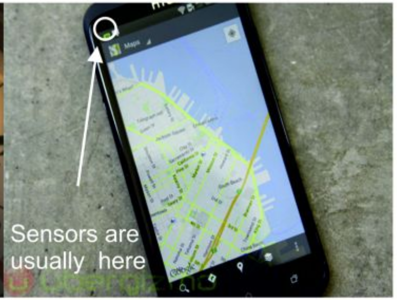
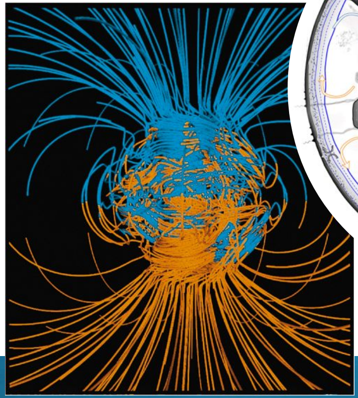
FISICA DELL'AMBIENTE:

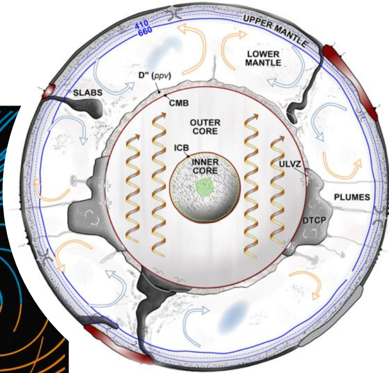
GEOMAGNETISMO

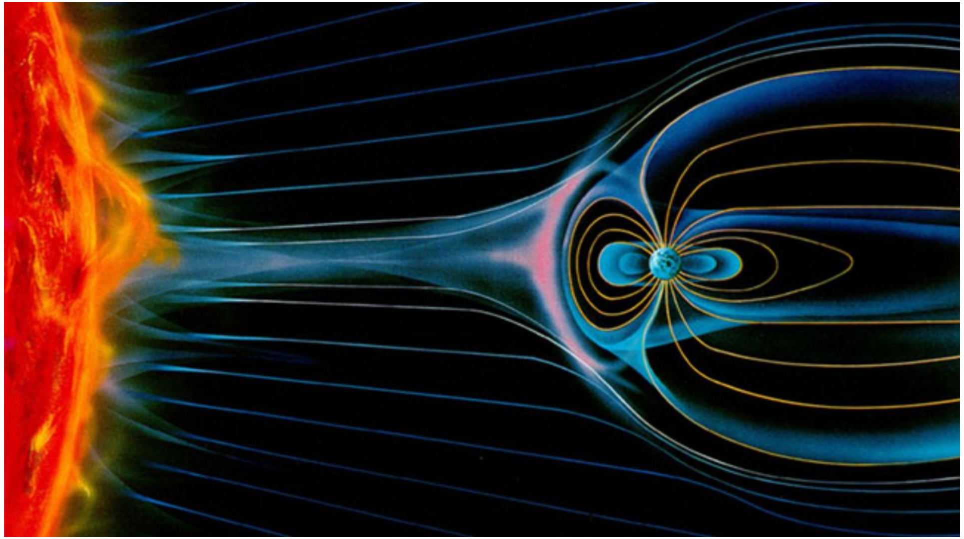
A.A. 2025/2026 | Matteo Costanzi - University of Trieste / INAF

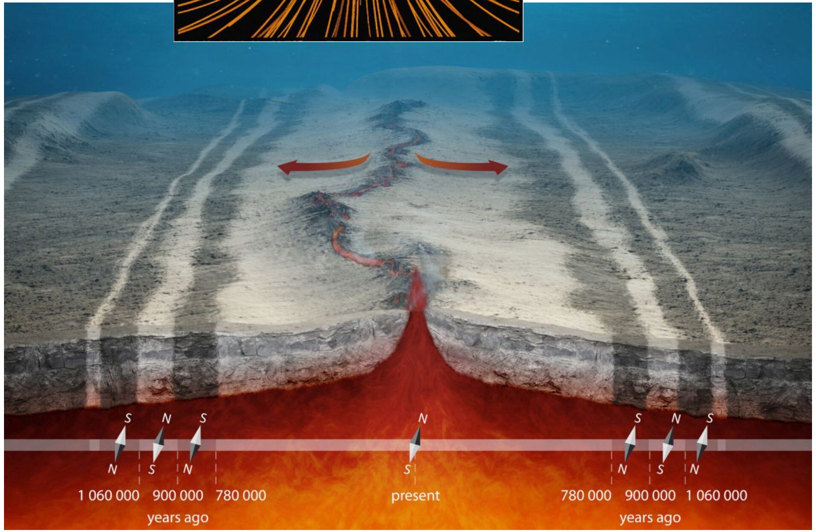
PERCHÉ STUDIARE IL GEOMAGNETISMO









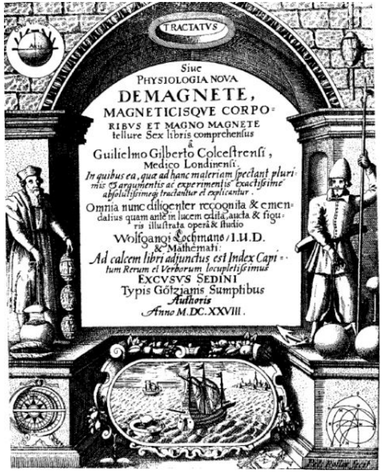


STORIA

È noto da centinaia di anni che la Terra ha un campo magnetico.

- Navigazione con bussola sviluppata intorno al 1100 D.C. indipendentemente in Cina e Europa
- Petrus Peregrinus: Epistola de Magnete (1269): uno dei primi trattati scientifici sul magnetismo
- William Gilbert, “The Magnete” (1600): “Magus magnetis ipse est globus terrestris”
- 1838, Carl Friedrich Gauss dimostrò che il 95% del campo magnetico terrestre è generato da sorgenti interne, ca.5% da sorgenti esterne (ionosfera, magnetosfera)

Si Nan (cercatore del sud): Bussola composta da un cucchiaio magnetizzato



TRACTATVS
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PHYSIOLOGIA NOVA
DE MAGNETE,
MAGNETICISQVE CORPO-
RIBVS ET MAGNO MAGNETE
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à
Guilielmo Gilberto Colcestrensi,
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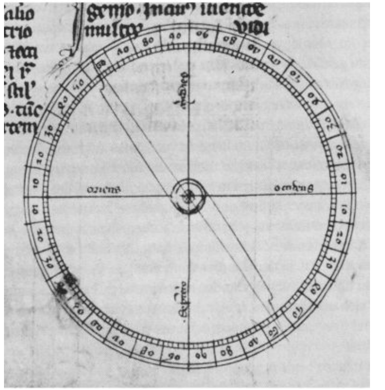


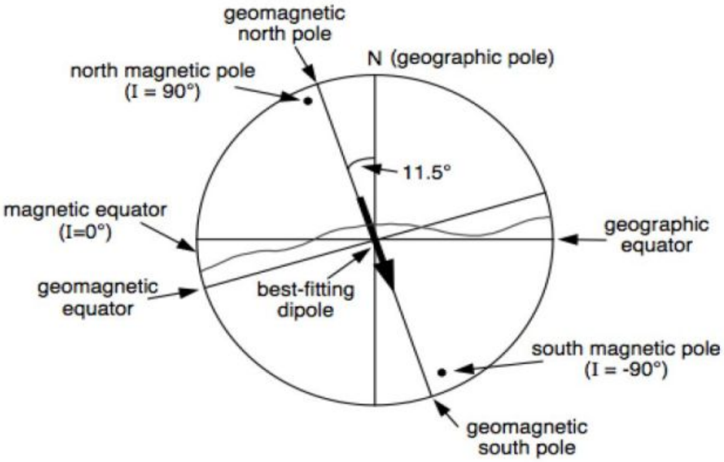
Illustrazione ago magnetizzato da “Epistola de Magnete”

DIPOLO MAGNETICO

- The earth magnetic field can be described ad the field generated by a magnetic bar with the centre corresponding to the centre of the planet.
- To be more accurate, the axis of the magnet :
  - have to be situated about **400 km** from the centre of the Earth
  - Have to make an angle of **11.2°** with the Earth rotational axis

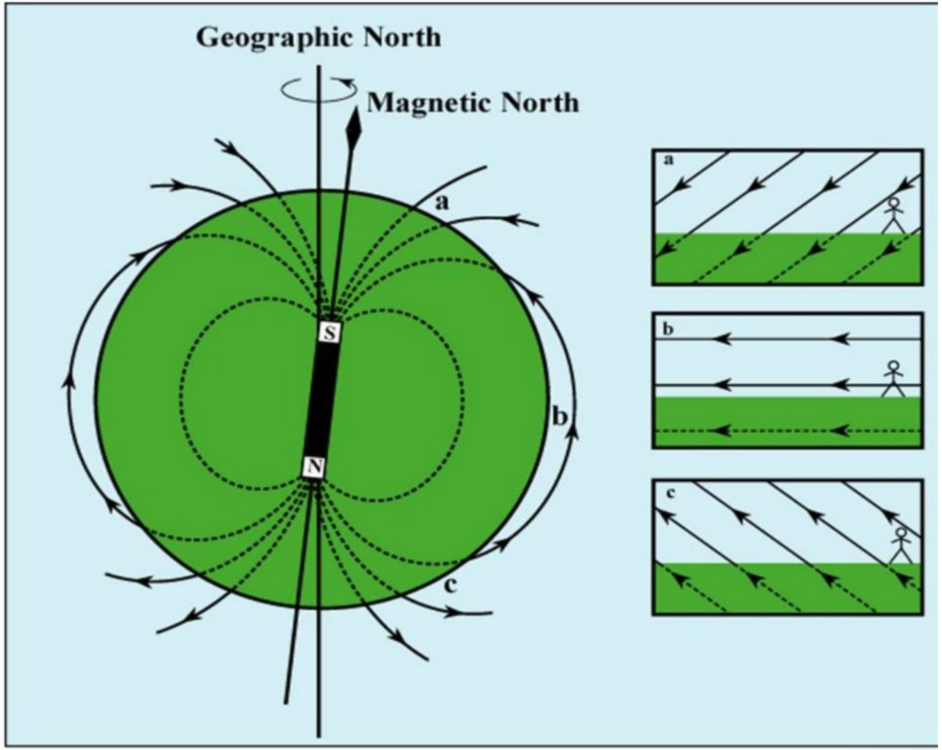
The 2 points of intersection define the geomagnetic poles:
North: 78.8 ° N, 289.1° E
South: 78.8 ° S, 109.1° E

(Magnetic North pole: 75.3 ° N, 101.8 ° W)



Direzione del campo

- Perpendicular to Earth surface at poles
- Parallel to Earth surface at equator
- Field points downward in the Northern Hemisphere
- Field points upward in the Southern Hemisphere.

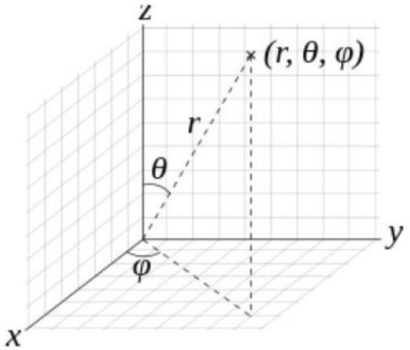


POTENZIALE MAGNETICO (Gauss)

- If we neglect the contribute of external current (which is ~ 5%) we can write:

$$\mathbf{J} = 0 \quad \Longrightarrow \quad \nabla \times \mathbf{B} = 0$$

- The magnetic field can than be expressed in terms of magnetic potential (due to internal sources)



$$\mathbf{B} = -\nabla\psi$$

$$\nabla^2\psi = 0$$ Laplace eq

$$\psi = \frac{R_E}{\mu_0}\sum_{n=1}^{\infty}\left(\frac{R_E}{r}\right)^{n+1}\sum_{m=0}^{n}\left(g_n^m cos(m\phi) + h_n^m sin(m\phi)\right) P_n^m cos(\theta)$$

Gaussian coefficients

Schmidt normalized associated Legendre functions

NOTA: TRASFORMATA DI FOURIER

Sine-cosine form

$$s_N(x) = a_0 + \sum_{n=1}^{N} \left(a_n \cos\left(2\pi \tfrac{n}{P} x\right) + b_n \sin\left(2\pi \tfrac{n}{P} x\right) \right)$$

Fourier coefficien

$$a_0 = \frac{1}{P} \int_P s(x)\, dx$$

$$a_n = \frac{2}{P} \int_P s(x) \cos\left(2\pi \tfrac{n}{P} x\right) dx,$$

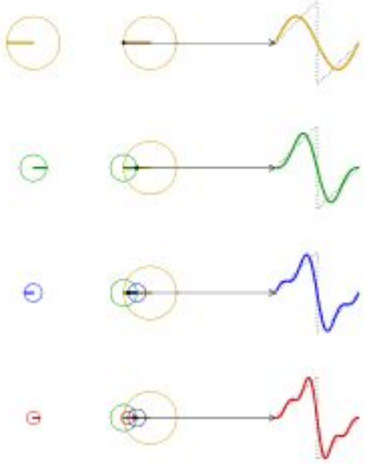
$$b_n = \frac{2}{P} \int_P s(x) \sin\left(2\pi \tfrac{n}{P} x\right) dx,$$

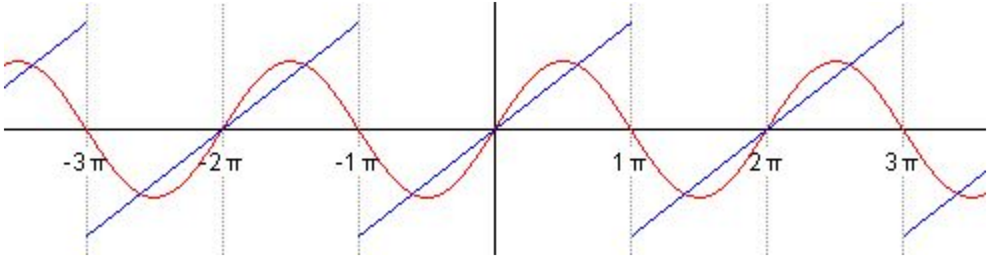
$$\frac{2\sin\theta}{-\pi}$$

$$\frac{2\sin 2\theta}{2\pi}$$

$$\frac{2\sin 3\theta}{-3\pi}$$

$$\frac{2\sin 4\theta}{4\pi}$$





IL DIPOLO MAGNETICO

- The potential due to the first term is the MAIN DIPOLE term

$$B_r = -\frac{\partial \psi}{\partial r} = 2\left(\frac{R_E}{r}\right)^3 g_1^0 cos(\theta)$$

$$B_\theta = -\frac{1}{r}\frac{\partial \psi}{\partial \theta} = 2\left(\frac{R_E}{r}\right)^3 g_1^0 sin(\theta)$$

$$\boxed{B = \sqrt{B_r^2 + B_\theta^2} = B_0\left(\frac{R_E}{r}\right)^3 \sqrt{1 + 3cos^2(\theta)}}$$

	Degree	Order	IGRF	SV
g/h	n	m	2010.0	2010-15
g	1	0	−29496.5	11.4
g	1	1	−1585.9	16.7
h	1	1	4945.1	−28.8

IGFR

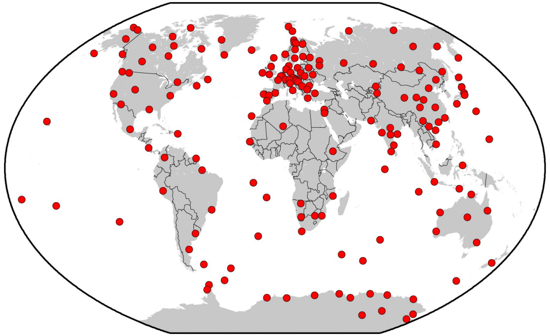
International Geomagnetic Reference Field: **modello matematico standard globale** del **campo magnetico principale della Terra**, cioè quello generato **dentro il pianeta** (nel nucleo), esclusi quindi i contributi esterni o locali.

