three invariants



and leading to a toroidal topology

Periodic motions and adiabatic invariants

- *I st adiabatic invariant*

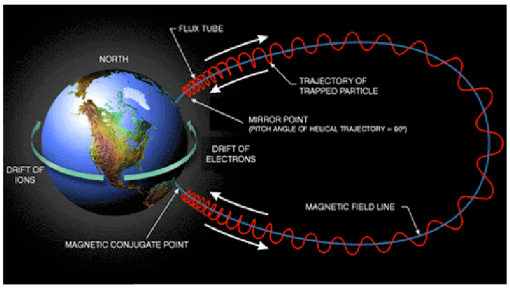
$$\mu = \frac{p_\perp^2}{2mB} \Rightarrow \mu = \frac{p^2 sin^2 a}{2mB}$$

- *2nd adiabatic invariant*

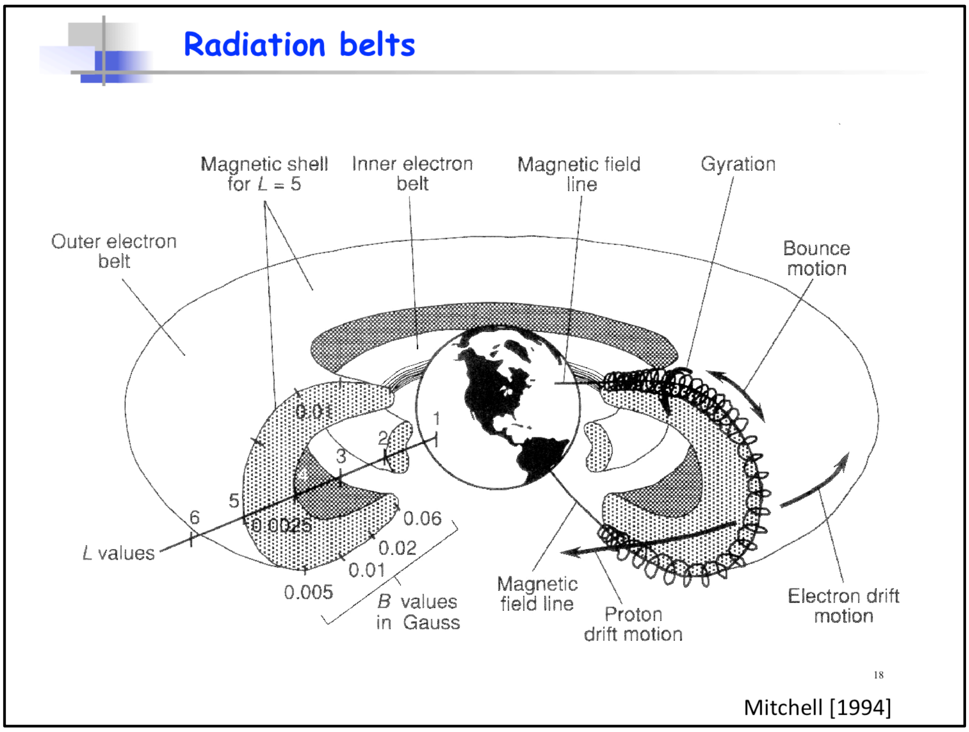
$$J = (8m_0\mu)^{1/2}\int_{a_m}^{b_m} B_m - B(s)ds$$

- *3rd adiabatic invariant*

$$\Phi = \oint u_{drift} r d\varphi$$



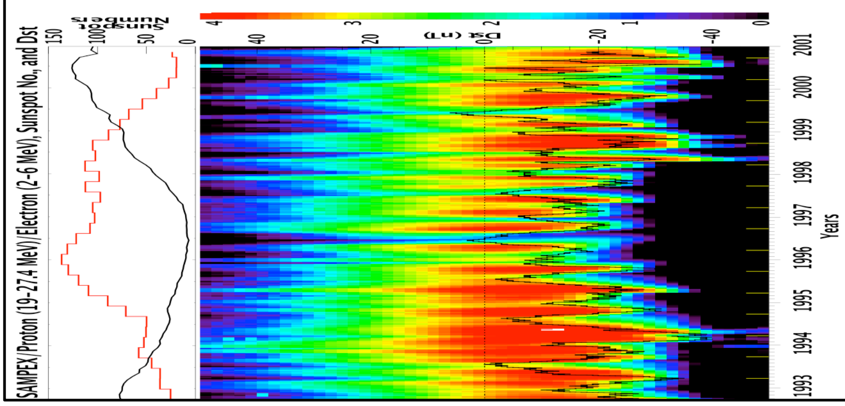
Electrons in the plasma sheet represent a source of high phase space density (PSD), and when the third adiabatic invariant is broken these particles can diffuse inwards in radial distance, gaining energy in the process.



