

# ESAC – Science Seminar

## Unbuckling the Van Allen Belts: from Discovery to Modern Models

**Lionel Métrailler**

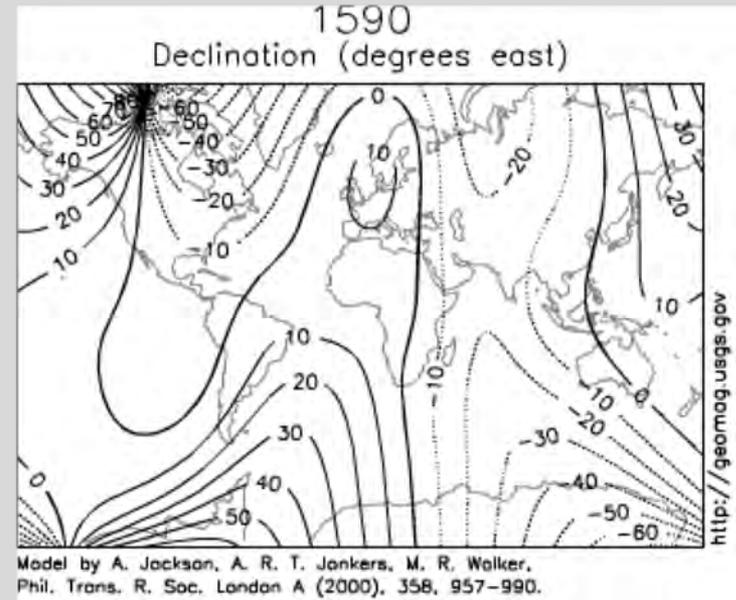
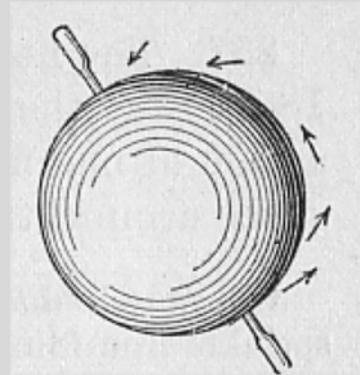
Swiss National Trainee at ESAC (Madrid)

INTEGRAL Science Operation Centre (ISOC)

25<sup>th</sup> of July 2019

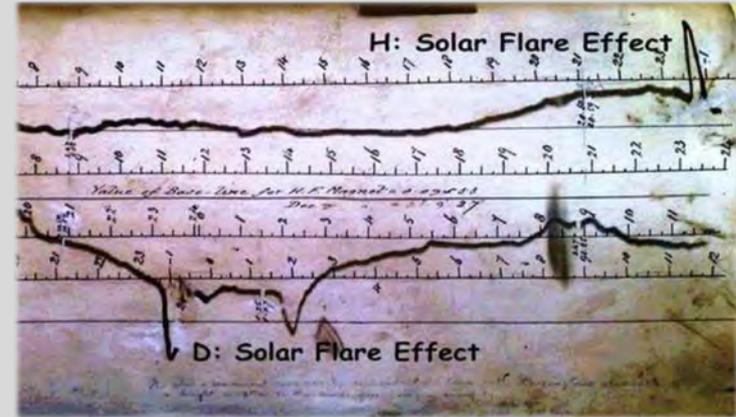
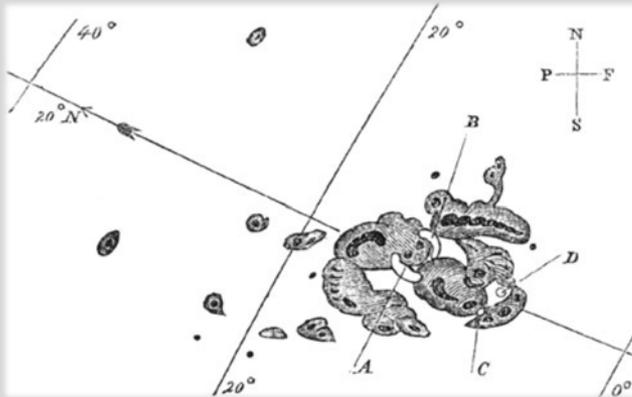
# Earth's Magnetic Field Discovery

- **Magnetic compass**, China, year <1000
- **Magnetic declination** discovery, China, ~1000
- **Earth is a magnet**, 1st "terrella", William Gilbert, 1600



# Earth's Magnetic Field Disturbances

- **Disturbances** in compass measurements, George Graham, 1724
- **Link with Sun spots**, Edward Sabine, 1852
- **Magnetic storms and solar events** link confirmed, Carrington, Sep 1, 1859
  - +17h: magnetic storm & low latitude auroras (Tahiti)
  - Sun → Earth charged particles transfer





**Frederic Edwin Church**

*Aurora Borealis*

1865

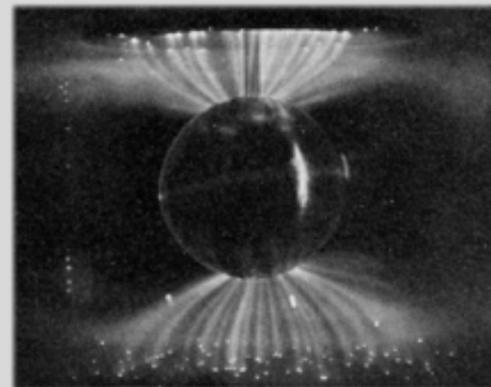
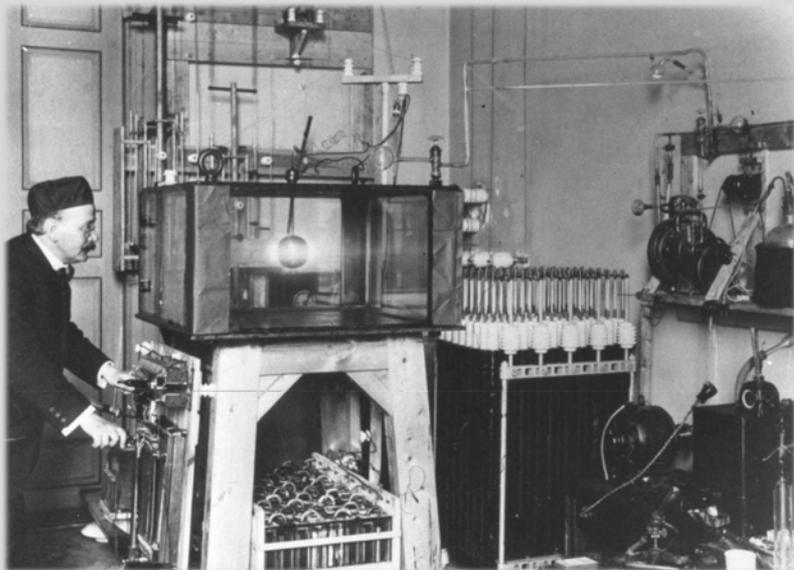
Oil on Canvas

