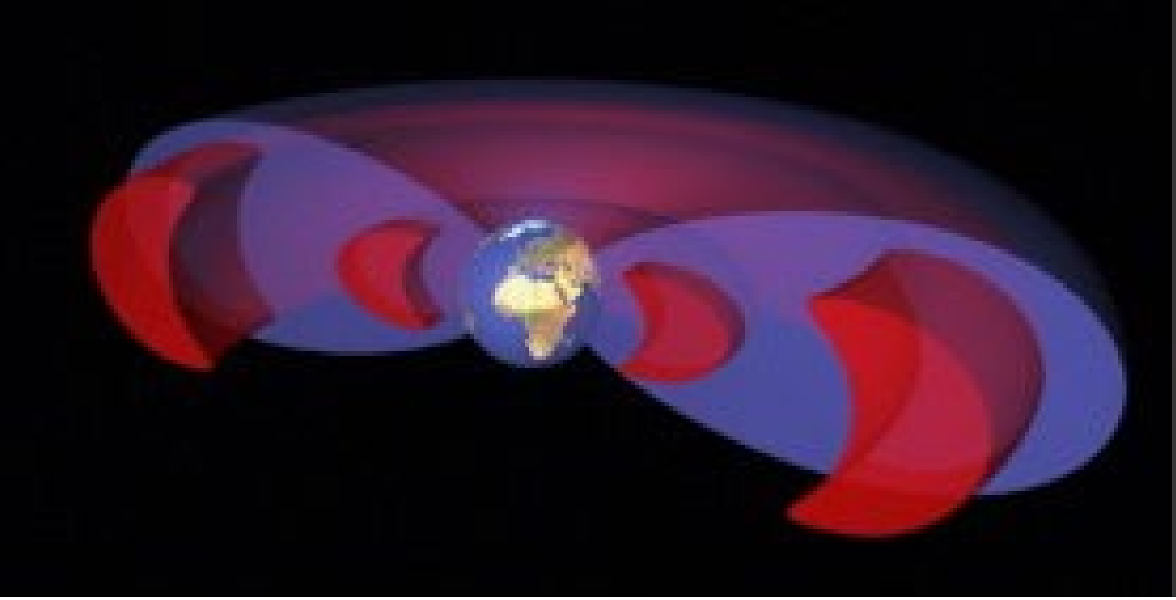

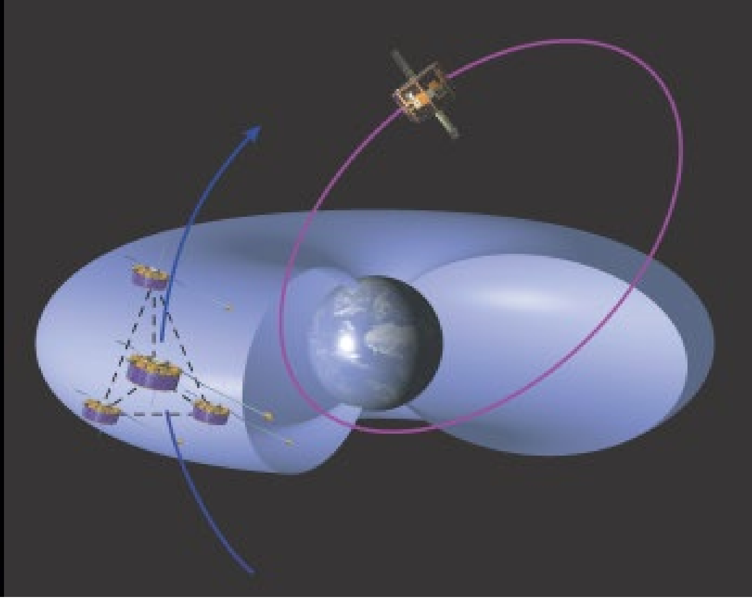

Plasmasphere

Fundamentals in plasmasphere

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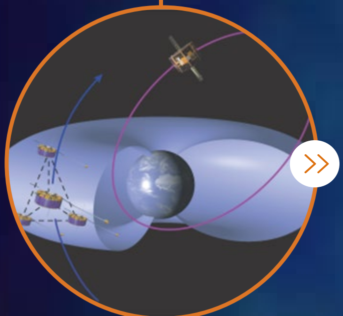
Royal Belgian Institute for Space Aeronomy

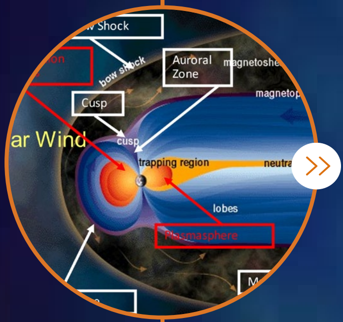
HORIZON 2020
The PITHIA-NRF project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101007599

Outline

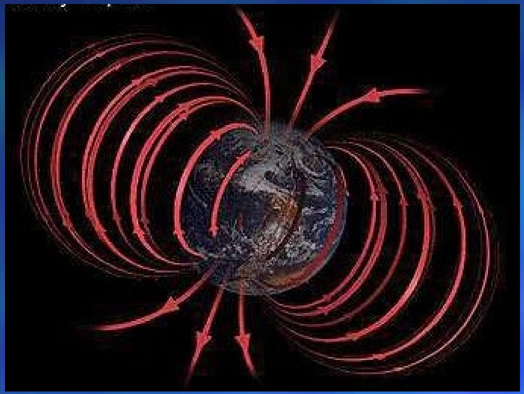


- **Introduction**
  - Earth’s magnetosphere
  - Inner magnetosphere
  - Plasmasphere
  - Density structures in the plasmasphere
  - Waves in the plasmasphere (whistler)
- Observations
  - Ground-based (VLF-Whistler)
  - Satellites (IMAGE, Cluster, RBSP, DE)
- Simulations - Models
- PITHIA-NRF
- Summary - Conclusion

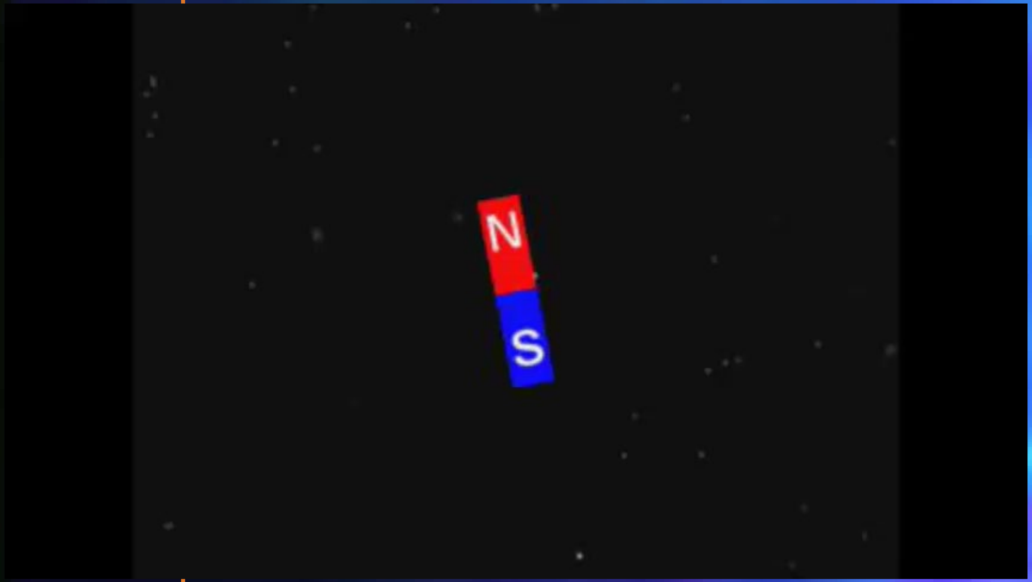
Earth’s Magnetosphere (1)