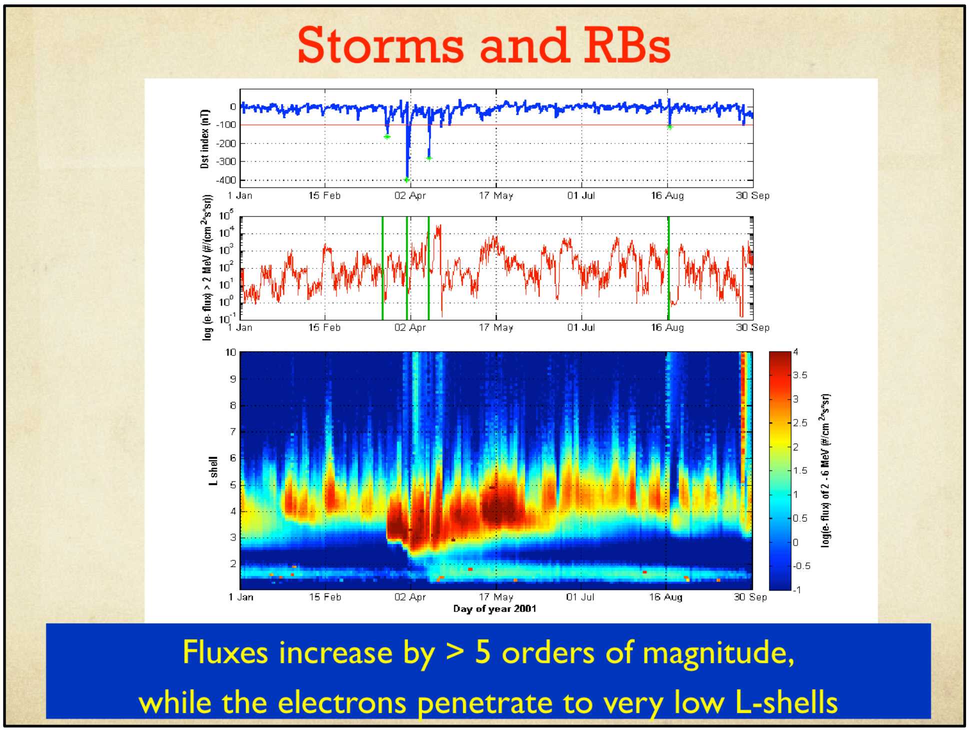
For quite some time the RBs were considered to be a pretty stable structure. There were no dedicated RadBelt missions for more than 3 decades. Even the nowadays considered as RB missions, CRRES and SAMPEX missions, had different main objectives. CRRES intended to study the Radiation Effects on new generation electronics – not the radiation itself! – while SAMPEX's main objectives were the galactic cosmic rays (from supernova explosions in our Galaxy); anomalous cosmic rays (from the interstellar gas surrounding our solar system); and solar energetic particles.

Storms and RBs

Successive paradigm shifts:
From quasi-linear diffusion theory
to dramatic variability on short time scales



SAMPEX observations 1991-2001. Fluxes vary by 4 to 5 orders of magnitude (Xinlin Li et al. 2001) on time scales down to minutes



However, there ARE storms, during which the flux increase of relativistic electrons and the earthward penetration is very impressive.
March – April 2001 storm

Storms and RBs

Net Loss or Net Gain:

