



SUN EARTH CONNECTIONS

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African Workshop on GNSS and Space Weather" online 05 -06 October 2020

SUN EARTH Connections

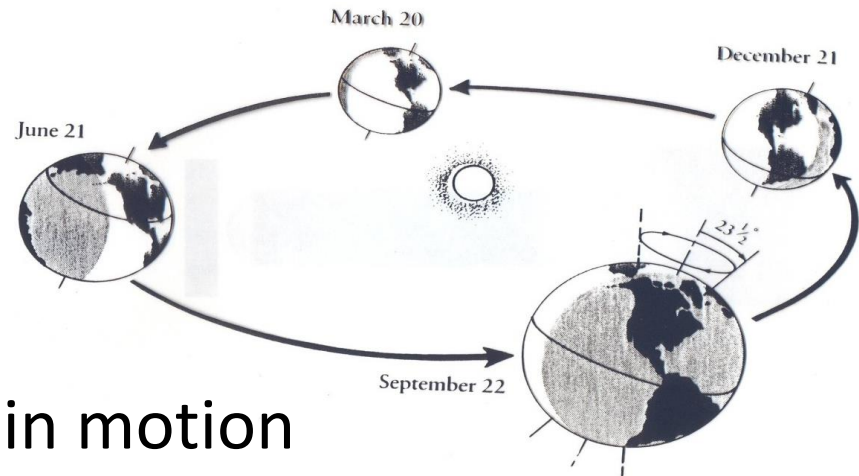
- Sun Earth Connections :
 - Motions of the Sun and the Earth,
 - Emissions from the Sun
- Sun : Sunspot cycle, What is a sunspot?, the true solar cycle
- Sun Earth Connections : Radiations channel –Solar Flare, Solar Bursts,
 - The regular ionosphere,
 - Ionization, electric currents magnetic field ground induced currents
 - Ionospheric dynamo
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 - CME : coronal Mass Ejection – HSSW : High Speed Solar Wind
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 - Irregularities of equatorial plasma
- Conclusion