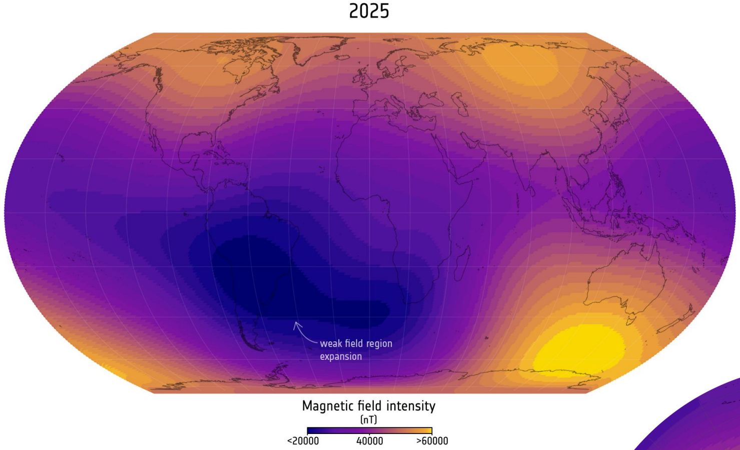
È il riferimento ufficiale utilizzato da: missioni satellitari, sistemi di navigazione e orientamento, studi geofisici e geologici, modelli di spazio circumterrestre e meteorologia spaziale.

- L’IGFR è manteunto dall'Associazione Internazionale di Geomagnetismo e Aeronomia (IAGA)
- I coefficienti di Gauss (fino al 13 ordine) definitivi vengono aggiornati ogni 5 anni, includendo un andamento lineare tra le epoche.
- L'ultima aggiornamento risale al 2021.

MISURE DEL CAMPO MAGNETICO

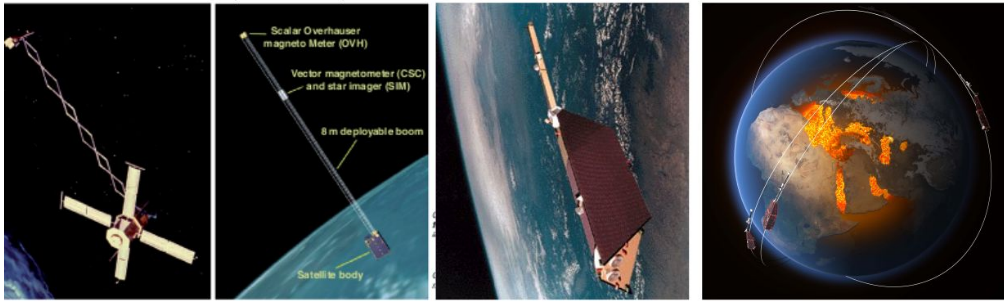
Locations of currently operating geomagnetic observatories





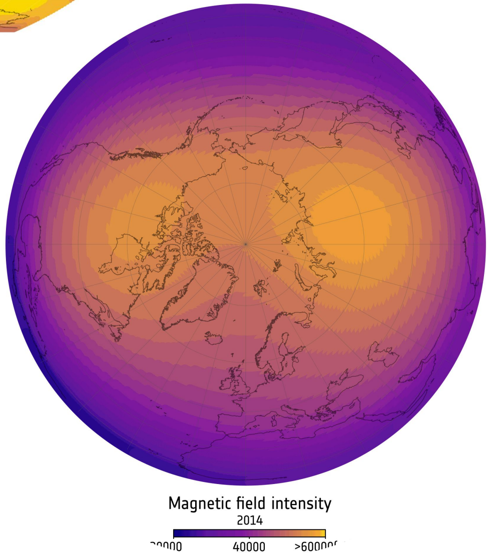
Mappa che mostra le intensità del campo magnetico terrestre in diverse aree del globo, così come rilevate dalla missione Swarm dell'Esa.

- Pogo (USA) 1960's
- Magsat (USA) 1980
- Oersted (Denmark) 1999–2013
- Champ (Germany) 2000–2010



- Swarm (ESA, since Nov. 2013) : constellation of 3 satellites

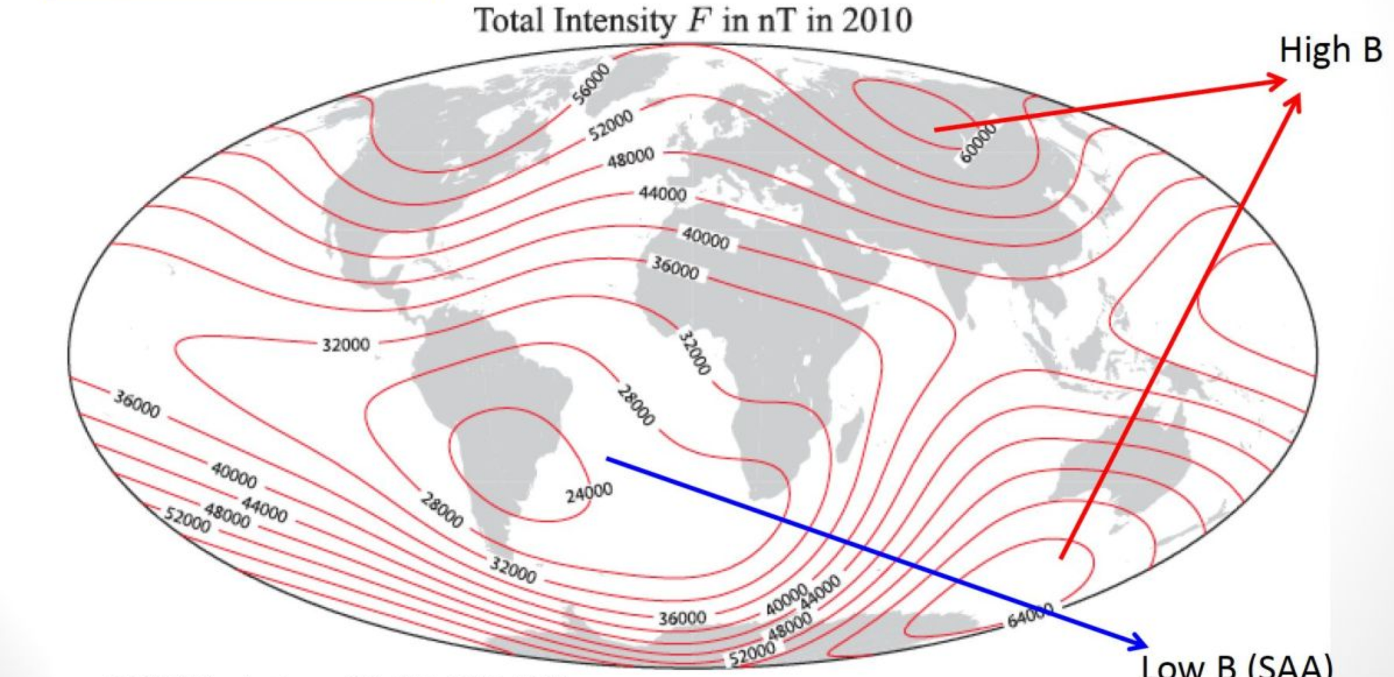
Mappa che mostra i cambiamenti di intensità del campo magnetico sopra il Canada e la Siberia.



L'INTENSITÀ DEL CAMPO MAGNETICO

$B_{poles} \sim 0.6 \times 10^{-4}$ T

$B_{eq} \sim 0.3 \times 10^{-4}$T



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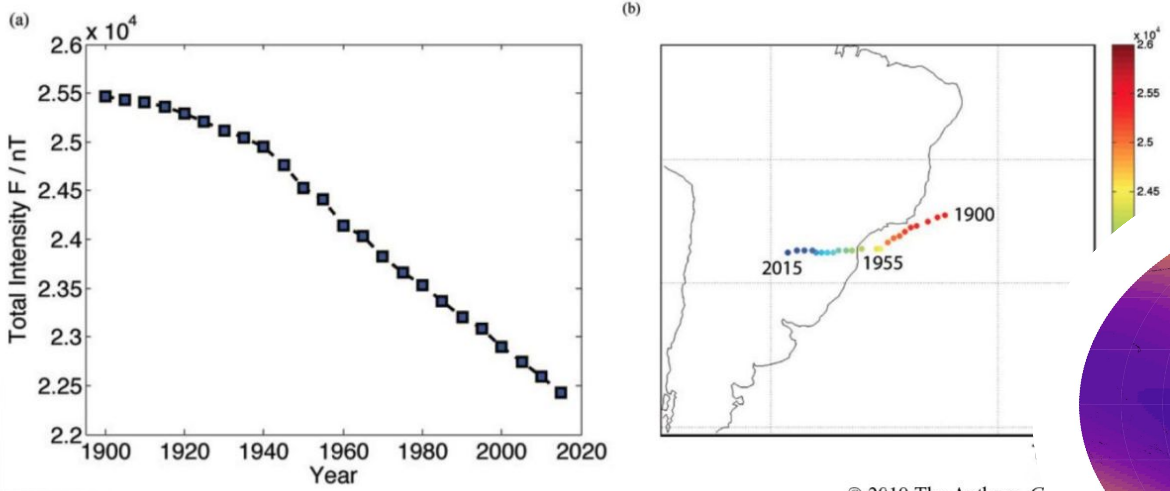
L’ANOMALIA SUD ATLANTICA

- The South Atlantic Anomaly:
  - B has systematically decreased and since the 1940 until the present the average decrease has been almost linear and equal to 34 nT yr^{-1}
  - The location of the point of lowest field intensity changed southward and westward



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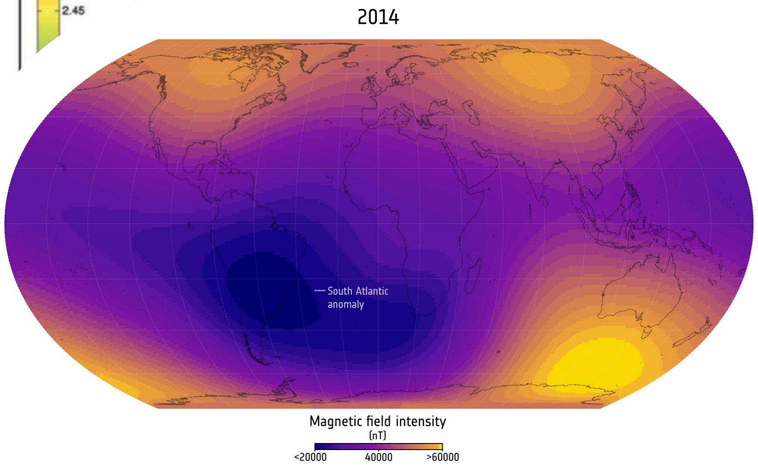
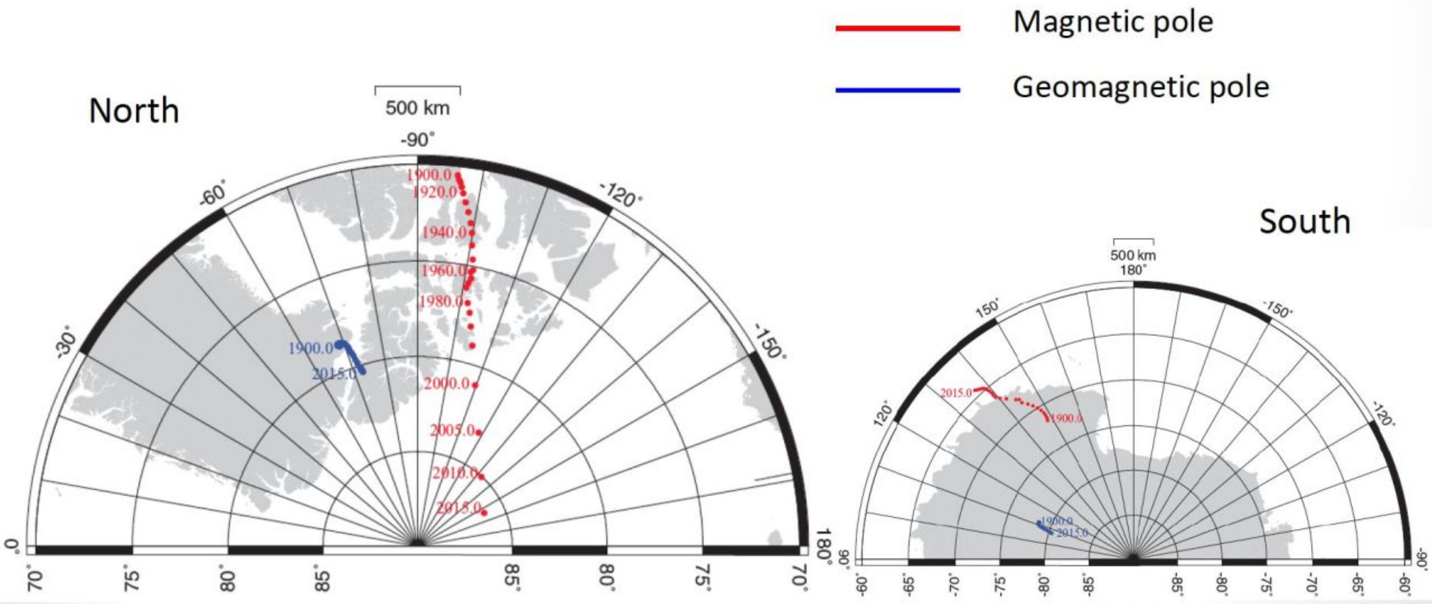
Using 11 years of magnetic field measurements from the European Space Agency’s Swarm satellite constellation, scientists have discovered that the weak region in Earth’s magnetic field over the South Atlantic – known as the South Atlantic Anomaly – has expanded by an area nearly half the size of continental Europe since 2014.



