SUN EARTH SYSTEM AND SPACE WEATHER
an historical approach-Physics

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SUN EARTH SYSTEM and SPACE WEATHER

- A definition of Space Weather (ESSW)
- Universal process DYNAMO in the Sun-Earth System
- Solar Dynamo :

poloïdal and Toroïdal component of the solar magnetic field

- Earth's Dynamo
- Connections between the Solar and the Earth's dynamos

2 channels : Electromagnetic emissions and particles (solar wind)

- Electromagnetic emissions */Ionospheric dynamo,*
- Particles-Solar wind/*Solar Wind-Magnetosphere Dynamo,*

Geomagnetic storms/ electric currents

- Conclusion

Sun Earth Connections are included in Space Weather

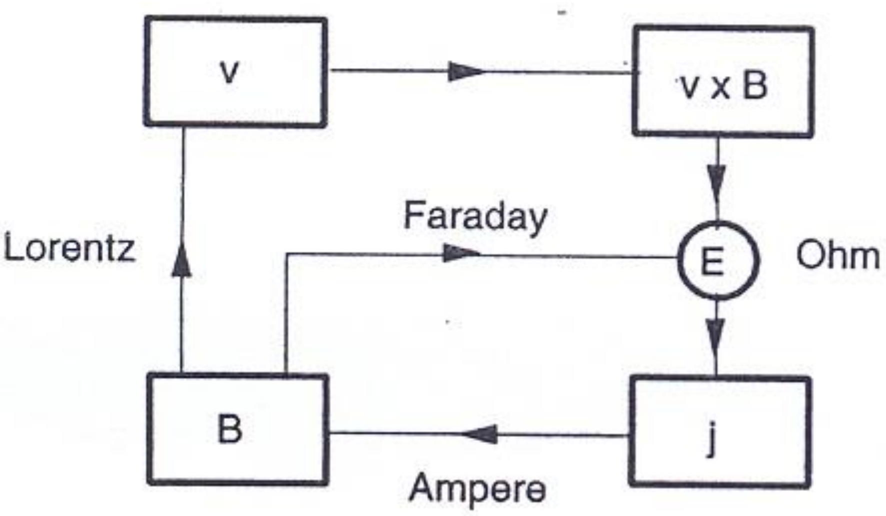
Space weather is the physical and phenomenological state of natural space environments. The associated discipline aims, through observation, monitoring, analysis and modelling, at understanding and predicting the state of the sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them; and also at forecasting and nowcasting the possible impacts on biological and technological systems

The Sun : a magnetic body in motion

Differential rotation between thepoles and equator

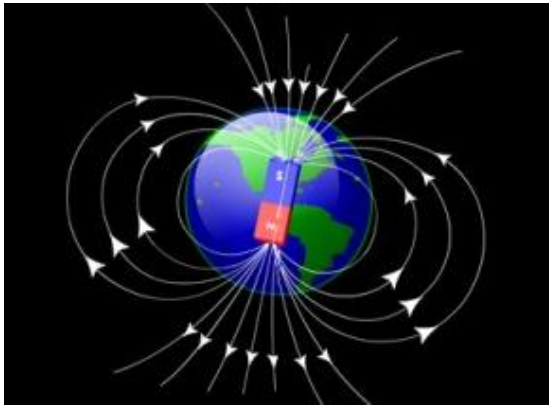
MOTION + MAGNETIC FIELD

DYNAMO Process



The Earth: a magnetic body in motion

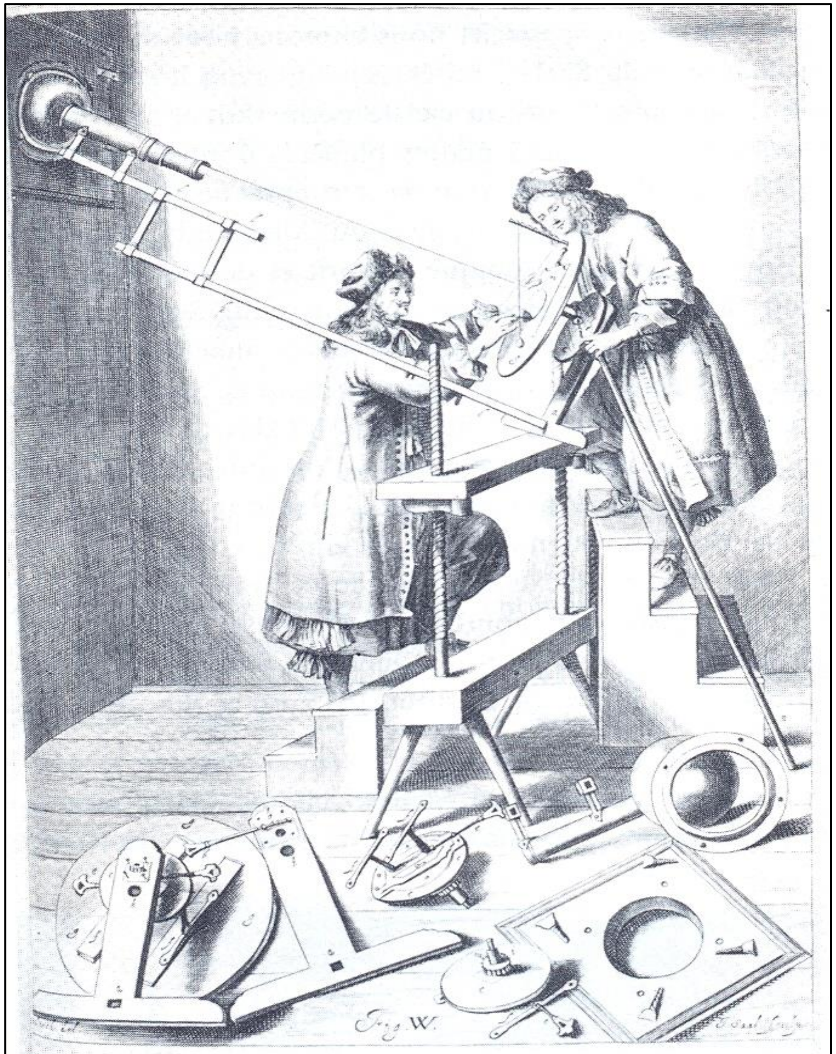
Rotation and revolution around the sun



Schematic representation between plasma motion and magnetic field [after Paterno, 2006]. Comments by Paterno 'A motion v across a magnetic field B induces an electric field vxB, which produces an electric current J=σ (E + v×B) via Ohm's law where s is the electric conductivity and E an electric field. This current produces in turn a magnetic field ∇XB = μJ, where μ is the permeability. The magnetic field creates both electric field E through Faraday's law ∇ E =-δB/δt and Lorentz force J×B which reacts on the motion v.

The Sun magnetic field : solar dynamo

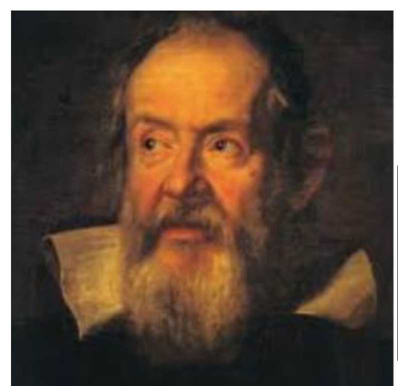
History : Observation of the Sun : Sunspots



Hévélius
1642- 1644

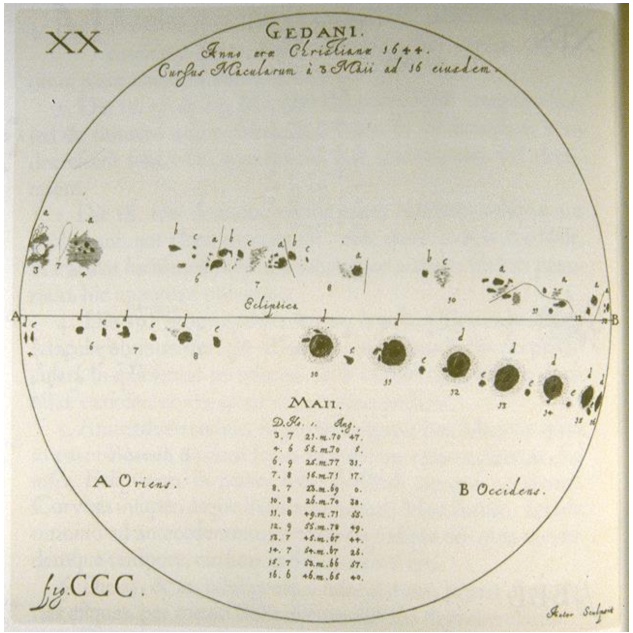
They used a telescope through an inversed wooden globe inserted in a circular width made in a shutter. They observed the sunspot by projection of its shadow on a cardboard

(Machinae Celestis, 1673
Legrand et al., 1991)

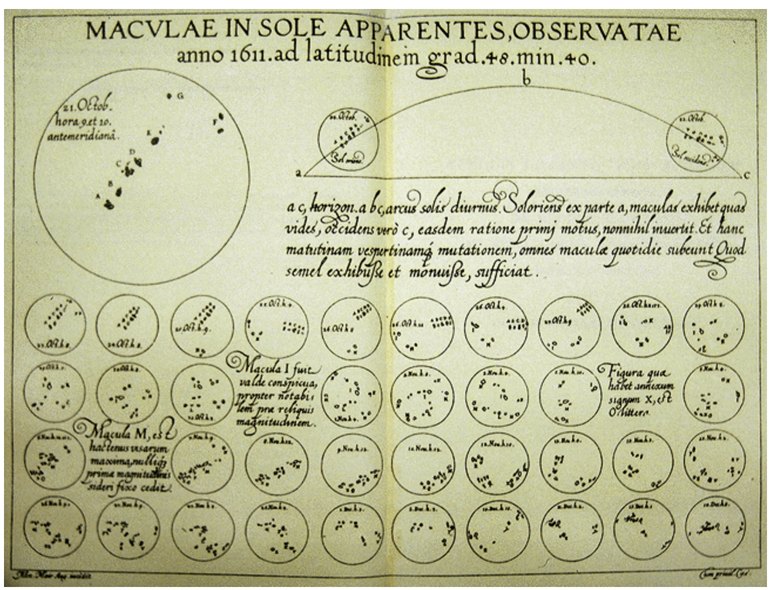


Galileo |1564-1642]
First telescope in 1609
Italy

Observation of the sun : Figures of Father Scheiner



Father Scheiner 1575-1650
Priest Jesuit mathematician
working at the university of
Ingolstadt
Germany

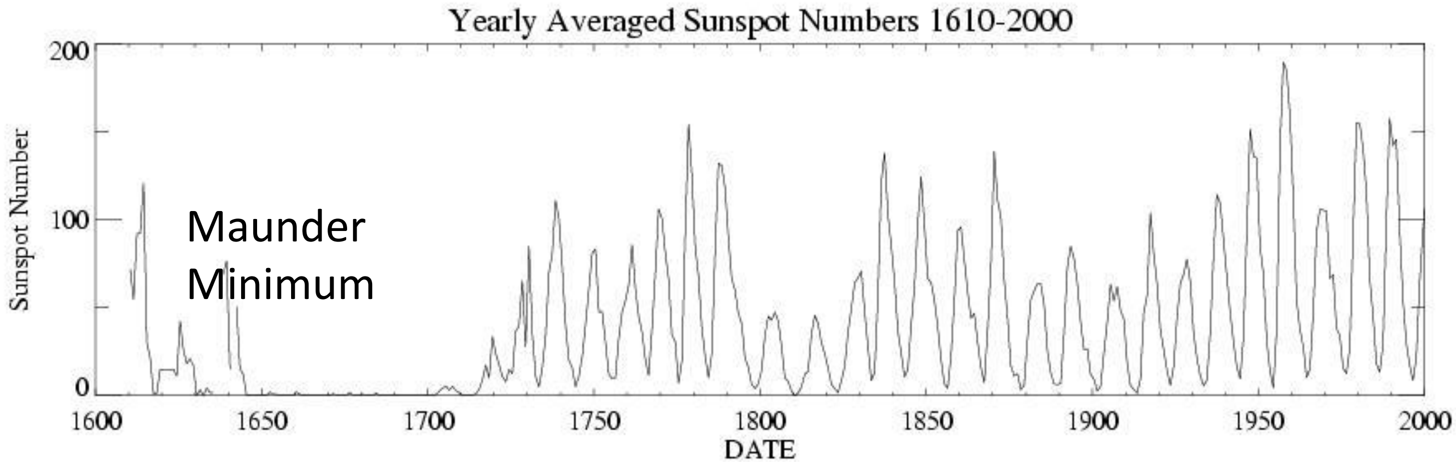


Father Scheiner “was the first to measure the equatorial rotation rate of the Sun and noticed that the rotation at higher latitudes is slower, so he can be considered the discoverer of solar differential rotation (“Rosa Ursine sive solis”, book 4, part 2, 1630)” wilkipedia

Galileo, Spring 1611
Christoph Scheiner, October 1611
Johannes Fabricius first publication, Autumn 1611

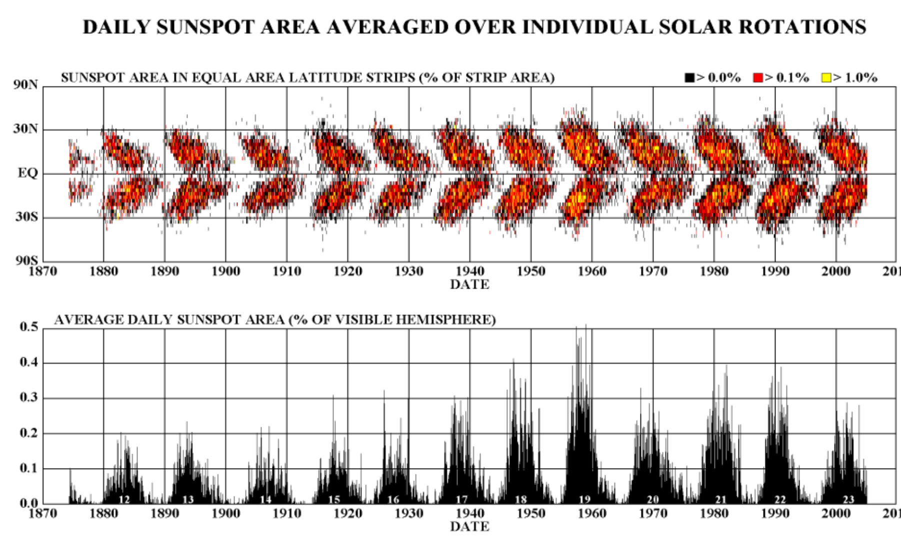
SUN : THE SUNSPOT CYCLE

H. Schwabe
[1789 -1875]
Germany



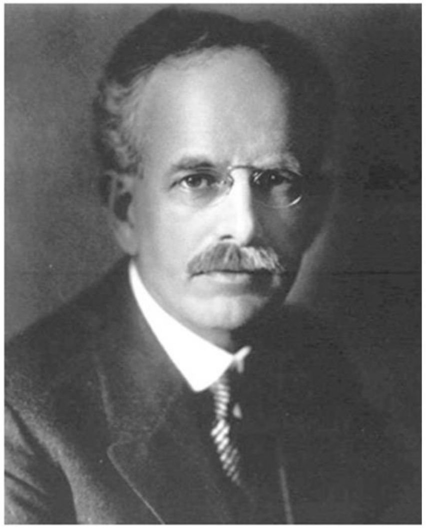
Sunspot Cycle of 11 years : Heinrich Schwabe 1859

Photo of the sun



Legrand J.P., M. Le Goff, C. Mazaudier , On the climatic changes and the sunspot activity during the XVIIth century, Annales Geophysicae, 8 (10), 637-644,1990. [on Maunder Minimum]

The Solar Magnetic field



Georges Ellery HALE
[1868-1938] USA

G. E. Hale discovered the magnetic field in sunspots. It is the first detection of a magnetic field beyond Earth

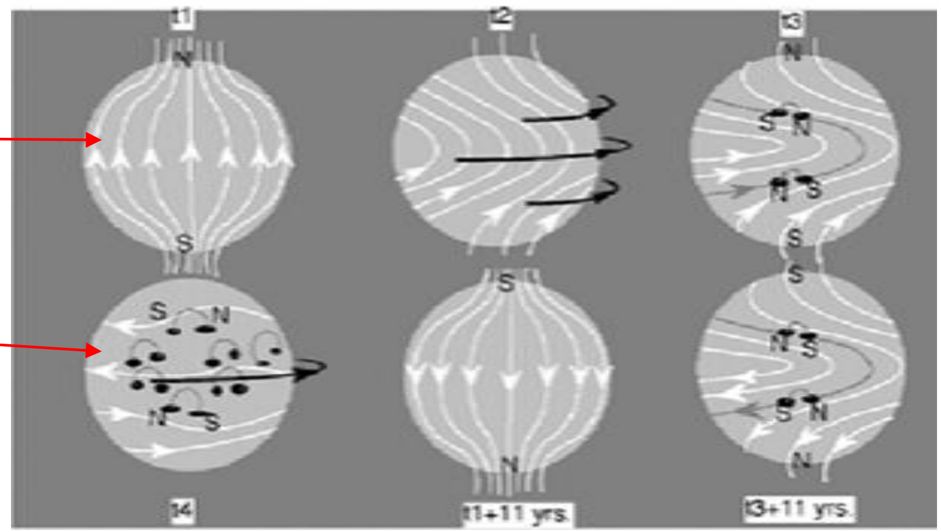
G.E Hale detected the magnetic field by the zeeman effect on the spectral lines of the sun.

