# SPACE WEATHER INTRODUCTORY COURSE

Collaboration of

**Solar-Terrestrial Centre of Excellence**

Koninklijke luchtmacht

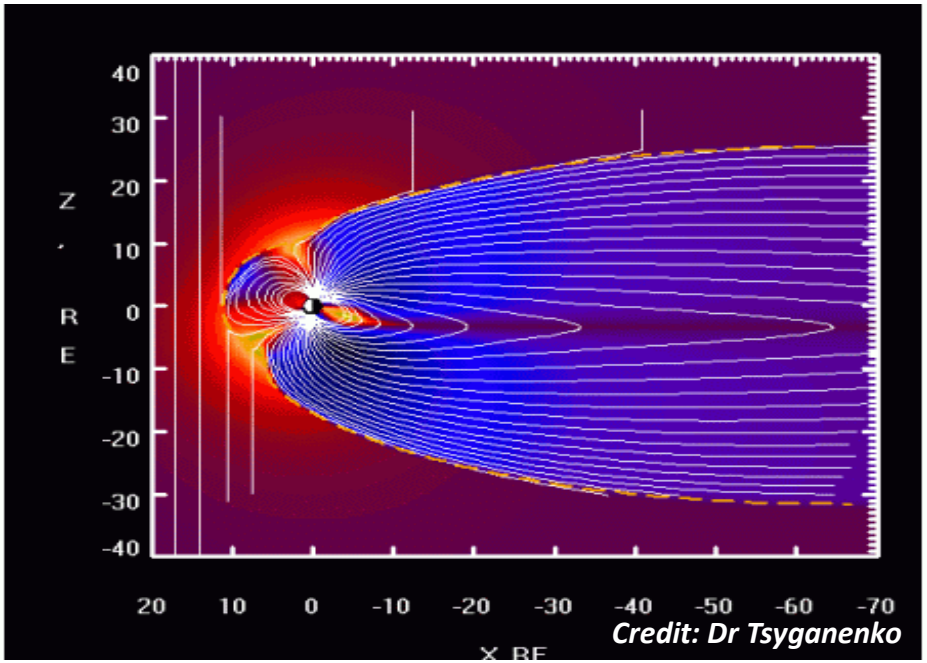
Koninklijk Nederlands
Meteorologisch Instituut
*Ministerie van Infrastructuur en Milieu*

# 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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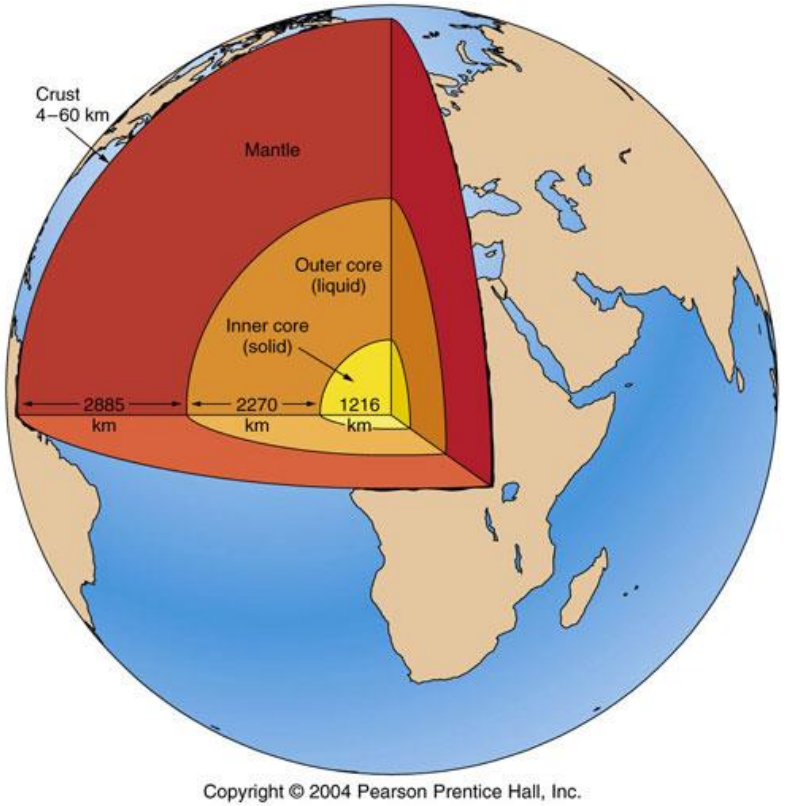
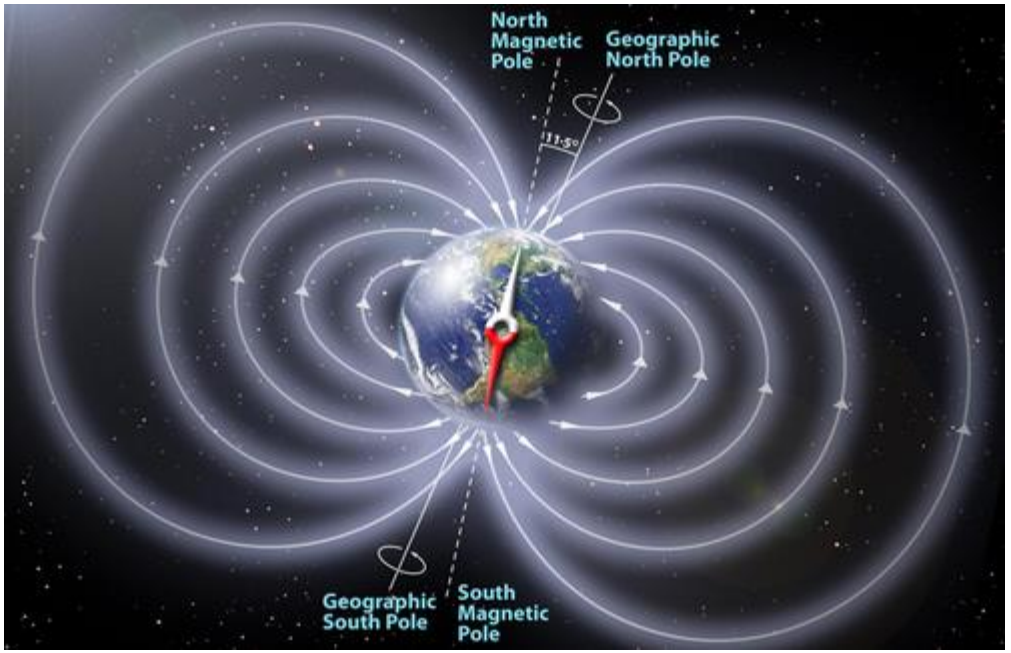
# The geomagnetic field

- Created in and by the Earth's interior



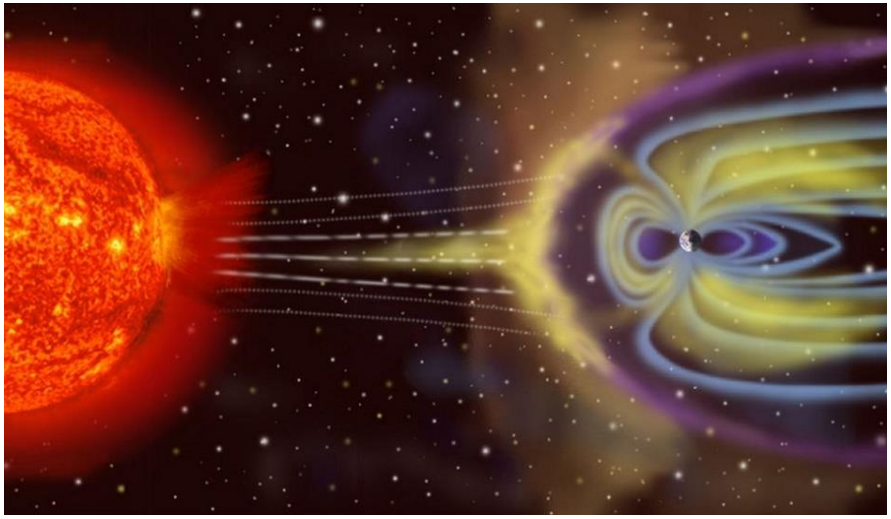
# The geomagnetic field

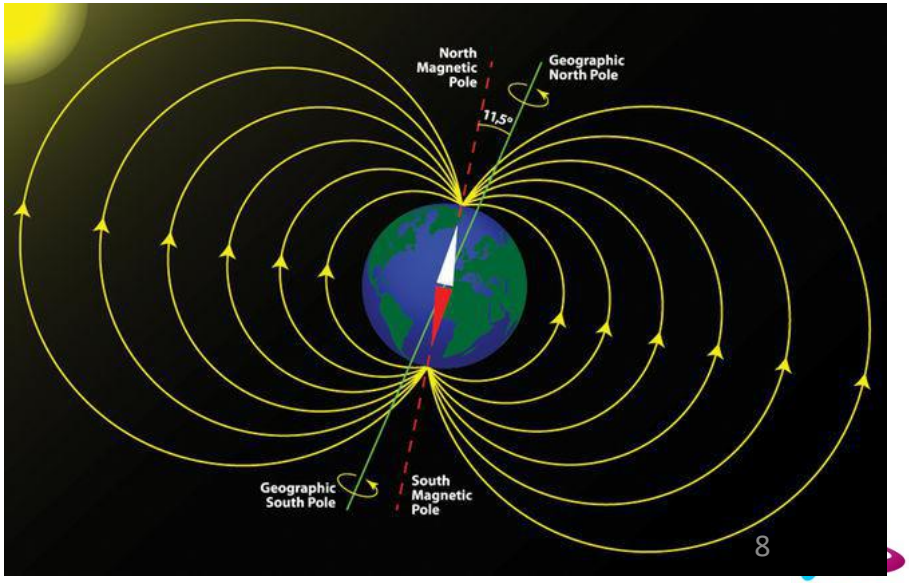
- Created in and by the Earth's interior
- Dipole *(not perfect)*
  - In absence of disturbances
  - Enters north pole (-), leaves at south pole (+)
  - Intensity:
    - 25000 – 65000 nT
    - Weakest at equator
    - Strongest at poles



# The geomagnetic field

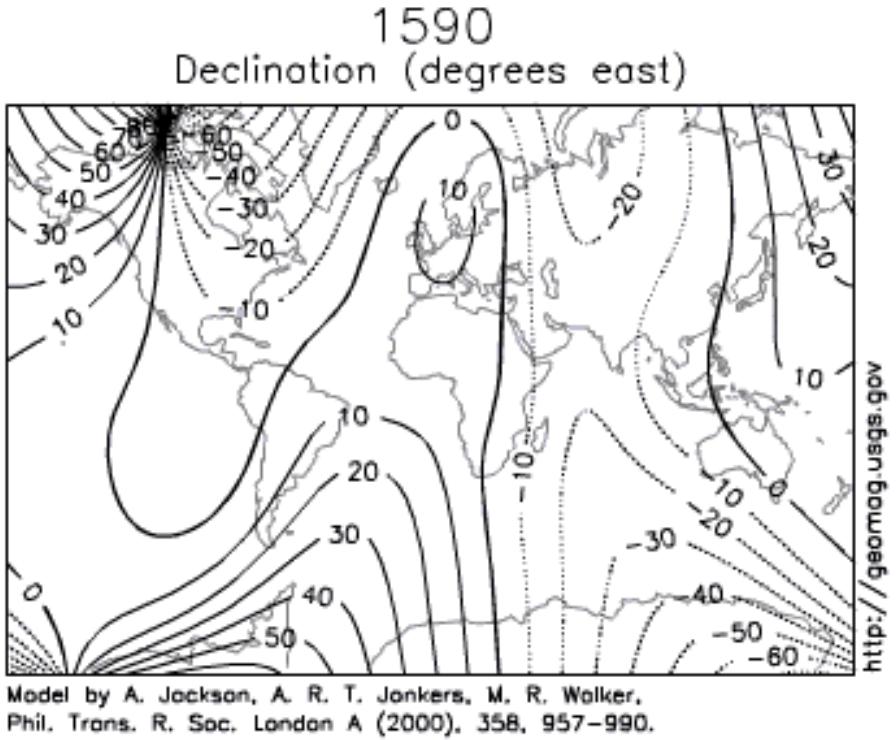
- Due to solar wind
  - Drop shape
    - 10 $R_E$ (earth radii) at dayside
    - >200 $R_E$ at nightside
- Magnetic axis
  - 11° tilt to Earth's rotational axis
    - Compass does NOT point to true north
  - 500 km offset to north
    - Weakness over Brazil