Magnetic field of the Earth (≈ dipole) + Solar wind from the Sun

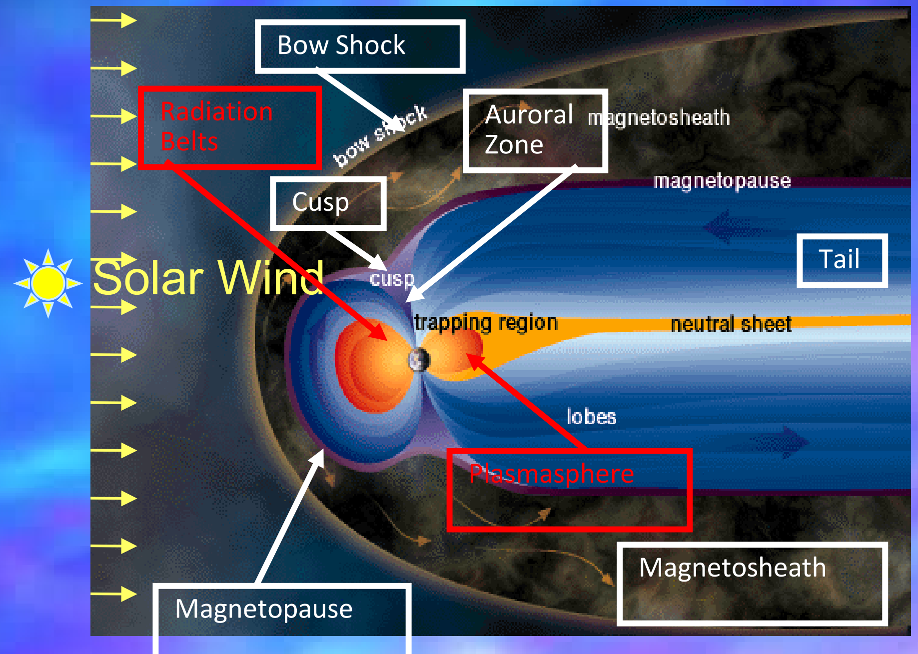


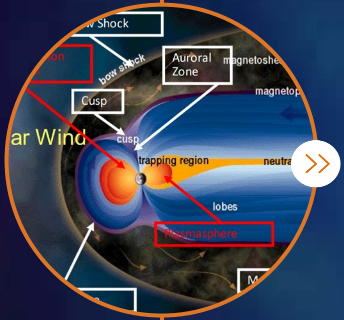
⇒ Magnetosphere of the Earth



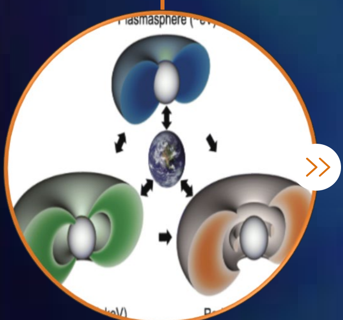
Earth’s Magnetosphere (2)

- Magnetosphere of the Earth:
  - Compressed towards the Sun (10 R_E), dayside
  - Elongated opposite to the Sun (several 100 R_E), nightside
  - Outside boundary: magnetopause
  - Ionosphere located between atmosphere and magnetosphere
  - Inner magnetosphere composed by:
    - Plasmasphere
    - Ring current
    - Radiation belts

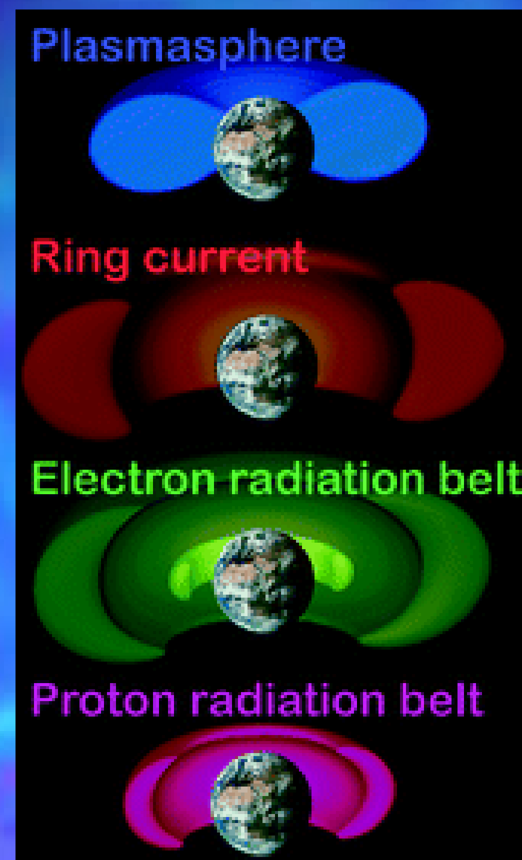




Inner Magnetosphere



- Inner magnetosphere of the Earth:
  - Co-location of 3 regions, different in terms of energy of the particles populating those regions
  - Interaction between those regions and with ionosphere
  - Density is an important parameter in those regions
  - Various dynamics of those regions



Energy

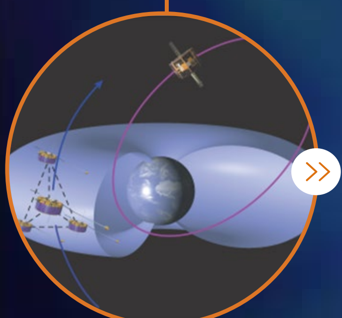
Few eV

10-100 keV

MeV

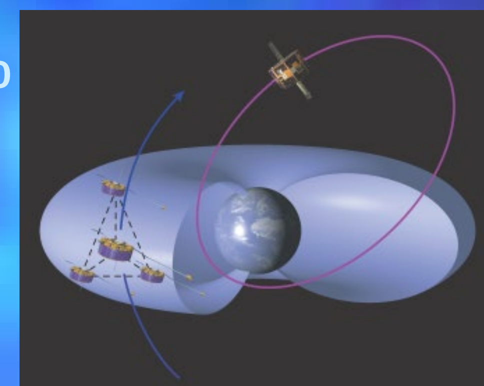
[Ebihara and Miyoshi, 2011]

Plasmasphere (1)



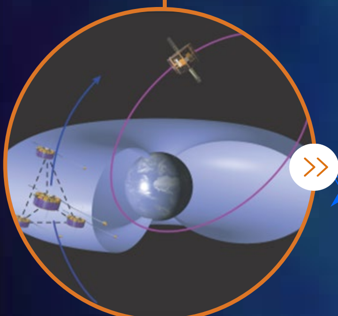
➢ Description

- Toroidal shape around the Earth (like a doughnut), at a distance of ~10000-20000 km
- Mainly in co-rotation with the Earth



- Populated by cold plasma (90% H^+ protons) originating mainly from the ionosphere (region between the atmosphere and the magnetosphere)
- Outside boundary: Plasmapause
- Particle energy: a few eV
- Temperature: ~10^4 K
- Density: $10\text{-}10^4$ cm^{-3}

Plasmasphere (2)



- Main phenomenon modifying the structure of the plasmasphere: erosion and refilling
- Erosion
  - Motion of the plasmapause towards the Earth (hours)
  - Variation of density
  - Creation of density structures (plumes for instance)
- Refilling
  - Motion of the plasmapause away from the Earth
  - Filling of plasmasphere from ionosphere (days)
  - Motion of density structures (and then are removed)
- Related to geomagnetic activity and geomagnetic storms
  - Storm: major disturbance of Earth's magnetosphere that occurs in case of very efficient exchange of energy from the solar wind into the magnetosphere

Plasmasphere (3)

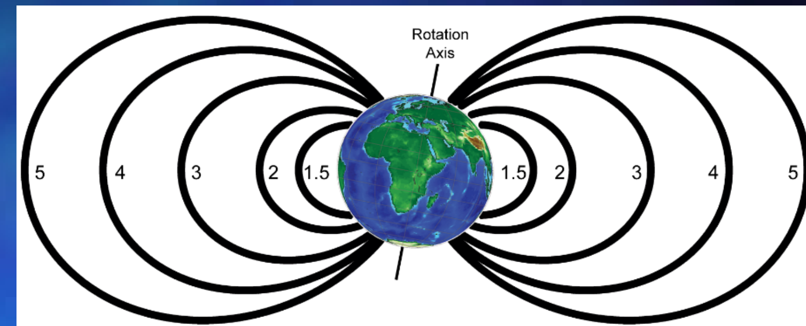
- Often associated with coronal mass ejections (CMEs) occurring at the Sun (talk earlier by Stefaan Poedts)
- Often in case of fast solar wind, under particular magnetic field conditions (strong B_Z)
- Expressed by geomagnetic indices calculated from ground-based data (Kp, Dst)
- Other example of phenomenon triggered by storms: aurora borealis – Northern lights

[Cessateur, 2023]

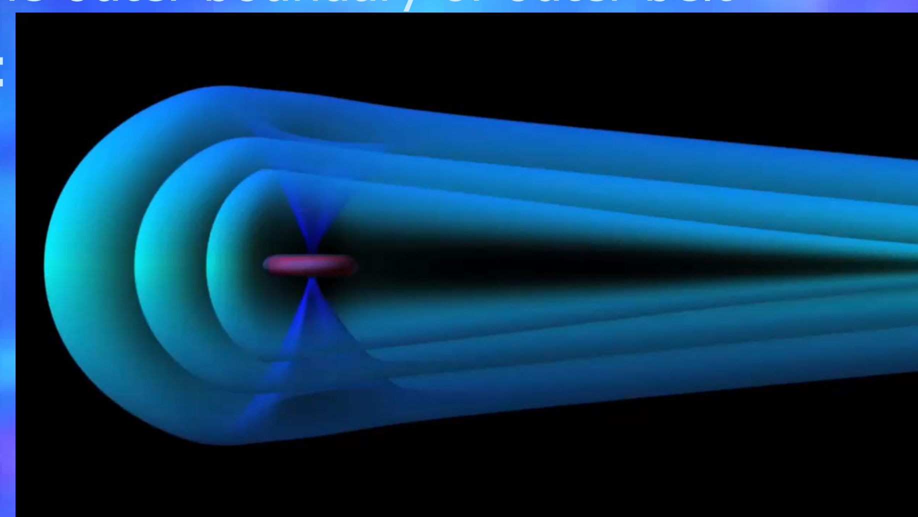
[NOAA]