SPOSTAMENTO DEI POLI

- The geomagnetic and magnetic poles moves about the geographic poles: termed secular variation in the magnetic pole position



V ~ 50 km yr^{-1}

INCLINAZIONE

- Map of the magnetic field inclination

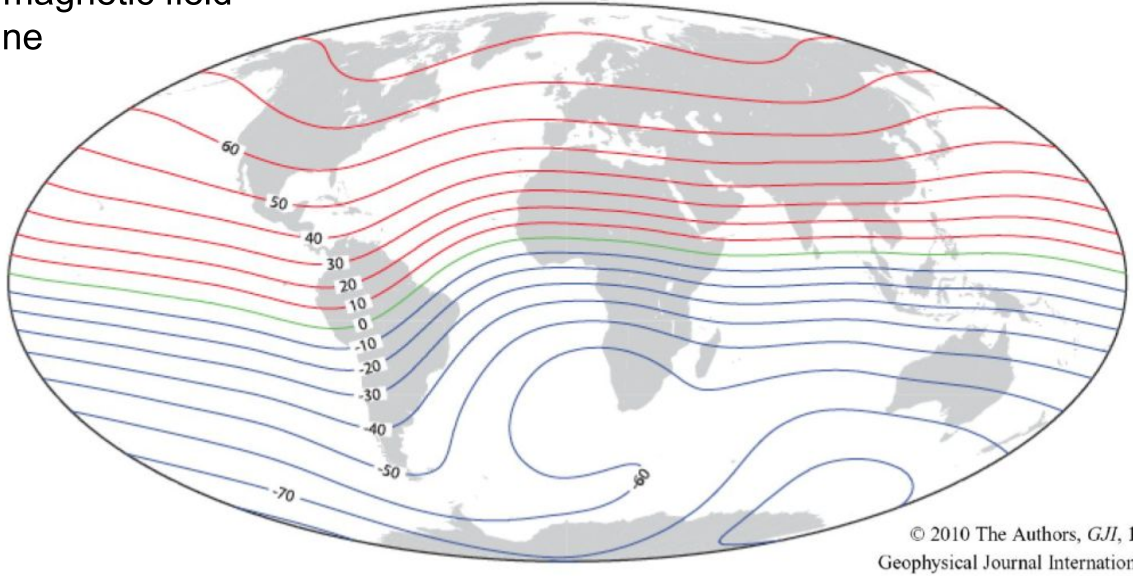
Negative contours

Zero line

Positive contours

I =angle between the magnetic field and the horizontal plane

Inclination I in degrees in 2010



DECLINAZIONE

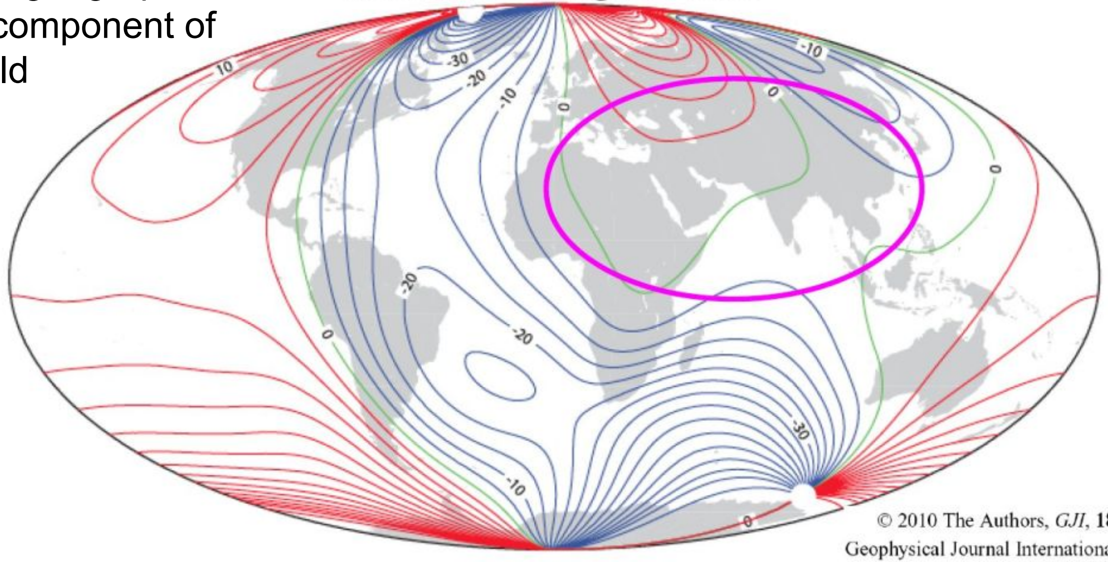
- Map of the magnetic field declination

Negative contours (W direction) — Agonic lines

Positive contours (E direction)

D =angle between the geographic north and horizontal component of the local magnetic field

Declination D in degrees in 2010



DECLINAZIONE

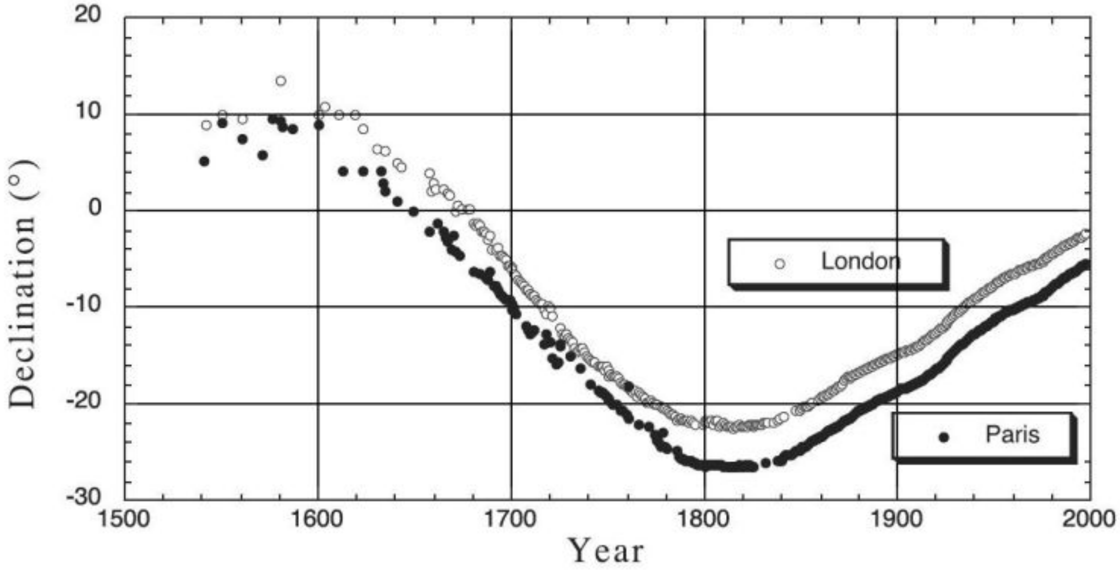
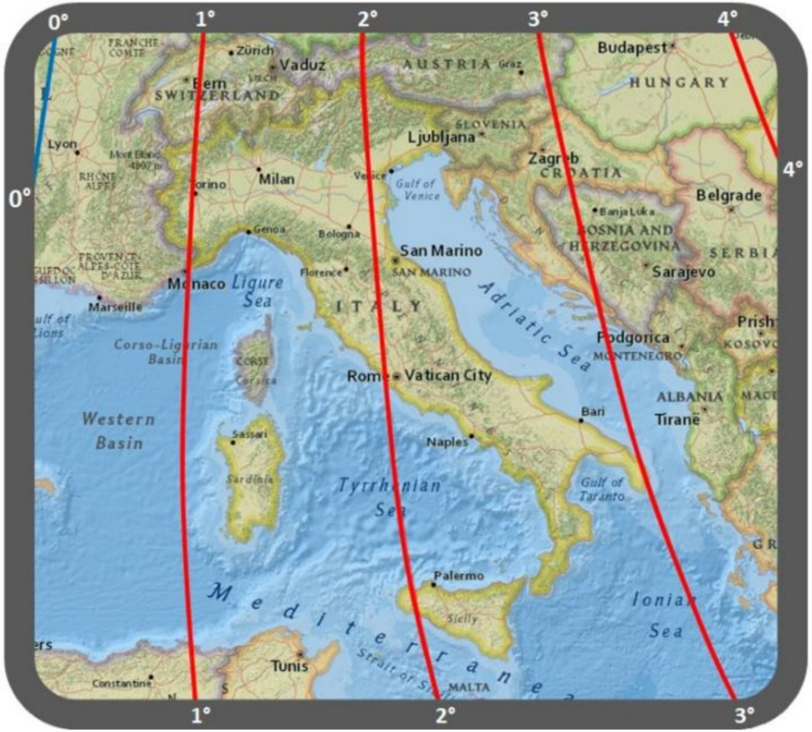


Figure 5. Reconstructed series of direct measurements of declination in Paris and London from the mid sixteenth century to the present [see *Alexandrescu et al.*, 1996, 1997].

DECLINAZIONE

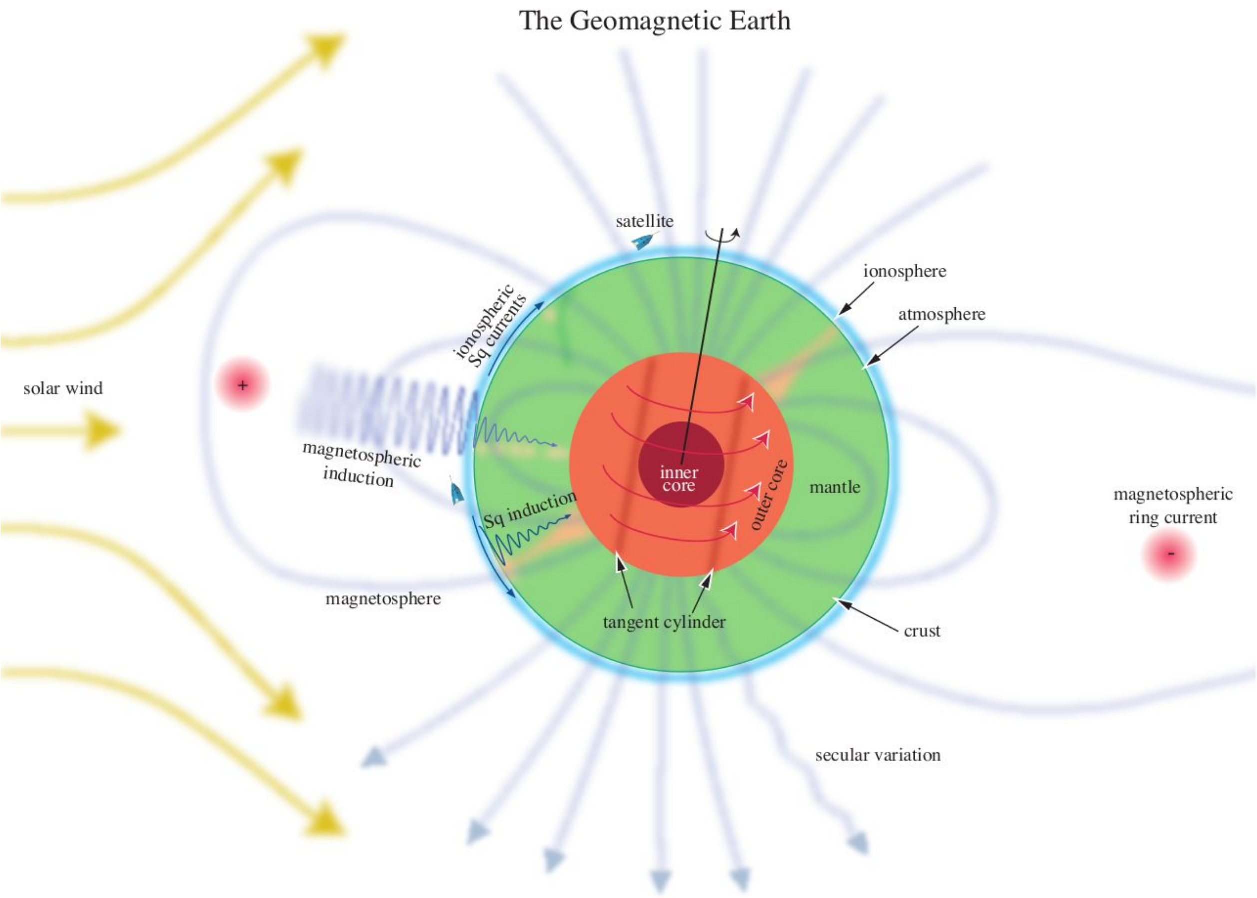
LA DECLINAZIONE MAGNETICA IN ITALIA

Declinazione magnetica nel 2009



Declinazione magnetica nel 2019

SORGENTI DEL CAMPO MAGNETICO



SORGENTI DEL CAMPO MAGNETICO

- The power of the sinusoidal components of the magnetic field can be measured by satellites. The different slopes in the plot discriminate sources in the core of the Earth from crustal anomalies

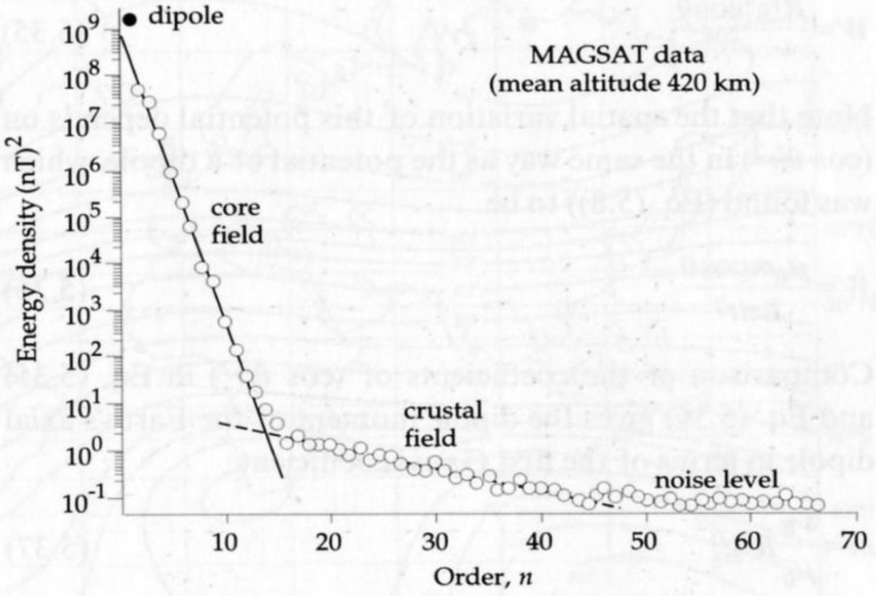
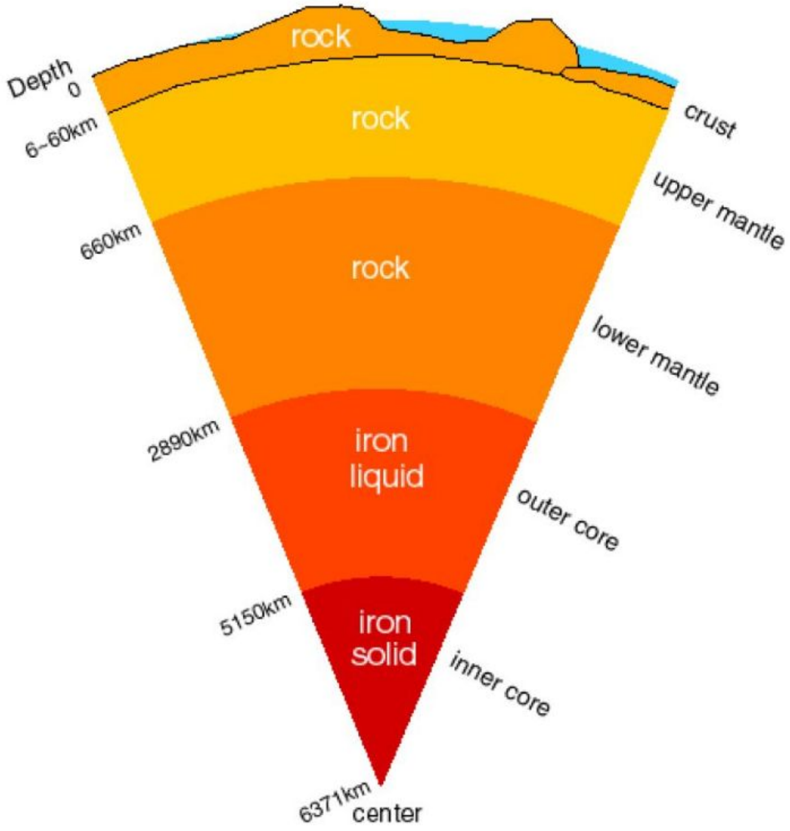


Fig. 5.33 The energy density spectrum derived from measurements of the geomagnetic field made by the MAGSAT Earth-orbiting satellite (after Cain, 1989).

