SPACE WEATHER INTRODUCTORY COURSE

Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

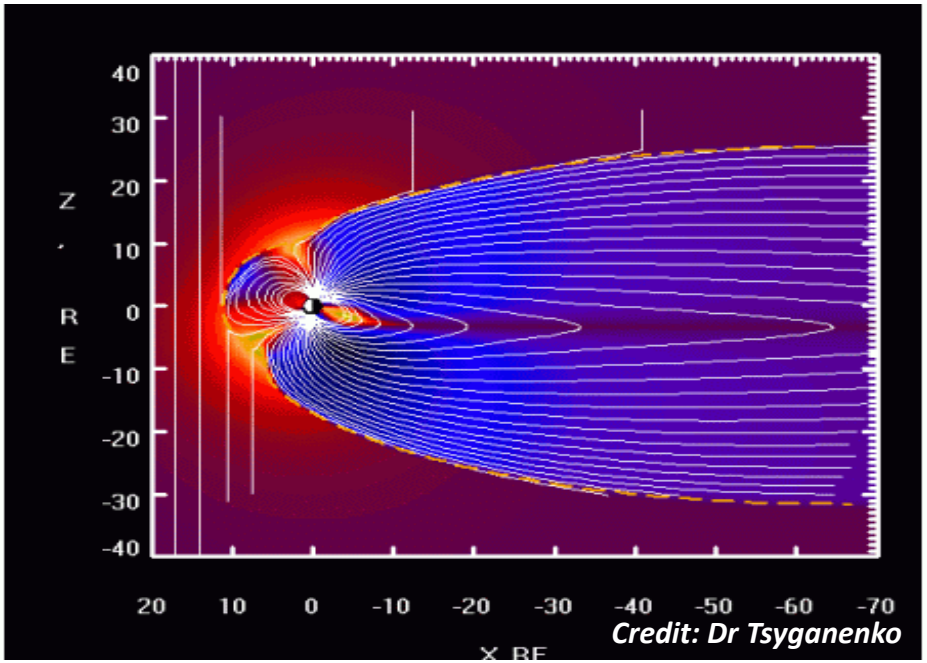
Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

The Magnetosphere

Jan Janssens, Dr Johan De Keyser (BISA)

The magnetosphere

- …that area of space, around a planet, that is controlled by the planet's magnetic field.
- Its … shape is the direct result of being blasted by solar wind.
- Field lines connect the magnetosphere with the ionosphere



The Magnetosphere - Contents

- The geomagnetic field
- Main features
- Geomagnetic (sub)storms
- Measuring magnetic fields
  - Geomagnetic indices
  - Networks
- Miscellaneous

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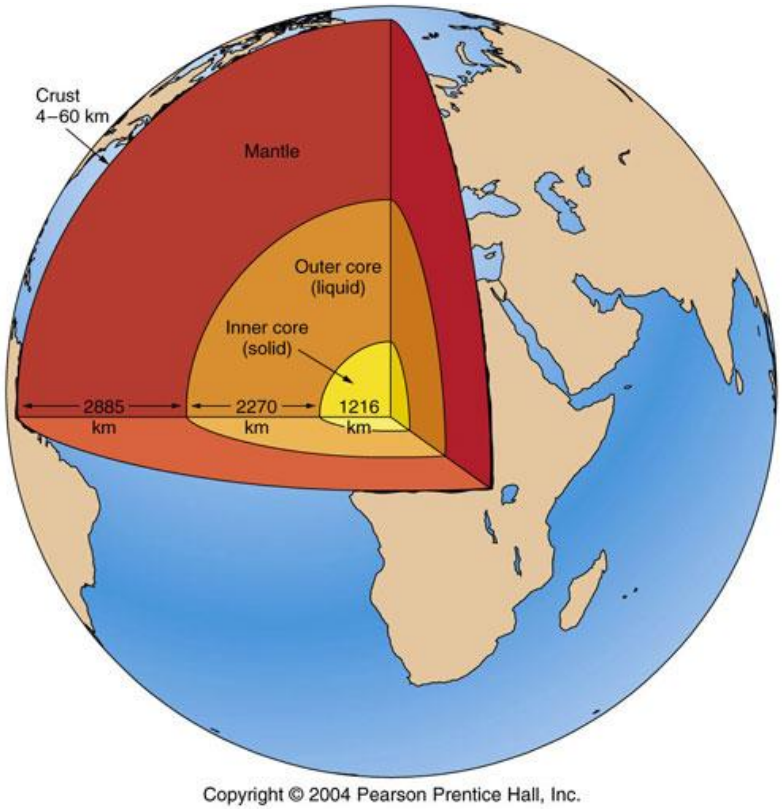
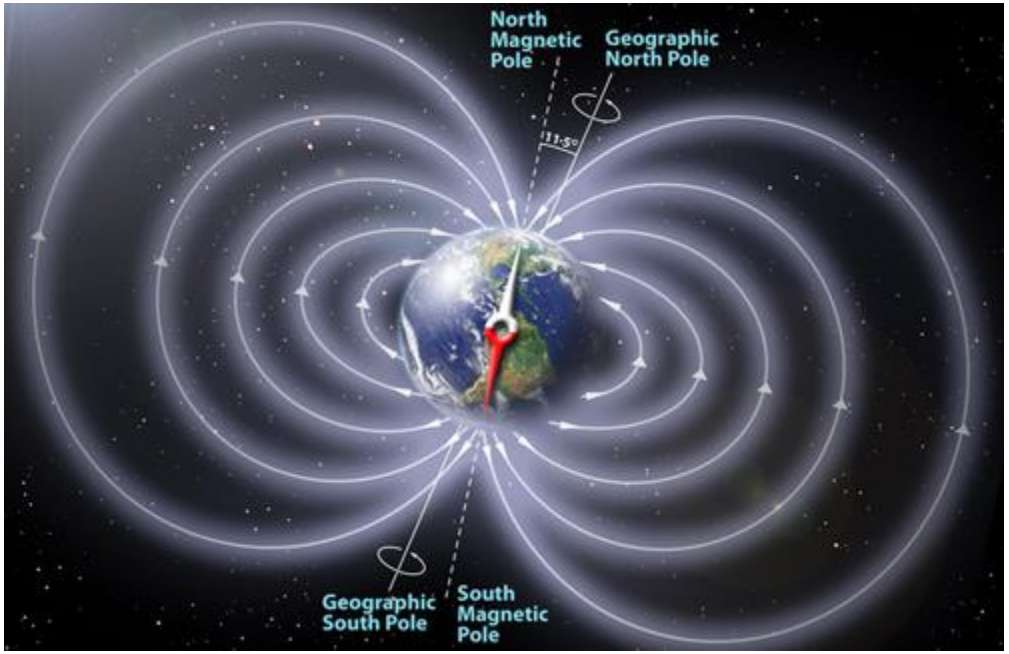
The geomagnetic field

- Created in and by the Earth's interior



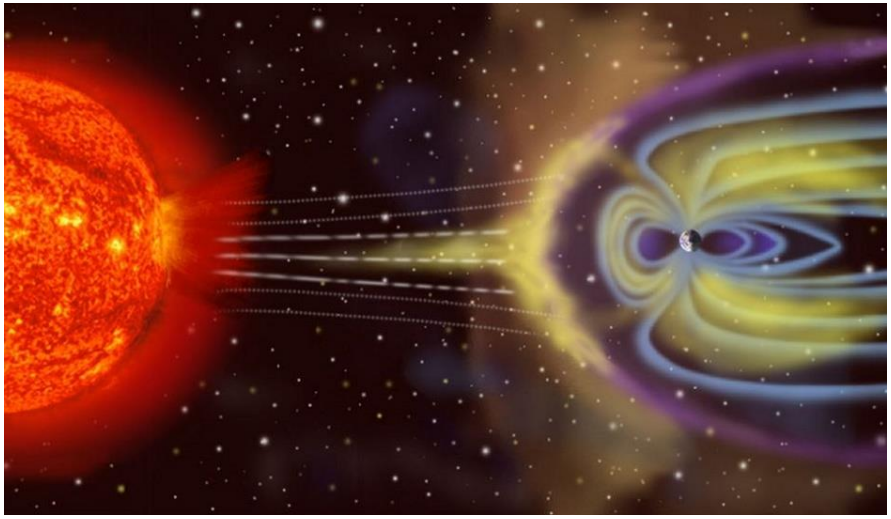
The geomagnetic field

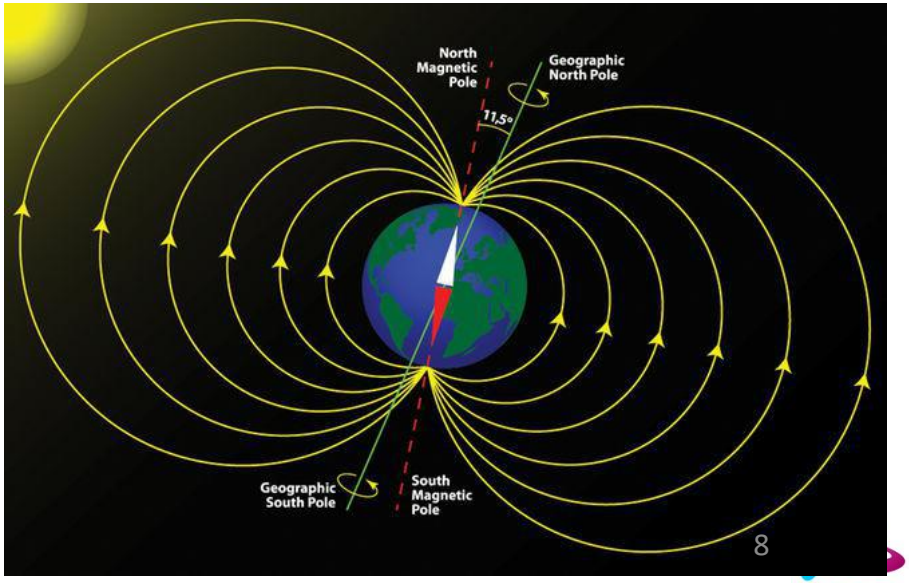
- Created in and by the Earth's interior
- Dipole *(not perfect)*
  - In absence of disturbances
  - Enters north pole (-), leaves at south pole (+)
  - Intensity:
    - 25000 – 65000 nT
    - Weakest at equator
    - Strongest at poles



The geomagnetic field

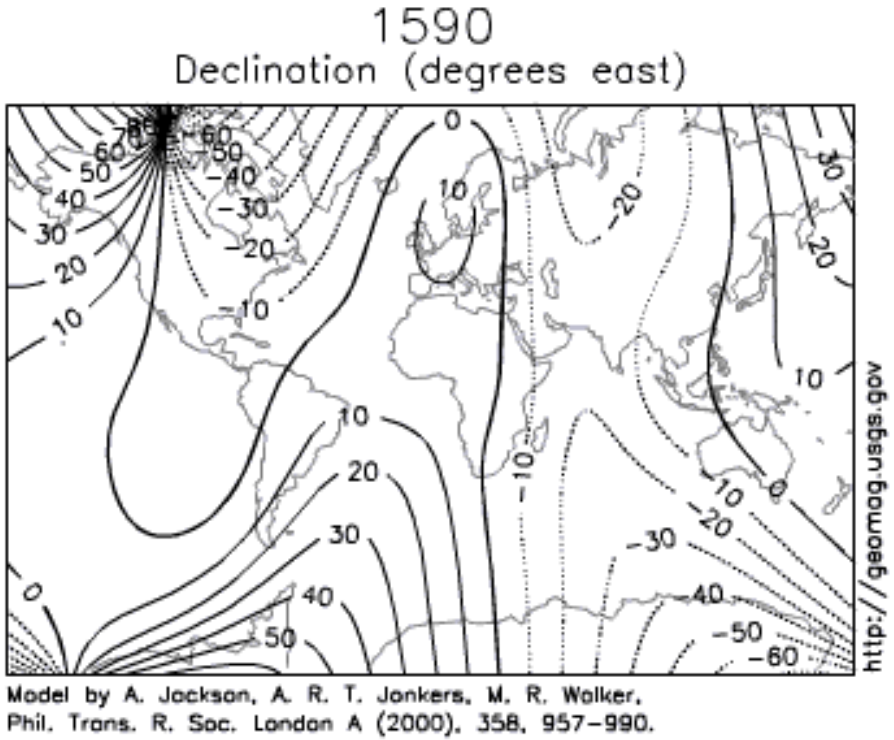
- Due to solar wind
  - Drop shape
    - 10 R_E (earth radii) at dayside
    - >200 R_E at nightside
- Magnetic axis
  - 11° tilt to Earth's rotational axis
    - Compass does NOT point to true north
  - 500 km offset to north
    - Weakness over Brazil



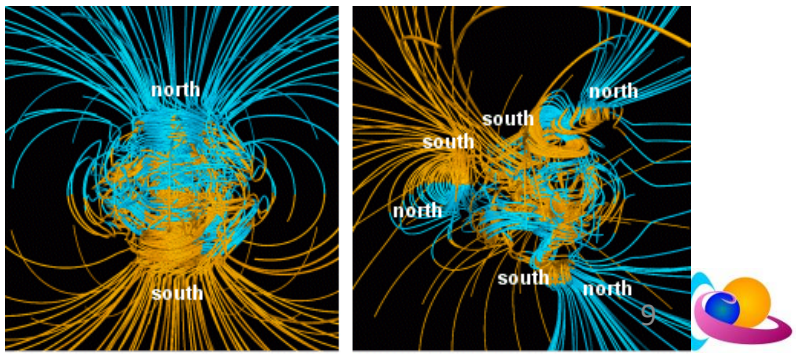


The geomagnetic field

- Continuously changing
  - Short-term
    - Slow enough that compass remains useable
      - Airport runways
  - Long-term
    - Polar field reversals
      - Magnetic field does NOT disappear
      - Slow
      - Frequency: +/- 450000 years
        - » 250000 years overdue
      - Compare to Sun: 11 years!!