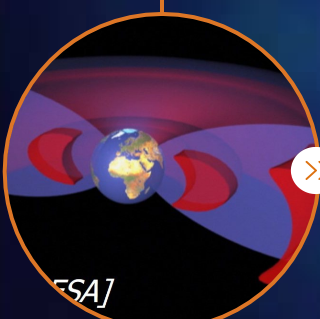
Plasmasphere (4)

- L parameter (McIlwain) ~ geocentric distance (R_E)
  - Describes a set of **B** lines which cross the magnetic equator at a number of Earth-radii equal to the L-value



- Links between the plasmapause and the radiation belt boundaries
  - Passive period: plasmapause located at L ~ 6 R_E and globally closer to the outer boundary of outer belt
  - More active period: plasmapause located closer to the Earth (L ~ 4-5 R_E) and very close to the inner boundary of outer belt



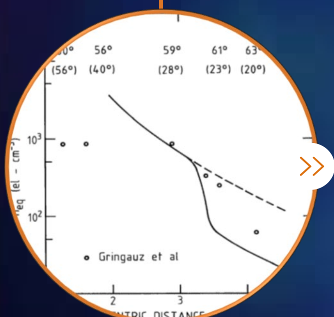


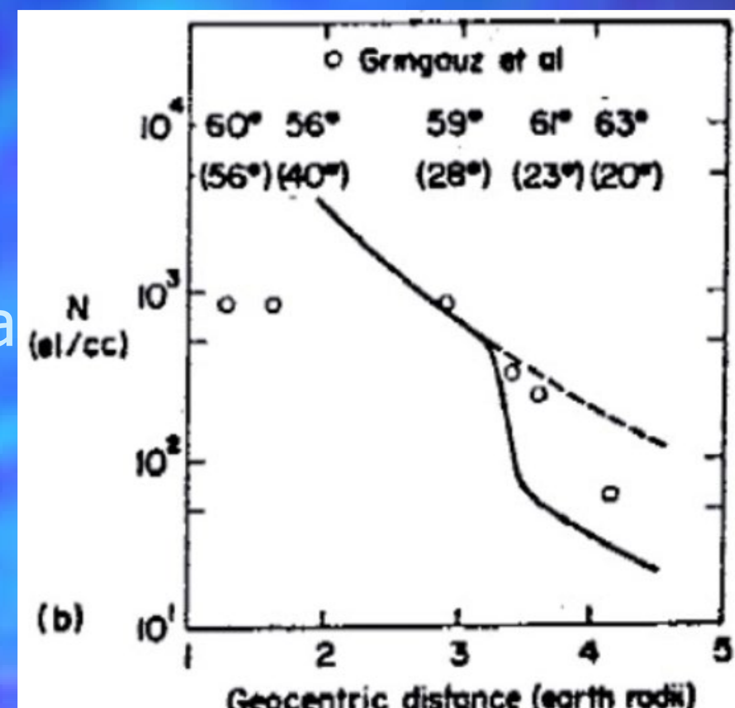
[ESA, 2013]

Plasmasphere (5)

History - Discovery

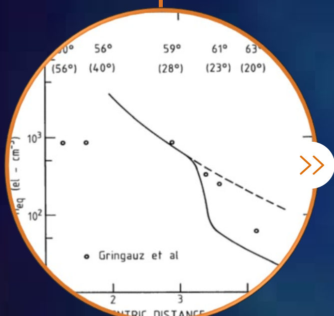
- Late 1940s: Owen Storey (UK) inferred the existence of a dispersive medium in near-Earth space to explain the propagation of whistler waves along the geomagnetic field lines *[Storey, 1953]*
- 1959: Konstantin Gringauz (URSS) used data measured by LUNIK 2 on its way to the Moon and revealed both a region of plasma density comparable to the one identified by Storey as well as an unexpected falloff in that density at an altitude of ~15000 km



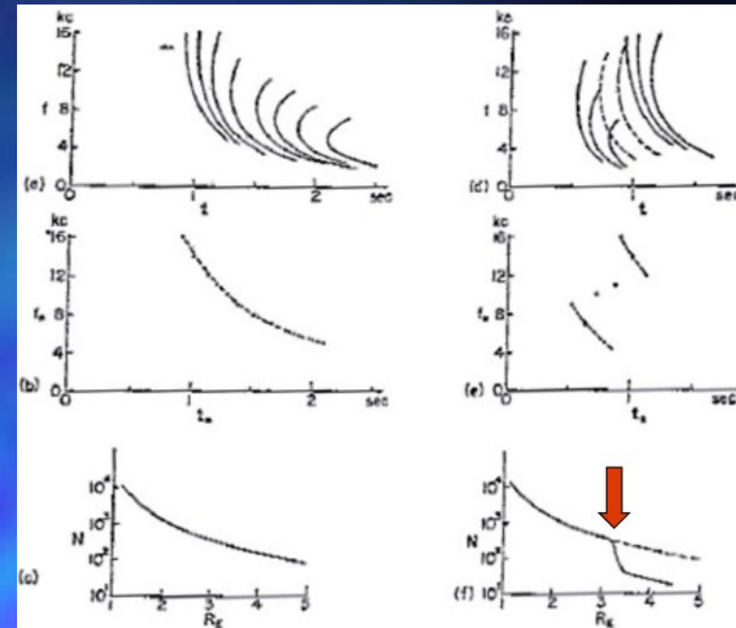


[Gringauz, 1963]

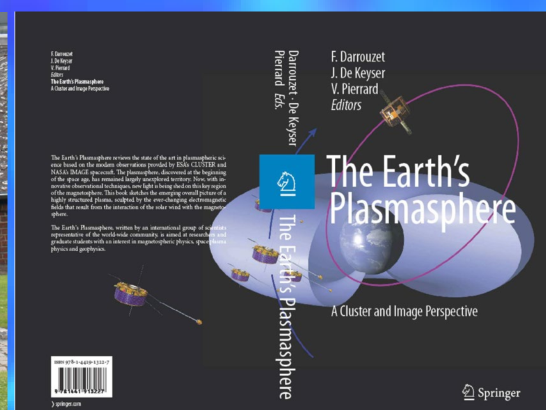
Plasmasphere (6)



- 1963: Don Carpenter (USA) used data from a spatial network of whistler ground-based receivers to identify a knee-like drop-off in the range 2-5 R_E in the equatorial profile of electron density



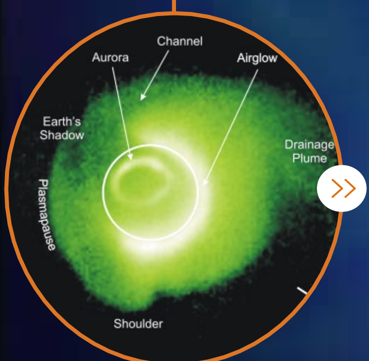
[Carpenter, 1963]



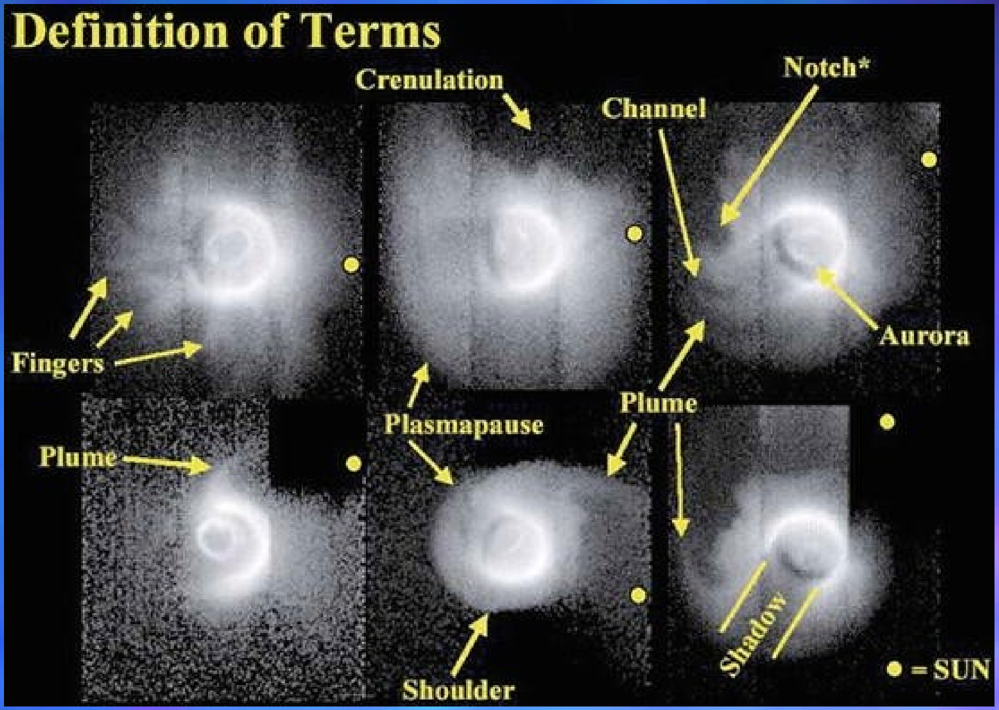
- Meeting in Brussels in 2007 with Don Carpenter: Book edited and published in 2009

Density structures

➢ Many various density structures exist in the plasmasphere (many of them discovered and named thanks to the NASA/IMAGE mission launched in 2000)



