The Geomagnetic Field and the Magnetosphere

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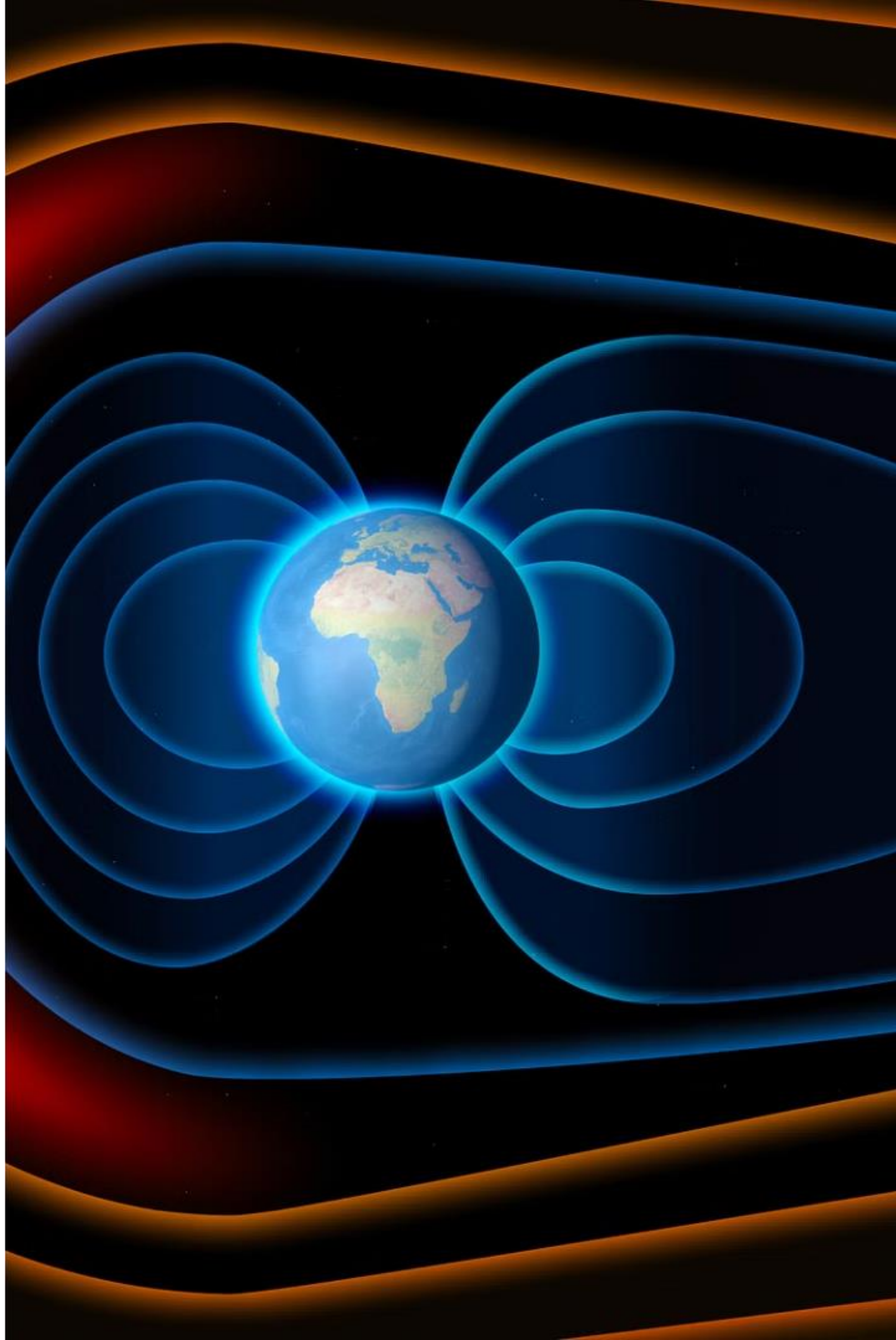


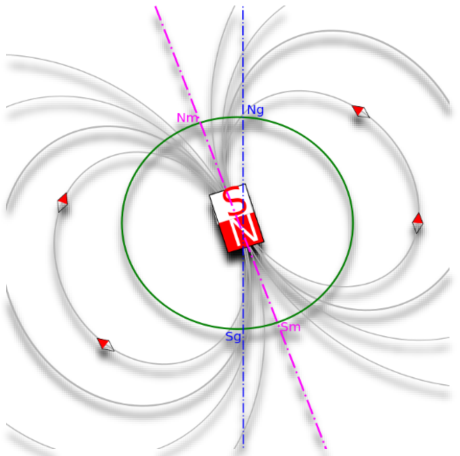
International School on **OPERATIONAL SPACE WEATHER FUNDAMENTALS**
L'Aquila, 13-17 May 2024

Key points about the Earth's Magnetic Field

1. **Our planet has had its own magnetic field for 3.8 billion years and has used for navigation in the last 1000 years**

Horizontal and vertical compass

2. **About 97-99% of the field can be approximated by a magnetic dipole, the *main field* (static or slowly changing).**
   The dipole axis is tilted at an angle of about 9.4° (as of 2020) from the Earth's spin axis.



Magnetic Field Lines

3. **The field intensity at the Earth's surface ranges from ~ 25000 nT at the equator to ~ 65000 nT at the poles**

Key points about the Earth's Magnetic Field

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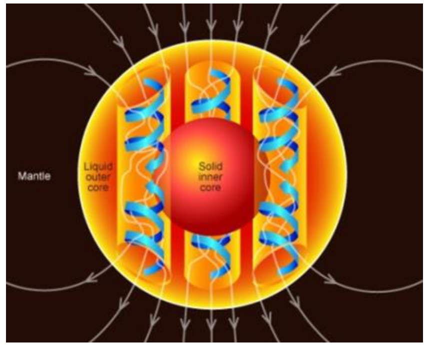
The main field (97-99%) originates in the Earth's outer core, by the motion of electrically conductive fluids (iron, nickel), driven by convection (temperature gradient from about 6000 °C at the inner core to 4000 °C at the core-mantle boundary) and Earth's rotation



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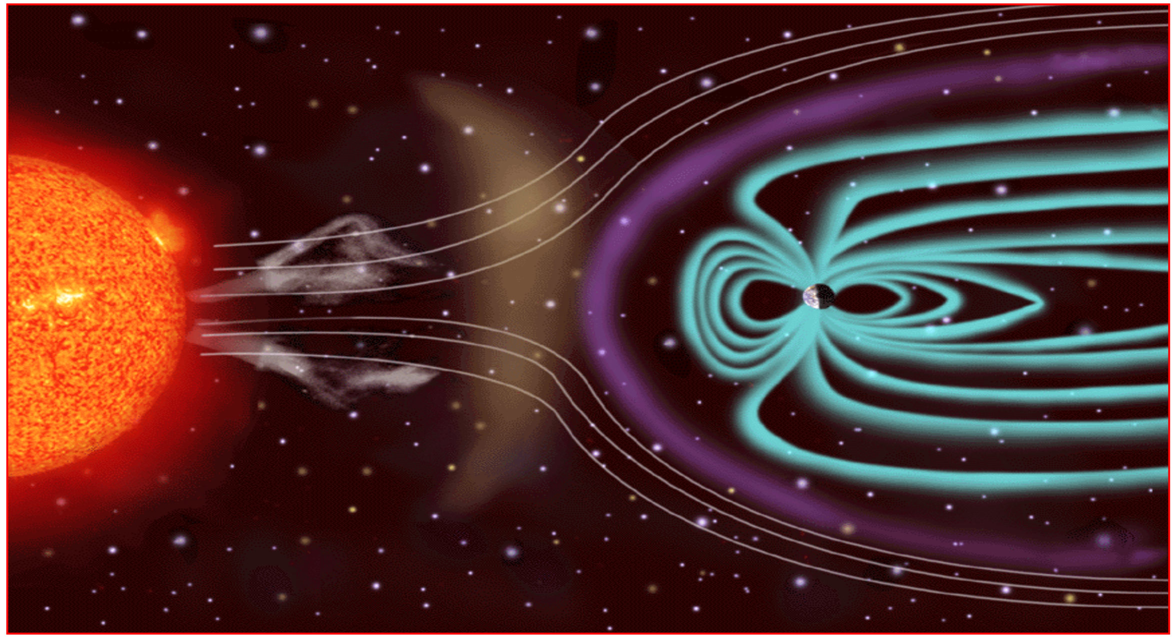
1% - 2% of the field originates in the Earth's crust

The remaining part is of external origin (interaction with the solar wind and the interplanetary magnetic field)



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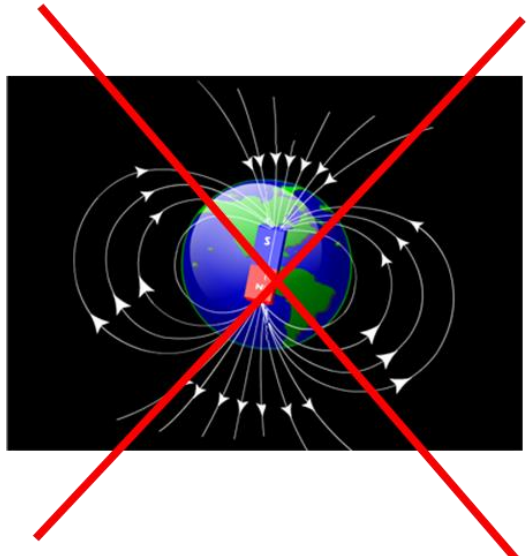
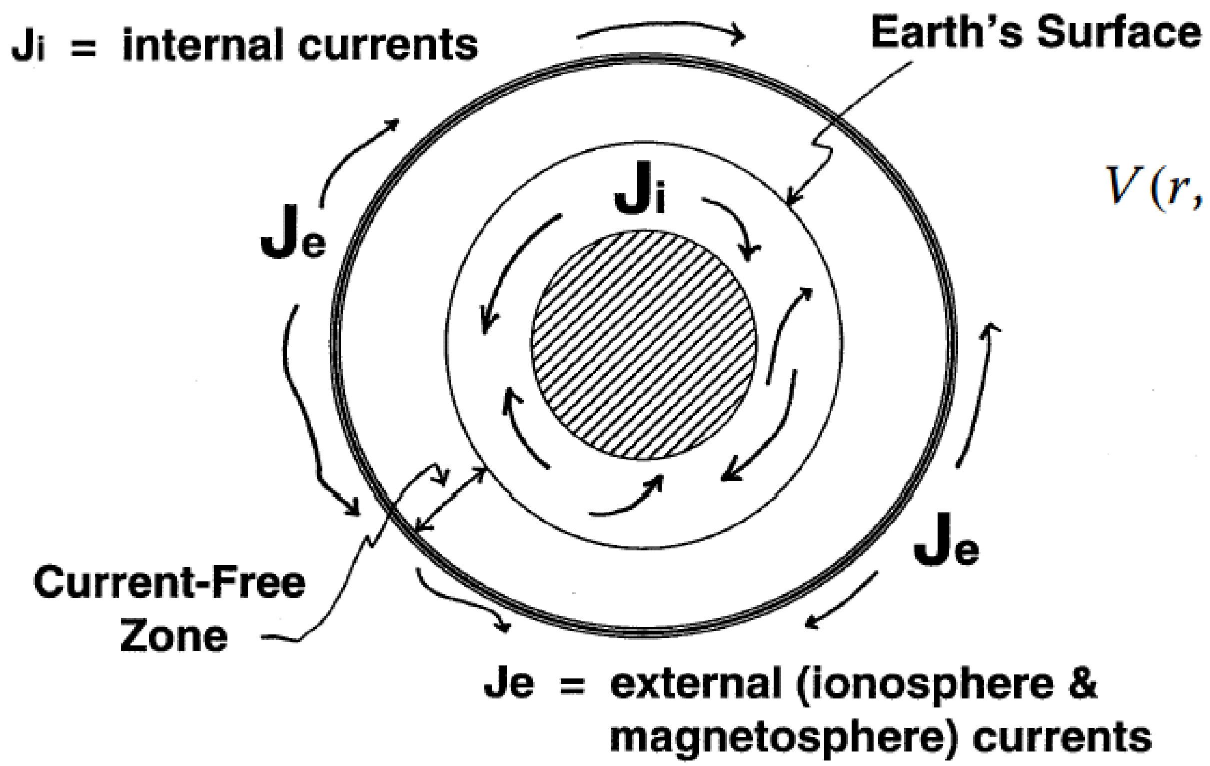
No *permanent giant magnet is* inside the Earth because of high temperature: at the depth of 25 km from the Earth surface (the Curie temperature) is reached for almost all the magnetic material)



THE SPHERICAL HARMONICS MODEL OF THE EARTH'S MAGNETIC FIELD (1/2)

The magnetic field at the surface of the earth is determined mostly by internal currents with some smaller contribution due to external currents flowing in the ionosphere and magnetosphere.

The Spherical Harmonics Model of the Earth's Magnetic Field is a mathematical representation **used to describe the complex and dynamic nature of the Earth's magnetic field**. It utilizes spherical harmonics, which are mathematical functions defined on the surface of a sphere, to approximate the magnetic field at different points on Earth's surface and in its interior.



In the current-free zone the main magnetic field can be described as the gradient of a scalar potential, **B** = −∇V, and the potential function V(r, θ, φ, t) is represented as a finite series expansion in terms of spherical harmonic coefficients, **g and h** , also known as the **Gauss coefficients**:

$$V(r,\theta,\phi,t) = a\sum_{n=1}^{N}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n+1}\left[g_n{}^m(t)\cos m\phi + h_n{}^m(t)\sin m\phi\right]P_n{}^m(\cos\theta)$$

Here, r, θ, ϕ refer to coordinates in a geocentric spherical coordinate system, with r being radial distance from the center of the Earth, and θ, ϕ representing geocentric co-latitude and longitude, respectively. A reference radius a = 6371.2 km is chosen to approximate the mean Earth radius. The P (cos θ) are Schmidt semi-normalized associated Legendre functions of degree n and order m.

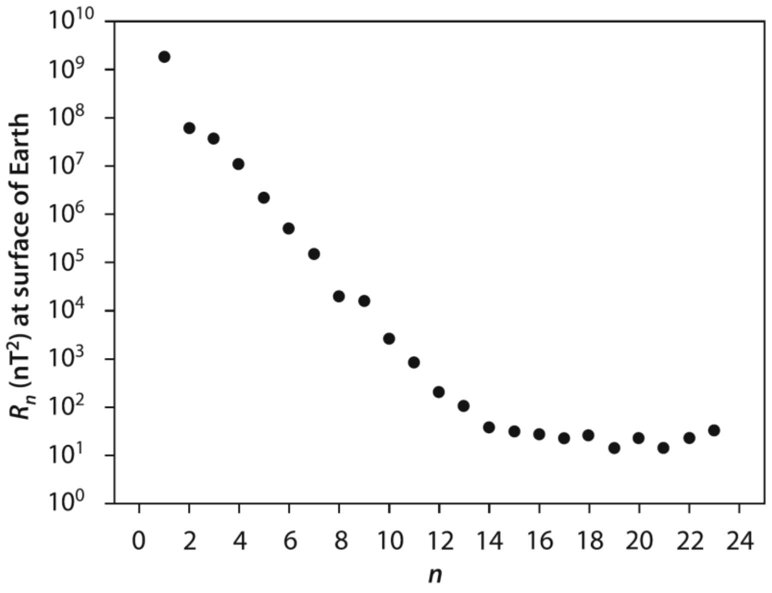
THE SPHERICAL HARMONICS MODEL OF THE EARTH'S MAGNETIC FIELD (2/2)

The **magnetic scalar potential V** can be written as a spherical harmonic expansion

The Spherical Harmonics Model of the Earth's Magnetic Field is a mathematical representation **used to describe the complex and dynamic nature of the Earth's magnetic field**. It utilizes spherical harmonics, which are mathematical functions defined on the surface of a sphere, to approximate the magnetic field at different points on Earth's surface and in its interior.

