SPACE WEATHER INTRODUCTORY COURSE

SWIC

Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

The Magnetosphere

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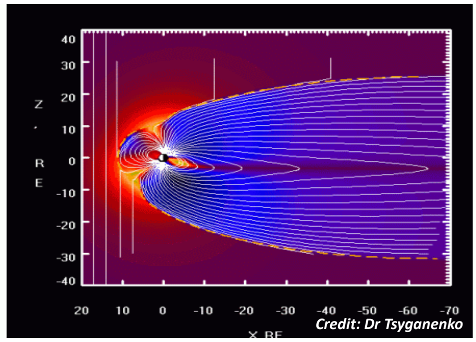
Animation made by Vincent van Leijen: http://fotovins.blogspot.be/2014/03/nl-in-nl.html
Concerns polar light observed on 27 February 2014 (Dst = -97 nT ; Kp = 5+)

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



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Definition from NASA: https://www.nasa.gov/mission_pages/sunearth/science/magnetosphere2.html

Animation from https://commons.wikimedia.org/wiki/File:Animati3.gif

Created by Dr Tsyganenko (NASA)
More info and animations at http://geo.phys.spbu.ru/~tsyganenko/modeling.html

Note that planets without a (strong) intrinsic magnetic field have an “induced magnetosphere”, for which the above defintion obviously is not applicable. However, this is also not the focus of this lecture, which will consider the earth environment only.

“Induced magnetospheres” by Luhmann et al. (2004)
https://www.sciencedirect.com/science/article/pii/S0273117704000158
Induced magnetospheres occur around planetary bodies that are electrically conducting or have substantial ionospheres, and are exposed to a time-varying external magnetic field. They can also occur where a flowing plasma encounters a mass-loading region in which ions are added to the flow. In this introduction to the subject we examine induced magnetospheres of the former type. The solar wind interaction with Venus is used to illustrate the induced magnetosphere that results from the solar wind interaction with an ionosphere.

The Magnetosphere - Contents

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

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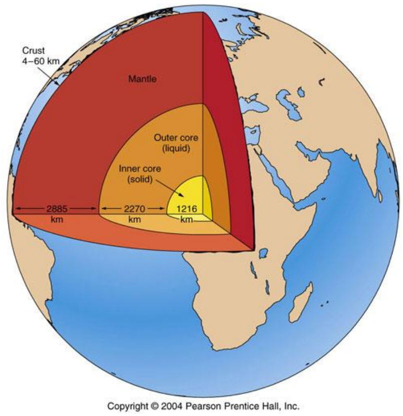
The geomagnetic field

- Created in and by the Earth’s interior



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From Wiki: https://en.wikipedia.org/wiki/Earth%27s_magnetic_field#Physical_origin
The Earth's magnetic field is believed to be generated by electric currents in the conductive material of its core, created by convection currents due to heat escaping from the core. However the process is complex, and computer models that reproduce some of its features have only been developed in the last few decades.
The interior **structure of the Earth** is layered in spherical shells: an outer silicate solid crust, a highly viscous mantle, a liquid outer core that is much less viscous than the mantle, and a solid inner core.

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

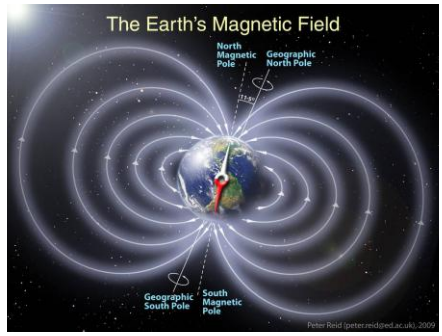

Figure: Peter Reid ; NASA: https://www.nasa.gov/image-article/representation-of-earths-invisible-magnetic-field/

From Wiki: https://en.wikipedia.org/wiki/Earth%27s_magnetic_field#Physical_origin
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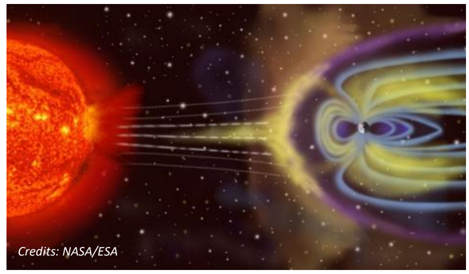
From Wiki: https://en.wikipedia.org/wiki/Earth%27s_magnetic_field#Main_characteristics
The interior **structure of the Earth** is layered in spherical shells: an outer silicate solid crust, a highly viscous mantle, a liquid outer core that is much less viscous than the mantle, and a solid inner core.
By comparison, a strong refrigerator magnet has a field of about 10,000,000 nanoteslas

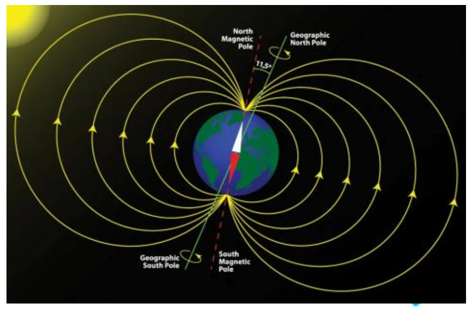
Also at BGS: http://www.geomag.bgs.ac.uk/education/earthmag.html

Note that the « entering » or « leaving » of magnetic field lines is not a physical reality, but entirely a matter of definition.

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





From Wiki: https://en.wikipedia.org/wiki/Earth%27s_magnetic_field#Magnetosphere
Earth's magnetic field, predominantly dipolar at its surface, is distorted further out by the solar wind. This is a stream of charged particles leaving the Sun's corona and accelerating to a speed of 200 to 1000 kilometres per second. They carry with them a magnetic field, the interplanetary magnetic field (IMF).
Top right figure: https://www.esa.int/ESA_Multimedia/Images/2007/10/The_Sun_Earth_connection (Credits NASA/ESA)

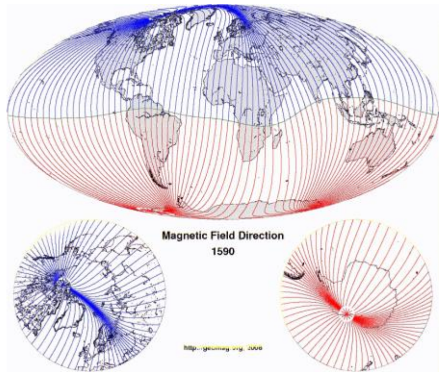
The solar wind exerts a pressure, and if it could reach Earth's atmosphere it would erode it. However, it is kept away by the pressure of the Earth's magnetic field. The magnetopause, the area where the pressures balance, is the boundary of the magnetosphere. Despite its name, the magnetosphere is asymmetric, with the sunward side being about 10 Earth radii out but the other side stretching out in a magnetotail that extends beyond 200 Earth radii.

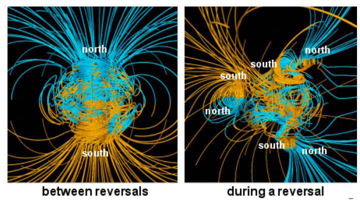
See also at NASA:
https://www.nasa.gov/audience/forstudents/postsecondary/features/29dec_magneticfield.html

From Wiki: https://en.wikipedia.org/wiki/Earth%27s_magnetic_field
Roughly speaking it is the field of a magnetic dipole currently tilted at an angle of about 11 degrees with respect to Earth's rotational axis, as if there were a bar magnet placed at that angle at the center of the Earth. The North geomagnetic pole, located near Greenland in the northern hemisphere, is actually the south pole of the Earth's magnetic field, and the South geomagnetic pole is the north pole.
Bottom right figure: https://www.livescience.com/21668-why-earth-magnetic-field-wonky.html (via Shutterstock)

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!!





NASA/JPL - University of California, Santa Cruz/Gary Glatzmaier

Animation from Geomag.us: https://geomag.us/info/declination.html
Another animation from USGS: https://www.usgs.gov/faqs/what-declination
Another good view on Earth's changing magnetic field is at http://wdc.kugi.kyoto-u.ac.jp/igrf/anime/index.html and https://wdc.kugi.kyoto-u.ac.jp/poles/polesexp.html

Lower right figure from Science at NASA: https://science.nasa.gov/science-research/earth-science/flip-flop-why-variations-in-earths-magnetic-field-arent-causing-todays-climate-change/ (University of California, Santa Cruz/Gary Glatzmaier)

Stassinopoulos et al. (2015) - Forty-Year "Drift" and Change of the SAA
https://ntrs.nasa.gov/search.jsp?R=20160003393
The SAA is really not an "anomaly" at all, but an apparent local depression of the Earth's magnetic field. When first observed, the SAA was considered an "anomaly" of the field, an aberration [1]. Later, the SAA was defined as stemming from the tilt, the eccentricity, and the displacement of the dipole axis from the center of the Earth i.e. the SAA is determined by (a) the tilt of the magnetic dipole axis to the axis of rotation (approximately ~11 degrees), (b) and is considered eccentric because it does not pass through the center of the planet, and (c) is displayed (by about 500 km) away from the center towards the North Pacific, thus producing a weaker magnetic field over Brazil and a stronger field over the North Pacific.

From NASA: https://www.nasa.gov/audience/forstudents/postsecondary/features/29dec_magneticfield.html
The magnetic field waxes and wanes, poles drift and, occasionally, flip. Change is normal, they've learned. And no wonder. The source of the field, the outer core, is itself seething, swirling, turbulent. "It's chaotic down there," notes Glatzmaier. The changes we detect on our planet's surface are a sign of that inner chaos.
They've also learned what happens during a magnetic flip. Reversals take a few thousand years to complete, and during that time--contrary to popular belief--the magnetic field does not vanish. "It just gets more complicated," says Glatzmaier. Magnetic lines of force near Earth's surface become twisted and tangled, and magnetic poles pop up in unaccustomed places. A south magnetic pole might emerge over Africa, for instance, or a north pole over Tahiti. Weird. But it's still a planetary magnetic field, and it still protects us from space radiation and solar storms.