142.3 cm x 212.2 cm

Smithsonian American Art  
Museum, Washington DC

# Charged Particles Motion

- **Confirmation of Aurora**, "terrella" experiment, Kristian Birkeland, 1896



Birkeland experiment

Tromso Museum, Norway



# Charged Particles Motion

Carl Stoermer, 1903-1955



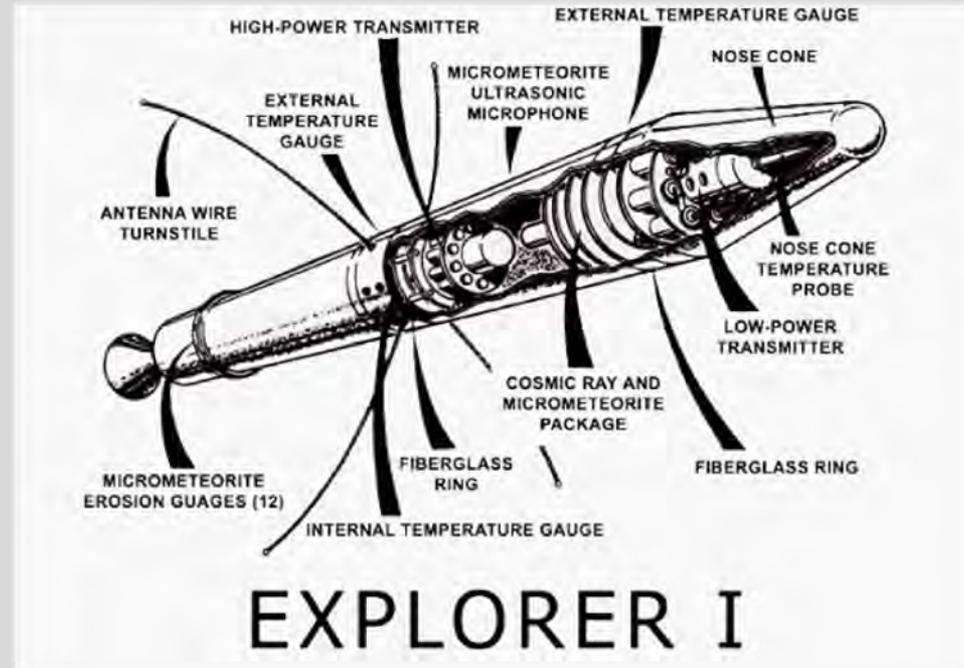
Stoermer & Birkeland, 1910

- Mathematical model
- No analytical solution
- **Stable trajectories**
- Theoretical links
  - Solar charged particles
  - Trapped particles
  - Magnetic storms
  - Ring currents
  - Aurora

## First Measurements

**Explorer 1**, February 1<sup>st</sup> 1958, first US satellite:

- 360 – 2500 km altitude orbit
- **Hint of the inner proton belt.**



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**Explorer 1**, February 1<sup>st</sup> 1958, first US satellite:

- 360 – 2500 km altitude orbit
- **Hint of the inner proton belt.**



The three men responsible for the success of Explorer 1. From left, William H. Pickering, James Van Allen, and Wernher von Braun. © NASA.



February 1<sup>st</sup>, 1958 at 03:48 UTC: Explorer 1 launch on the Jupiter-C rocket

## First Measurements

**Explorer 3**, March 26<sup>th</sup>, 1958:

- 190 – 2800 km altitude orbit
- **Proton belt discovery confirmation**

**Pioneer 3**, December 6<sup>th</sup> 1958:

- Failed lunar flyby mission: orbit apogee 102'360 km
- **Outer electron belt discovery => Van Allen Belts**

They could have been called the "*Vernov Belts*"

- Sputnik 2, November 3<sup>rd</sup>, 1957, Laika
  - *No data... on time!*

## Apollo Era



As seen from Honolulu. Image courtesy of US Govt. Defense Threat Reduction Agency

- **Clear out** proton belt with **nuclear bomb**, Van Allen, 1962
  - NASA refused
- **Starfish Prime nuclear test**, US defence, July 9<sup>th</sup> 1962



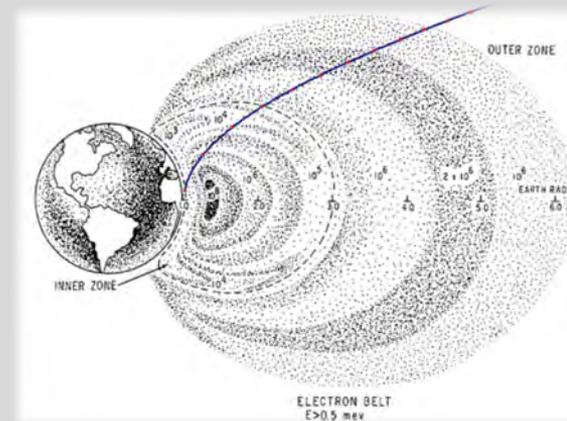
- 400km altitude
- Added more radiation

As seen from plane a few minutes after the explosion. Image courtesy of US Govt. Defense Threat Reduction Agency

## Apollo Era

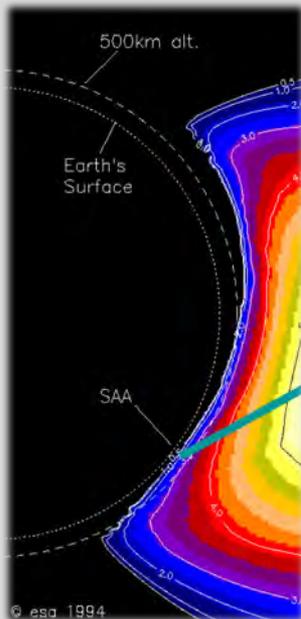
NASA decided to proceed

- **Avoid** the densest radiation regions
- **Quick fly** through the belts
- **Dosimeter** carried by each astronaut
- **Mission limits:** 400 rads (X-rays), 2.5 rads ( $\alpha$  particles)

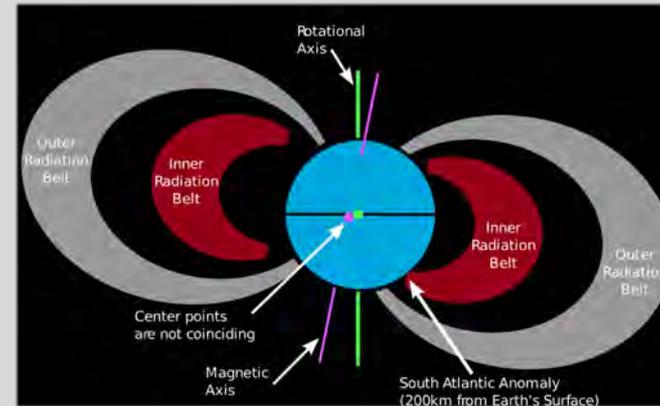


Apollo Mission	7	8	9	10	11	12	13	14	15	16	17
Skin Dose, rads	0.16	0.16	0.20	0.48	0.18	0.58	0.24	1.14	0.30	0.51	0.55

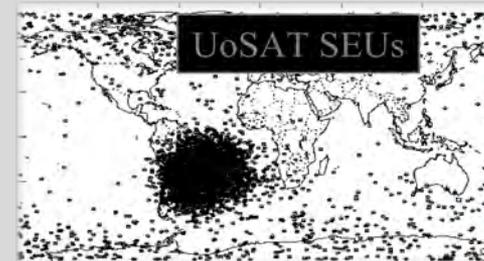
# The South Atlantic Anomaly



- Discovered in 1958
- **Inner proton belt**
- ~200 km altitude
- **Magnetic centre shift**