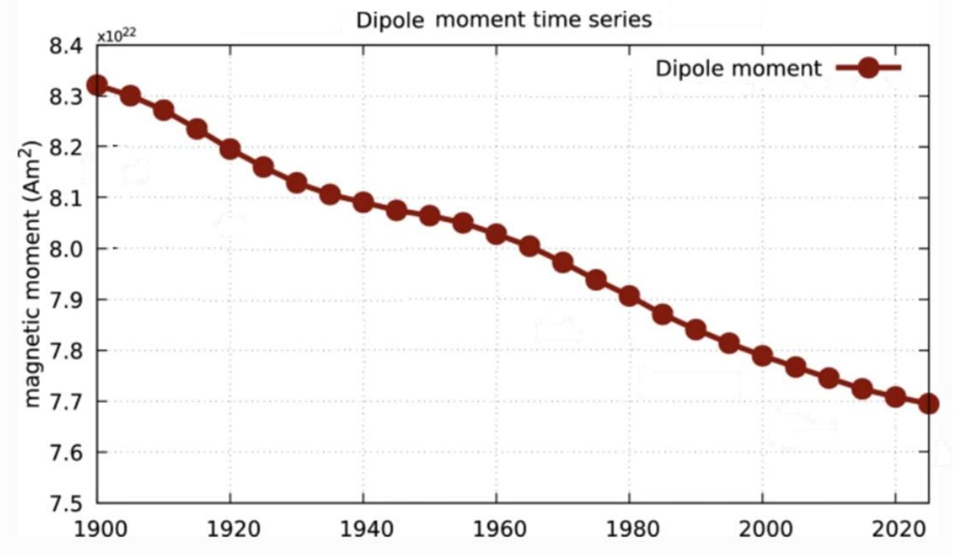
$$R_n = (n+1)\sum_{m=0}^{n}\left[(g_n^m)^2 + (h_n^m)^2\right]$$

When only internal sources are considered all contributions to the geomagnetic field, i.e. the sum of all Gauss coefficients up to a given degree *n*, can be shown on in a semi-logarithmic scale plot as a function of the order number *n. Power spectra of R reveals that*



Power spectra of R versus n reveals two contributions: the outer core (n < 10-12) and the crust (n<12)

Since 1839, when Gauss firstly computed the coefficients, the dipole magnetic moment (n = 1) has decreased from 9.6 × 10^{22} → 7.7 × 10^{22} $A \cdot m^2$ (1900 → 2020)



GEOMAGNETIC FIELD ELEMENTS and WHAT INSTRUMENTS ARE USED TO MEASURE THEM?

At any location on the Earth, the magnetic field can be represented by a vector with **intensity F**.

Its direction on the horizontal plane can be determined by a compass. The angle relative to the geographic North direction is the ***Declination (D)***.

The angle between the magnetic field and the horizontal plane is the ***Inclination (I)*** or *magnetic dip*. Both angles are measured by means of a **geomagnetic theodolite**.

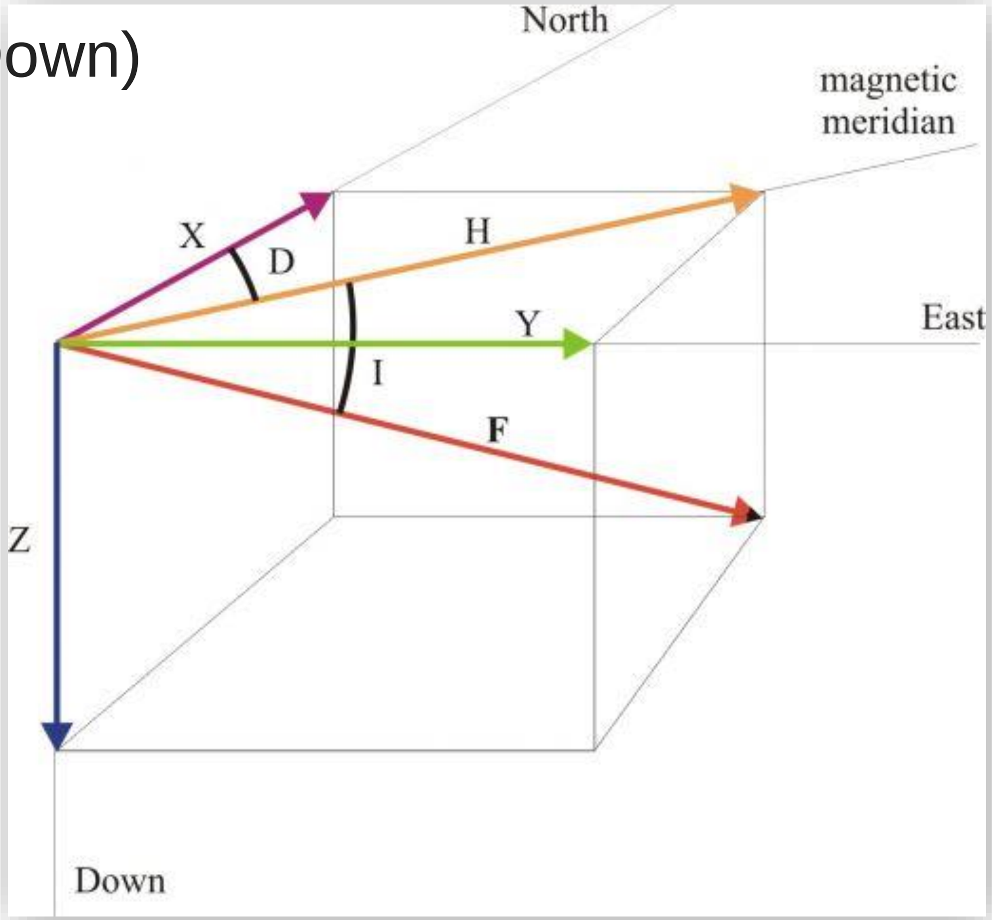
Another common representation is in *X* (North), *Y* (East) and *Z* (Down) geographic coordinates:

$$H = \sqrt{X^2 + Y^2}, \quad F = \sqrt{X^2 + Y^2 + Z^2},$$

$$D = \arctan(Y/X), \quad I = \arctan(Z/H).$$

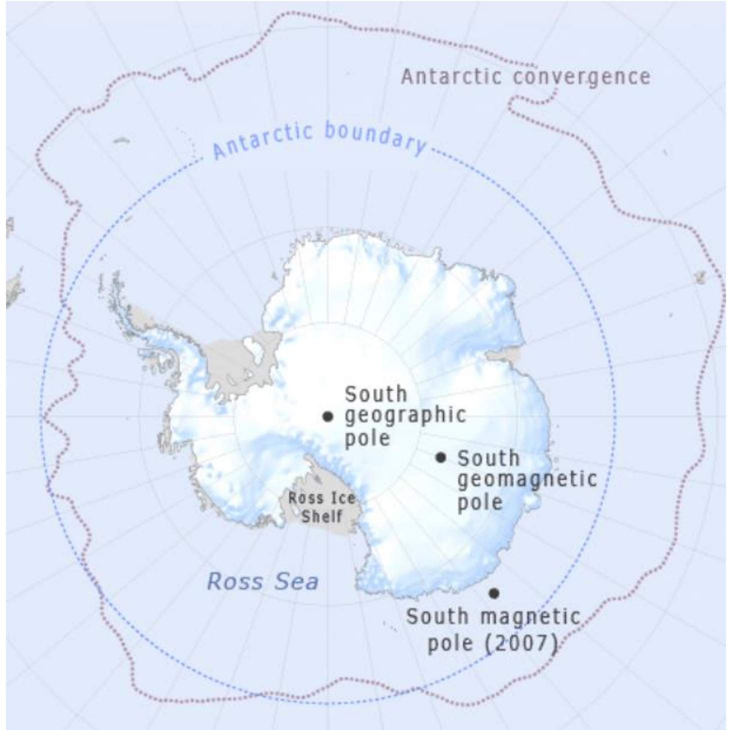
Vector Magnetometer

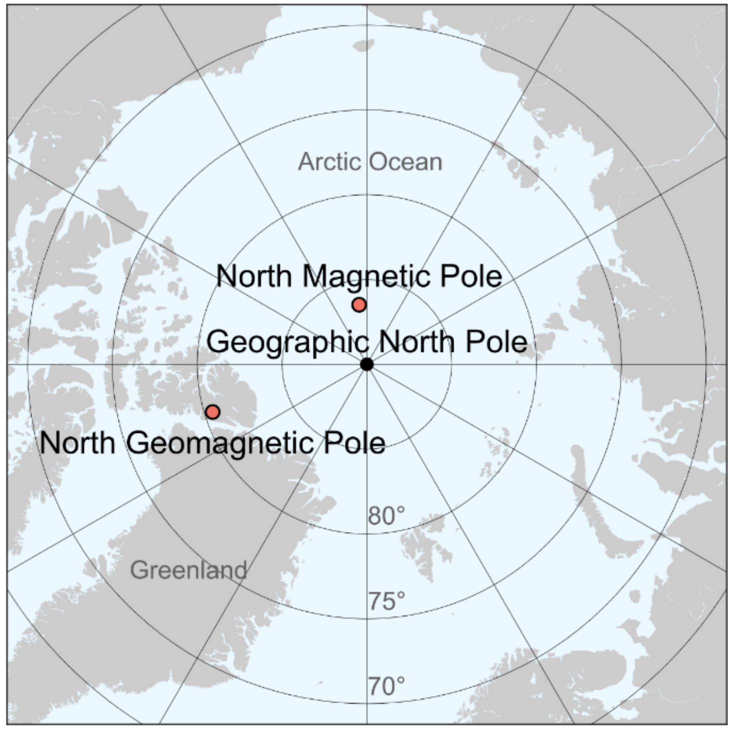
Scalar Magnetometer

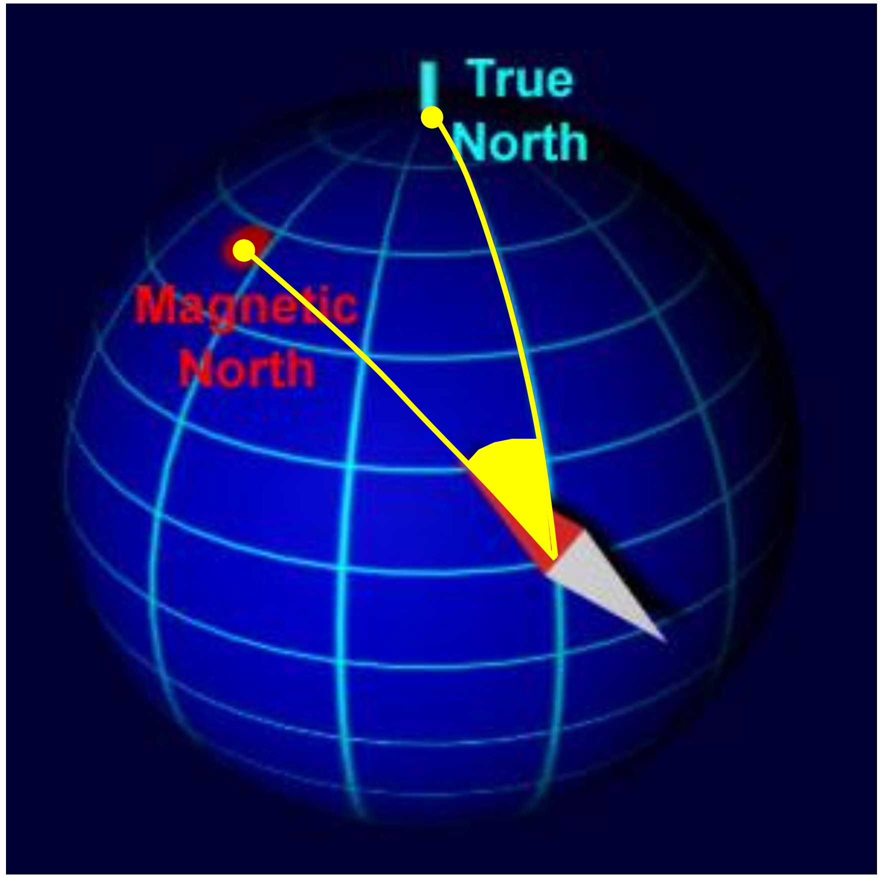


GEOMAGNETIC FIELD ELEMENTS ON THE GLOBE

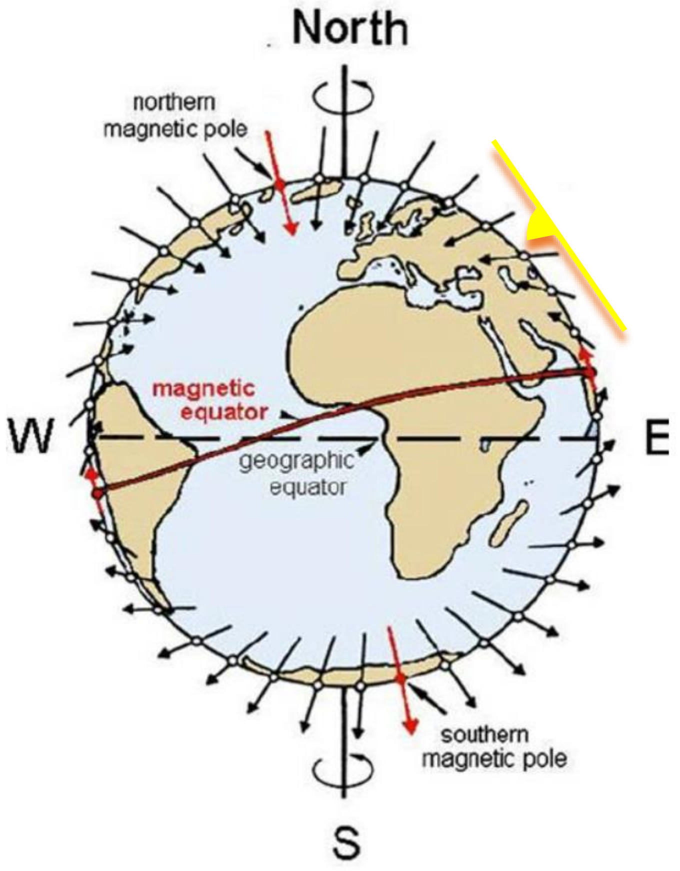
The magnetic poles or dip poles, the points where the magnetic field lines are vertical, are slightly offset from the geographic poles. The magnetic equator, where the magnetic field lines are horizontal, also differs from the geographic equator.