SUN EARTH CONNECTIONS : MOTIONS

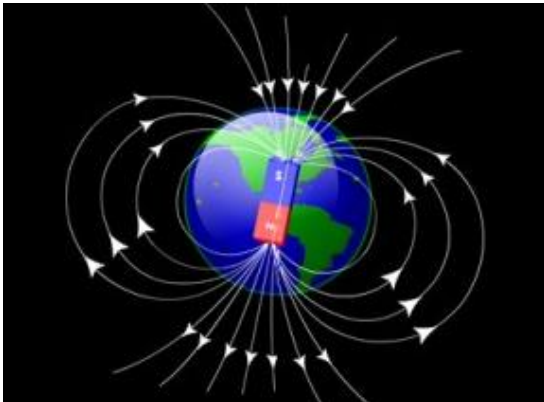
The Sun : a magnetic body in motion



Variability \sim 27 days



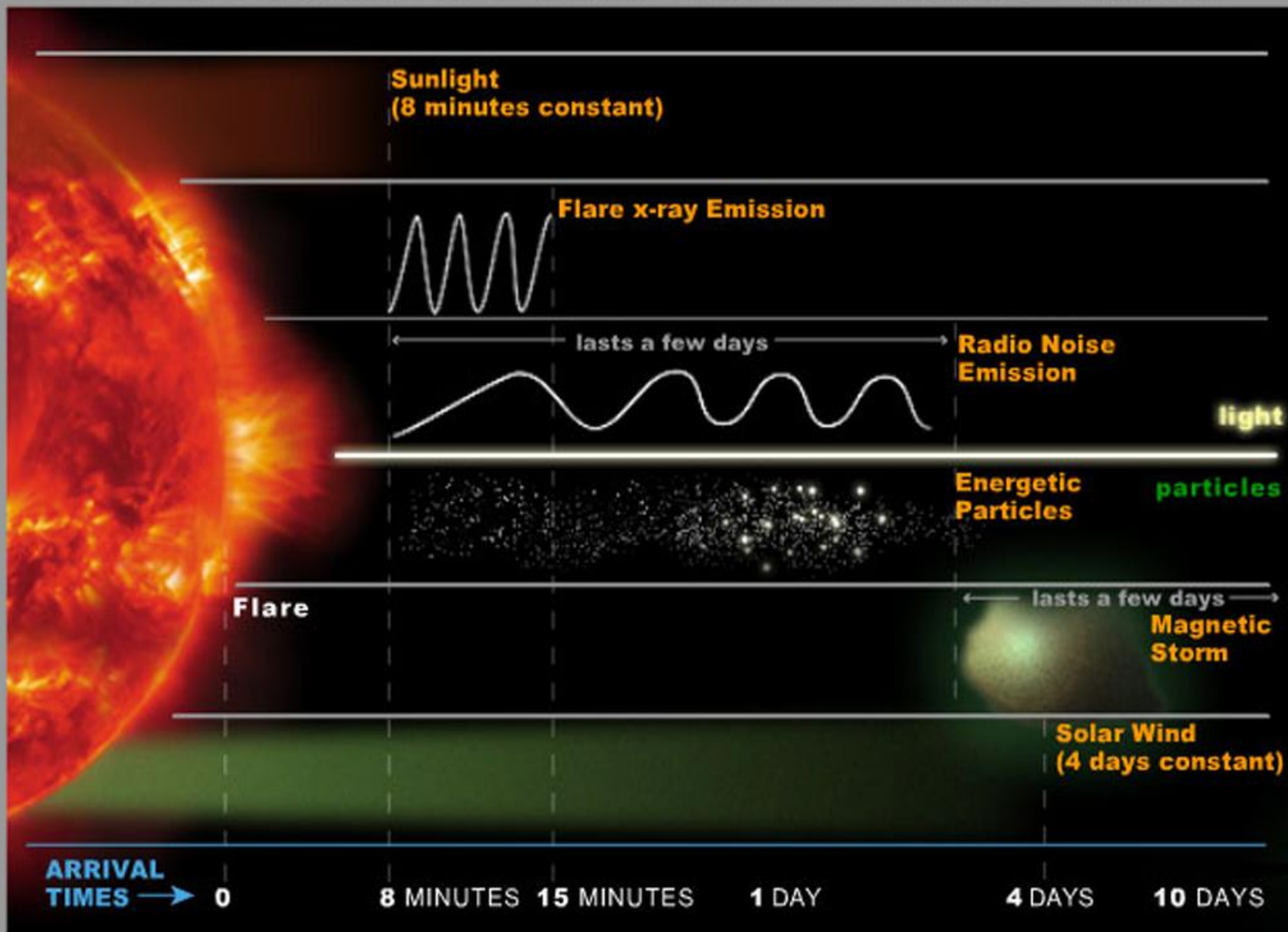
The Earth: a magnetic body in motion



Variability : diurnal , seasonal/annual

SUN EARTH CONNECTION : EMISSIONS FROM THE SUN

DYNAMIC AND CONSTANT SOLAR EFFECTS ON EARTH

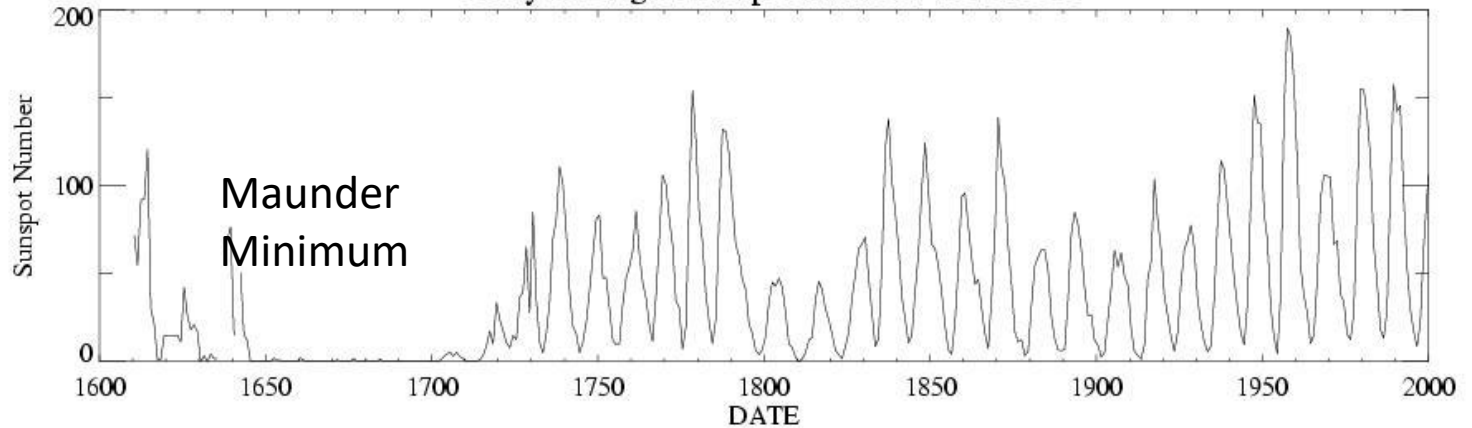


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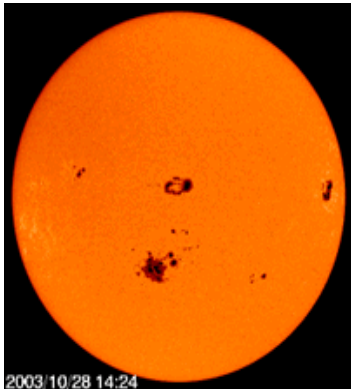
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SUN : THE SUNSPOT CYCLE