Airports Keep Renaming Runways for a Peculiar Reason: Magnetism
https://www.popularmechanics.com/flight/airlines/a15759858/earth-magnetic-field-airport-runways/

Also this STCE newsitem: "Quo vadis, magnetic pole? " - https://www.stce.be/news/651/welcome.html

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Main features

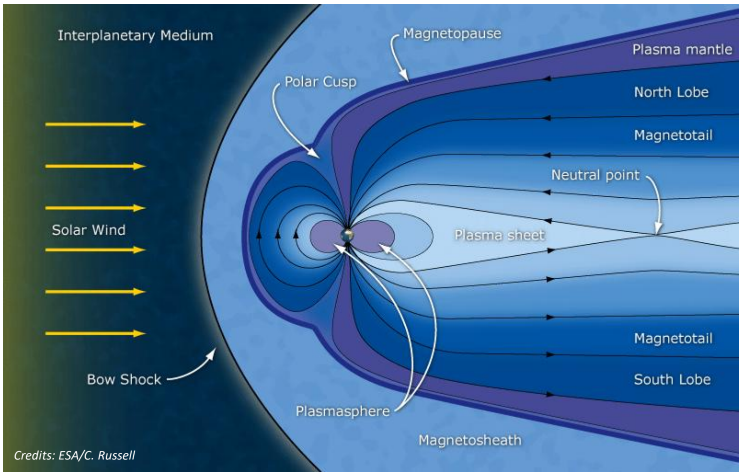
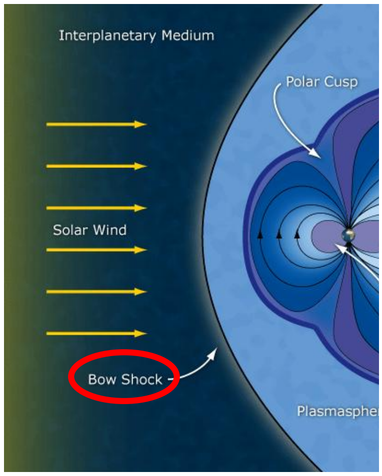


Figure from ESA/ C. Russell
http://sci.esa.int/cluster/50633-cluster-looks-into-waves-in-the-magnetosphere-s-thin-boundaries/

Note that, in the above figure, the placement of "Magnetotail" may be a bit confusing. It seems to suggest that the tail is somehow between plasma sheet and lobes, but this is not the case: The magnetotail is the whole magnetosphere stretching out on the night side.

Main features



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

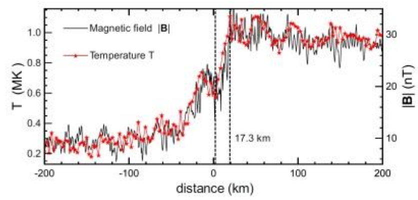


Figure from ESA/ C. Russell
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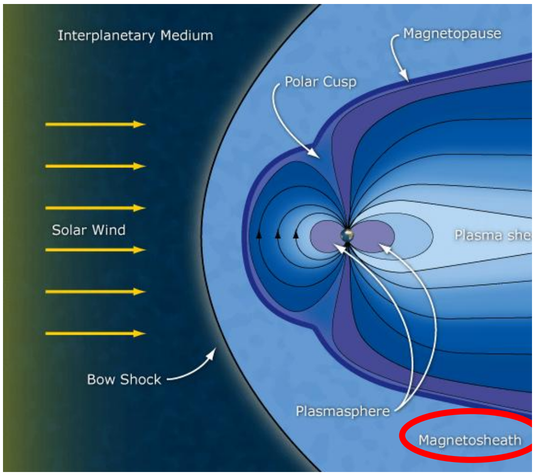
From ESA/Cluster
http://sci.esa.int/cluster/49643-cluster-measures-the-size-of-earth-s-bow-shock/
The bow shock is a standing shock wave that forms when the solar wind encounters the magnetosphere of our planet.
the bow shock formed by the solar wind as it encounters Earth's magnetic field is remarkably thin: it measures only 17 km across.
Thin astrophysical shocks such as this are candidate sites for early phases of particle acceleration.

Also at https://www.nuclearpowerdaily.com/reports/Cluster_reveals_Earth_bow_shock_is_remarkably_thin_999.html

Cluster: http://www-ssg.sr.unh.edu/tof/Outreach/music/cluster/index.html#graph
The region around the Earth that is controlled by the Earth's magnetic field, called the Magnetosphere, acts for the solar wind as an obstacle, like a rock in a flowing river. Since the solar wind with a speed of 250 – 800 km/s is highly supersonic, the situation is more like a supersonic jet plane rushing through the air. As a jet produces the audible supersonic boom, a loud shock wave (to be heard after the jet has passed already the observer's position), the Earth's Magnetosphere produces the equivalent structure, the so-called Bow Shock, in the solar wind.
Such shock waves are formed in many places in the universe with violent motion, around planets, at the Sun, around the solar system where the solar wind is stopped, and where supernovae blast into their neighborhood. In all these cases these shock waves slow down the solar wind, compress the flowing gas or plasma and the magnetic field, heat it up, and accelerate some particles to very high energies. The Cluster satellites cross the Earth's Bow Shock usually several times during orbits that lead into the solar wind. Thus they can study this shock wave at our front doorstep in detail.

More on supersonic/subsonic speeds in interplanetary space:
- https://en.wikipedia.org/wiki/Shocks_and_discontinuities_(magnetohydrodynamics)

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

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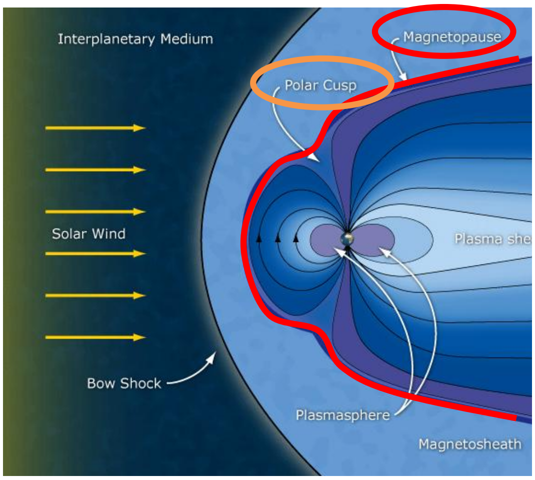
Figure from ESA/ C. Russell
http://sci.esa.int/cluster/50633-cluster-looks-into-waves-in-the-magnetosphere-s-thin-boundaries/

Wiki: https://en.wikipedia.org/wiki/Magnetosphere#Magnetosheath
The magnetosheath is the region of the magnetosphere between the bow shock and the magnetopause. It is formed mainly from shocked solar wind, though it contains a small amount of plasma from the magnetosphere. It is an area exhibiting high particle energy flux, where the direction and magnitude of the magnetic field varies erratically. This is caused by the collection of solar wind gas that has effectively undergone thermalization. It acts as a cushion that transmits the pressure from the flow of the solar wind and the barrier of the magnetic field from the object.

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
    - Dayside aurora (invisible)

R_E : Earth radii ; MF: Magnetic Field

Figure from ESA/ C. Russell
http://sci.esa.int/cluster/50633-cluster-looks-into-waves-in-the-magnetosphere-s-thin-boundaries/

Wiki: https://en.wikipedia.org/wiki/Magnetopause
During high solar activity, i.e. the passing of strong coronal mass ejections, the magnetopause may be pushed much closer to the Earth than usual, sometimes even closer than 6.6RE which is the location of the GOES satellites. At that point, these satellites become entirely exposed to the solar wind particles, which can be seen in erratic measurements of e.g. Hp. This is called a magnetopause crossing. See the course chapter on SWx effects.

Cusp: In the "open" model of the magnetosphere, the polar cusps are narrow regions of recently "opened" or merged magnetic field lines mapping to the high-latitude ionosphere just poleward of the last closed field line on the Earth's day side. The open field lines of the cusps are connected with those of the interplanetary magnetic field, which allows the shocked solar wind plasma of the magnetosheath to enter the magnetosphere and to penetrate to the ionosphere. Associated with the cusp is the "cleft ion fountain," from which plasma flows upward from the ionosphere into the magnetosphere, with the peak outflow occurring in the pre-noon sector.

BIRA-IASB (https://www.aeronomie.be/en/encyclopedia/auroral-ovals-two-geomagnetic-poles):
Solar wind plasma reach the atmosphere through polar cusps - The polar cusps correspond to the region of separation between the field lines directed towards the Sun and those directed towards the magnetospheric tail (or short: magnetotail). They allow the direct entry of the solar wind plasma. Particles that reach the atmosphere produce an **auroral emission on the day side** of the oval, invisible to the naked eye from the Earth's surface.

Meng et al. 2001 (https://doi.org/10.1016/S1464-1917(00)00088-X): The auroral oval is generally weaker on the dayside than on the nightside because the particles that produce it have significantly less energy. While the nightside aurora is powered by intense, explosive magnetic reconnection in the magnetotail, the dayside aurora is driven by different, generally less energetic processes, including solar wind-magnetosphere coupling and direct entry of solar wind particles through the cusp.

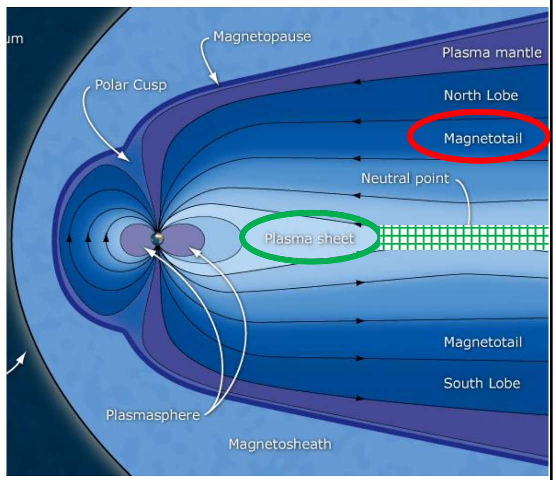
The Earth's magnetosphere is the area within the red line, so without the magnetosheath and the bow shock.

Magnetopause: As there is pressure balance, this means that the sum of magnetic + plasma pressure is constant. The plasma pressure usually is considerably larger on the magnetosheath side than on the magnetospheric side, and the magnetic field thus is typically smaller on the magnetosheath side.

See also Oulu's "Space Physics textbook": http://magbase.rssi.ru/REFMAN/SPPHTEXT/Welcome.html

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

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Figure from ESA/ C. Russell
http://sci.esa.int/cluster/50633-cluster-looks-into-waves-in-the-magnetosphere-s-thin-boundaries/

From Wiki:https://en.wikipedia.org/wiki/Magnetosphere#Magnetotail
Opposite the compressed magnetic field is the magnetotail, where the magnetosphere extends far beyond the astronomical object. It contains two lobes, referred to as the northern and southern tail lobes. Magnetic field lines in the northern tail lobe point towards the object while those in the southern tail lobe point away. The tail lobes are almost empty, with few charged particles opposing the flow of the solar wind. The two lobes are separated by a plasma sheet, an area where the magnetic field is weaker, and the density of charged particles is higher.

NASA: The tail of the magnetosphere
https://pwg.gsfc.nasa.gov/Education/wtail.html

Note that, in the above figure, the placement of "Magnetotail" may be a bit confusing. It seems to suggest that the tail is somehow between plasma sheet and lobes, but this is not the case: The magnetotail is the whole magnetosphere stretching out on the night side.

Also, reconnection tends to occur always. During quiet times, it happens in the distant tail. During disturbed times, you can have reconnection closer to Earth (at ~20 R_E).