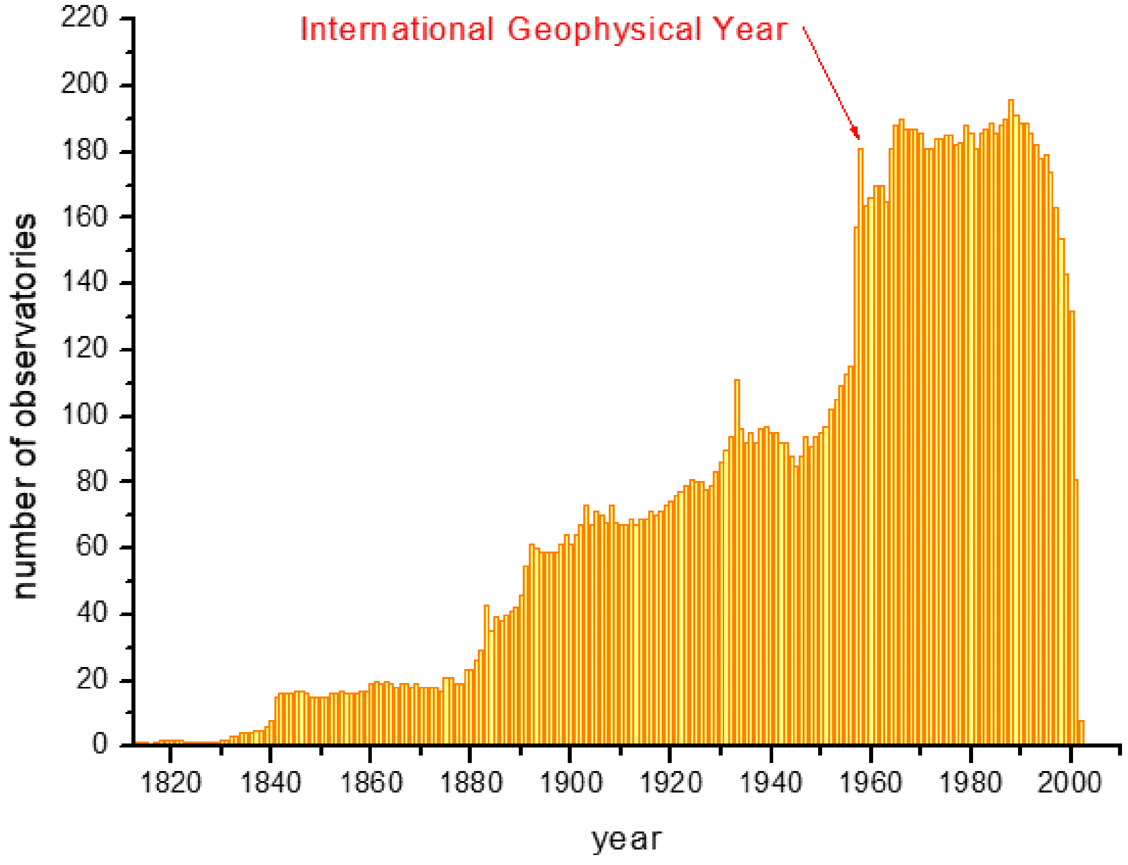


MAGNETIC DECLINATION



MAGNETIC INCLINATION

OBSERVING THE GEOMAGNETIC FIELD



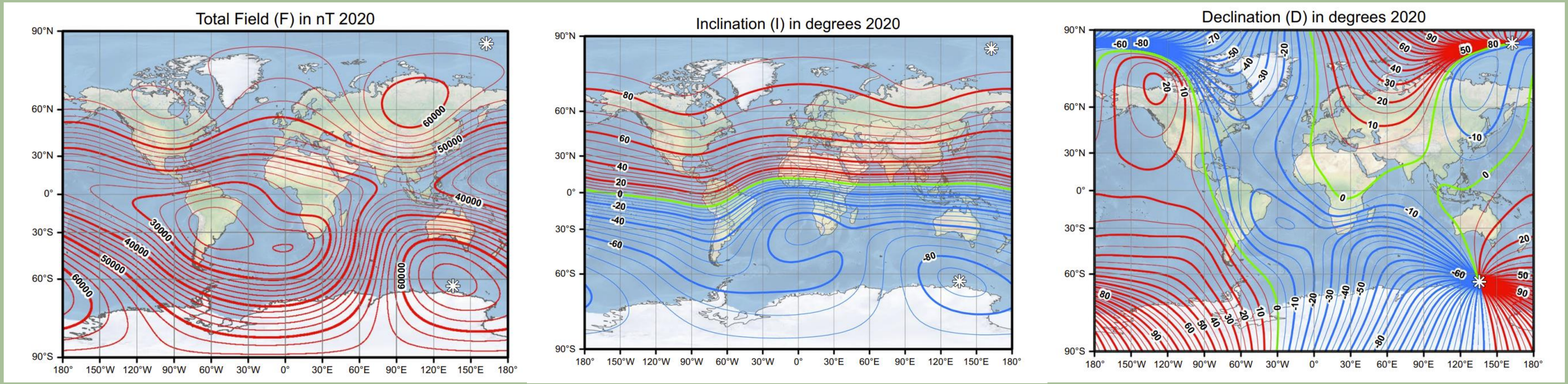
The growth in numbers of the OBSs around the world

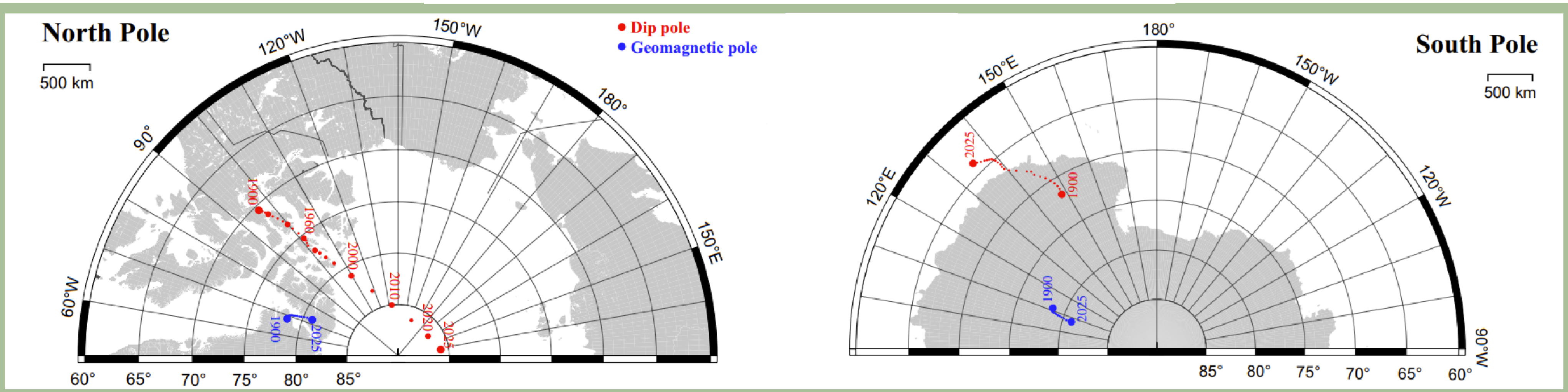
Distribution of the geomagnetic OBSs in the world

Constellation of satellites dedicated to the Eart's magnetic field recording ESA - Swarm

Topology of the Earth’s magnetic field

Components of the Earth's magnetic field at the surface from the IGRF model (13th generation) for 2020





Alken, P., Thébault, E., Beggan, C.D. *et al.* International Geomagnetic Reference Field: the thirteenth generation. *Earth Planets Space* 73, 49 (2021). https://doi.org/10.1186/s40623-020-01288-x

A geomagnetic observatory is an amagnetic, topographically stable infrastructure far from:

- **anthropogenic disturbances (railways, power plants, etc.)**
- **crustal magnetic anomalies (volcanic areas)**

where automatic recordings are collected and absolute measurents are routinely manually performed.

Shelter for absolute measurements (Declination, Inclination and scalar F intensity)

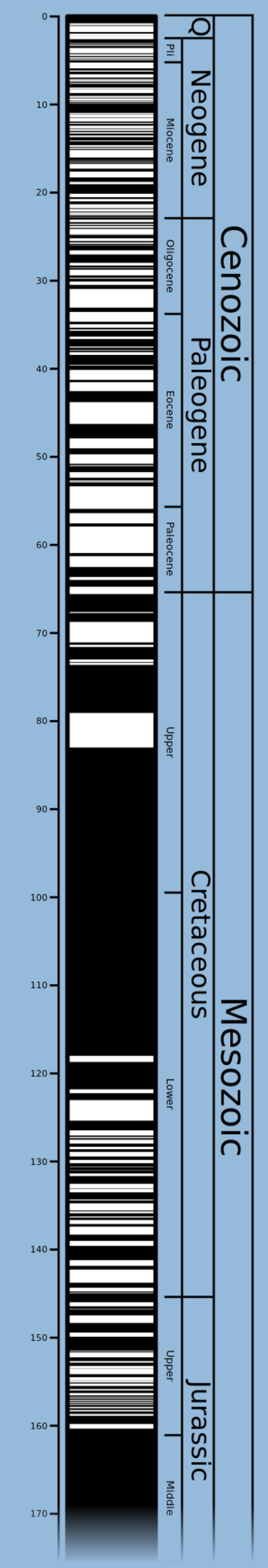
Shelter for automatic recordings (X, Y and Z, additional scalar F intensity)

CONCORDIA Geomagnetic observatory, Italy and France, DOME C - Antarctica

WHY IS THE GEOMAGNETIC FIELD IS CONTINUOUSLY MONITORED? BECAUSE IT CONTINUOSLY CHANGES IN A HUGE TIME SCALE RANGE….