Yearly Averaged Sunspot Numbers 1610-2000

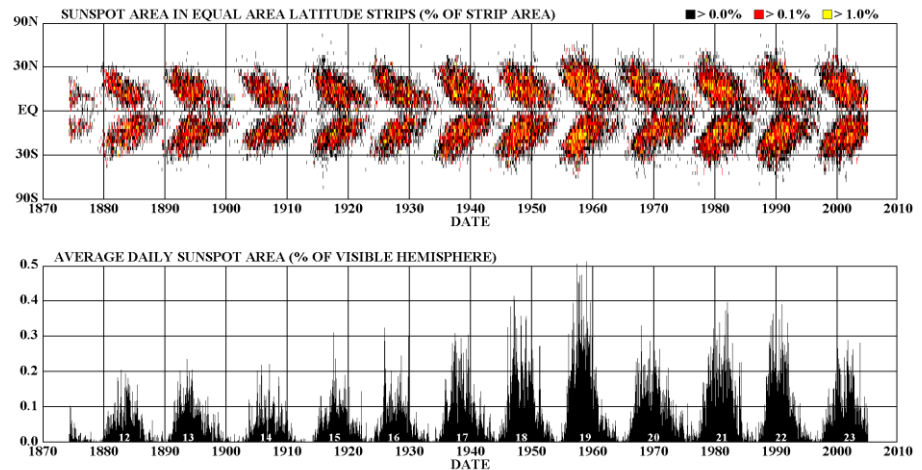


Sunspot Cycle of 11 years : Heinrich Schwabe 1859



Legrand et al. 1990
On Maunder minimum

DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS



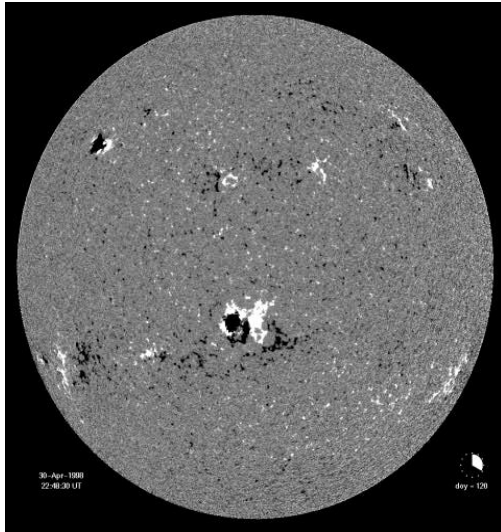
<http://science.msfc.nasa.gov/ssl/pad/solar/images/bfly.gif>

NASA/NSSTC/HATHAWAY 2005/03

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.

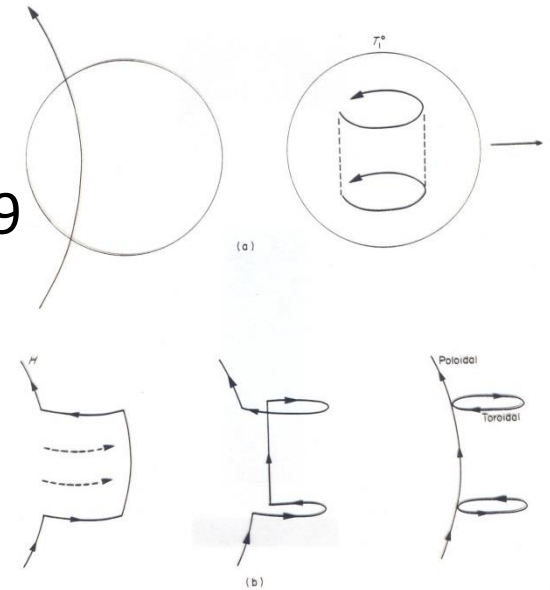
SUN : What is a sunspot ?