Model by A. Jackson, A. R. T. Jonkers, M. R. Walker, Phil. Trans. R. Soc. London A (2000), 358, 957–990.



between reversals during a reversal

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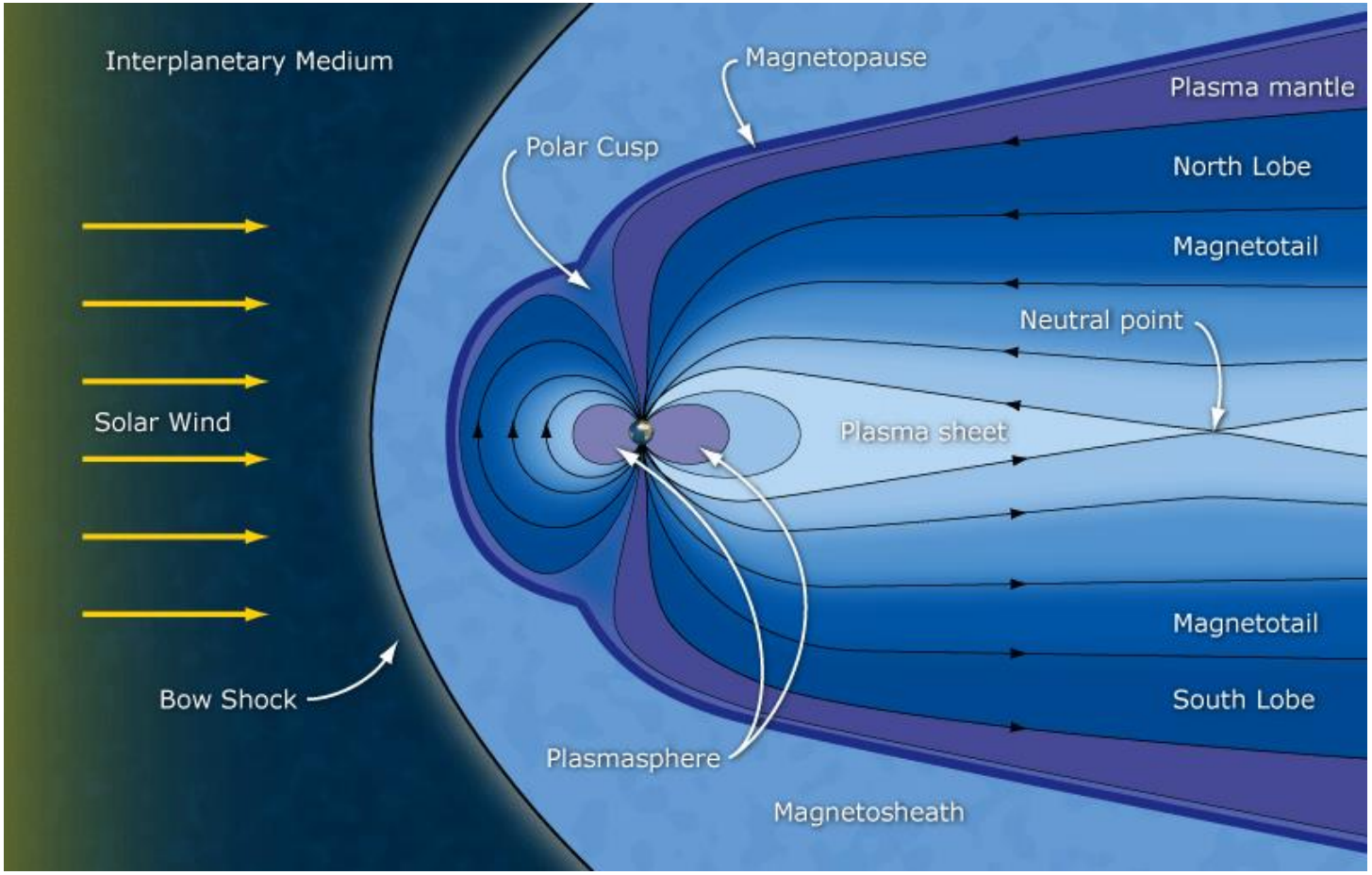
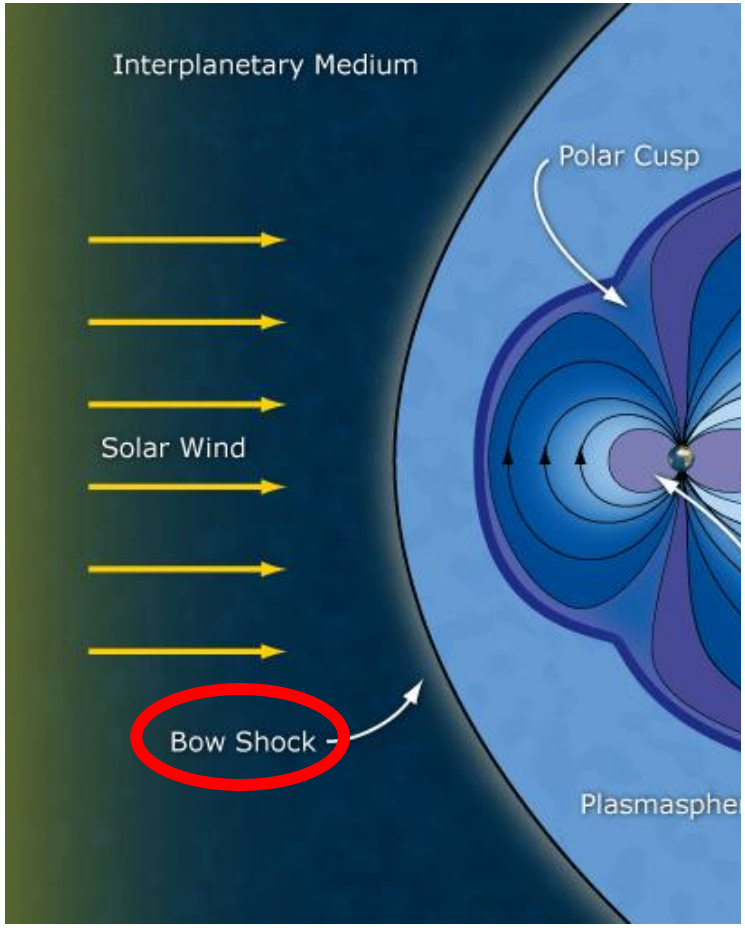
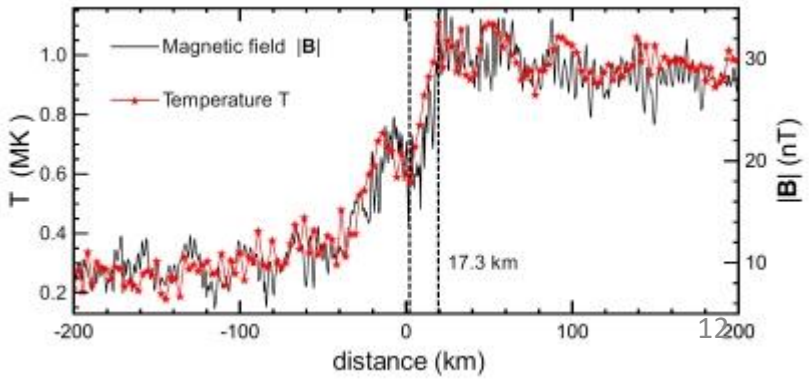
Main features



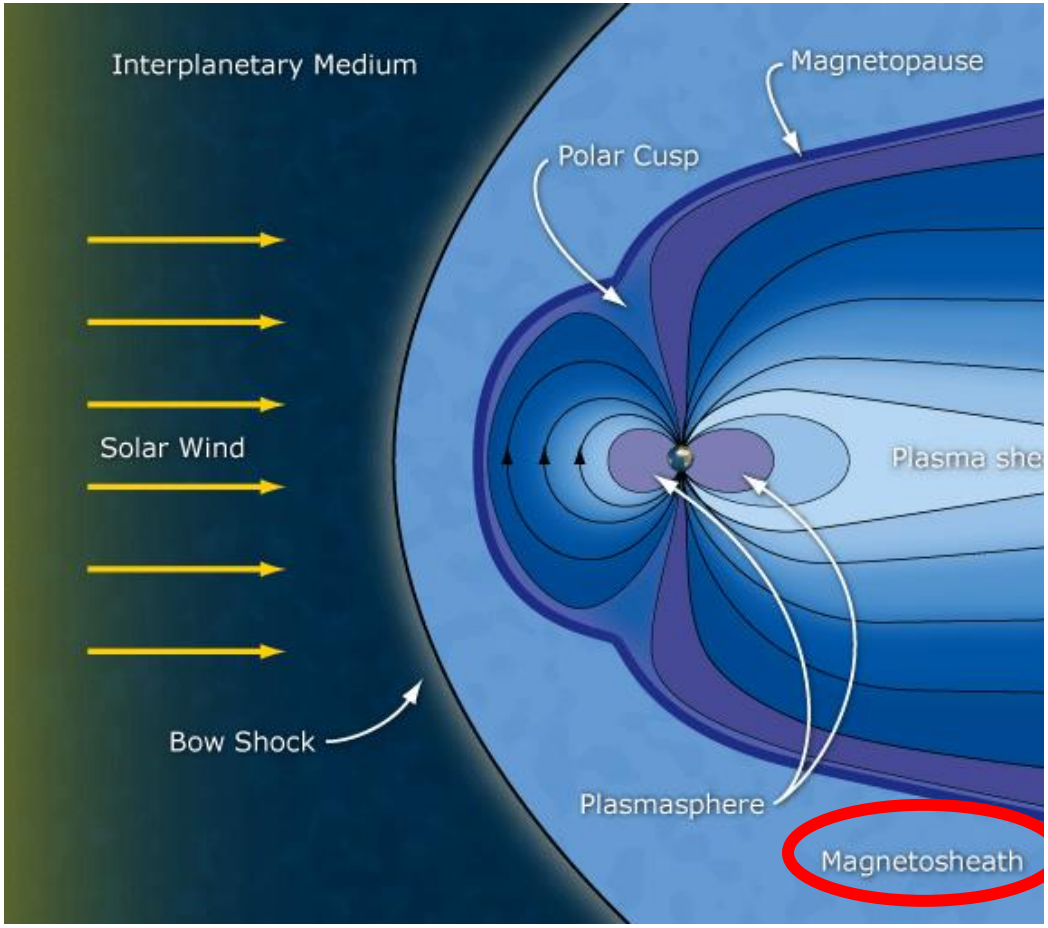
Main features



- Bow shock
  - First interaction w/ solar wind
    - Speed reduction
    - Increase T, B
    - Shock: very thin
  - Location
    - +/- 90.000 km upstream
      - Variable!