- **Spacecraft Single Events Effects (SEE)**
- Flashes in astronauts' eyes



# Space Exploration

Sun, Magnetosphere, and Van Allen belts (**Space Weather**) in-situ studies:

- **NASA**

- Cluster II, Geotail, MMS, Van Allen probes, CeREs, and 43 other missions

- **ESA**

- Cluster, Proba 2, Swarm, Solar Orbiter, etc

**Help understanding all physical processes taking place in the magnetosphere**

# Outline

1. Van Allen Belts Through History
  - Theorisation, discoveries, in-situ research
2. **Physics of Trapped Particles**
  - **Physical processes, particle motion, loss mechanisms, and dynamics**
3. Overview of the Van Allen Belts
  - What? Why? How?
4. Models
  - Goals and examples
5. Conclusion

# Lorentz Equation

**Lorentz Force**  $F_L$  acting on charged particles:

$$F_L = q\cancel{E} + q\mathbf{v} \times \mathbf{B} \quad \text{assuming no electric field}$$

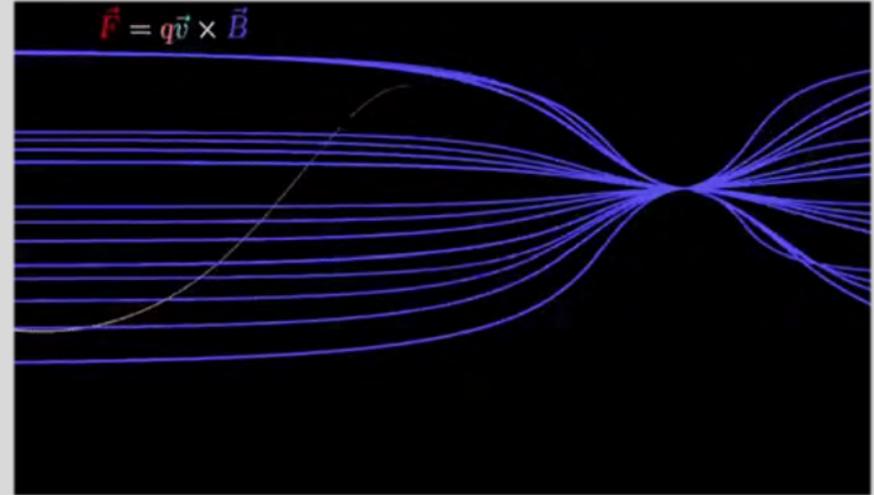
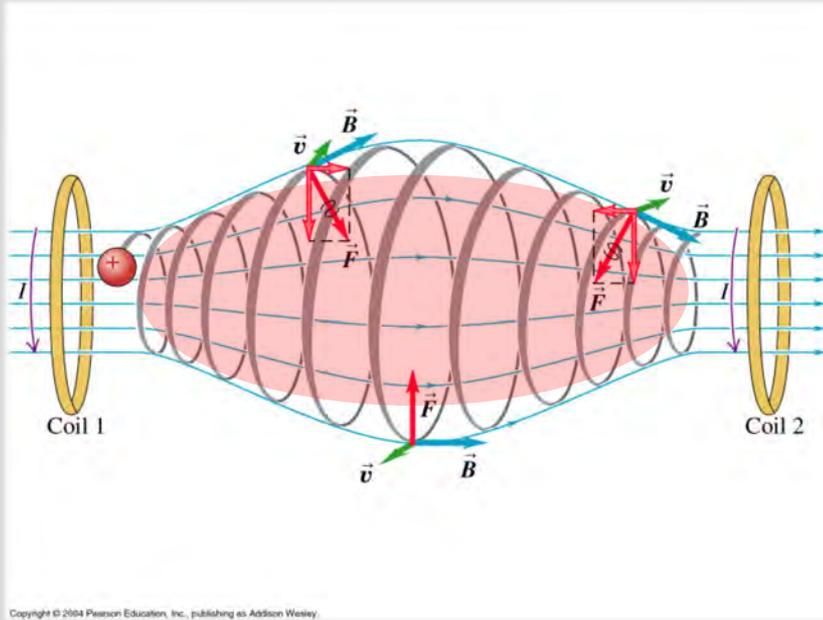
$$\Rightarrow F_L = q\mathbf{v} \times \mathbf{B}$$

$$\Rightarrow F_L \perp \mathbf{v}$$

**Magnetic force** only change **the direction of the velocity vector!**

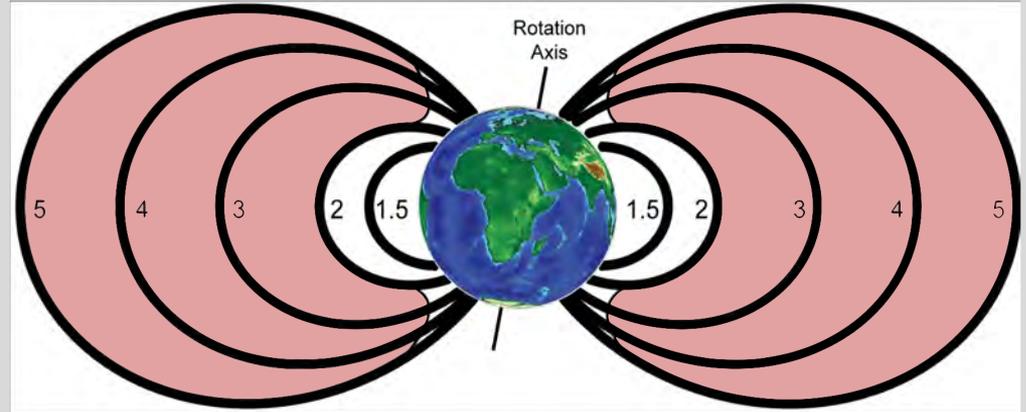
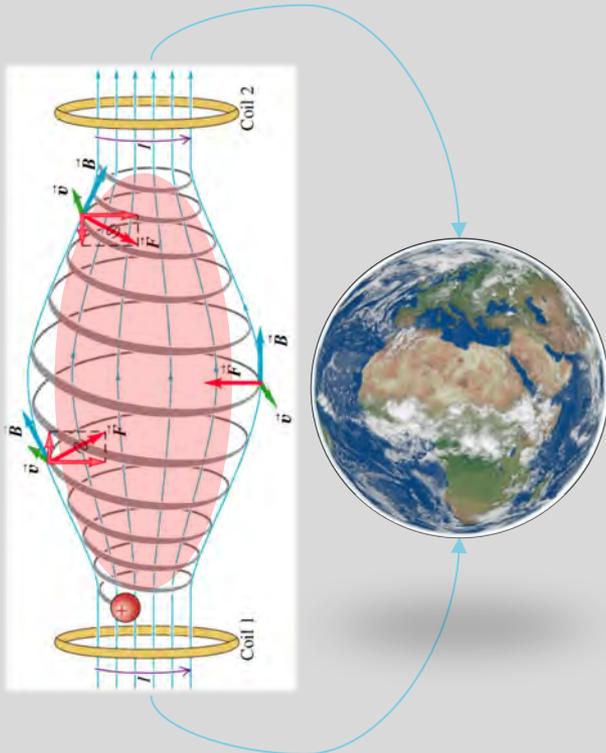
This property can be used to create a **“magnetic trap”**.