Figure from Friedman, 1987

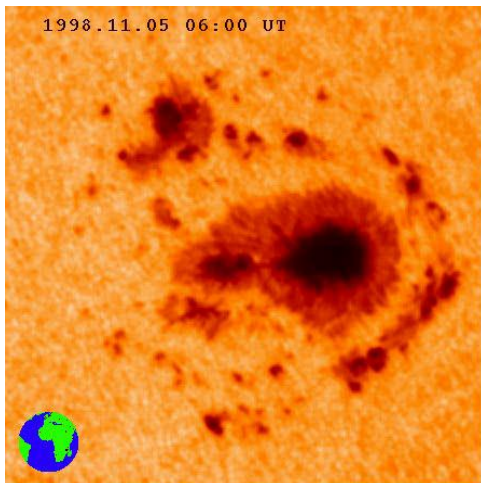


Poloïdal component
~ 10 G
discovered by Hale 1919

Toroïdal component
Sunspot
~ 3-5 kG



Magnetogram of the Sun
SOHO satellite data



Physical process : Dynamo

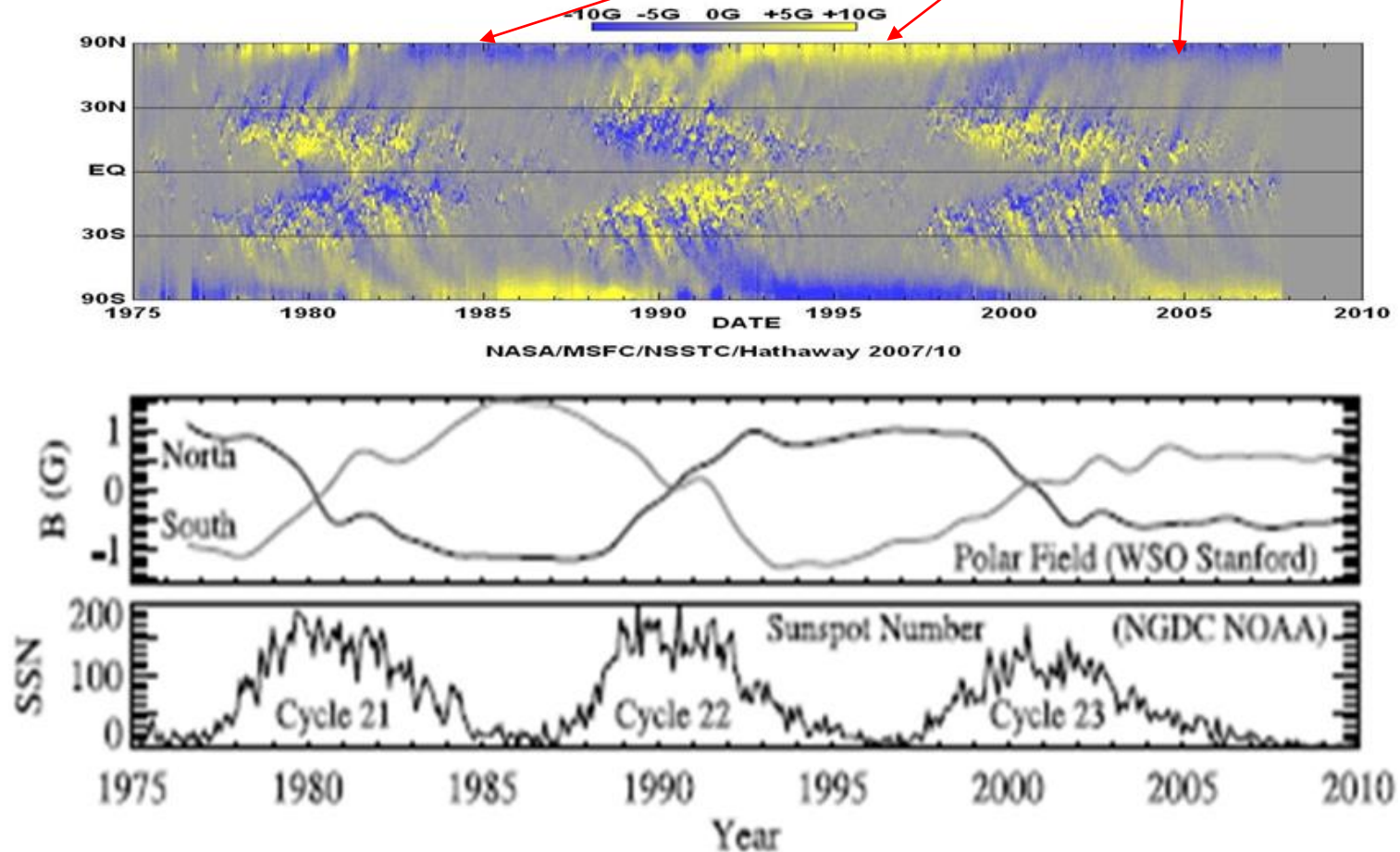
- *The sun turns on itself.
- **Its rotation speed is faster at the equator than at the poles (~ 27 days against ~ 31 days).
- ***This differential rotation twists the lines of the poloidal magnetic field and generates magnetic loops called sunspots