CAMPO MAGNETICO NUCLEARE

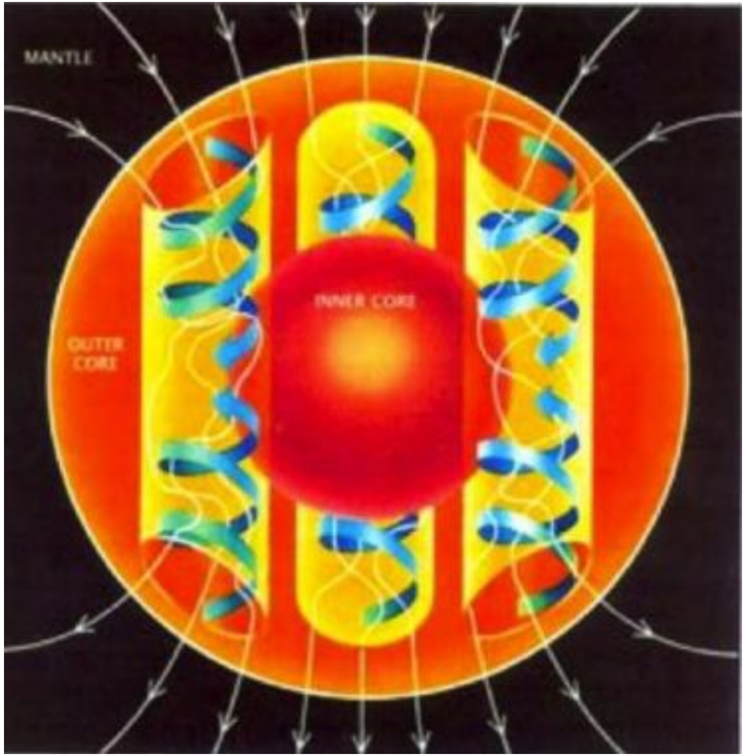
- The Earth's magnetic field is generated by electric currents in the outer liquid core, which mainly consists of iron
- The iron in the core moves turbulently. When the electrically conductive metal moves in the magnetic field, a new magnetic field is generated which may amplify the existing field
- This self-amplifying effect is called the Geo-dynamo



CAMPO MAGNETICO NUCLEARE

Il moto convettivo del fluido conduttore è alimentato da il calore residuo e radioattivo del nucleo esterno, e dal raffreddamento del nucleo interno.

La rotazione terrestre (forza di Coriolis) “organizza” i moti convettivi in colonne allineate lungo l’asse di rotazione terrestre, inducendo una simmetria assiale ed un campo prevalentemente dipolare.



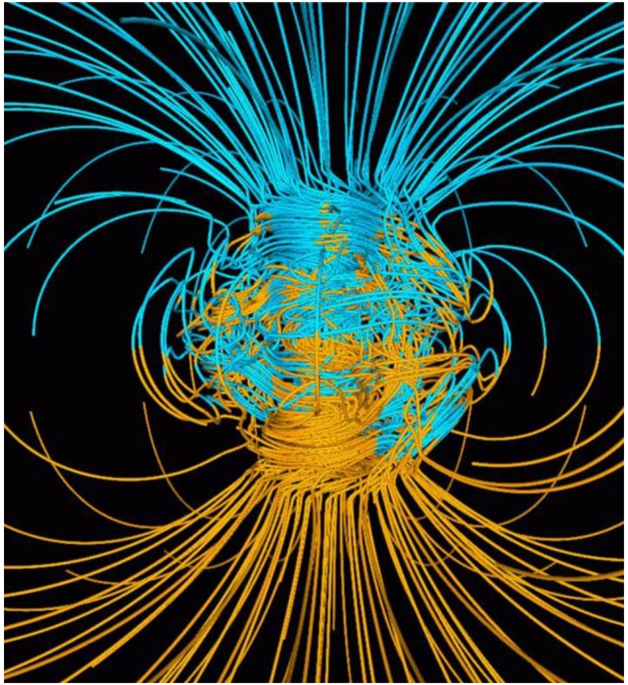
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

- $\mathbf{v}$ = velocità del fluido conduttore
- $\eta = \frac{1}{\mu_0 \sigma}$ = diffusività magnetica (σ è la conducibilità elettrica)

Due termini competono:

- **Termine induttivo** $\nabla \times (\mathbf{v} \times \mathbf{B})$: genera e amplifica il campo
- **Termine diffusive** $\eta \nabla^2 \mathbf{B}$: tende a dissiparlo

CAMPO MAGNETICO NUCLEARE



a) Dynamo experiments — laboratorio di simulazione del nucleo

Questi esperimenti cercano di riprodurre **l'effetto dinamo**, cioè la generazione di un campo magnetico da un fluido conduttore in moto (come nel nucleo terrestre).

⚙️ Principio fisico

- Le correnti fluide di metallo liquido (Fe, Na, Ga) in un campo magnetico debole inducono correnti elettriche → che a loro volta **amplificano** il campo.
- Si studia se e come il sistema può **autosostenere** un campo magnetico.

🌪️ Esperimenti famosi

Nome / Luogo	Descrizione	Risultato
Riga Dynamo (Lettonia)	Flusso di sodio liquido in tubi elicoidali (fine anni '90).	Prima **auto-generazione del campo magnetico** in laboratorio.
Karlsruhe Dynamo (Germania)	52 canali di sodio liquido che simulano moti elicoidali coerenti.	Conferma sperimentale dell'**effetto α–ω** della dinamo.
Madison Dynamo (USA, Wisconsin)	Grande sfera di acciaio piena di sodio liquido in rotazione.	Studio delle condizioni di **transizione alla dinamo** e dell'**inversione di polarità**.
VKS – von Kármán Sodium (Francia, CEA Saclay)	Due dischi controrotanti in sodio liquido.	Osservate **inversioni spontanee** del campo, analoghe a quelle terrestri.

b) Esperimenti su convezione magnetica e rotazione

- Alcuni laboratori (es. **Cornell, Princeton, Leeds**) simulano la **convezione di fluidi conduttori in rotazione** in geometrie sferiche o cilindriche.
- Si misura come la **rotazione differenziale e la forza di Coriolis** organizzino le correnti in **colonne di Taylor** (come nel nucleo esterno della Terra).

CAMPO MAGNETICO DELLA CROSTA

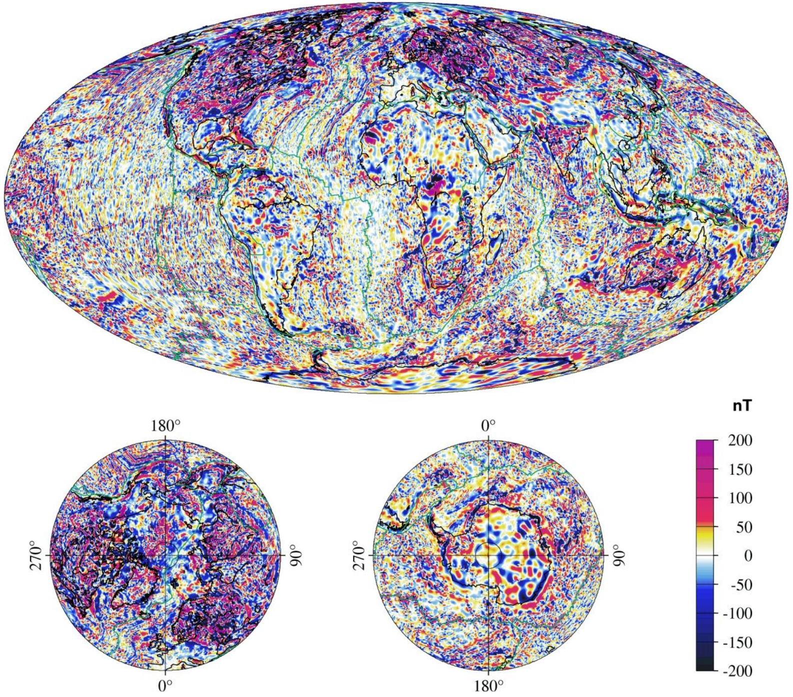
Sources:

- **Remanent magnetization:** rocks acquire magnetization when they form (especially volcanic and igneous rocks) and align with the ambient geomagnetic field of that time.
- **Induced magnetization:** rocks can also become temporarily magnetized by the current geomagnetic field.

Together, these contributions create **magnetic anomalies** — local deviations from the smooth, global field generated by the Earth's core.

From crustal magnetic maps we can learn:

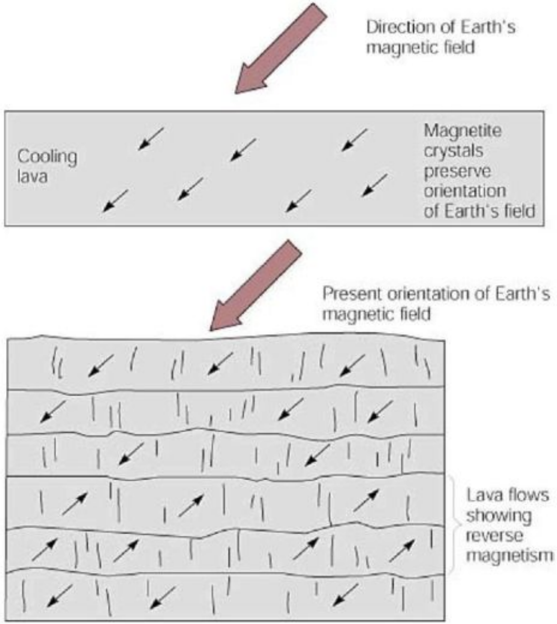
- **Tectonics:** The magnetic stripes on the ocean floor (clearly visible along mid-ocean ridges) record **geomagnetic reversals** and provide evidence for **seafloor spreading**
- **Crustal composition:** Magnetic anomalies reveal variations in crustal lithology, thickness, and thermal structure.
  Mineral exploration: Magnetic surveys help locate iron-bearing mineral deposits.

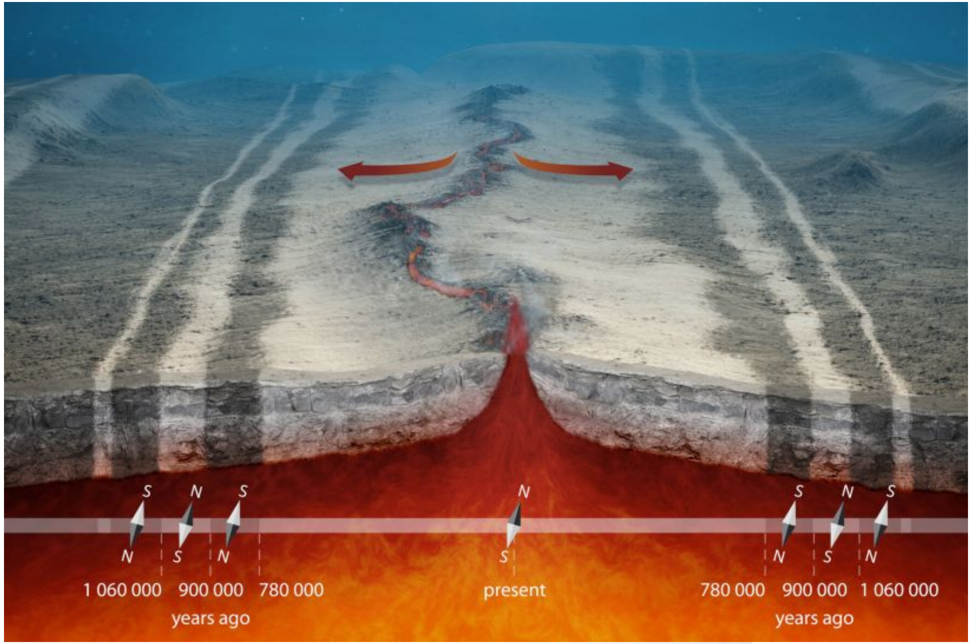


Vertical component of the Earth's crustal magnetic field, that is, the part of the magnetic field that arises **from magnetized rocks in the Earth's crust**, not from the Earth's core.

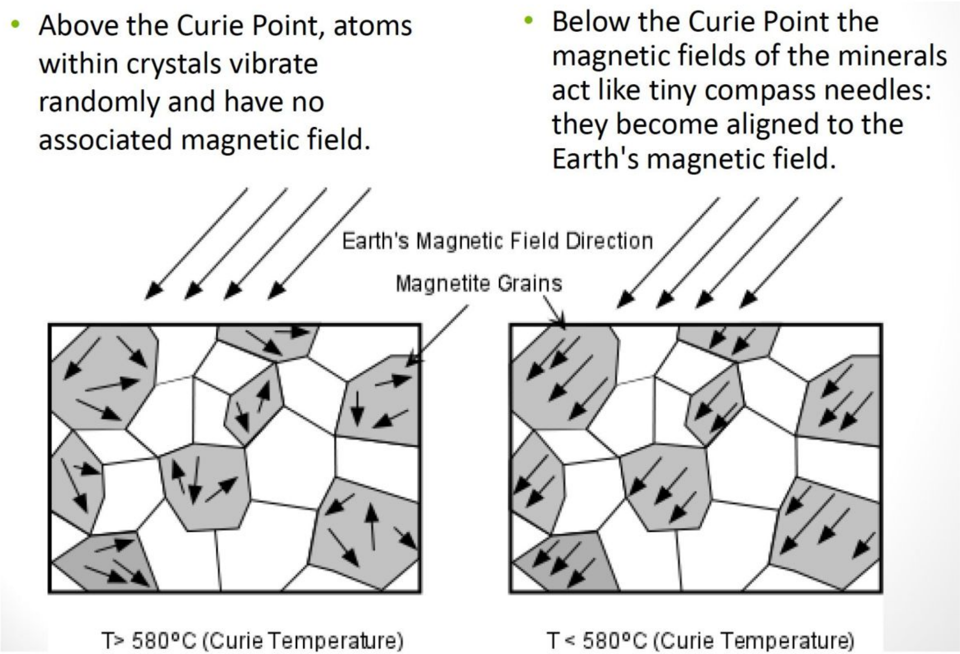
MAGNETIZZAZIONE ROCCE IGNEE

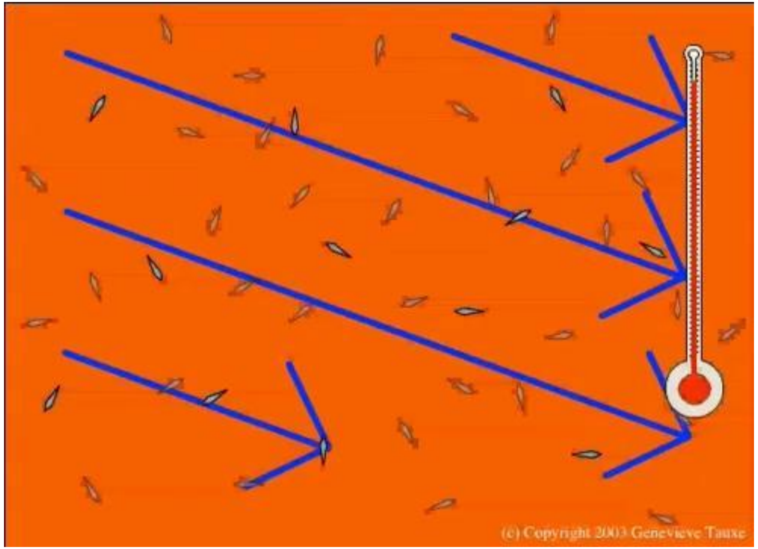
- Igneous rocks record direction + intensity at time of formation. Look at sequence of lava flows – find N-S reversals.
- Magnetism "frozen" in when lava drops below **Curie Point** – this is 580˚C for magnetite.