# “Magnetic Trap”



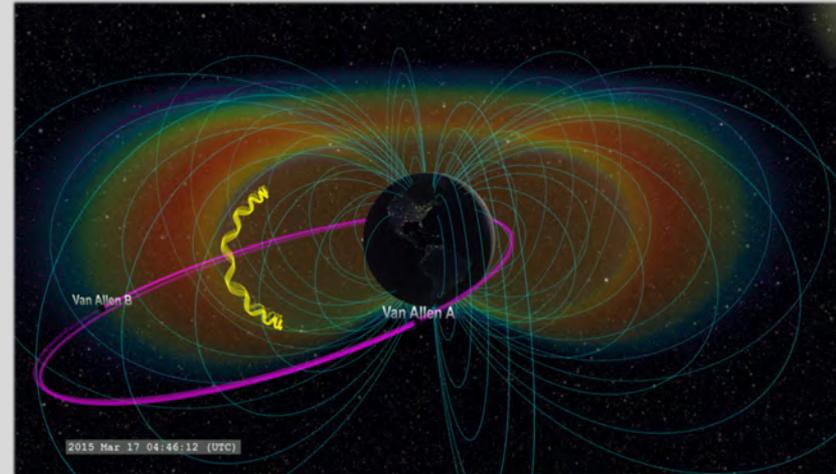
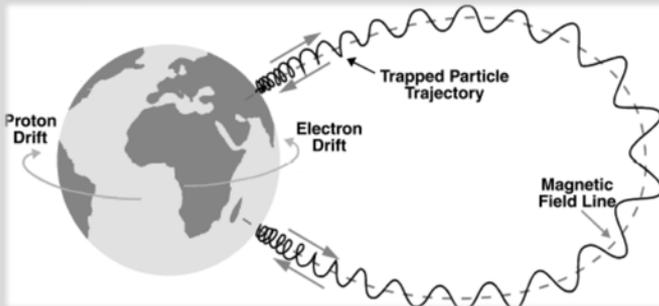
Simulation from Dr. Michael R. Gallis, Penn State Schuylkill

# “Magnetic Trap”



## Triple Motion

- Motions linked to the “Magnetic trap”
  - **Gyration**  $\sim 10^{-5} - 10^{-3}$  s
  - **Bounce**  $\sim 10^{-1} - 1$  s
- Motion linked to the magnetic gradient
  - **Drift**  $\sim 10^2 - 10^4$  s



© Nasa

# Dynamics

Non-disturbed ideal conditions:

- **Predictable** trajectories
- **Stable** Van Allen Belts

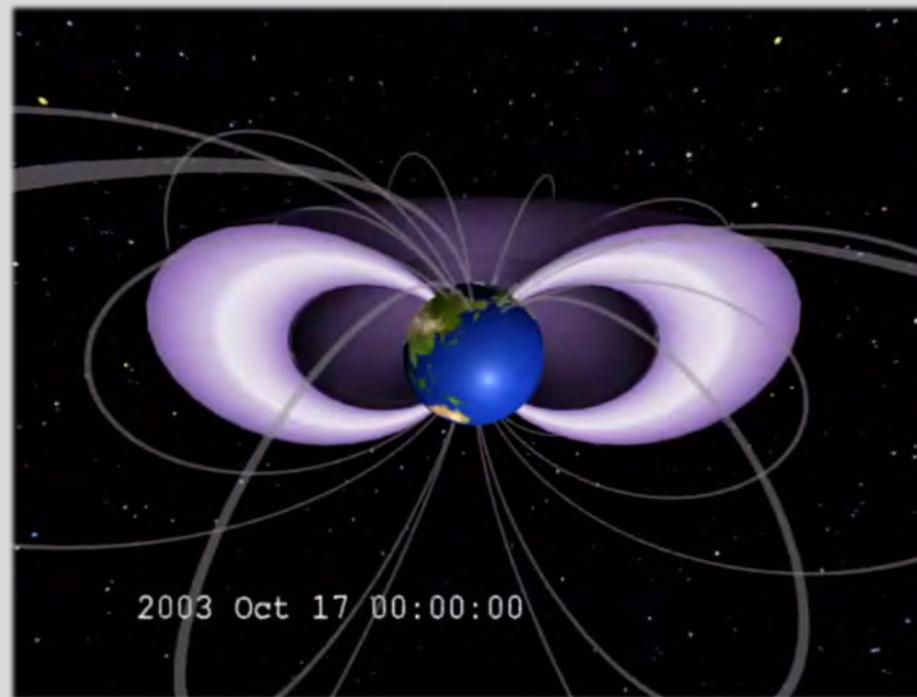
However, nature never makes it easy!

- **Non-adiabatic conditions**

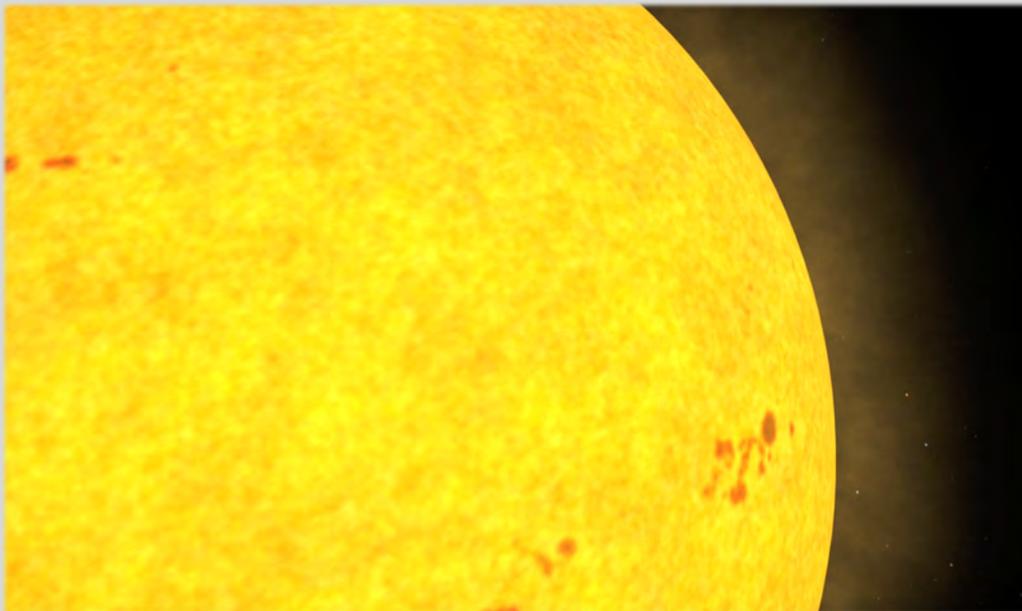
**Strong dynamics: Injection, Acceleration, Diffusion, and Loss**

# Dynamics

Strong variability of the Radiation Belts as seen by the NASA Van Allen Probes at the end of 2003.