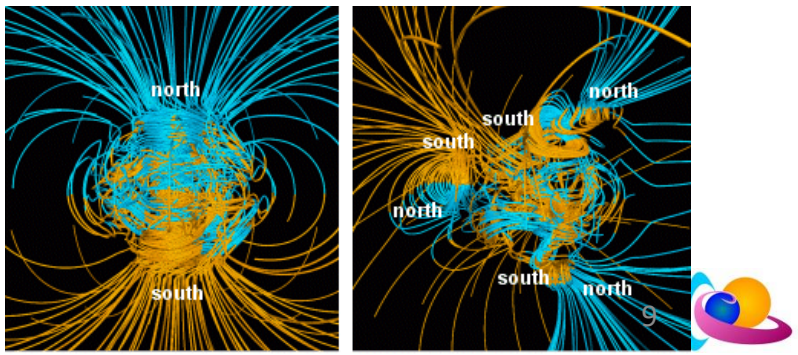


# The geomagnetic field

- 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.



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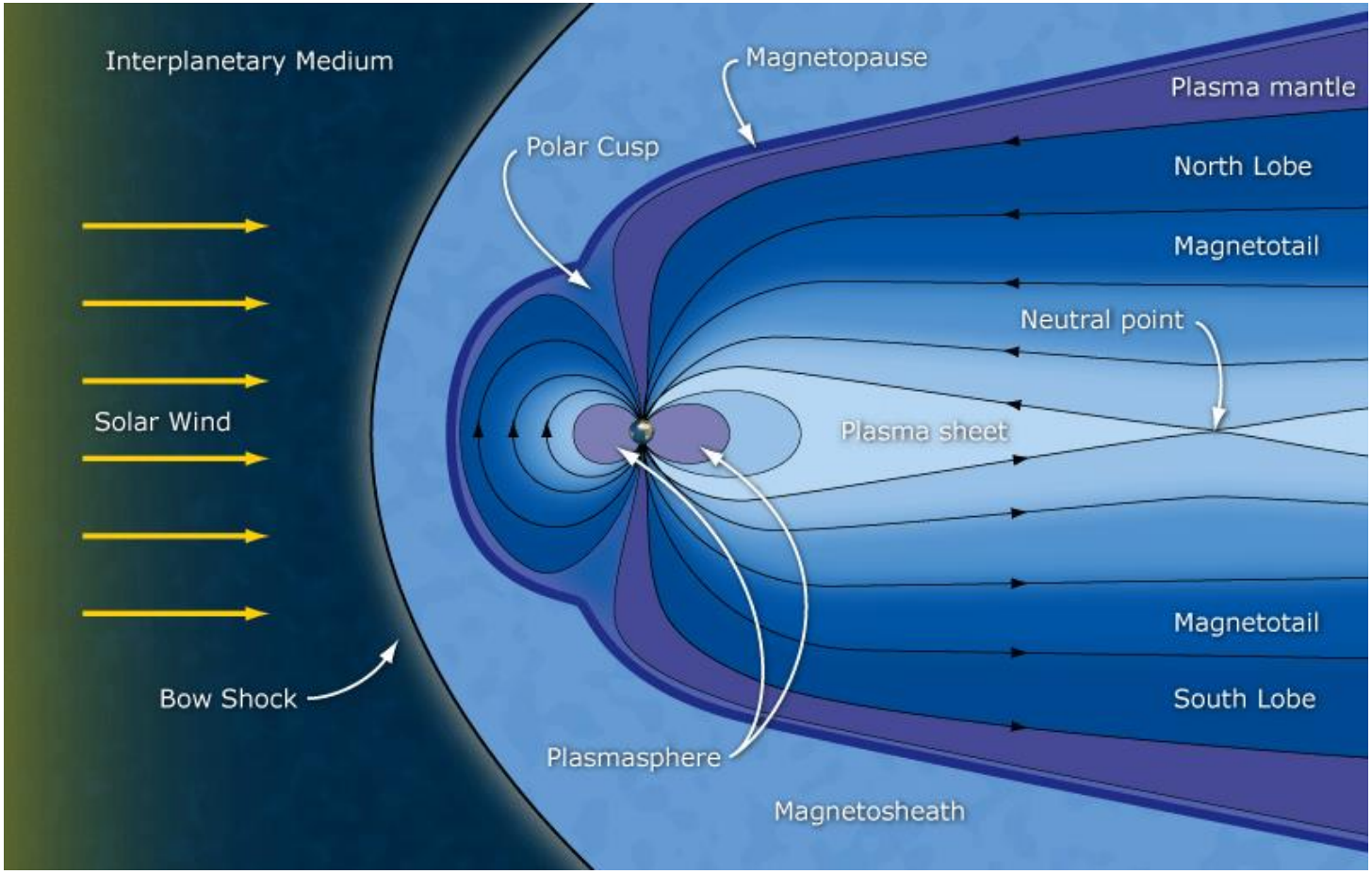
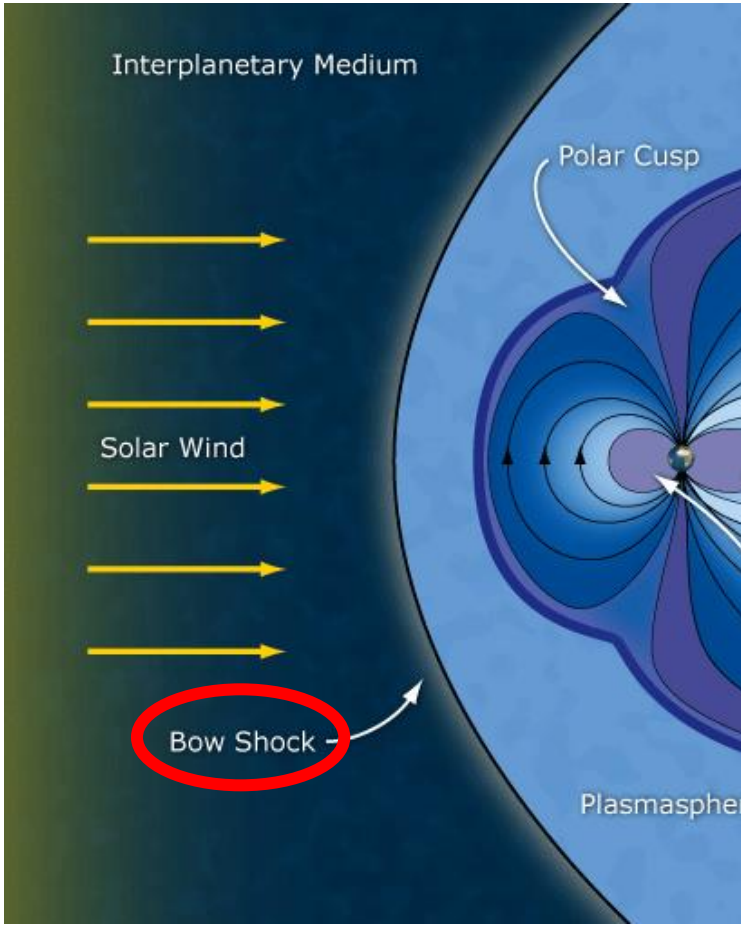
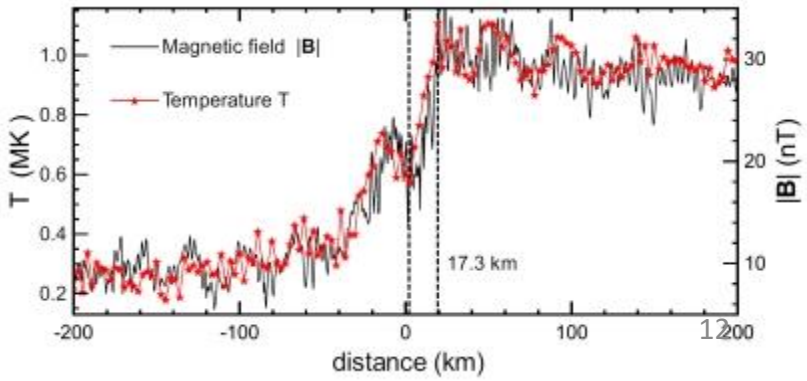
# Main features