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

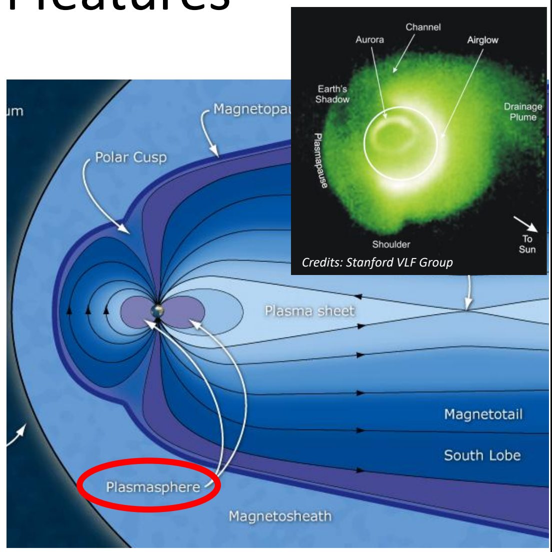

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Figure from ESA/ C. Russell
http://sci.esa.int/cluster/50633-cluster-looks-into-waves-in-the-magnetosphere-s-thin-boundaries/

Stanford: http://vlf.stanford.edu/research/extreme-ultraviolet-imaging-plasmasphere

NASA: https://plasmasphere.nasa.gov/
The upper reaches of our planet's atmosphere are exposed to ultraviolet light from the Sun, and they are ionized with electrons that are freed from neutral atmospheric particles. The electrons in plasma gain more energy, and they are very low in mass . They move along Earth's magnetic field lines and their increased energy is enough to escape Earth's gravity. Because electrons are very light, they don't have to gain too much kinetic energy from the Sun's ultraviolet light before gravity loses its grip on them. For a planet like Earth with a strong planetary magnetic field, these outward moving particles remain trapped near the planet unless other processes further draw them away and into interplanetary space. Over only a short time period of hours and days this escaping plasma can, in some places, build up in concentration until an equilibrium is reached where as much plasma flows inward into the ionosphere as flows outward. This "donut shaped" region of cold (about 1 electron volt in energy) plasma encircling the planet is called the plasmasphere.

Generally, that region of space where plasma from the ionosphere has the time to build up to become identified as the plasmasphere rotates or nearly rotates with the Earth. That region shrinks in size with increased space weather activity and expands or refills during times of inactivity. As it shrinks with increasing activity, some of the plasmasphere is drawn away from its main body (plasmaspheric erosion) in the sunward direction toward the boundary in space between that region dominated by Earth's magnetic field and the much larger region dominated by the Sun's magnetic field.

Moldwin et al. (2002): A new model of the location of the plasmapause: CRRES results
https://ui.adsabs.harvard.edu/abs/2002JGRA..107.1339M/abstract

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

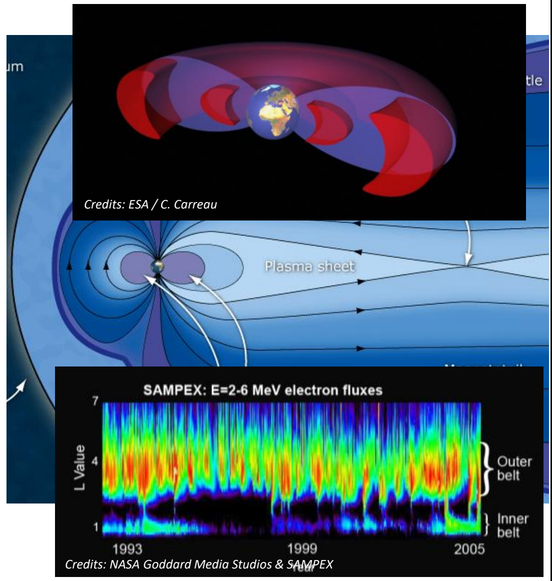

Figure from ESA/ C. Russell
http://sci.esa.int/cluster/50633-cluster-looks-into-waves-in-the-magnetosphere-s-thin-boundaries/

ESA: http://sci.esa.int/cluster/52831-earth-plasmasphere-and-the-van-allen-belts/ (Figure top right: Credits: ESA / C. Carreau)
The plasmasphere – the innermost part of the Earth's magnetosphere – is a doughnut-shaped region of low energy charged particles (cold plasma) centred around the planet's equator and rotating along with it. Its toroidal shape is determined by the magnetic field of Earth. The plasmasphere begins above the upper ionosphere and extends outwards, with the outer boundary varying (depending on geomagnetic conditions) from 4.5 Earth radii (R_E) to 8 R_E.
The two Van Allen radiation belts are concentric, tyre-shaped belts (shown in blue) of highly energetic (0.1–10 MeV) electrons and protons, which are trapped by the magnetic field and travel around the Earth. These radiation belts partly overlap with the plasmasphere. The inner Van Allen belt is located typically between 6000 and 12 000 km (1 - 2 Earth radii [R_E]) above Earth's surface, although it dips much closer over the South Atlantic Ocean. The outer radiation belt covers altitudes of approximately 25 000 to 45 000 km (4 to 7 R_E).

SAMPEX figure from NASA Goddard Media Studios: https://svs.gsfc.nasa.gov/11212

Thorne et al. 2007 - Refilling of the slot region between the inner and outer electron radiation belts during geomagnetic storms
https://doi.org/10.1029/2006JA012176
Under quiet geomagnetic conditions, a pronounced "slot" or gap forms between the two belts … The quiet-time slot is most pronounced at energies above several hundred keV. The basic structure of the slot has been explained as a balance between slow inward radial diffusion from a source population in the outer zone and precipitation losses from the inner magnetosphere, primarily due to resonant scattering by plasmaspheric hiss and other whistler mode waves [VLF electromagnetic waves]. Owing to the long timescales associated with radial diffusion in the inner magnetosphere, only electrons with energies below the minimum energy for resonance with whistler mode waves … are able to diffuse into the inner zone without substantial loss.

Main features

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  - Inner belt
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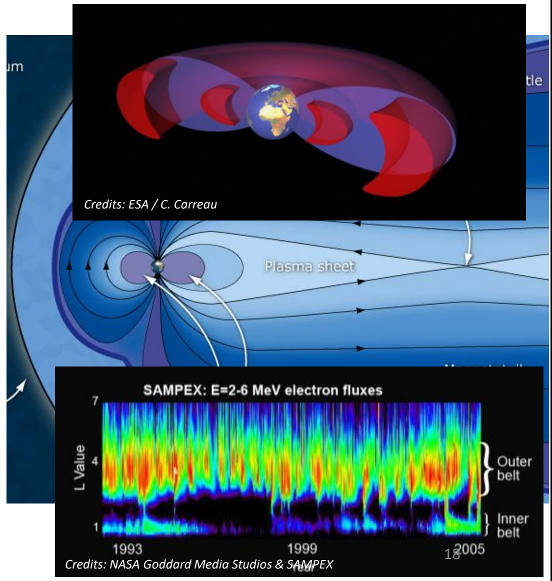
    - Injection of > 15MeV p^+ and > 3MeV e^- which can reach all the way down into the Inner Radiation Belt



Main characteristics
Outer Radiation Belt – mostly e- - 0.1 – 10 MeV – 3 < L < 8 (ESA; variable) - the outer belt starts at L= 3.5, especially for electrons with E>1 MeV
Baker et al. (2017): Space Weather Effects in the Earth's Radiation Belts
https://ui.adsabs.harvard.edu/abs/2018SSRv..214...17B/abstract

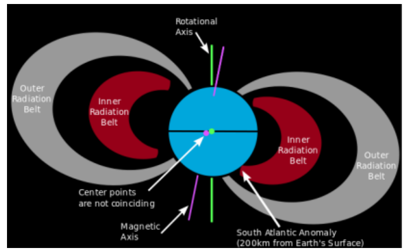
Inner Radiation belt
10 - 500 MeV protons at 1.5 < L < 2
100-500 keV e- at 1.2 < L < 2.5 - In the SAA and in the inner belt, there are no electrons with E>2 MeV.

South Atlantic Anomaly – e- and p+ - 1.03 < L < 1.2 (lower edge Inner Belt) - the SAA is created by electrons and protons of the inner belt. In the SAA and in the inner belt, there are no electrons with E>2 MeV.

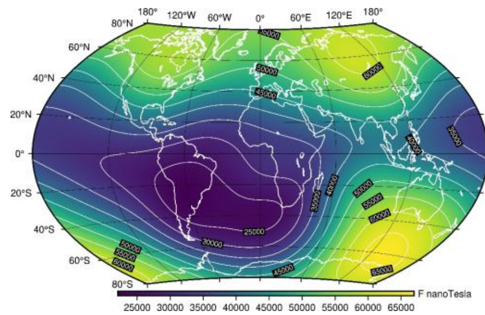
Occasionally, during strong geomagnetic storms, there can be an injection of > 15MeV p+ and > 3MeV e- which can reach all the way down into the Inner Radiation Belt and cause even the presence of a third radiation belt during several days.

Main features

- Radiation belts
  - South Atlantic Anomaly (SAA)
    - Extension of Inner belt closest to Earth
      - altitude: 200 km
      - Over Brazil
        - » Drift westward at 3°/decade



Credits: Marko Markovic



Credits: BGS/IGRF14

Top right figure: Marko Markovic - https://commons.wikimedia.org/wiki/File:South_Atlantic_Anomaly.svg
Bottom right figure: BGS/IGRF14 - https://geomag.bgs.ac.uk/research/modelling/IGRF.html

ESA: http://sci.esa.int/cluster/52831-earth-plasmasphere-and-the-van-allen-belts/
The plasmasphere – the innermost part of the Earth's magnetosphere – is a doughnut-shaped region of low energy charged particles (cold plasma) centred around the planet's equator and rotating along with it. Its toroidal shape is determined by the magnetic field of Earth. The plasmasphere begins above the upper ionosphere and extends outwards, with the outer boundary varying (depending on geomagnetic conditions) from 4.5 Earth radii (R_E) to 8 R_E. The two Van Allen radiation belts are concentric, tire-shaped belts (shown in blue) of highly energetic (0.1–10 MeV) electrons and protons, which are trapped by the magnetic field and travel around the Earth. These radiation belts partly overlap with the plasmasphere. The inner Van Allen belt is located typically between 6000 and 12 000 km (1 - 2 Earth radii [R_E]) above Earth's surface, although it dips much closer over the South Atlantic Ocean. The outer radiation belt covers altitudes of approximately 25 000 to 45 000 km (4 to 7 R_E).

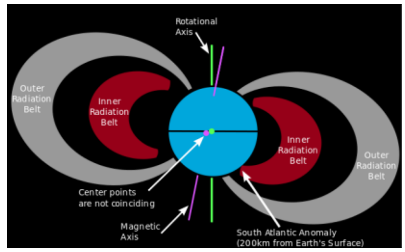
Figure from Spaceflight101: https://spaceflight101.com/rbsp/science-overview/
Figure from Sky and Telescope: https://skyandtelescope.org/astronomy-news/observing-news/earth-briefly-gains-third-radiation-belt/
From SpaceSafety: www.spacesafetymagazine.com/media-entertainment/radiation

Reminder: the SAA exists due to the fact that the geomagnetic field is not perfectly symmetric; one can approximately say that the bar magnet inside Earth is located slightly off-center. See the inserted figure and slide 8.