# Injection

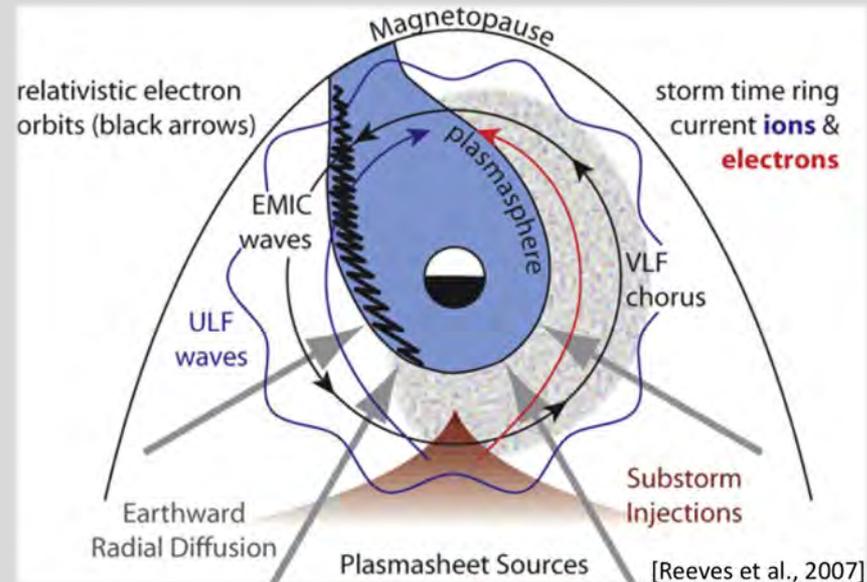


Sun is the **main supplier** of charges particles

- Solar wind
- Magnetic storms
  - CMEs, flares
- Magnetic sub-storms
  - Reconnections

# Transport and Acceleration

- **Magnetic gradients**
  - Triple motion
  - Ring currents
- **Ultra Low Frequency (ULF) waves**
  - Magnetospheric resonance
- **Very Low Frequency (VLF) waves**
  - Plasmaspheric resonance
  - Human induced radio signals
- **ElectroMagnetic Ion Cyclotron (EMIC) Waves**
  - In the plasmasphere



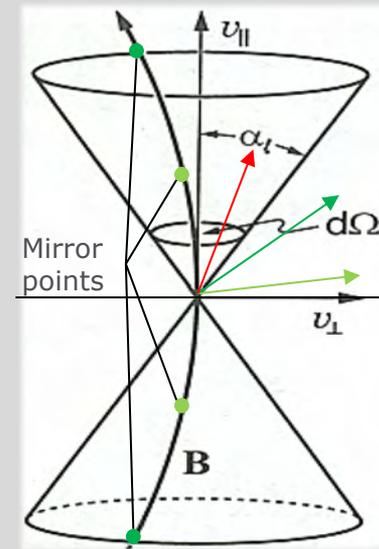
## Particle Loss

Loss of trapped particle

- **Accelerated** and lost in space
- **Precipitation** into the atmosphere

The loss cone

- **high pitch angle** - mirror points closer to equator  
=> **trapped**
- **low pitch angle** - mirror points in atmosphere  
=> **lost** (aurora)

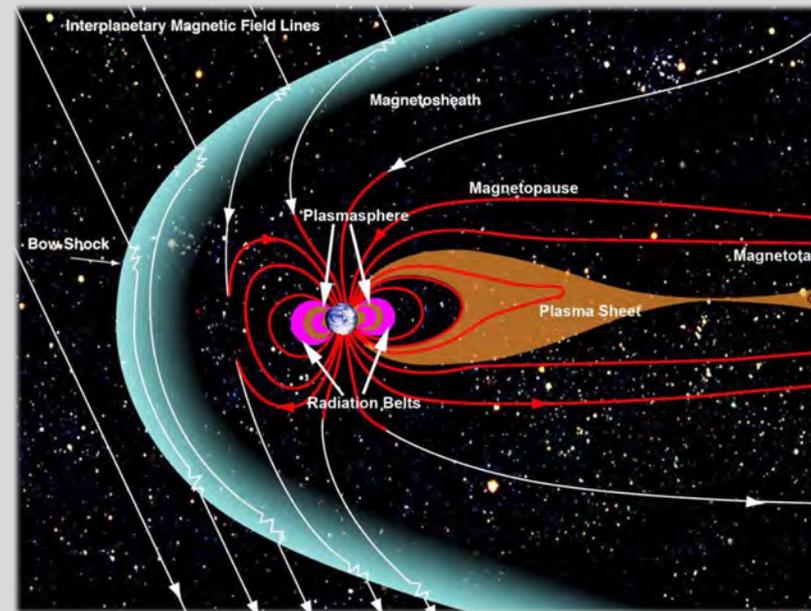


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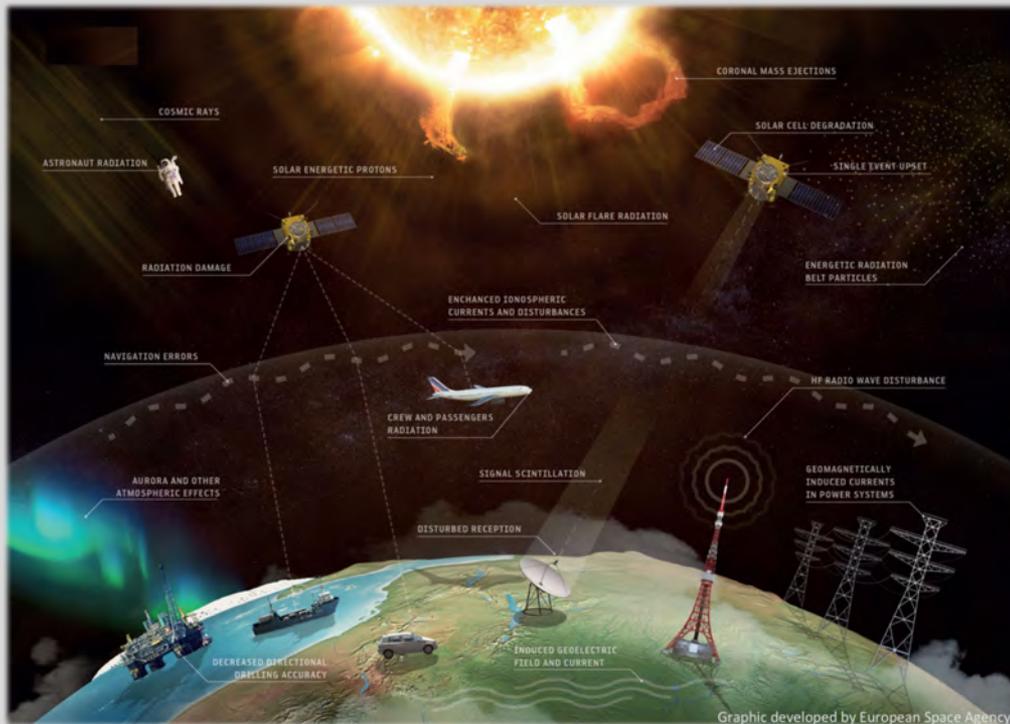
# Earth's Radiation Belts

- What are they?
  - Result of solar wind, solar events, cosmic rays, Earth magnetosphere, and Earth atmosphere complex interactions
  - Inner proton belt, “stable”
    - ~10 - 100 MeV
    - ~500 - 6,000 km altitude
  - Outer electron belt, dynamic
    - ~100 keV - 10 MeV
    - ~10,000 - 40,000 km altitude