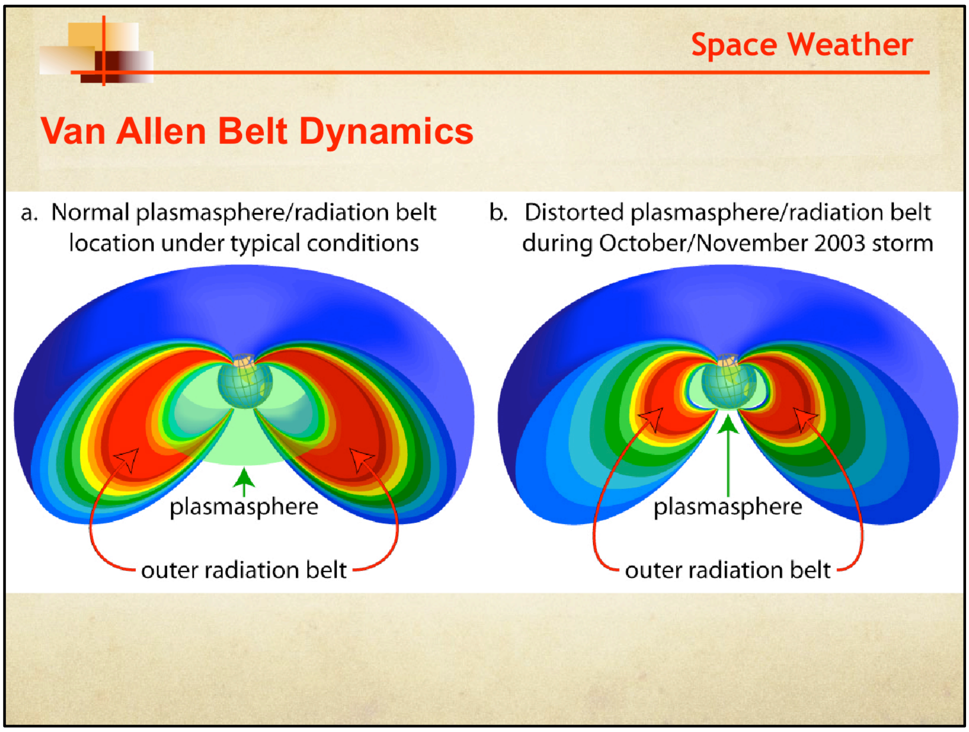
the synergistic result

of a mixture of collaborating or competing

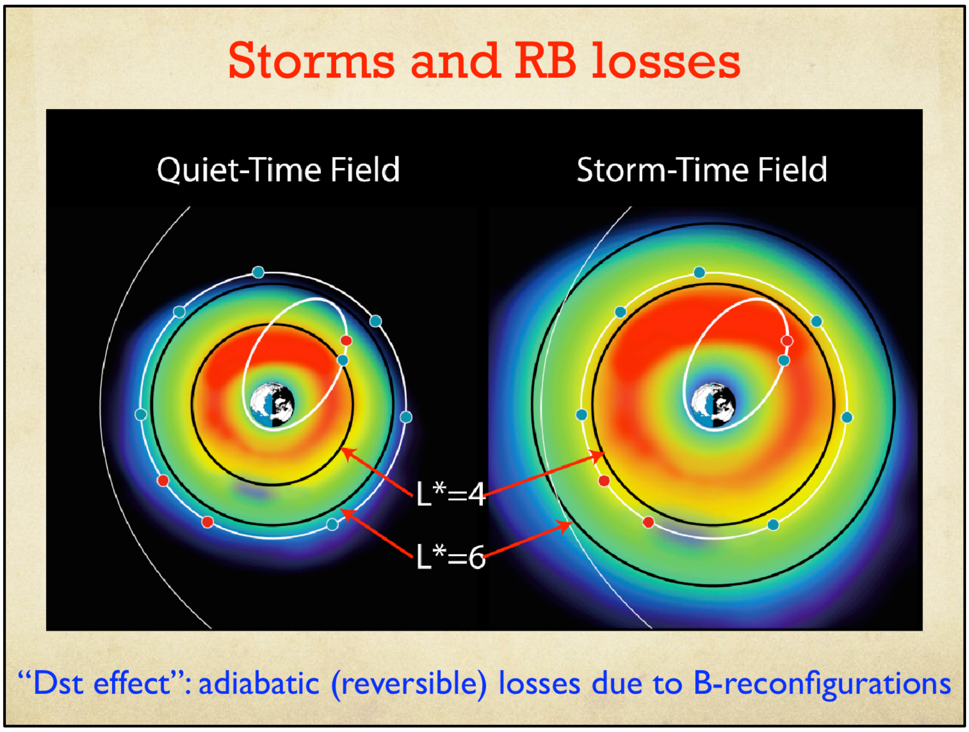
acceleration, transport and loss processes

involving waves and plasmas

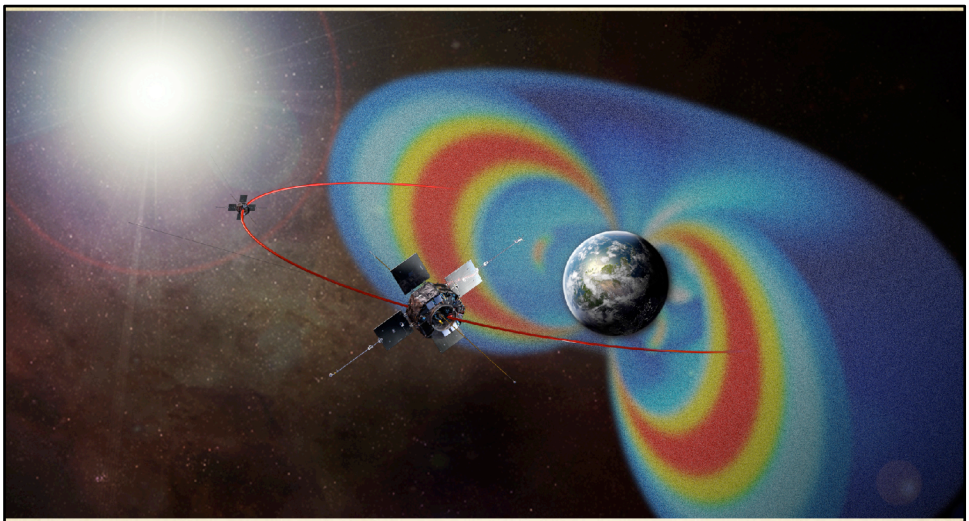
involving waves and plasmas **and their interactions**



We further have realized that the coldest plasmas control the hottest particles – because the cold plasmaspheric plasma influences the propagation of electromagnetic waves, which can accelerate electrons to relativistic energies.



The Dst effect: adiabatic effect due to the temporary reconfiguration of the near-Earth B-field



The conditions and phenomena in space and specifically in the near-earth environment that may affect space assets or space operations. Space weather may impact spacecraft and ground-based systems.

Locations of Operational Space Environment Hazards

Single Event Effects (SEEs)

- inner (proton) belt and higher L shells with solar particle event
- quiet-times from galactic cosmic rays

Internal charging and resulting **electrostatic discharges (ESD)**

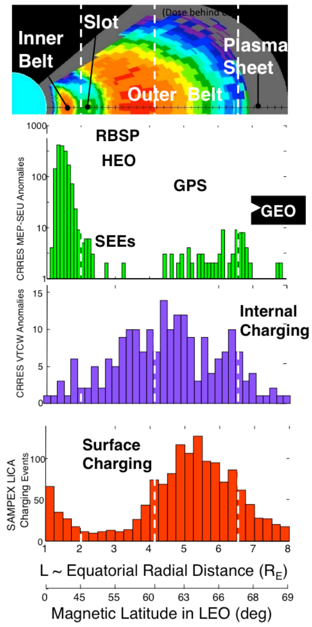
- broad range of L values
- corresponding to the outer belt
- where penetrating electron fluxes are high

Surface charging and resulting **ESD**

- spacecraft or surface potential elevated
- 2000-0800 local time in the plasma sheet
- regions of intense field-aligned currents
- observed, but not explained, at very low L

Total ionizing dose

- electronics and solar panels degrade over time



Janet Green, 2013

Storms and RB losses

Non-adiabatic (irreversible) losses due to

1. pitch-angle scattering into the **atmospheric loss cone**
EMIC or chorus waves, plasmaspheric hiss

2. **magnetopause** shadowing
via outward radial diffusion & magnetopause compression
PC5 waves

Hiss Generation mechanisms under debate

Both the PC5 waves that cause radial diffusion, and the SW high pressure are usually associated with magnetic storms

Chorus waves are associated with substorms, which are more numerous and stronger during storms.