Solar Dynamo : the true solar cycle by solar physicists

The solar polar magnetic field reverses each 11 years

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

The 2 components of the magnetic solar cycle and anti correlated



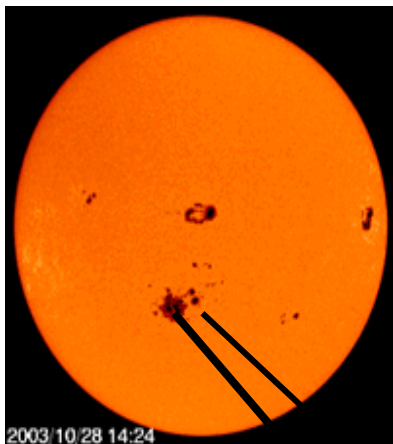
Variability \sim 11 and 22 years

Liu et al., 2011

<http://solarscience.msfc.nasa.gov/dynamo.shtml>

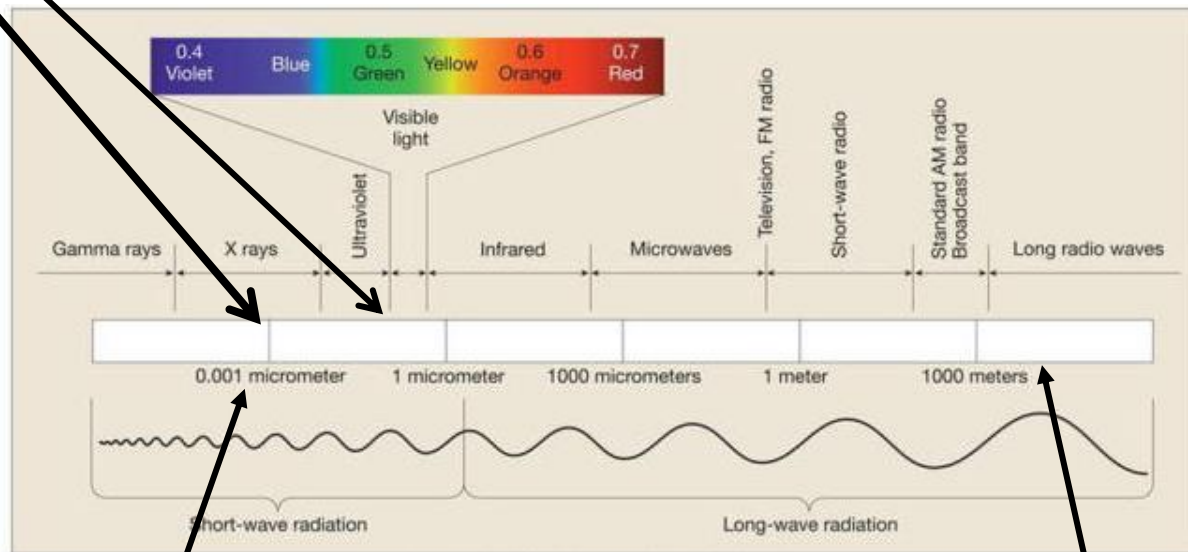
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SUN : RADIATIONS Channel **(REGULAR)**
Speed of Light

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

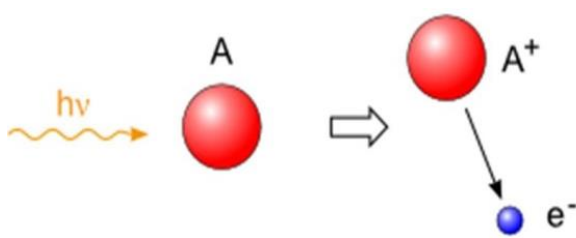


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SOLAR FLARE
Extra X rays

SOLAR BURST
Extra Radio waves

RADIATIONS Channel **(Disturbed)**



SUN EARTH CONNECTIONS

Ionosphere ↔ Regular solar radiations

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

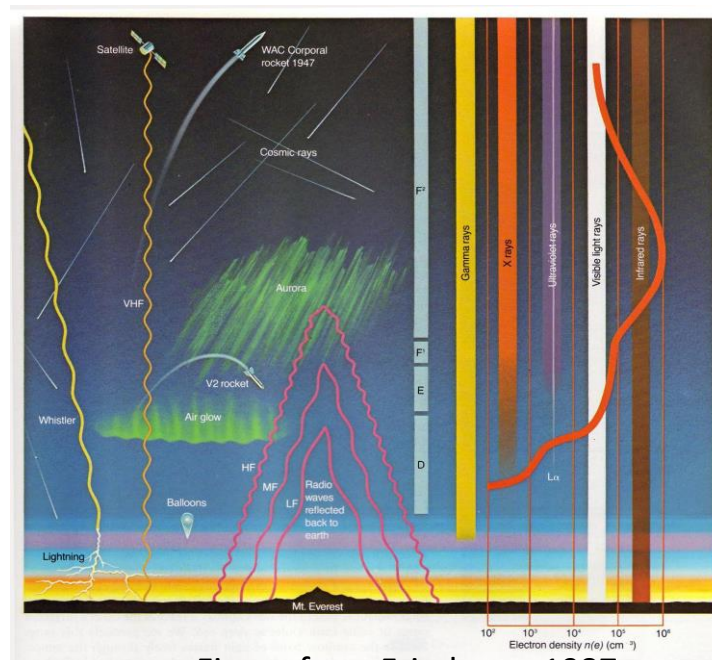
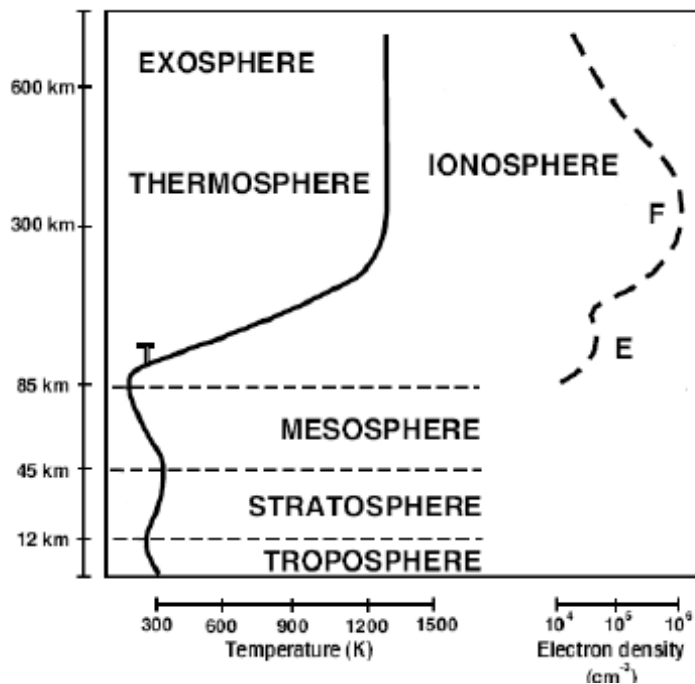