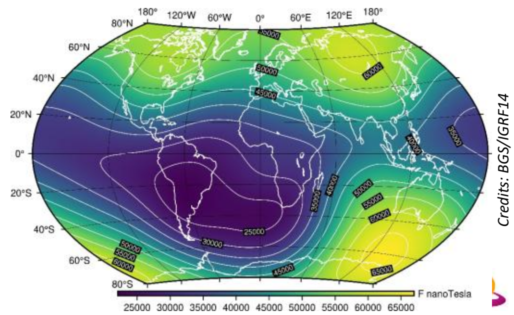
Space.com: Van Allen radiation belts: facts and findings - https://www.space.com/33948-van-allen-radiation-belts.html
NASA press conference on 3rd radiation belt: https://www.youtube.com/watch?v=yLw9a5t-sUs
Sky and telescopre: https://skyandtelescope.org/astronomy-news/observing-news/earth-briefly-gains-third-radiation-belt/

Main features

- Radiation belts
  - South Atlantic Anomaly (SAA)
    - Extension of Inner belt closest to Earth
      - altitude: 200 km
      - Over Brazil
        - » Drift westward at 3°/decade



Credits: Marko Markovic



Credits: BGS/IGRF14

Top right figure: Marko Markovic - https://commons.wikimedia.org/wiki/File:South_Atlantic_Anomaly.svg
Bottom right figure: BGS/WMM - https://geomag.bgs.ac.uk/research/modelling/IGRF.html

Main characteristics
Outer Radiation Belt – mostly e- - 0.1 – 10 MeV – 3 < L < 8 (ESA; variable) - the outer belt starts at L= 3.5, especially for electrons with E>1 MeV
Baker et al. (2017): Space Weather Effects in the Earth's Radiation Belts
https://ui.adsabs.harvard.edu/abs/2018SSRv..214...17B/abstract

Inner Radiation belt
10 - 500 MeV protons at 1.5 < L < 2
100-500 keV e- at 1.2 < L < 2.5 - In the SAA and in the inner belt, there are no electrons with E>2 MeV.

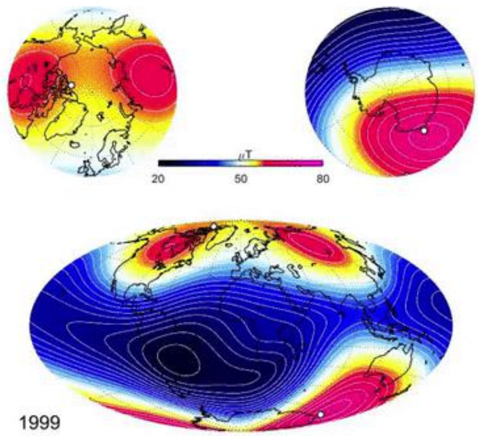
South Atlantic Anomaly – e- and p+ - 1.03 < L < 1.2 (lower edge Inner Belt) - the SAA is created by electrons and protons of the inner belt. In the SAA and in the inner belt, there are no electrons with E>2 MeV.

Occasionally, during strong geomagnetic storms, there can be an injection of > 15MeV p+ and > 3MeV e- which can reach all the way down into the Inner Radiation Belt and cause even the presence of a third radiation belt during several days.

Wiki: https://en.wikipedia.org/wiki/South_Atlantic_Anomaly
What are the radiation belts? https://www.youtube.com/watch?v=3zNmgu6sQXk
Scientists Explain the Formation of the Unusual Third Van Allen Radiation Ring (1 Sep 2012) - https://scitechdaily.com/scientists-explain-formation-unusual-third-van-allen-radiation-ring/

Main features

South Atlantic Anomaly (1999-2016) by SWARM



ESA / DTU Space

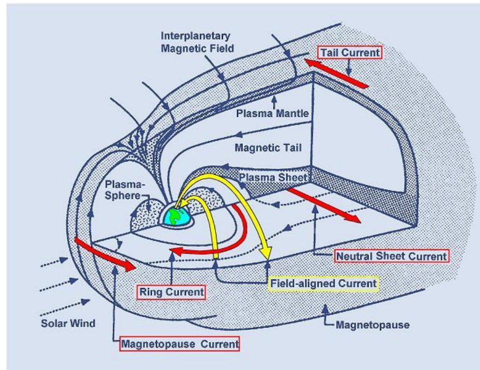
Animation ESA:
http://www.esa.int/spaceinvideos/Videos/2016/05/Changes_in_strength_of_Earth_s_magnetic_field
Article ESA:
http://www.esa.int/Our_Activities/Observing_the_Earth/Swarm/Earth_s_magnetic_heartbeat
SAA growing in intensity: NASA/GSFC: https://svs.gsfc.nasa.gov/4840

Title Changes in strength of Earth's magnetic field
Released: 10/05/2016
Language English
Footage Type Animation
Copyright DTU Space
Description

Based on results from ESA's Swarm mission, the animation shows how the strength of Earth's magnetic field has changed between 1999 and mid-2016. Blue depicts where the field is weak and red shows regions where the field is strong. The field has weakened by about 3.5% at high latitudes over North America, while it has grown about 2% stronger over Asia. The region where the field is at its weakest field – the South Atlantic Anomaly – has moved steadily westward and further weakened by about 2%. In addition, the magnetic north pole is wandering east.

Main features

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



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Geomag/US: http://geomag.us/info/magnetosphere.html

Note that during times of unusually large solar wind ram pressure the magnetopause may move substantially Earthwards. Indeed, sometimes the magnetopause is observed inside geosynchronous orbit (6.6 RE).
The magnetopause current layer is important in two other ways. First, the magnetic field associated with the current layer is also observable at the surface of the Earth. This is particularly true during times when the magnetopause is compressed Earthwards, leading to an increase in the magnetic field measurable at the surface (since the current layer's field adds to the Earth's field inside the magnetopause). As seen in Lecture 15, this effect can lead to an increase in the geomagnetic activity index at the start of a geomagnetic substorm, while the subsequent increase of the ring current leads to major decrease of the surface field (Section 14.3). Second, and perhaps more importantly, the magnetopause current layer is a global phenomenon that persists wherever the magnetopause does.

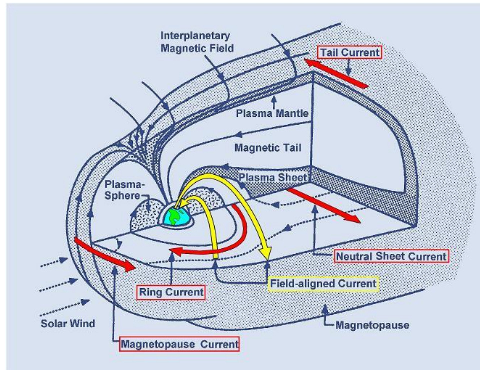
Chapman-Ferraro current: https://www.britannica.com/science/Chapman-Ferraro-current-system
Based on: Plasma Space physics:
https://canvas.kth.se/files/3056805/download?download_frd=1
A perspective view of the northern portion of the magnetopause current, as seen from above the ecliptic plane. Charged particles in the solar wind are deflected in opposite directions by the Earth's main field, creating a boundary current. This current confines the field inside a finite volume called the magnetosphere (*see* text).

« The Sun, The Earth and Near-Earth space » by John A. Eddy (Fig. pp. 83)
The dayside magnetopause current has a nighttime equivalent (tail current or night-time magnetopause current).

Ring current (pp. 87):
The third obligatory motion is an induced, slower drift in longitude that results from the curvature of the MF lines and the diminished strength of the field with distance above the surface of the planet. The effect is to nudge to gyrating particle a little bit in longitude – an e- in the eastward direction, a p+ or other positive ions westward – each time it bounces. Repeated nudging pushes it bit by bit around the Earth, such that the pole-to-pole motions of the particle sweep over the entire surface of the planet, all in about one hour. … is a ring of current flowing around the magnetic equator of the Earth…

Main features

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



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Ring current (Wiki: https://en.wikipedia.org/wiki/Ring_current)
Earth's ring current is responsible for shielding the lower latitudes of the Earth from magnetospheric electric fields. It therefore has a large effect on the electrodynamics of geomagnetic storms. The ring current system consists of a band, at a distance of 3 to 8 Re, which lies in the equatorial plane and circulates clockwise around the Earth (when viewed from the north). The particles of this region produce a magnetic field in opposition to the Earth's magnetic field and so an Earthly observer would observe a decrease in the magnetic field in this area. The negative deflection of the Earth's magnetic field due to the ring current is measured by the Dst index. The ring current energy is mainly carried around by the ions, most of which are protons.

Field-aligned currents (FAC, also called the Birkeland currents) are essential to the coupling between the solar wind - magnetosphere system and the ionosphere. The main large scale FAC systems are the Region 1 and 2 currents.

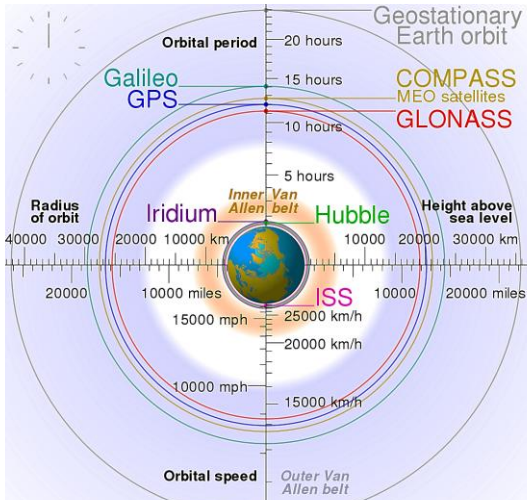
Plasma universe: https://www.plasma-universe.com/Birkeland_current
A **Birkeland current** usually refers to the electric currents in a planet's ionosphere that follows magnetic field lines (i.e. field-aligned currents), and sometimes used to described any field-aligned electric current in a space plasma. They are caused by the movement of a plasma perpendicular to a magnetic field.

Also at https://en.wikipedia.org/wiki/Birkeland_current
A **Birkeland current** is a set of currents that flow along geomagnetic field lines connecting the Earth's magnetosphere to the Earth's high latitude ionosphere. In the Earth's magnetosphere, the currents are driven by the solar wind and interplanetary magnetic field and by bulk motions of plasma through the magnetosphere (convection indirectly driven by the interplanetary environment). The strength of the Birkeland currents changes with activity in the magnetosphere (e.g. during substorms). Small scale variations in the upward current sheets (downward flowing electrons) accelerate magnetospheric electrons which, when they reach the upper atmosphere, create the Auroras Borealis and Australis. In the high latitude ionosphere (or auroral zones), the Birkeland currents close through the region of the auroral electrojet, which flows perpendicular to the local magnetic field in the ionosphere.