Storms and RB acceleration

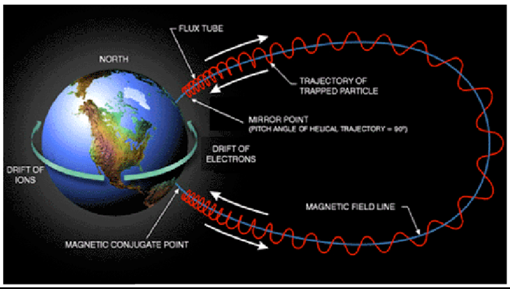
(i) inward radial diffusion
(ii) local acceleration via wave–particle interactions

Their combination yields strong increases of relativistic e^-
(i), fueled by enhanced convection and substorm injections, provides a seed population of 10s-100s keV e^- to outer belt.
Seed e^- are further accelerated to relativistic energies by lower band chorus waves (ii)

Inward radial diffusion, supported by **storm-time** enhanced convection and substorm injections provides a seed population of 10s to 100s keV e^-, which are accelerated to relativistic energies by lower band chorus waves (ii)

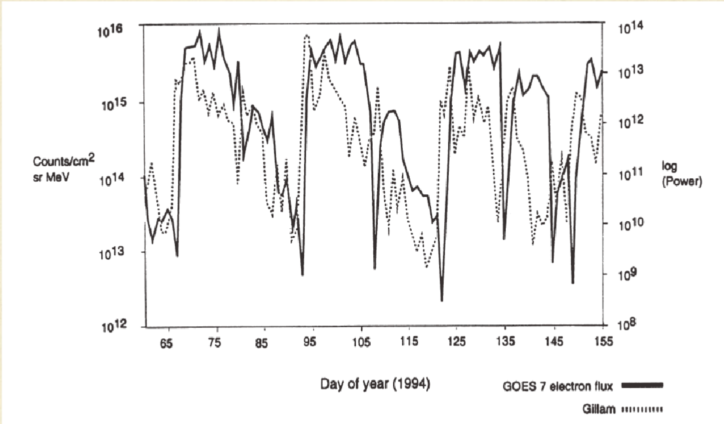
Radial diffusion

Pc5 waves with period matching the particle drift motion period can <u>break the drift invariant</u>. Earthward radial diffusion results in increased flux levels as particles are transported to regions of stronger magnetic fields.



Inward radial diffusion is driven by Pc5 waves, which have periods matching the particle drift motion period, and therefore break the drift invariant, **while maintaining the gyro and bounce invariants, can break the drift invariant**

Pc5 waves – RB connection



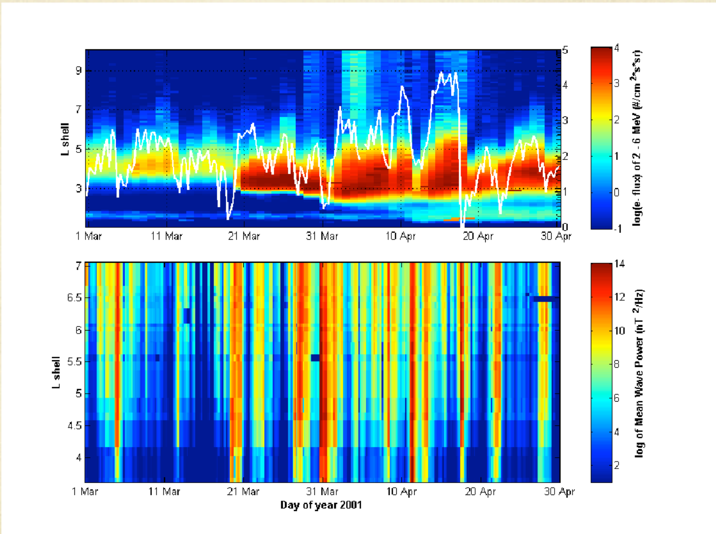
Rostoker et al., 1995

Increases in the Pc5 wave power
observed by ground magnetometers match
increases of the relativistic electron flux observed by GOES-7

Pc5 waves have been closely tied to dynamical variations in the radiation belts.