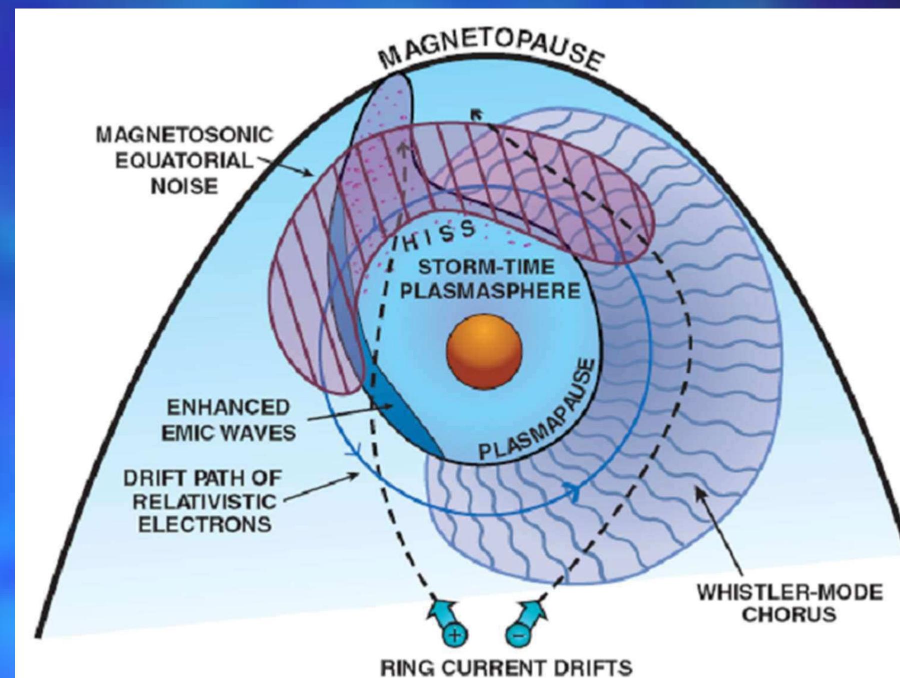
- Channel
- Finger
- Notch
- Shoulder
- Crenulation
- Plume



[Green, 2000]

Waves in the plasmasphere

- A wide variety of electromagnetic waves are present in the magnetosphere, and in particular in the plasmasphere

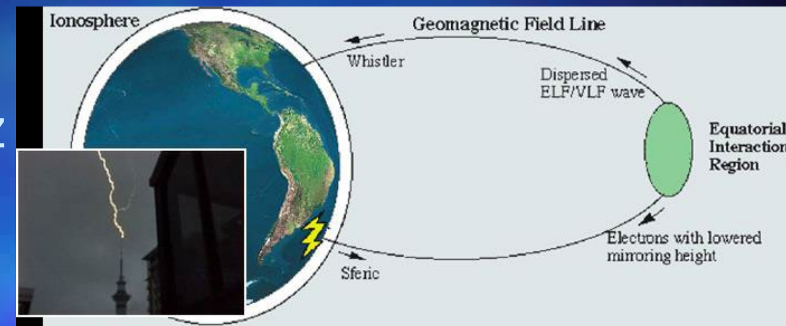


[Thorne, 2010]

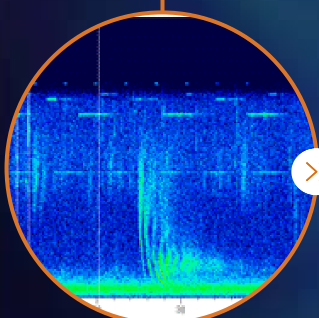
- Hiss
- Chorus
- EMIC
- Magnetosonic
- Whistler (directly related to plasmasphere discovery and studies)

Whistler waves

- Electromagnetic waves
- In VLF frequency range (2-20 kHz)
  - Human: 20 Hz - 20 kHz
  - Whistler: 5-15 kHz



- Duration ~1 second
- Signal transposed into an acoustic signal gives the impression of whistling...



- Created by lightning's storm
- Propagate along magnetic field line from 1 hemisphere to another and cross equatorial plasmasphere
- The propagation time depends on the plasma density along their path: possible to determine electron density in magnetic equatorial plane

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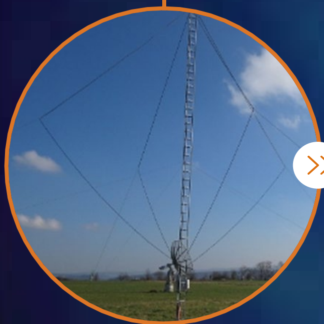
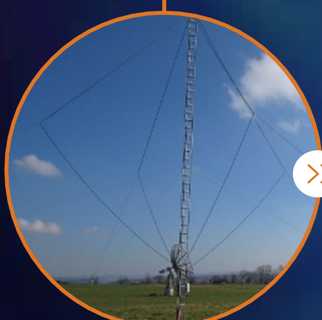


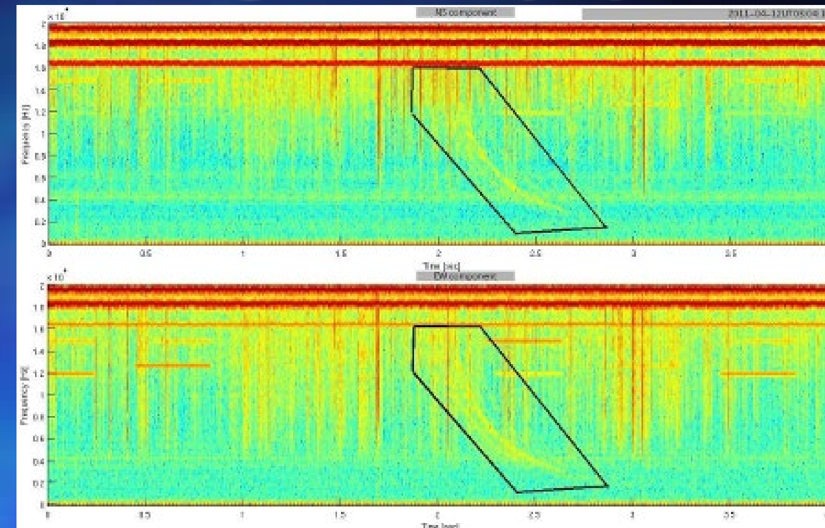
VLF antenna in Belgium (1)

- VLF antenna
  - Installed in 2010-2011 in Humain near Rochefort (Lat. ~ 50.11° N, Long. ~ 5.15° E)
  - Consisting of 2 perpendicular magnetic loops (oriented North-South and East-West, each covering an area of around 50 m^2) + preamplifier + VLF data-logger + computer
  - Installation of a 12-metre mast in November 2010 and hardware installed during winter 2010-2011

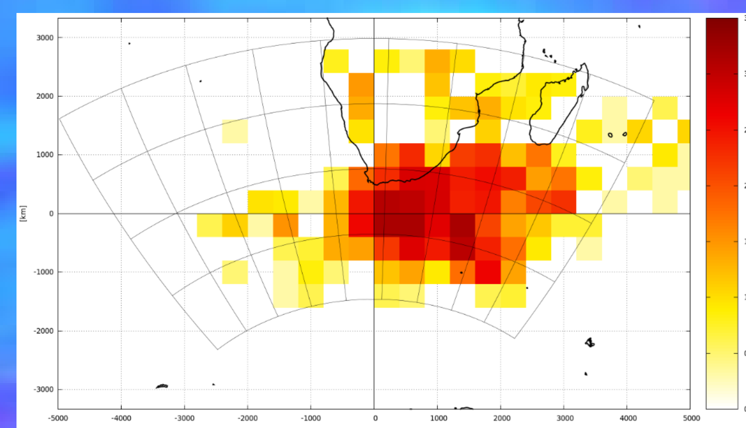


VLF antenna in Belgium (2)

- Observations
  - Time-frequency spectrograms of the magnetic field (North-South top, East-West bottom), 4 seconds, up to 20 kHz



- Results
  - Determining the source region of the whistlers (around the conjugate magnetic point)
    - Use of the World-Wide Lightning Locator Network (WWLLN) to find the lightning at the origin of the whistlers
    - Lightning strikes near the conjugate point, but mainly to the east of this point