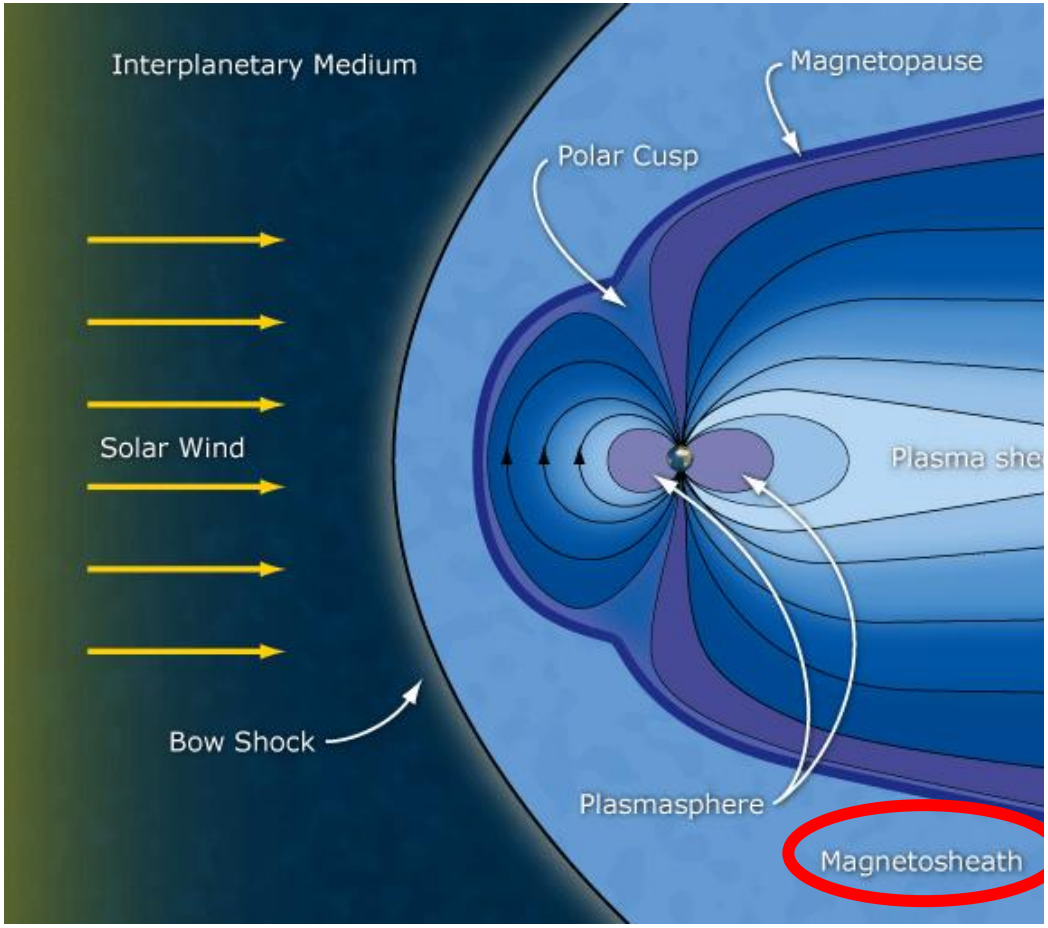
# Main features




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

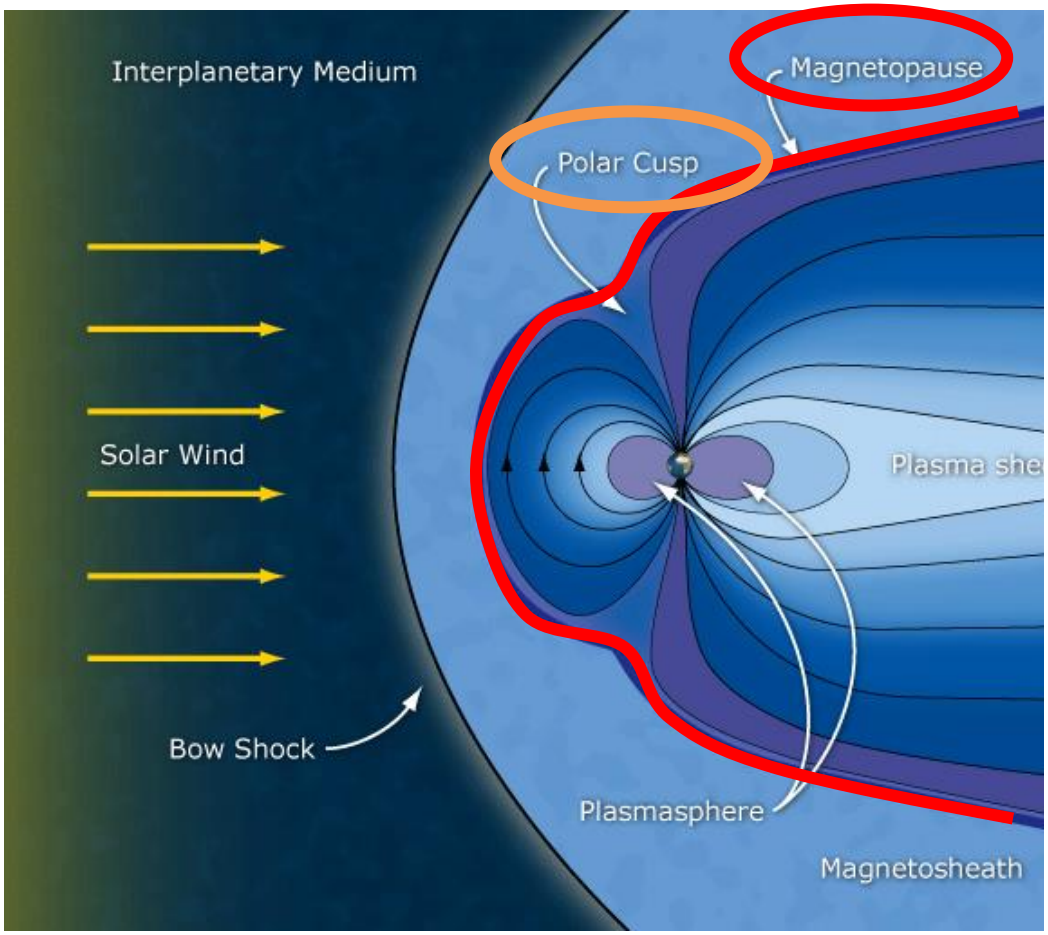


# Main features




- 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

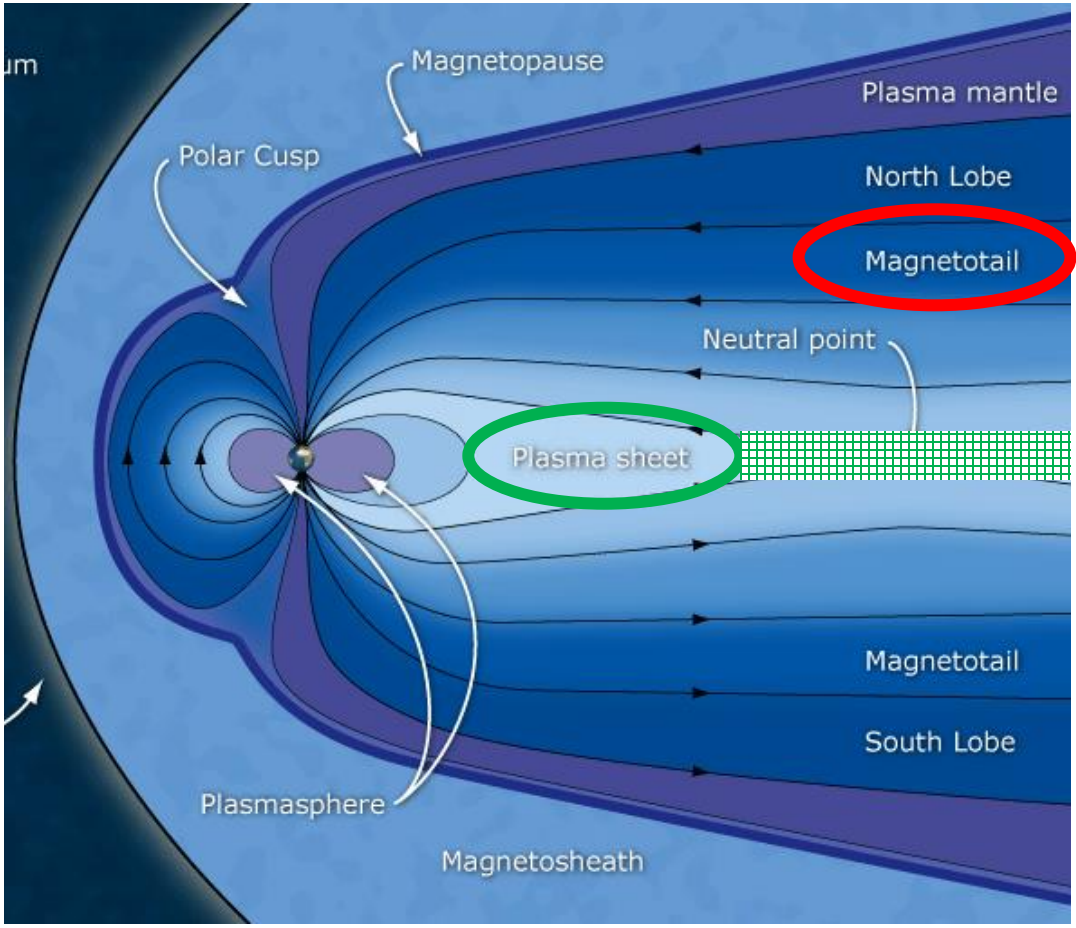



- Magnetopause
  - Sharp boundary
    - Pressure balance
    - = sum of magnetic + plasma pressure is constant
  - Earth vs. Solar Wind
  - Magnetic reconnection
    - Current sheet
  - Location:
    - 10-12 $R_E$ (6-15 $R_E$)
  - **Cusp**
    - Narrow regions of opened/merged MF lines
    - In/outflow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

$R_E$ : Earth radii ; MF: Magnetic Field

# Main features

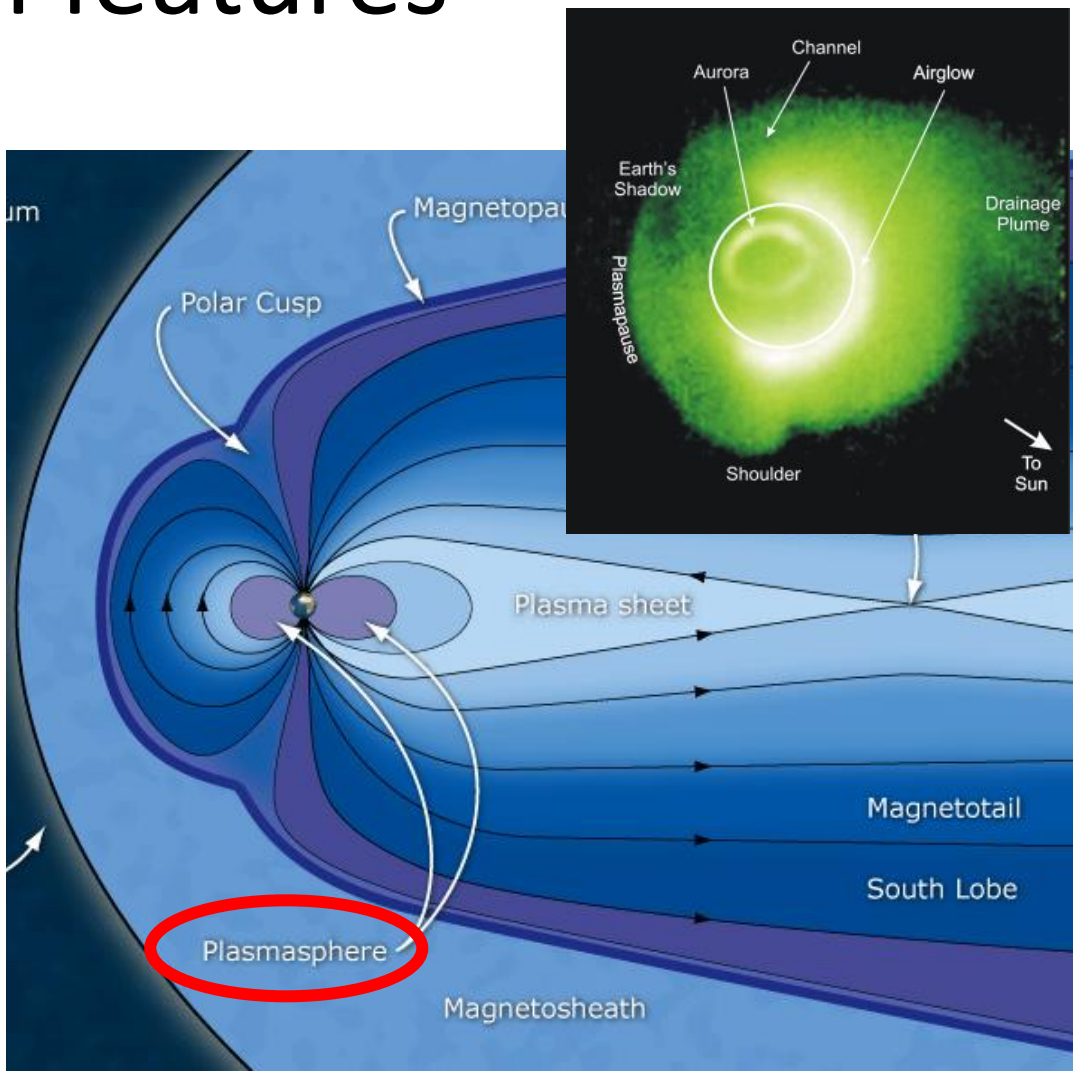
- Magnetotail
  - Several 100 $R_E$ long
  - Two lobes
    - Northern: MF points towards Earth
    - Southern: MF points away from Earth
  - Separated by **plasma sheet**
    - Reconnection closer to Earth during strong disturbances
      - Source of aurora