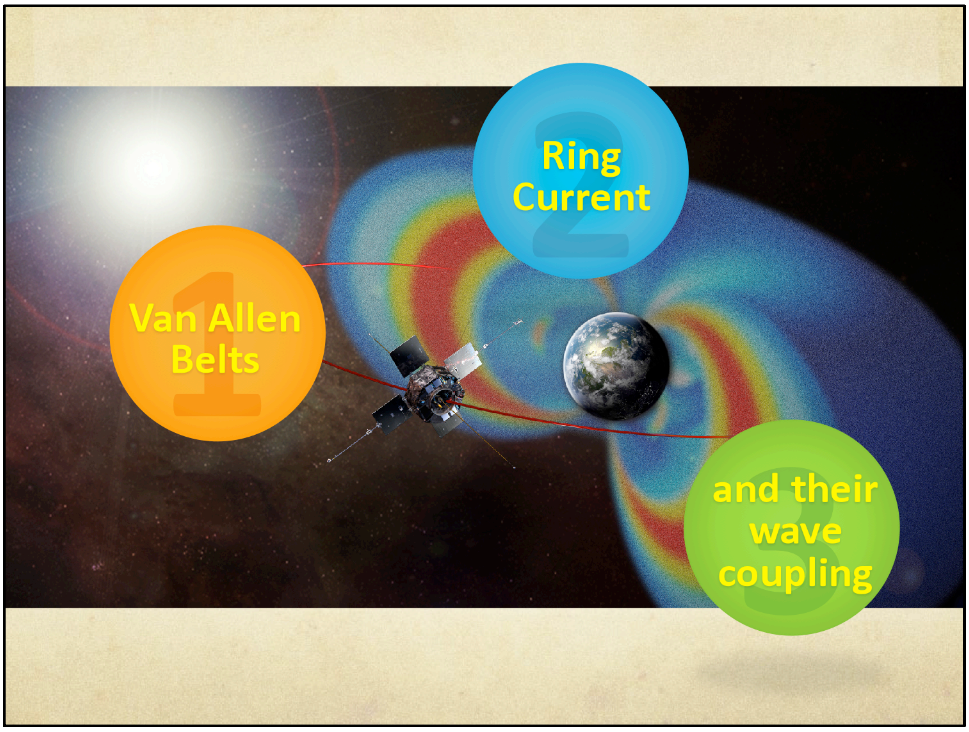
This observation forged / supported the paradigm of diffusion-controlled RB variability.

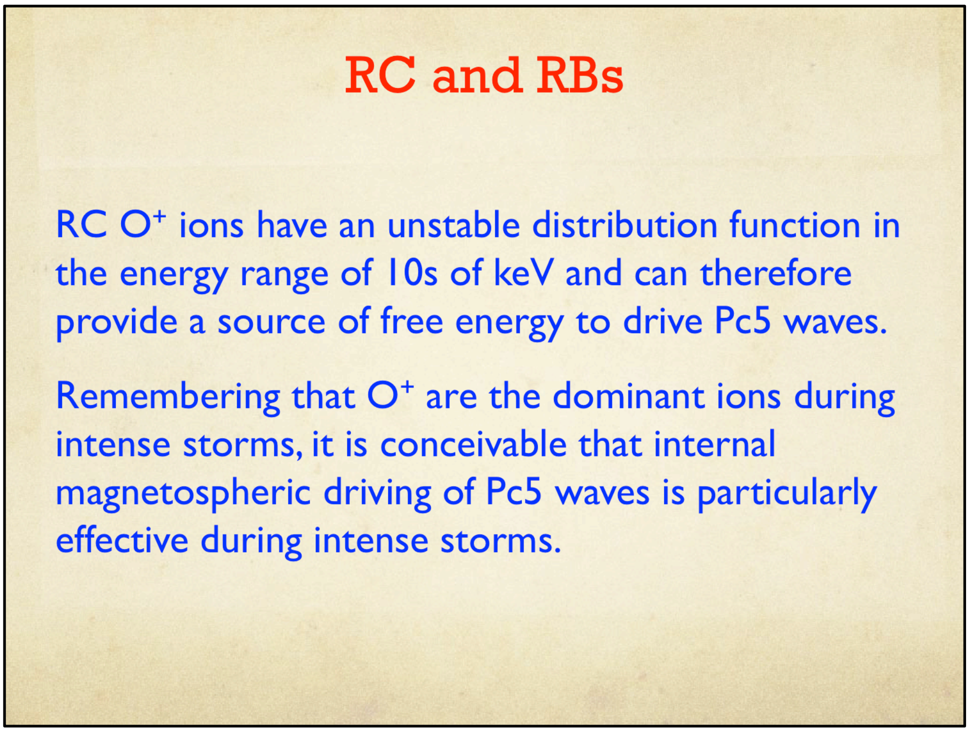
Pc5 waves – RB connection



Latitudinal distribution of electron fluxes > 2 MeV and Pc5 wave activity during the period from 1 March to 30 April 2001 [Georgiou et al., 2015]

Discrete enhancement and penetration of relativ. el., concurrently with Pc5 enhancement and penetration


Ring Current
Van Allen Belts
and their wave coupling



There are a couple of ways the RC can influence RB dynamics through its effects on wave growth.

Low-frequency mirror and drift Instabilities and anisotropies of ring current ions significantly contribute to the growth of Pc5 waves.

O+ in particular …

RC and RBs

The activity level of chorus waves depends on substorm injections.

Substorm injections tend to penetrate increasingly deeper into the inner magnetosphere with increasing O^+ density.

This may contribute to the expansion of chorus wave activity and, consequently, to a spatially more extended electron acceleration.

The activity level of chorus waves, which accelerate e^- to relativistic energies, depends on substorm injections – i.e. on the same mechanism that contributes to the enhancement of the storm-time ring current.