MAGNETIZZAZIONE ROCCE IGNEE





While the lava is still well above the Curie temperature, crystals start to form, but are non-magnetic. Below the Curie temperature but above the blocking temperature, certain minerals become magnetic, but their moments continually flip among the easy axes with a statistical preference for the applied magnetic field. As the lava cools down, the moments become fixed, preserving a thermal remanence.

MAGNETIZZAZIONE ROCCE SEDIMENTARIE

When magnetic particles are eroded from a source rock and are deposited as a sediment, the particles may align with the geomagnetic field to give rise to a depositional remanent magnetization.

a) Magnetic grains wobble about magnetic field vector as they sink

b) Along the bottom magnetic grains can still rotate

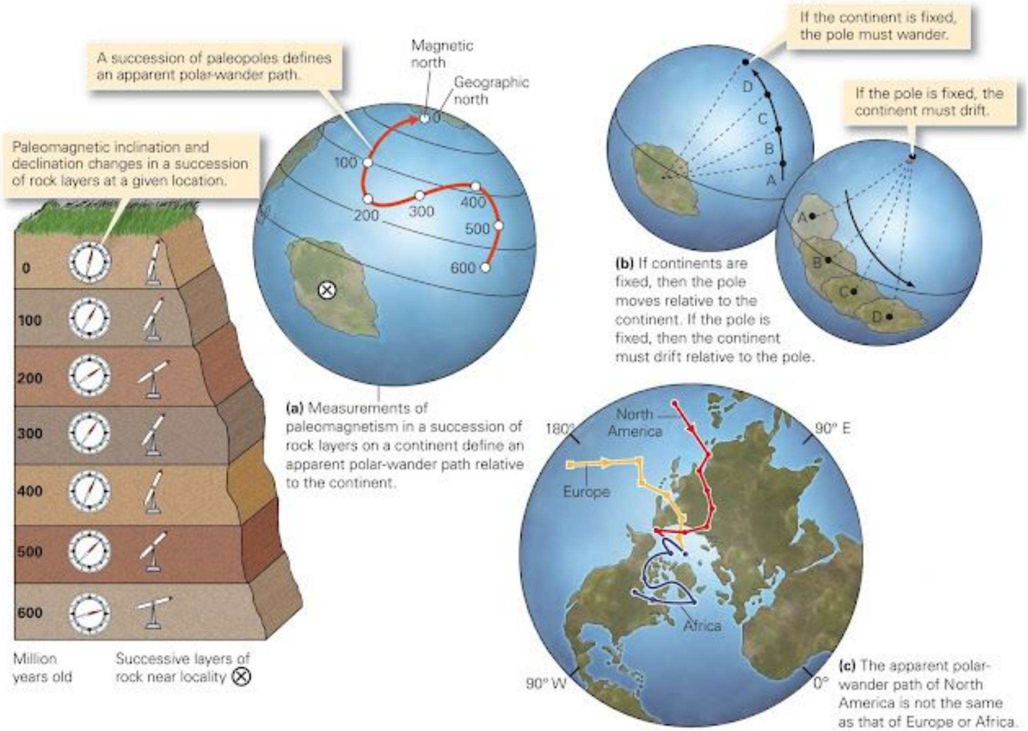
c) When the bottom gets compacted, magnetic grains lock into place

PALEOMAGNETISMO

- Mentre le misurazioni dirette del campo terrestre risalgono solo a poche centinaia di anni fa, abbiamo informazioni sul suo comportamento che risalgono a diversi miliardi di anni attraverso misurazioni paleomagnetiche
- Sebbene la maggior parte dei minerali che formano le rocce non siano magnetici, tutte le rocce presentano alcune proprietà magnetiche dovute alla presenza di tracce di ossidi di ferro.
- La magnetizzazione di questi può essere utilizzata per determinare sia la direzione locale che l'intensità del campo terrestre nel momento in cui si è formata la roccia.
- Un comportamento su scala temporale relativamente breve può essere determinato da sequenze di colate laviche e un comportamento su scala temporale più lunga da rocce sedimentarie.

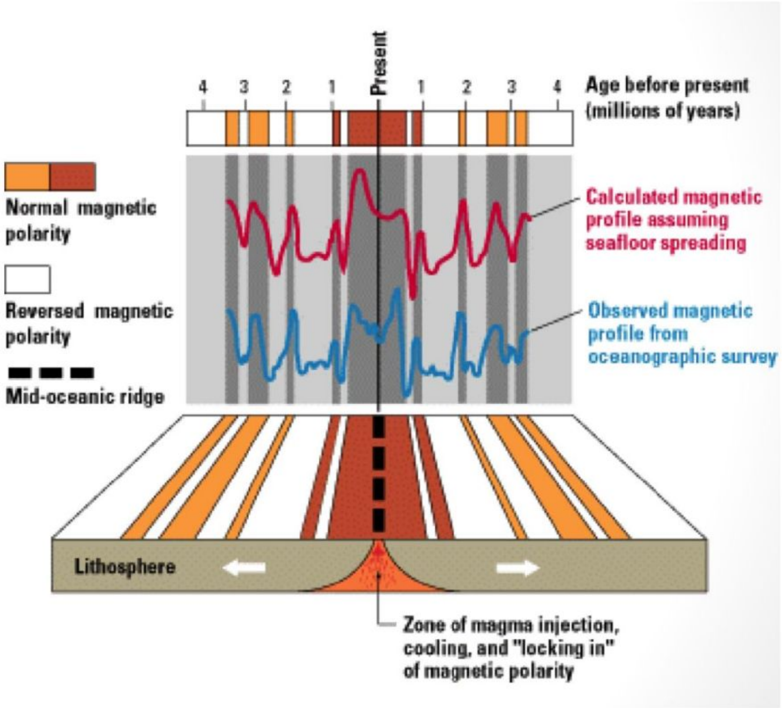
Queste misure hanno particolare rilevanza per: Teoria della tettonica a placche, Inversione del campo magnetico, Deriva dei continenti

Paleomagnetismo e deriva dei continenti

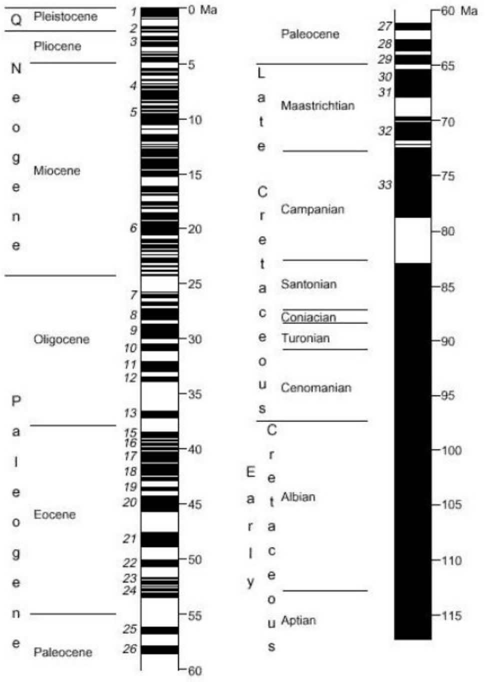


PALEOMAGNETISMO

- Magnetic reversals recorded in ocean flow Record back to late Jurassic.
- Earth magnetic field reversed 9 times in 4 milion years



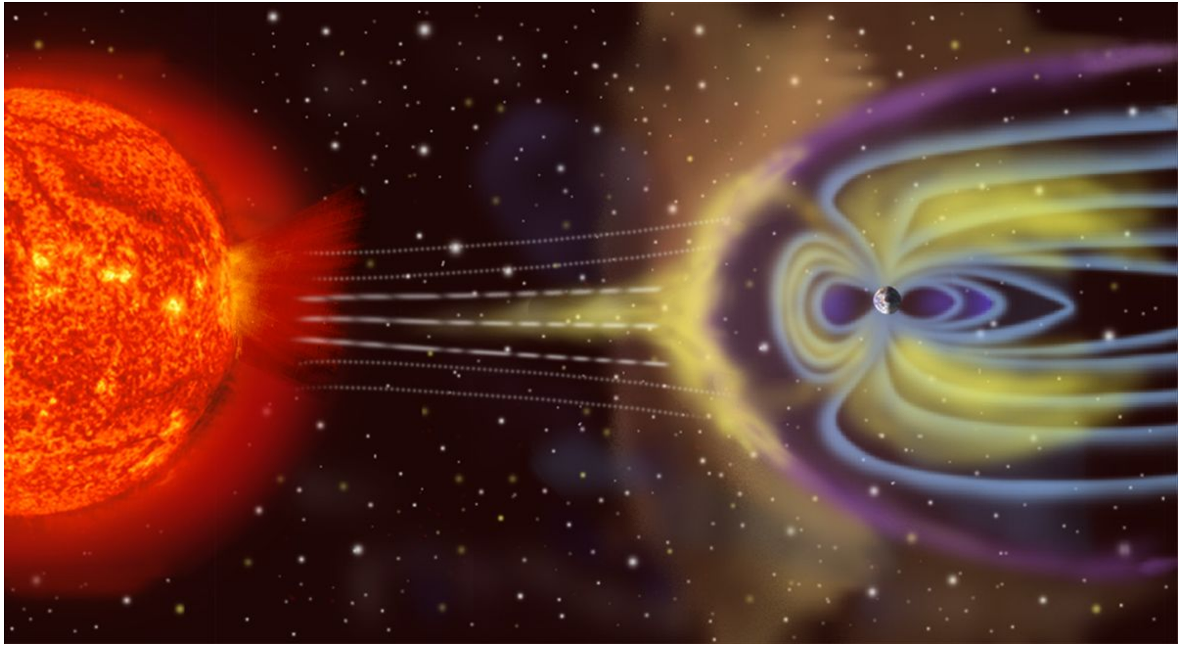
Black bars = normal polarity
White bars = reversed polarity.



- inversions every 100,000 yr to 1 Myr, unpredictable

MAGNETOSFERA

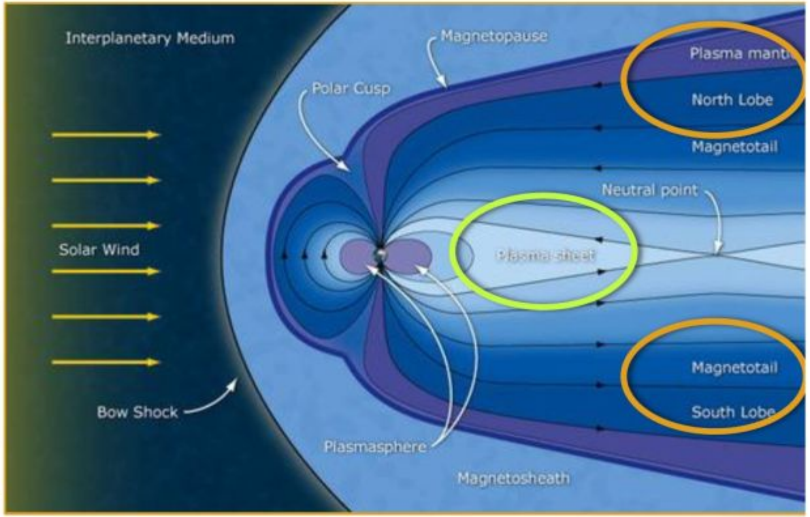
- Dopo 5 – 6 $R_\oplus$ le caratteristiche del campo magnetico cambiano per effetto del vento solare che confina il campo magnetico terrestre in una cavità chiamata **magnetosfera**.
- La forma della magnetosfera è simile a quella di un proiettile, compressa nella direzione del sole e allungata nella direzione opposta



CODE MAGNETICHE

- The night-side region of the magnetosphere is called **magnetotail**:
  - 2 separate lobes of oppositely-directed magnetic flux
  - well-defined even at 200-220 $R_\oplus$
  - is quite dynamic (ions and electrons are often energized)
  - Separating the two tail lobes is the "**plasma sheet**"

Region	Particle density
Solar wind near Earth	6 ions/cm^3
Dayside outer magnetosphere	1 ion/cm^3
"Plasma sheet" separating tail lobes	*0.3 -- 0.5 ions/cm^3*
Tail lobes	**0.01 ions/cm^3**



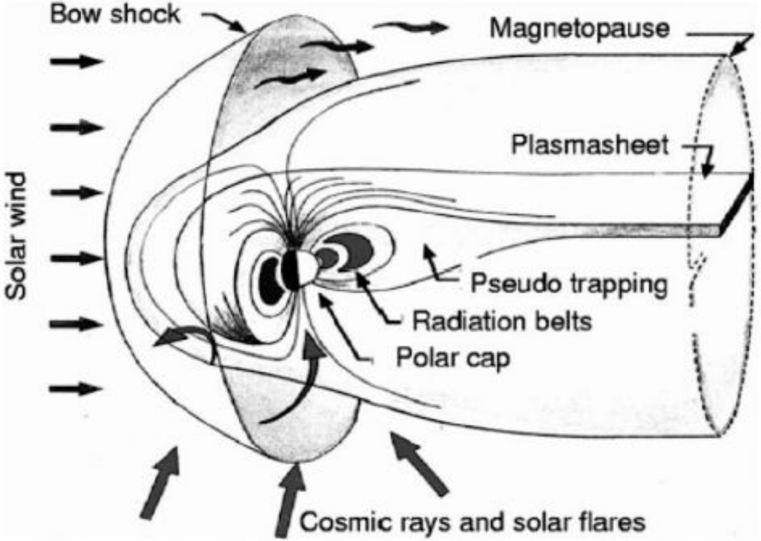
ONDA D'URTO "BOW SHOCK"

- The bow shock is the boundary at which the speed of the solar wind abruptly drops as a result of its approach to the magnetopause
  - Thick ~ 17 km (ESA's Cluster mission)
  - Position ~ 90 000 km from Earth (~ 15 R_E)

$V_b >$ $$c_s^2 = \frac{\gamma p}{\rho}$$

$V_b <$ $$c_s^2 = \frac{\gamma p}{\rho}$$

γ = Cp/Cv, p= pressure, ρ = density



MAGNETOPAUSA

The **magnetopause** is the area of the magnetosphere in which the pressure from the planetary magnetic field is balanced with the pressure from the solar wind