$R_E$ : Earth radii ; MF: Magnetic Field

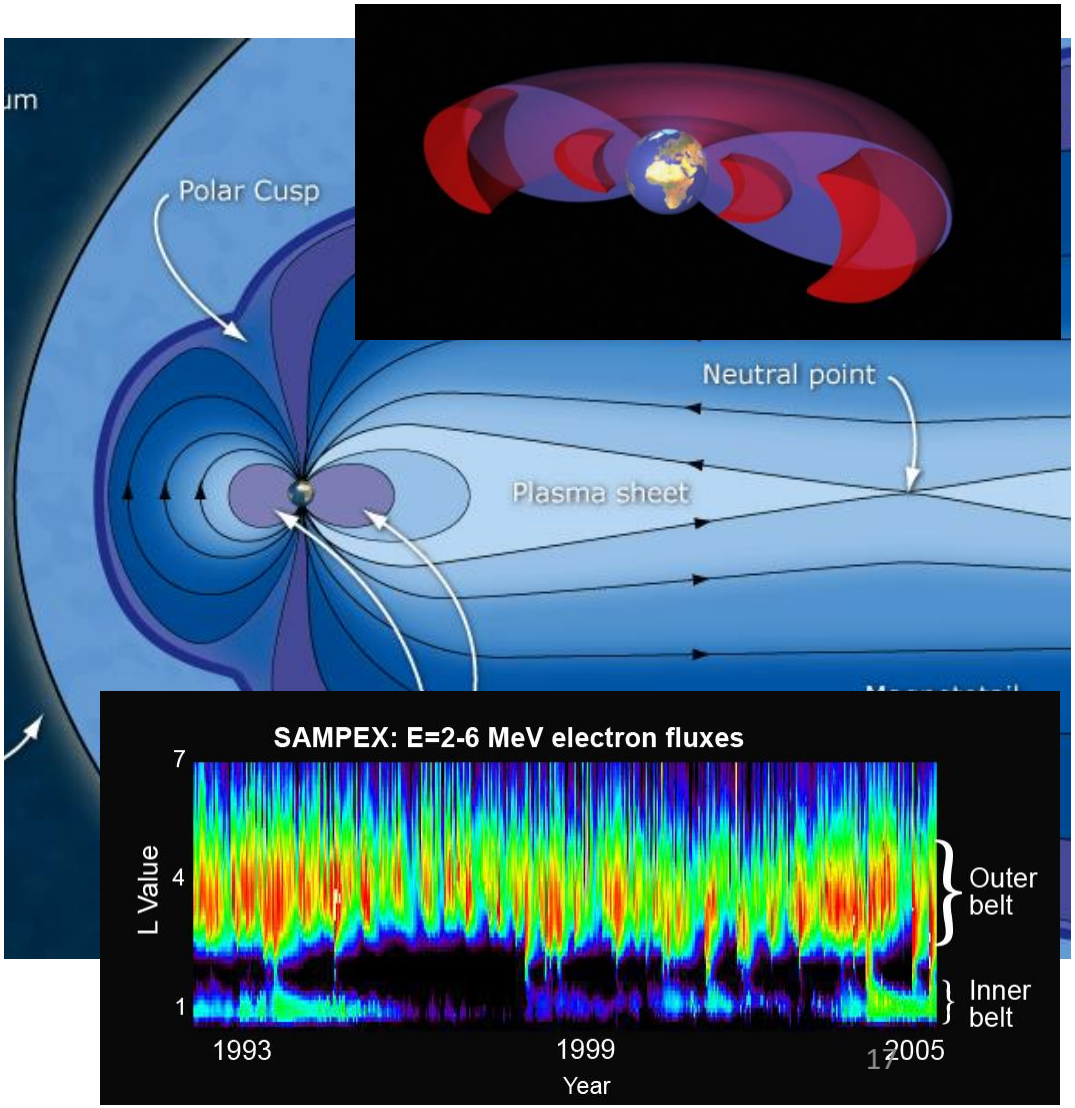
# Main features

- 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



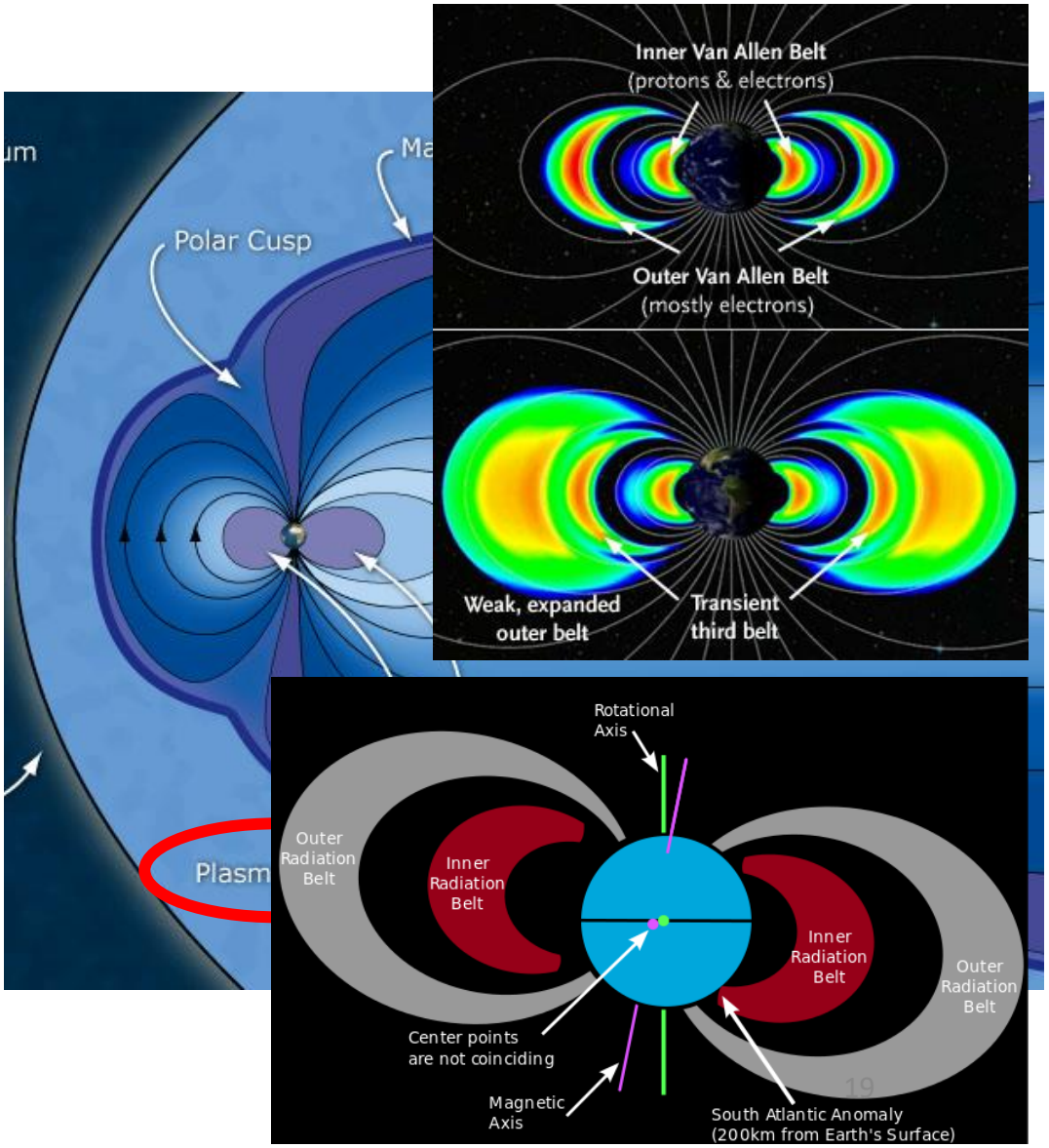
# Main features

- Radiation belts
  - Outer belt
    - Mostly electrons ($e^-$)
    - 0.1-10 MeV
    - 3-8 earth radii
  - Inner belt
    - Mostly protons ($p^+$)
    - 10-500 MeV
    - 1.2-2.5 earth radii
  - Strong geomagnetic storms
    - Injection of > 15MeV $p^+$ and > 3MeV $e^-$ which can reach all the way down into the Inner Radiation Belt