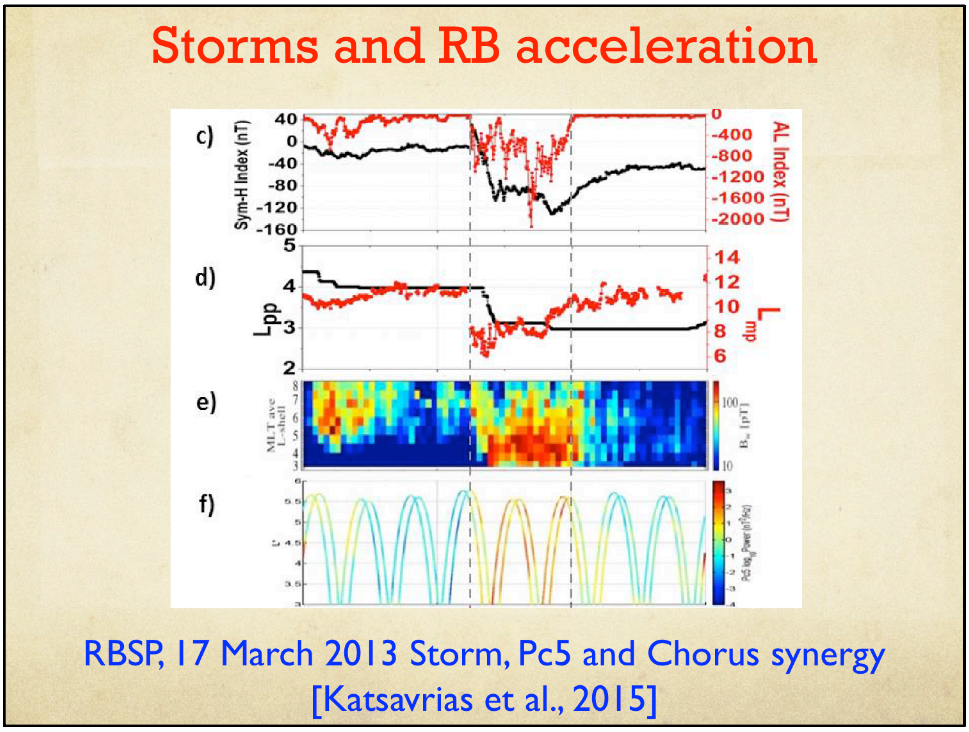
RC - Waves – RB connection

Ring current contributing to wave growth

and leading to synergy between
Pc5 waves
diffusing electrons earthwards
and **chorus** waves
further accelerating them locally

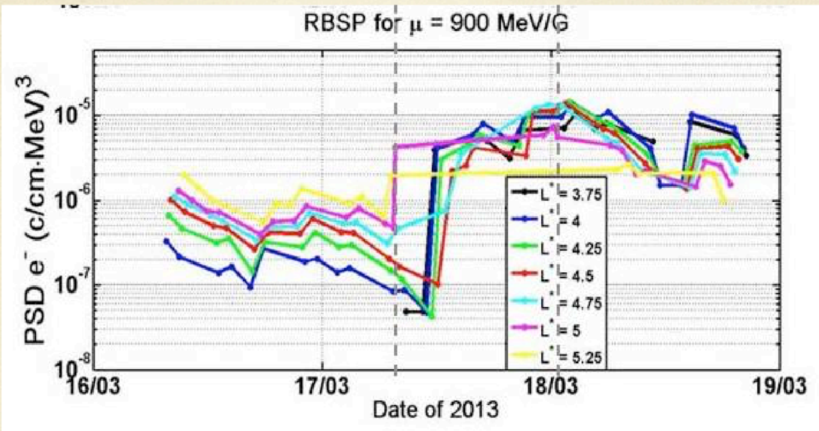
to **relativistic energies**

The RC has the potential of contributing to wave growth and thus to favor the synergy between Pc5 and chorus waves



A nice example of wave synergy during the intense magnetic storm of March 17, 2013, observed by Van Allen Probes. Data from MAGEIS.
Chorus wave amplitudes from the ratio of precipitating and trapped electron fluxes over the energy of 30–100 keV (measured by POES satellites)
Pc5 from the fluxgate magnetometers of RBSP.