Figure from Friedman, 1987



Ionosphere is a ionized part of the atmosphere
1 atom among 1 000 000

[BOOKS : Risbeth and Gariott, 1969](#)
[Friedman, 1987, Kelley ,2009](#)

SUN EARTH CONNECTIONS : THE IONOSPHERE

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)

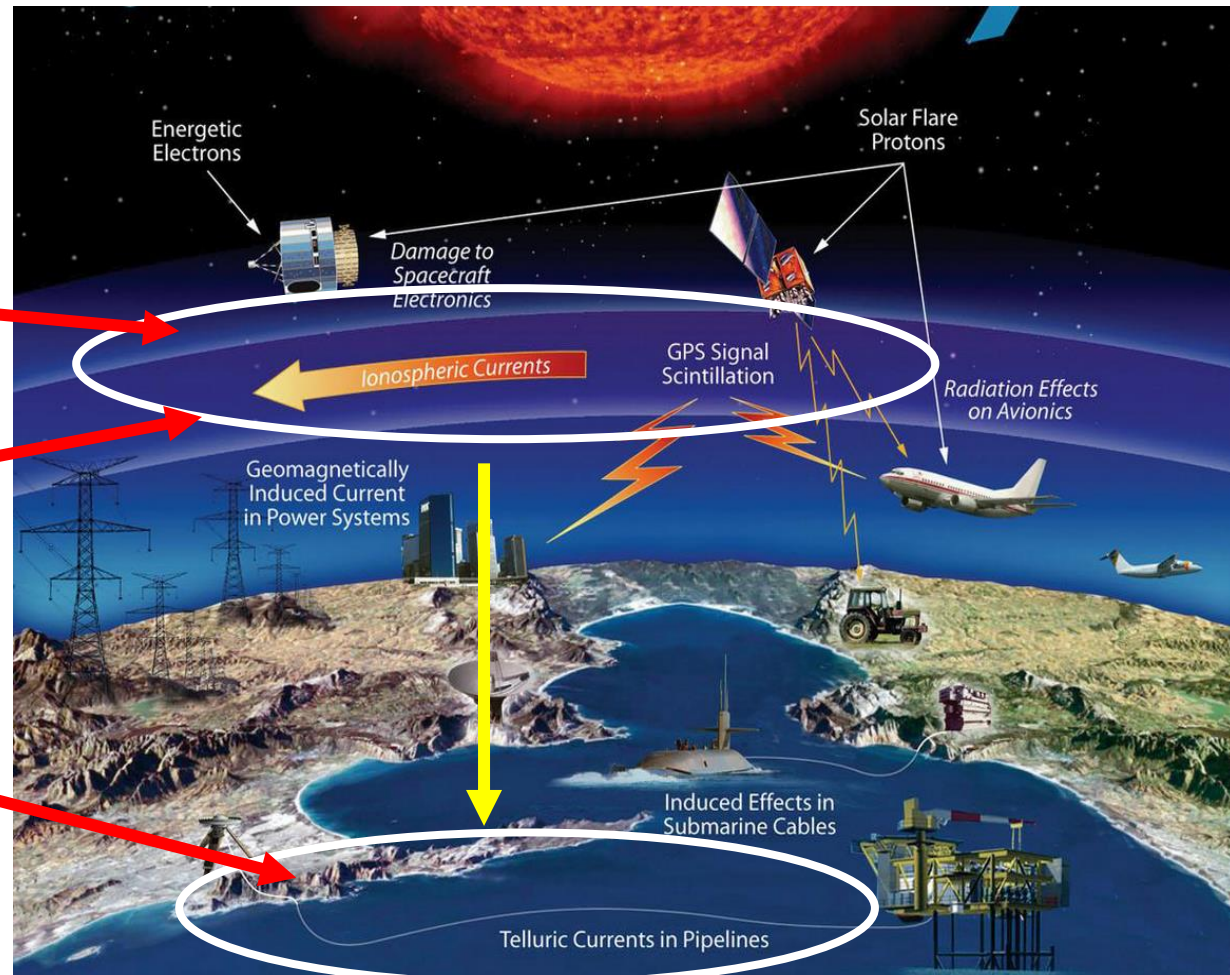
The ionosphere is the largest source of perturbations for GNSS