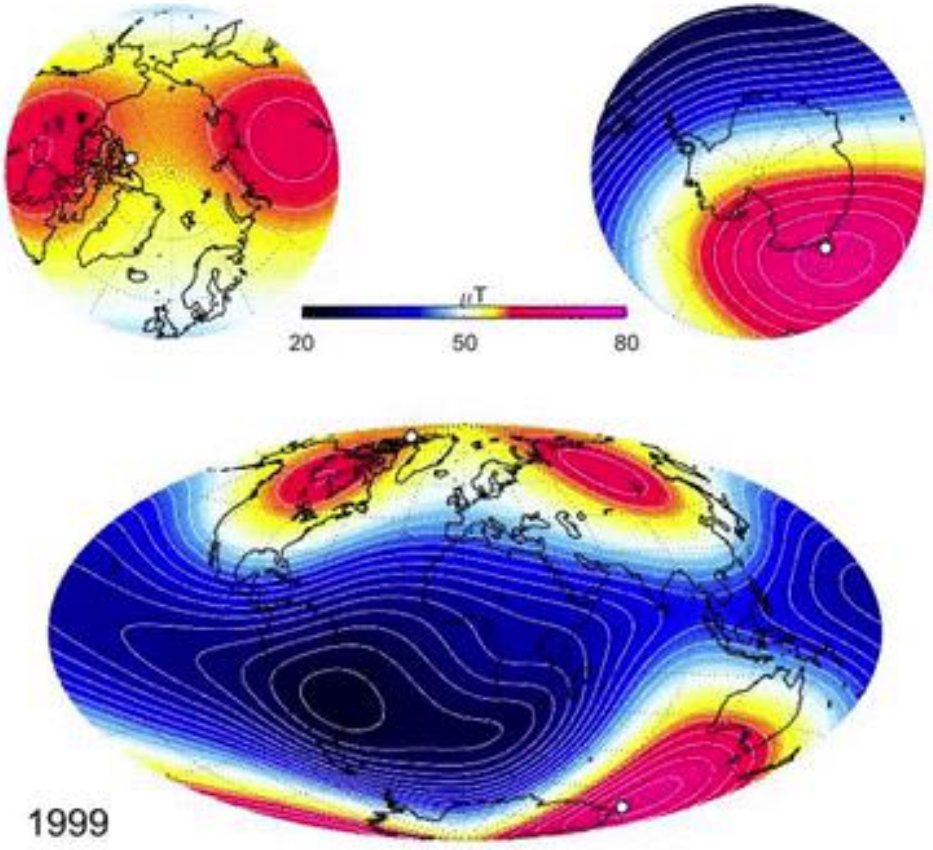
# Main features

- 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

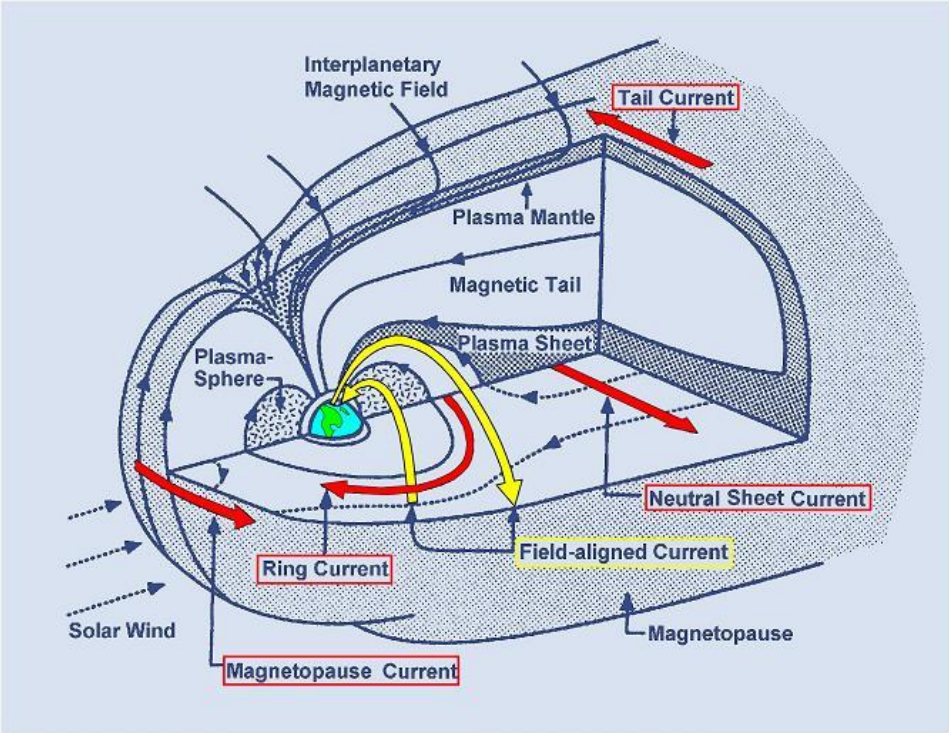
**South Atlantic Anomaly (1999-2016) by SWARM**




*ESA / DTU Space*

# Main features

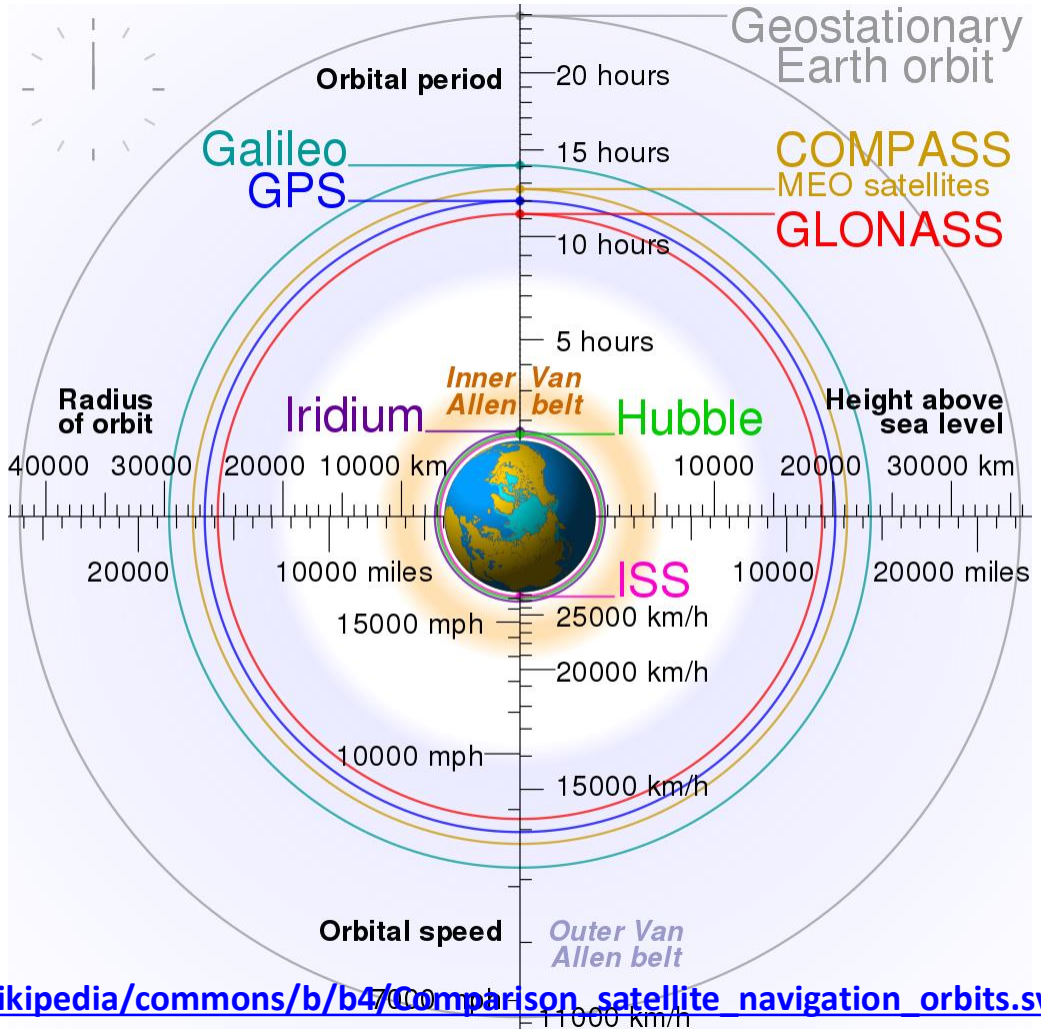
- Magnetospheric Currents
  - Magnetopause current
  - Ring current
  - Field-Aligned Current (FAC)
  - Neutral sheet current
  - Tail current



# 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

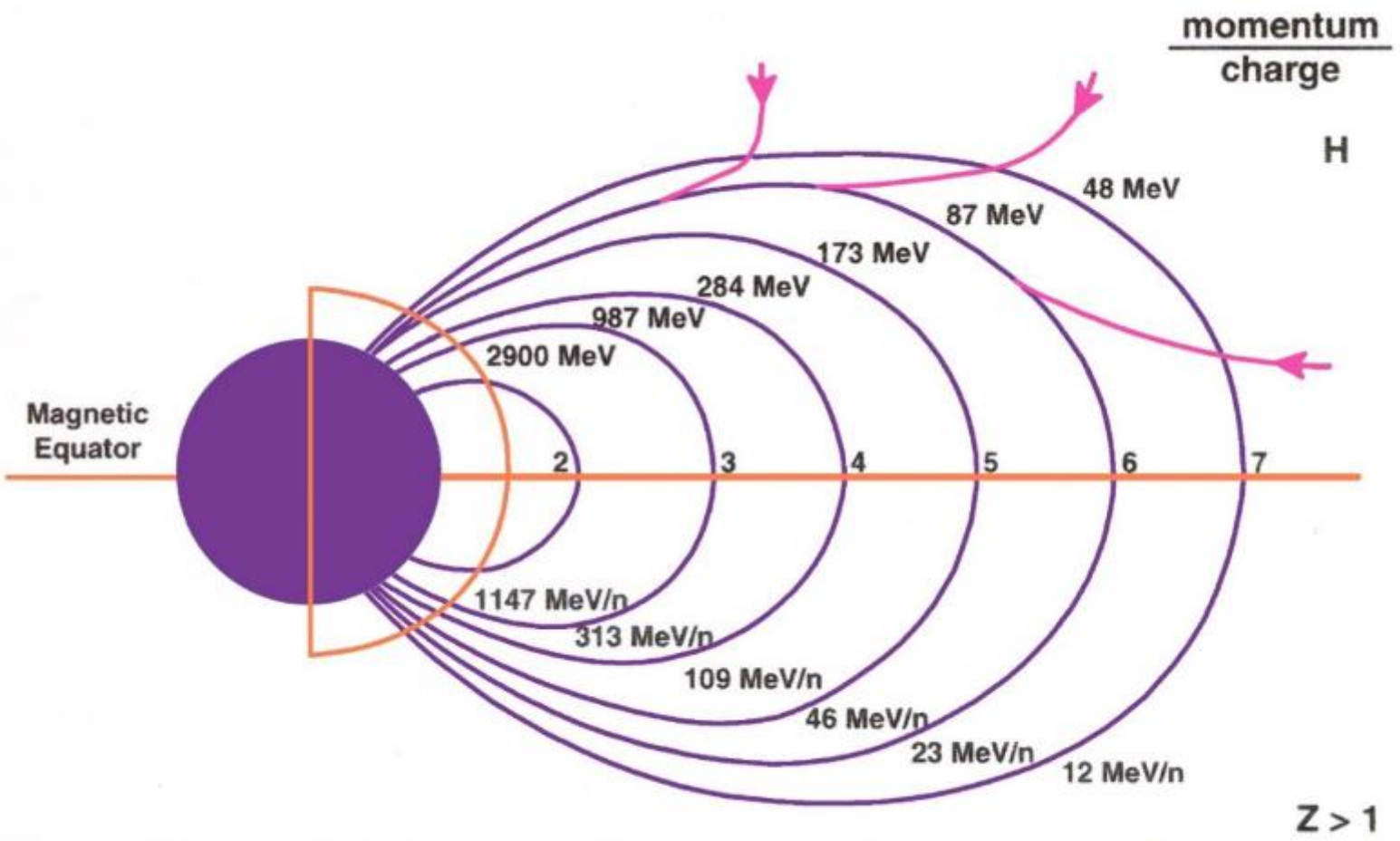
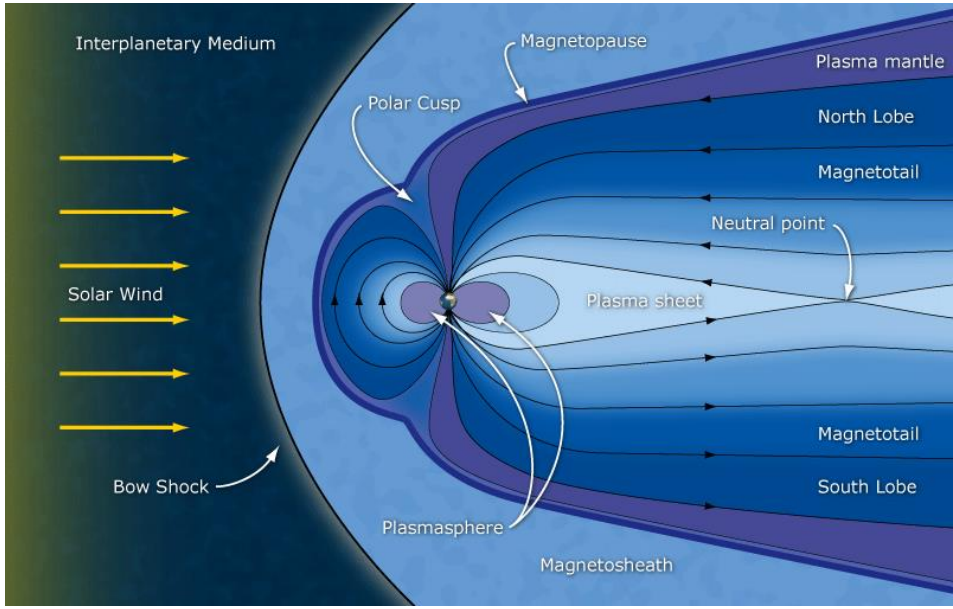



Figure 66: L-shell contours with rigidity imposed energy penetration limits.