© Nasa

# Earth's Radiation Belts

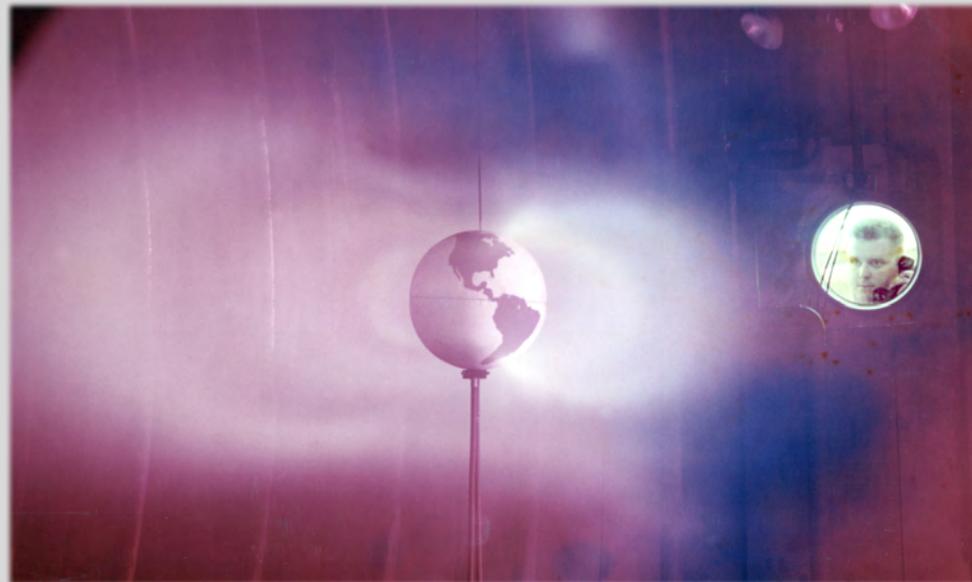


- Why study them?
  - Space Weather
  - Understand their dynamics
  - Mitigate possible hazards
- Main Risks
  - Single Events Effects (SEEs)
  - Deep-dielectric charging
  - Surface charging
  - Radiation dose

# Earth's Radiation Belts

## How to study them?

- Laboratory Experiments
  - Limited by the setup
- In-Situ
  - Limited by the number of satellites and volume to cover
- Theoretically
  - Limited by the complexity and the dynamics of the VAB



*Simulated Van Allen Belts generated by plasma thruster* © Nasa

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## Variety of Models

Different approaches - different goals:

- Coverage: *local* or *global* for *electrons* or *protons*
- Time dependences: *static* or *dynamic*, *precise and short* or *rough and long* time predictions
- Coordinates: *3D Solar Magnetic*, *2D McIlwain's* coordinate systems
- Source: *theoretical* or *data-driven* model
- Parameters: use of *external space weather parameters* or *not*
- ...

**A wide variety of models is possible depending on one's needs!**

## Some models

British Atlantic Survey – Radiation Belt Model **BAS-RBM**, 2013

- e-, global, dynamic, theory- & data-driven model, external parameters, McIlwain's (B, L\*)

Global Radiation Earth ENvironment model **GREEN**, 2018, ONERA & CNES

- e-, p, global, collection of various existing models, McIlwain's (B, L\*)

Electron Slot Region Radiation Environment Model **e-SRREM**, 2014, Consortium (ESA)

- e-, slot region, data-driven model, McIlwain's ( $a_{eq}$ , L\*)

**AE8** min/max, 1991, **AP8** min/max, 1976, USA (NASA)

- Most well known, electrons 0.04 – 7 MeV and protons 0.1 – 400 MeV, McIlwain's (B, L)

**IRENE-AE9/AP9**, 2013, USA (NASA)

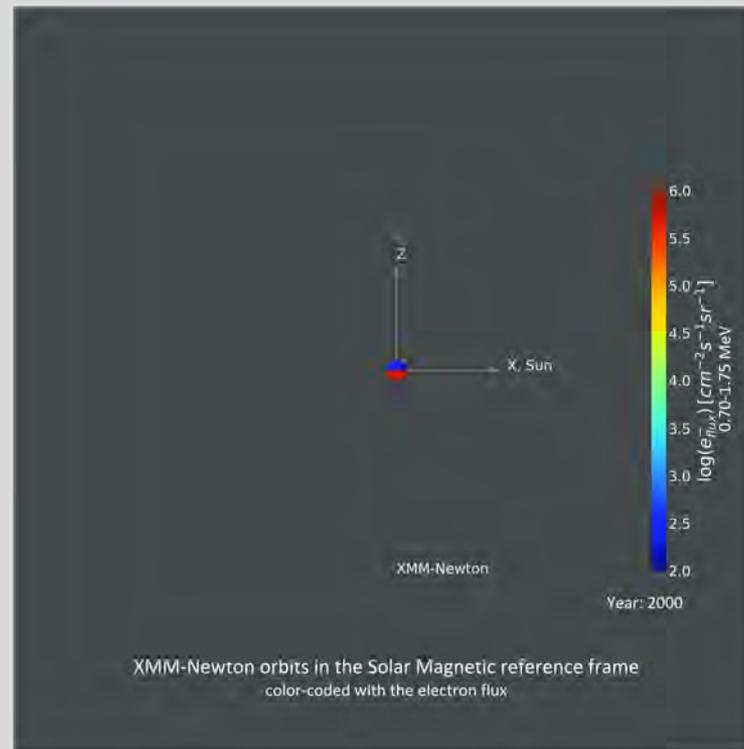
- Update of the AE8/AP8 models
- Electrons 0.04 – 10 MeV and protons 0.1 MeV – 2 GeV, McIlwain's (B, L\*)

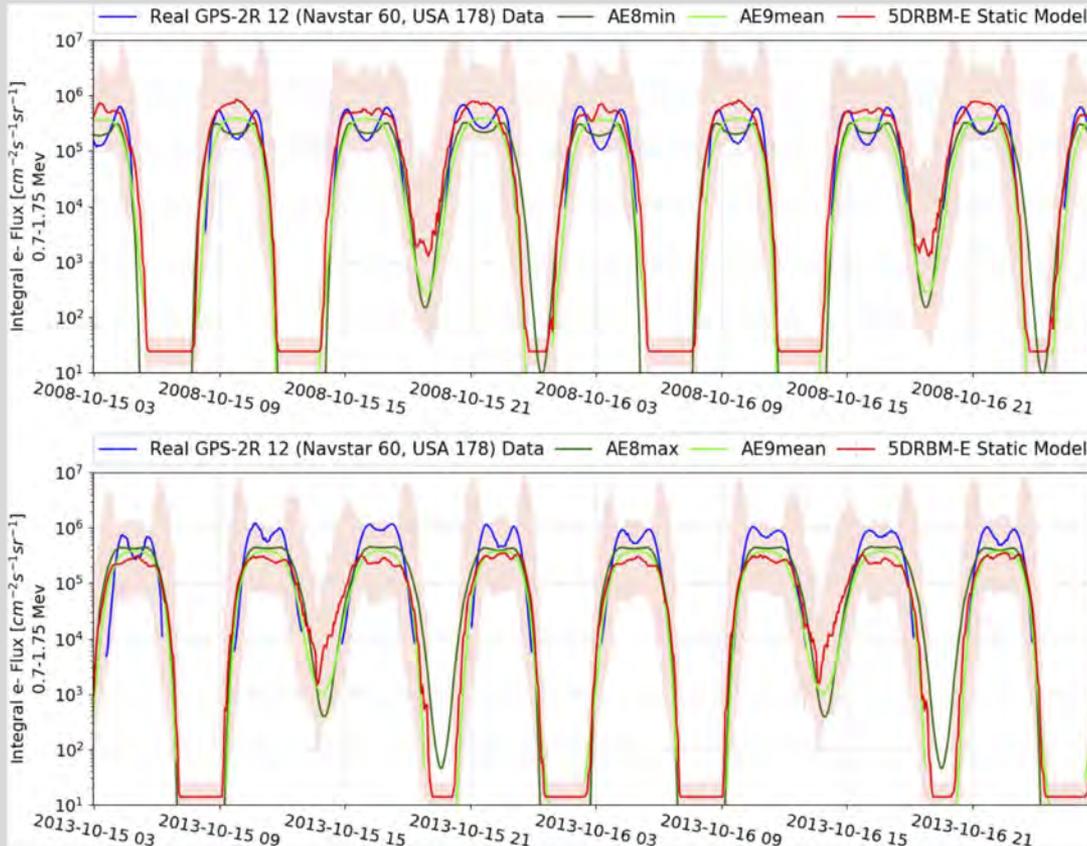
**We want an easy-to-use model and tailor-made for INTEGRAL and XMM-Newton!**