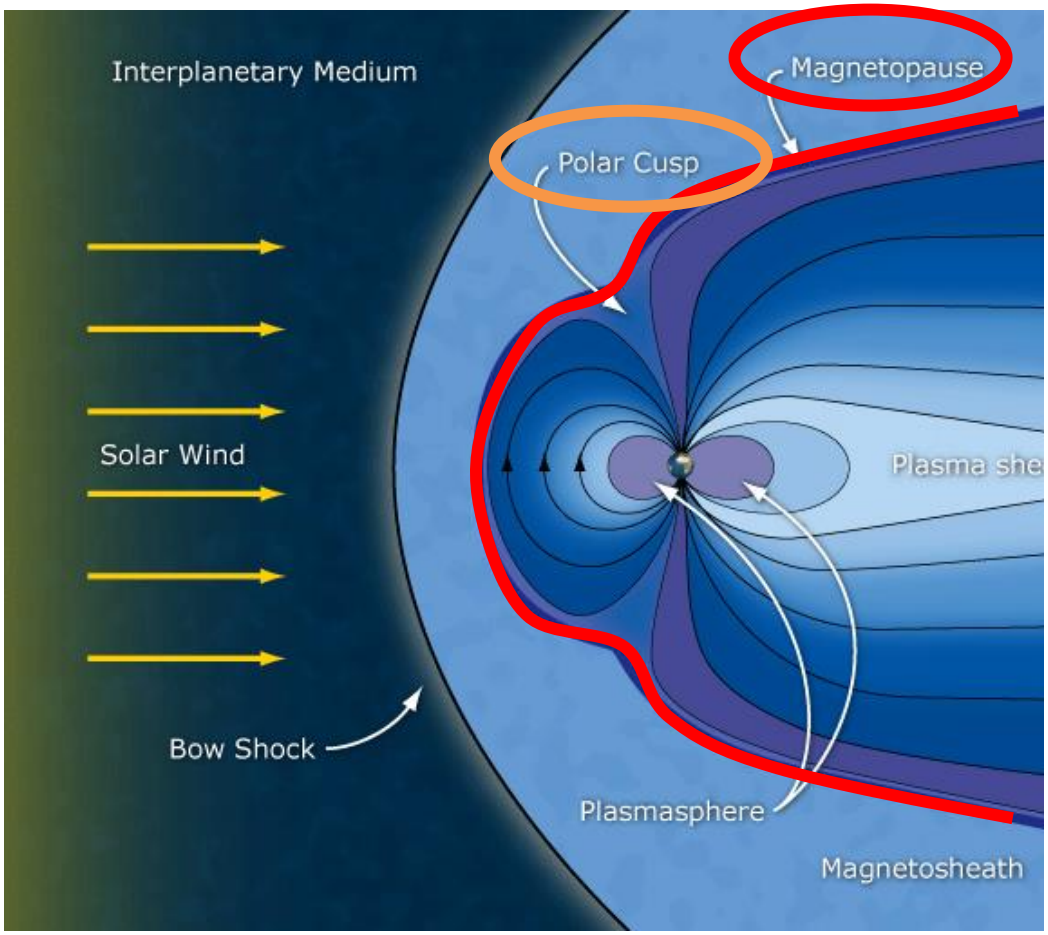


Main features



- Magnetosheath
  - Turbulent region between bow shock and magnetopause
  - Solar wind dominated
    - Deflected above and below the magnetopause
  - High particle energy flux
    - « shocked »
    - MF varies erratically
    - Much smaller than geomagnetic field

Main features

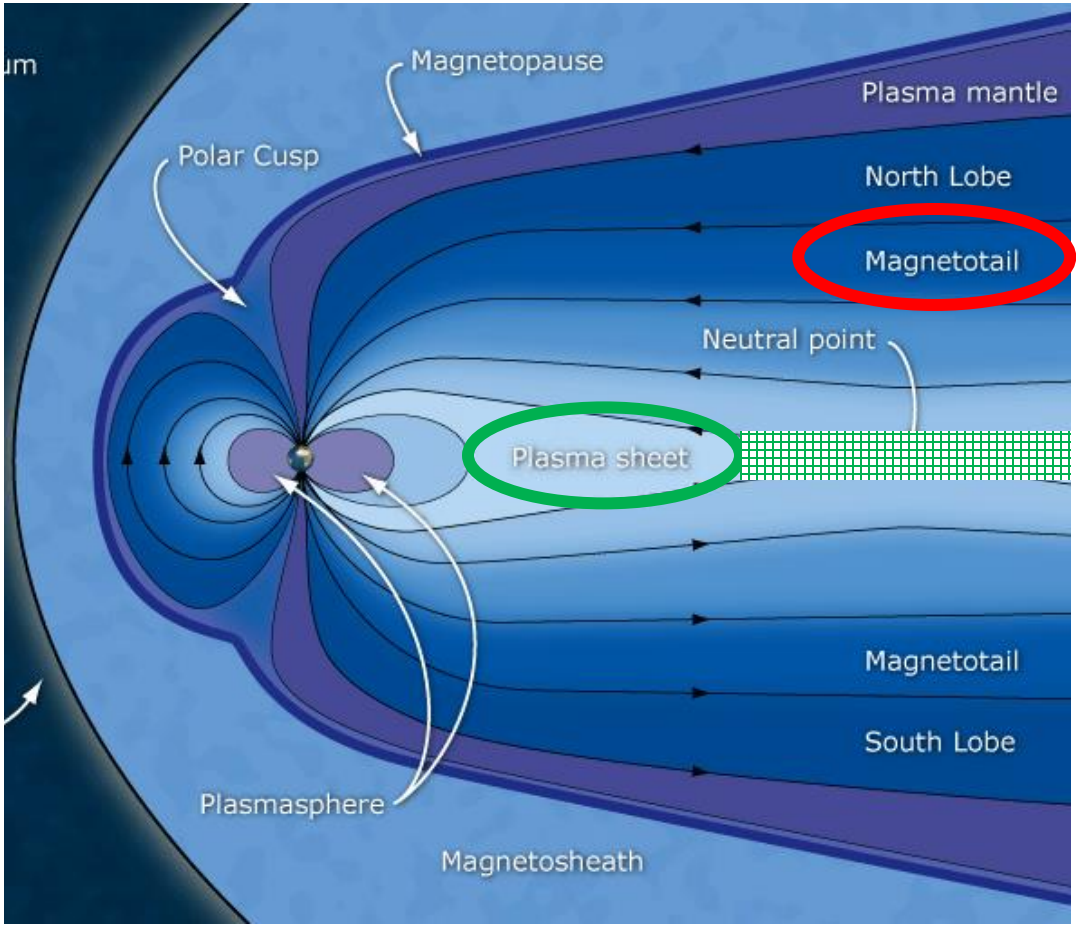


- Magnetopause
  - Sharp boundary
    - Pressure balance
    - = sum of magnetic + plasma pressure is constant
  - Earth vs. Solar Wind
  - Magnetic reconnection
    - Current sheet
  - Location:
    - 10-12 R_E (6-15 R_E)
  - **Cusp**
    - Narrow regions of opened/merged MF lines
    - In/outflow of particles

R_E : Earth radii ; MF: Magnetic Field

Main features

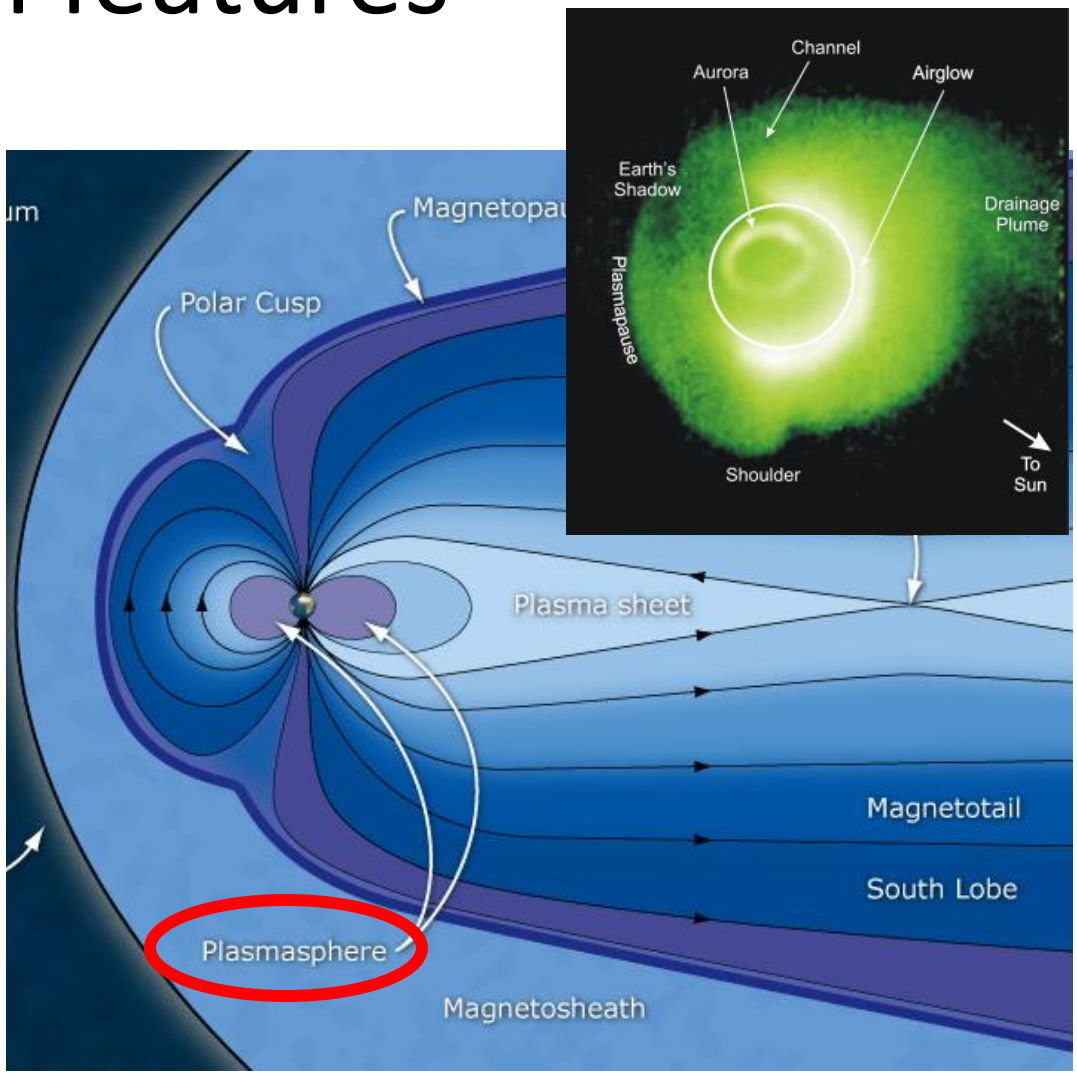
- Magnetotail
  - Several 100 R_E long
  - Two lobes
    - Northern: MF points towards Earth
    - Southern: MF points away from Earth
  - Separated by **plasma sheet**
    - Reconnection closer to Earth during strong disturbances
      - Source of aurora