# 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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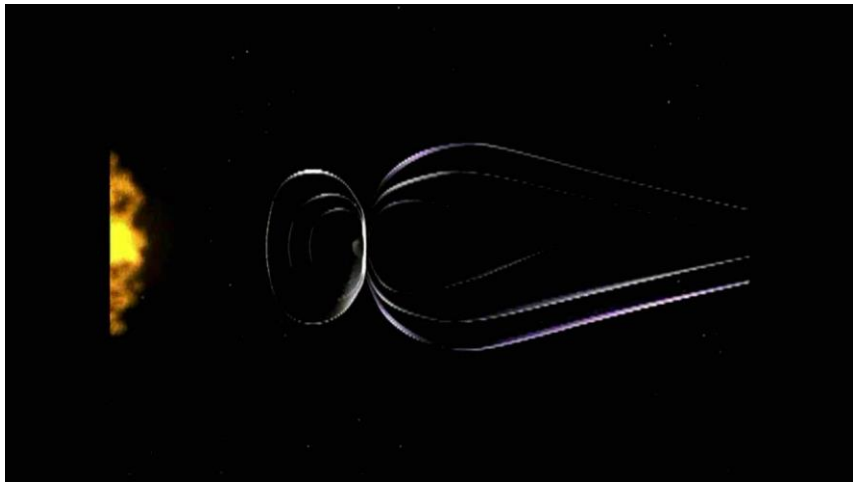
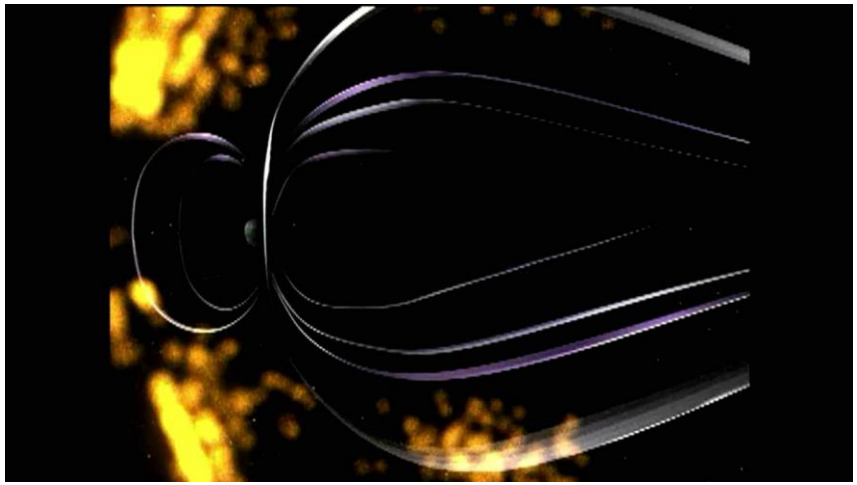
# Geomagnetic (sub)storm

- 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



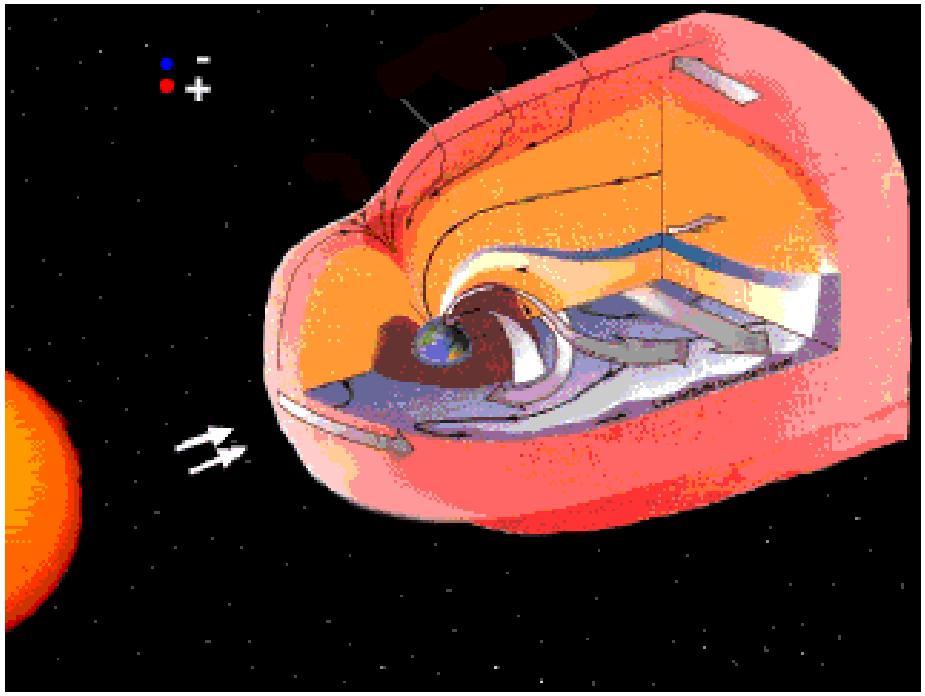
# Geomagnetic (sub)storm

- 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**).

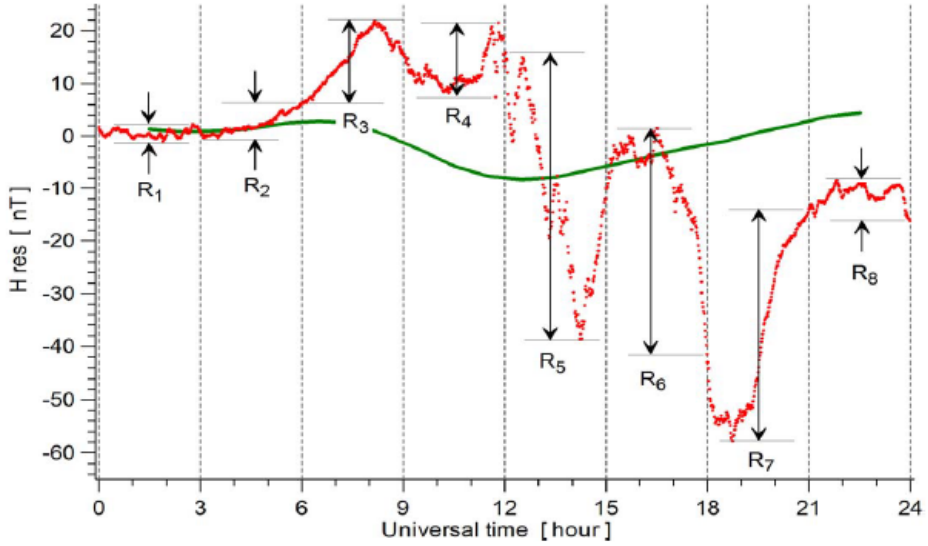



**Fig.2**. Calculation of the 3-hour K index over a 24 hour period. A daily record of 1-min measurements of the H component is presented here to illustrate the elimination of the solar regular variation, the $S_R$ curve (the solid line), and the consequent determination of the 8 ranges ($R_i$, $i$=1,8). 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**

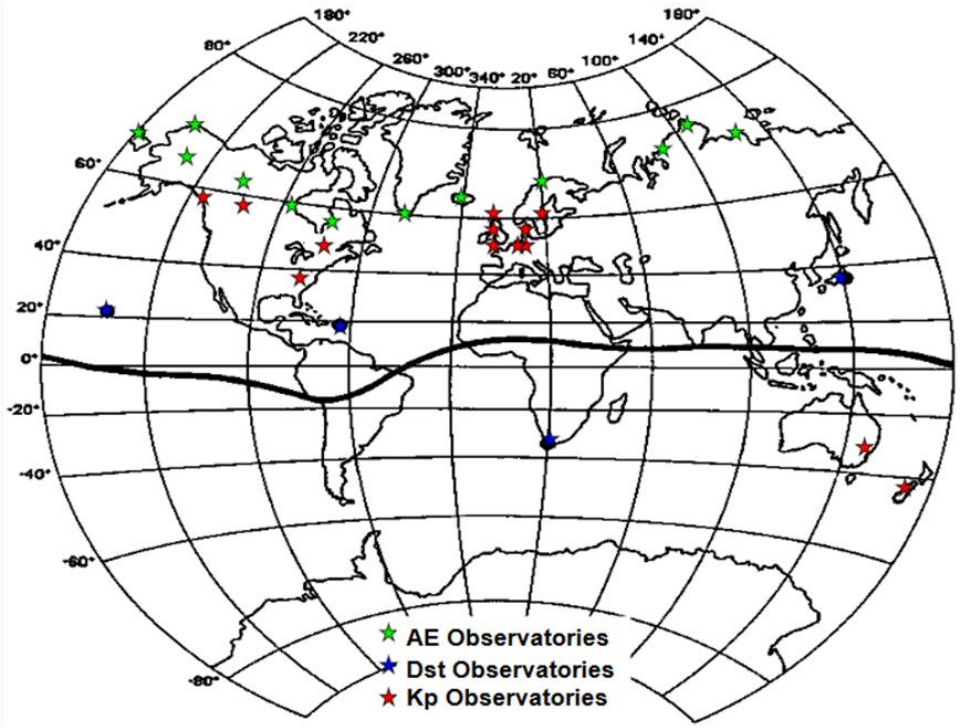
- Kennziffer
- Local
  - E.g. Dourbes
- Quasi-logaritmic scale
- Expressed in full units
  - 0, 1, … , 9
- 3hrs interval
  - 0-3UT, … , 21-24UT
  - 1hrs possible (Dourbes)

**Kp index**

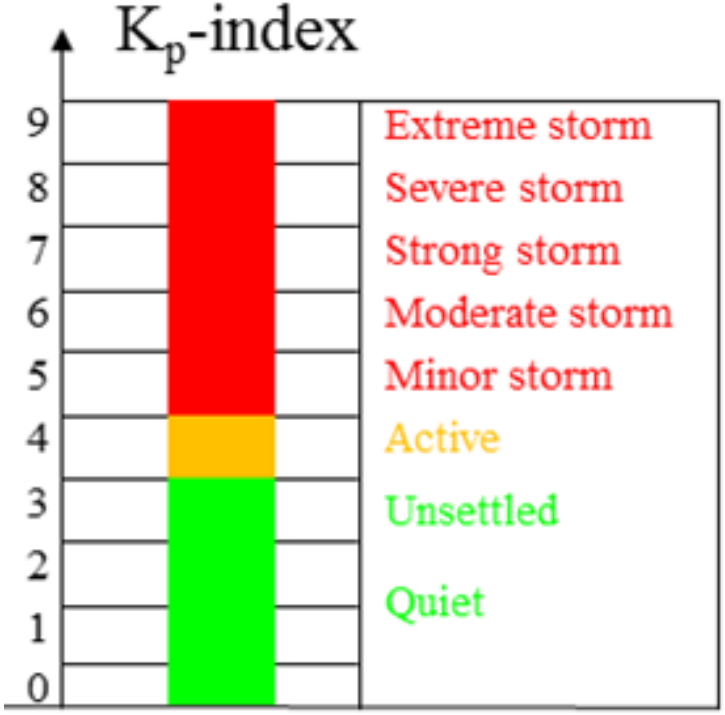
- Planetarische Kennziffer
- From network
  - 13 observatories (subauroral)
- Quasi-logaritmic scale
- Expressed in 1/3
  - 0o, 0+, … => … , 9-, 9o
- 3hrs interval
  - 0-3UT, … , 21-24UT
- Used in NOAA scales (G)
  - Auroral visibility maps
- Estimated Kp
- Going back to 1932