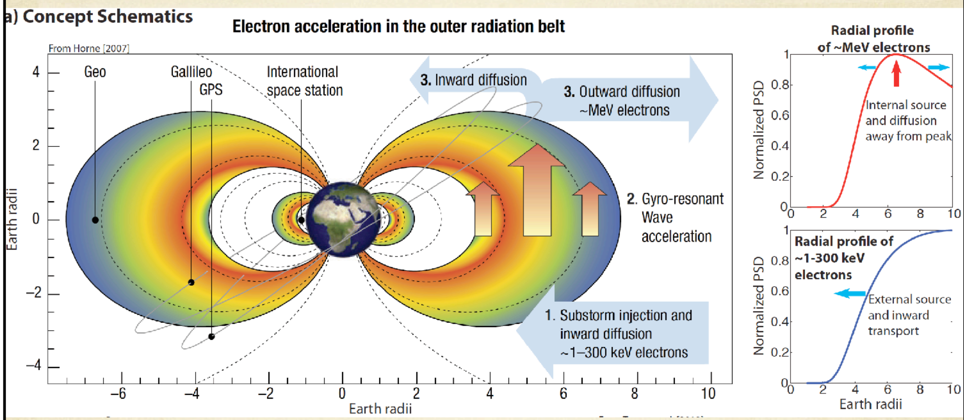
Storms and RB acceleration



Pc5 and Chorus synergy
resulting in net enhancement of relativistic electrons

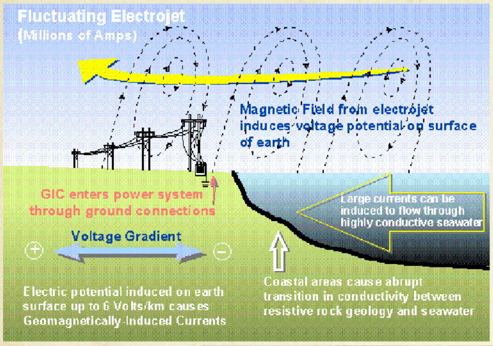
1 MeV electrons

Storms and RB acceleration



electrons interact with chorus waves via Doppler-shifted cyclotron resonance, resulting in energy diffusion. Provided many such interactions take place as electrons drift around the Earth, individual electrons could be stochastically accelerated up to relativistic energies

Geomagnetically-Induced Currents



- power grids,
- oil and gas pipelines (increased corrosion)
- train light signals can be affected (two documented events in Sweden)

Damage to a transformer at a power plant in Delaware, New Jersey in March 1989 (10 M$)

Synopsis I

The dynamics of Space Storms – defined by the interplanetary driver and the evolution of the Ring Current – and changes in the Van Allen Radiation Belts are intimately intertwined

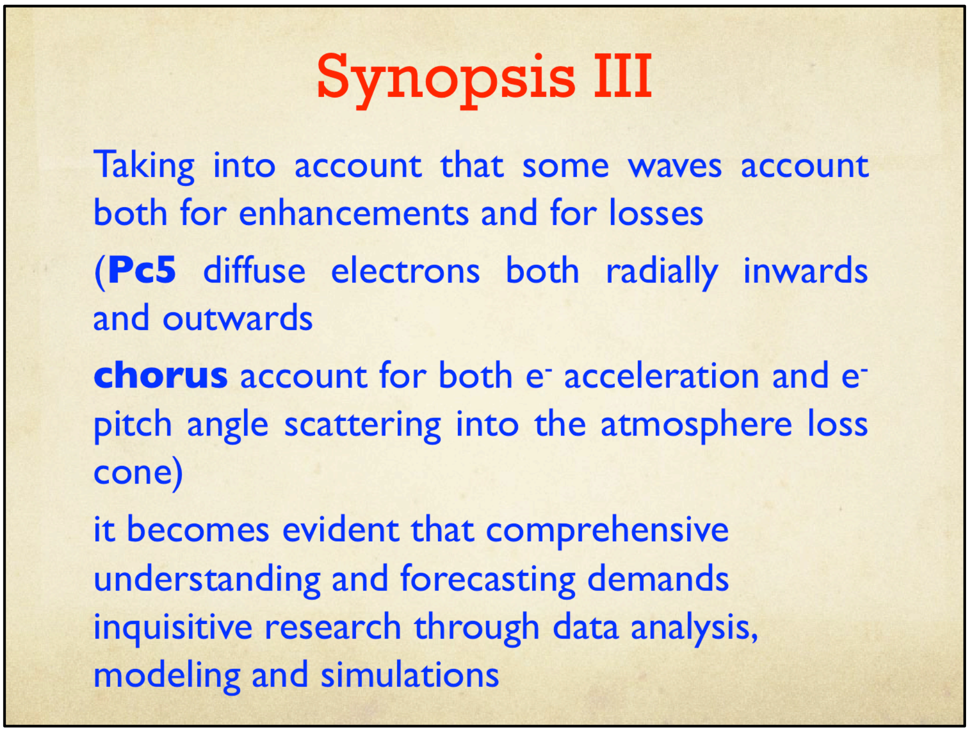
Net Loss or Net Gain of relativistic e^- in the RBs is the synergistic result of
collaborating / competing
acceleration / transport / loss processes
involving waves-particle interactions

Synopsis II

Ultimately, relativistic electron enhancements result from source mechanisms dominating over loss mechanisms.

Frequent and intense substorms, although not capable of accelerating electrons to relativistic energies, play a crucial role through the supply of seed electrons and their role in chorus wave growth.

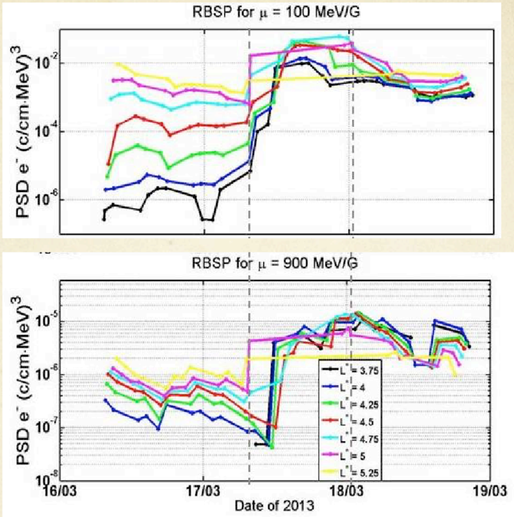
Frequent and intense substorms, characteristic of intense storms,



depending on PSD gradients

Role of plasmasphere! (not touched in this presentation)