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

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Table from radio-electronics https://www.electronics-notes.com/articles/satellites/basic-concepts/satellite-orbits-types-definitions.php

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

From Wiki: https://en.wikipedia.org/wiki/Medium_Earth_orbit
Medium Earth orbit (MEO), sometimes called intermediate circular orbit (ICO), is the region of space around the Earth above low Earth orbit (altitude of 2,000 km) and below geostationary orbit (altitude of 35,786 km).

The most common use for satellites in this region is for navigation, communication, and geodetic/space environment science. The most common altitude is approximately 20,200 kilometres, which yields an orbital period of 12 hours, as used, for example, by the Global Positioning System (GPS). Other satellites in medium Earth orbit include Glonass (with an altitude of 19,100 kilometres and Galileo (with an altitude of 23,222 kilometres) constellations. Communications satellites that cover the North and South Pole are also put in MEO.

The orbital periods of MEO satellites range from about 2 to nearly 24 hours.[1] Telstar 1, an experimental satellite launched in 1962, orbited in MEO.

Main features

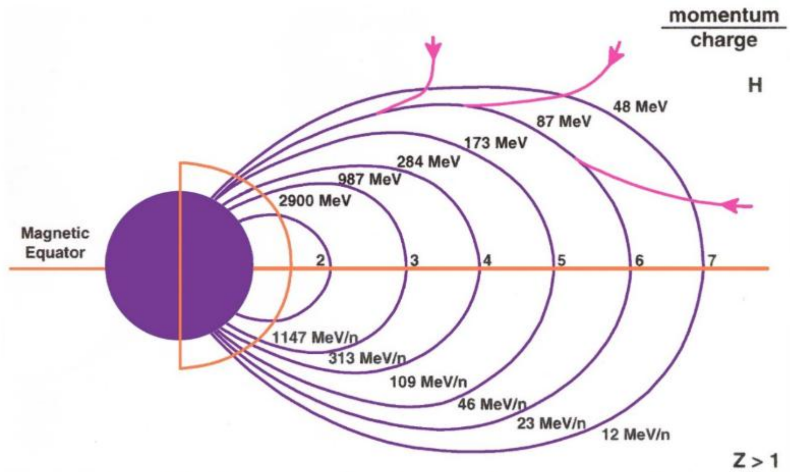

Figure 66: L-shell contours with rigidity imposed energy penetration limits.

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From NASA: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160003393.pdf
https://ntrs.nasa.gov/search.jsp?R=20160003393

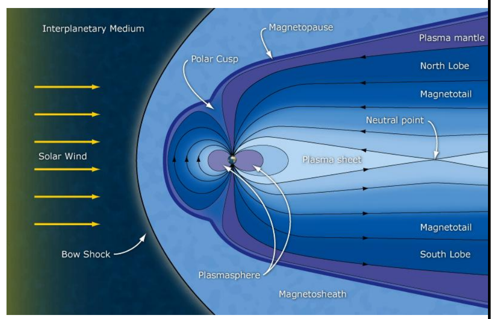
The question of energetic proton penetration into the inner zone of the Van Allen belts, and hence the SAA , is of particular importance because it is frequently mentioned in several publications, which claim that these particles affected their measurements in the SAA and had an impact on the SAA ’s evolution. However, the “ rigidity principle ” applies to the inner zone of the radiation belts, and consequently the SAA ; protons must have energies greater than 2.9 GeV (as mentioned above) at least, to be able to reach the low altitude range of the anomaly.

Cosmic Rays. A few papers mentioned concern about the penetration of cosmic rays into the SAA region. Solar and galactic cosmic rays are high- energy heavy ions : 90% hydrogen, 9% alpha particles, and 1% nuclei of heavier elements. In order for these particles to reach the inner zone of the Van Allen belts, and hence the SAA , they must have energies in excess of 1.15 GeV per nucleon . All cosmic rays with lower energies are deflected by the Earth’s magnetic field (rigidity cutoff). Most workers consider the galactic cosmic rays reaching the vicinity of the Earth (about 1 AU) as fully ionized , which means maximum deflection. As a consequence, very few of these particles reach the SAA . A solar cycle variation has been observed in the cosmic ray flux levels between solar minimum and solar maximum. During the active phase of the solar cycle, the cosmic ray intensities are about a factor of two or so lower than during solar minimum. It is obvious, considering Figure66, that more cosmic rays have access to the higher latitude regions than near the equator, with a free unimpeded penetration over the poles, where open field lines connect directly to the interplanetary medium.

Interesting reading: the STARFISH prime project
https://en.wikipedia.org/wiki/Starfish_Prime

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

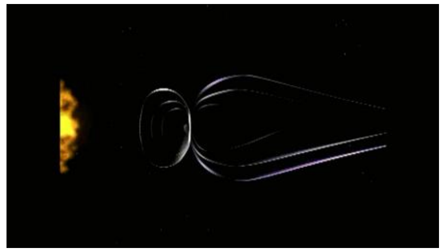


The Magnetosphere - Contents

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

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



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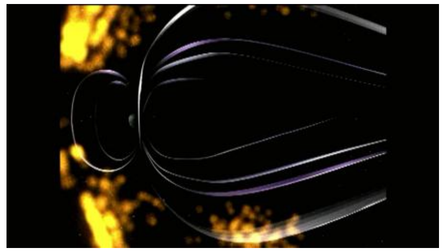
Animation from SOHO: https://soho.nascom.nasa.gov/gallery/Movies/animations.html
See http://sci.esa.int/cluster/51744-magnetic-reconnection-in-earth-s-magnetosphere/ for another animation

A full description of the evolution of a geomagnetic (sub)storm can be found in the SIDC SWx Forecast Guide: http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf

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



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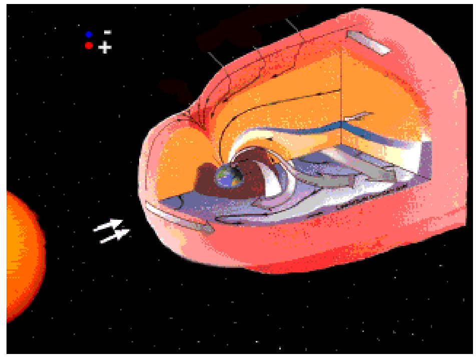
Geomagnetic (sub)storm

- 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



From; Windows to the Universe
https://www.windows2universe.org/glossary/plasmaspheric_gain.html&edu=high

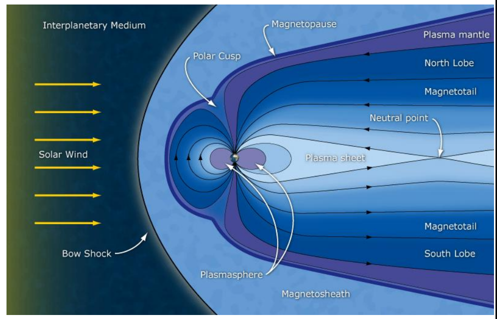
Movie with substorm: NASA: https://svs.gsfc.nasa.gov/20097

Magnetosphere from ESA: http://sci.esa.int/cluster/54025-model-of-changing-magnetosphere/

A full description of the evolution of a geomagnetic (sub)storm can be found in the SIDC SWx Forecast Guide: http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf

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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See also at http://sci.esa.int/cluster/51744-magnetic-reconnection-in-earth-s-magnetosphere/

A full description of the evolution of a geomagnetic (sub)storm can be found in the SIDC SWx Forecast Guide: http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf

The Magnetosphere - Contents

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

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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**).

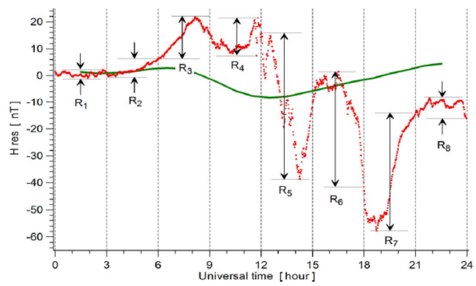

Fig.2. Calculation of the 3-hour K index over a 24 hour period. A daily record of 1-min measurements of the H component is presented here to illustrate the elimination of the solar regular variation, the S_R curve (the solid line), and the consequent determination of the 8 ranges (R_i, i=1,8). The difference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

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Figure from Stankov et al. (2010): Local Operational Geomagnetic Index K Calculation (K-LOGIC) from digital ground-based magnetic measurements
http://ionosphere.meteo.be/sites/ionosphere.meteo.be/files/documentation/publications/Team-Reports/STR-RMI-2010-01_K-LOGIC.pdf

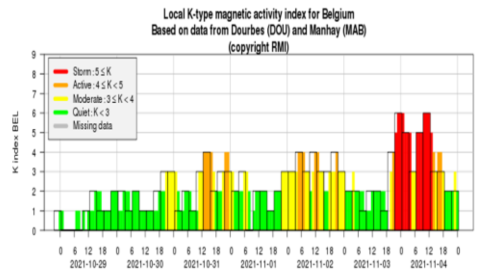
Geomagnetic indices

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)

$K_{Belgium}$

- RMI Geophysical Centre of Dourbes
  - 2 local K-indices (Dourbes, Manhay)



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On the K and Kp index: SWPC: https://www.swpc.noaa.gov/sites/default/files/images/u2/TheK-index.pdf
Potsdam: https://www.gfz-potsdam.de/en/section/geomagnetism/data-products-services/geomagnetic-kp-index

The reported values, be they updated every hour or every 3 hours, always cover the recordings of the last 3 hours.
E.g. the 10UT value reported by Dourbes covers the interval 07-10UT.

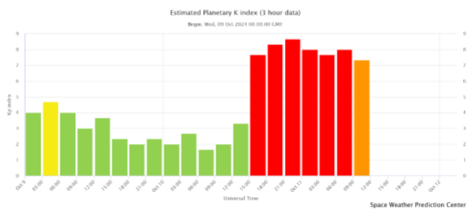
The estimated Kp values are the ones that can be found at NOAA/SWPC:
https://www.swpc.noaa.gov/products/planetary-k-index

The final Kp values are determined by GFZ Potsdam and can be downloaded at Kyoto WDC:
http://wdc.kugi.kyoto-u.ac.jp/kp/index.html
The geomagnetic three-hourly Kp index was introduced by J. Bartels in 1949 and is derived from the standardized K index (Ks) of 13 magnetic observatories. It is designed to measure solar particle radiation by its magnetic effects and today it is considered a proxy for the energy input from the solar wind to Earth.