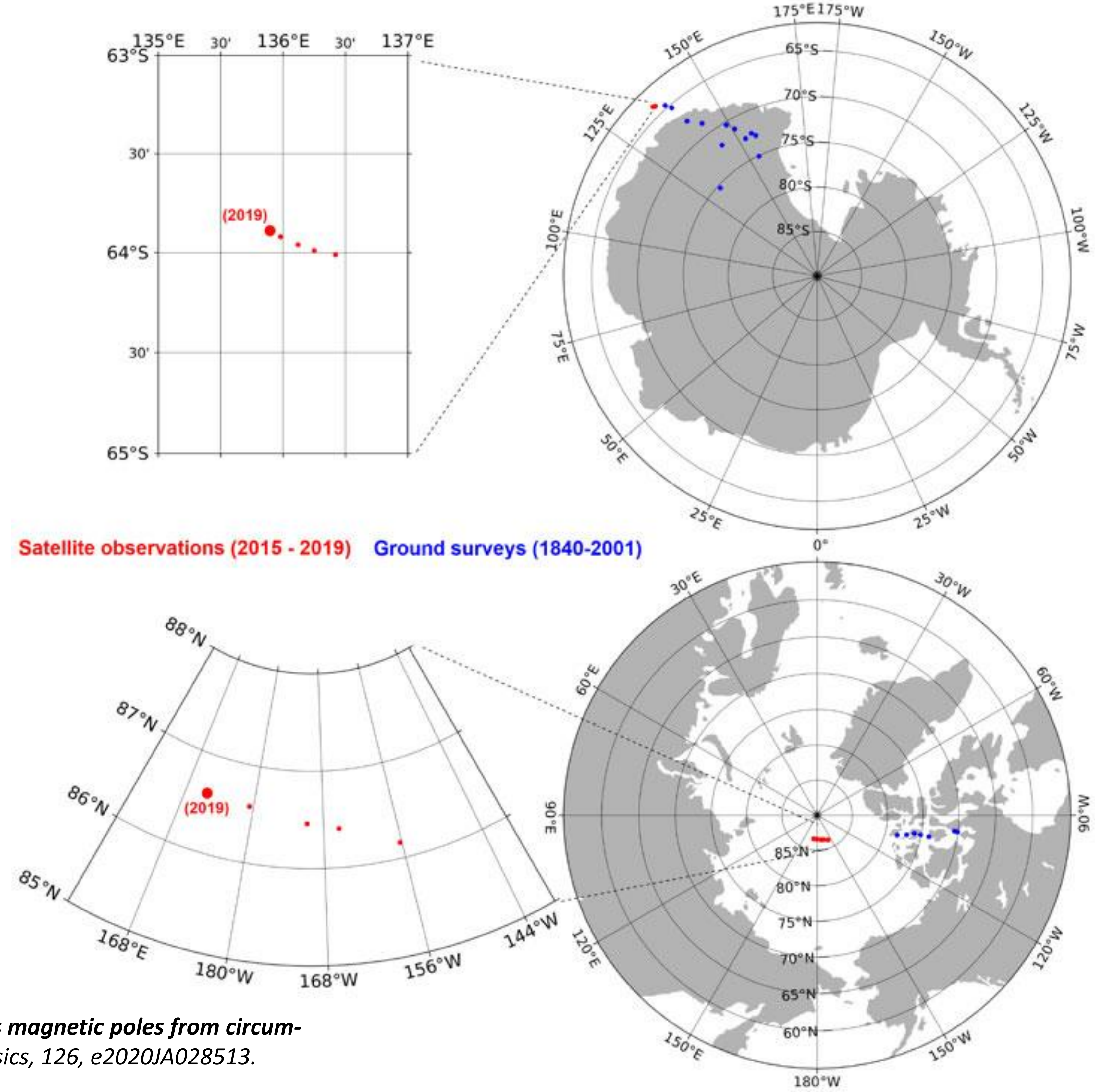
EARTH'S MAGNETIC FIELD TIME VARIATIONS AND RELATED INFORMATION

		DENOMINATION	SOURCE LOCATION	MAXIMUM INTENSITY	MORPHOLOGY	CHARACTERISTIC TIME	VARIATION ORIGIN	DETECTION
INTERNAL EARTH CONTRIBUTION		MAIN FIELD	FLUID CORE (1230- 3500 km from Earth's center)	Average 45000-nT (25000 to70000 nT)	DIPOLAR + MULTIPOLAR	Existing since 3.8 Gyears POLARITY REVERSALS ($10^5$$10^6$ YEARS) SECULAR VARIATION (T > 1-100/nT YEAR)	ELECTRICAL CURRENTS AND (MHD) WAVES IN CONVECTIVE AND TURBOLENT REGIME IN THE FLUID CORE	SURVEYS (GEOMAGNETIC OBSERVATORIES, SHIPS AEROMOBILE AND SATELLITE SURVEYS) ROCK MAGNETISM
		LOCAL FIELD	EARTH'S CRUST down to Curie point temeperature depths	200 nT (AVERAGE WITH MAXIMA AROUND 10^4 nT)	Mainly locally dipolar and IRREGULAR (down to scales of a few m)	Oldest magnetized rocks 3.8 Gyears Stable on Geological time scale	Ferromagnetic minerals and magnetic induction in the crust	LOCAL SURVEYS SHIP AEROMOBILE AND SATELLITE SURVEYS) ROCK MAGNETISM
EXTERNAL EARTH CONTRIBUTION	IRREGULAR TIME VARIATIONS	MAGNETIC STORM	MAGNETOSPHERIC CURRENTS	Dst 100-200 nT (500 nT max)	FIELD UNIFORM ON A GLOBAL SCALE, LATITUDE DEPENDENT	FROM 4 TO 12 HOURS; RECOVERY PHASE GOES FROM 1 TO 3 DAYS	SOLAR WIND INTERACTION WITH MAGNETOSPH. AND IONOSPHERIC PLASMA	
		SUBSTORMS (BAYS AT MID LATITUDES)	IONOSPHERIC AND FIELD ALIGNED ELECTRIC CURRENTS	100 nT (200 nT IN AURORAL ZONE	UNIFORM ON A LOCAL SCALE STRONGLY LATITUDE DEPENDENT	5 TO 100 MINUTES	SOLAR WIND INTERACTION WITH MAGNETOSPH. AND IONOSPHERIC PLASMA	GEOMAGNETIC OBSERVATORY MAGNETOGRAMS, TEMPORARY STATIONS AND SATELLITES
		PULSATIONS Continuous/Irregular	MHD MAGNETOSPHERIC WAVES AND CURRENTS FIELD LINE OSCILLATIONS	Few nT (max100 nT in AURORAL ZONE	ALMOST UNIFORM FILD, MORE INTENSE IN AURORAL ZONES Quasi periodic	Pc1: 0.2-5 sec Pc2: 5-10 sec Pc3: 10-45 sec Pc4: 45-150 sec Pc5: 150-600 sec Pi1: 1-40 sec Pi2: 40-150 sec Pg : Giant Pulsations	FIELD LINES RESONANCE IN MAGNETOSPHERE	
	REGULAR TIME VARIATIONS	DIURNAL VARIATION	TIDAL IONOSPHERIC CURRENTS	50-100 nT (200 nT in equatorial zone)	UNIFORM FIELD MORE INTENSE IN EQUATORIAL ZONE	T = 24, 12, 8, 6 HOURS		
		SOLAR	PHOTOIONIZATION	10-50 nT	UNIFORM	STRONG SEASONAL AND SOLAR CICLE CONTROL	IONOSPHERIC TIDES	GEOMAGNETIC OBSERVATORY MAGNETOGRAMS,
		LUNAR	ATMOSPHERIC TIDES	2-5 nT	UNIFORM	T = 24h 50m LUNAR		
INTERNAL EARTH SECONDARY CONTRIBUTION		EM INDUCTION BY EXTERNAL TIME VARIATION	CONTINENTAL AND OCEANIC CRUST AND UPPER MANTLE	SMALLER AMPLITUDE THAN PRIMARY; MAINLY IN Z	UNIFORM WITH IRREGULAR MORPHOLOGY	SIMILAR TO EXTERNAL PRIMARY, PHASE SHIFTS	ELECTROMAGN. INDUCTION BY PRIMARY EXTERNAL TIME VARIATIONS	GEOMAGNETIC OBSERVATORY MAGNETOGRAMS, TEMPORARY STATIONS



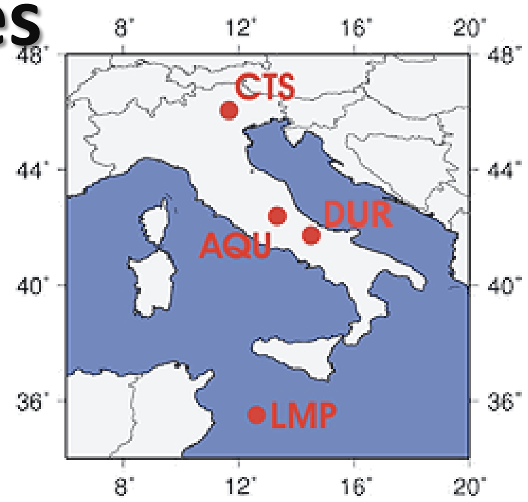
EVERYTHING CHANGES, EVEN THE MAGNETIC POLE POSITIONS….

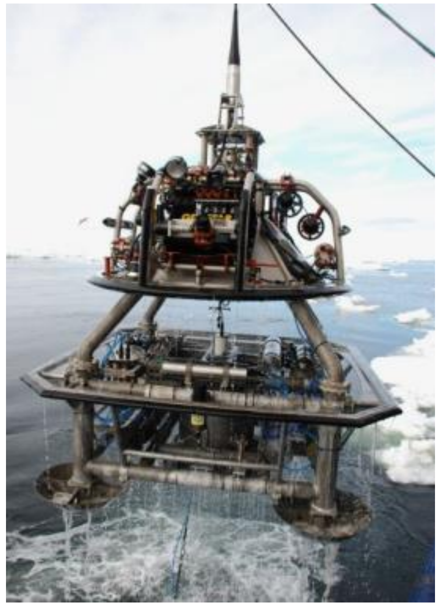
The magnetic poles move in a northwest direction at different speeds. While the North Magnetic Pole moves at a speed of approximately 37-72 km per year, the South Pole moves at about 5-9 km per year, eight times slower.

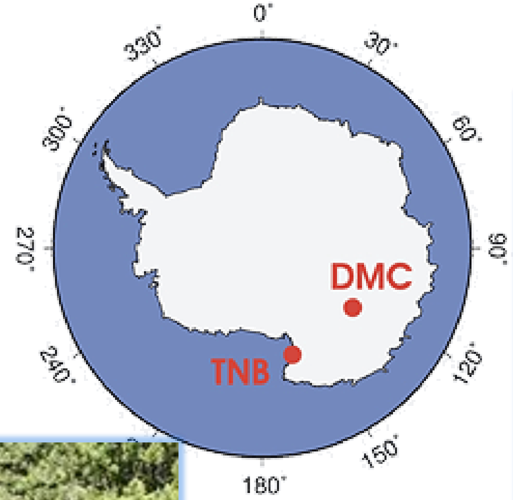


Regi, M., Di Mauro, D., & Lepidi, S. (2021). ***The location of the Earth's magnetic poles from circum-terrestrial observations.*** *Journal of Geophysical Research: Space Physics, 126, e2020JA028513.*

The Italian Geomagnetic Observatories in Italy and in Antarctica

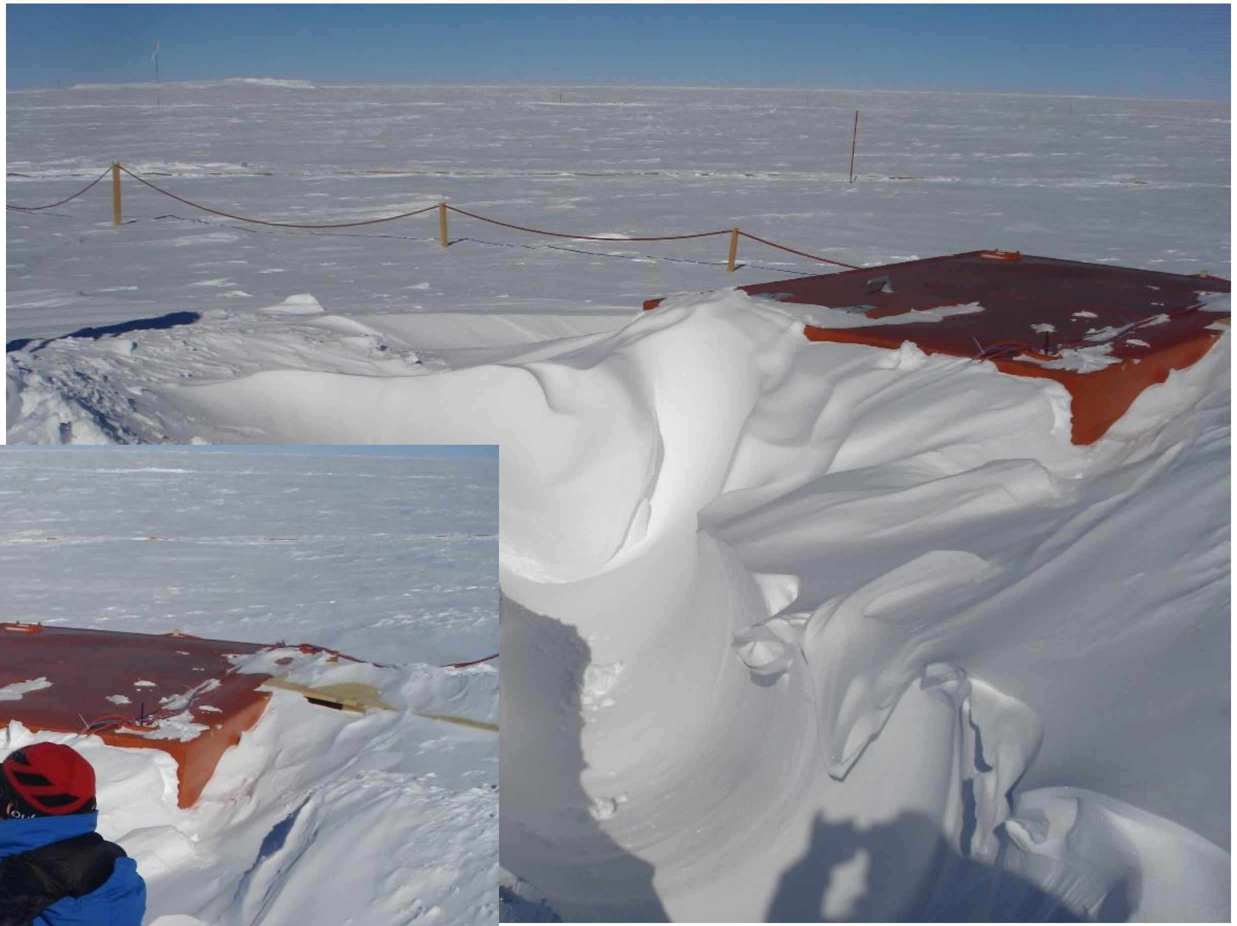


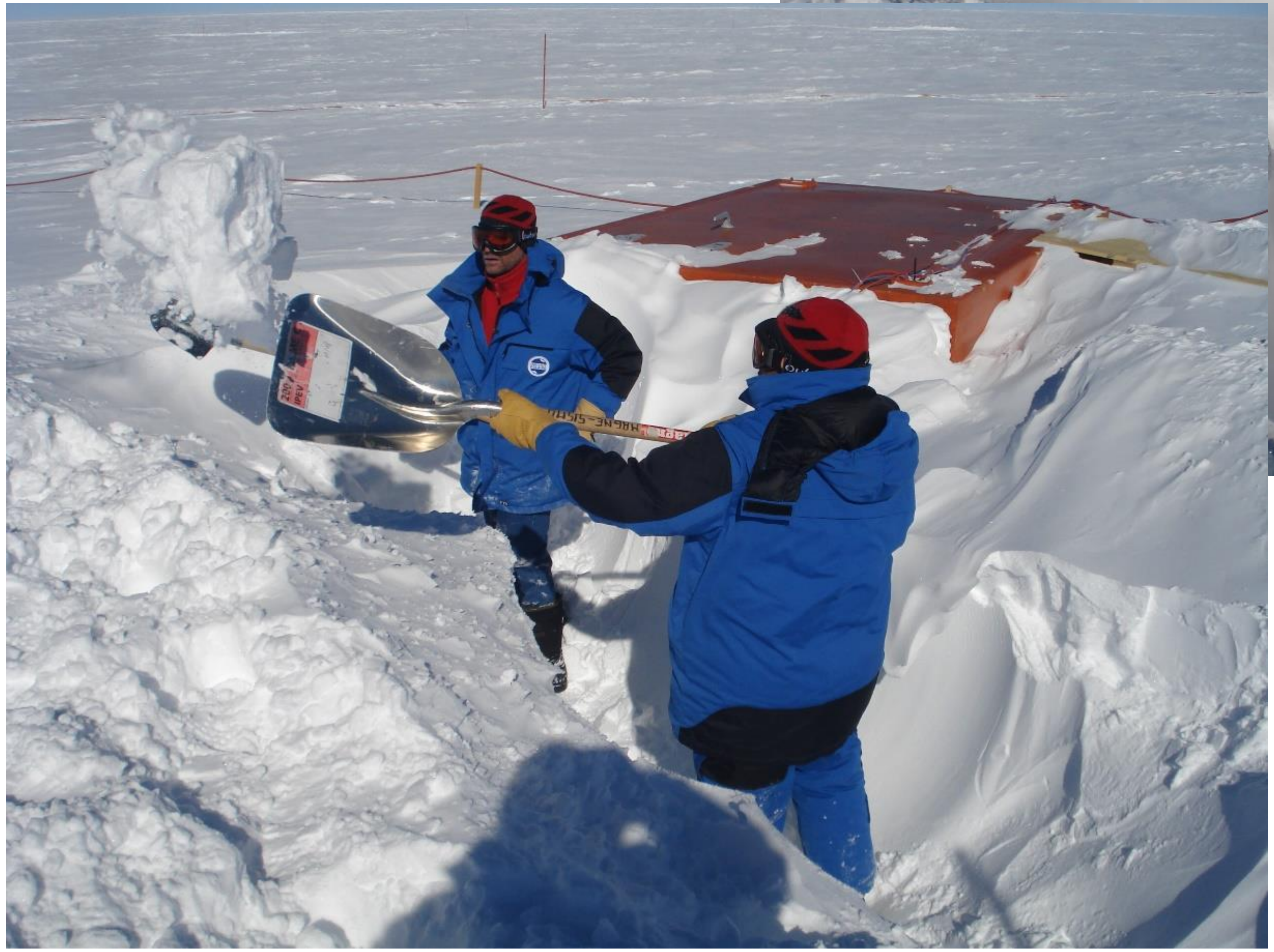




Geomagnetic Observatory in Lampedusa

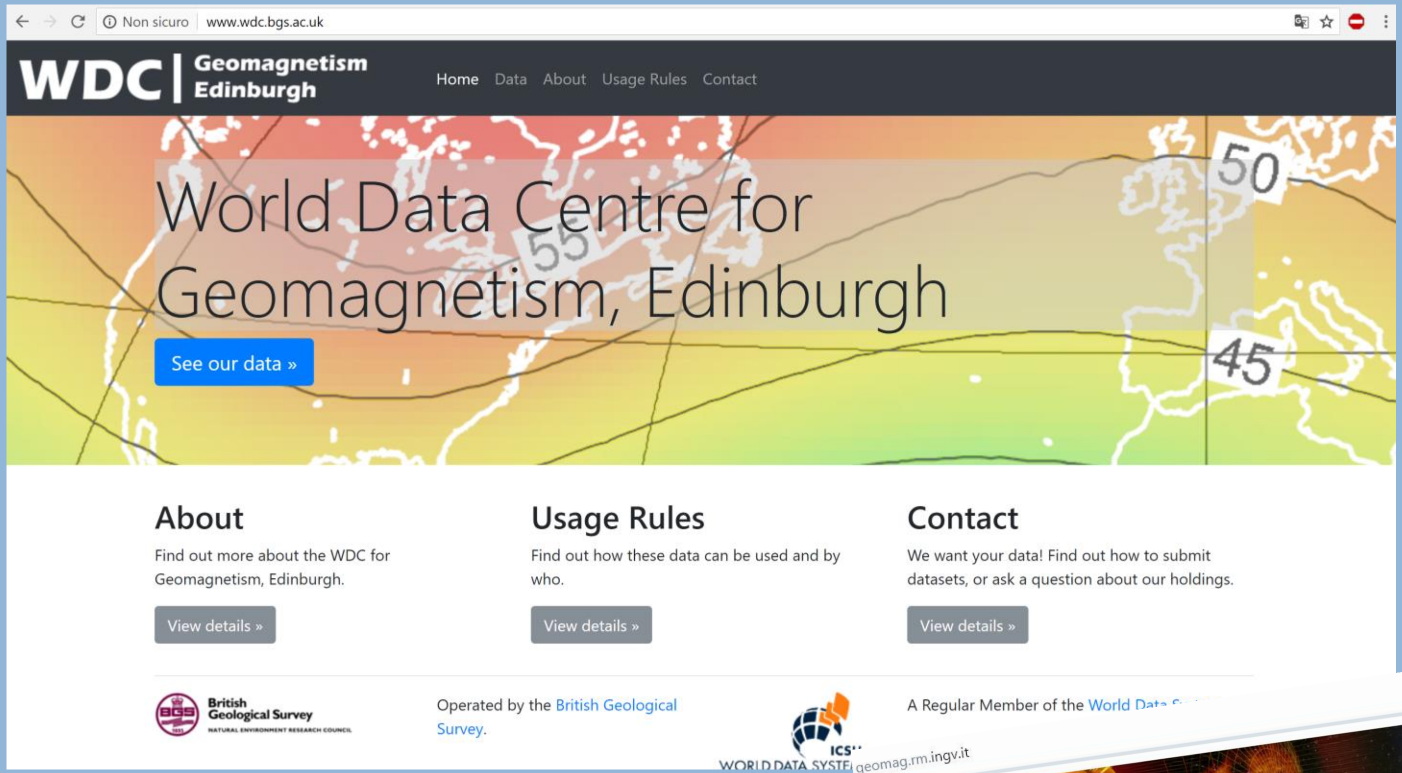
A pillar rooted on a floating basement (DMC, Concordia – Antarctica)