R_E : Earth radii ; MF: Magnetic Field

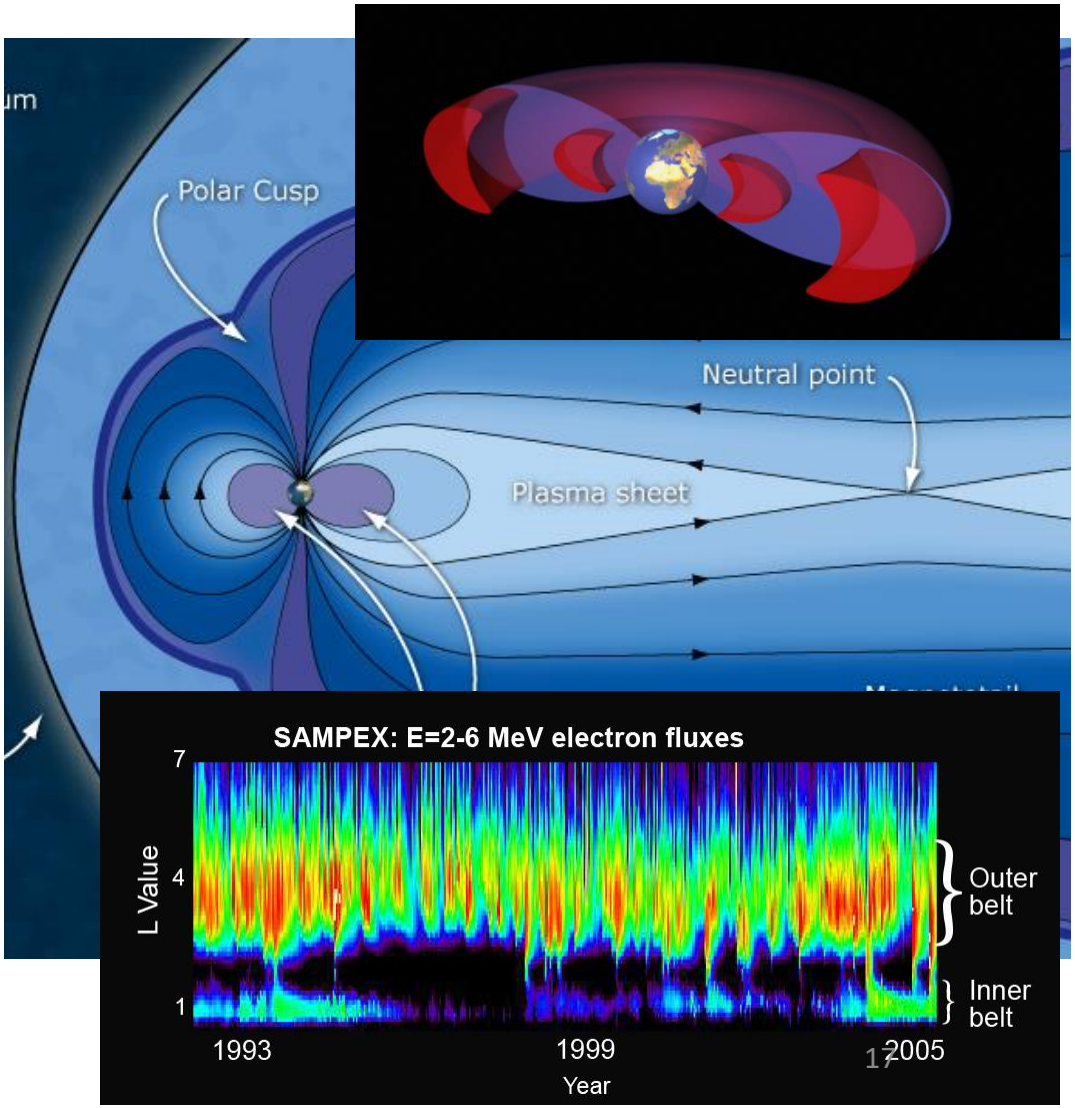
Main features

- Plasmasphere
  - Donut shaped region
    - Specific features
  - Cold plasma
    - From ionosphere
  - Strong geomagnetic storms
    - Plasmapause moves closer to inner boundary of outer region
      - « Erosion » of the plasmasphere



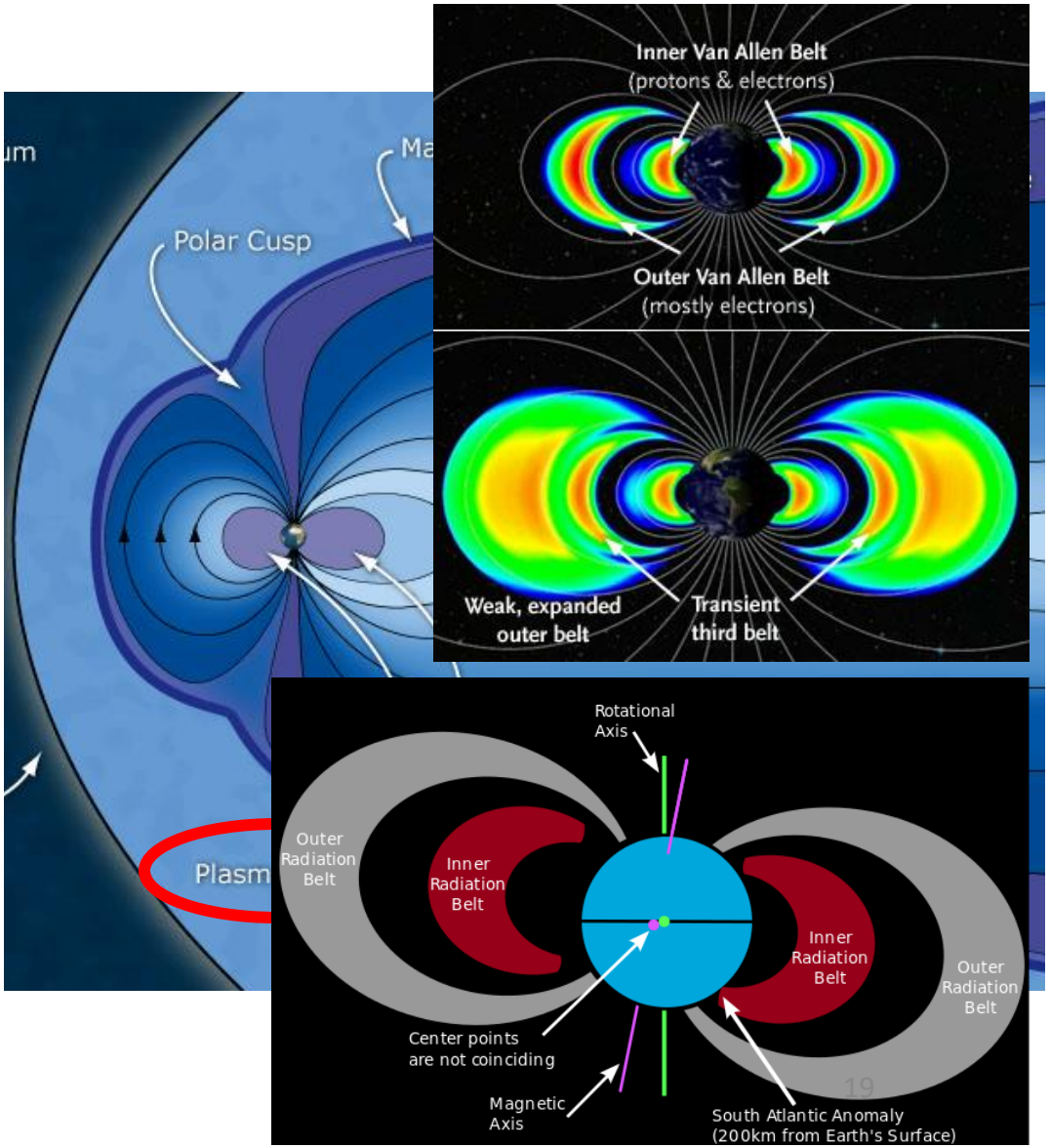
Main features

- Radiation belts
  - Outer belt
    - Mostly electrons (e^-)
    - 0.1-10 MeV
    - 3-8 earth radii
  - Inner belt
    - Mostly protons (p^+)
    - 10-500 MeV
    - 1.2-2 earth radii
  - Separated by slot region
  - Strong geomagnetic storms
    - Injection of > 15MeV p^+ and > 3MeV e^- which can reach all the way down into the Inner Radiation Belt



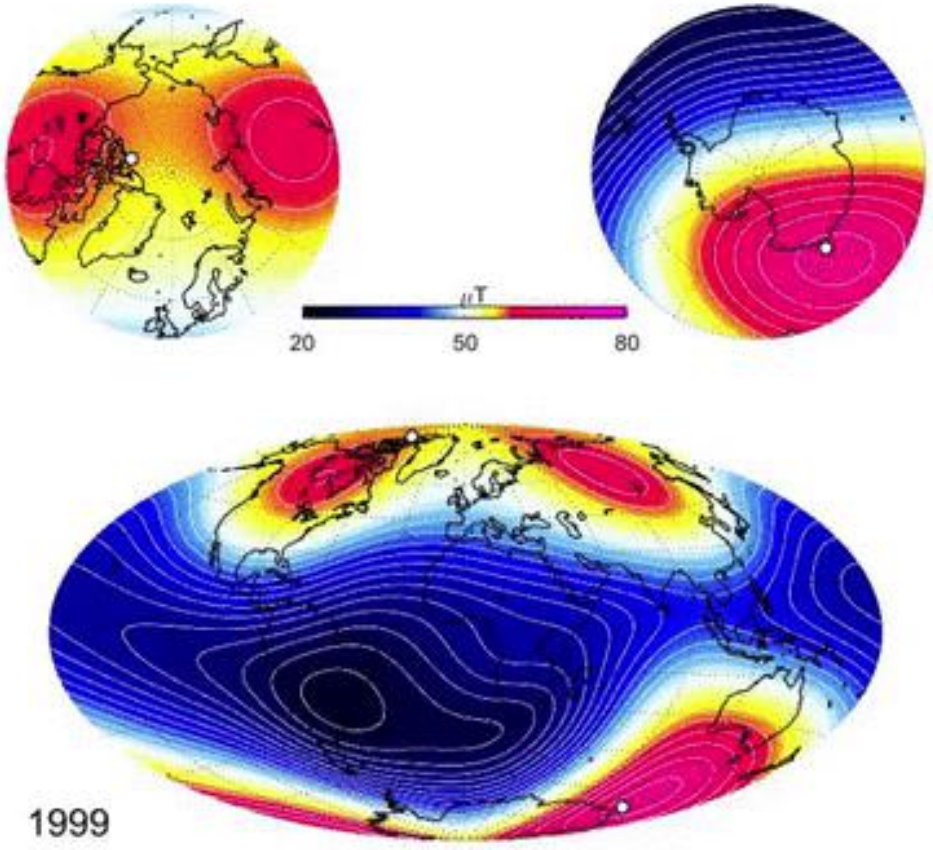
Main features

- Radiation belts
  - Strong geomagnetic storms
    - …/…
    - Creation of a third radiation belt during several days
  - South Atlantic Anomaly (SAA)
    - Extension of Inner belt closest to Earth
      - altitude: 200 km
      - Over Brazil
        - » Drift westward at 3°/decade



Main features

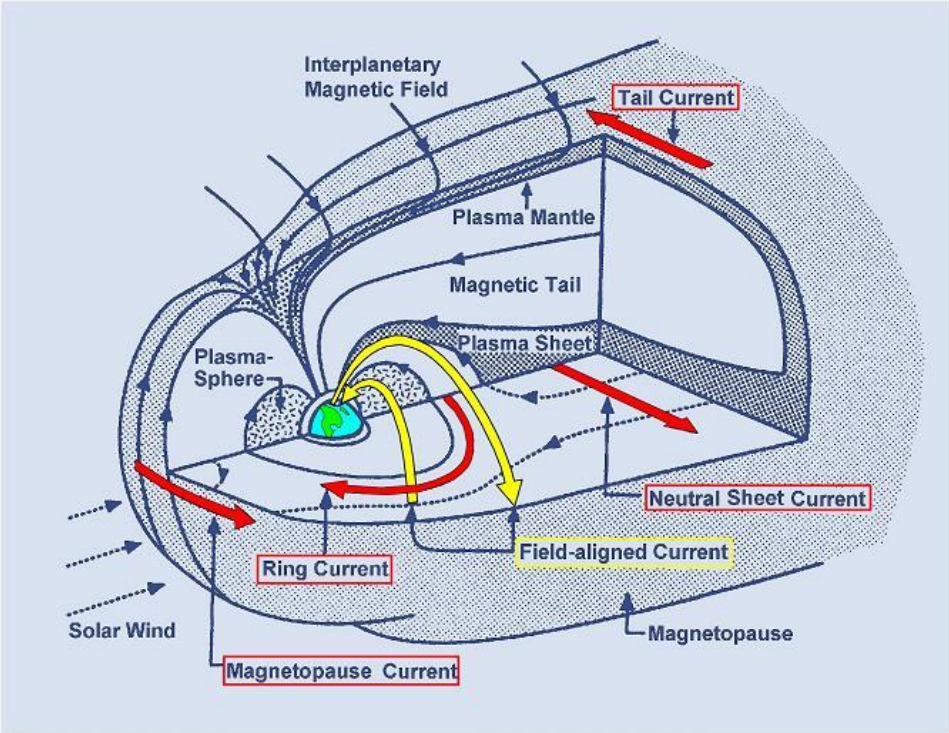
South Atlantic Anomaly (1999-2016) by SWARM