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

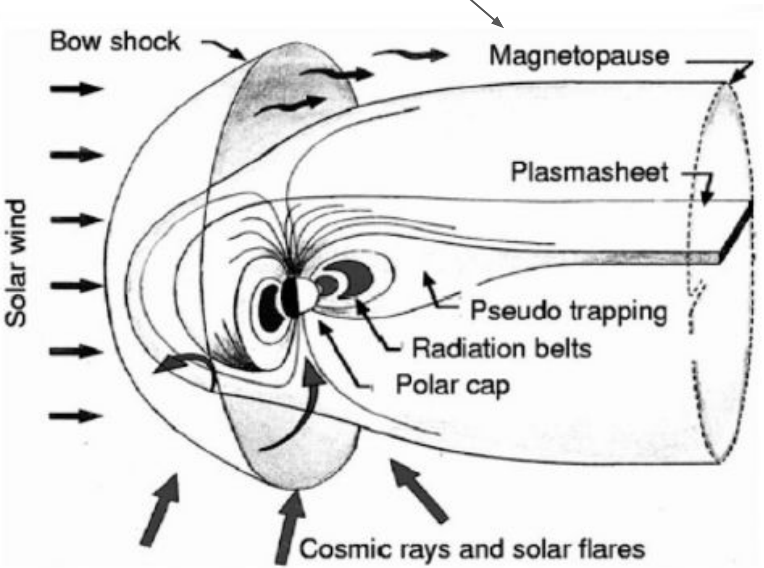
Solar wind dynamic pressure ≈ Earth' magnetic pressure

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

Dipolar field: $B \sim B_0/r^2$

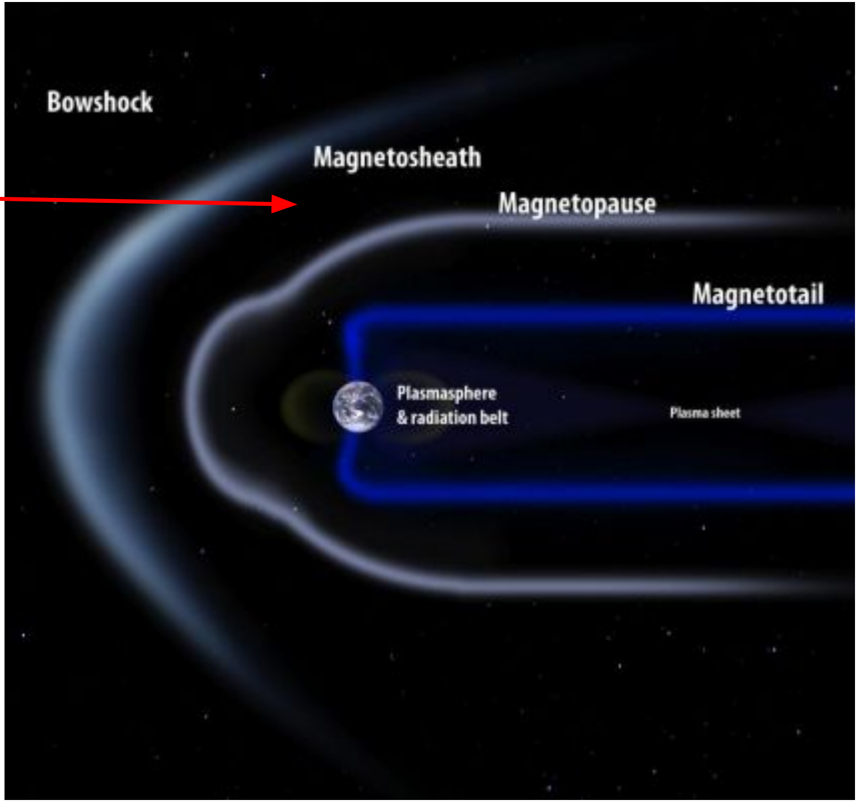
$$\boxed{r \approx \sqrt[6]{\frac{2B_0^2}{\mu_0 \rho v^2}}}$$

Magnetopause distance



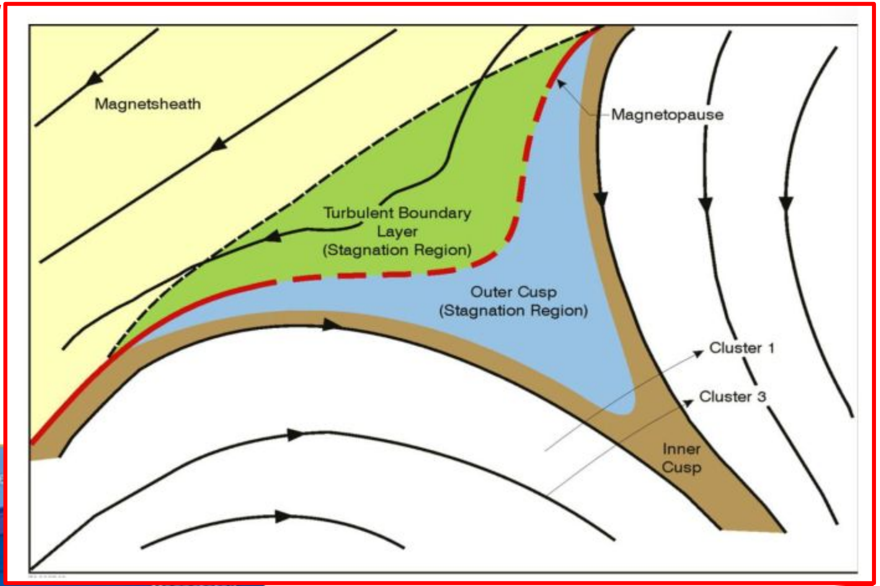
GUAINA MAGNETICA

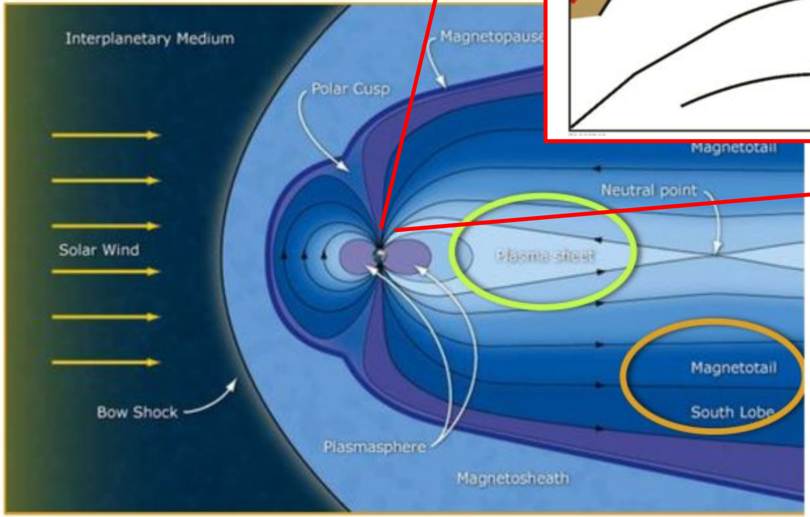
The region between the bow shock and the magnetopause, the **magnetosheath**, is characterized by very turbulent plasma. For the Earth, along the Sun-Earth axis, the magnetosheath is about 2 Earth radii thick.



CUSPIDI POLARI

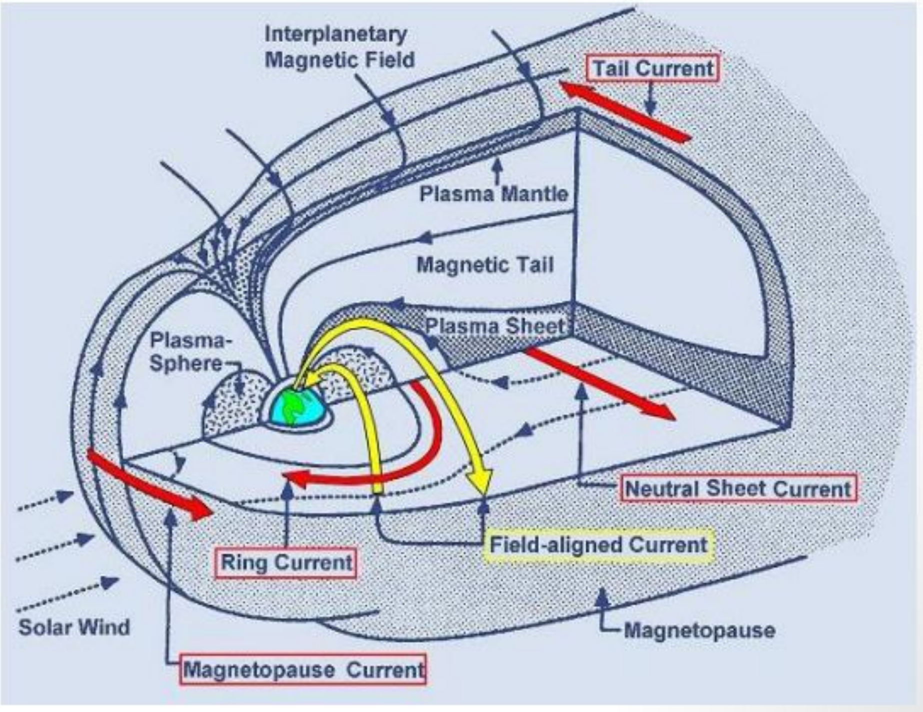
The polar cusp is a region where the magnetic field lines switch from closing on the dayside to being swept back into the tail; this is the region where the magnetosheath plasma has direct access to the ionosphere





CORRENTI NELLA MAGNETOSFERA

Earth's magnetosphere present a really complicated current system, whose structure is influenced by the interaction with the interplanetary magnetic field. These plasma circuits **connects the solar wind, magnetosphere, and ionosphere**, controlling geomagnetic activity and energy transfer throughout Earth's space environment.



Magnetopause Current

- Flows on the **dayside magnetopause**, where the solar wind is deflected around Earth.
- Shields the Earth's field from direct solar wind penetration, forming the **boundary of the magnetosphere**.

Ring Current

- A **westward current** circulating around Earth at ~3–6 $R_{\oplus}$, mainly in the **equatorial plane**.
- Responsible for **geomagnetic storms**, as it temporarily reduces the surface magnetic field intensity.

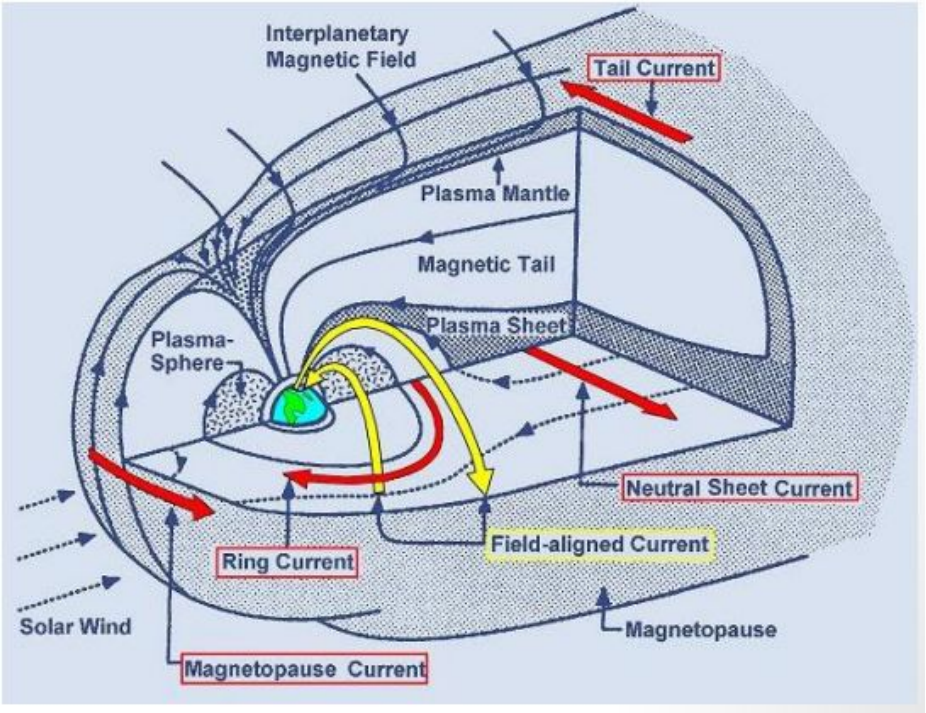
CORRENTI NELLA MAGNETOSFERA

Neutral Sheet Current

- Flows **across the plasma sheet** in the magnetotail, from dawn to dusk direction.
- Balances the opposite magnetic fields of the northern and southern tail lobes.
- Plays a crucial role in **magnetic reconnection** and substorm dynamics.

Field-Aligned Currents

- Flow **along magnetic field lines** between the **magnetosphere** and the **ionosphere**.
- Connect the outer magnetosphere to high-latitude ionospheric regions.
- Drive **auroral phenomena**, as they carry energetic electrons that precipitate into the upper atmosphere.



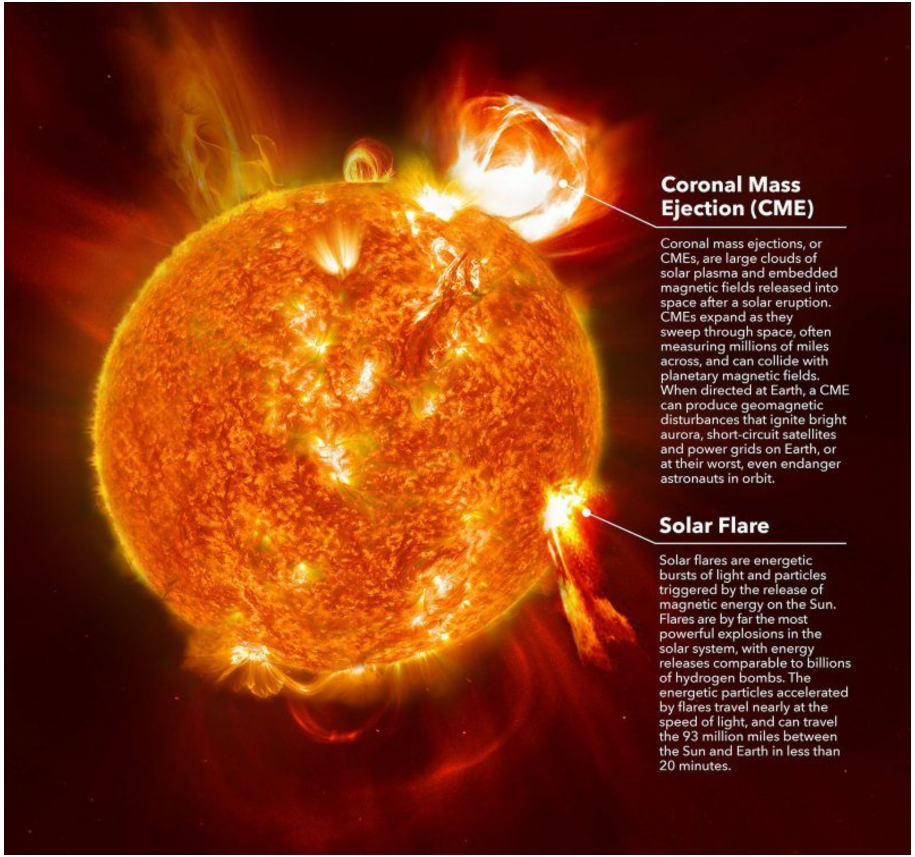
ATTIVITÀ GEOMAGNETICHE

Geomagnetic activity refers to disturbances in Earth's magnetic field, caused by the interaction between the solar wind and the planet's magnetosphere.

Cause: The primary cause is the transfer of energy from the solar wind into the magnetosphere, often triggered by solar events like coronal mass ejections (CMEs) or solar flares.