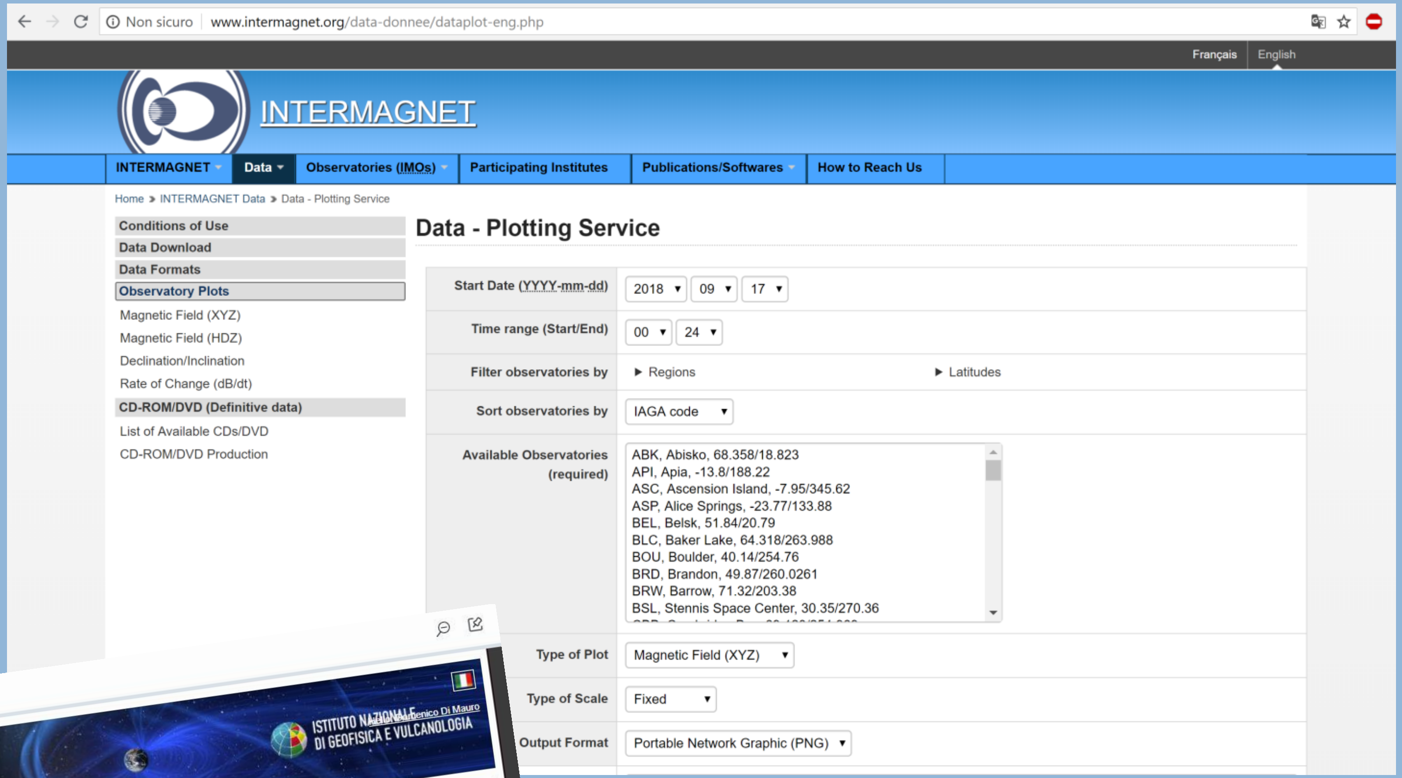


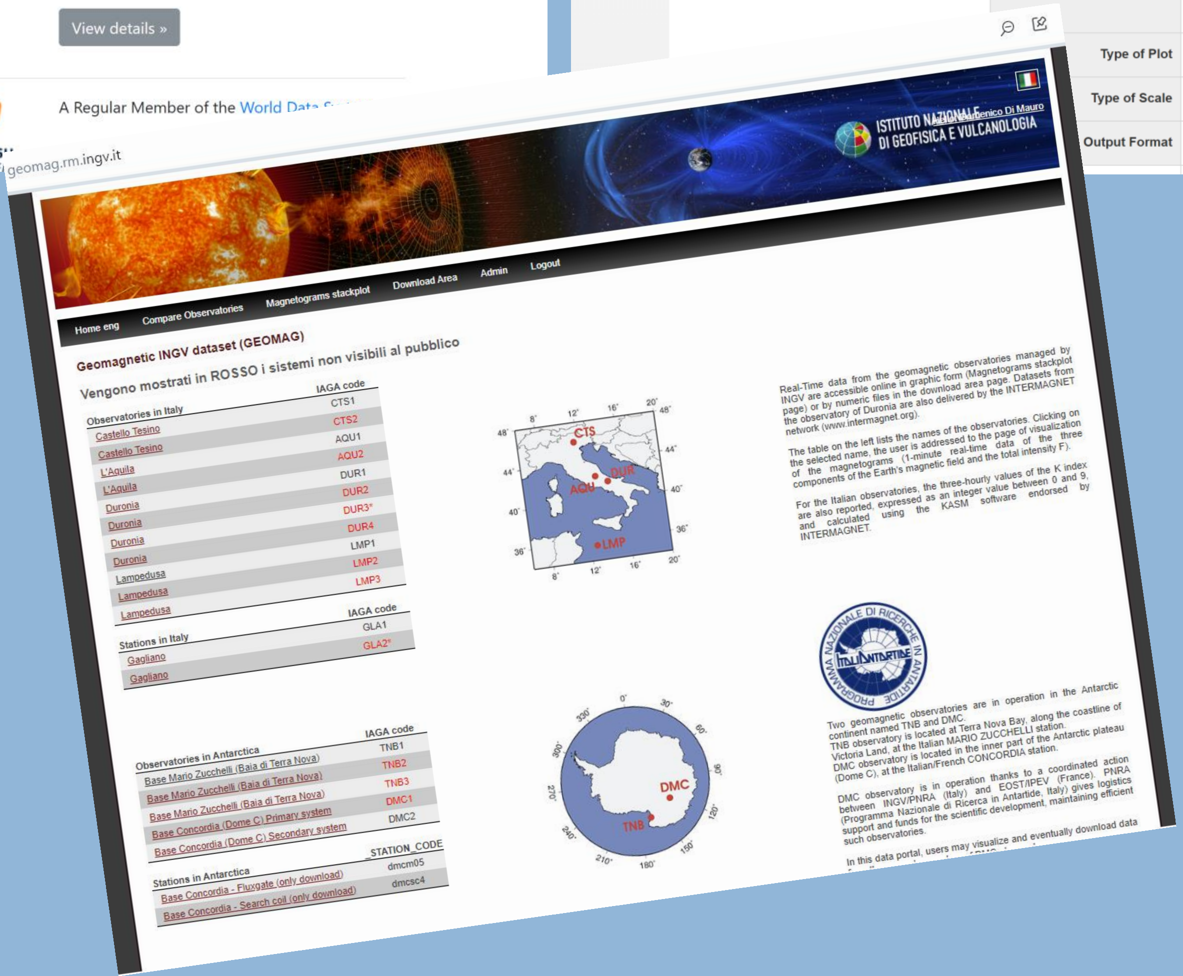


MAIN PRODUCTS from a geomagnetic observatory: bulletin, yearbooks, maps and data

WHERE TO FIND DATA: LOCAL DATA PORTAL, WORLD DATA CENTERS, INTERMAGNET







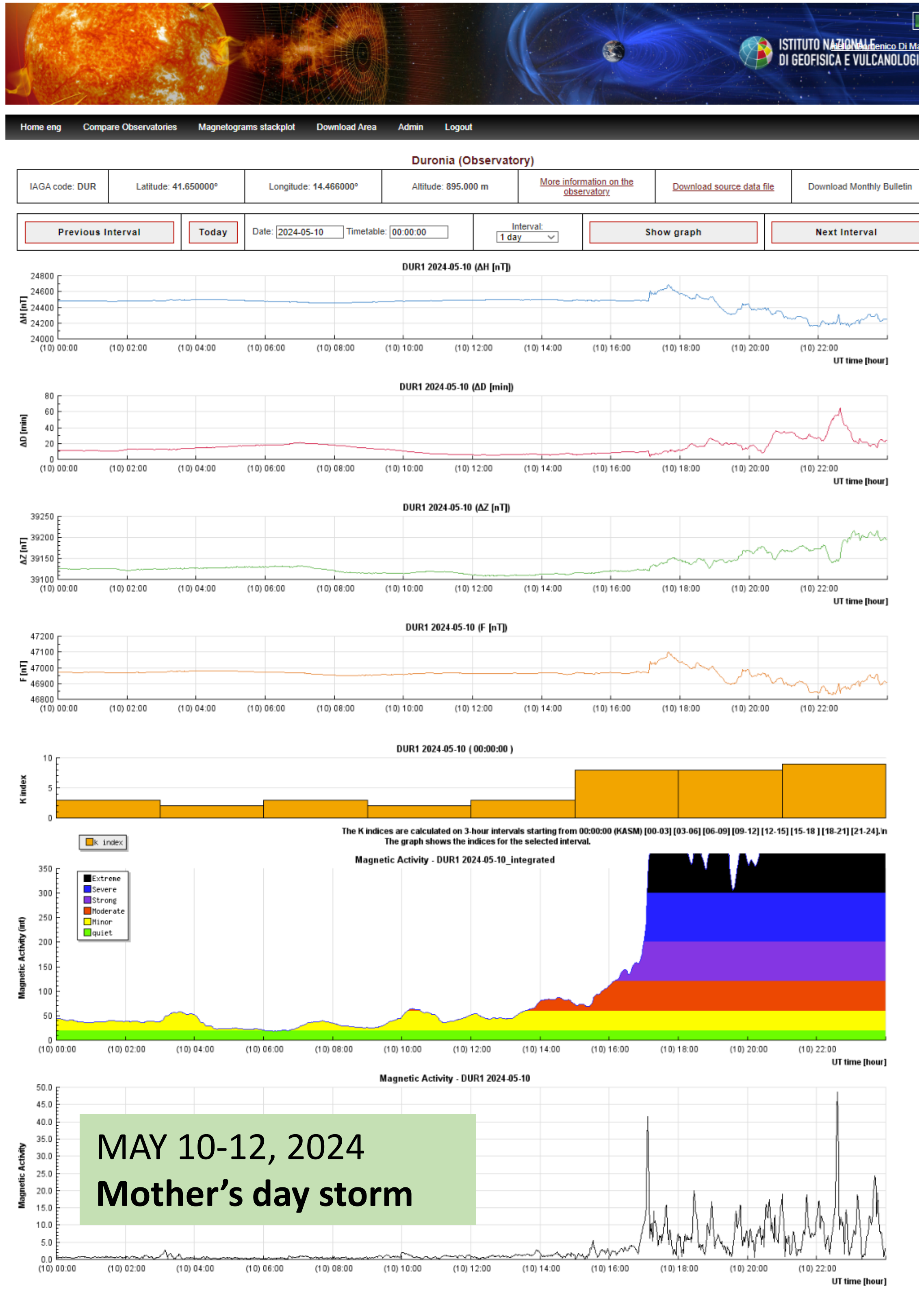
www.wdc.bgs.ac.uk

www.intermagnet.org

geomag.rm.ingv.it

PRODUCTS from a geomagnetic observatory (DURONIA – DUR, ITALY):

REAL-TIME MAGNETOGRAMS



GEOMAGNETIC INDICES

Various geomagnetic indices, such as the Kp-index, Dst index, and AE index, are used monitor and classify space weather conditions.

These indices provide valuable information for understanding the state of the Earth's magnetic field and its interactions with the solar wind.

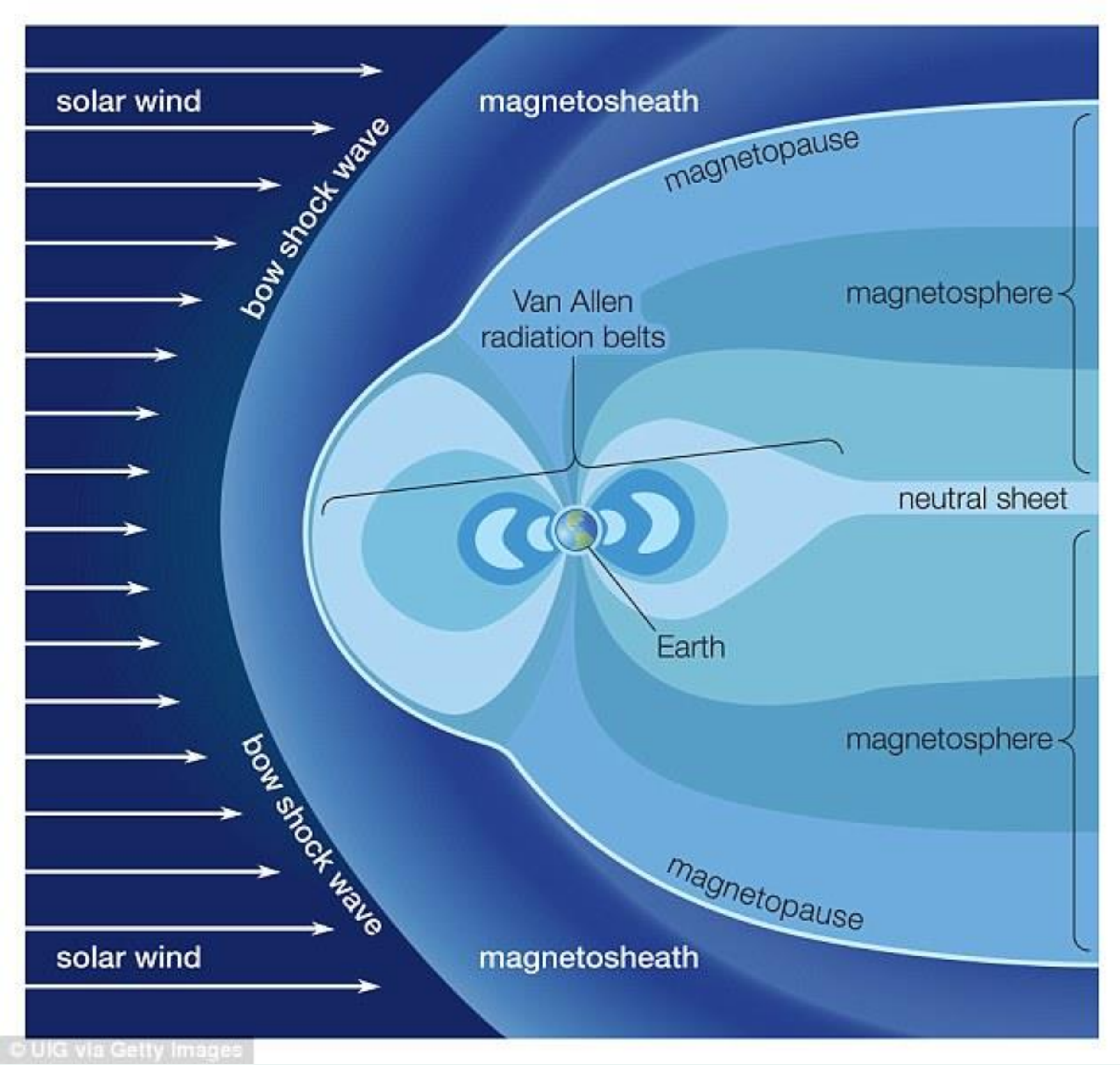
NOAA classifies the severity of a geomagnetic storm (from G1 to G5) using the ground-based Kp index!