The **Zeeman effect** is the **effect** of splitting of a spectral line into several components in the presence of a static magnetic field

Hale and his colleagues found that sunspots in northern and southern hemispheres reverse polarity every 11 years.

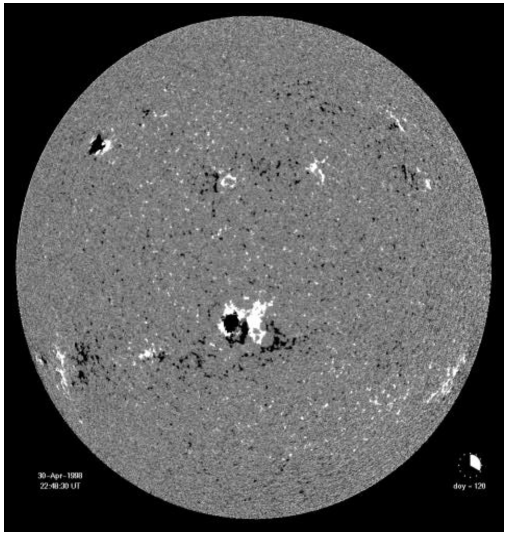
Poloïdal

Toroïdal



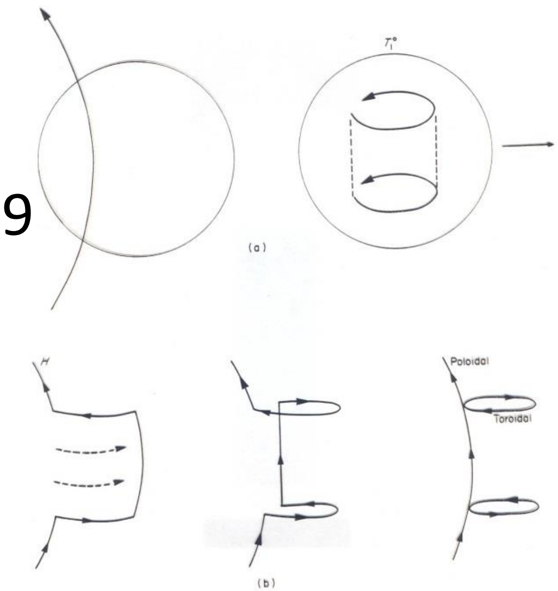
SUN : What is a sunspot ?

Figure from Friedman, 1987



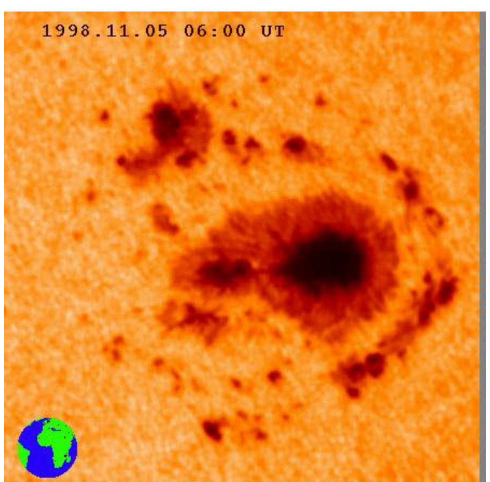
Poloïdal component
~ 10 G
discovered by Hale 1919

Toroïdal component
Sunspot
~ 3-5 kG



Magnetogram of the Sun

SOHO satellite data



Physical process : Dynamo

*The sun turns on itself.

**Its rotation speed is faster at the equator than at the poles (~ 27 days against ~ 35 days).

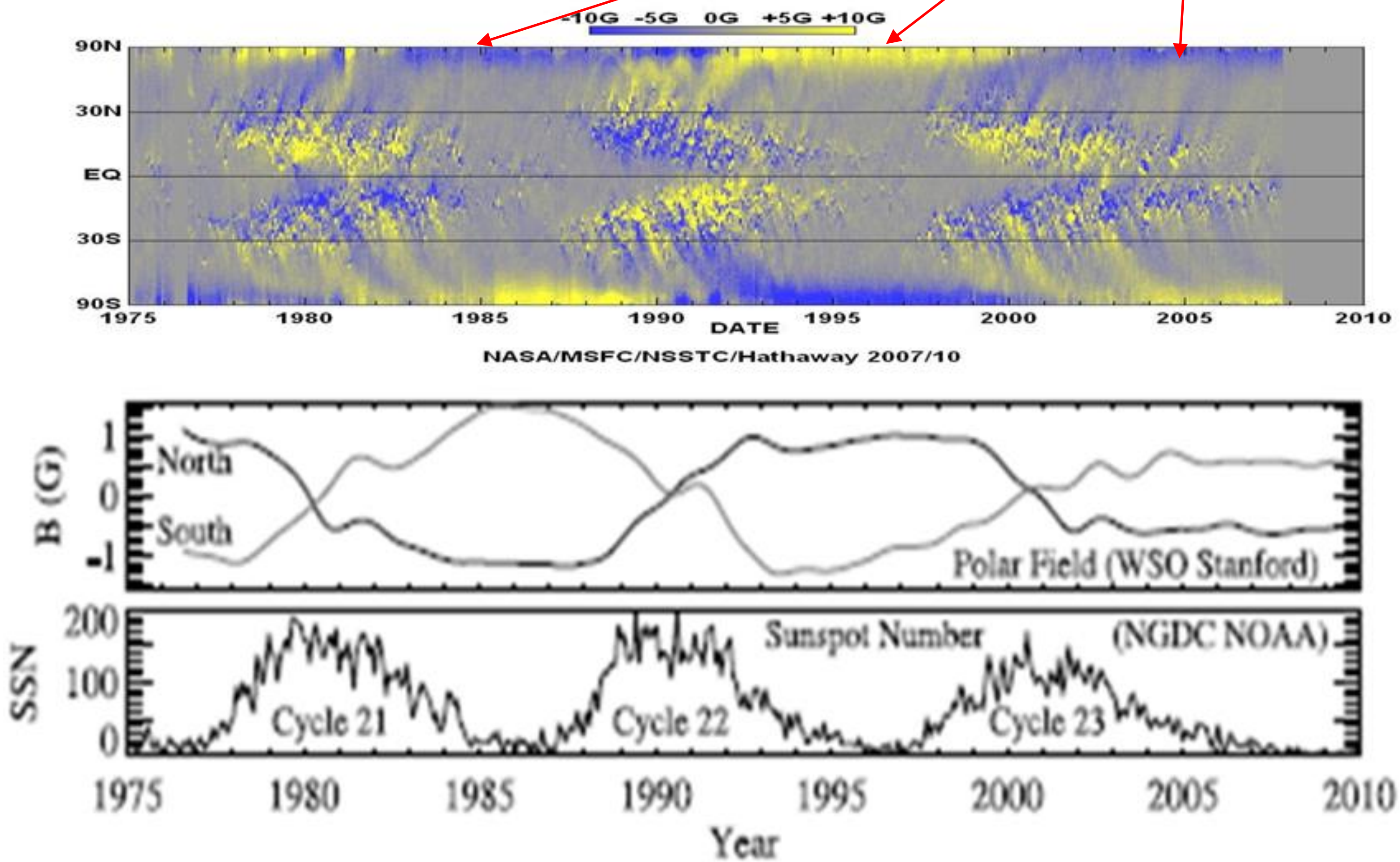
***This differential rotation twists the lines of the poloïdal magnetic field and generates magnetic loops called sunspots

Solar Dynamo : the true solar cycle by solar physicists

The solar polar magnetic field reverses each 11 years

The cycle of the toroïdal solar magnetic field (sunspot) is 11 years

The 2 components of the magnetic solar cycle and anti correlated



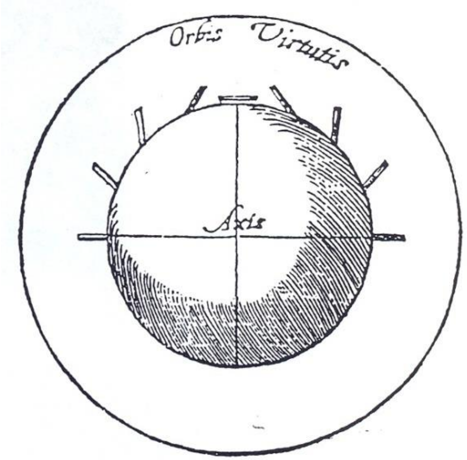
Variability ~ 11 and 22 years

Liu et al., 2011

http://solarscience.msf.nasa.gov/dynamo.shtml

The Earth’s Dynamo

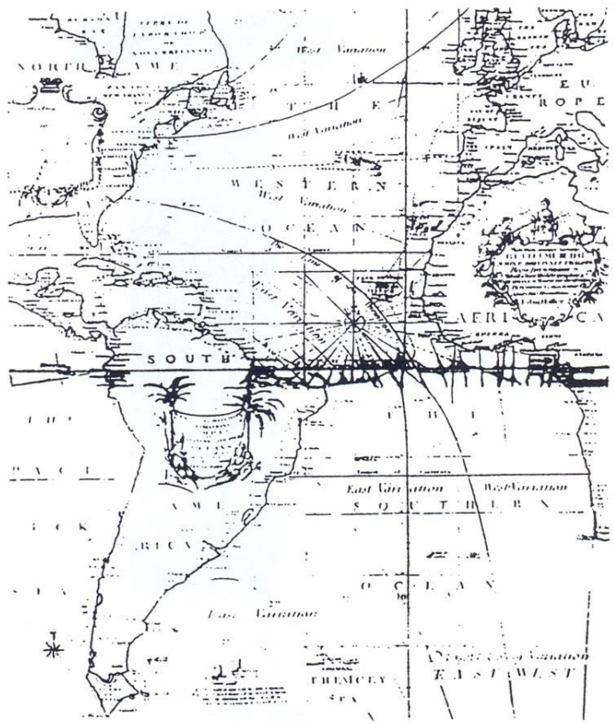
EARTH'S MAGNETIC FIELD => EARTH'S DYNAMO
Earth's magnetic field is known since more 2 millenaries

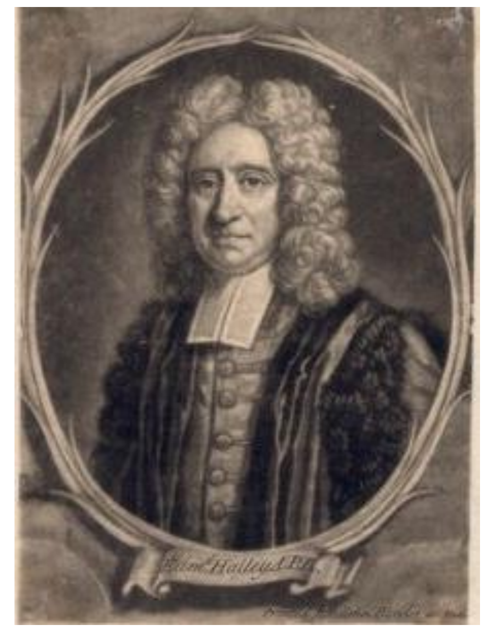


W. Gilbert, 1600
concept of the Earth's dipole magnet inside the Earth

First map of the Earth's magnetic field by Halley 1701

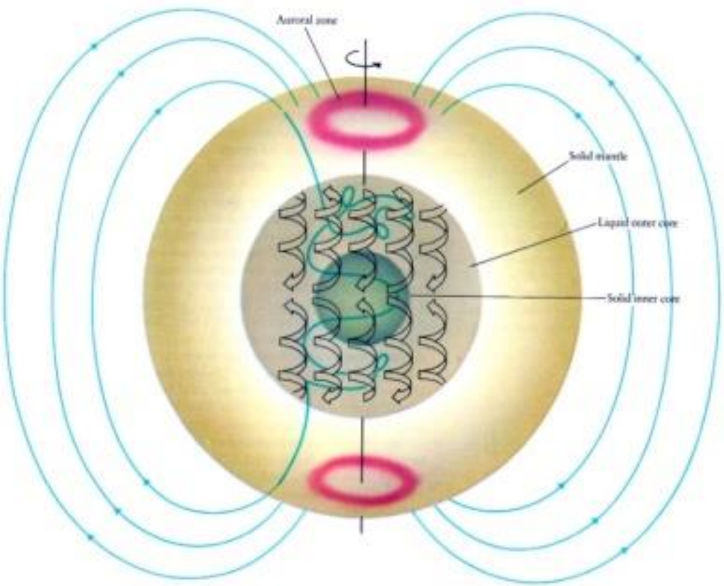
[1544–1603]
England



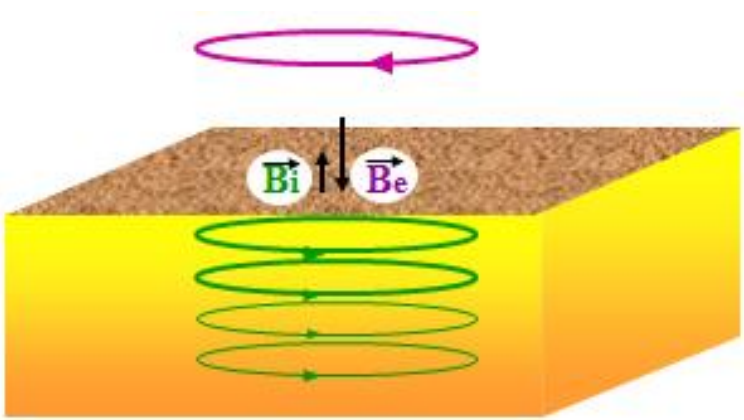


[1656- 1741]
England

The Earth's dynamo



Model of the terrestrial magnetic field IGRF
http://www.iugg.org/IAGA/iaga_pages/pubs_prods/igrf.htm



$$B = Bp + Ba + Be + Bi$$

Bp = main field (secular variations)
(30000-60000nT)

Ba = magnetization of the rocks in the Lithosphere (constant)
(~ 10 ~1000 nT)

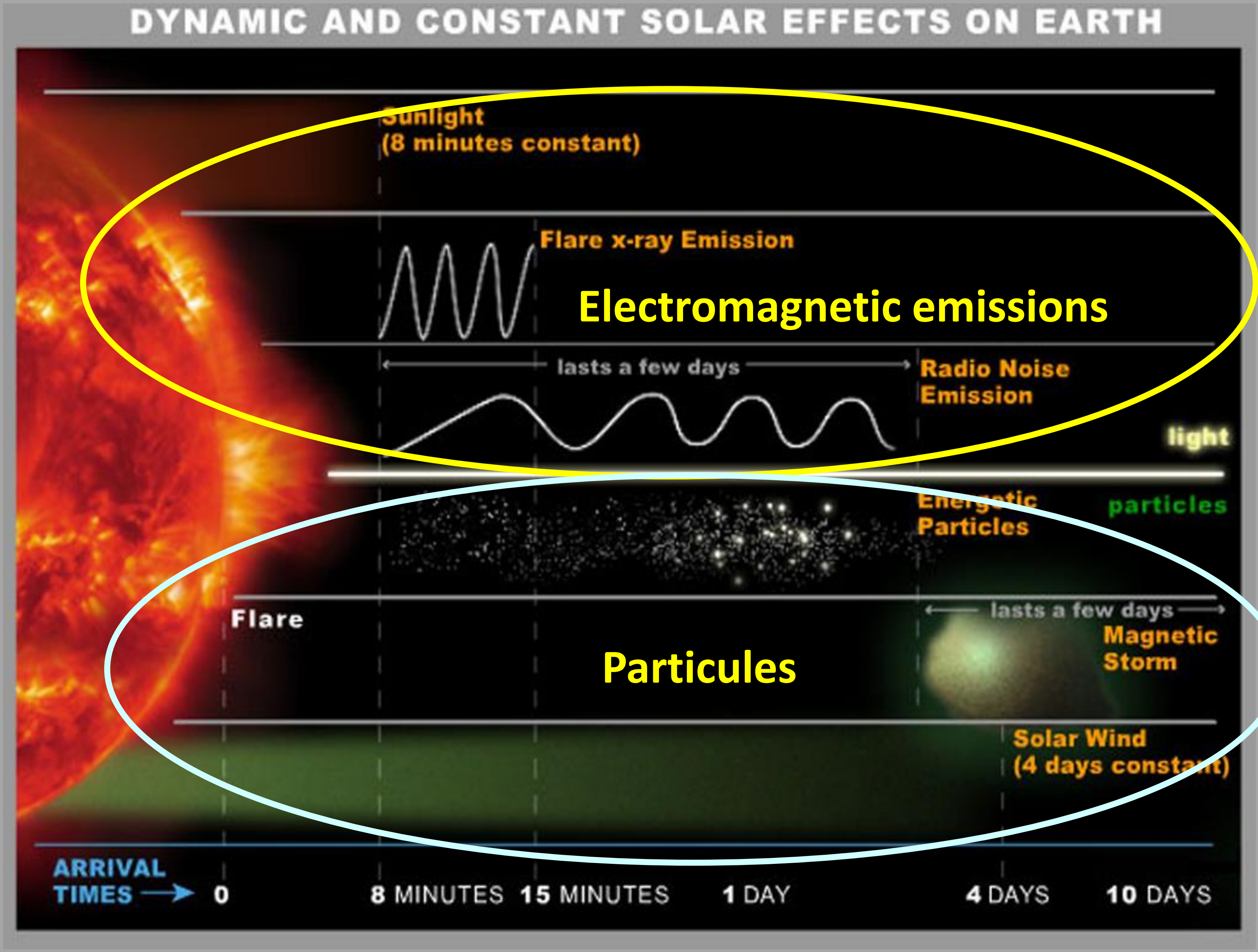
(transient variations)
Be = external field related to Ionosphere and magnetosphere (10nT to 2000nT)
Solar wind/Magnetosphere Dynamo
Ionospheric Dynamo

⬇

Bi = induced field generated by the external field Be , (Kamide and Brekke, 1975) /(% of Be)