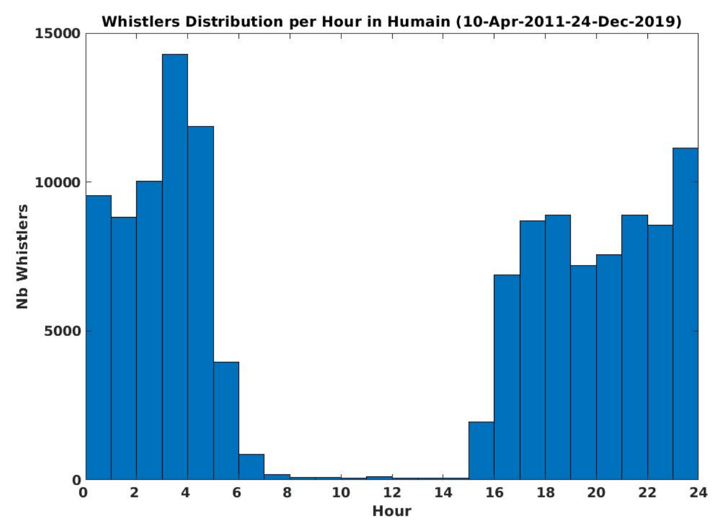


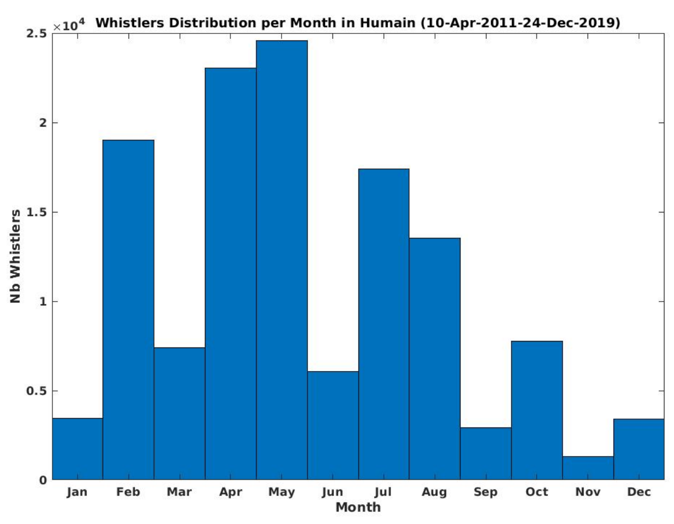
VLF antenna in Belgium (3)

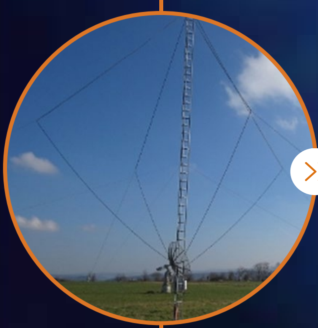
- Statistical analysis of whistlers during 8 years (2011-2019)

As a function of UT time

As a function of month



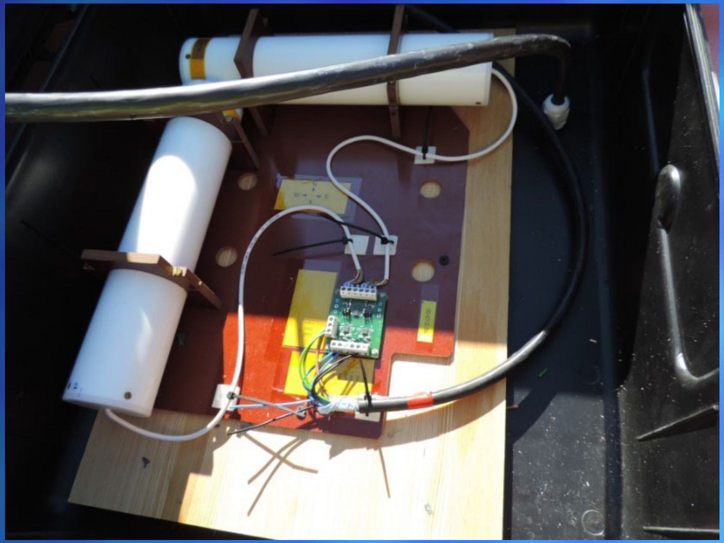




- Few whistlers between 08 and 15 UT: link with ionosphere
- More whistlers in spring and summer (few in winter): more thunderstorms at this time in the Southern hemisphere

VLF antenna in Antarctica (1)

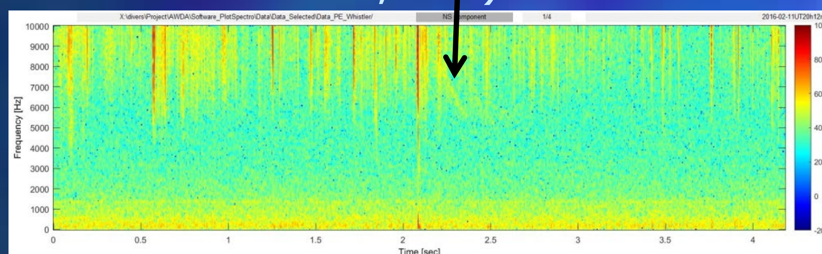
- VLF antenna
  - Installed in 2016 at Princess Elisabeth station in Antarctica (Lat.~71.57° S, Long.~23.20° E)
  - 2 magnetic search coils fixed in a waterproof plastic box placed in a bigger thermal insulated box fixed on a table

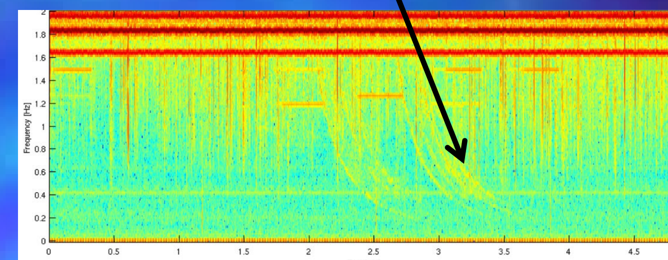


  - Why here ??
    - Need clean electromagnetic environment + power and internet + a medium magnetic latitude to detect whistlers

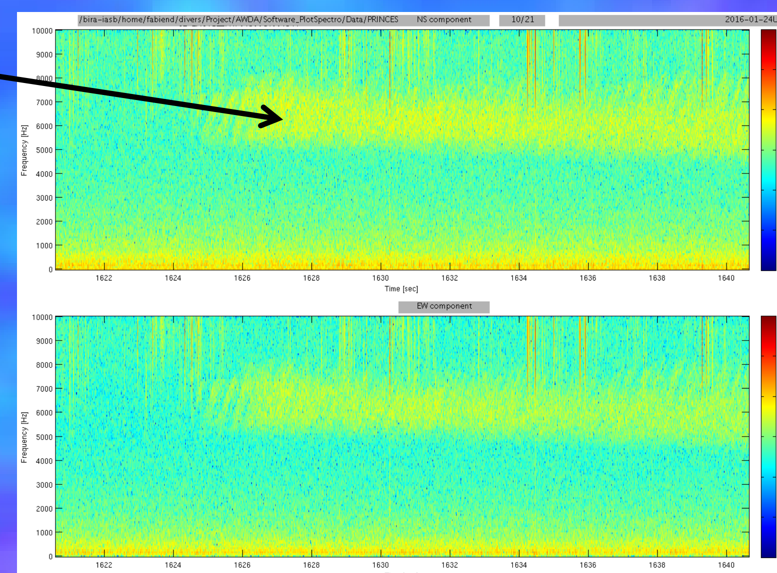
VLF antenna in Antarctica (2)

- Observations of whistlers
  - Weak whistler detected in both directions (left)
  - Cleaner signal than that measured at Human (right)
    - Less electromagnetic interference (horizontal lines from transmitters, submarines communication, background noise, etc.)



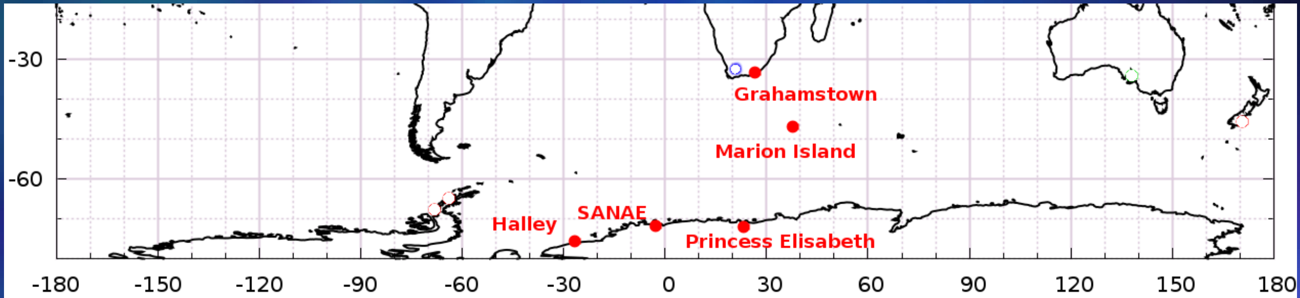


- Observations of chorus
  - Another type of electromagnetic wave linked to the plasmasphere
  - Also 2-20 kHz
  - Source region at the magnetic equator



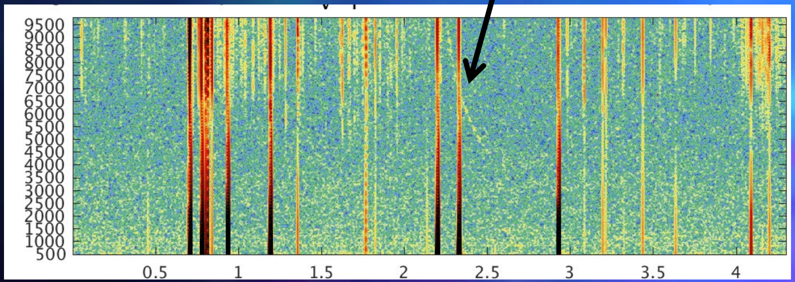
VLF antenna in Antarctica (3)