ESA / DTU Space

Main features

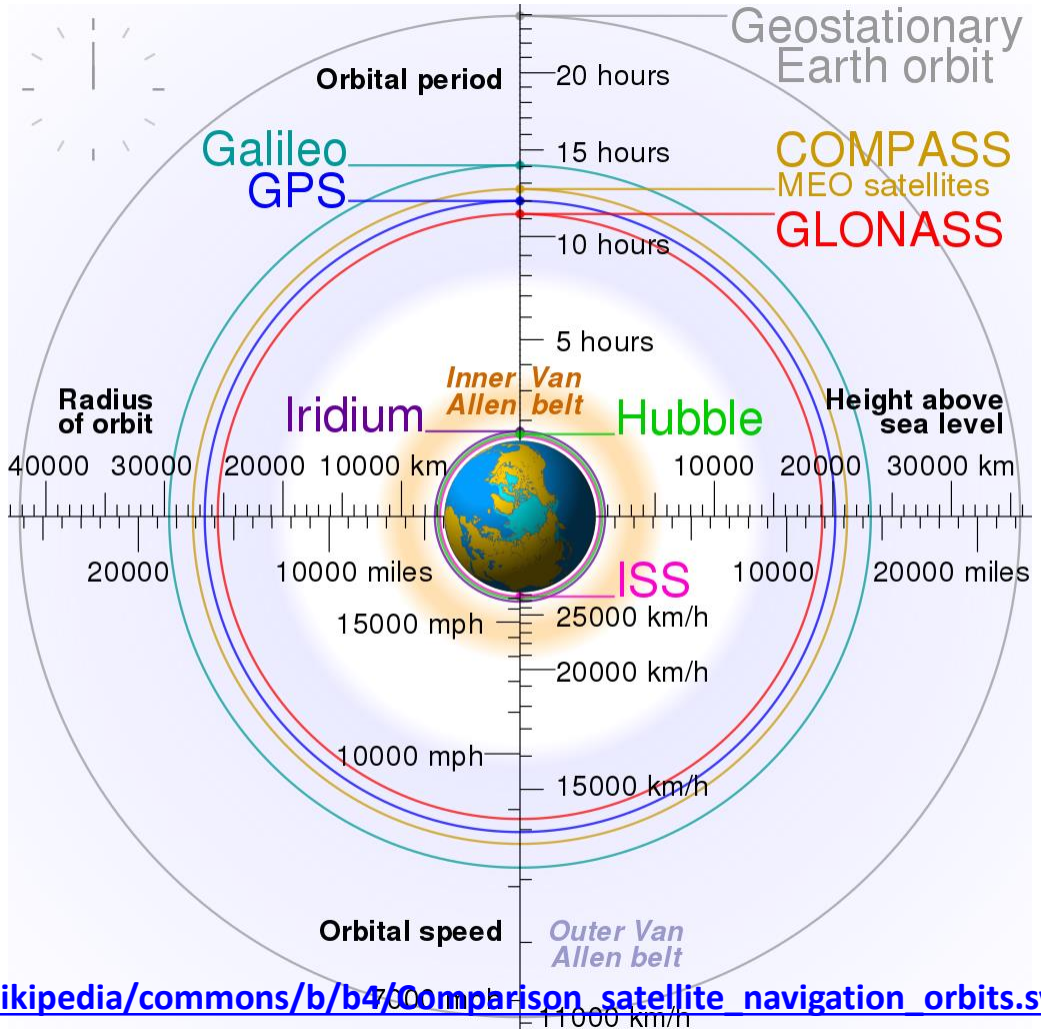
- Magnetospheric Currents
  - Magnetopause current
  - Ring current
  - Field-Aligned Current (FAC)
  - Neutral sheet current
  - Tail current



Main features

- Satellite Earth orbits

ORBIT NAME	ORBIT INITIALS	ORBIT ALTITUDE (KM ABOVE EARTH'S SURFACE)
Low Earth Orbit	LEO	200 - 1200
Medium Earth Orbit	MEO	1200 - 35790
Geosynchronous Orbit	GSO	35790
Geostationary Orbit	GEO	35790
High Earth Orbit	HEO	Above 35790



https://upload.wikimedia.org/wikipedia/commons/b/b4/Comparison_satellite_navigation_orbits.svg

Main features

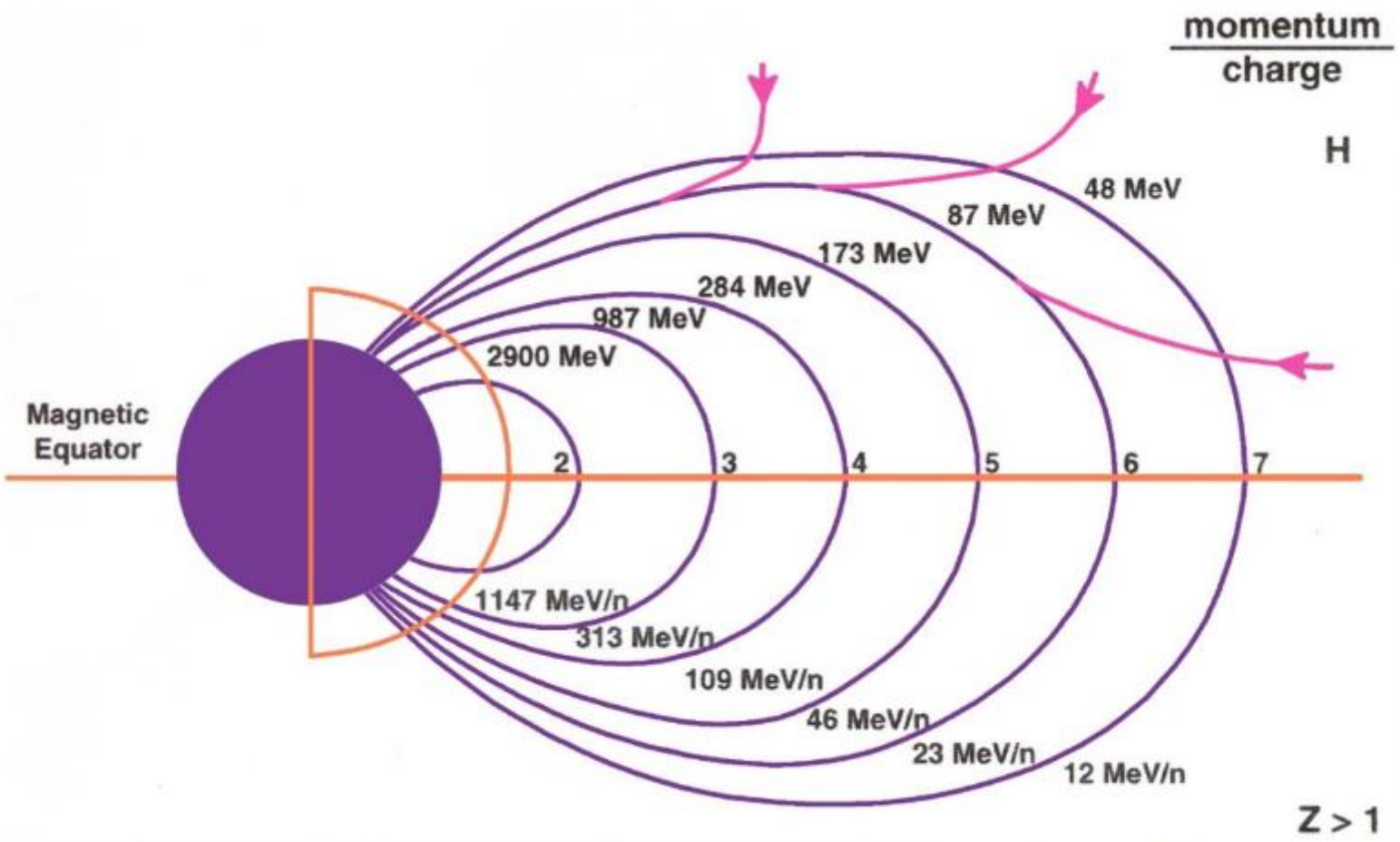
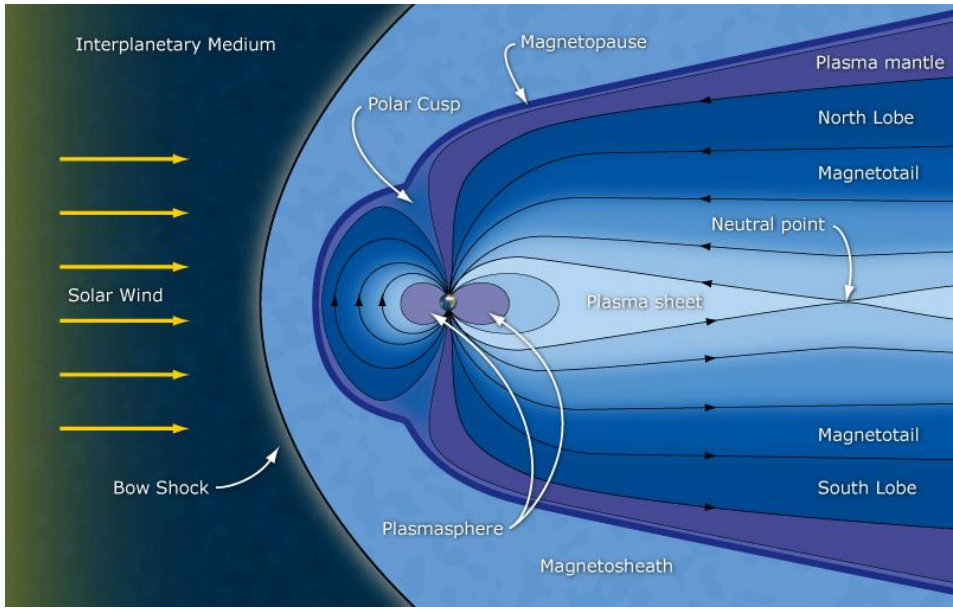


Figure 66: L-shell contours with rigidity imposed energy penetration limits.

Exercise: Magnetosphere

- The magnetosphere
  a. Stretches all the way to the bow shock
  b. Stretches all the way to the magnetopause
  c. Contains only specific areas such as the radiation belts



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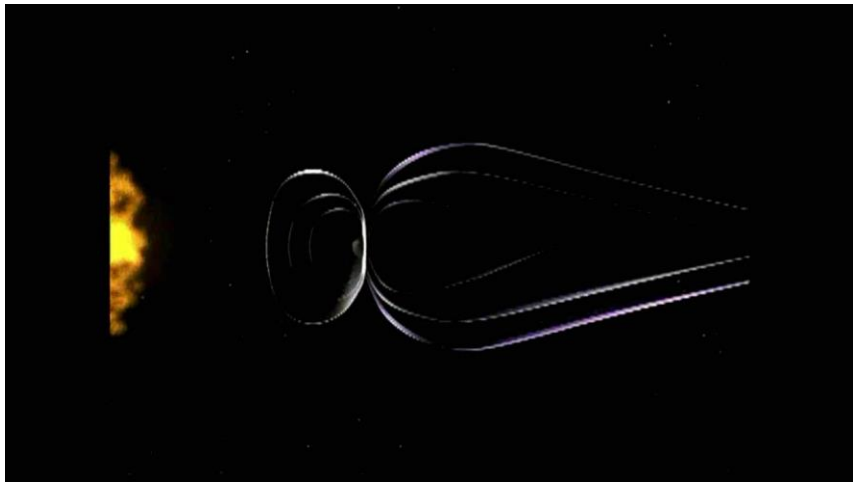
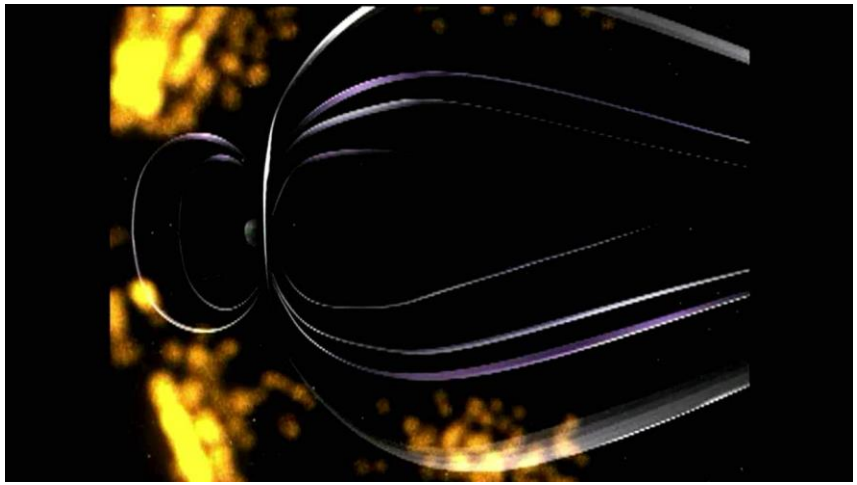
Geomagnetic (sub)storm