The maps for auroral visibility can be found at https://www.swpc.noaa.gov/content/tips-viewing-aurora

Geomagnetic indices

Estimated Kp **(NOAA/SWPC)**



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
  - Final Kp: GFZ Potsdam
  - https://kp.gfz-potsdam.de/en/
- Going back to 1932

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On the K and Kp index: SWPC: https://www.swpc.noaa.gov/sites/default/files/images/u2/TheK-index.pdf
Potsdam: https://www.gfz-potsdam.de/en/section/geomagnetism/data-products-services/geomagnetic-kp-index

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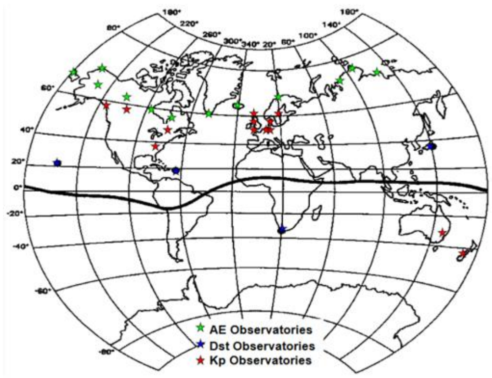
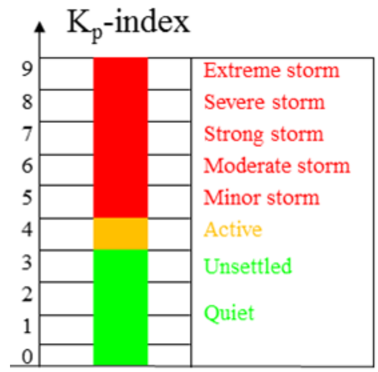
Geomagnetic indices

- Observatories



- Nomenclature



Left figure taken from HAO/UCAR SW103 Lecture 4: Geomagnetic indices and space weather models. https://www2.hao.ucar.edu/sites/default/files/users/whawkins/SW102_4_Indices.pdf (no longer accessible)
Maps with locations of geomagnetic stations for each index is also available at https://isgi.unistra.fr/

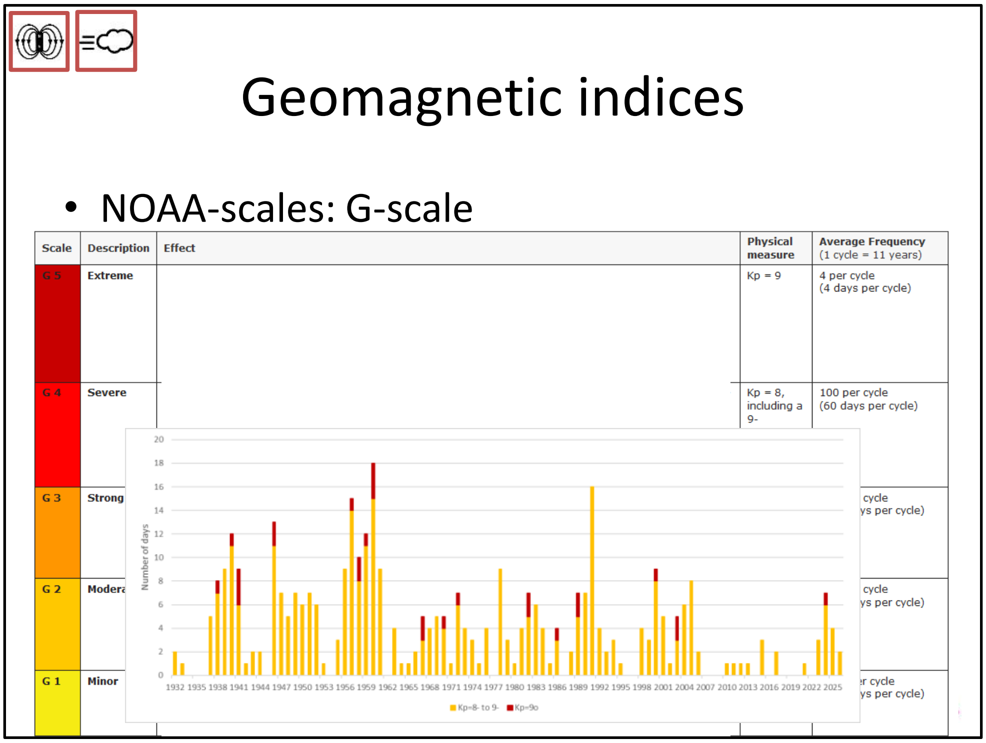
The nomenclature is the one mentioned in NOAA/SWPC ' User guide.
https://www.swpc.noaa.gov/sites/default/files/images/u2/Usr_guide.pdf

The 13 observatories for Kp are (currently operational: https://www.gfz-potsdam.de/en/section/geomagnetism/data-products-services/geomagnetic-kp-index
Sitka, Alaska, USA; Meanook, Canada; Ottawa, Canada; Fredericksburg, Virginia, USA; Hartland, UK; Wingst, Germany; Niemegk, Germany; Canberra, Australia; Brorfelde, Denmark; Eyerewell, New Zealand; Uppsala, Sweden; Eskdalemuir, UK; Lerwick, UK.

All these stations have geomagnetic latitudes between 35° and 60°. This zone is called the subauroral zone.

The main purpose of the standardized index Ks is to provide a basis for the global geomagnetic index Kp which is the average of a number of "Kp stations", originally 11. The Ks data for the two stations Brorfelde and Lovö/Uppsala, as well as for Eyerewell and Canberra, are combined so that their average enters into the final calculation, the divisor thus remaining 11.

The Estimated 3-hour Planetary Kp-index is derived at the NOAA Space Weather Prediction Center using data from the following ground-based magnetometers: Sitka, Alaska; Meanook, Canada; Ottawa, Canada; Fredericksburg, Virginia; Hartland, UK; Wingst, Germany; Niemegk, Germany; and Canberra, Australia.



From the SWPC webpage:

NOAA Space Weather Scales : https://www.swpc.noaa.gov/noaa-scales-explanation

The NOAA Space Weather Scales were introduced as a way to communicate to the general public the current and future space weather conditions and their possible effects on people and systems. Many of the SWPC products describe the space environment, but few have described the effects that can be experienced as the result of environmental disturbances. These scales are useful to users of our products and those who are interested in space weather effects. The scales describe the environmental disturbances for three event types: geomagnetic storms, solar radiation storms, and radio blackouts. The scales have numbered levels, analogous to hurricanes, tornadoes, and earthquakes that convey severity. They list possible effects at each level. They also show how often such events happen, and give a measure of the intensity of the physical causes.

The « G » stands for Geomagnetic storms. Note it starts only from Kp =5 or higher.

More at https://www.stce.be/news/366/welcome.html and https://www.stce.be/content/sc25-tracking
For the SC17-SC24, there have been on the average ***41 days per solar cycle*** with at least one 3-hour interval of *severe geomagnetic storming* (Kp=8- to 9-), and another ***3 days per solar cycle*** with at least one 3-hour interval of *extremely severe geomagnetic storming* (Kp=9o). The values vary from one SC to the next: During SC24, there were resp. only 9 and 0 such days, but during SC19 there were 74 and 7 such days!

Miscellaneous 1

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

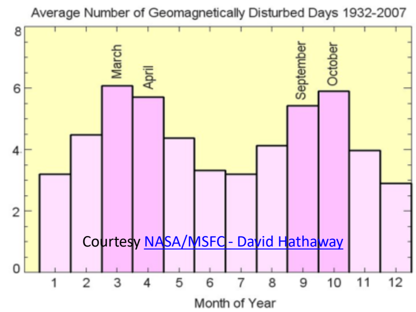
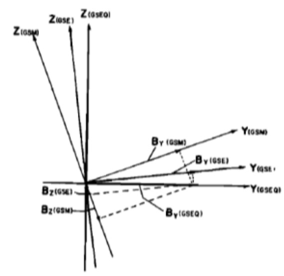
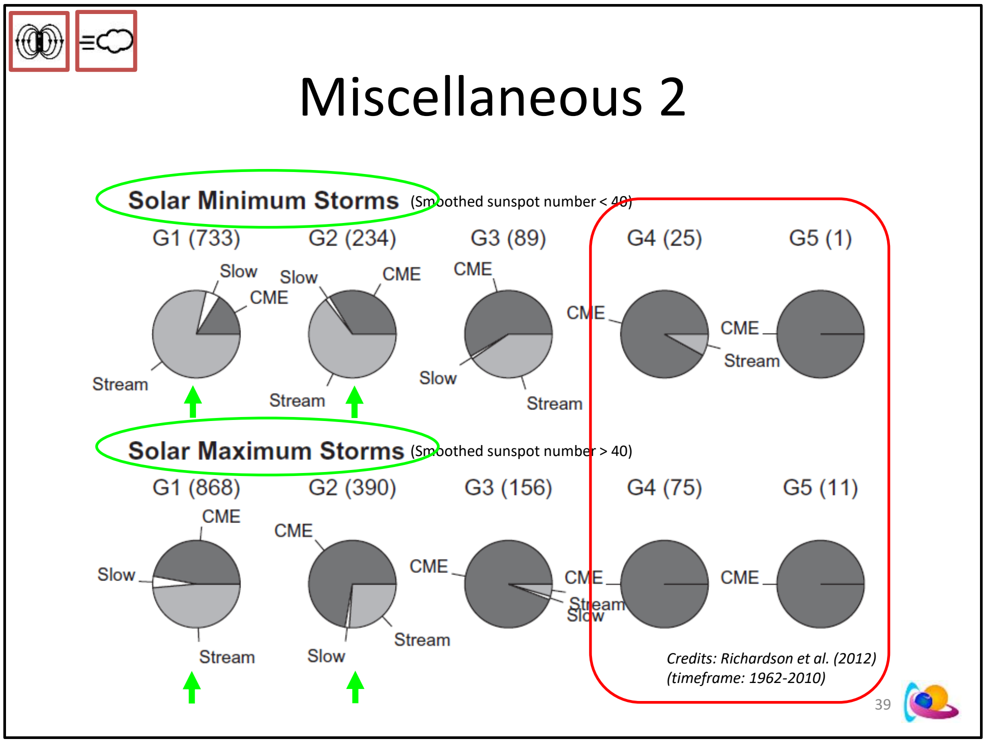


Fig. 4. One of the possible orientations of the Y-Z planes of the solar equatorial (GSEQ), solar ecliptic (GSE), and solar magnetospheric (GSM) coordinates, showing how a vector in the solar equatorial plane can have a southward (along the $-Z$ axis) GSE and GSM component.