The Earth's magnetic field reflects all the variations of electric currents of the Sun-Earth system

SUN EARTH CONNECTIONS



R A D I A T I O N S

P A R T I C L E S

from Nasa website

The two main channels

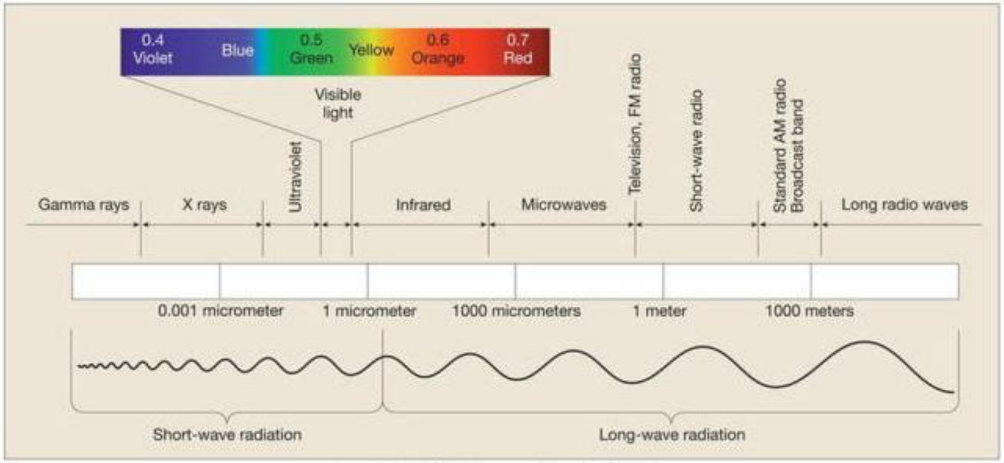
Electromagnetic emissions [8’]

*Regular

**Disturbed

Solar flare: X rays

Solar bursts : Radio emissions



SOLAR WIND - PARTICLES [1-4 days]

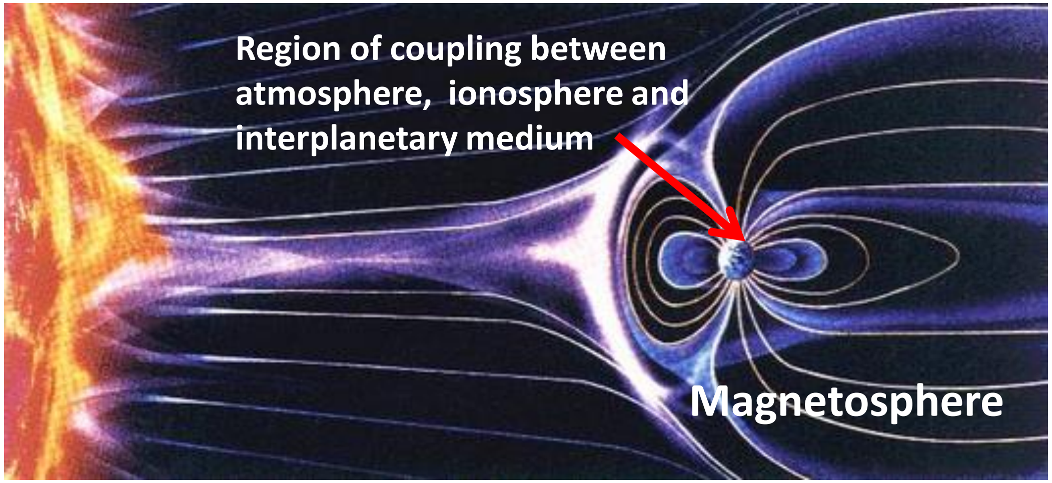
*Regular

**Disturbed by

Coronal Mass Ejection

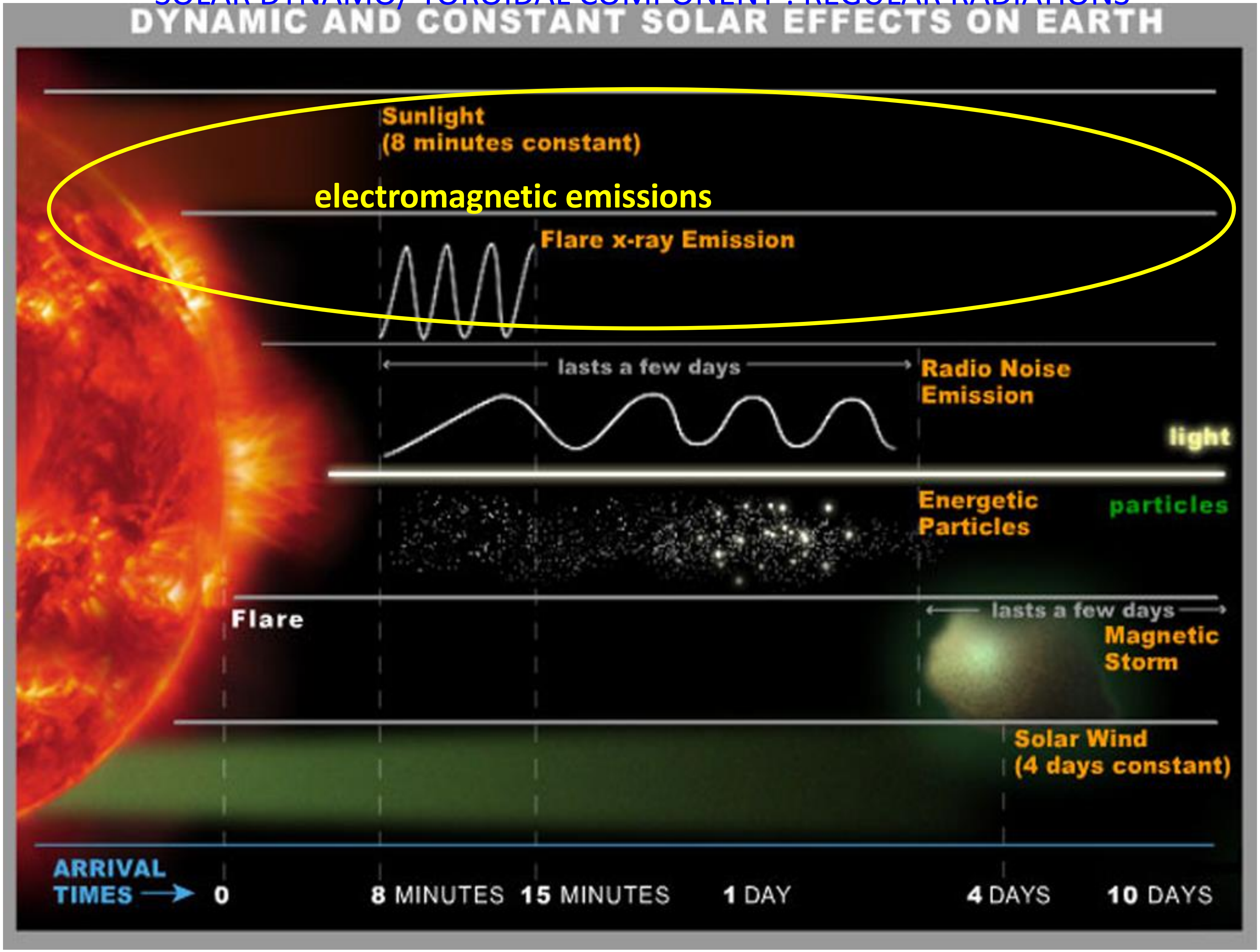
High speed solar wind from coronal hole, etc…

The solar wind is the constant stream of solar coronal material that flows off the sun. Its consists of mostly electrons, protons and alpha particles with energies usually between 1.5 and 10 kEV



The Earth's magnetic field acts as a shield for solar wind particles. However, there are regions of the ionosphere that are directly connected with the interplanetary medium and thus the solar wind flow

SOLAR DYNAMO/ TOROÏDAL COMPONENT : REGULAR RADIATIONS

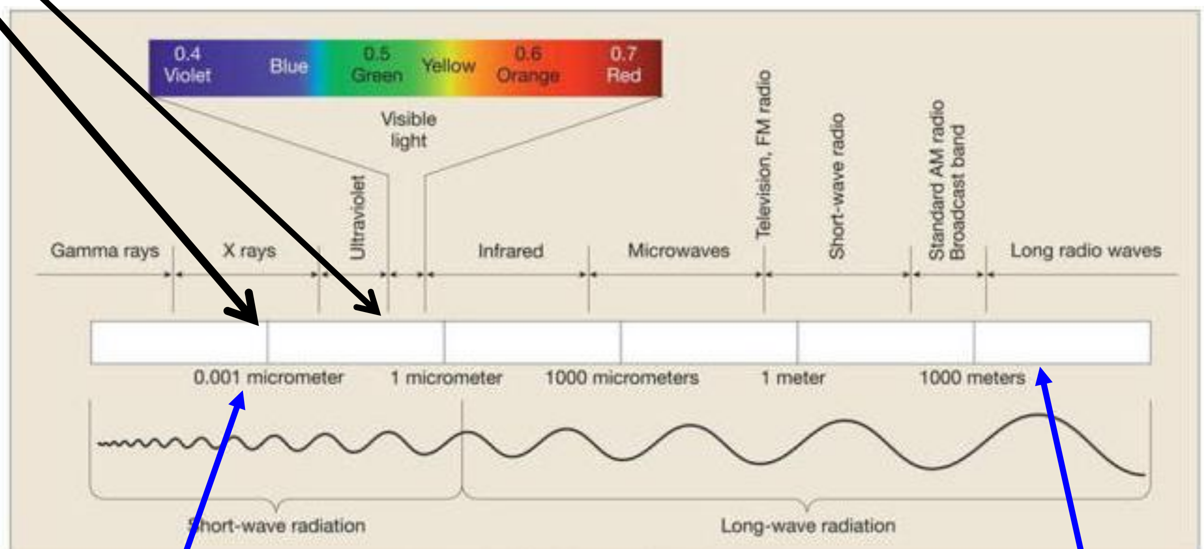


SUN : Electromagnetic emission Channel

<u>(REGULAR)</u>

Speed of Light

around sunspots => emissions of EUV, UV, X rays



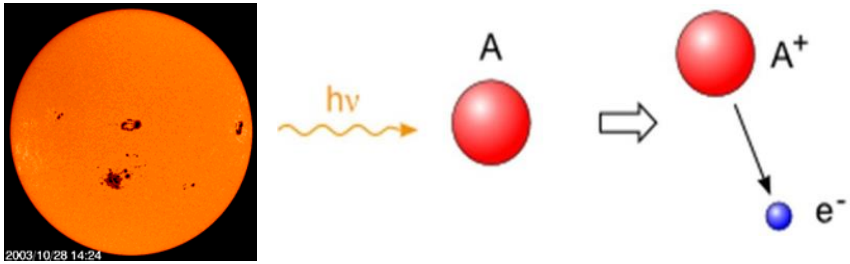
SOLAR FLARE

Extra X rays

SOLAR BURST

Extra Radio waves

RADIATIONS Channel **<u>(Disturbed)</u>**



SUN EARTH CONNECTIONS

Ionosphere ⇔ Regular solar radiations

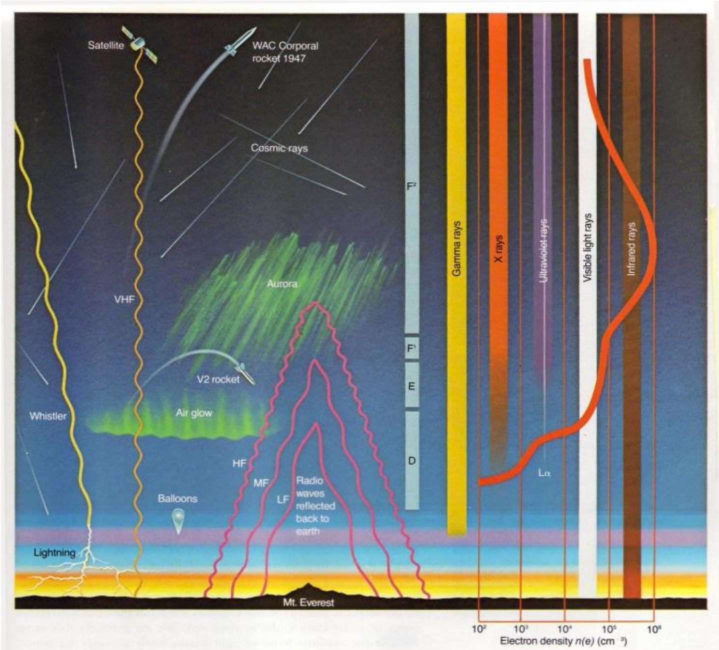
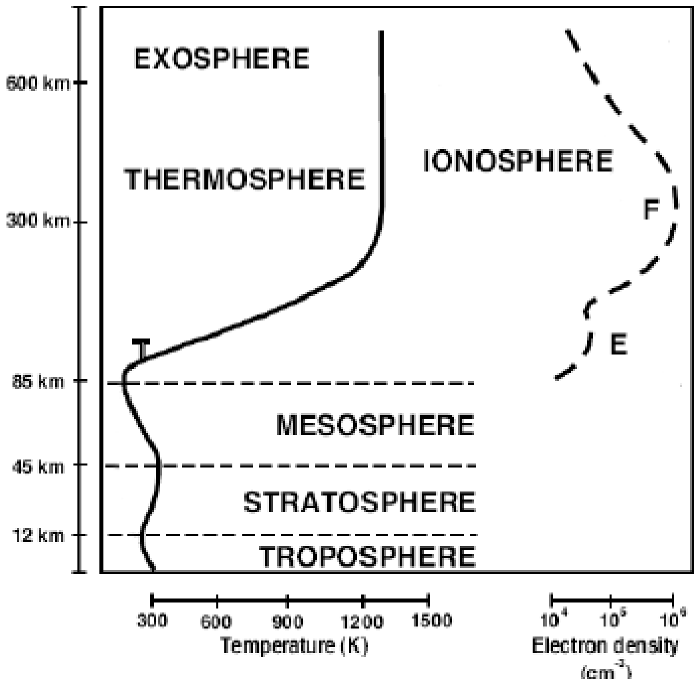


Figure from Friedman, 1987

Physical process : Photo ionisation

The ionosphere is created by ionization of the atmosphere by UV, EUV and X radiations in the altitude range from 50 km up to ~800 km



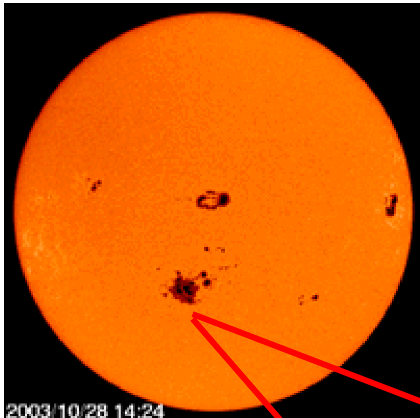
Ionosphere is a ionized part of the **atmosphere**

1 atom among 1 000 000

BOOKS : Risbheth and Gariott, 1969

Friedman, 1987, Kelley ,2009

Ionospheric Dynamo

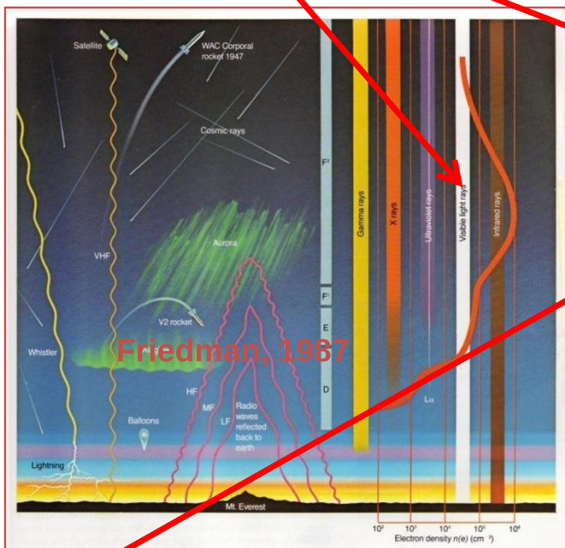


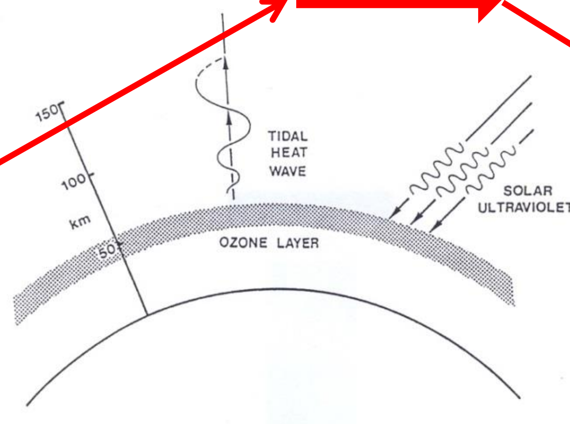
IONOSPHERIC DYNAMO

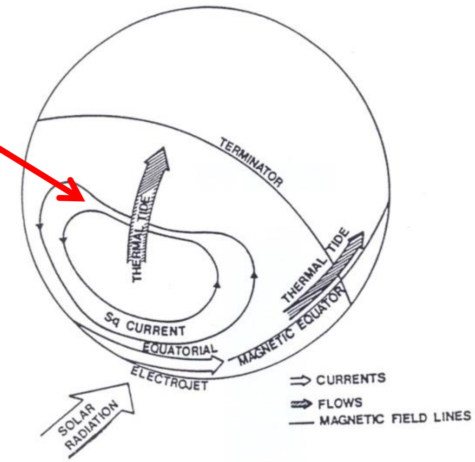
Solar Radiation/Regular transient variations of the Earth's magnetic field, Diurnal process