# Geomagnetic indices

- Observatories




- Nomenclature



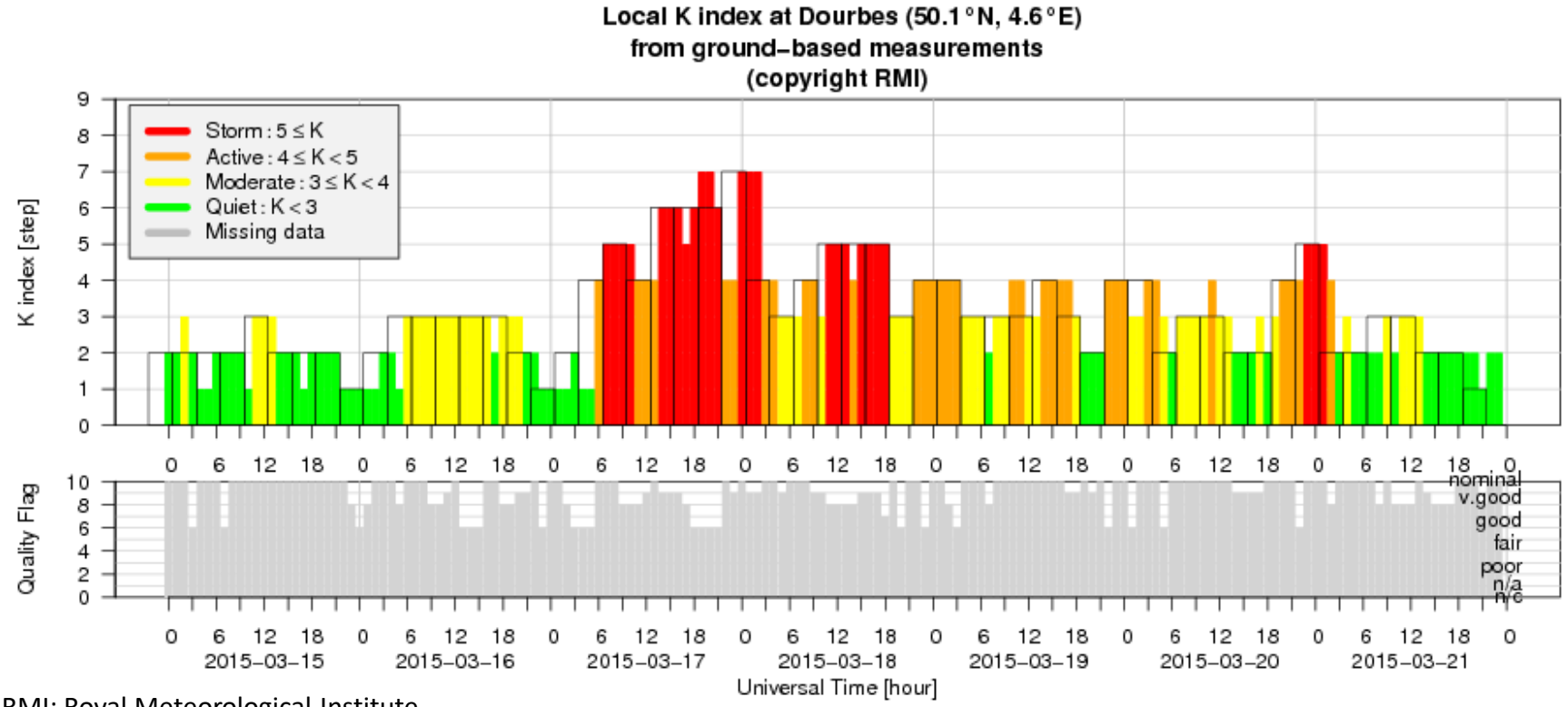
# Geomagnetic indices

- 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

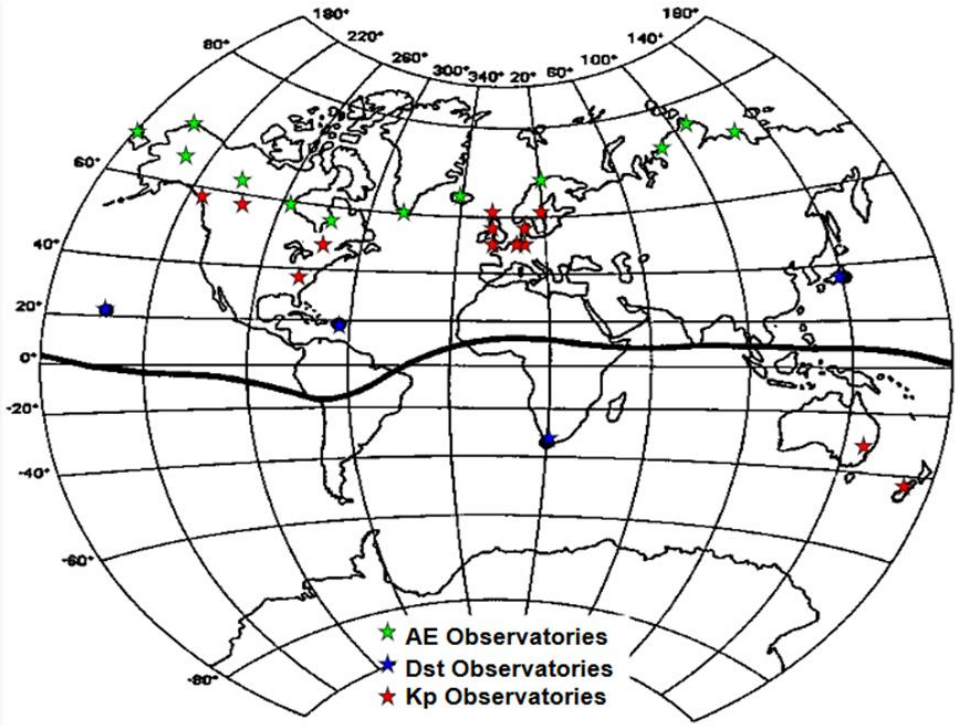
- aa
  - Derived (weighted average) from K indices from 2 antipodal , subauroral stations
    - Canberra
    - Hartland
  - Unit: nT
  - Going back to 1868
    - One of the oldest indices

| 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

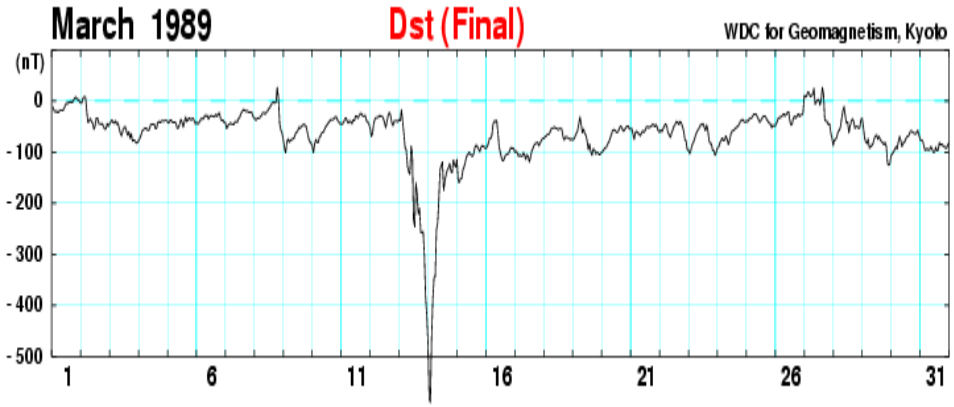
- Dst
  - Storm-time Disturbance index
    - Severity of magnetic storms
  - Depression of the intensity of the H-component
    - Westward current
      - Related to changes in the ring current
  - Measured by 4 stations close to magnetic equator
    - But not too close…



# Geomagnetic indices

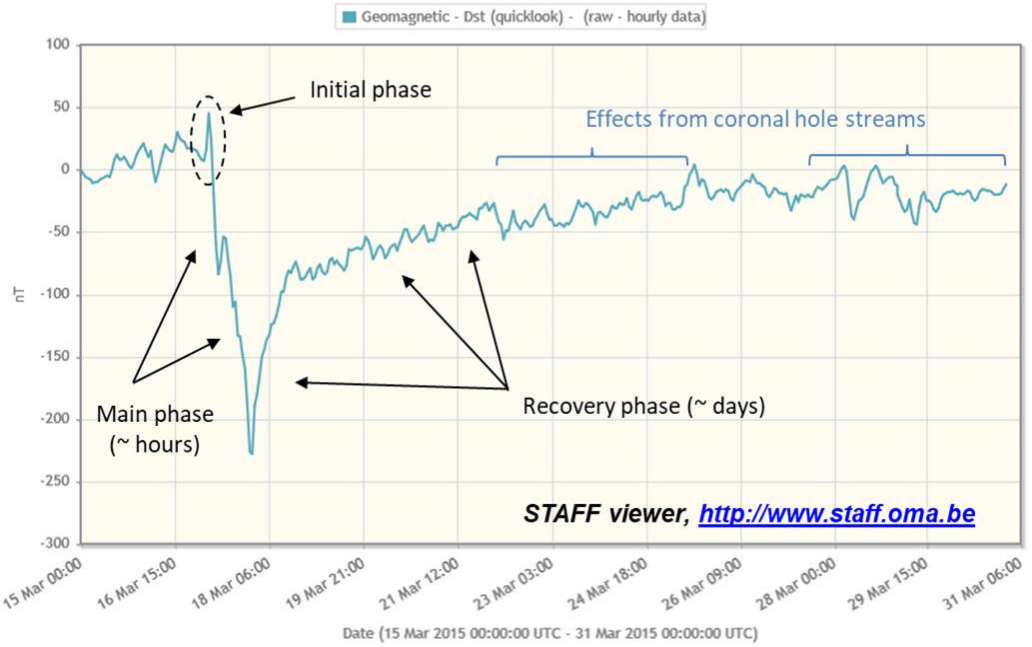
- Dst
  - Hourly measurements
  - Unit: nT
    - NOT a range index
  - Nomenclature
    - > -30 nT: Quiet
    - -30 - -50 nT: Weak storm
    - -50 - -100 nT: Moderate storm
    - -100 - -250 nT: Intense storm
    - < -250 nT: Extreme storm
    - See also https://www.stce.be/educational/classification

- 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 (-223 nT)
    - 23 Jun 2015 (-204 nT)
  - Extreme storms
    - 30 Oct 2003: -383 nT
    - 14 Mar 1989: -589 nT



:Issued: 2014 Apr 17 1325 UTC
:Product: documentation at http://www.sidc.be/products/tot
#-----------------------------------------------------------------------------------------------#
# DAILY BULLETIN ON SOLAR AND GEOMAGNETIC ACTIVITY from the SIDC #
#-----------------------------------------------------------------------------------------------#
SIDC URSIGRAM 40417
SIDC SOLAR BULLETIN 17 Apr 2014, 1304UT

Finding your way in the URSIgram

SIDC FORECAST (valid from 1230UT, 17 Apr 2014 until 19 Apr 2014)
SOLAR FLARES : Active (M-class flares expected, probability >=50%)
GEOMAGNETISM : Quiet (A<20 and K<4)
SOLAR PROTONS : Quiet

PREDICTIONS FOR 17 Apr 2014 10CM FLUX: 180 / AP: 013
PREDICTIONS FOR 18 Apr 2014 10CM FLUX: 184 / AP: 007
PREDICTIONS FOR 19 Apr 2014 10CM FLUX: 188 / AP: 005

COMMENT: Eleven sunspot groups were reported by NOAA today. NOAA ARs 2035,2036, and 2037 (Catania numbers 24, 25, and 26 respectively) maintain the beta-gamma configuration of the photospheric magnetic field. The strongest flare of the past 24 hours was the M1.0 flare peaking at 19:59 UT yesterday in the NOAA AR 2035 (Catania number 24). The flare was associated with an EIT wave and a weak coronal dimming, but the associated CME was narrow and is not expected to arrive at the Earth.
We expect further flaring activity on the C-level, especially in the NOAA ARs 2035 and 2037 (Catania numbers 24 and 26 respectively) as well as in the NOAA AR 2042 (no Catania number yet) that yesterday appeared from behind the east solar limb, with a good chance for an M-class event.