Regular and irregular variations

1) Ionization

2) Ionospheric Electric current

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

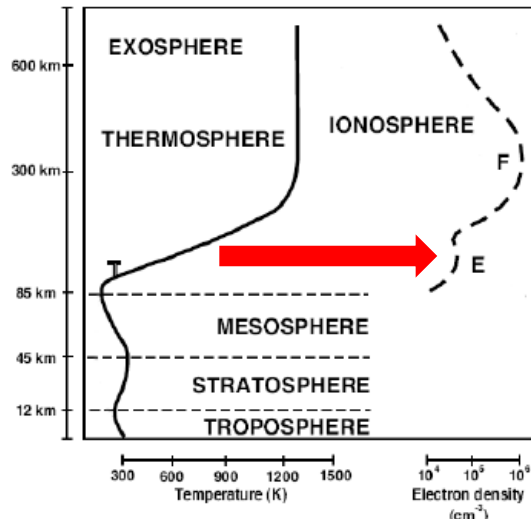
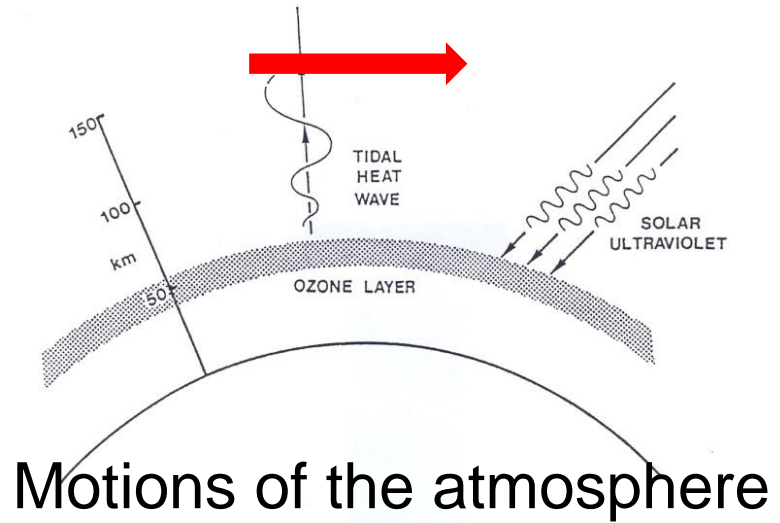


Ionosphere due to photoionisation => Earth's magnetic field

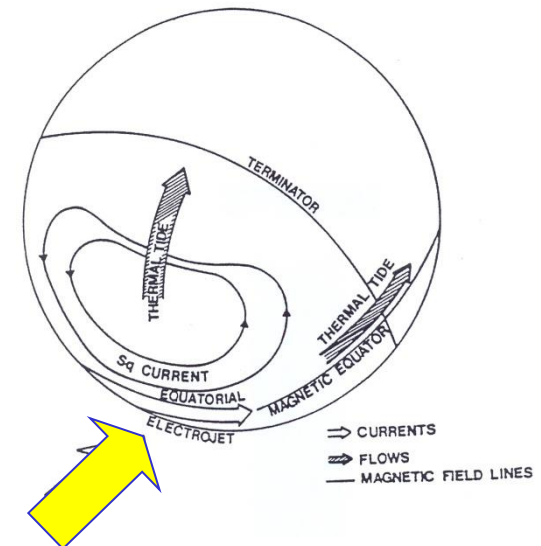
The UV, EUV and X radiations create the ionosphere at the origin of regular variation S_q/S_R and EEJ of the Earth's magnetic field

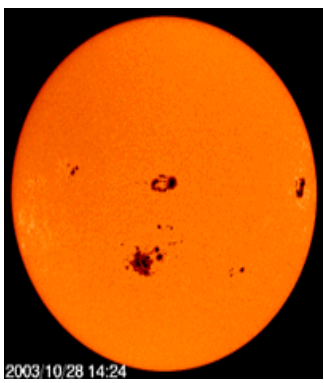


Ionospheric electric currents
 $90\text{km} < h < 150\text{km}$
 $J = Ne \cdot e (V_i - V_e)$