E Region of the Ionosphere (90km< h< 150km)

Sq : Chapman and Bartels, 1940 / S_R : Mayaud 1965







$$\vec{J} = \bar{\bar{\sigma}} (\vec{E} + \vec{V}n \times \vec{B})$$

J : electric current density

σ : electric conductivities

Vn : neutral wind

B: Earth's magnetic

E : Electric field e

Atmospheric Tides

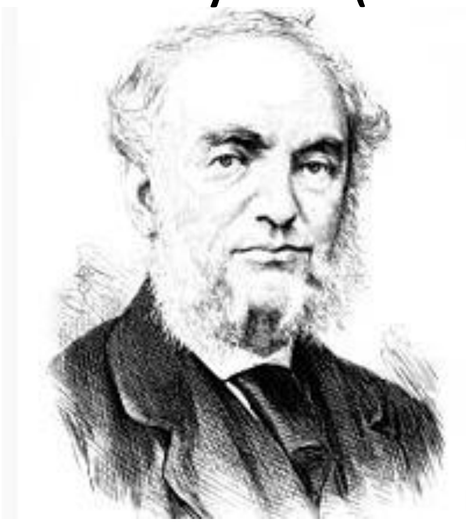
Evans 1977

Vertical coupling

Dynamics of the Atmosphere

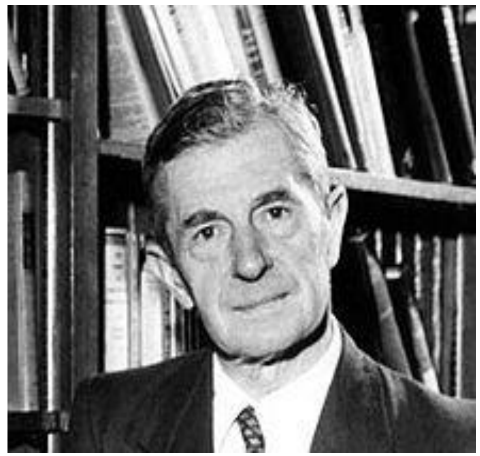
Ionospheric Electrodynamics

Concept of the Ionospheric Dynamo (1882)



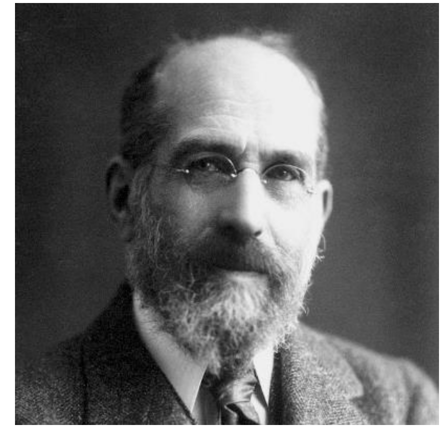
Balfour STEWART
1828-1887
Scotish physicist

DynamoTheory
Atmospheric tides
Geomagnetism
etc...



Sydney CHAPMAN
1888-1970
Bristish mathematician

First Map of «Sq » (1889)



Arthur SCHUSTER
1851-1934
German physicist

Stewart B., Terrestrial magnetism, Encyclopaedia Britannica, 9th ed., Vol. 16, 159-184, **1882.**
Schuster, A., The diurnal variation of the Terrestrial Magnetism, Phil. trans. Roy. Soc. Lond., series A, 180, 467, **1889.**
Chapman S., The solar and Lunar diurnal variations of Terrestrial Magnetism, Phil. Trans. of Roy. Soc. of London, A., 218, 1, **1919.**
Chapman, S. and J. Bartels, Geomagnetism, Oxford University Press, New York, **1940.**
Chapman, S., R.S. Lindzen, Atmospheric tides : thermal and gravitational, D. reidel publishing company/ Dordretch, Hollande, **1970.**

The most important source of heating is the solar heating, it is easily evaluated.
*Dissipation of internal gavity waves is the most important heat input after the solar heating, this source is geographically widespread.
*Auroral Joule heating may rival or exceed the solar heat input, but only for relatively short periods.

VERTICAL COUPLING

Lower Thermosphere

Mesosphere

Eddy

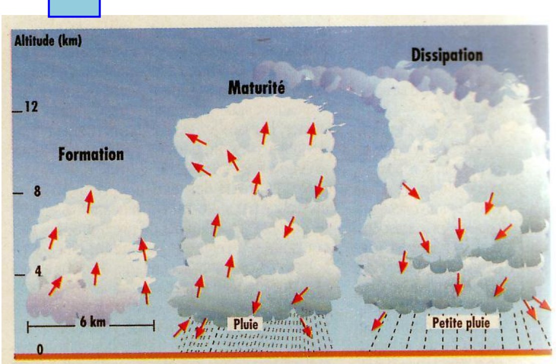
Migrating Tides

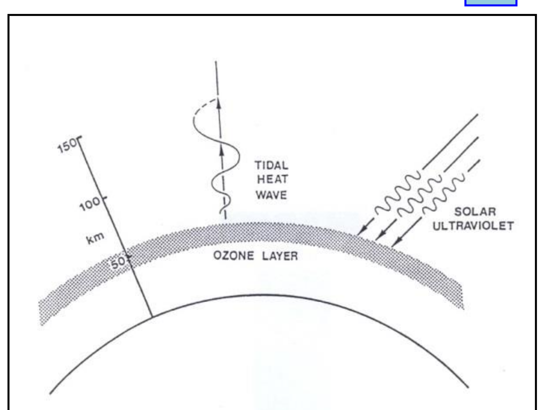
Stratosphere

waves

Warming

Non migrating tides





Evans, 1977

Eddy

waves

Low Atmosphere-Troposphere

IONOSPHERIC DYNAMO (Stewart 1882)

Motion of the neutral atmosphere | $\mathbf{V_n}$ | $\mathbf{B_t}$ | **Earth's magnetic field**

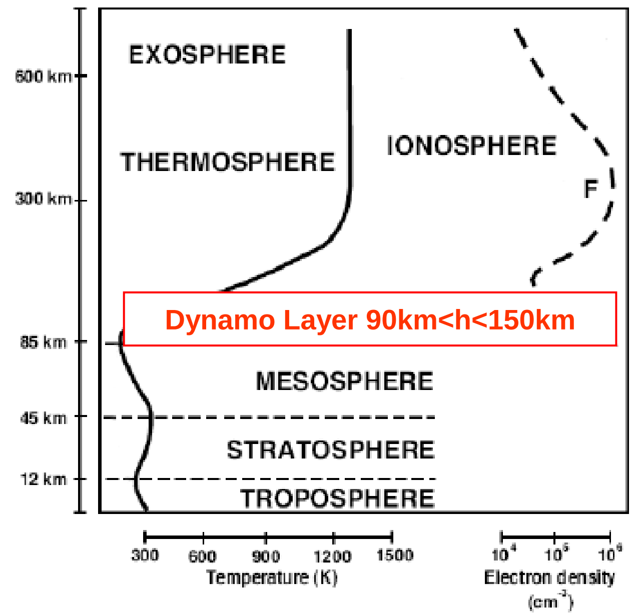
DYNAMO electric field | $\mathbf{V_n x B_t}$ | **E** | **POLARISATION electric field**

IONOSPHERIC OHM'S LAW

$$\vec{J} = \sigma_p \left(\vec{E}_\perp + \vec{V}_n \Lambda \vec{B} \right) + \sigma_h \vec{b} \Lambda \left(\vec{E}_\perp + \vec{V}_n \Lambda \vec{B} \right) + \sigma_{//} \vec{E}_{//}$$

$$\sigma_p = \frac{N_e e}{B} \left(\frac{\nu_{in} \Omega_i}{\nu_{in}^2 + \Omega_i^2} + \frac{\nu_{en} \Omega_e}{\nu_{en}^2 + \Omega_e^2} \right)$$

$$\sigma_h = \frac{N_e e}{B} \left(\frac{\Omega_e^2}{\nu_{en}^2 + \Omega_e^2} - \frac{\Omega_i^2}{\nu_{in}^2 + \Omega_i^2} \right)$$

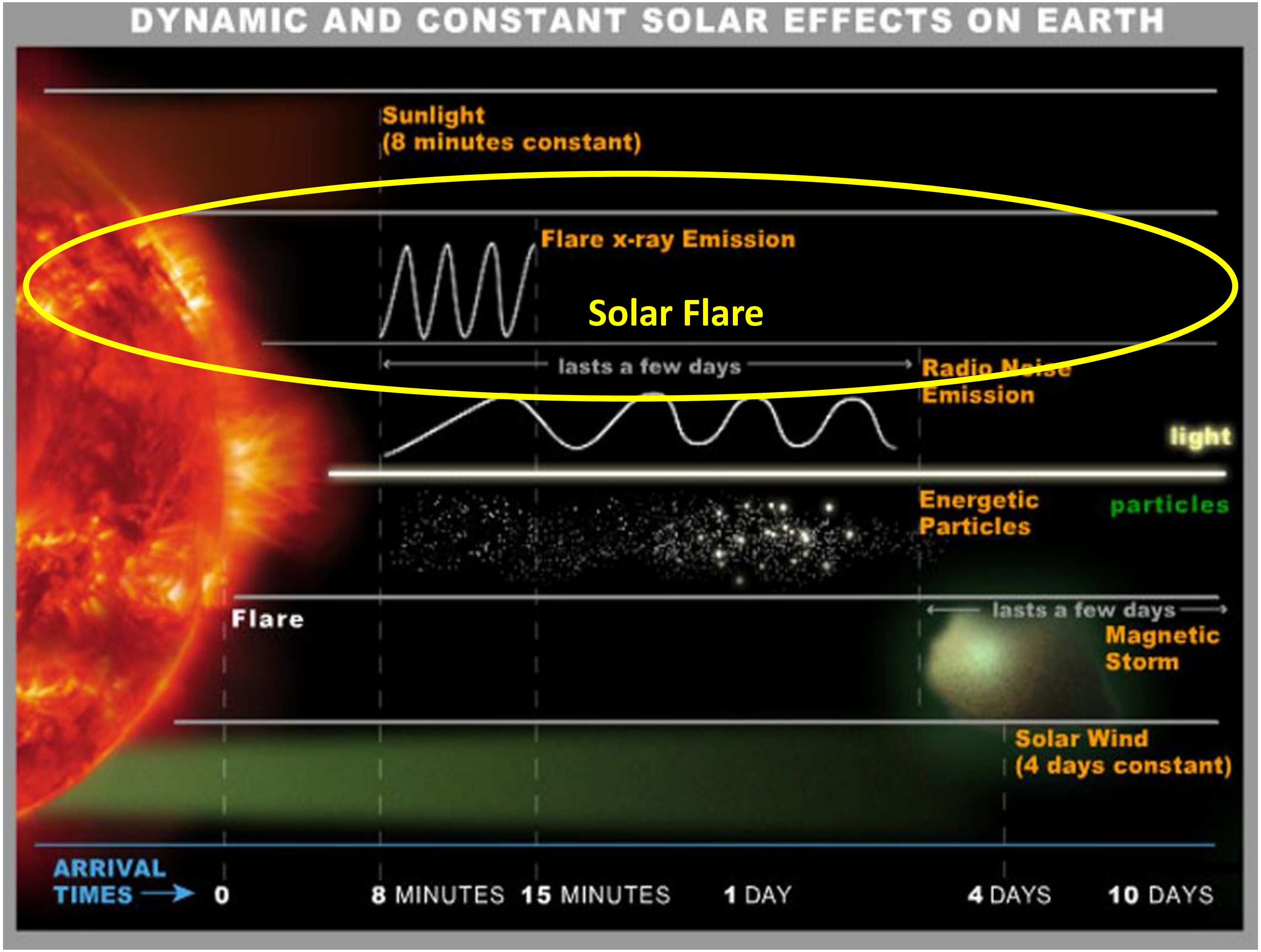


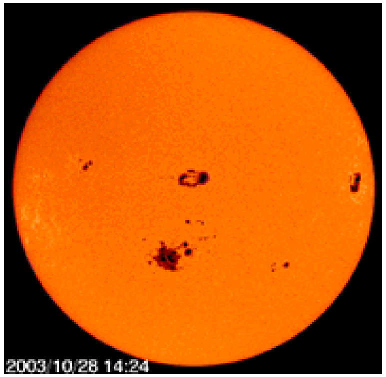
$\Omega_e = \frac{eB}{m_e}$ $\Omega_i = \frac{eB}{m_i}$ **Gyrofrequencies of electrons ans ions**

σ_p: Pedersen conductivity ⊥ B et // E

σ_h: Hall conductivity ⊥ B et E

υ_{in} et υ_{en}: collisions frequencies


DYNAMIC AND CONSTANT SOLAR EFFECTS ON EARTH
Sunlight
(8 minutes constant)
Flare x-ray Emission
Solar Flare
lasts a few days
Radio Noise
Emission
light
Energetic
Particles
particles
Flare
lasts a few days
Magnetic
Storm
Solar Wind
(4 days constant)
ARRIVAL
TIMES
0
8 MINUTES
15 MINUTES
1 DAY
4 DAYS
10 DAYS



SOLAR FLARE (8′)

Disturbed solar electromagnetic emission

Physical processes

extra Solar Radiation => Photo ionisation

The extra X-rays emitted by the solar Flare directly ionize the atmosphere and thus increase the electron density and the TEC.

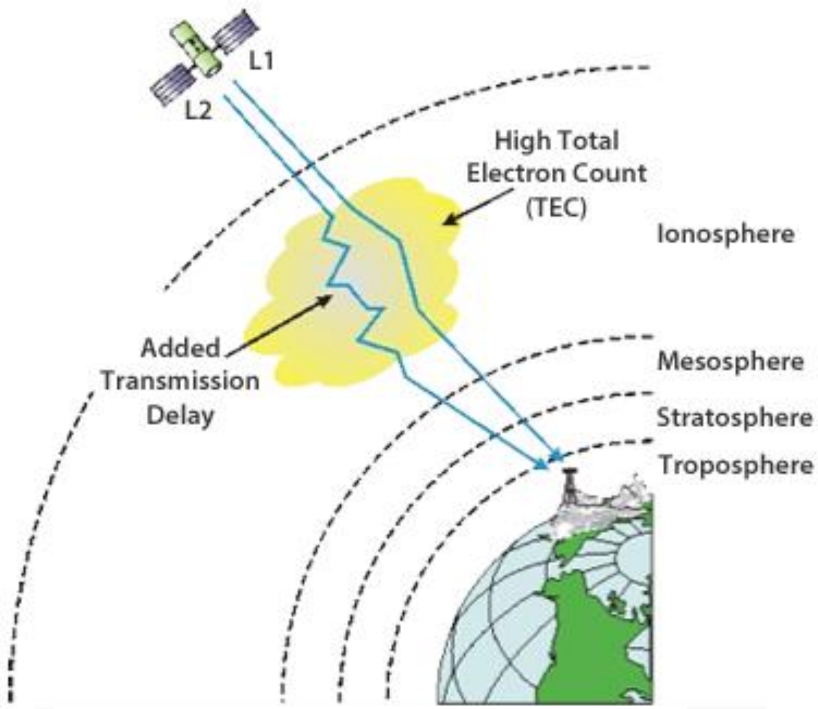
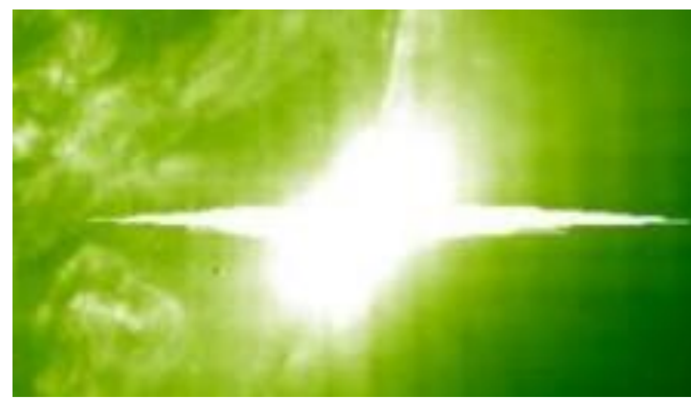