From the SIDC SWx Forecast Guide:
http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf
Another element is the seasonal variation of the geomagnetic disturbances (Figure 52). Already in 1856, Edward Sabine showed from magnetic recordings that "… January and June are the months of minimum disturbance, September and April the months of maximum disturbance. The aggregate value of the disturbances in the equinoctial months is about three times as great as in the solstitial months." (Sabine 1856). This finding has been assessed and confirmed on numerous occasions and for various geomagnetic indices (e.g. Cliver et al. 2001, Svalgaard et al. 2002, Balan et al. 2017). The semiannual variation has been interpreted in terms of the (1) axial hypothesis based on the variation of the heliospheric latitude of the Earth with time of year (e.g., Cortie 1912), (2) equinoctial hypothesis based on the variation of the angle between the Earth–Sun line and Earth's dipole axis (e.g., Bartels 1932) and (3) Russell–McPherron (RM) effect based on the varying angle between the GSM (geocentric solar magnetospheric) Z-axis and GSE (geocentric solar ecliptic) Y-axis (Russell and McPherron 1973). From a review of subsequent papers, Bothmer et al. 2007 concluded that hypothesis (1) does not seem to play a key role in the origin of the semiannual variation.

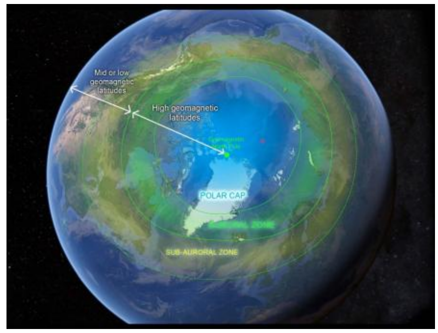
Russell, C. T., McPherron, R. L. (1973): Semiannual variation of geomagnetic activity
https://ui.adsabs.harvard.edu/abs/1973JGR....78...92R/abstract
*** … geomagnetic activity is caused by substorms, and, whereas the magnitude of the southward component has been shown to control substorm activity, the solar wind velocity, which controls the Kelvin-Helmholtz instability, has not. … The semiannual variation of geomagnetic activity is a manifestation of the varying probability of a southward component occurring in solar magnetospheric coordinates due to the changing orientation of the solar magnetospheric coordinate system relative to the solar equatorial system. This theory is both an axial theory, because the solar equatorial system depends on the heliographic latitude of the earth, and an equinoctial hypothesis, because the orientation of the solar magnetospheric coordinate system depends on the orientation of the earth's rotation axis relative to the solar wind. … We can further test the models, though, by examining auxiliary predictions of the models.
In particular, the southward component model predicts that the spring maximum in activity is associated on the average with fields toward the sun and the fall maximum with fields away from the sun.***



Richardson et al. (2012): Solar wind drivers of geomagnetic storms during more than four solar cycles
https://ui.adsabs.harvard.edu/abs/2012JSWSC...2A..01R/abstract
Generally, the number of CME-associated storms (black curves in Fig. 1) follows solar activity levels, as would be expected since the ICME rate at 1 AU (Richardson & Cane 2010) and the CME rate at the Sun (Robbrecht et al. 2009; Webb & Howard 1994; Yashiro et al. 2004) increase from solar minimum to solar maximum. Furthermore, Figure 1 indicates that the maximum rate of storms driven by CME associated flows approximately follows the size of the sunspot cycle, i.e. storm rates are higher in cycles 21 and 22 than in cycles 20 and 23.
Stream-associated storms … are typically most prominent for 3–4 years during the declining phase of the Cycle The solar minimum intervals are (arbitrarily) bounded by the years in which the smoothed sunspot number fell below or rose above 40 (cf. Fig. 1), i.e., 1962 (though the analysis commenced in 1964)–1966, 1973–1977, 1984–1987, 1993–1997, and 2004–2010. Thus, these results again show the different contribution of streams and CME-associated flows at solar minimum and maximum, though CME-associated flows tend to be responsible for the most severe storms throughout the solar cycle. This conclusion is consistent with other studies, such as that of Zhang et al. (2007) which found that only ~13% of intense (Dst < -100 nT) geomagnetic storms in 1996–2005 were driven by streams, while the remainder involved CME-associated flows (ICMEs and/or upstream sheaths) (see also Echer et al. 2008).

Geomagnetic indices

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



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

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Figure from https://auroraborealisobservatory.com/2020/12/28/the-kp-index-any-good-for-aurora-chasing/

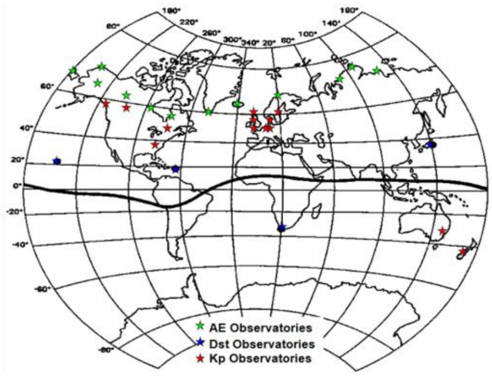
Table from GFZ/Potsdam: https://isgi.unistra.fr/indices_kp.php
The three-hour index ap and the daily indices *Ap*, … are directly related to the *Kp* index. In order to obtain a linear scale from *Kp*, J. Bartels gave the [above] table to derive a three-hour equivalent range, named ap index. This table is made in such a way that at a station at about dipole latitude 50 degrees, *ap* may be regarded as the range of the most disturbed of the two horizontal field components, expressed in the unit of 2nT.

On the aa-index: F. De Meyer (2006): The geomagnetic aa index as precursor of solar activity www.meteo.be/meteo/download/de/520427/pdf/
The availability of magnetic records from two old observatories, Greenwich (51.5° N,0.0° E) and Melbourne (37.8° S,145.0° E), which are almost antipodal, gave the possibility of obtaining a reliable long series if K scalings were made on their records (Mayaud, 1972). The two stations are nearly at the same geomagnetic latitude (one in the northern hemisphere, Greenwich: 50.1°, and one in the southern hemisphere, Melbourne: {48.9°) and about 10 h apart in longitude. The K indices from these two observatories at sub-auroral latitudes were first standardized for the corrected geomagnetic latitude of 50° in order to obtain a value identical with the one that would be obtained at a distance of 19° from the auroral zone. The converted equivalent amplitudes ak of the two stations were then averaged to provide the three-hourly index aa (expressed in units of nanotesla), which aims at monitoring the average intensity of the transient magnetic variations at sub-auroral latitudes.

More information on the aa-index (1868 – present) also at BGS: http://www.geomag.bgs.ac.uk/data_service/data/magnetic_indices/aaindex.html and ISGI: https://isgi.unistra.fr/

Geomagnetic indices

- Dst
  - Disturbance storm-time 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…



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Source: Love J.J., Remick K.J. (2007) Magnetic Indices. In: Gubbins D., Herrero-Bervera E. (eds) Encyclopedia of Geomagnetism and Paleomagnetism. Springer, Dordrecht
https://doi.org/10.1007/978-1-4020-4423-6_178
https://geomag.usgs.gov/downloads/publications/Magnetic_Indices.pdf

One of the most systematic effects seen in ground-based magnetometer data is a general depression of the horizontal magnetic field as recorded at near-equatorial observatories (Moos, 1910). This is often interpreted as an enhancement of a westward magnetospheric equatorial ring current, whose magnetic field at the Earth's surface partially cancels the predominantly northerly component of the main field. The storm-time disturbance index Dst (Sugiura, 1964) is designed to measure this phenomenon. Dst is one of the most widely used indices in academic research on the magnetosphere, in part because it is well
motivated by a specific physical theory. The calculation of Dst is generally similar to that of AE, but it is more refined, since the magnetic signal of interest is quite a bit smaller. One-min resolution horizontal intensity data from low-latitude observatories are used, and diurnal and secular variation baselines are subtracted. A geometric adjustment is made to the resulting data from each observatory so that they are all normalized to the magnetic equator.
The average, then, is the Dst index. It is worth noting that, unlike the other indices summarized here, Dst is not a range index.

The 4 stations are Kakioka (Japan), Hermanus (South Africa), Honolulu (Hawaii, USA), San Juan (USA).

Geomagnetic indices

- Dst
  - Disturbance storm-time index
    - Severity of magnetic storms
  - Depression of the intensity of the H-component
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  - Measured by 4 stations close to magnetic equator
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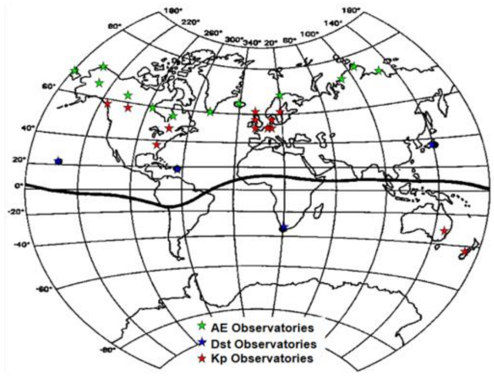

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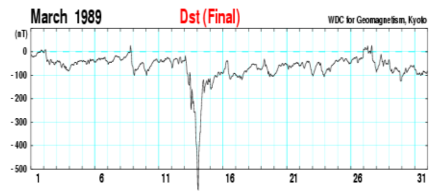
From the SIDC SWx Forecast Guide:
http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf
The Dst or disturbance storm time index is a measure of geomagnetic activity used to assess the severity of magnetic storms. It is often considered to reflect variations in the intensity of the symmetric part of the ring current that circles Earth at altitudes ranging from about 3 to 8 Earth radii (RE), and is proportional to the total energy in the drifting particles that form the ring current (Wanliss et al. 2006, and references therein). It is calculated as an hourly index from the horizontal magnetic field component (H) at four observatories located close enough to the magnetic equator that they are not strongly influenced by auroral current systems. At the same time, these stations are far enough away from the magnetic equator so that they are not significantly influenced by the equatorial electrojet current that flows in the ionosphere. They are also relatively evenly spaced in longitude … . The convolution of their magnetic variations forms the Dst index, measured in nT, which is thought to provide a reasonable global estimate of the variation of the horizontal field near the equator.

So: Dst represents an induced magnetic field caused by the ring current particles, which are plasmasheet particles that are accelerated towards Earth during (sub)storms, where electrons rotate around Earth in one sense, and the ions in the other sense (as in the radiation belts) thus creating a current.

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

- Most intense storms of SC24
  - 17 March 2015 (-234 nT)
  - 23 Jun 2015 (-198 nT)
- Most intense storms of SC25
  - ***10-11 May 2024 (-406 nT)***
  - *10-11 October 2024 (-333 nT)*
- Extreme storms
  - 30 October 2003: -383 nT
  - 14 March 1989: -589 nT
  - Carrington event: ~ -850 nT
  - 15 May 1921: ~ -907 nT



Real time monitoring at http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html
See also https://www.stce.be/educational/classification

A description on how the Dst index is determined can be found at http://wdc.kugi.kyoto-u.ac.jp/dstdir/dst2/onDstindex.html
3. INTERPRETATION OF THE Dst INDEX
The Dst index represents the axially symmetric disturbance magnetic field at the dipole equator on the Earth's surface. Major disturbances in Dst are negative, namely decreases in the geomagnetic field. These field decreases are produced mainly by the equatorial current system in the magnetosphere, usually referred to as the ring current. The neutral sheet current flowing across the magnetospheric tail makes a small contribution to the field decreases near the Earth. Positive variations in Dst are mostly caused by the compression of the magnetosphere from solar wind pressure increases.