- Comparison of observations (Jan-May 2016) with 4 "neighboring" stations (900-4300 km)

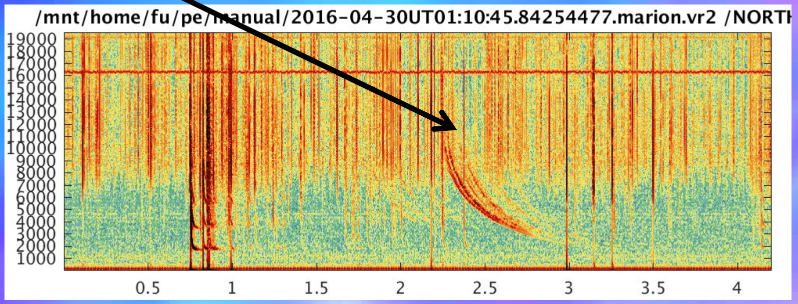


- 357 whistlers detected at Princess Elisabeth
- More than 75% of whistlers detected in 2 stations
- 10 whistlers detected in 3 stations : Princess Elisabeth (PE), Sanae (PE Dist. = 900 km), Marion Island (PE Dist. = 2900 km)
- Comparative density analysis could be done…

Princess Elisabeth



Marion Island



VLF antenna in Antarctica (4)

- Final goal is to derive electron density in equatorial plasmasphere for all whistler events detected by antennas (also product that should be delivered to PITHIA e-science center)
- Analysis not yet automatic but possible to analyse some particular events
  - 8 March 2016, 21h34m04s UT
  - $L = 3.04 \pm 0.08\ R_E$ – $Neq = 879 \pm 29\ cm^{-3}$
  - L location of the station is about 5 R_E
  - Propagation of whistler along lower L field line and then towards station through Earth-ionosphere wave guide

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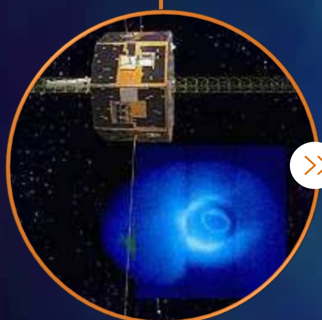
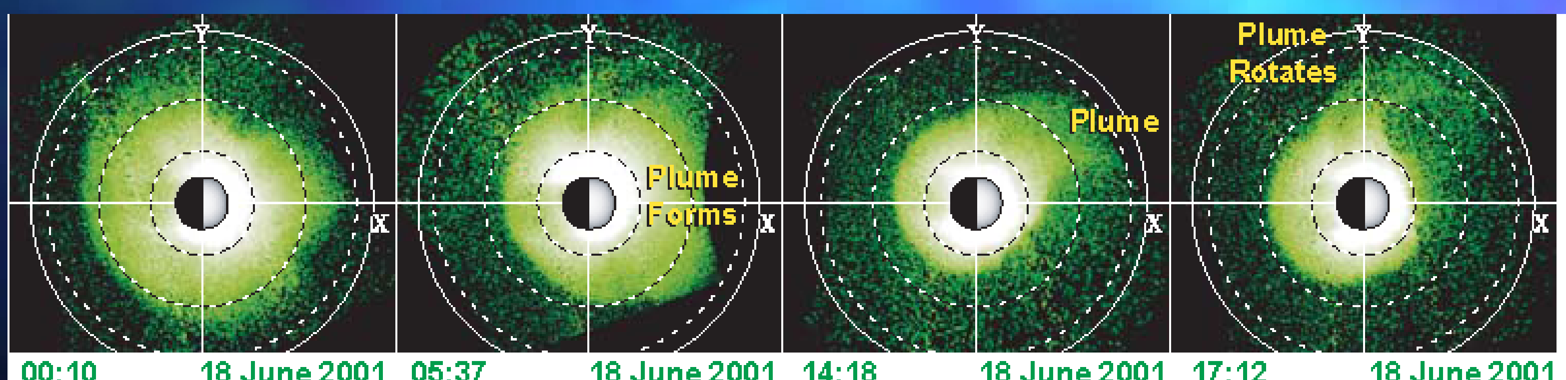
Observations: IMAGE



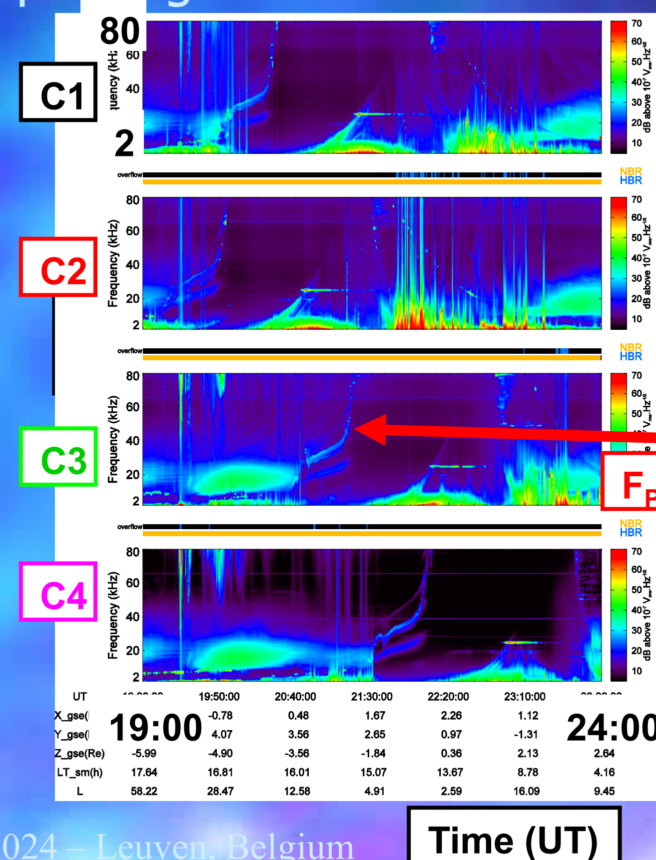
- NASA/IMAGE mission
  - 1 spacecraft, 6 instruments, launch in 2000
  - Polar orbit (high inclination), apogee at 8.2 R_E, period 13.5 h
- EUV imager
  - Detection of light emitted in the 30.4 nm range scattered by helium He^+ ions in the plasmasphere
- Observations
  - Visualization of the plasmasphere, its evolution, its characteristics (formation of plume for example)



[Goldstein et al., 2004]

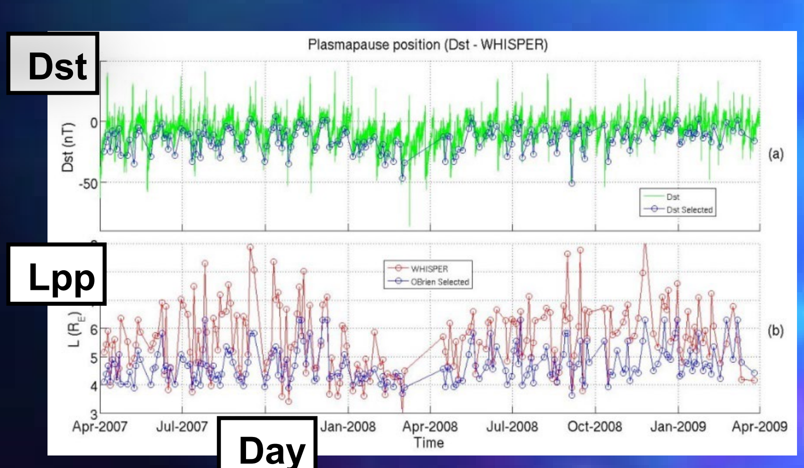
Observations: Cluster (1)

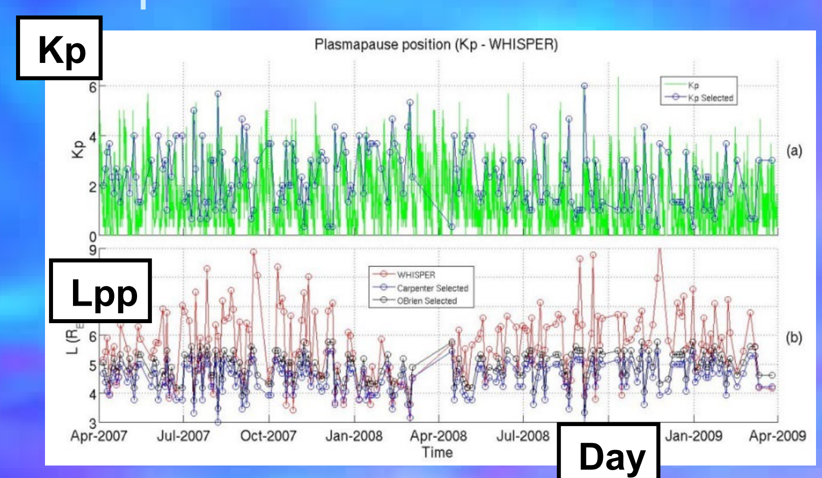
- ESA/Cluster mission
  - 4 identical spacecraft, 11 instruments, launch in 2000
  - Polar orbit, 4 x 19 R_E, period 57 h
- WHISPER data during a plasmasphere crossing
  - Time-frequency electric field spectrograms
- Method
  - Determination of the plasma frequency Fp, which is directly related to the density Ne : $Fp[kHz] = 9(Ne[cm^{-3}])^{1/2}$
  - Search of largest jump of Ne
  - Derivation of average innermost position of plasmapause