Effects:

- **Auroras:** Visible in polar regions, and can be seen at lower latitudes during major storms.
- **Technological impact:** Can disrupt or damage satellites, affect power grids, and interfere with radio communications, GPS signals.



TEMPESTE MAGNETICHE

Geomagnetic storms are large disturbances in the near-Earth environment, which are caused by coherent solar wind and interplanetary field structures that originate from solar disturbances such as coronal mass ejections. These storms are associated with:

- Major disturbances in the geomagnetic field.
- Strong increase of energetic (tens to hundreds of keV) ions in the (ring current) region.
- Occasionally intense fluxes of relativistic (MeV) electrons in the outer van Allen radiation belt.

This visualization shows the Earth's magnetosphere being hit by a geomagnetic storm. The MAGE model simulates real events that happened throughout May 10-11, 2024.
White orbit trails: All satellites orbiting Earth during the storm
Orange orbits: Proposed orbits for six GDC spacecraft
Orange-to-purple lines: Magnetic field lines around Earth
Blue trails: Solar wind velocity tracers
Green clouds: Electric field current intensity

[link to video]

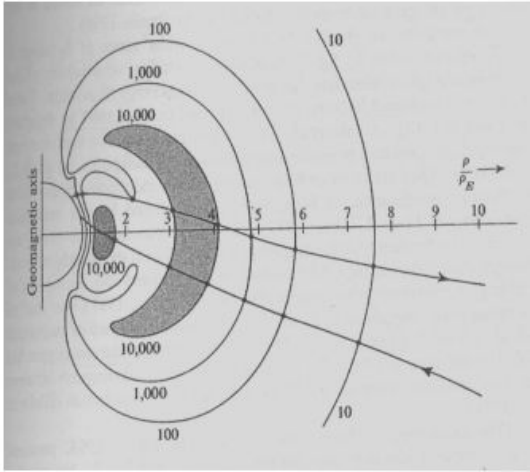
FASCE DI VAN ALLEN

- Jan 1958: Explorer 1 (US)
  - *Geiger-Muller counter; J. van Allen*
  - LEO elliptical
  - > n cosmic rays up to 800km. At higher r no counts

Too much interactions saturated the receiver

- Explorer 2 =failed,
- March 25, **1958** Explorer 3:
  - Data recorder
  - Saturate
- Explorer 2 with 2 Geiger counter for different energy range

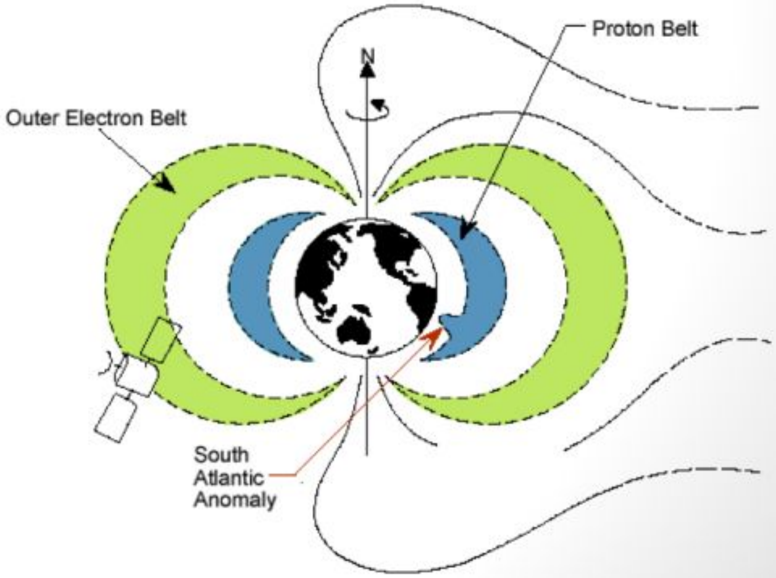
Toroidal ring filled with charged particles

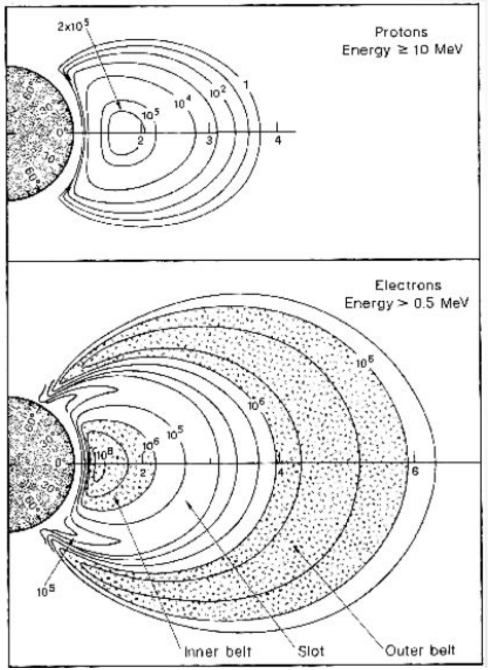


FASCE INTERNE ED ESTERNE

	Inner belt	Outer belt
Particles	p, e^-	e^-
Position	< 2.5 R_E	> 2.5 R_E, < 12 R_E
Energies	~100 keV (e^-), ~ 100 MeV (p)	0.1 ÷ 10 MeV

Due to the tilt of the geomagnetic axis relative to Earth's rotation axis the bottom of the belts is only 500 km above the southern Atlantic.



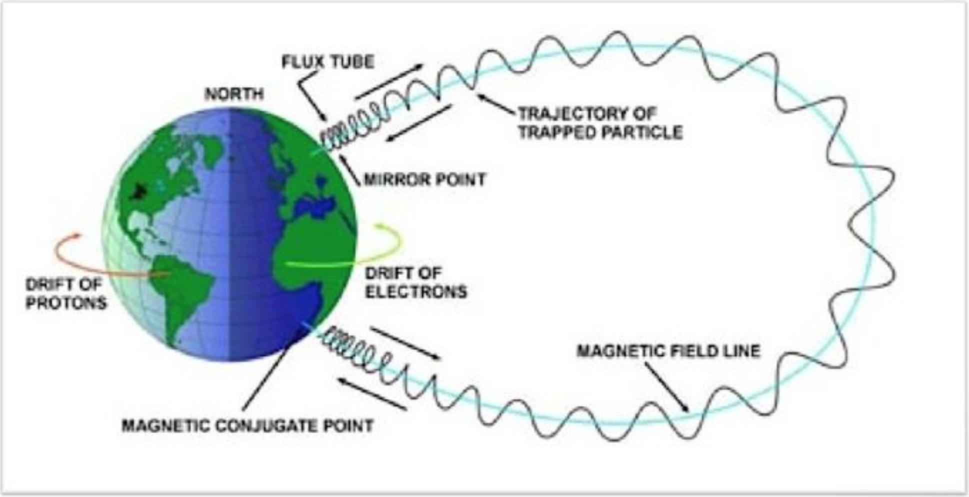


The numbers give the omnidirectional flux in particles per square centimeter per second

PARTICELLE CARICHE NEL CAMPO MAGNETICO

- A charged particle became trapped in those regions where the magnetic field lines are closed. Tree possible effects:

Circular motions with gyro-radius about the field line
Bounce back and forth along a field line. Reversing direction at a mirror point
Drift of particles around the Earth: Electrons drift to east, protons drift to west



(Solar Cosmic Rays)

Origin: **Solar flares** and **Coronal Mass Ejections** (CME)

p, e & **He** emitted by the sun in burst during **'solar storms'**

-energies > 10 MeV/nucleon

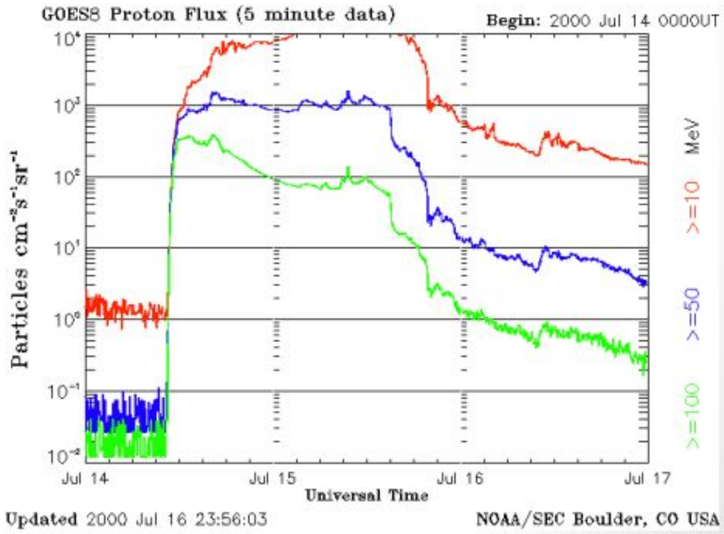
-access to open magnetic fields of polar cap.

Produce also : X-rays; gamma-rays, UV light burst and very fast wind flow which can inject protons into the trapping region (even create 'second proton belt')

Fluence: from 10^5 to 10^11 part/cm^2

Duration of event: from one to several days

"Bastilia" Solar Event
14 July 2000



RAGGI COSMICI

Galactic Cosmic Rays:

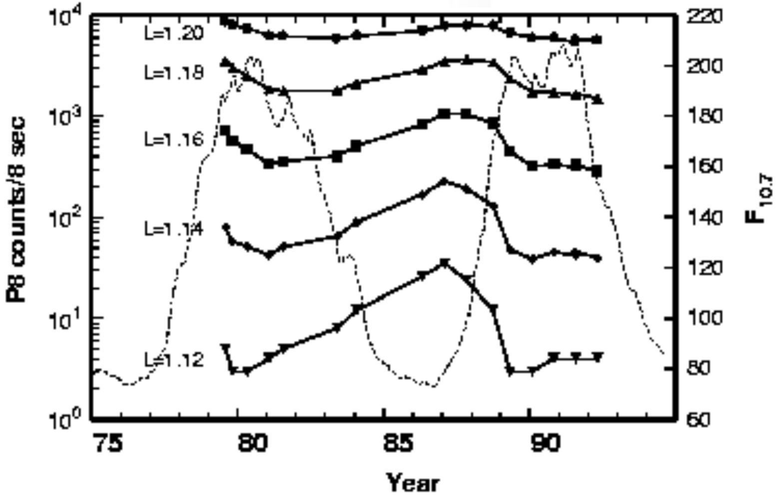
fully ionized particles of all stable elements (90% p ~7% He)

Origin: galactic and extragalactic; Energies up to TeV

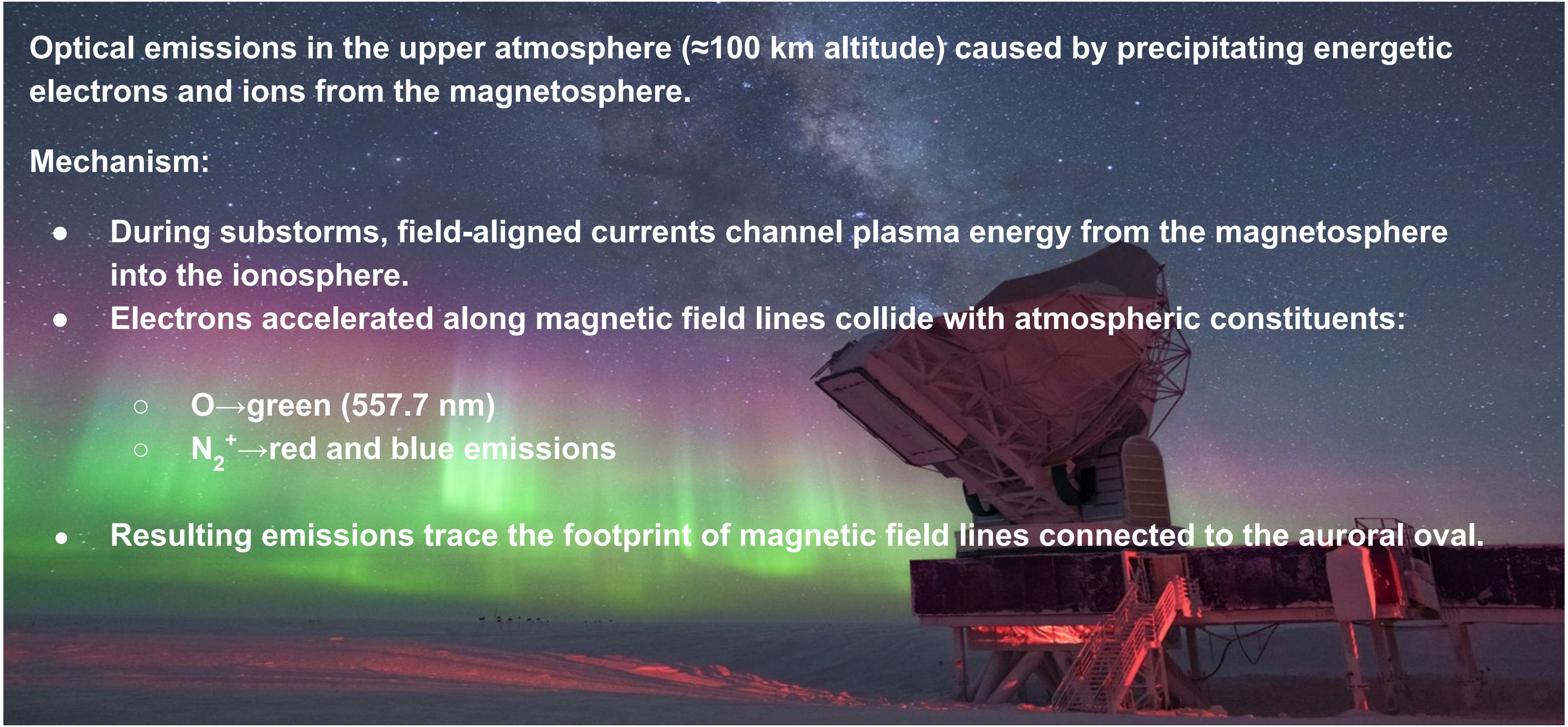
Energy spectrum max at 0.3-1 GeV/nucleon

The incoming charged particles are ‘**modulated**’ by the **solar wind** and **IMF** which decelerates and **partially excludes the lower energy** GCR from the inner solar system. There is a significant **anticorrelation** between solar activity and the intensity of the CR with E< 10 GeV.