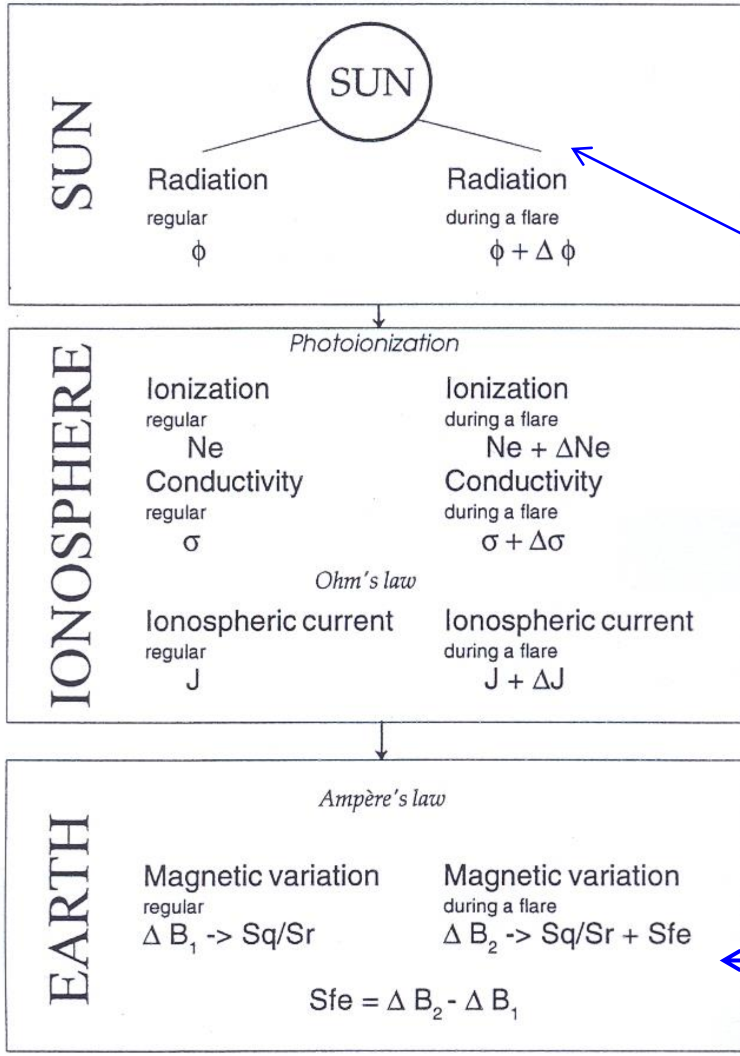
Figure from http://reflexions.ulg.ac.be

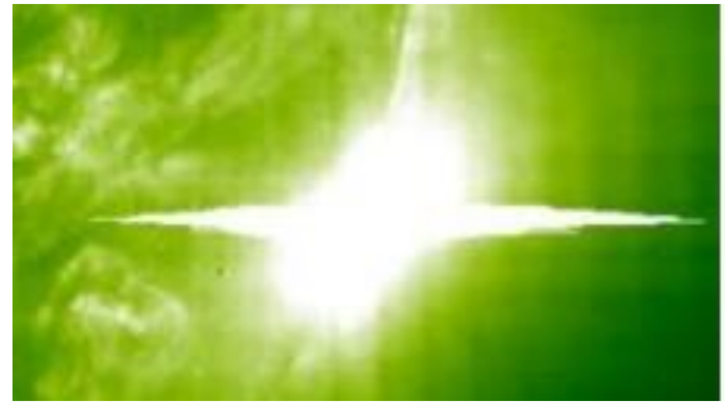
Big solar flare of November 2003



SOHO data

SUN EARTH CONNECTIONS : DISTURBED MAGNETIC VARIATIONS





Magnetic crochet due to solar flare

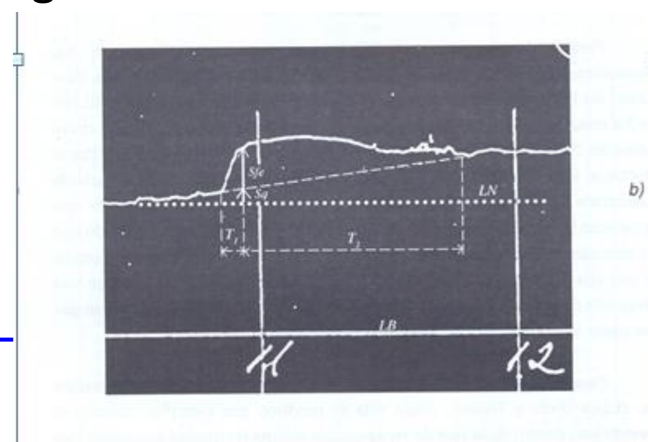


Fig. III.1 Registro magnético de un sfe en Ebro (dibujo superior) y detalle del mismo sfe para la componente H (dibujo inferior).

Curto, J-J. et al., "Study of Solar Flare Effects at Ebre : 2. Unidimensional physical integrated model, J. of Geophys. Research, A, 12 23289-23296,1994.

Ionospheric dynamo

Dynamo layer 90-160km

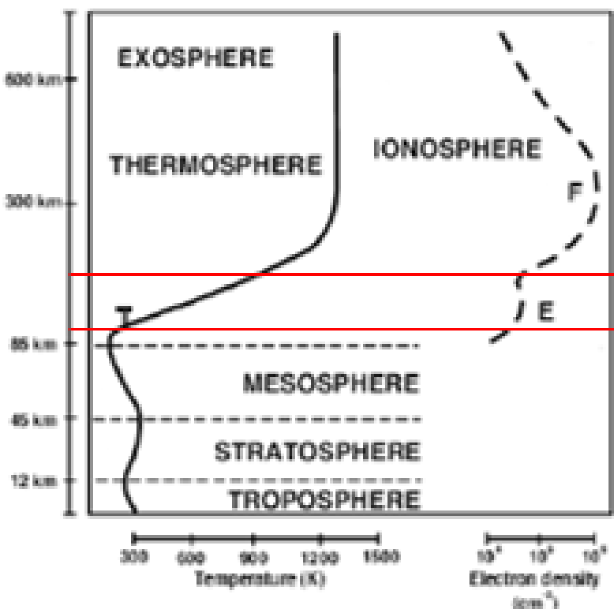
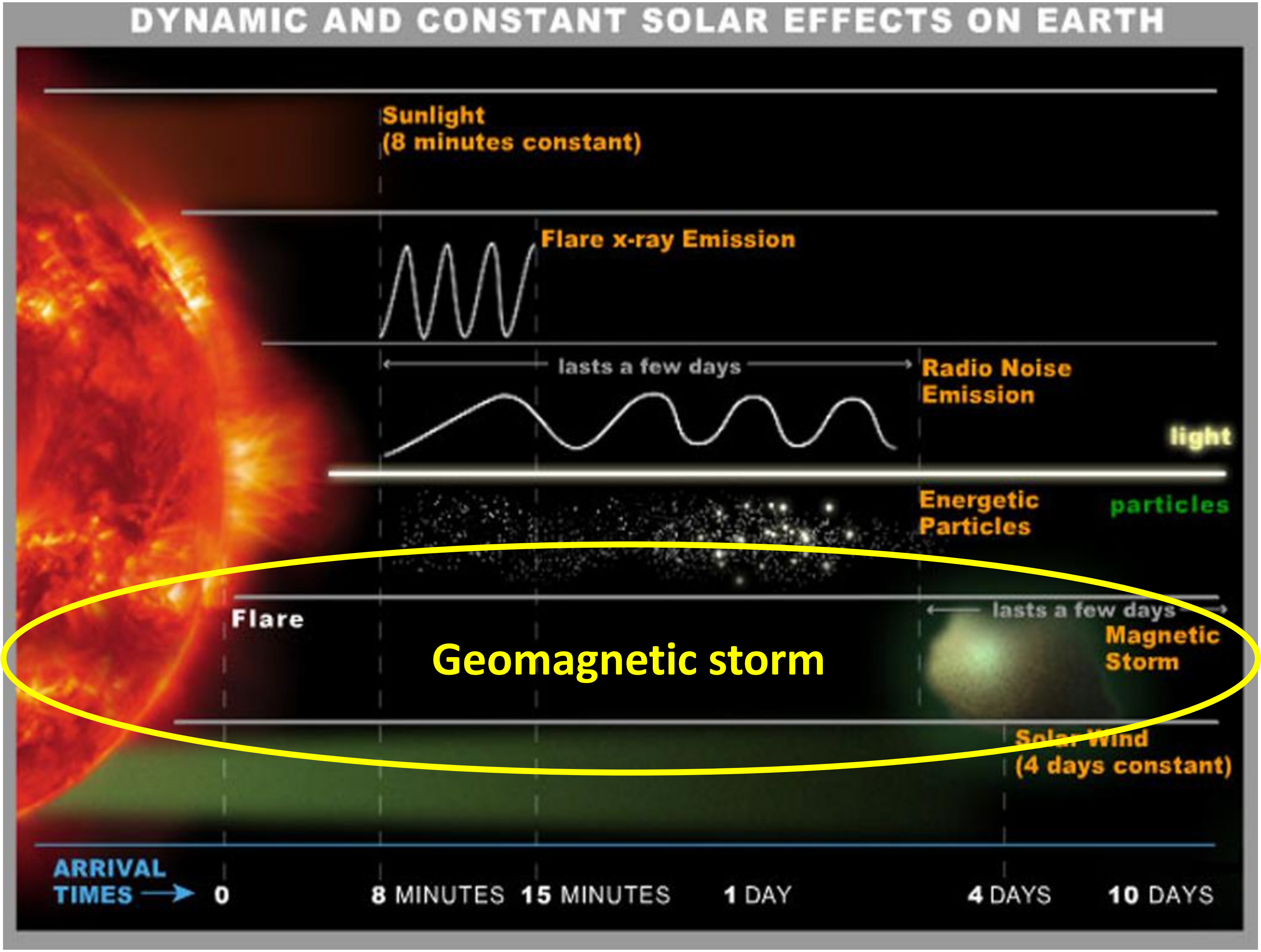


Table 1. Main Processes and Related Models Used.

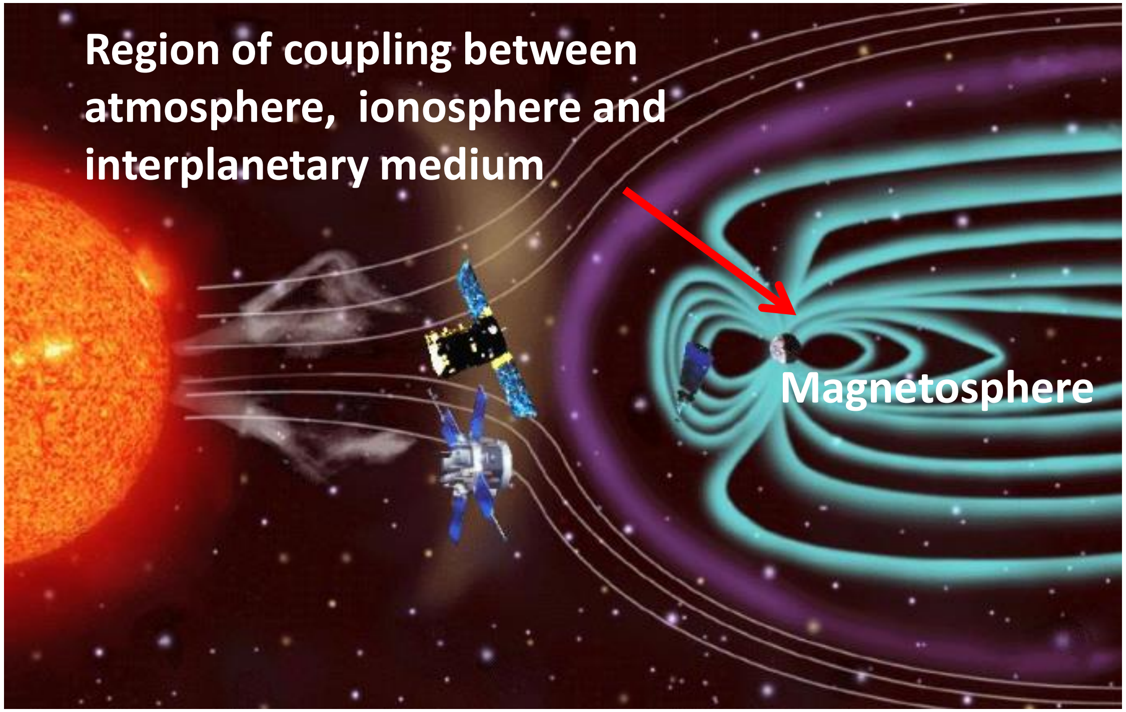
	Source	
Sun Processes		
Models		
regular radiation flux	*Heroux et al.* [1974]	1
flare radiation flux	*Donnelly* [1976]	
Ionosphere Processes		
Equations		
ion production rate	*Dymek* [1989]	
continuity equation	*Dymek* [1989]	2
collision frequencies	*Stubbe* [1968]	
Conductivity tensor (σ)	$\bar{\bar{\sigma}} = \begin{pmatrix} \sigma_P & \sigma_H & 0 \\ -\sigma_H & \sigma_P & 0 \\ 0 & 0 & \sigma_{\|} \end{pmatrix}$	
Ohm's law	$J = \sigma (E_p + V_n x B)$	3
Models		
Neutral composition	*Hedin* [1987]	
Ion composition	*Oliver* [1975]	
Electric fields (Ep)	*Blanc and Amayemc* [1979]	
Neutral winds (Vn)	*Bernard* [1978]	
Electric current	*Mazaudier and Blanc* [1982]	
Ground Level Processes		4
Ampere's law	$\Delta B = 2\pi/ 10 f \int j dz$	

Curto, J-J. et al., "Study of Solar Flare Effects at Ebre : 2. Unidimensional physical integrated model, J. of Geophys. Research, A, 12 23289-23296,1994.


DYNAMIC AND CONSTANT SOLAR EFFECTS ON EARTH
Sunlight
(8 minutes constant)
Flare x-ray Emission
lasts a few days
Radio Noise
Emission
light
Energetic
Particles
particles
Flare
lasts a few days
Magnetic
Storm
Geomagnetic storm
Solar Wind
(4 days constant)
ARRIVAL
TIMES
0
8 MINUTES
15 MINUTES
1 DAY
4 DAYS
10 DAYS

SUN EARTH CONNECTIONS : PARTICLES Channel : Regular solar wind : V ~ 350-400km/s , Time ~ 2-3 days

The solar wind carries part of the solar magnetic field towards the Earth : Interplanetary Magnetic Field, IMF.



The solar wind is the constant stream of solar coronal material that flows off the sun. Its consists of mostly electrons, protons and alpha particles with energies usually between 1.5 and 10 kEV

The Earth's magnetic field acts as a shield for solar wind particles. However, there are regions of the ionosphere that are directly connected with the interplanetary medium and thus the solar wind flow

SOLAR WIND-MAGNETOSPHERE DYNAMO

INTERACTION BETWEEN THE SOLAR WIND and THE MAGNETOSPHERE

Physical processes : Reconnection and Dynamo

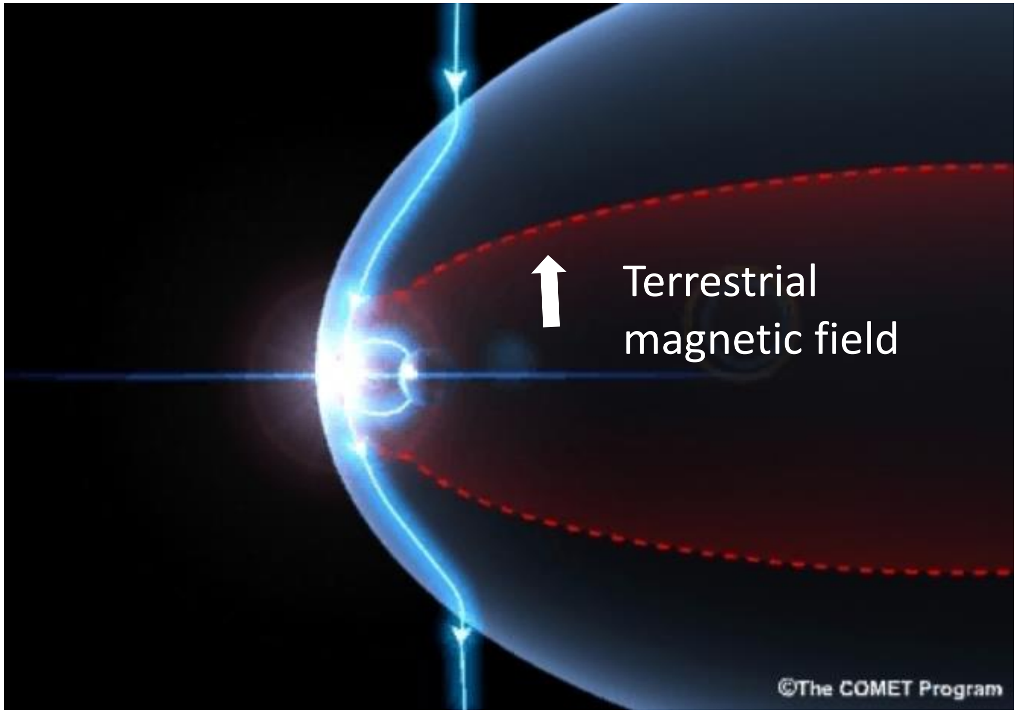
If the Interplanetary Magnetic Field , IMF field is opposite to the terrestrial magnetic field, i.e directed toward the South, there is reconnection (Dungey,1961) between the IMF and the Earth's magnetic field and **there is a geomagnetic storm**

Key parameters for Space Weather :B_z IMF

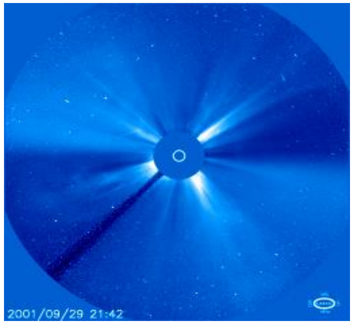
Vs : solar wind speed

E_y=- V_x.B_z

Alexander Von HUMBOLD
[1769-1859] Germany

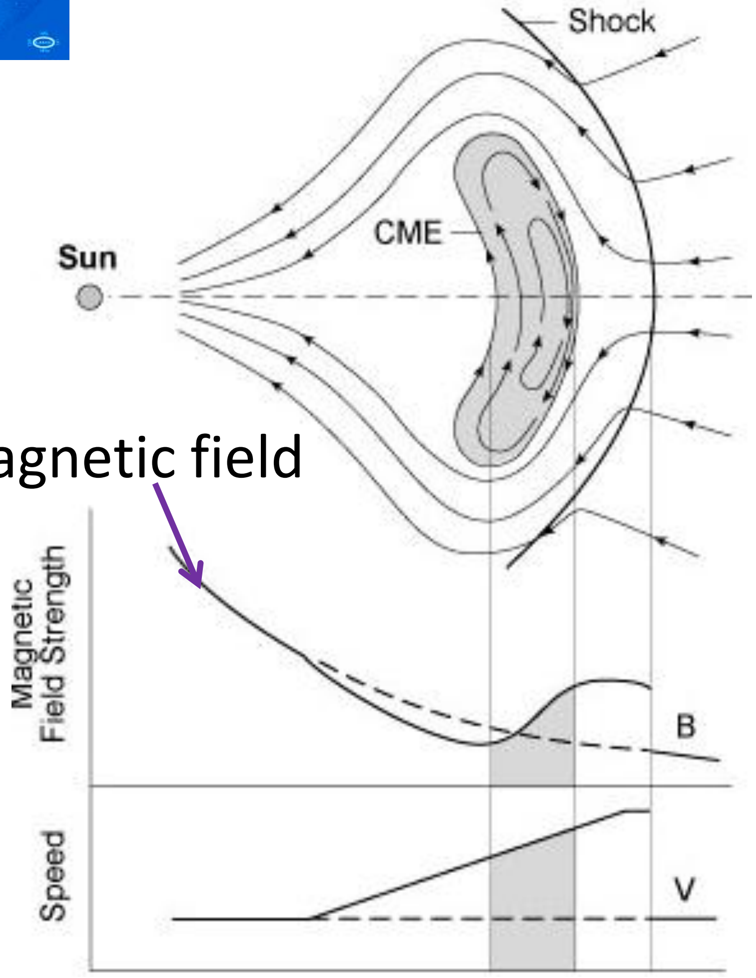


Solar wind – Magnetosphere Dynamo : E=VsxB movement is converted into electrical energy