Observations: Cluster (2)

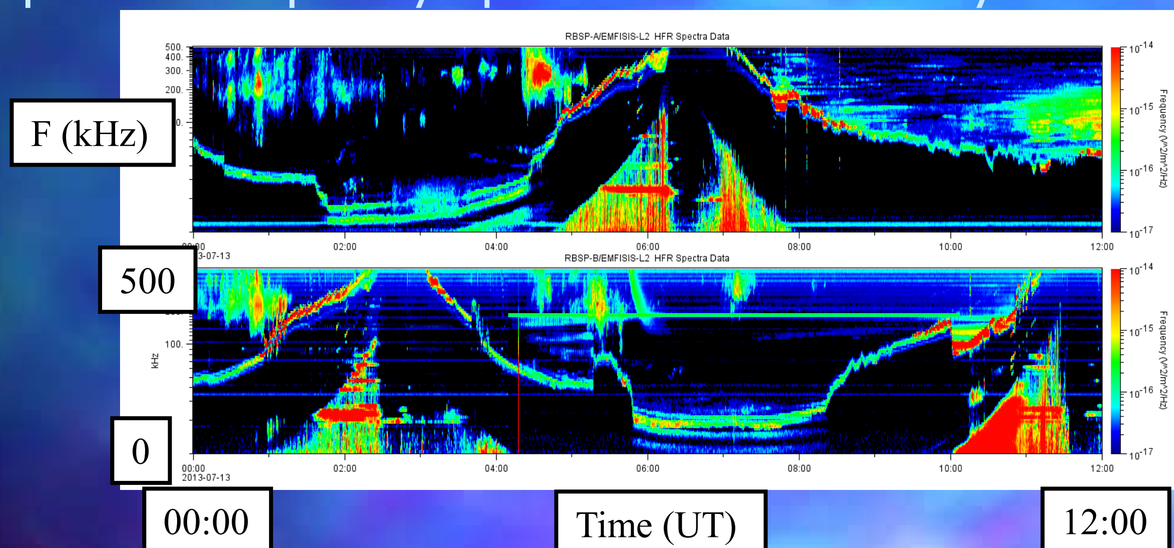
- Analysis of plasmapause position as a function of geomagnetic activity (Kp and Dst index), and comparison with models
  - $Lpp = 6.3 - 1.57 \log_{10}|Dst_{min}|$ O'Brien & Moldwin model blue left
  - $Lpp = 5.9 - 0.43\ Kp_{max}$ O'Brien & Moldwin model black right
  - $Lpp = 5.6 - 0.46\ Kp_{max}$ Carpenter & Anderson model blue right
- Results *[Darrouzet et al., 2013]*
  - Plasmapause (WHISPER, red) at higher L than models
  - Variations with Dst and Kp well recovered





Observations: RBSP (1)

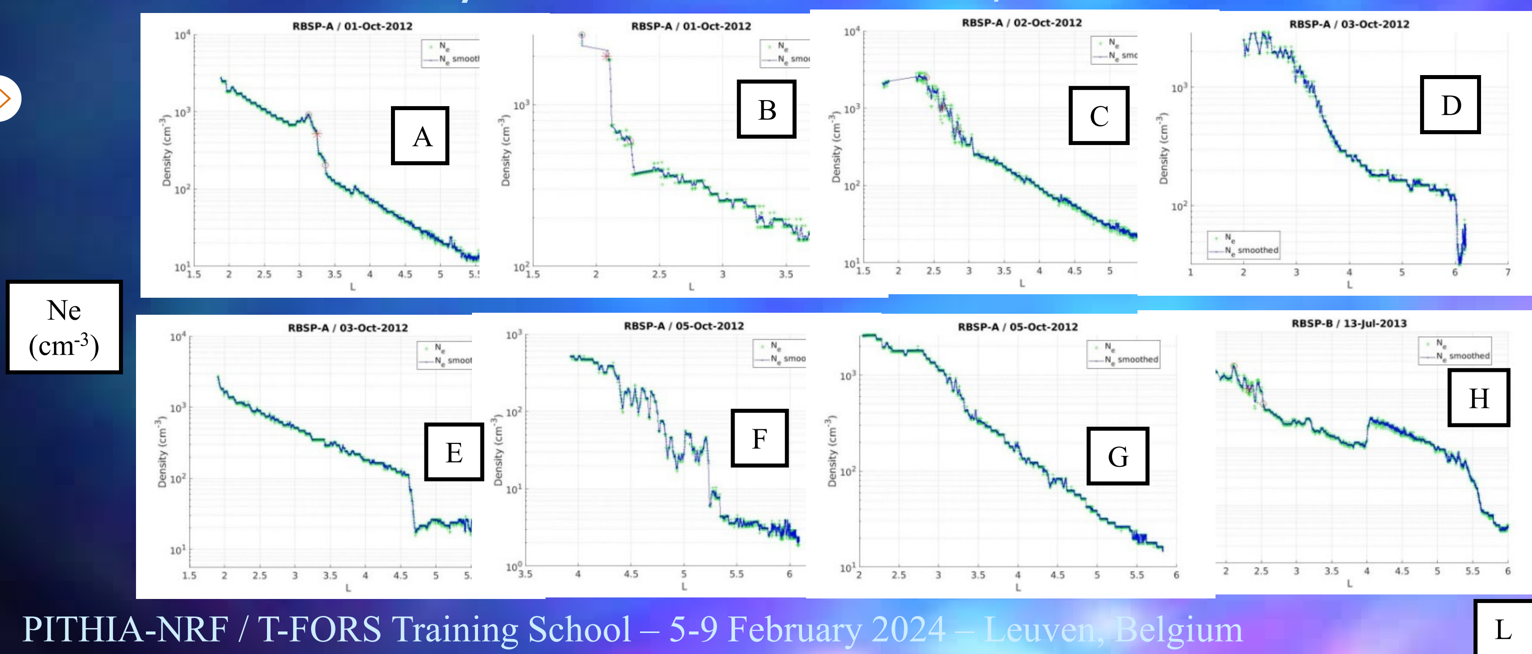
- NASA / Van Allen Probes (RBSP)
  - 2 satellites (A and B), launch in 2012, 5 instruments
  - 600 x 32 000 km, inclination 10°, period 9h
- EMFISIS data during a plasmasphere crossing
  - Time-frequency electric field spectrograms
- Method
  - Single electric field component of waves (10-500 kHz) → upper hybrid resonance frequency Fuh ⇒ electron plasma frequency Fpe ⇒ electron density Ne



Observations: RBSP (2)

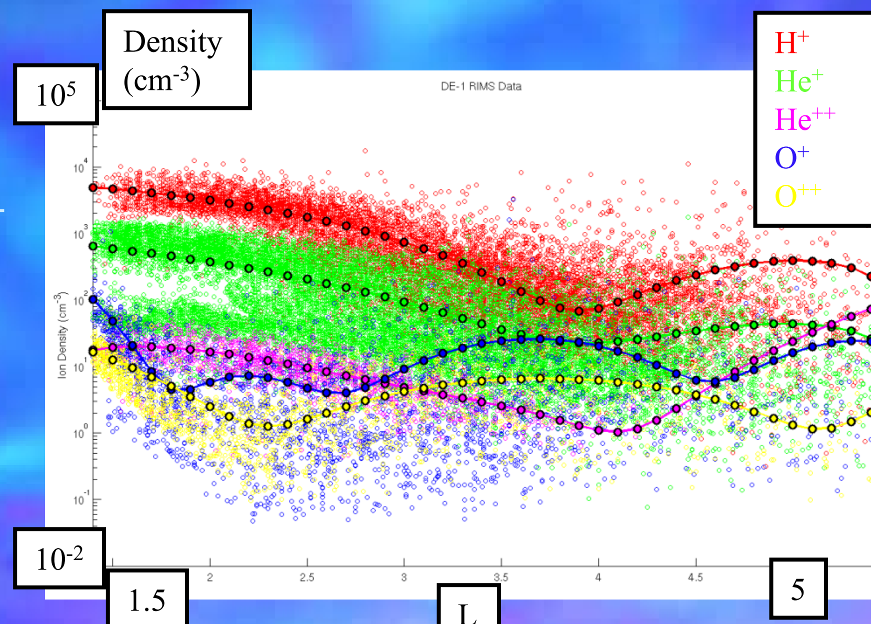
- Plasmapause not easy to determine automatically
  - Very different density profiles, large or short PBL in terms of L-scale (E-F)
  - Many density irregularities and plumes observed (C-H)
  - Density values outside the plasmapause (plasmatrough) variable (B-D)
  - Simply no plasmapause boundary (G)

⇒ The usual condition "Location closest to the Earth where Ne increases by a factor of 5 within 0,5 L" does not work !!