## Some models

### 5D Radiation Belt Model (5DRMB) for trapped electrons

- With/for XMM and INTEGRAL
- Electron 0.7-1.75 MeV
- 3D Solar Magnetic
- Global semi-dynamic data-driven model
- No external parameters needed
- **Long-term radiation characterisation**





GPS-2R 12 spacecraft

- 20'500 km altitude
- 55° inclination

Good comparative results

Métrairier, L. et al., 2018, *Data-Driven Modelling of the Van Allen Belts: The 5DRBM Model for trapped Electrons*, Advances in Space Research, ASR-D-19-00407R1

# Conclusion

Main historical dates:

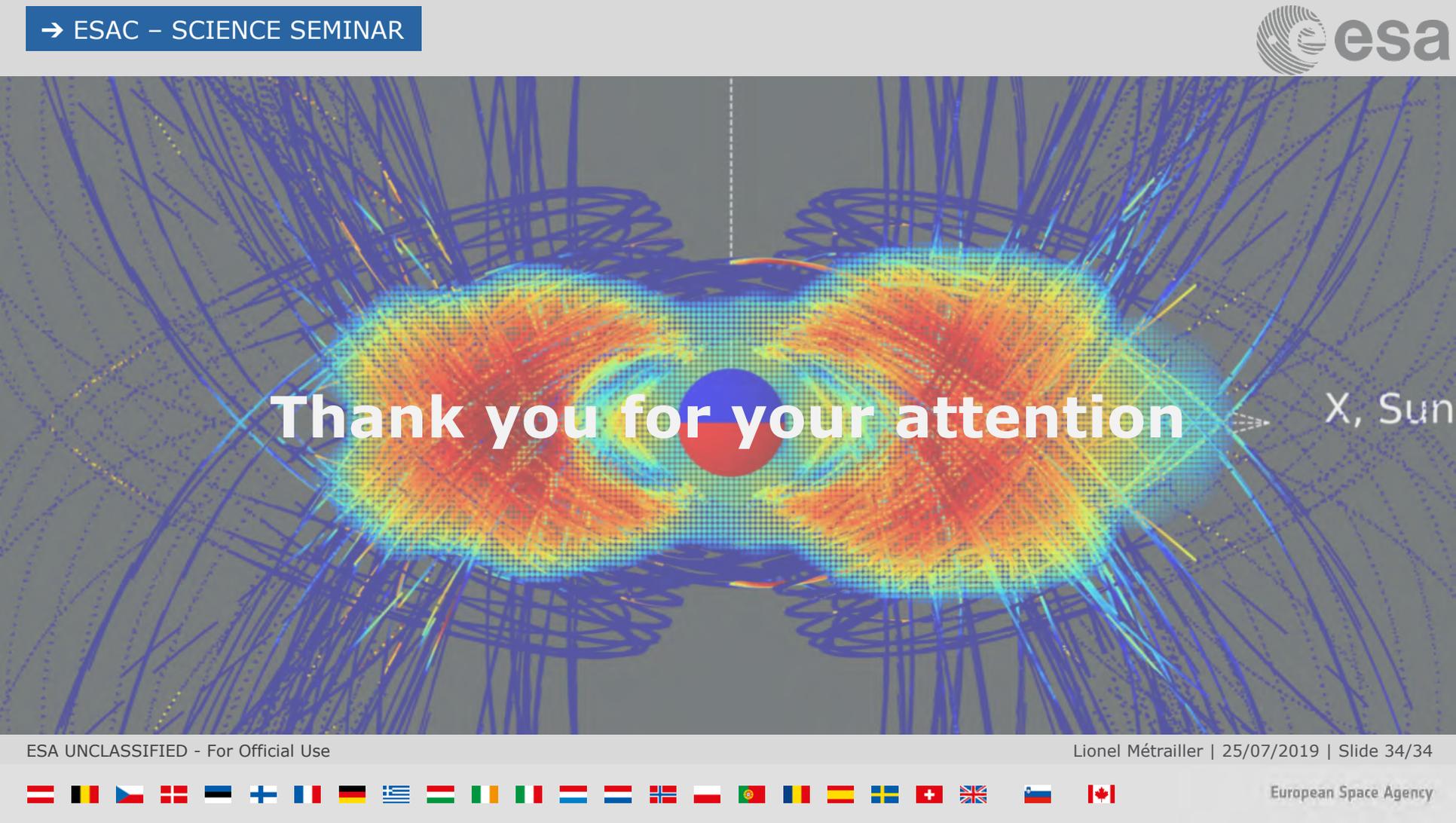
- **Earth magnetic field discovery**, <1000, compass
- **Sun – Magnetic Storms – Aurora**, Sep 1, 1859, Carrington event
- **Radiation Belts discovery**, 1958, Explorer and Pioneer programs

Physics:

- **Triple motion** of charged particles (gyration, bounce, drift)
- **Non-adiabatic processes** (acceleration, diffusion, loss)
- **Injection** of energetic particles (flares, CMEs, reconnections)
- **Highly dynamic** (wave-particle interactions)