Interplanetary CME Shocks

http://ase.tufts.edu/cosmos/pictures/sept09/



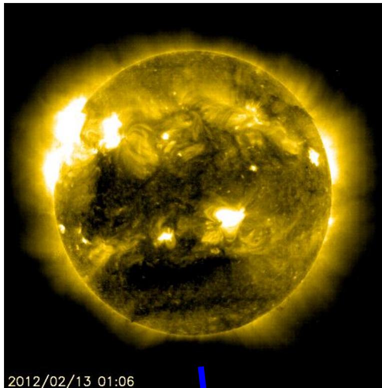
Strong magnetic field

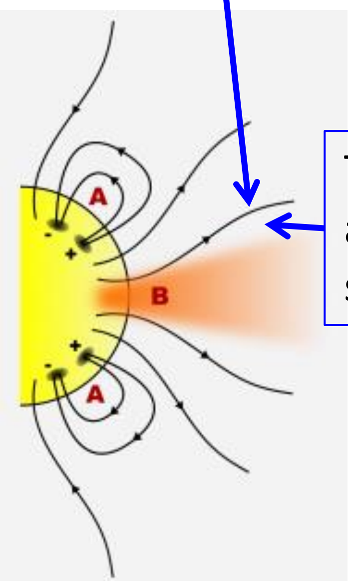
A fast coronal mass ejection CME pushes an interplanetary shock wave

Increases of solar wind speed V and magnetic field strenght B by the interplanetary shock wave in front f the CME

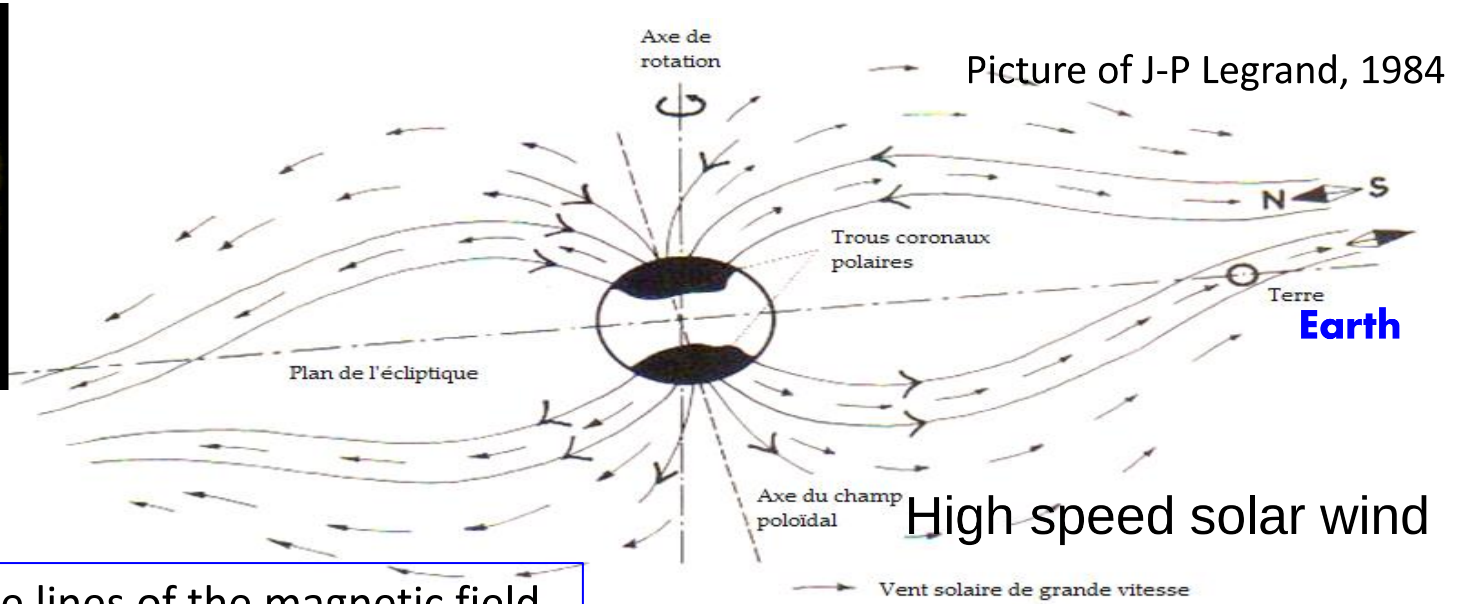
Maximum occurrence of CME during the maximum of the solar sunspot cycle

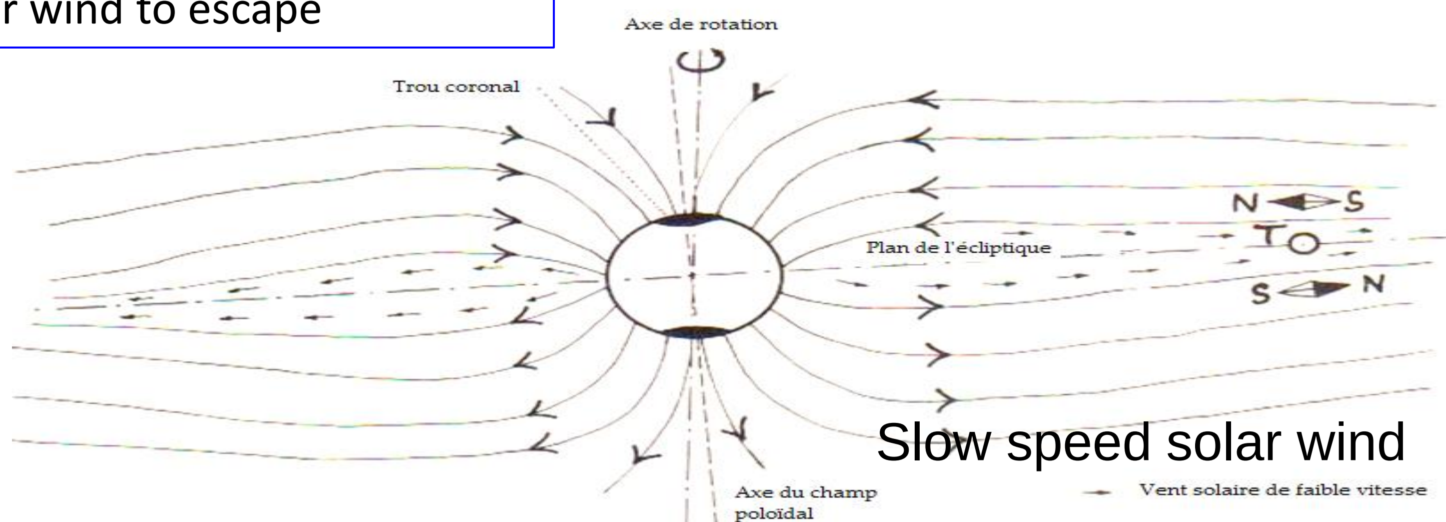
CORONAL HOLE – recurrent geomagnetic activity





The lines of the magnetic field are open .This allows for the solar wind to escape



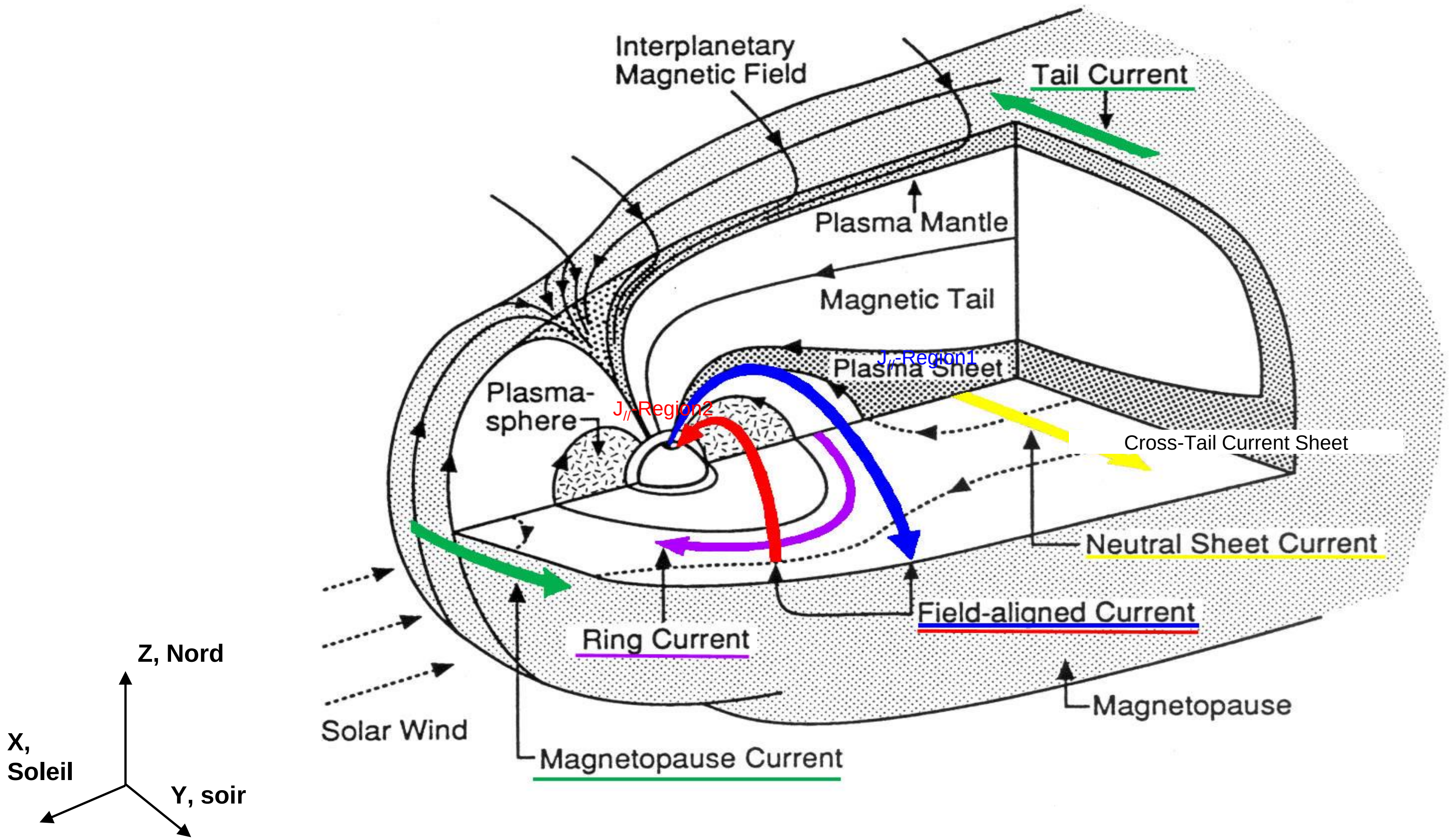


Maximum occurrence during the declining and minimum phases of solar sunspot cycle

Solar wind magnetosphere dynamo (Vs, Bi)

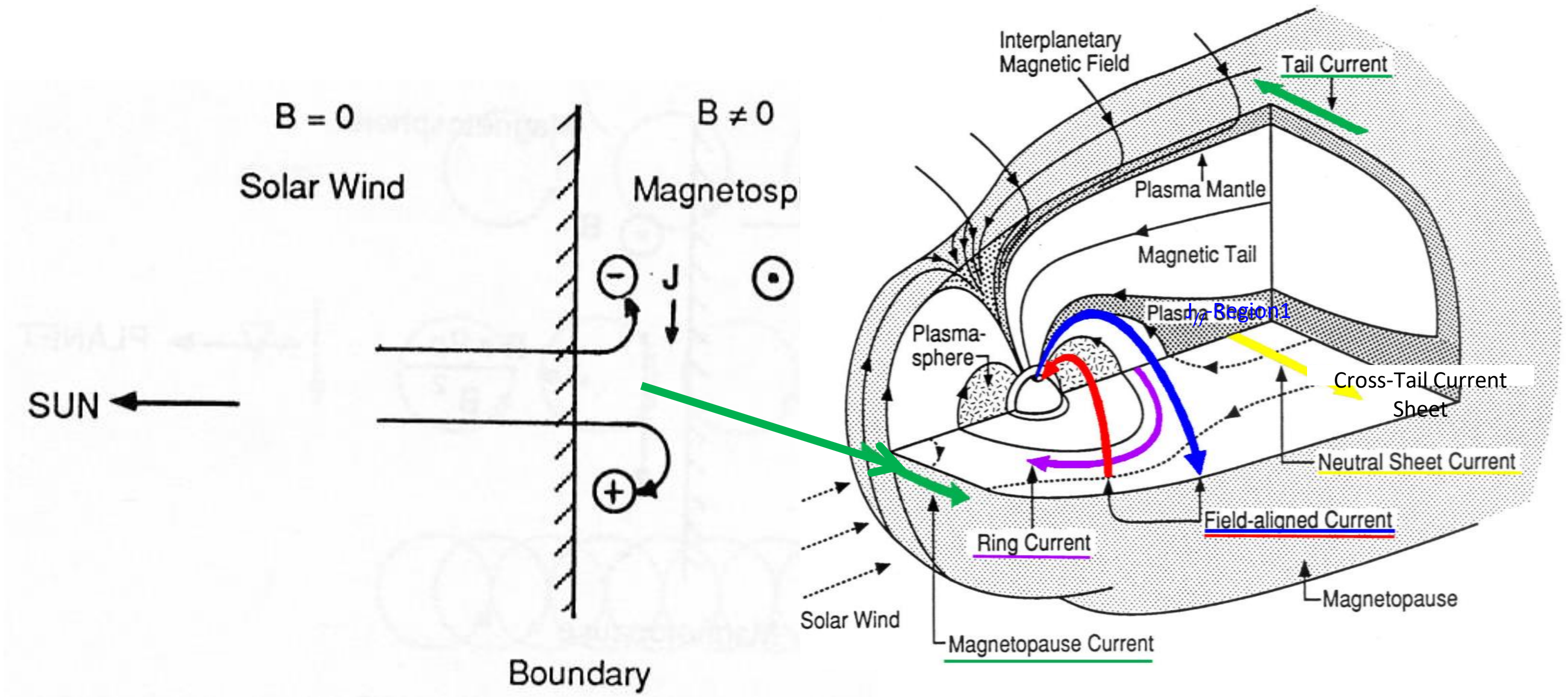
(Vs : solar wind speed/ Bi : interplanetary magnetic field)

Electric currents in the magnetosphere



V.C.A FERRARO
English Physicist
1907- 1974

CHAPMAN-FERRARO MAGNETOSPHERIC ELECTRIC CURRENTS

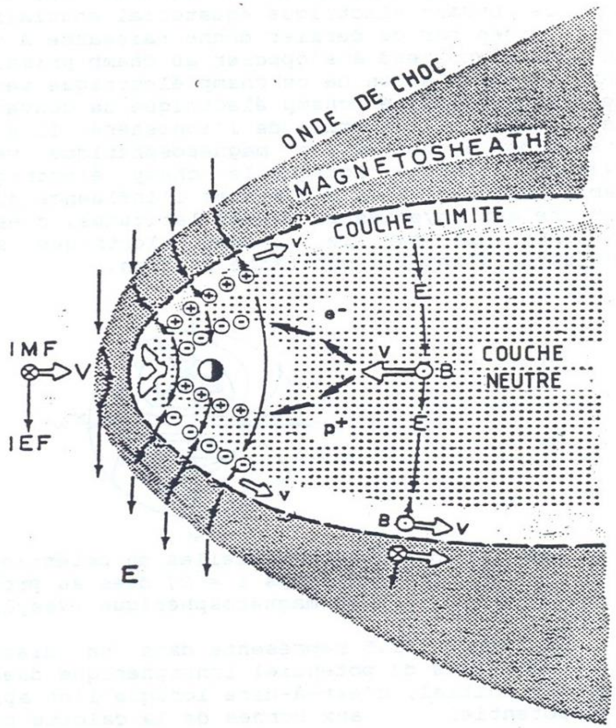


The Chapman Ferraro currents flow in the Magnetopause layer, the boundary between the solar wind and the geomagnetic field. At the nose of the magnetopause the geomagnetic field pressure is balanced by the dynamic pressure of the solar wind

$$K_1 N_i m_i V_i^2 = \frac{B_{mp}^2}{2\mu_0}$$

dynamic pressure of the solar wind ⇔ geomagnetic field pressure

K_1 is the correction factor for flow deflection in magnetosheath and compression of B. The order of magnitude of the Chapman Ferraro current is ~ 30 nT (Gosling et al. 1990).