The Earth’s Magnetosphere

Definition and Boundaries

The **magnetosphere** is the region surrounding the Earth where the geomagnetic field dominates. The boundary between the Earth's magnetic field and the solar wind is known as the **magnetopause.**

The magnetosphere acts as a **shield**, protecting the Earth from the direct impact of the solar wind.
The interaction between the magnetosphere and the **supersonic solar wind** creates a boundary known as **bow shock** that deflects and slows down the solar wind particles.



The magnetosphere is asymmetric, extending about 10 Earth radii sunward and 200 Earth radii in the opposite direction towards the magnetotail

Magnetospheric Sub-regions

The magnetosheath is the region upstream of the magnetosphere, between the bow shock and the magnetopause.
The magnetosphere is composed of various sub-regions and is characterized by different current systems. The magnetotail is the region on the nightside of the Earth where the magnetic field lines are stretched out.

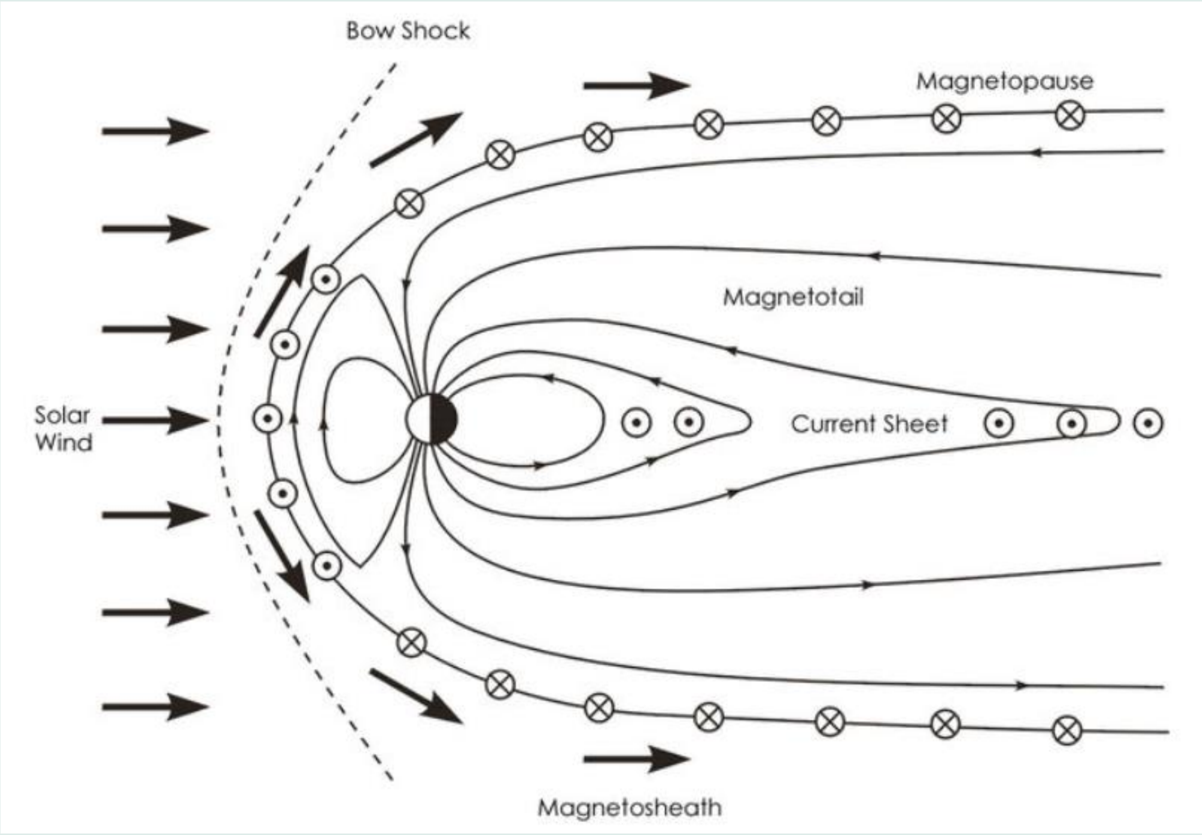
The Earth's Magnetopause

The location of the magnetopause is determined by the balance between the pressure of the Earth's magnetic field and the dynamic pressure of the solar wind

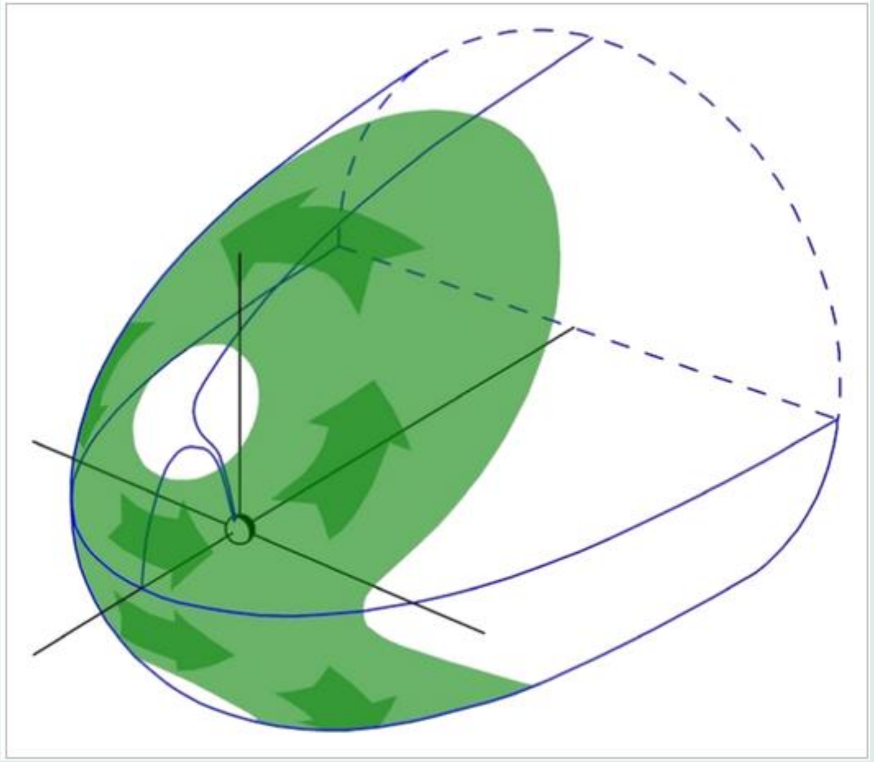
$$(\rho v^2)_{sw} \approx \left(\frac{4B(r)^2}{2\mu_0}\right)_m$$

$$r \approx \sqrt[6]{\frac{2B_0^2}{\mu_0 \rho v^2}}$$

B_0: Earth's magnetic moment

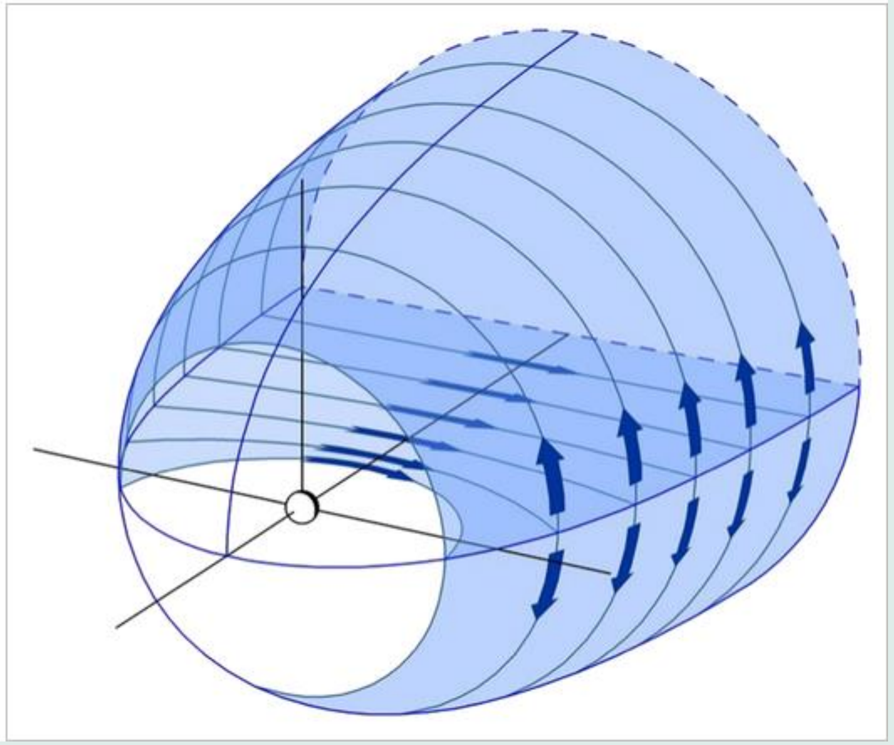


The Chapman-Ferraro dayside magnetopause currents

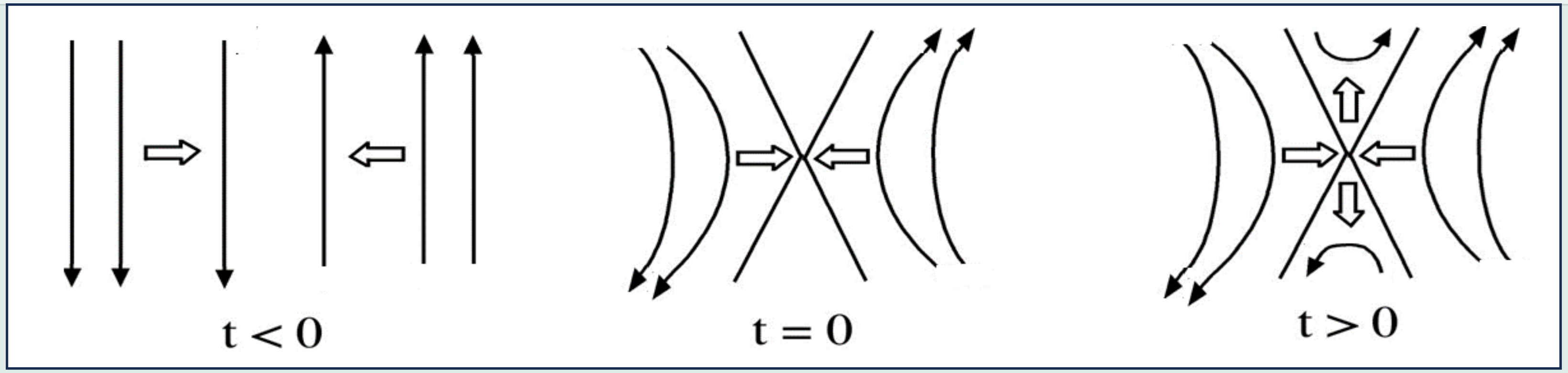


Ganushkina et al. 2018

The tail current with closure via return current on magnetopause



The Earth’s Magnetosphere: the magnetic reconnection

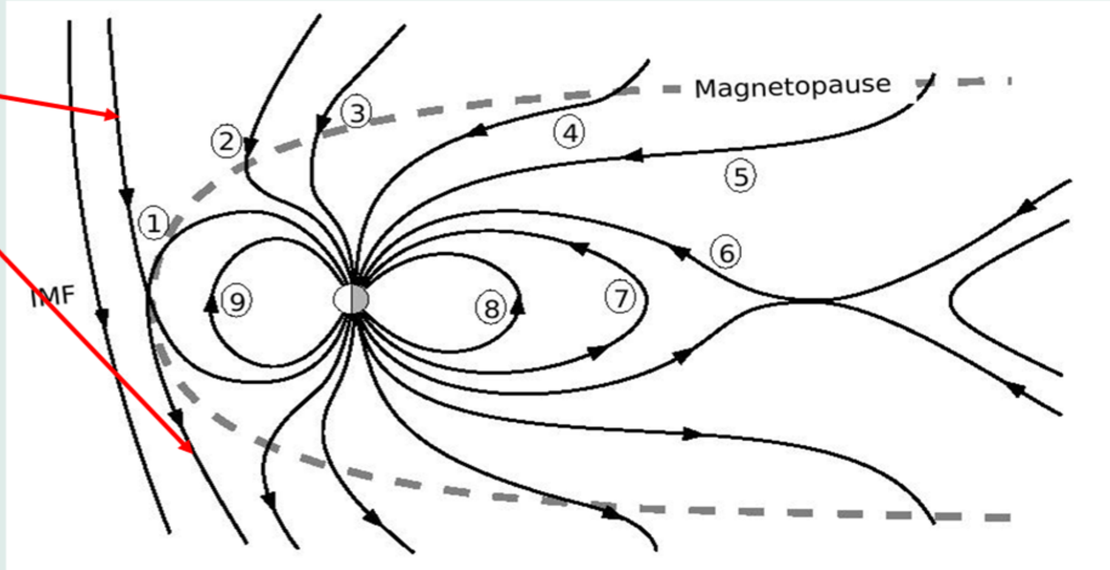


Interplanetary field directed **southward**, which is **antiparallel to the geomagnetic field**.

Before reconnection:
Purely **geomagnetic field line** with both ends attached to the Earth
Interplanetary field line with both ends on the Sun (or stretching far from the Earth)

Near the front of the magnetosphere, at magnetopause, a **magnetic X-line** forms.
Reconnection occurs.