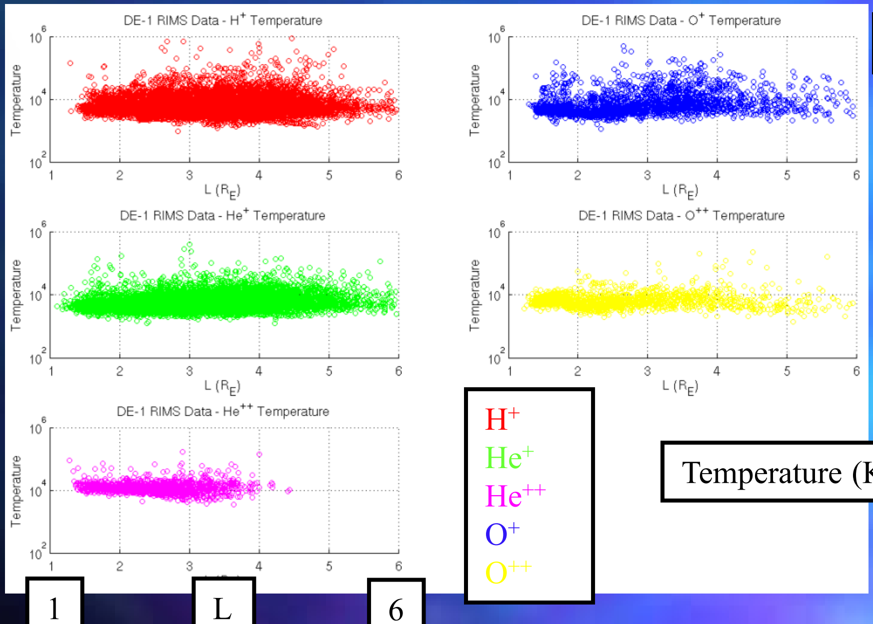
Observations: DE-1 (1)

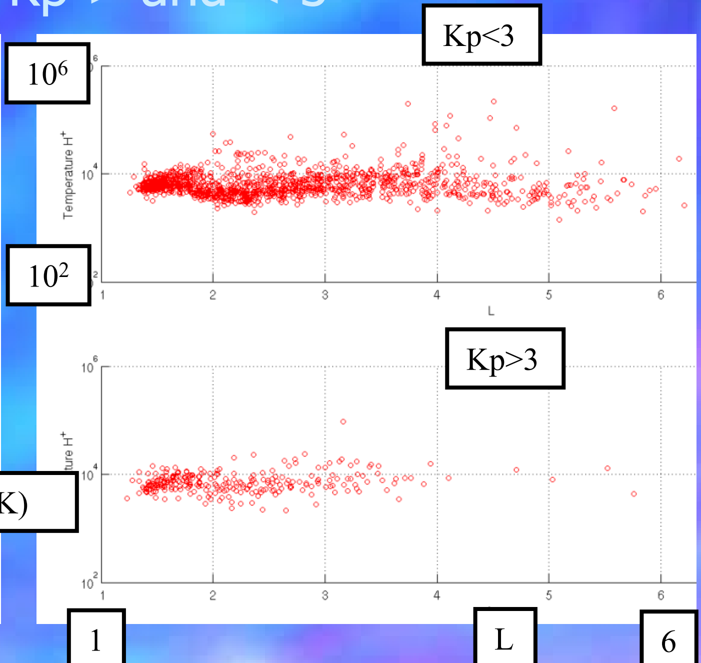
- Dynamics Explorer - 1
  - Launch August 1981, 6 instruments
  - Polar orbit, 567 x 23289 km, period 6.5 h
- RIMS
  - Retarding potential analyzer + ion-mass spectrometer
  - Density, temperature, and bulk-flow characteristics of H^+, He^+ and O^+ ions (and also He^{++} and O^{++})
- Results on density
  - Higher density ratio with respect to H+ at low L~2: 90% H^+ - 9% He^+ - 0.2% He^{++} - 0.1% O^+ - 0.1% O^{++}
  - Higher O^+ and O^{++} density at L=3-4.5 (oxygen torus)



Observations: DE-1 (2)

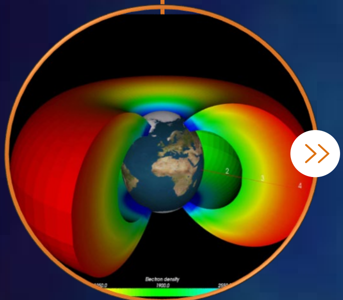
- Results on temperature inside plasmapause (and/or PBL, plasmasphere boundary layer)
  - On average about 10^4 K
  - Similar values and shape between all ions as a function of L
  - Larger dispersion for H+ (more data)
  - Quite constant as a function of L
  - No significant difference for Kp > and < 3





Outline

- Introduction
  - Earth's Magnetosphere
  - Inner Magnetosphere
  - Plasmasphere
  - Density structures in the plasmasphere
  - Waves in the plasmasphere (whistler)
- Instruments-Observations
  - Ground-based (VLF-Whistler)
  - Satellites (IMAGE, Cluster, RBSP, DE)
- **Simulations - Models**
- PITHIA-NRF
- Summary - Conclusion

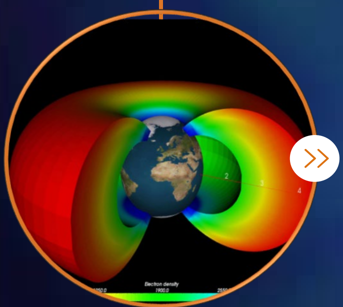


Simulations – Models (1)

- Empirical model of the plasmasphere developed at BIRA by Viviane Pierrard (talk on Tuesday) based on theoretical studies of Joseph Lemaire

[Pierrard et al., 2021]

- Description
  - Based on interchange mechanism
  - Use electric field model (E5D from McIlwain)
  - Need geomagnetic indices as input (Kp)
- Results
  - Plasmasphere density in equatorial plane and meridional plane
  - Not much activity (Kp in top panel) but small variation and co-rotation



Simulations – Models (2)

Many other models describe the plasmasphere

- Neural network model
  - Approach to model the global evolution of both the total electron density and the hiss wave amplitudes in the plasmasphere and plume
  - Network trained with RBSP/EMFISIS density + waves data
- Results

[Huang et al., 2023]

  - Simulation of the evolution of the plasmasphere density (bottom left), hiss amplitude (bottom center) and chorus amplitude (bottom right) in the equatorial plane
  - Top: evolution of geomagnetic indices

Simulations – Models (3)

- Plasmapause test particle (PTP) model: Time-dependent global plasmapause represented by the evolution of the test particle ensemble in an empirical inner magnetospheric E model depending on E_{SW} and index Kp
- Results
  - 6 rows: E_{SW}, Kp, virtual density on RBSP-A and B, EMFISIS density on RBSP-B
  - Bottom panel: evolution of plasmasphere in equatorial plane, with orbits of C1-C2-C3-C4, RBSP-A, RBSP-B
  - Plume formed the day before and in co-rotation around the Earth (small outward expansion of the plume)
  - Plume crossed by RBSP-B but not by RBSP-A and later by Cluster

[Goldstein et al., 2014]

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PITHIA-NRF (1)

- Some of the data and models described in this presentation are available on the PITHIA-NRF e-Science Centre (VLF densities not yet)
  - WHISPER density in the plasmasphere

PITHIA e-Science Centre

Home | Scientific Metadata | Space Physics Ontology

Home > All Scientific Metadata > Data Collection-related Metadata > Data Collections > WHISPER/Cluster collection of Electron Density and Electron Plasma Frequency in the Plasmasphere

WHISPER/Cluster collection of Electron Density and Electron Plasma Frequency in the Plasmasphere

  - 3D model of the plasmasphere

PITHIA e-Science Centre

Home | Scientific Metadata | Space Physics Ontology

Home > All Scientific Metadata > Data Collection-related Metadata > Data Collections > BSPM: 3D-Kinetic plasmasphere model > Interact with BSPM: 3D-Kinetic plasmasphere model via API

Interact with BSPM: 3D-Kinetic plasmasphere model via API

PITHIA-NRF (2)

- Geomagnetic indices also available in the PITHIA-NRF e-Science Centre
  - Kp indice (very useful for plasmaspheric studies)

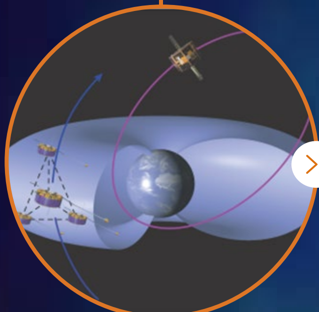
PITHIA
e-Science Centre

Home Scientific Metadata Space Physics Ontology

Home > All Scientific Metadata > Data Collection-related Metadata > Data Collections > ActivityIndicator: Collection of Kp, ap, and Ap indices by GFZ, with F10.7 from DRAO and Sn from WSC SILSO

ActivityIndicator: Collection of Kp, ap, and Ap indices by GFZ, with F10.7 from DRAO and Sn from WSC SILSO

Summary - Conclusion



Summary

- Plasmasphere is the extension of the ionosphere
- Plasmapause position and density structures depend on geomagnetic activity
- Ground-based and satellite observations as well as models show the dynamics and evolution of the plasmasphere
- Plasmaspheric density dataset and plasmaspheric model available in the PITHIA-NRF e-Science Centre

Thanks for your attention !!

HORIZON 2020

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