Since yesterday evening the Earth is situated inside a solar wind structure with an elevated interplanetary magnetic field magnitude (occasionally up to 10 nT). It may be a weak ICME or the compression region on the flank of an ICME that missed the Earth. The solar origin of this structure is not clear. The north-south magnetic field component Bz was not strong, so no significant geomagnetic disturbance resulted (K index stayed below 4). Currently the solar wind speed is around 380 km/s and the IMF magnitude is around 8 nT.
We expect quiet to unsettled (K index up to 3) geomagnetic conditions, with active geomagnetic conditions (K = 4) possible, but unlikely.

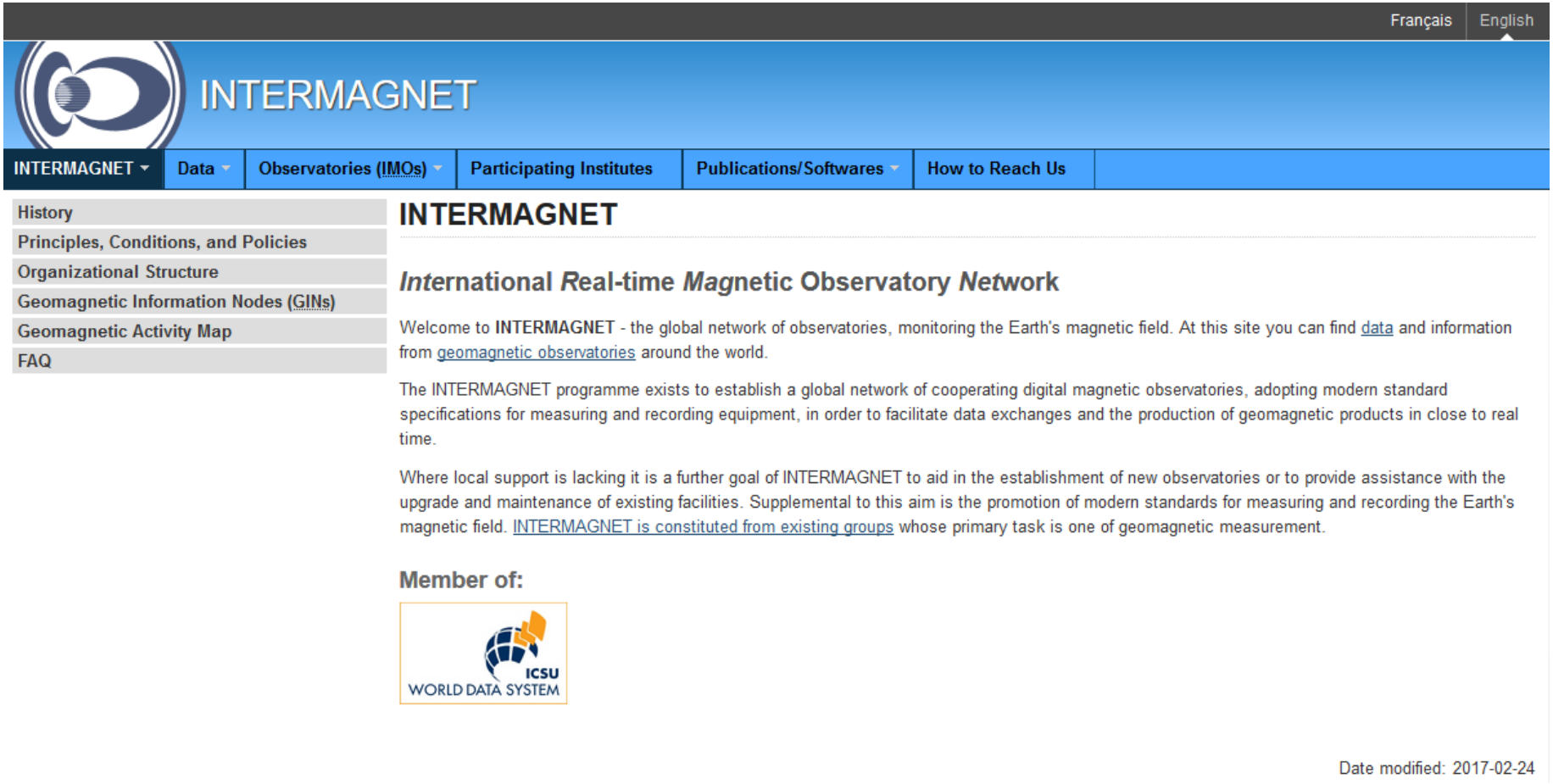
TODAY'S ESTIMATED ISN : 145, BASED ON 17 STATIONS.
99999

SOLAR INDICES FOR 16 Apr 2014
WOLF NUMBER CATANIA : ///
10CM SOLAR FLUX : 184
AK CHAMBON LA FORET : 012
AK WINGST : 004
ESTIMATED AP : 004
ESTIMATED ISN : 139, BASED ON 29 STATIONS.

## Geomagnetic activity

NOTICEABLE EVENTS SUMMARY
DAY BEGIN MAX END LOC XRAY OP 10CM Catania/NOAA RADIO_BURST_TYPES
16 1954 1959 2004 S14E09 M1.0 1N 24/2035 II/2
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)

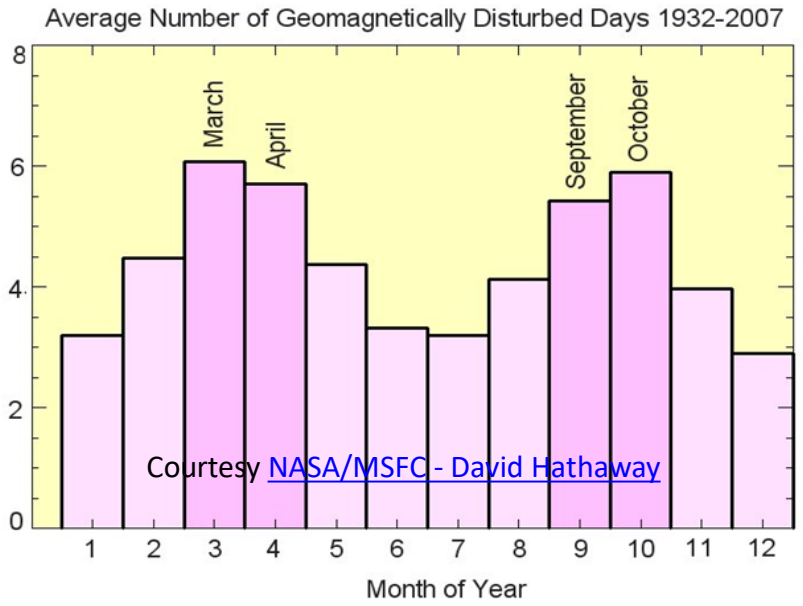
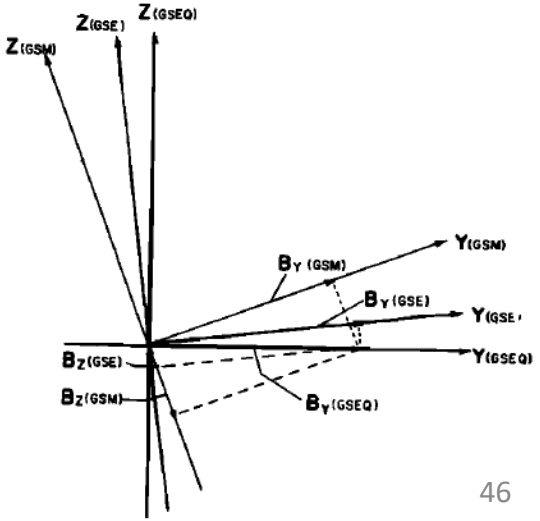
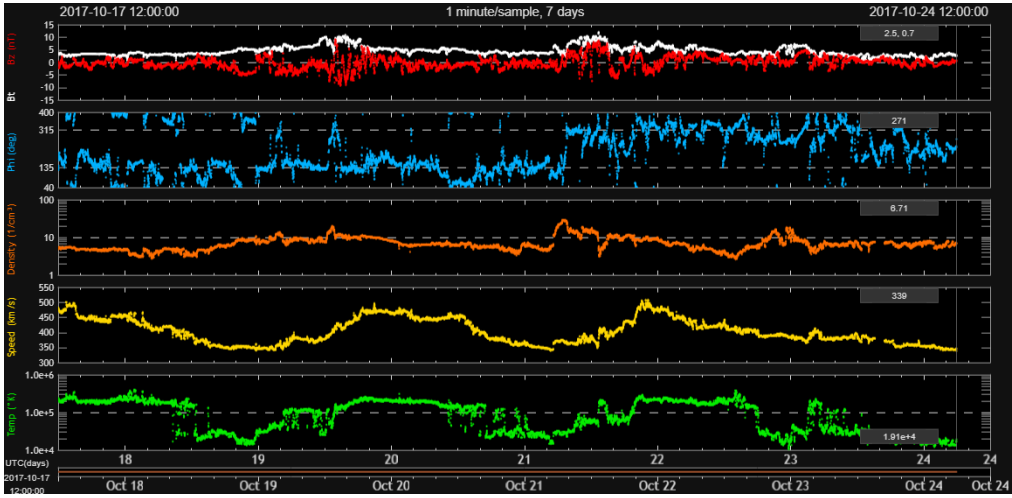


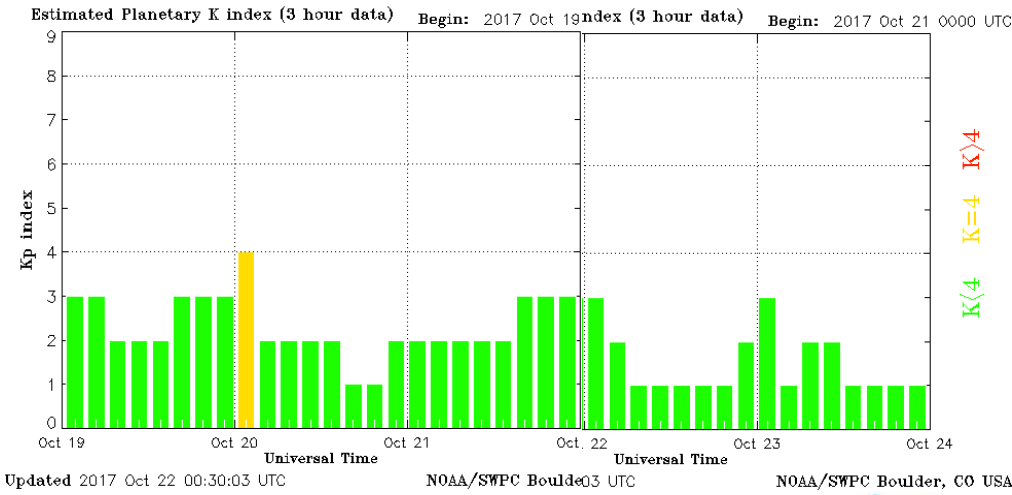

Fig. 4. One of the possible orientations of the *Y-Z* planes of the solar equatorial (GSEQ), solar ecliptic (GSE), and solar magnetospheric (GSM) coordinates, showing how a vector in the solar equatorial plane can have a southward (along the —*Z* axis) GSE and GSM component.



# 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