Ring current

Dawn-dusk voltage drop difference

↓

Particles follow trajectories from the tail of the magnetosphere toward the Earth

↓

In the region where the curvature and gradient of the Earth's 's magnetic field are strong, particles are separated, the electrons are diverted to the morning side and the ions to the evening side.

Formation of the ring current

The expression of the drift due to gradient and curvature and the resulting current i

$$\vec{V}_{gc} = \frac{1}{2} m V_{\perp}^2 \frac{B \times \nabla B}{qB^3} + m V_{LL}^2 \frac{B \times (b.\nabla)\hat{b}}{qB^2}$$

$$J_{gc} = NqV_{gc}^{ions}$$

This current is mainly carried by ions.

There is also an additional contribution of the magnetic moments of all particles:

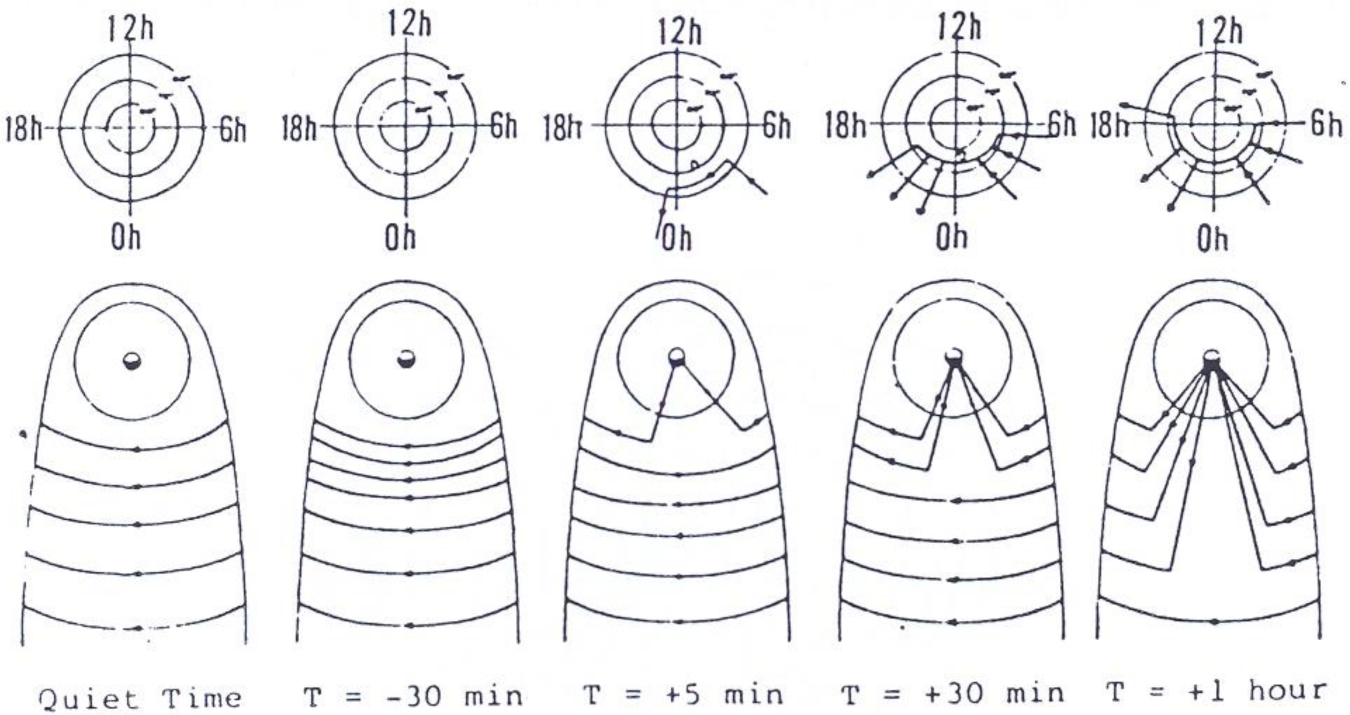
$$\vec{M} = -N_i \frac{1}{2} \frac{m_i V_{i\perp}^2}{B} \hat{b} - N_e \frac{1}{2} \frac{m_e V_{e\perp}^2}{B} \hat{b}$$

$$\vec{J}_m = \nabla \times \vec{M}$$

The ring current keeps the pressure gradient and the Lorentz force in balance.

Carl STORMER
1874-1957
Norvegian Astrophysicist
and mathematician

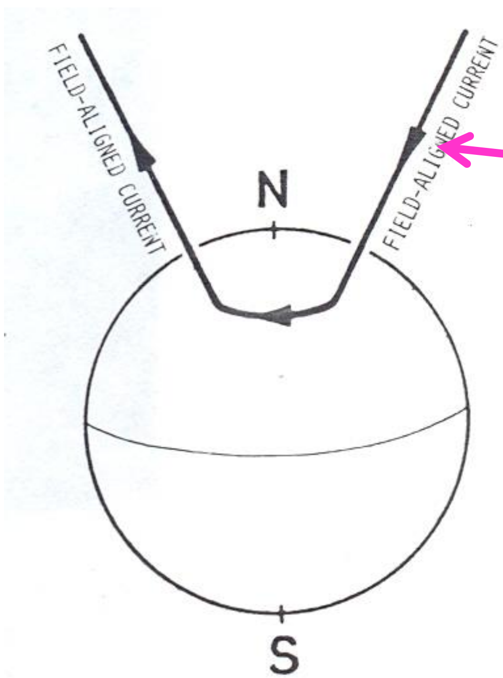
Tail currents / 1972

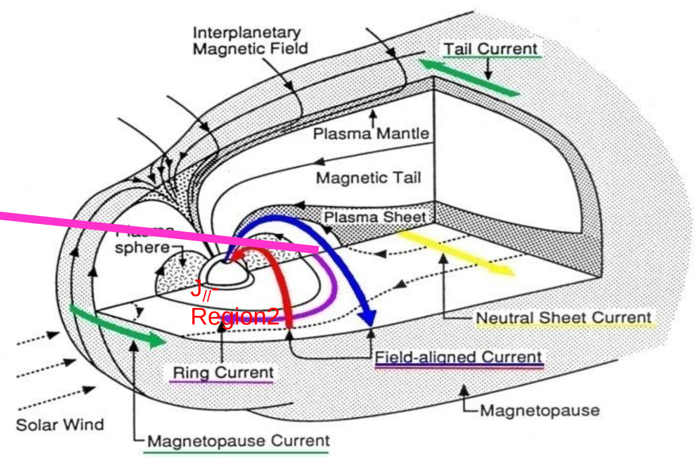


Syun-Ichi AKASOFU
1930-
American Geophysicist

Proposed by Akasofu in 1972, the tail currents flowing at the boundary of the plasma sheet are disrupted and deflected toward the Earth on the evening side. These currents via Birkeland (field aligned current) be converted to a westward electrojet

Field aligned currents/1908





Birkeland, 1908

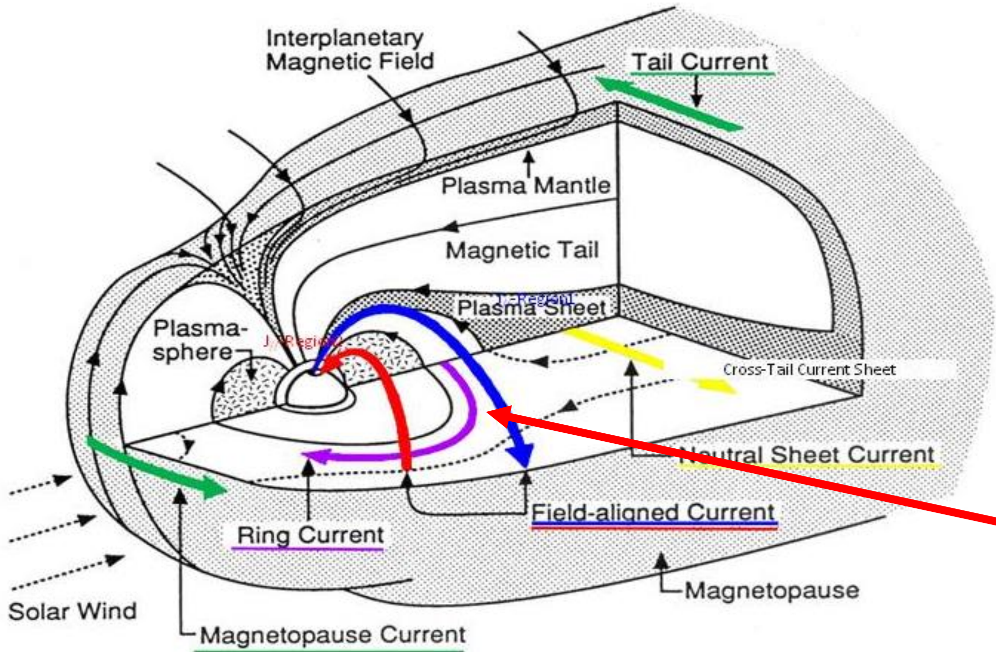
Kristian BIRKELAND
1867-1917
Norvegian Physicist

You can reproduce the experience of Birkeland

$$\nabla \vec{j} = \nabla_{\perp} \vec{j}_{\perp} + \nabla_{II} j_{II} = 0$$

The closure of the magnetospheric current loops requires field aligned currents flowing into and out of the ionosphere. The origin of the field aligned currents is near the equatorial edge of the magnetopause (region1), in the plasma sheet where the ring current is divergent (region 2) and at the magnetopause at high latitudes in the dayside.

SOLAR WIND MAGNETOSPHERE DYNAMO :ELECTRIC CURRENTS



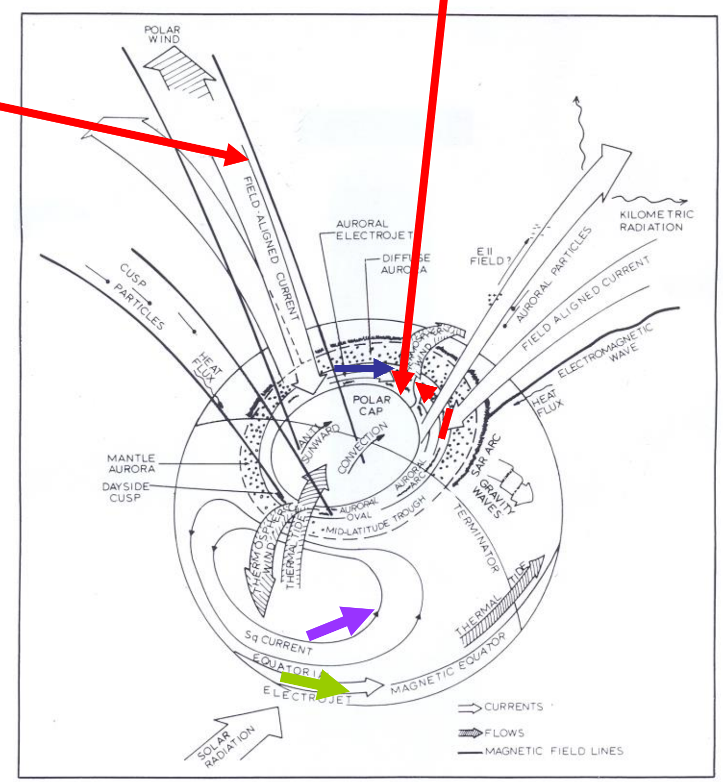
AURORAL ZONE

*Field aligned electric currents

*Precipitation

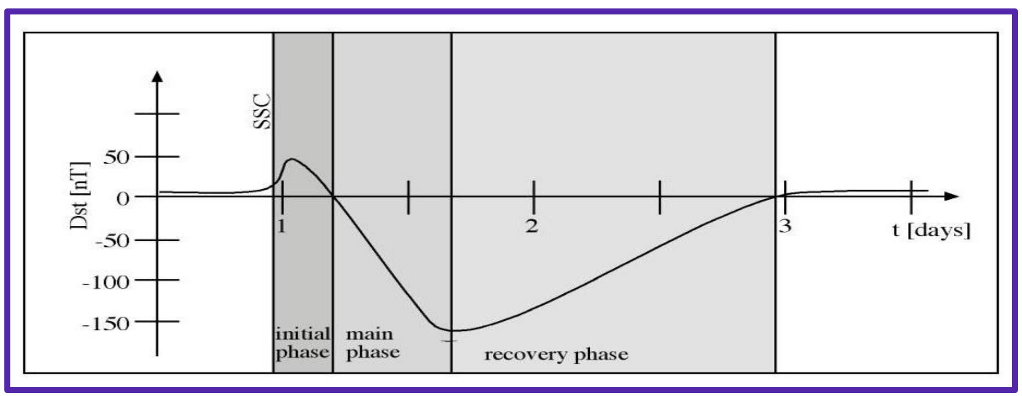
*Convection electric field

* Ionospheric electric currents



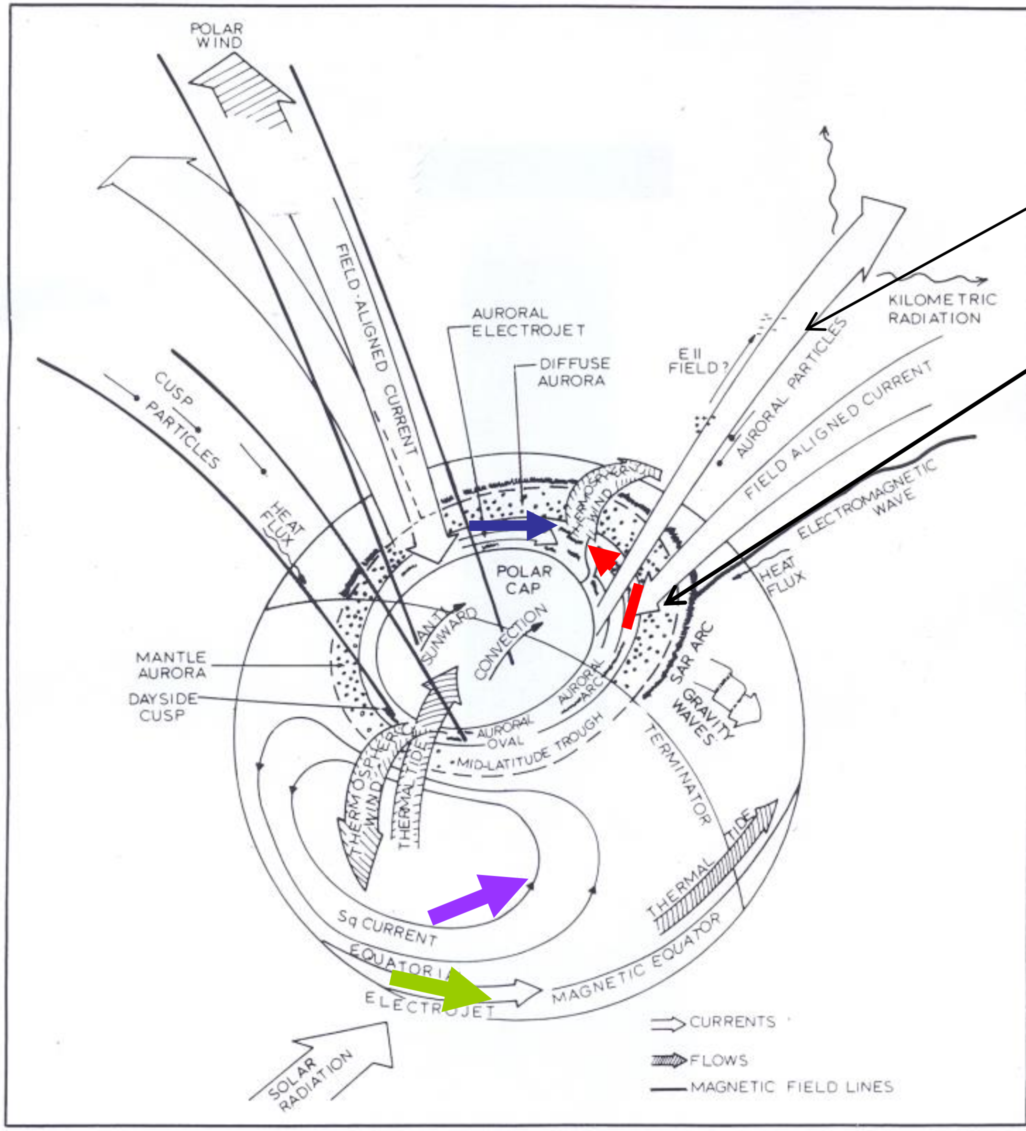
MAGNETOSPHERE

Electric currents



Magnetic storm indices Dst, SYM-H, ASYM-H

Ionospheric electric currents related to the Solar Wind Magnetosphere dynamo and Ionospheric dynamo