- Growth phase
  - Reconnection at magnetopause
    - Magnetic erosion
  - Open field lines are swept back into magnetotail
    - Some particles get access via cusps
    - Building of magnetic flux in magnetotail



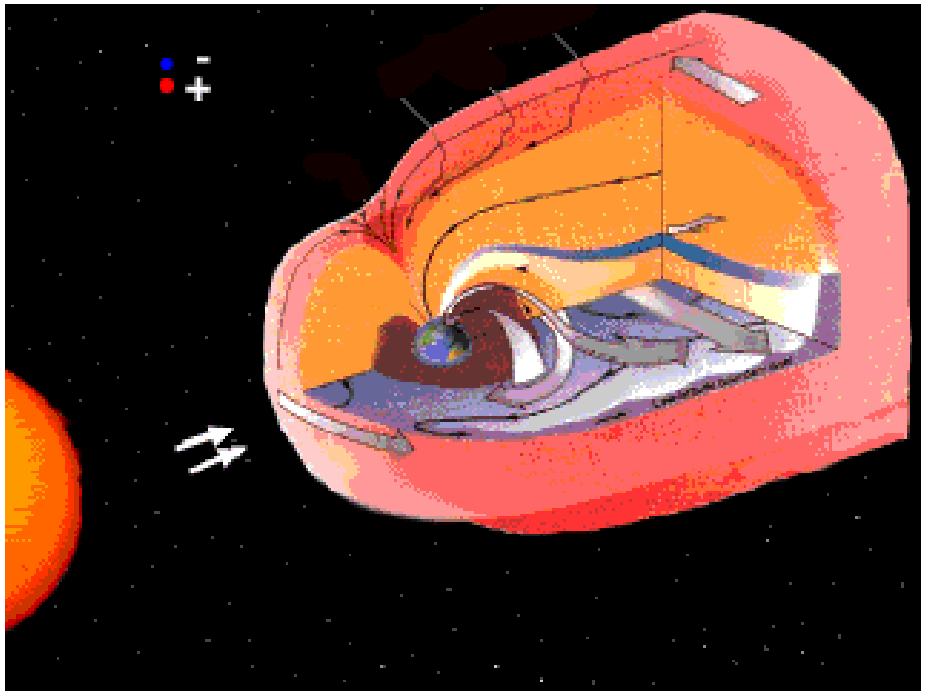
Geomagnetic (sub)storm

- Expansion phase
  - Explosive release of built-up energy in magnetotail
    - Particles get accelerated to Earth
      - Aurora, Ring current enhancement,…
    - A plasmoid gets ejected tailward back into solar wind



Geomagnetic (sub)storm

- In summary
  - Growth phase
    - Reconnection at magnetopause
  - Expansion phase
    - Reconnection in near-tail
    - Particle acceleration
  - Recovery phase
- 4 to 5 substorms / day
  - Energy input of 30-60’
  - 2-3 hours each
- If energy input > 3 hrs
  - Development of geomagnetic storm



Exercise: Geomagnetic (sub)storms

- In the magnetosphere, magnetic reconnection can take place:
  a. Near the magnetopause
  b. In the plasmasheet
  c. In the plasmasphere
  d. In the Van Allen radiation belts

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Geomagnetic indices

- Measure for geomagnetic unrest
- Ground-based magnetometer networks
  - Intensity and changes in intensity of the geomagnetic field
  - Corrected for diurnal and seasonal variations (quiet Sun)

The K index is derived from the amplitude of the variations of the field's horizontal components (the H and D pair, or alternatively, the X and Y components) after subtracting the daily solar regular (S_R) variation for the particular component (cf. **Fig.2**).

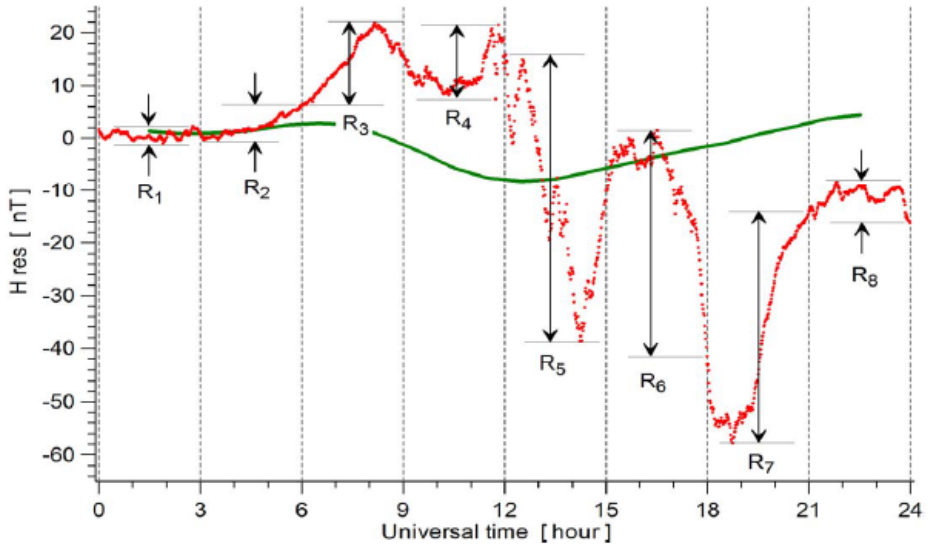


Fig.2. Calculation of the 3-hour K index over a 24 hour period. A daily record of 1-min measurements of the H component is presented here to illustrate the elimination of the solar regular variation, the S_R curve (the solid line), and the consequent determination of the 8 ranges (R_i, i=1,8). The difference between the upper (maximum) and lower (minimum) envelopes that are parallel to the S_R curve, determines the disturbance range within every 3-hour interval.

Geomagnetic indices

K index

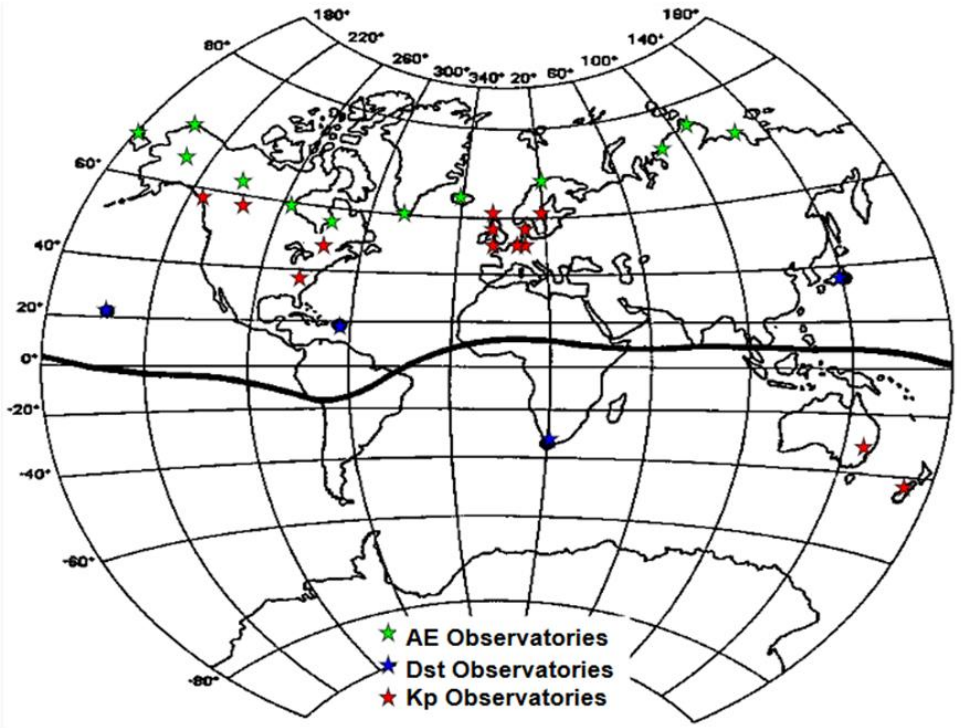
- Kennziffer
- Local
  - E.g. Dourbes
- Quasi-logaritmic scale
- Expressed in full units
  - 0, 1, … , 9
- 3hrs interval
  - 0-3UT, … , 21-24UT
  - 1hrs possible (Dourbes)

Kp index

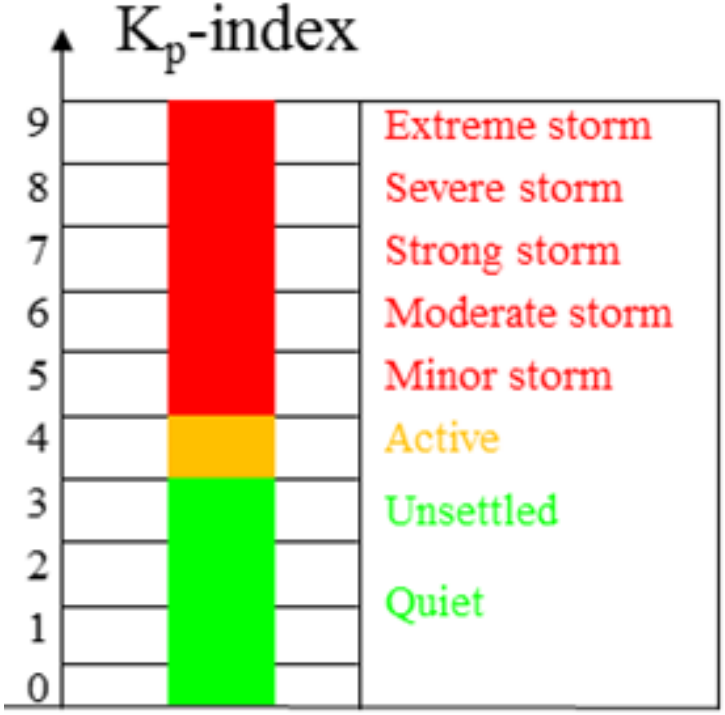
- Planetarische Kennziffer
- From network
  - 13 observatories (subauroral)
- Quasi-logaritmic scale
- Expressed in 1/3
  - 0o, 0+, … => … , 9-, 9o
- 3hrs interval
  - 0-3UT, … , 21-24UT
- Used in NOAA scales (G)
  - Auroral visibility maps
- Estimated Kp
- Going back to 1932