Models

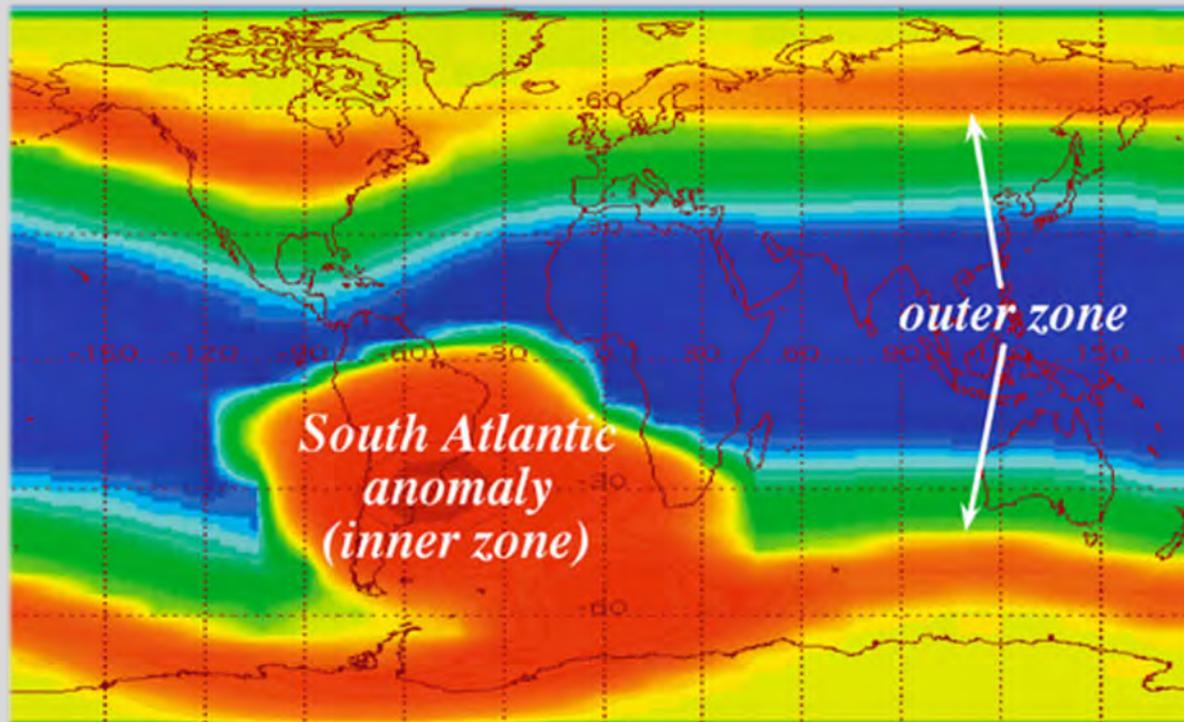
- **Large variety** of models with different goals
- **SDRBM** for trapped electrons (INTEGRAL & XMM)



Thank you for your attention

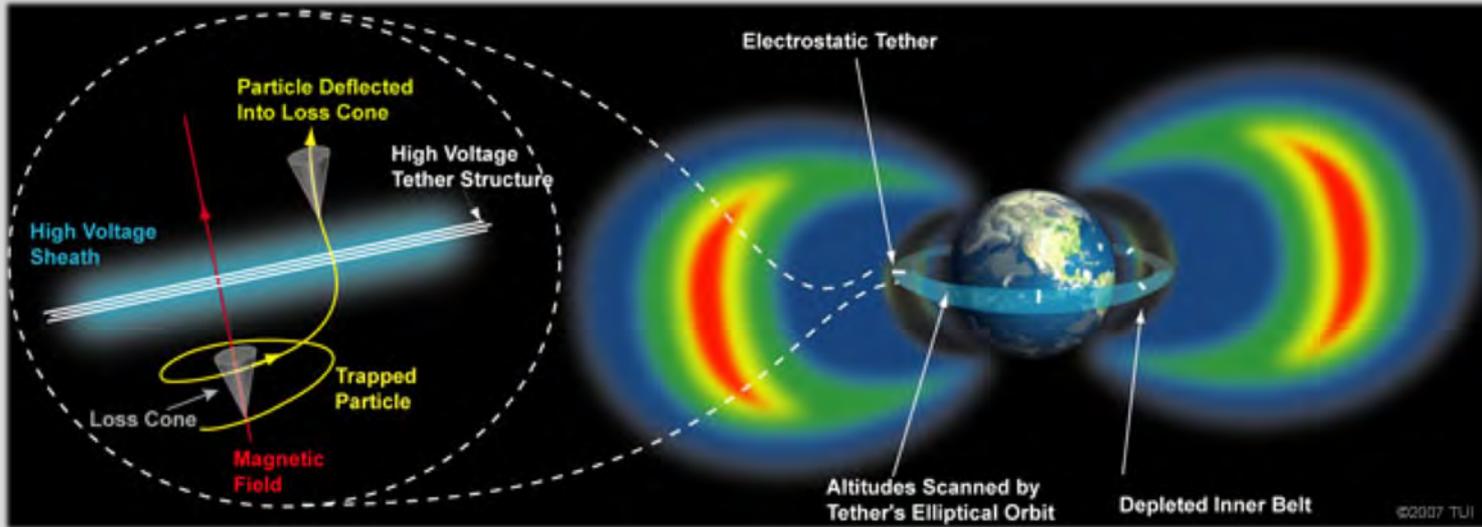
X, Sun

# The South Atlantic Anomaly



Count rate of protons and electrons greater than 0.5 MeV in low Earth orbit measured by the NASA/SAMPEX satellite.

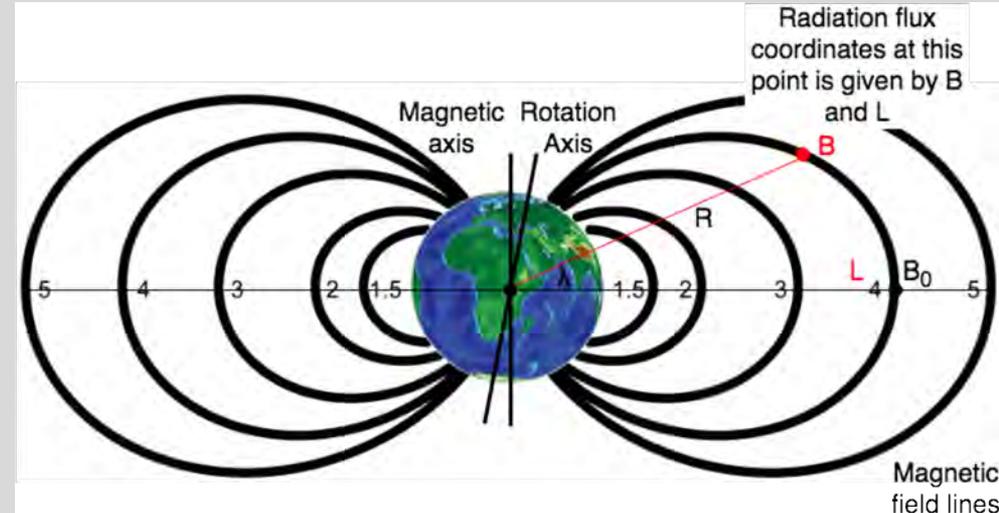
# Particle Loss



# Coordinate systems

McIlwain's coordinate system

- 2D ( $B, L$ ) or ( $a_{eq}, L^*$ )
- $B$  is the magnetic intensity along the magnetic field line
- $L$  is the equatorial radius of a drift shell
- Non trivial transformation to 3D coordinates
- Not ideal for asymmetries in the VAB
- Not ideal for visualisations
- Excellent to increase statistics
- Good link with physics



# Coordinate systems

## Solar Magnetic coordinate system

- 3D (x, y, z)
- z axis: Earth magnetic dipole axis
- x axis: in the plane containing z and the Earth-Sun line, pointing towards the Sun
- y axis: to have an orthogonal system
- Not ideal for good statistics, need a lot of data
- Not easy to relate to physics => for data-driven models
- Good for asymmetries in the VAB
- Good for intuitive visualisation
- Trivial conversion of coordinates SM → GEI