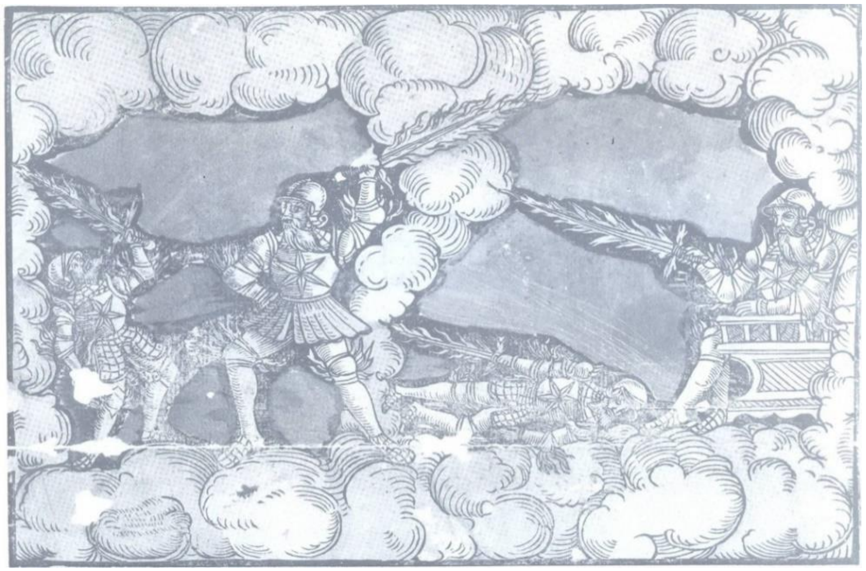
Auroral latitudes

Middle latitudes

Equatorial latitudes

AURORA

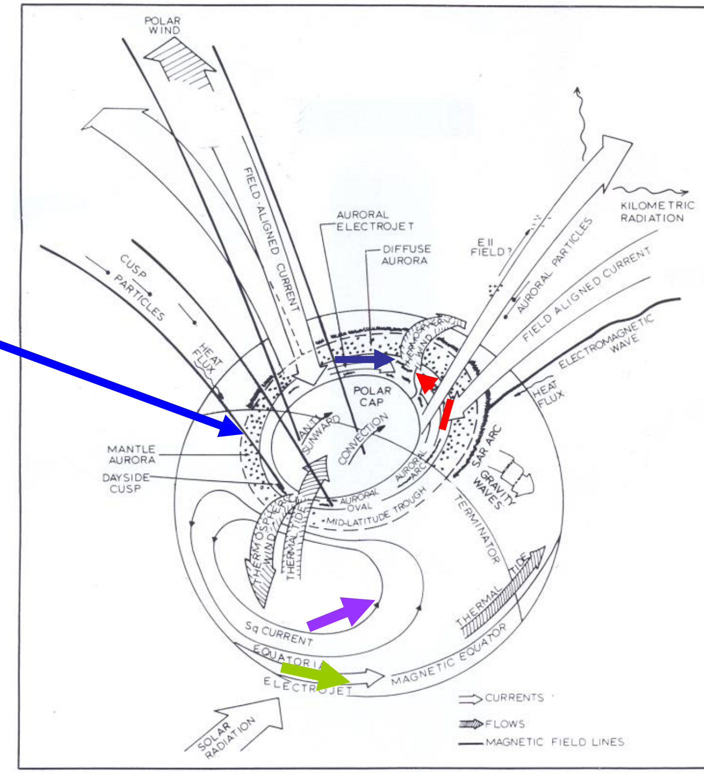
Picture of the By aurorae observed on June 24, 1554 in Germany and Switzerland, Legrand et al. 1991
The aurorae is at 100km height



During strong magnetic storms, the effects of aurora can be observed at low latitudes
Aurora observed at Rouen (near Paris /France), On April 11 2001

Tycho BRAHE [1546-1601]
Danemark

AURORA



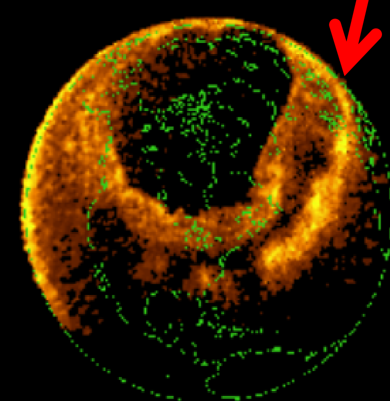
Jean DORTOUS DE MAIRAN -1733

Academician -> reign of the king LOUIS XIV (France)

He explained the auroras by matter coming from the sun, rushing through the atmosphere and colliding with the atom in the atmosphere, before the discovery of solar wind - First satellite in 1957

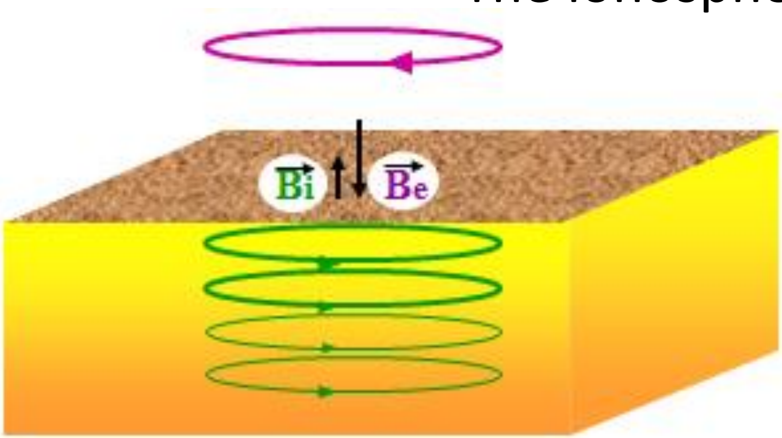
IMPACT of Magnetic storm Ionospheric electric currents

The auroral oval extends toward middle latitudes the auroral ionospheric electric currents strongly affects low latitudes



March 13, 1989 - The Quebec Blackout Storm - Most newspapers that reported this event considered the spectacular aurora to be the most newsworthy aspect of the storm. Seen as far south as Florida and Cuba, the vast majority of people in the Northern Hemisphere had never seen such a spectacle in recent memory. Electrical ground currents created by the magnetic storm found their way into the power grid of the Hydro-Quebec Power Authority and the entire Quebec power grid collapsed. Six million people were affected as they woke to find no electricity to see them through a cold Quebec wintry night. This storm could easily have been a $6 billion catastrophe affecting most US East Coast cities.

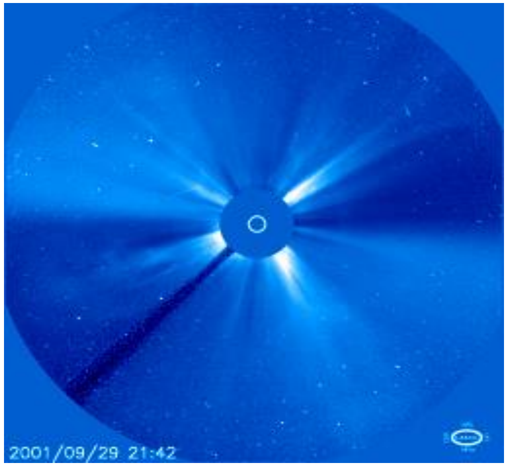
The ionospheric electric currents induce telluric currents

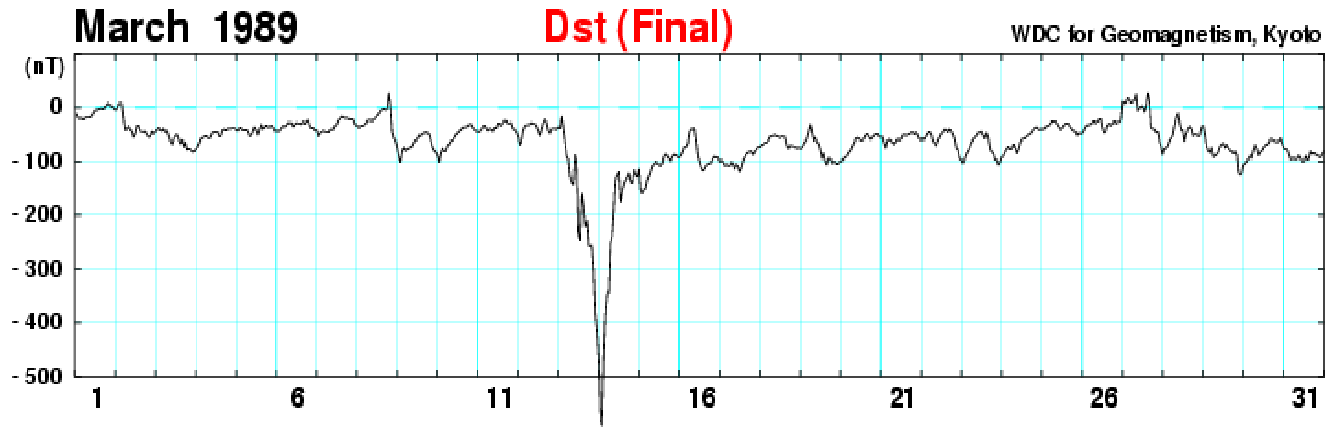


Power failure

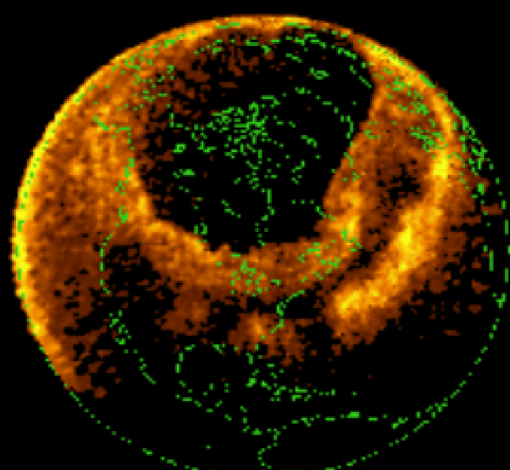
Transformer damaged

MAGNETIC STORM OF MARCH 15, 1989
the auroral oval extends toward low latitudes





Power failure



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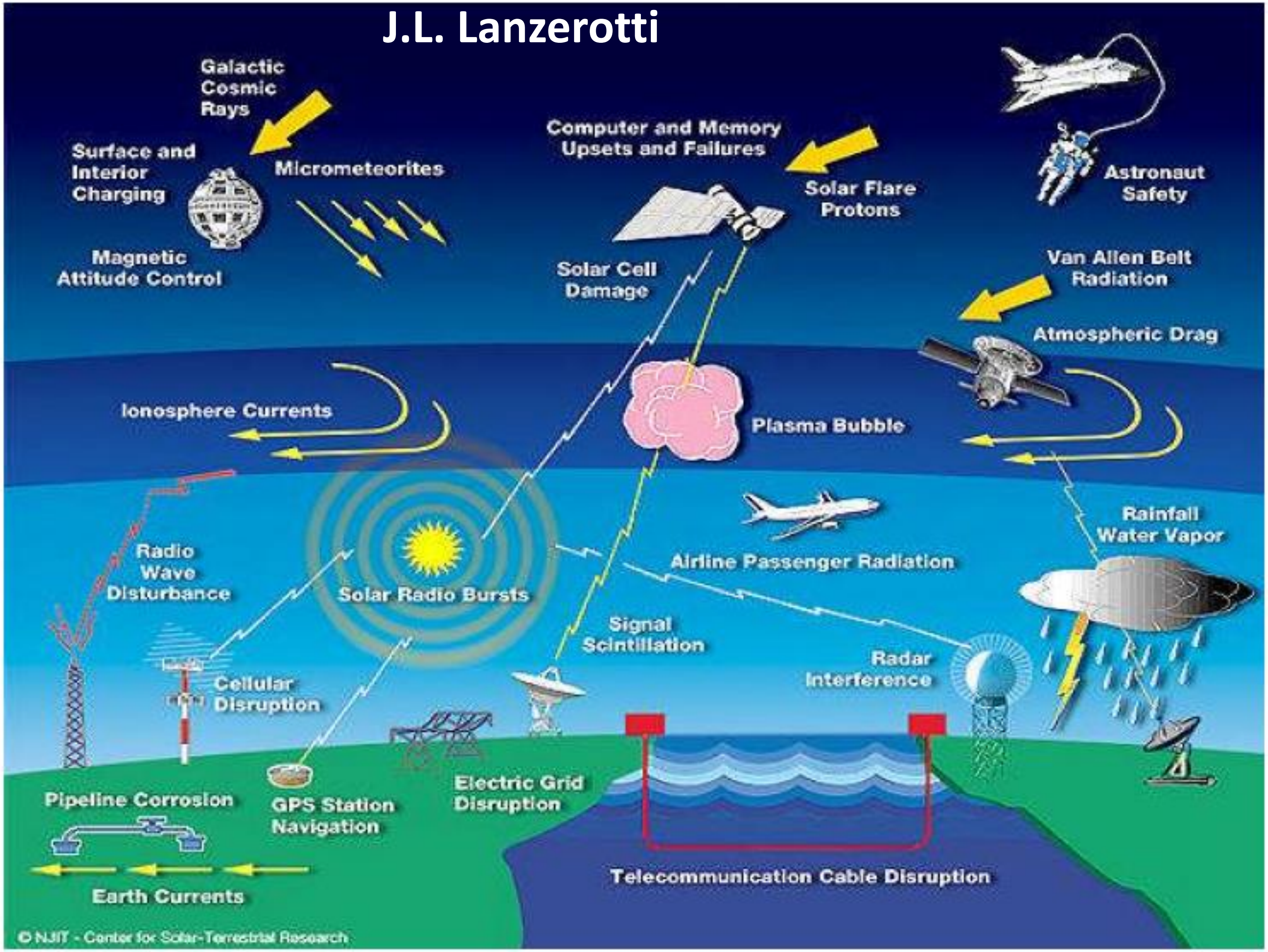
SPACE WEATHER (technological systems))



IMPACT on Technologies

The ionosphere is a ionized layer around the Earth (from ~ 50 km up to 800 km).

Ionospheric electric currents are at the origin of variations of the Earth's magnetic field and Ground Induced Electric Currents (GIC)

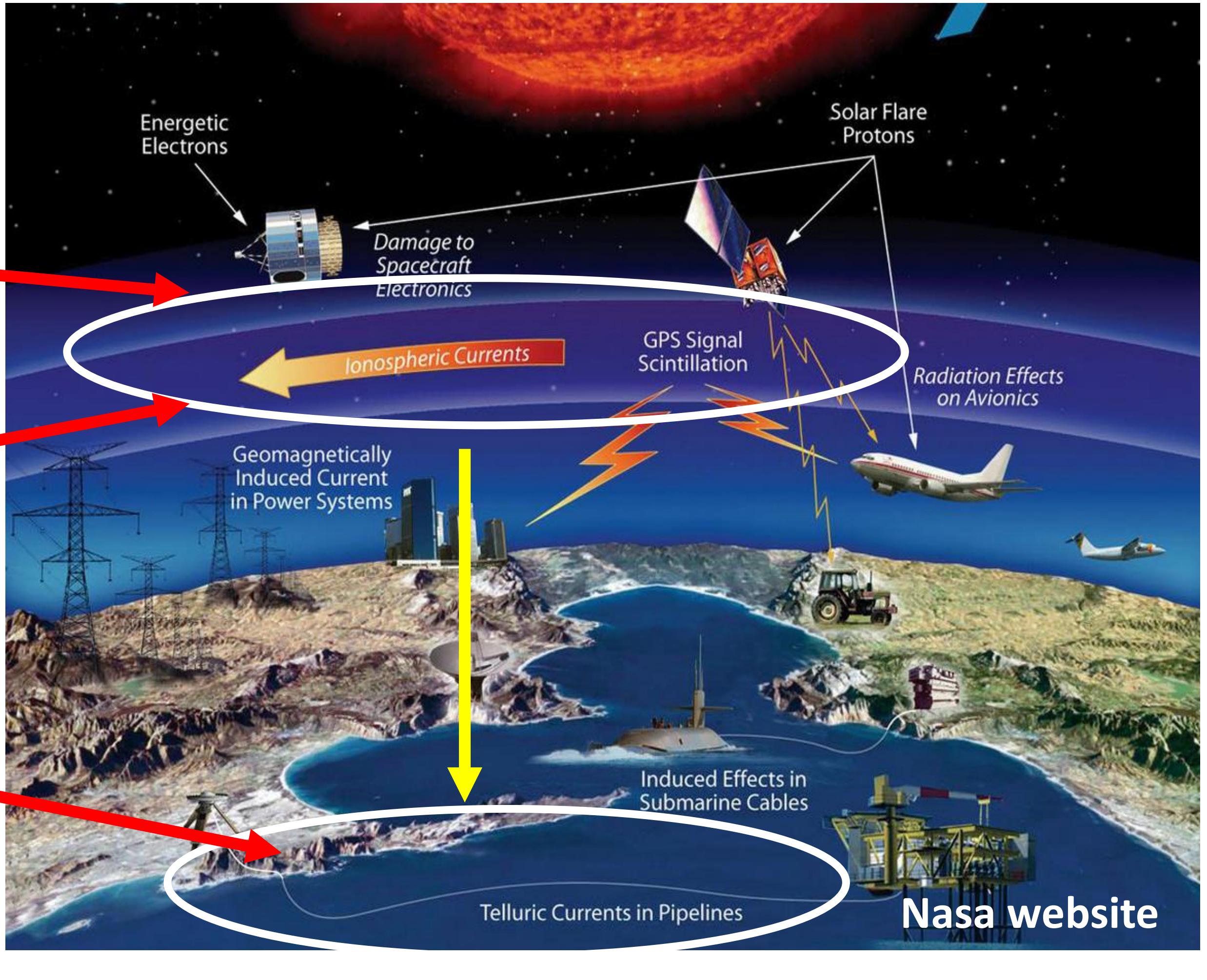
The ionosphere is the largest source of perturbations for GNSS

Regular and irregular variations

1) Ionization
Propagation electromagnetic waves

2) Ionospheric Electric current

3) Variations of the Earth's magnetic field and GIC



Conclusion

- With the development of society and the use of new technologies sensitive to the electromagnetic environment of the earth,
- Space weather combines past knowledge of the Sun-Earth system and aims to predict the impact of solar events. on new technologies
- To develop the physics of Space weather it is necessary to integrate all the physics developed separately in different disciplines concerning the sun, the solar wind, the magnetosphere, the ionosphere, the atmosphere and the Earth.