Storms and RB acceleration



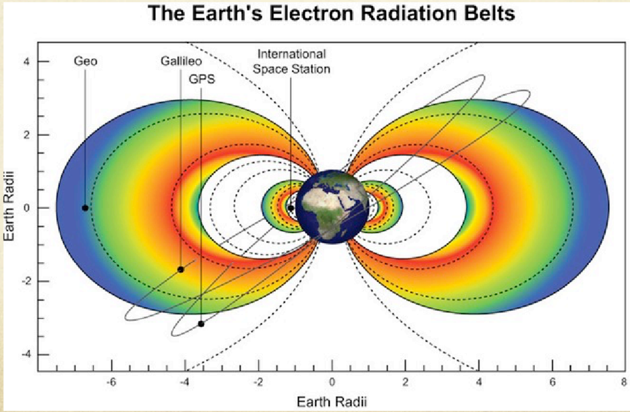
Pc5 and Chorus synergy
resulting in net enhancement of relativistic electrons

Van Allen Radiation Belts

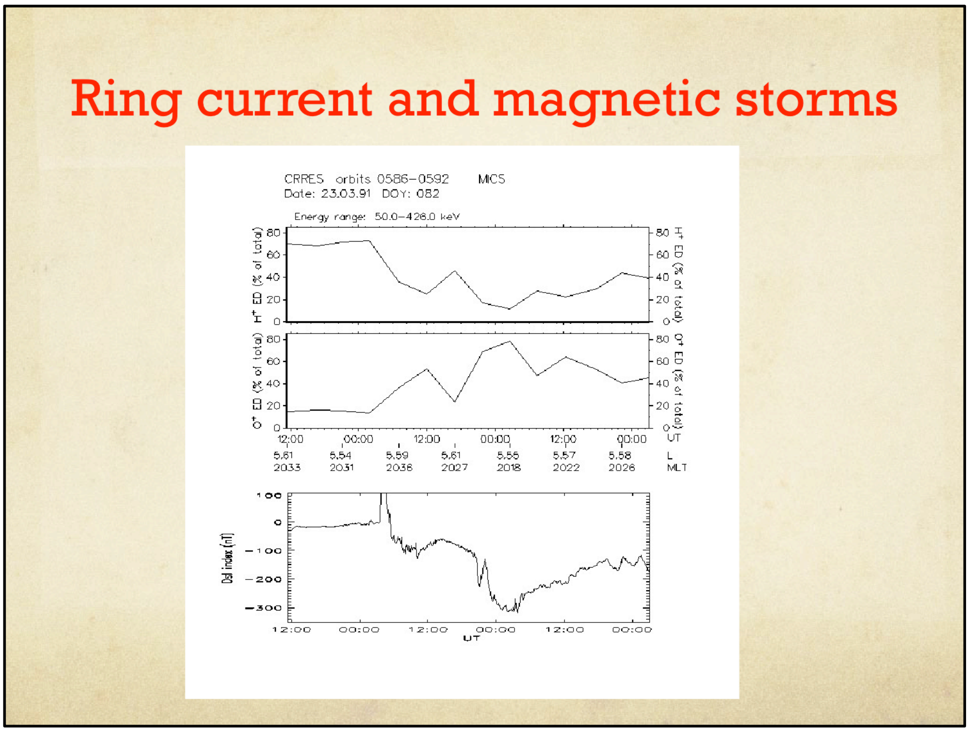
Distinguished by their very high energies:

100 keV – 20+ MeV (400+ MeV)

and posing considerable threat to space assets



However: RBs have much higher energies.

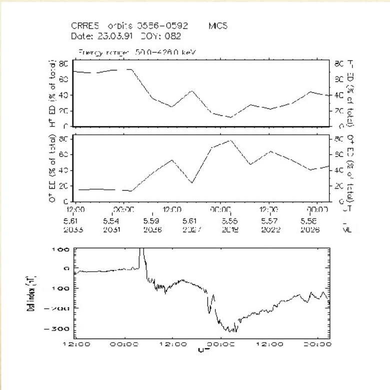


An extreme example is the March 1991 storm, during which more than 70% of the RC energy density was provided by O+ ions.

Ring current and magnetic storms

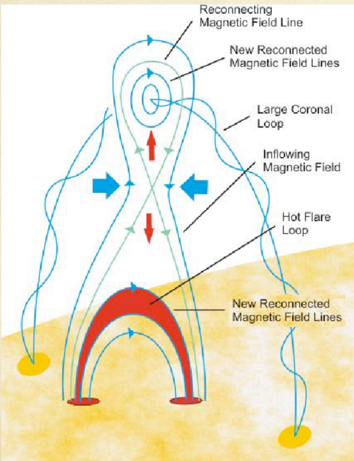
O^+ dominance leads to

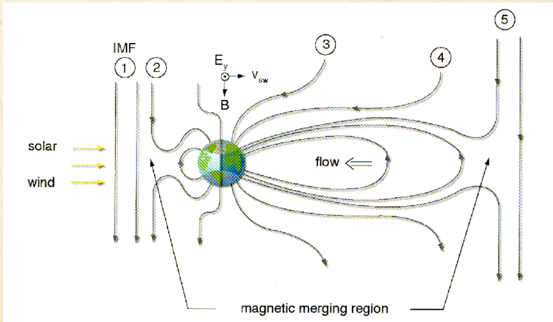
- deeper Dst minima (greater storm magnitude)
- faster initial storm recovery



The O^+ dominance (which is characteristic of intense storms) leads to … **because O^+ ions are lost faster than H^+ (due to MP shadowing and charge-exchange)**

Magnetic reconnection:
Transforming magnetic to kinetic energy





The fundamental process: Magnetic **Reconnection on the Sun and in Geospace.**