Variations of proton counts E=80-215 MeV of MEPED detector aboard the TIROS/NOAA spacecraft



AURORE POLARI



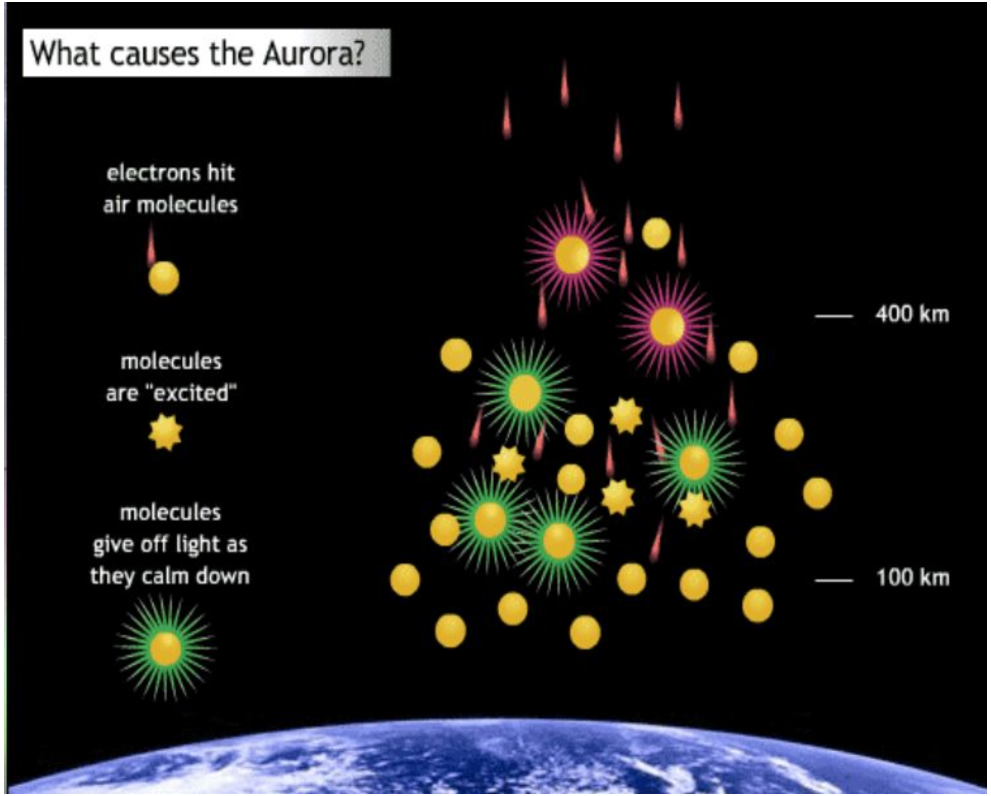
Optical emissions in the upper atmosphere (≈100 km altitude) caused by precipitating energetic electrons and ions from the magnetosphere.

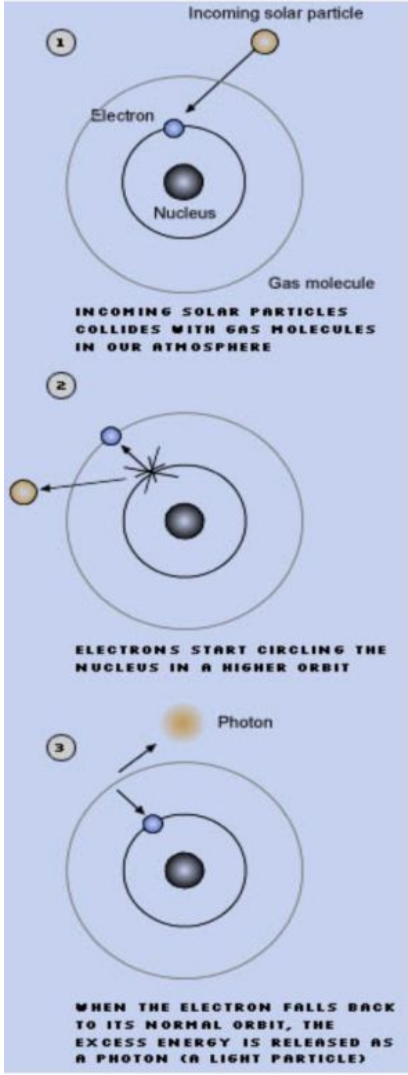
Mechanism:

- **During substorms, field-aligned currents channel plasma energy from the magnetosphere into the ionosphere.**
- **Electrons accelerated along magnetic field lines collide with atmospheric constituents:**
  - **O→green (557.7 nm)**
  - **N_2^+→red and blue emissions**
- **Resulting emissions trace the footprint of magnetic field lines connected to the auroral oval.**

ORIGINE DELLE AURORE

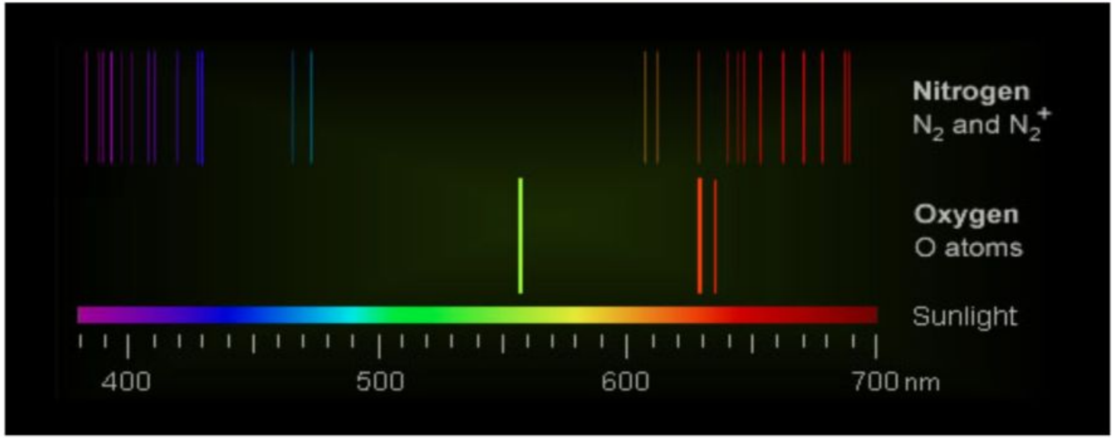
- Le Aurore sono una manifestazione visibile dell’interazione sole-terra.
- Le particelle cariche del vento solare, la cui dinamica e’ vincolata dal campo geomagnetico terrestre, interagiscono con gli atomi della parte superiore dell’atmosfera.





LO SPETTRO DELLE AURORE

- Le Aurore sono una sorgente di radiazione nelle bande dei raggi X, UV, Ottici,IR e radio



Green colour: atomic oxygen line at 557.7 nm, 100-200 km altitude

Red colour: atomic oxygen spectral triplet at 630.0, 636.4, 639.1 nm, h >200 km

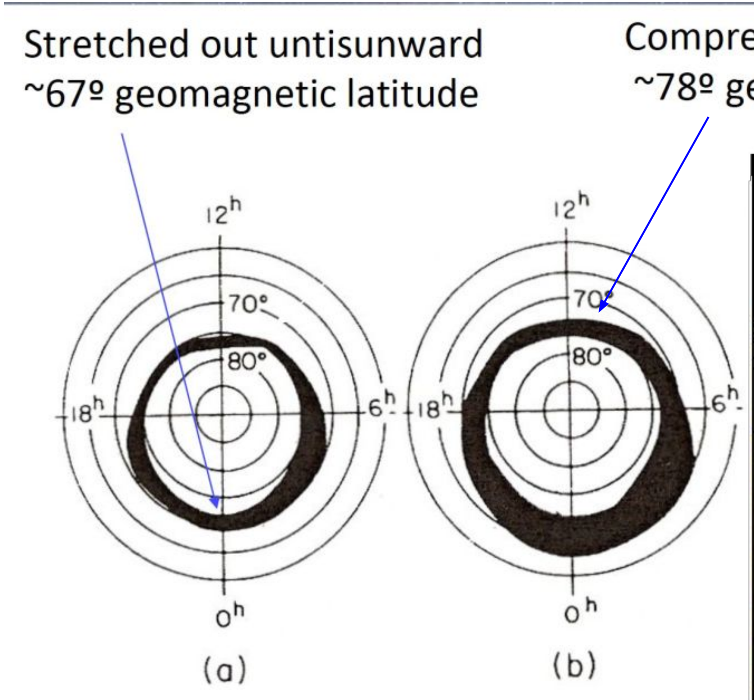
Violet or Blue colour: molecular nitrogen line at 391.4, 427.0 ,470.0 nm, h <100 km

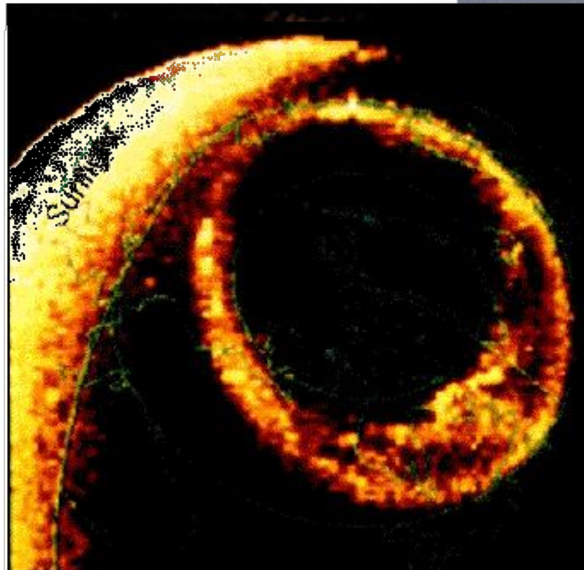
OVALE AURORALE

Viste dallo spazio, le aurore boreali e australi appaiono come degli **ovali centrati sui poli magnetici**.

Coincidono con i punti della ionosfera dove arrivano le linee di campo magnetico collegate al plasma della coda magnetica, cioè l'area in cui le particelle energetiche provenienti dalla magnetosfera penetrano nell'atmosfera.

Durante le tempeste magnetiche l'ovale espande verso l'equatore, riflettendo la deformazione del campo magnetico

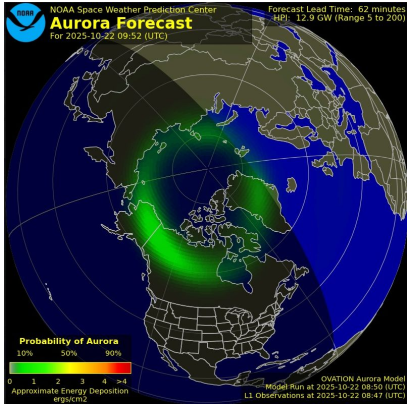




INCIDENZA AURORALE

Entro le zone auorali, le aurore sono chiaramente visibili nelle notte chiare invernali:

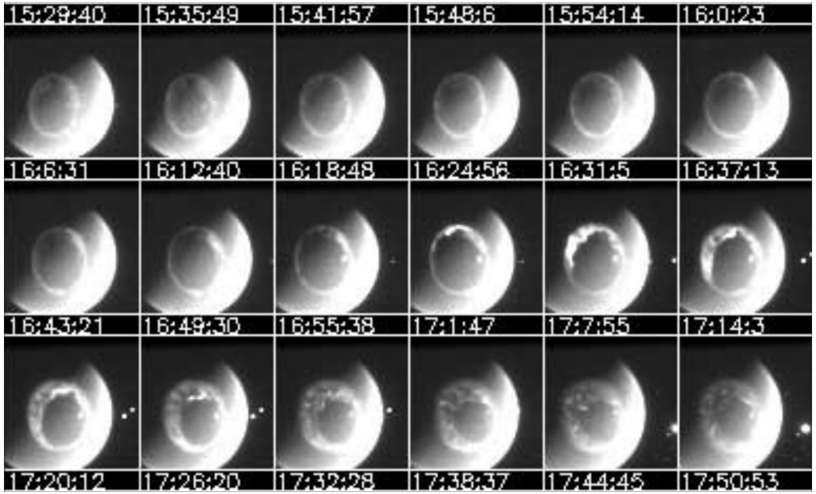
- Intervalli di 27 giorni
- Piu’ frequenti in tardo autunno ed inizio primavera
- L'attività’ aurorale segue strettamente l'attività’ solare, con cicli di 11 anni
- Le variazioni tra minimi e massimi del ciclo solare comportano variazioni aurorali del 20-30%



La durata delle aurore può essere molto variabile:

- Quiet aurora → continuous arc near 67°–70° geomagnetic latitude.
- Substorm(*) onset → auroral breakup, brightening, and poleward expansion.

(*) Localized, short-term disturbances in the **magnetotail** and **auroral ionosphere**, lasting 1–3 hours, involving the explosive release of stored magnetic energy from solar wind.



STRUTTURE AURORALI

- *Arcs*: green,sometimes with red above and purple below, quiet phase
- *Bands or Arcs with Structure*:

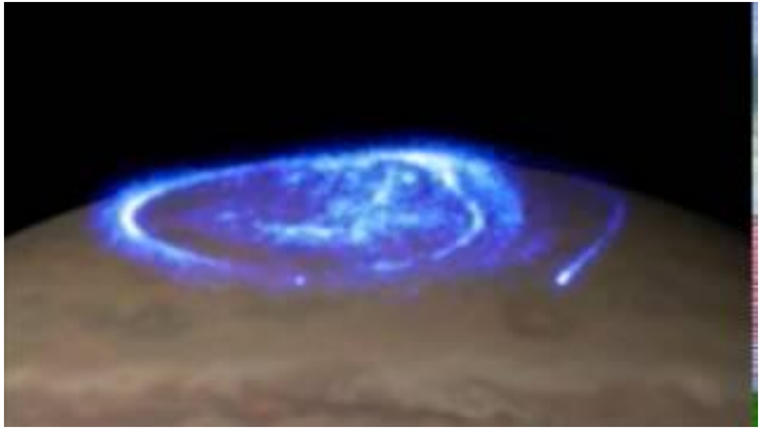
  green,sometimes with red above and purple below, expansion phase
- *Corona*: Geometric perspective effect, expansion phase
- *Diffuse Glows*: greenish at high latitudes, red at lower latitudes, recovery phase, faint

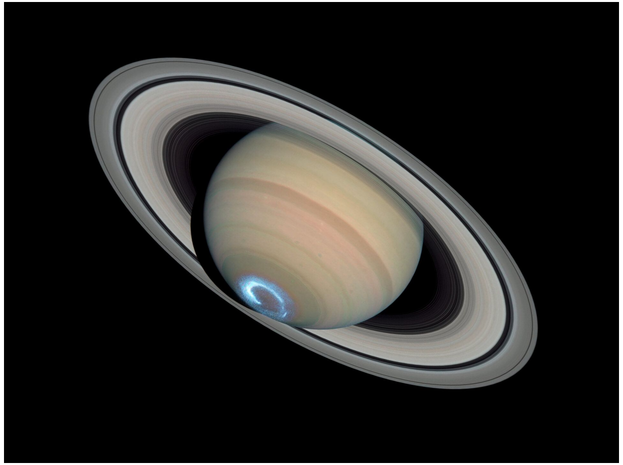
AURORE SU ALTRI PIANETI

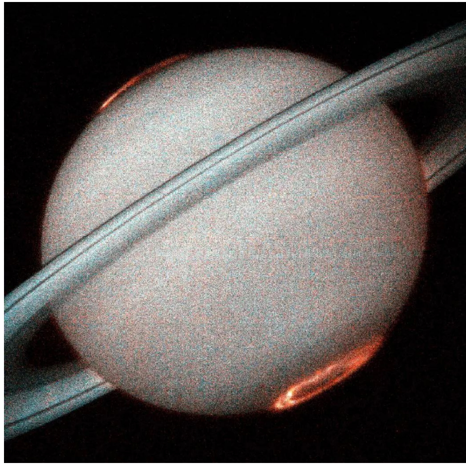
Le aurore possono generarsi su ogni pianeta dotato di campo magnetico, di atmosfera, ed una sorgente di particelle cariche.

Il processo di genesi delle aurore è lo stesso, correnti magneto-sferiche accelerano particelle che si scontrano con atomi e molecole nell’alta atmosfera

I colori e la variabilità possono differire di molto rispetto alle aurore terrestri in funzione del campo magnetico e composizione dell’atmosfera.







Hubble Space Telescope UV image