After reconnection:
Two new field lines:
- Each has **one end attached to the Earth** (one near the North Pole, one near the South Pole)
- and the **other end stretching** out into interplanetary space



The Earth’s Magnetosphere: the auroral oval

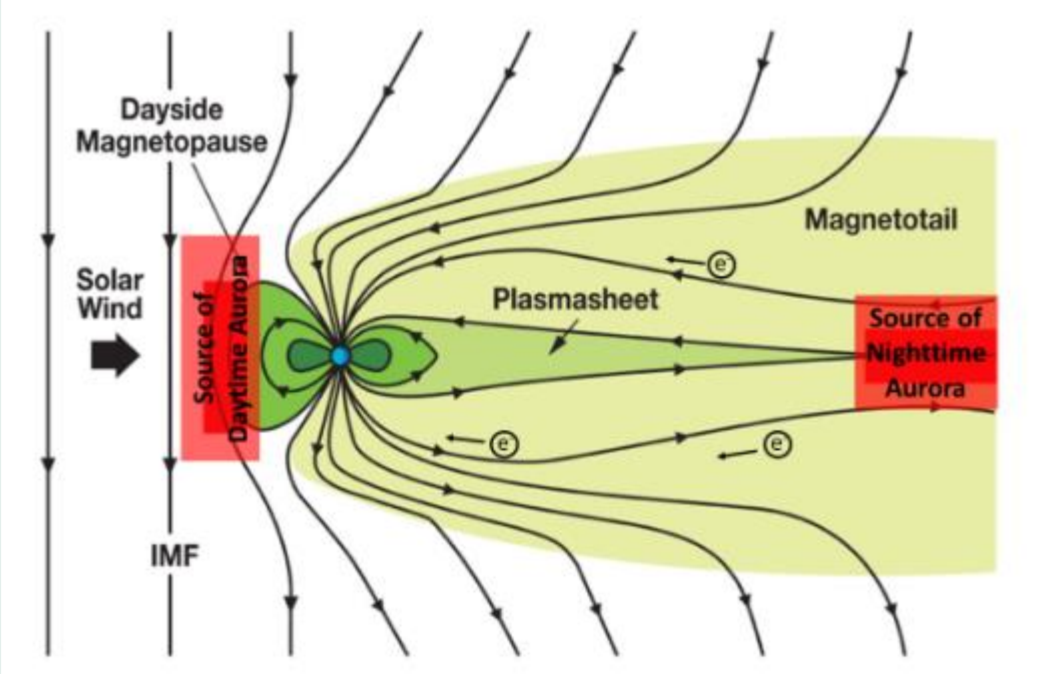
The auroral oval is the footprint in the atmosphere of the boundary between the highly stretched field lines of the polar cap and the nearly dipolar field lines at lower latitudes.

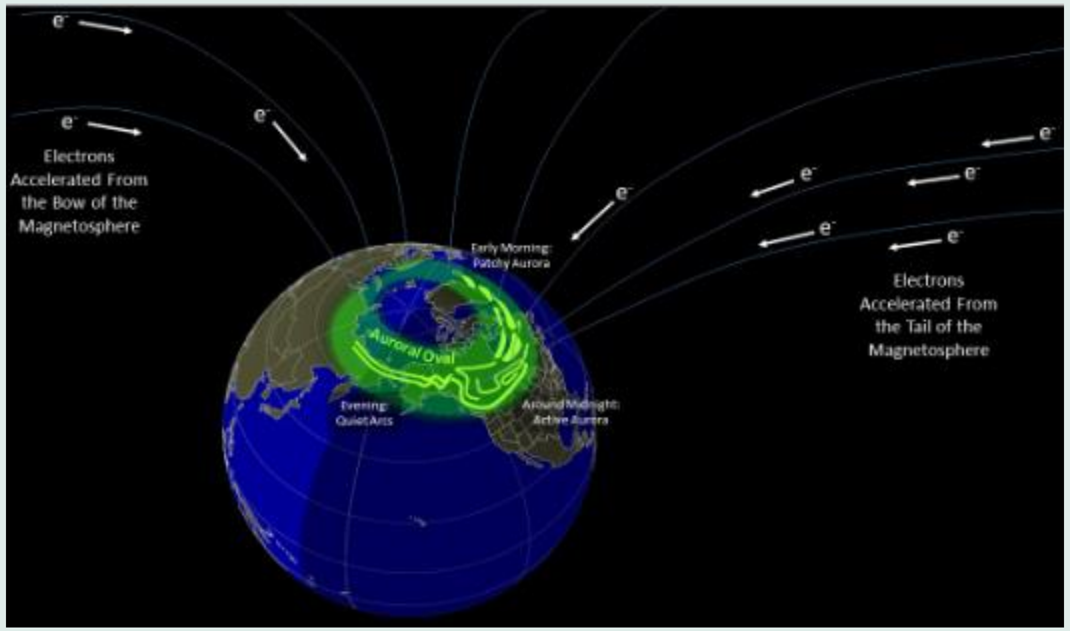
The auroral oval is the region where auroras are most frequently observed.

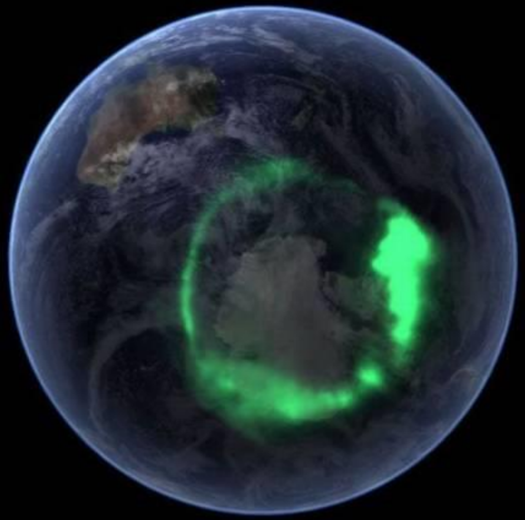
The auroral oval is an elliptical or oval-shaped region roughly centered around the magnetic pole (with a more elliptical form in the Northern hemisphere).

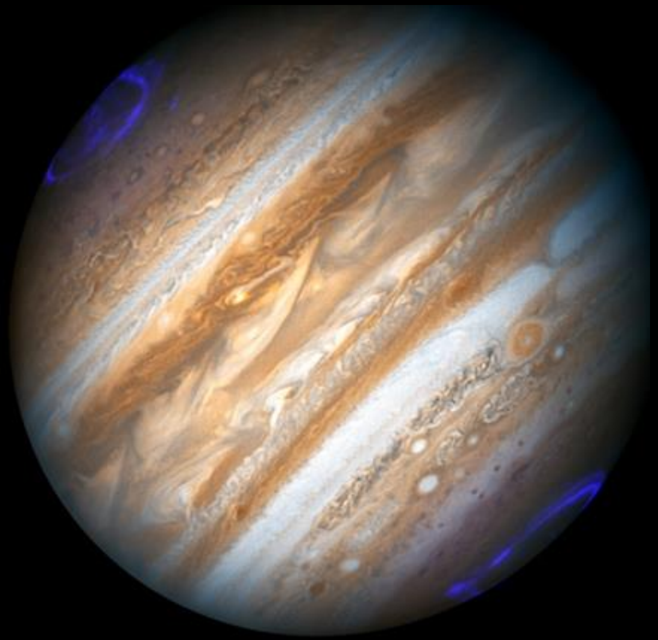
It typically extends between 60° and 75° north and south of the magnetic pole.

The size and location of the auroral oval can vary depending on the interaction with the solar wind. During periods of high geomagnetic activity, with reconnection occurring due to southward directed IMF, the auroral oval can expand and move closer to the equator, while during quiet periods, it may contract and move closer to the poles.





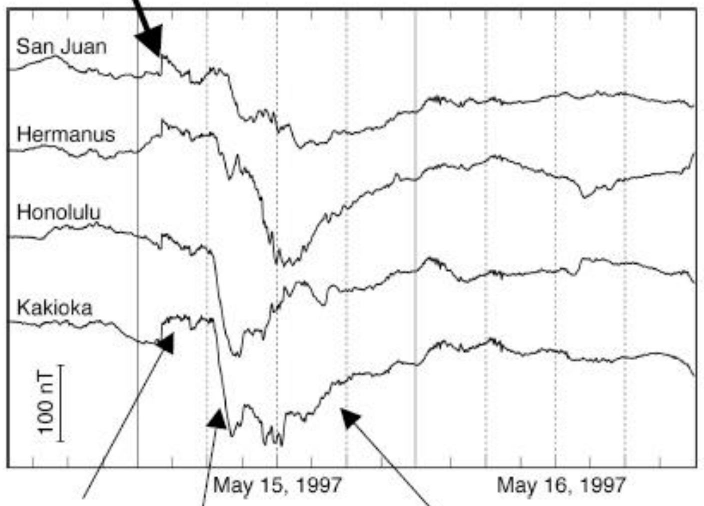


MAGNETIC STORM

Major disturbances in the magnetosphere triggered by the interaction with the solar wind

Magnetic storm: World-wide depression of magnetic horizontal (H, ~ north) component due to enhanced westward ring current

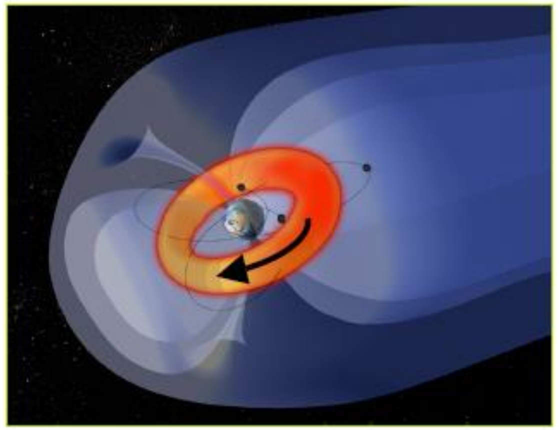
storm sudden commencement (SSC)
(shock hitting the magnetopause)



initial phase

main phase
strong southward IMF
in the shocked flow
or in the CME

recovery phase

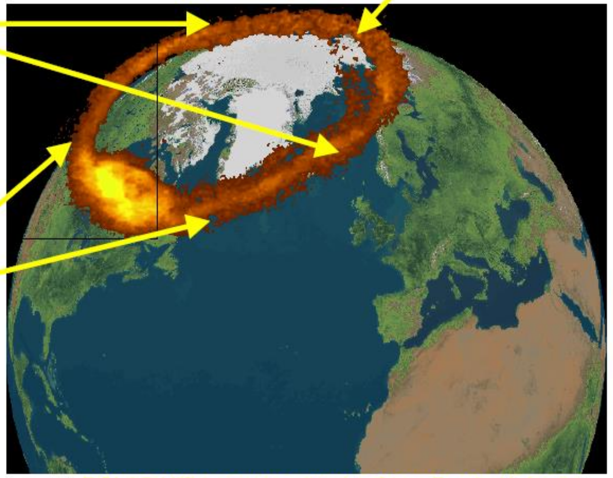


Substorms (Akasofu and Chapman, 1961) are magnetic and auroral activations at high latitudes (auroral zone). They occur both during storms and other times.

Dayside and solar wind

Magnetospheric boundaries

Nightside plasma sheet



POLAR VIS imager, courtesy of Lou Frank, U. Iowa

ULF Waves in Earth's Magnetosphere: pulsations

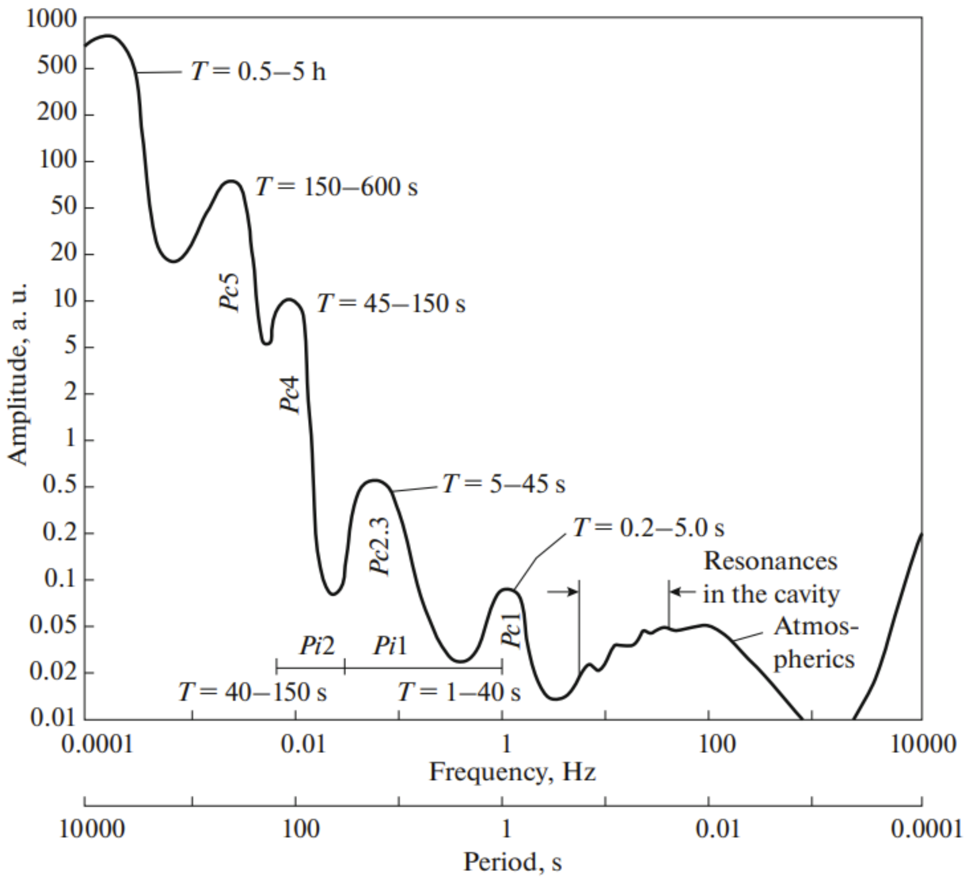
Waves naturally occurring in the Earth's magnetosphere with frequency **from mHz to hundreds of mHz** and amplitude from **tenths to hundreds of nT**. Crucial role in understanding the complex dynamics of the Earth's magnetic environment.

Classification	Period (s)	Frequency (mHz)
Pc1	0.2-5	200-500
Pc2	5-10	100-200
Pc3	10-45	22-100
Pc4	45-150	7-22
Pc5	150-600	2-7

Dungey, 1954: pulsations are interpreted for the first time in terms of magnetohydrodynamic (MHD) waves.

MHD theory concerns ionized gases immersed in a magnetic field. In an ordinary gas, waves are generated by pressure and gravitational gradients. In an MHD fluid, the magnetic field also plays a role.
MHD waves are low-frequency waves (when f < ion gyrofrequency).

Therefore, the MHD description is valid only for low-frequency pulsations, namely Pc3-5 pulsations (f<100 mHz).