Reminder: Dst represents an induced magnetic field caused by the ring current particles, which are plasmasheet particles that are accelerated towards Earth during (sub)storms, where electrons rotate around Earth in one sense, and the ions in the other sense (as in the radiation belts) thus creating a current.

Geomagnetic indices

- Dst
  - Phases of a geomagnetic storm
    - Initial phase
    - Main phase
    - Recovery phase
  - Main advantages compared to Kp
    - Open-ended
    - Higher time-resolution
      - 1h vs 3h
    - Captures also the decreasing end of a storm
      - Ring current vs global MF

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Real time monitoring at http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html

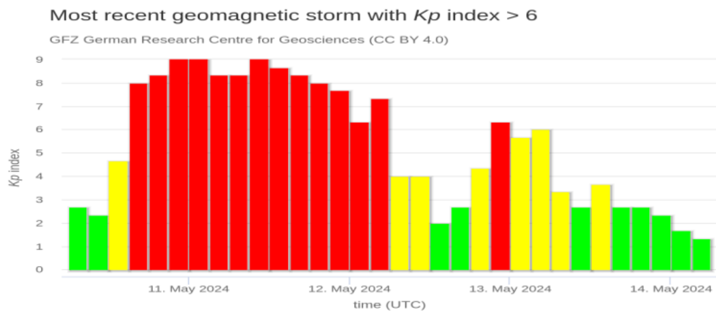
From the SIDC SWx Forecast Guide:
http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf
Magnetic storms occur when the number and energy of positive ions and electrons drifting in the outer radiation belts increase significantly. Since electrons and protons drift in opposite directions they produce a ring current around the Earth. The direction of this current is westward causing a decrease in the surface field. The Dst index is a measure of the total energy of these drifting particles. A magnetic storm typically consists of three phases (Figure above). The initial phase is a result of an increase in solar wind dynamic pressure. This increase presses the magnetopause current closer to the Earth causing a positive perturbation in H. The main phase is a consequence of a southward turning of the interplanetary magnetic field (IMF). When the IMF turns southward, magnetic reconnection occurs on the dayside allowing a fraction of the solar wind electric field to penetrate the magnetosphere. This field transports ions from the tail to the inner magnetosphere where they are trapped in the ring current, causing the Dst index to become more negative. The recovery phase is a consequence of the IMF turning northward shutting off the magnetospheric electric field. Particle injection decreases while the drifting ions charge exchange with atmospheric neutral particles losing their energy and thereby decreasing the strength of the ring current (McPherron et al. 2001)

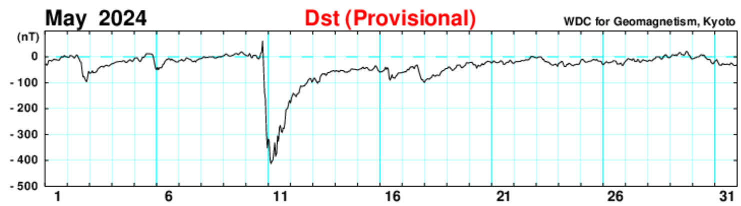
From the SWPC glossary: https://www.swpc.noaa.gov/content/space-weather-glossary#suddenimpulse
Sudden Impulse (SI): A sudden perturbation, positive or negative, of several nanotesla in the northward component (X component of the horizontal component) of the low-latitude geomagnetic field, *not* associated with a following geomagnetic storm. An SI becomes a Storm Sudden Commencement (SSC) if a storm follows.

SWPC sends alerts for these SI: https://www.swpc.noaa.gov/content/subscription-services
A Geomagnetic Sudden Impulse (SI) Expected Warning is issued when a shock has been observed in the upstream, in situ solar wind data. Based on the post-shock velocity, space weather forecasters generate a warning period indicative of when this disturbance is expected at Earth. The Geomagnetic Sudden Impulse Summary product is issued when the shock is actually observed at Earth, as indicated by the response of ground-based magnetic observatories. These products are useful in that they can confirm the actual arrival of anticipated coronal mass ejection (CME).

The great storm of 10-11 May 2024

(preliminary values)





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From the SIDC Weekly Bulletin for the week of 06-12 May 2024

Solar wind -------------------- … Earth came under the influence of strongest ICMEs in 20 years on the evening of May 10. The first shock was detected in the solar wind data around 16:42 UTC on May 10. The interplanetary magnetic field jumped from 4 nT to 44 nT, the solar wind speed jumped from 460 km/s to 700 km/s and the solar wind density at the shock increased from 5/cm3 to 30/cm3. The second shock was observed on around 21:39 UT on May 10. The solar wind speed increased as high as 800 km/s, the interplanetary magnetic field increased as high as 74 nT, and Bz component decreased as low as -50 nT. These two shocks were related to the CMEs observed during May 08-09, and possibly two to four associated ICMEs arrived at Earth during May 10-11. The third shock-like structure was detected in the solar wind data around 17:55 UTC on May 11. The interplanetary magnetic field jumped from 8 nT to 47 nT, the solar wind speed jumped from 800 km/s to 895 km/s. The fourth shock-like structure was detected around 08:59 UTC on May 12. The interplanetary magnetic field jumped from 5 nT to 12 nT, the solar wind speed jumped from 830 km/s to 900 km/s. The fifth shock-like structure was observed on 08:58 UTC on May 12, during which the speed increased from 830 km/s to 850 km/s and the interplanetary magnetic field increased from 5 nT to 12 nT. These three shock-like structures were probably related to the arrival of ICMEs associated with CMEs observed during May 09-11. HSS originating from two CHs, which started to cross the central meridian on May 08, also possibly started to arrive at Earth on May 11. With the arrival of multiple ICMEs and HSS, the solar wind speed increased as high as about 1000 km/s. By the end of the week, the solar wind speed was about 830 km/s and the interplanetary magnetic field returned to stable with a magnitude below 5 nT.

Geomagnetism -------------------- … Geomagnetic conditions were globally at severe to extreme storm levels (NOAA Kp 8 to 9) from 15:00 UTC on May 10 to 16:00 UTC on May 11, and then remained at major storm levels until the end of the past week. Locally over Belgium, geomagnetic conditions were at severe storm levels (K BEL=8) from 17:00 UTC on May 10 to 01:00 UTC on May 11 and again from 09:00 UTC to 14:00 UTC on May 12, reaching the extreme storm levels (K BEL=9) from 11:00 UTC to 12:00 UTC on May 12. This was due to the arrival of multiple interplanetary coronal mass ejections (ICMEs), associated to CMEs observed during May May 08-11, as well as due to the arrival of high speed streams originating from coronal holes that started to cross the central meridian on May 08. At the end of the past week, geomagnetic conditions was at active conditions (K BEL=4) locally over the Belgium.

: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

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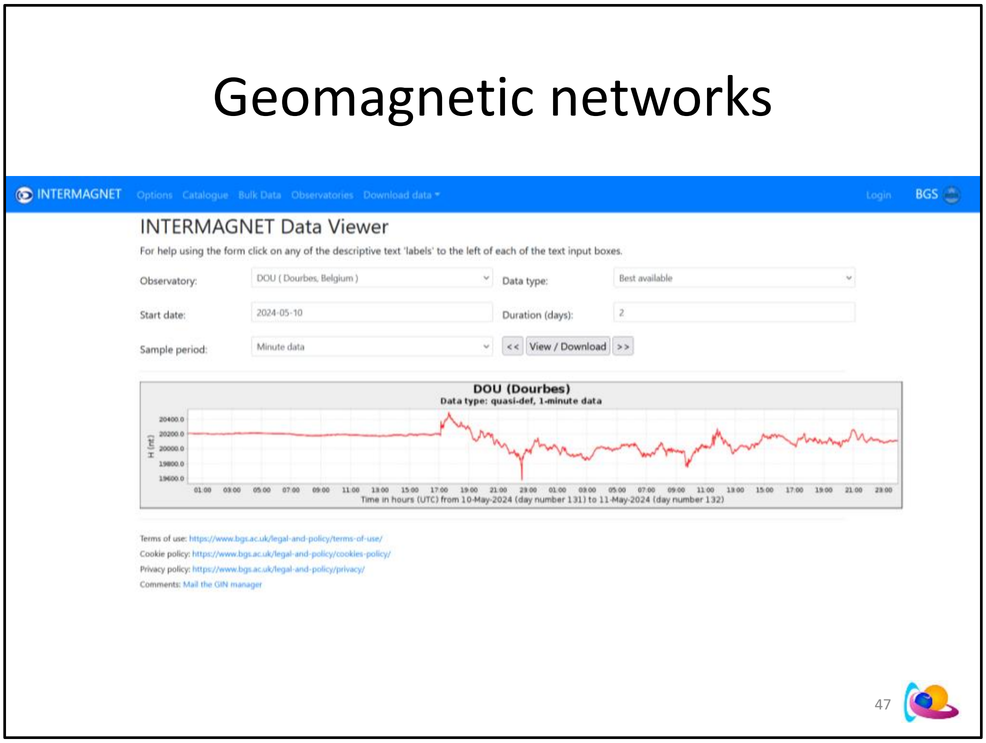

Dourbes: http://ionosphere.meteo.be/geomagnetism/ground_K_dourbes
K_BEL: http://ionosphere.meteo.be/geomagnetism/K_BEL/

An important network of geomagnetic observatories is « Intermagnet » (maintained by BGS: British Geological Survey)
https://imag-data.bgs.ac.uk/GIN_V1/GINForms2

INTERMAGNET has its roots in discussions held at the Workshop on Magnetic Observatory Instruments in Ottawa, Canada, in August 1986 and at the Nordic Comparison Meeting in Chambon La Foret, France, in May 1987. A pilot scheme between the United States and British Geological Surveys was described in the sessions of Division V of the International Association of Geomagnetism and Aeronomy at the 19th General Assembly of the International Union of Geodesy and Geophysics in Vancouver, Canada, in August 1987. This scheme used the GOES East satellite to successfully transfer geomagnetic data between the two organisations. INTERMAGNET was founded soon after in order to extend the network of observatories communicating in this way. In order to direct the work and oversee the operations of INTERMAGNET, an Executive Council and an Operations Committee were set up. The first Geomagnetic Information Node (GIN) was established in 1991, the first CD-ROM/DVD was also published in 1991.

Other important networks of geomagnetic observatories are « USGS » (USA; U.S. Geological Survey: https://geomag.usgs.gov/plots/), NRCan (https://geomag.nrcan.gc.ca/plot-tracee/sdp-en.php), and “Izmiran” (Russia; http://spaceweather.izmiran.ru/eng/forecasts.html). An overview of smaller networks is at http://flux.phys.uit.no/Last24/ , allowing also for real-time monitoring of selected stations with the tool “Stackplot” at http://flux.phys.uit.no/stackplot/

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