Geomagnetic indices

- Observatories



- Nomenclature



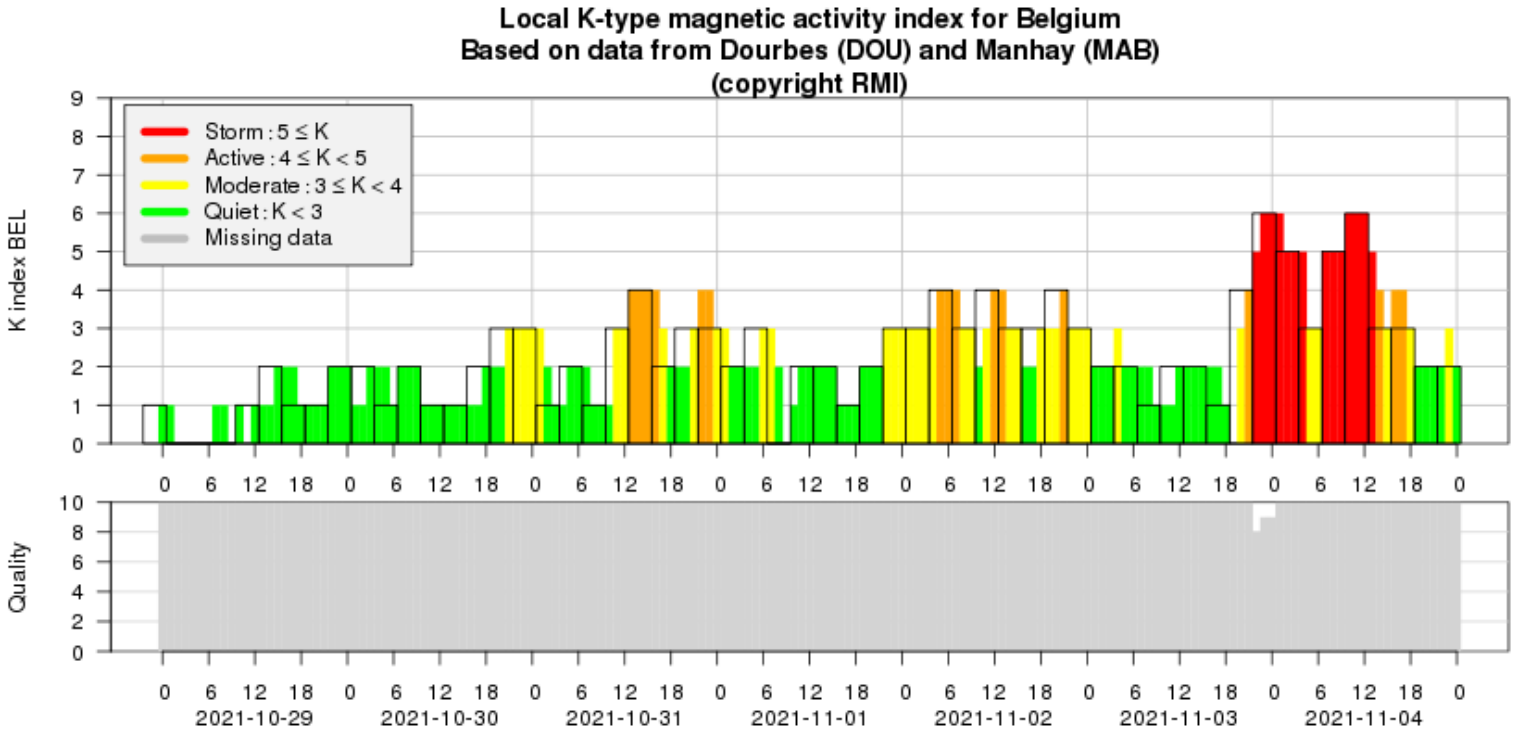
Geomagnetic indices

- NOAA-scales: G-scale

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme		Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe		Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong		Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate		Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor		Kp = 5	1700 per cycle (900 days per cycle)

Geomagnetic indices

- RMI Geophysical Centre of Dourbes
  - $K_{BELGIUM}$, 2 local K-indices (Dourbes, Manhay)



RMI: Royal Meteorological Institute

Geomagnetic indices

- Ap, ap
  - Derived from Kp
  - Required for daily averaging
  - « ap » value per interval (Kp)
    - Ap is the average of the 8 ap values for that day
  - Unit: nT

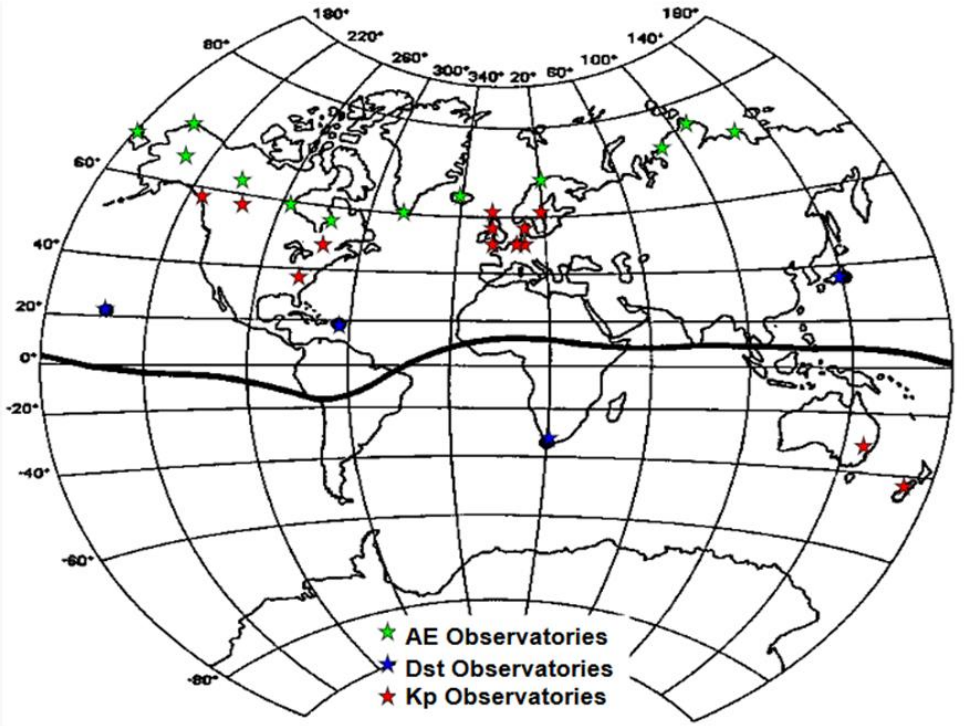
- aa
  - Derived (weighted average) from K indices from 2 antipodal , subauroral stations
    - Canberra
    - Hartland
  - Unit: nT
  - Going back to 1868
    - One of the oldest indices

Kp	0o	0+	1-	1o	1+	2-	2o	2+	3-	3o	3+	4-	4o	4+
ap	0	2	3	4	5	6	7	9	12	15	18	22	27	32

Kp	5-	5o	5+	6-	6o	6+	7-	7o	7+	8-	8o	8+	9-	9o
ap	39	48	56	67	80	94	111	132	154	179	207	236	300	400

Geomagnetic indices

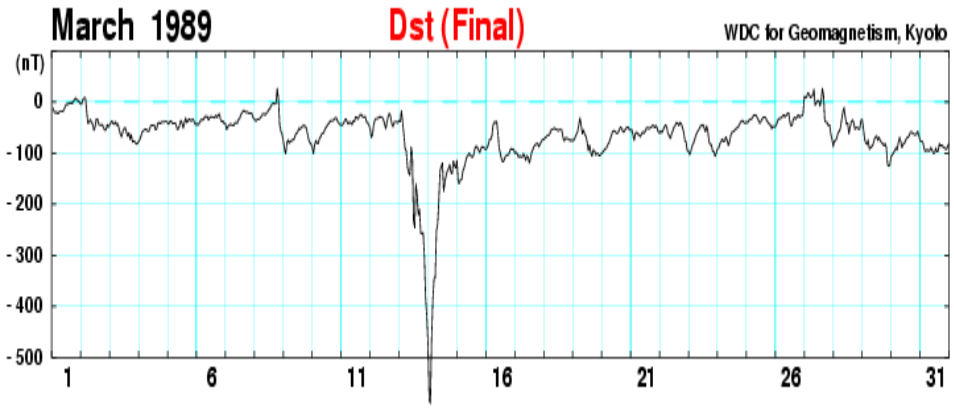
- Dst
  - Storm-time Disturbance index
    - Severity of magnetic storms
  - Depression of the intensity of the H-component
    - Westward current
      - Related to changes in the ring current
  - Measured by 4 stations close to magnetic equator
    - But not too close…



Geomagnetic indices

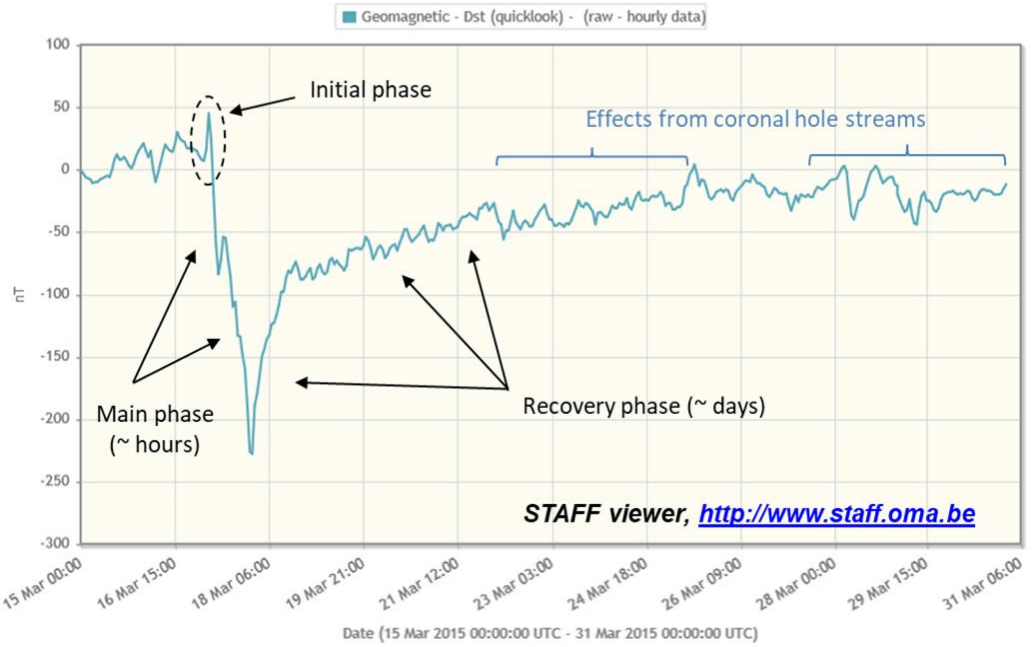
- Dst
  - Hourly measurements
  - Unit: nT
    - NOT a range index
  - Nomenclature
    - > -30 nT: Quiet
    - -30 - -50 nT: Weak storm
    - -50 - -100 nT: Moderate storm
    - -100 - -250 nT: Intense storm
    - < -250 nT: Extreme storm
    - See also https://www.stce.be/educational/classification

- Real-time monitoring at Kyoto, WDC (World Data Center)
  - http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html



Geomagnetic indices

- Dst
  - Phases of a geomagnetic storm
    - Initial phase
    - Main phase
    - Recovery phase
  - Most intense storms of SC24
    - 17 March 2015 (-234 nT)
    - 23 Jun 2015 (-198 nT)
  - Most intense storms of SC25
    - *27 February 2023 (-132 nT)*
    - *23-24 March 2023 (-163 nT)*
    - *23-24 April 2023 (-213 nT)*
    - *5 November 2023 (-172 nT)*
  - Extreme storms
    - 30 Oct 2003: -383 nT
    - 14 Mar 1989: -589 nT



:Issued: 2024 Mar 17 1231 UTC
:Product: documentation at http://www.sidc.be/products/tot
#---#
DAILY BULLETIN ON SOLAR AND GEOMAGNETIC ACTIVITY from the SIDC
#---#
SIDC URSIGRAM 40317
SIDC SOLAR BULLETIN 17 Mar 2024, 1231UT
SIDC FORECAST
SOLAR FLARES : M-class flares expected (probability >=50%)
GEOMAGNETISM : Quiet (A<20 and K<4)
SOLAR PROTONS : Quiet
PREDICTIONS FOR 17 Mar 2024 10CM FLUX: 144 / AP: 007
PREDICTIONS FOR 18 Mar 2024 10CM FLUX: 146 / AP: 007
PREDICTIONS FOR 19 Mar 2024 10CM FLUX: 148 / AP: 007

Finding your way in the URSIgram

Solar Active Regions and flaring: There are five active regions visible on the solar disk. They all have simple beta or alpha magnetic field configuration and produced minor C-class flaring. The main activity in the last 24 hours has been observed from active regions behind the east limb, that will rotate into view in the next hours. The strongest was an M3.5 flare peaking at 16:35 UTC on 16 March, from a region not yet visible, located behind the east limb. As these regions rotate into view, we expect more M-class and possible X-class flares in the next 24 hours.

Coronal mass ejections: There was a partial halo CME (angular width about 180 degrees) directed towards the south, first seen at 03:24 UTC by LASCO C2. This CME originates from a filament eruption in the southern hemisphere. Since the filament was located close to the disk center, an ICME may arrive to the Earth on 20-21 March (a better estimation will be given when more data become available).

Solar wind: Solar wind: The Earth is inside slow solar wind, with speeds close to 350 km/s and an interplanetary magnetic field around 5 nT. Similar conditions are expected for the next 24 hours.