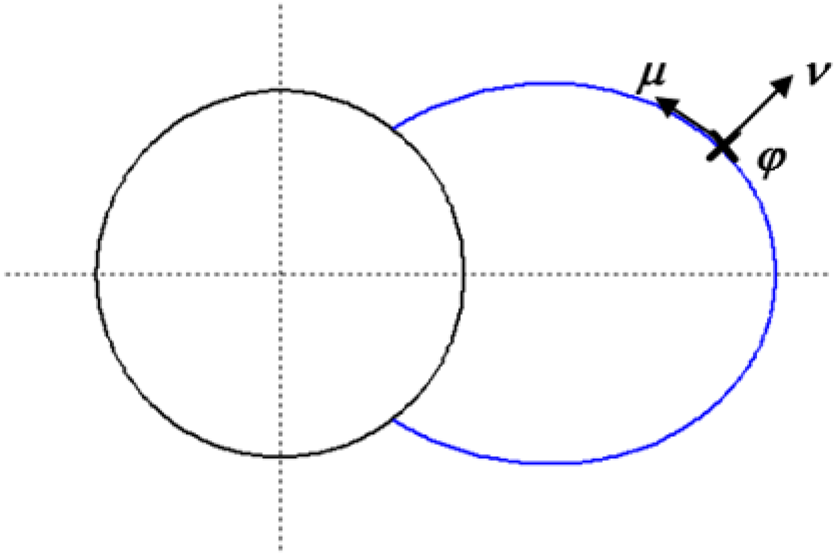


Power spectrum of the emission power of the magnetosphere at extremely low frequencies (pulsations).
Pc is regular oscillations and Pi is irregular oscillations.

MHD WAVES in a dipolar field

Alfvén wave: transverse wave, guided along the ambient field

Fast wave: compressional wave, isotropic



- μ Along the field line
- ν In the meridional plane, perpendicular to the field line
- φ In the azimuthal direction

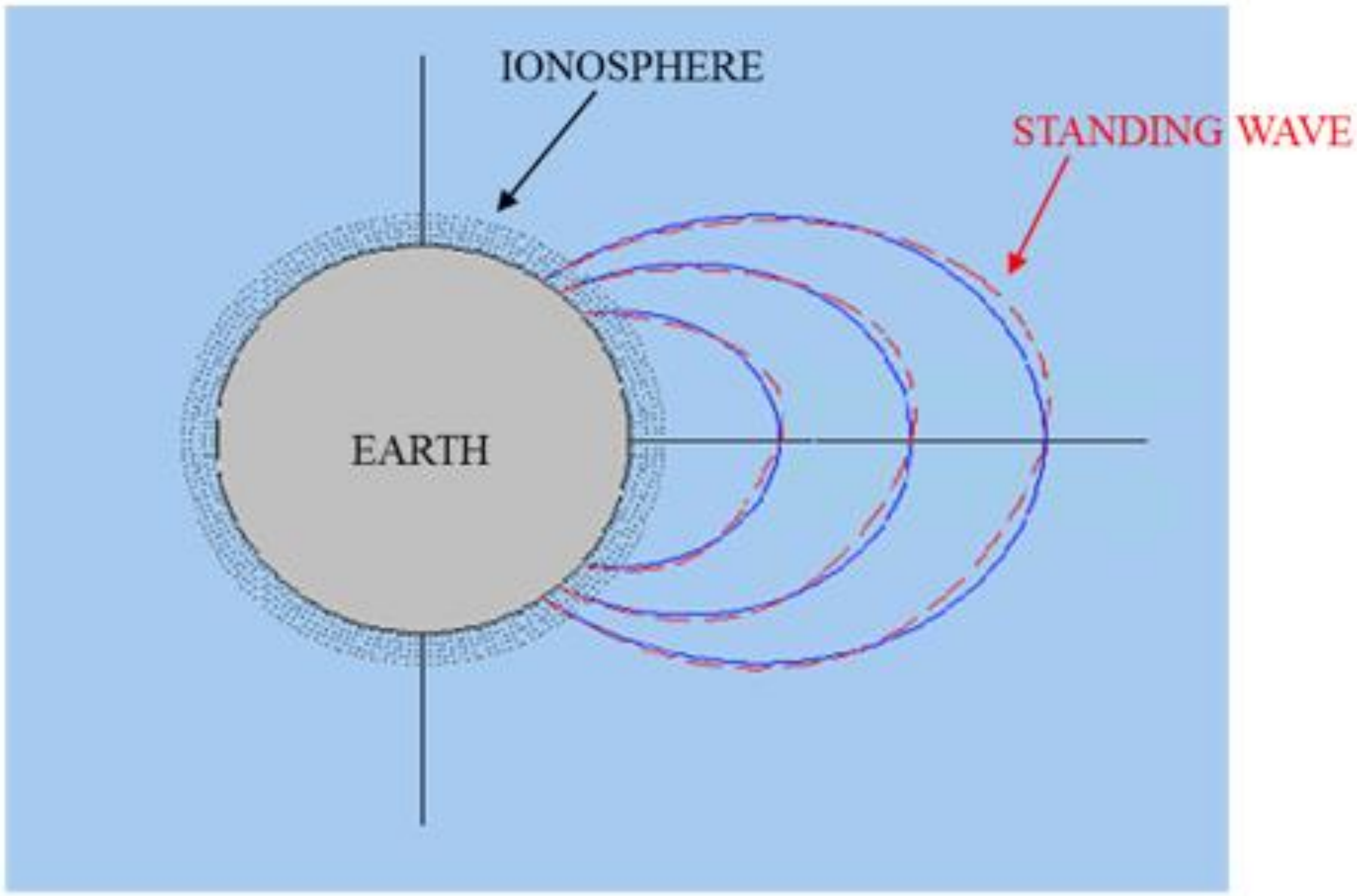
Alfvén wave: A disturbance generates azimuthal oscillations of an entire magnetic shell, changes in direction ϕ.

Fast wave: A disturbance compresses the field line and propagates causing changes in directions μ and ν

Fast and Alfvén waves are coupled

STANDING WAVES in the magnetosphere

The field lines of the geomagnetic field behave like strings with fixed ends in the ionosphere. Multiple reflections of Alfvén waves generate a standing wave.



$\lambda = 2l/n$

$T = 2l/nV_A$

Fundamental period

$$T(L) \cong 2\int_l \frac{ds}{V_A(s)} =$$

$$= 2\mu_o^{1/2} \int_l \frac{\rho^{1/2}(s)}{B(s)} ds$$

Any oscillation is stationary if its frequency matches the eigenfrequency of the field line ⇒ field line resonances

Kelvin-Helmotz instability (KHI) on the magnetopause

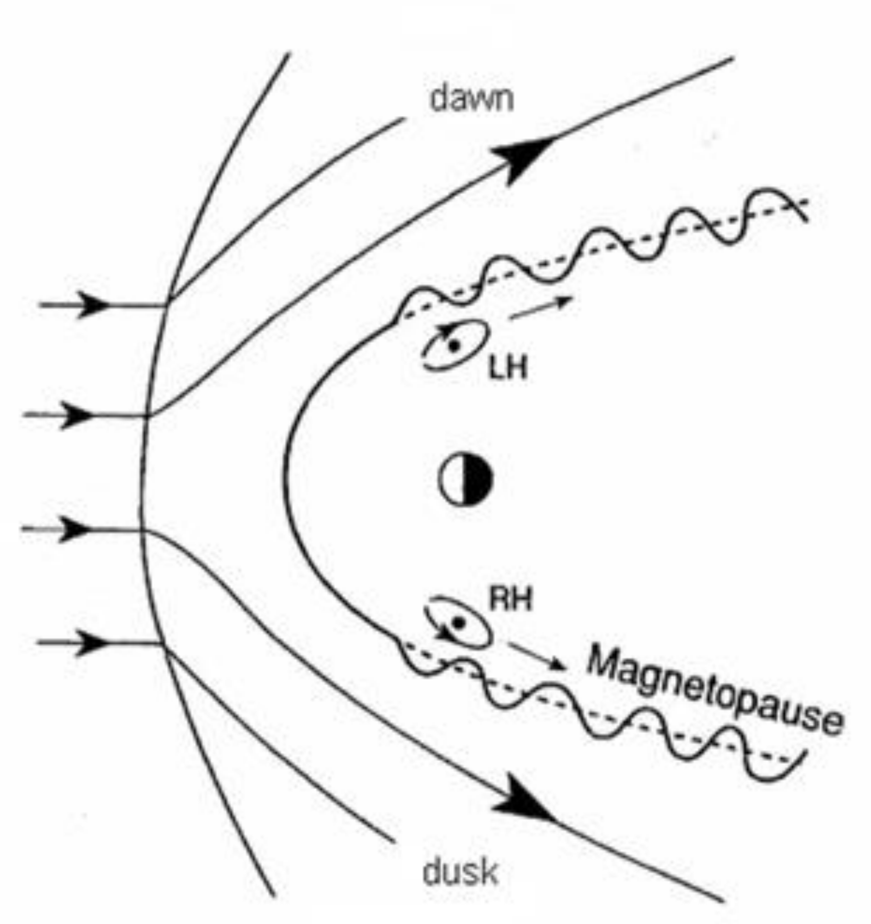
Pc5-4 pulsations (f ~ 1-22 mHz)

Propagation in the antisolar direction

Amplification of waves during fast wind conditions

Reversal of polarization direction at noon.

Field line resonances at high latitudes



Ecliptic plane

Solar wind pressure pulses impinging on the magnetopause

Excited by solar wind pressure pulses, the magnetospheric cavity 'resonates' at its eigenfrequencies.

Compressive waves propagate through the magnetosphere and are reflected at boundary surfaces ⟹ **Cavity modes**

Cavity modes frequencies: 1.3, 1.9, 2.6, 3.4 and 4.2 mHz (Pc5)

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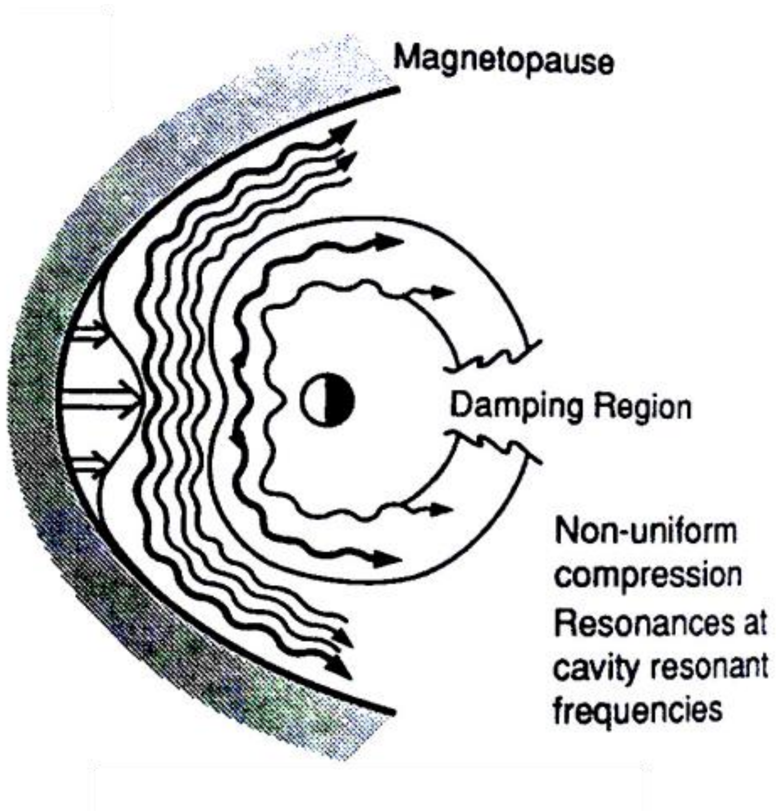
Field line resonances at high latitudes



Ecliptic plane

Pc3-4 Pulsations (f~10-100 mHz)

Upstream waves

generated upstream of the bow shock in the foreshock region, where ϑ_{nB} <45°, through wave-particle interaction phenomena: wave amplification due to a cyclotron resonance of backstreaming ions (mainly protons).

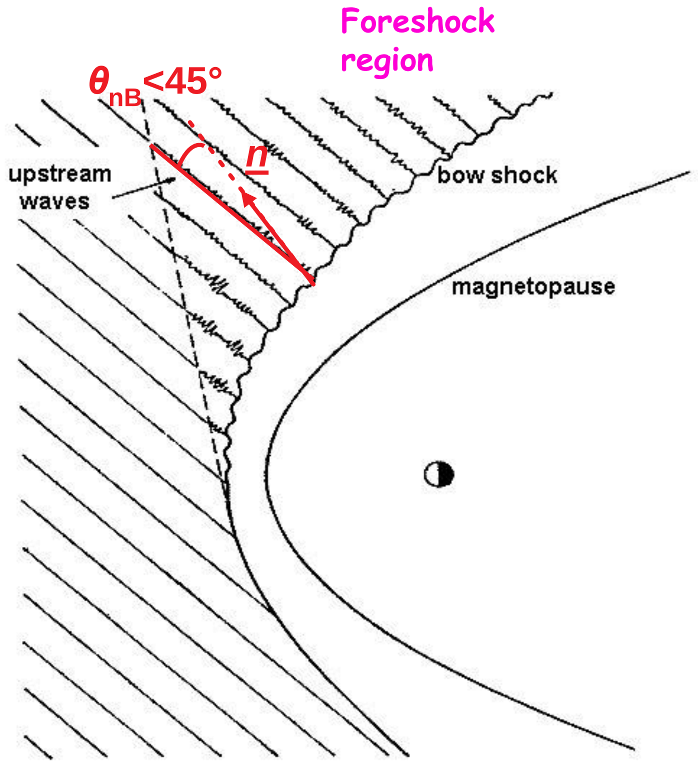
ϑ_{nB} : angle between the IMF and the bow shock normal

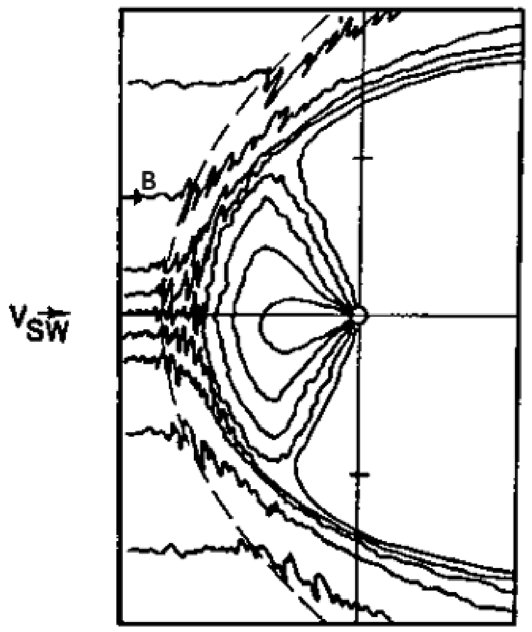
f (mHz) ≈ 6B (nT) ⇒ Pc3

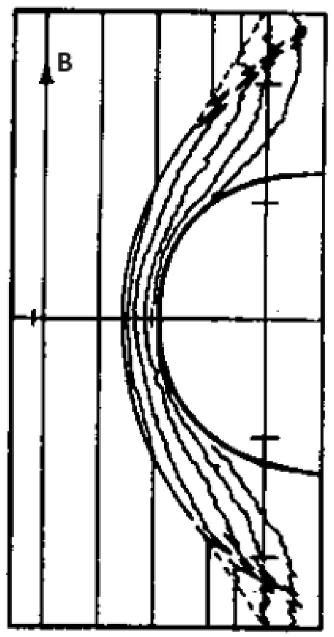
For the transmission to ground, it is crucial the cone angle ϑ_{xB} between the IMF and the Sun-Earth direction

⇓

Field line resonances at low-middle latitudes







Grazie……Thanks !!

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