Geomagnetism: Geomagnetic conditions were quiet both global and locally (NOAA_Kp up to 1 and K_BEL up to 1). Similar conditions can be expected for the next 24 hours.

Proton flux levels: The 10 MeV proton flux (measured by GOES-18) has come below the 10 pfu threshold, but remains elevated. It is expected that it will go back to low levels in the next 24 hours.

Electron fluxes at GEO: The greater than 2 MeV electron flux from GOES 16 was below the threshold level in the last 24 hours. It is expected to remain below the threshold during the next 24 hours. The 24h electron fluence was at normal level and is expected to remain so.

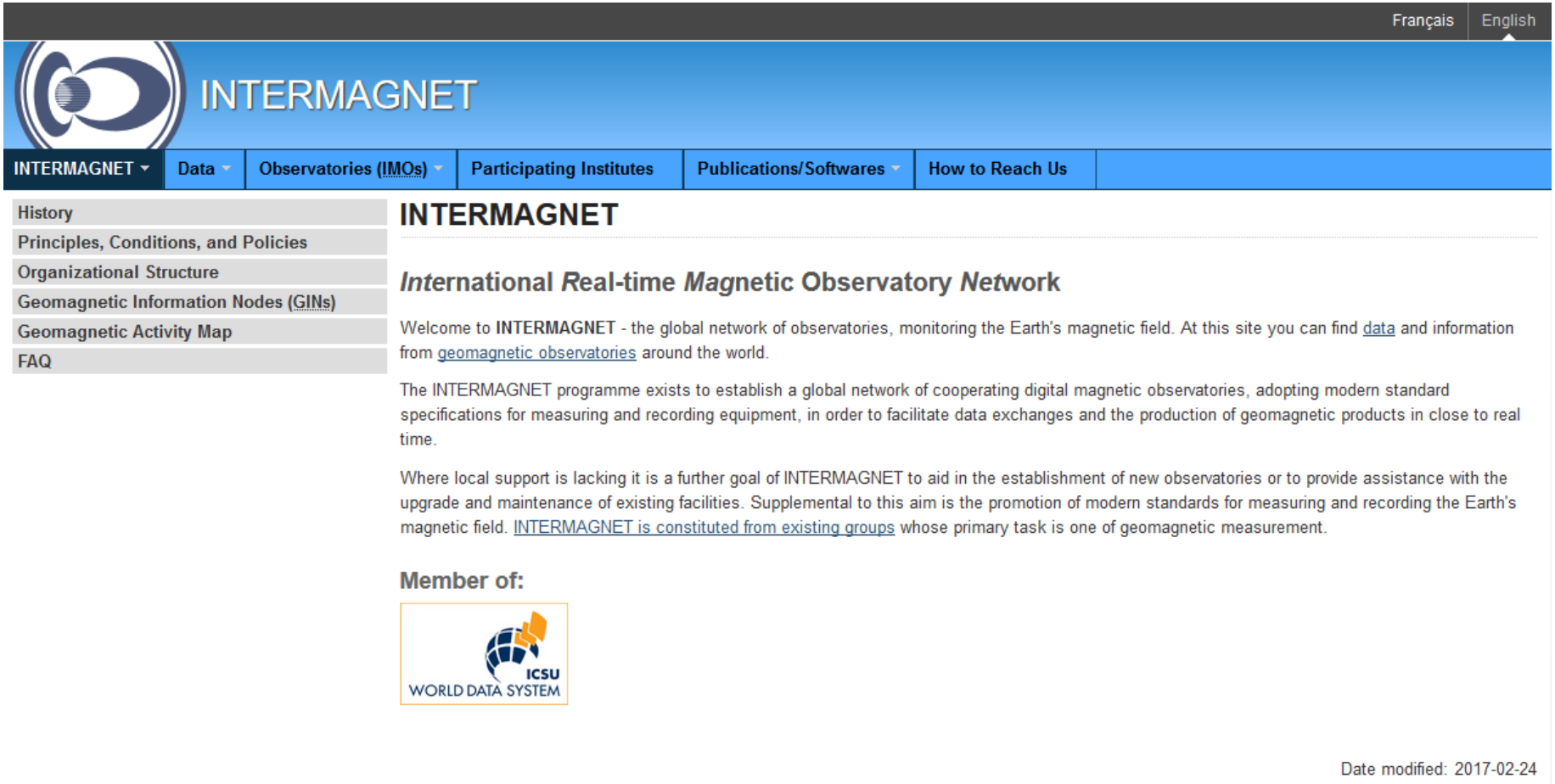
TODAY'S ESTIMATED ISN : 074, BASED ON 10 STATIONS.

Geomagnetic activity

SOLAR INDICES FOR 16 Mar 2024
WOLF NUMBER CATANIA : ///
10CM SOLAR FLUX : 144
AK CHAMBON LA FORET : 005
AK WINGST : 002
ESTIMATED AP : 002
ESTIMATED ISN : 058, BASED ON 23 STATIONS.

NOTICEABLE EVENTS SUMMARY
DAY BEGIN MAX END LOC XRAY OP 10CM Catania/NOAA RADIO_BURST_TYPES
16 1622 1635 1644 ////// M3.5 ///////
16 2127 2155 2211 ////// M1.1 ///////
END

Geomagnetic networks



The Magnetosphere - Contents

- The geomagnetic field
- Main features
- Geomagnetic (sub)storms
- Measuring magnetic fields
  - Geomagnetic indices
  - Networks
- Miscellaneous

Miscellaneous

- Seasonal variation
  - More geomagnetic storms during equinoxes than during solstices
  - Probable explanation by Russell & McPherron (1973)

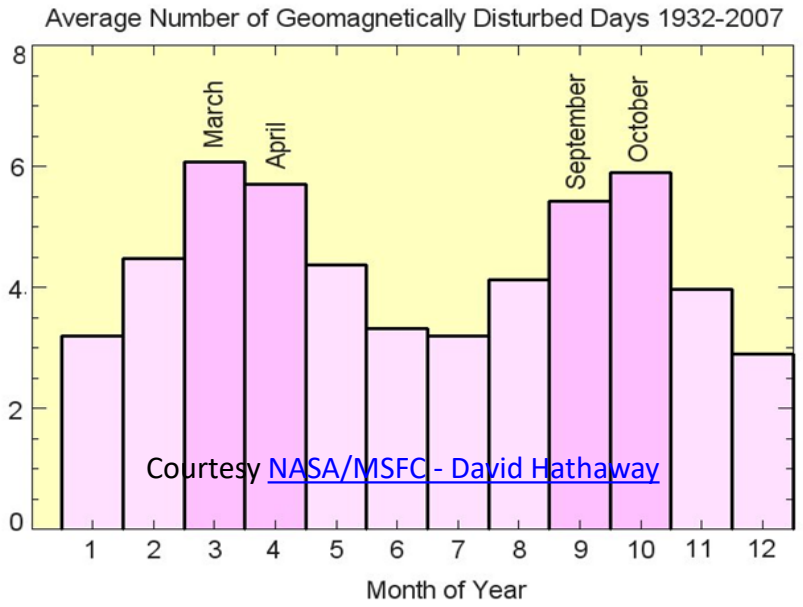
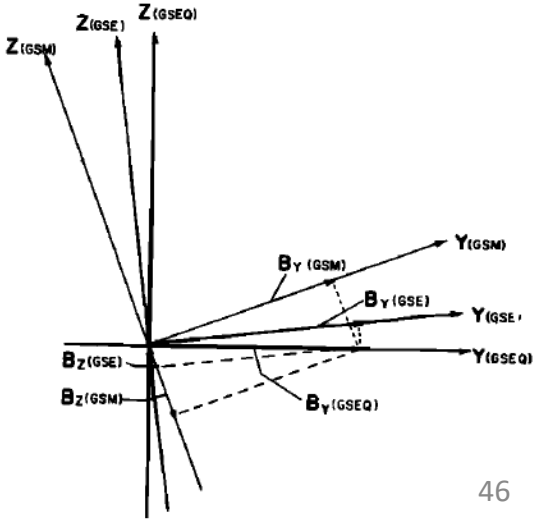
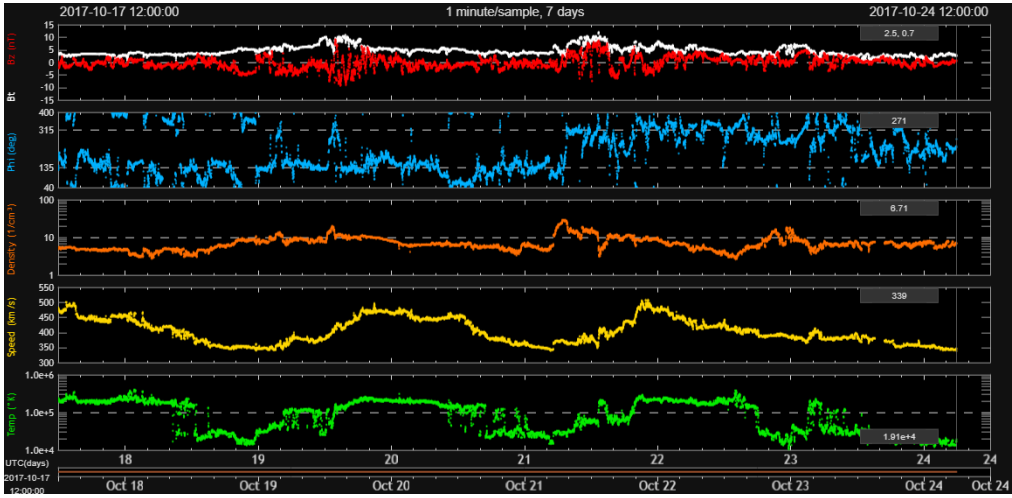


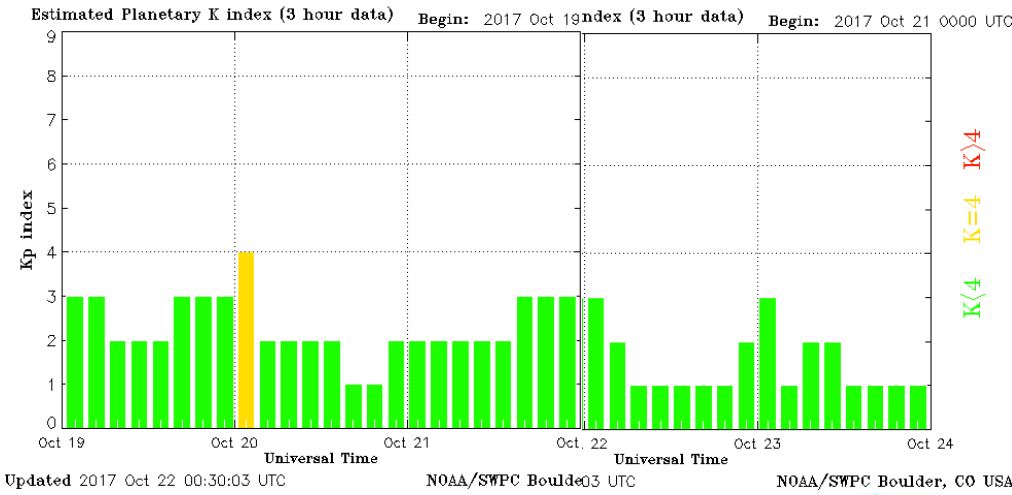
Fig. 4. One of the possible orientations of the *Y-Z* planes of the solar equatorial (GSEQ), solar ecliptic (GSE), and solar magnetospheric (GSM) coordinates, showing how a vector in the solar equatorial plane can have a southward (along the —*Z* axis) GSE and GSM component.



Miscellaneous

- **SNAP** effect
  - Concerns Coronal Holes
  - More intense storms
    - In **S**pring
      - From **N**egative pol. CHs
        - » Phi-angle towards the Sun (~315°)
    - In **A**utumn
      - From **P**ositive pol. CHs
        - » Phi-angle away from Sun (~135°)
  - Results from Russell-McPherron effect





Summary

- The magnetosphere
  - Has a drop-shape
    - Compressed at sunside, stretched at nightside
  - Contains several zones w/ particles of varying energies
    - Van Allen radiation belts,…
  - Protects us against high-energetic particles
- Geomagnetic storm
- The most often used geomagnetic indices are:
  - Kp, Ap, Dst