Regular variations of the Earth's magnetic field





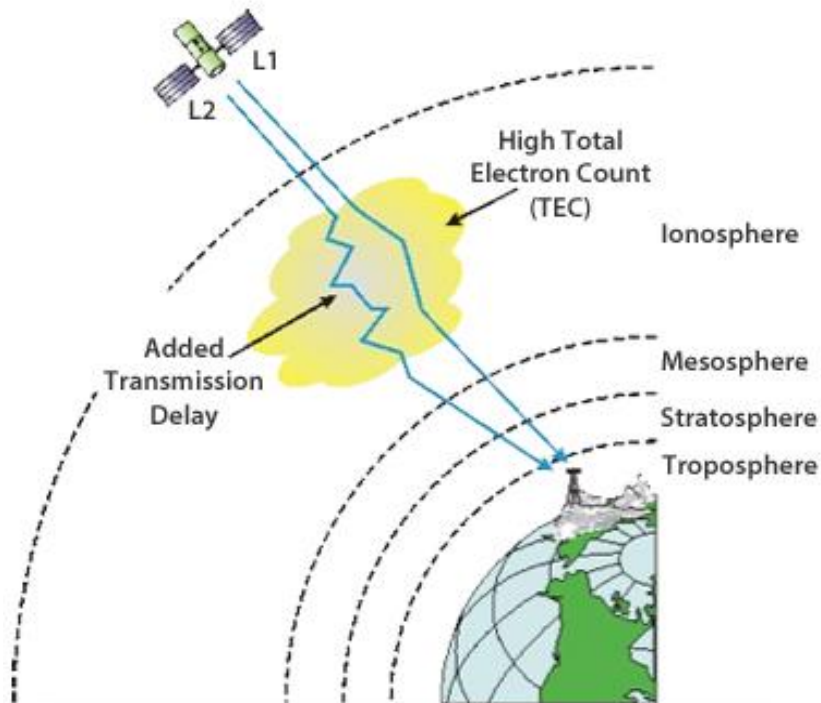
SOLAR FLARE (8')

Disturbed solar radiation

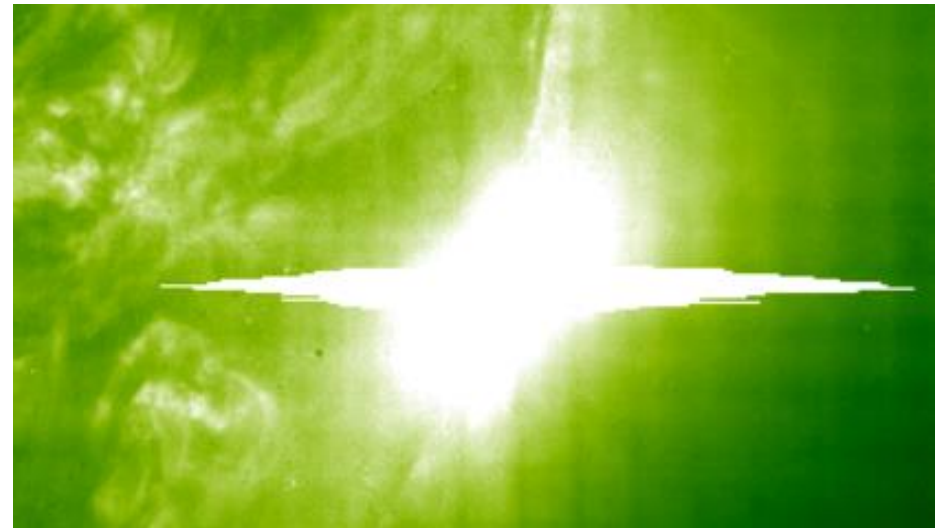
Physical processes

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.

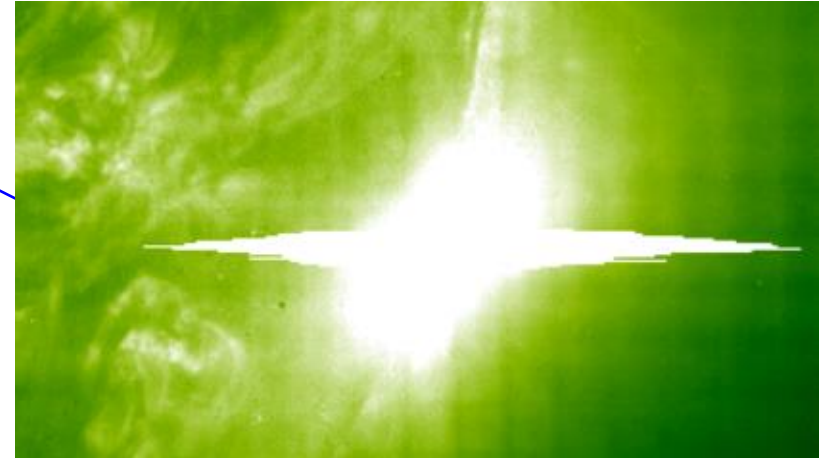
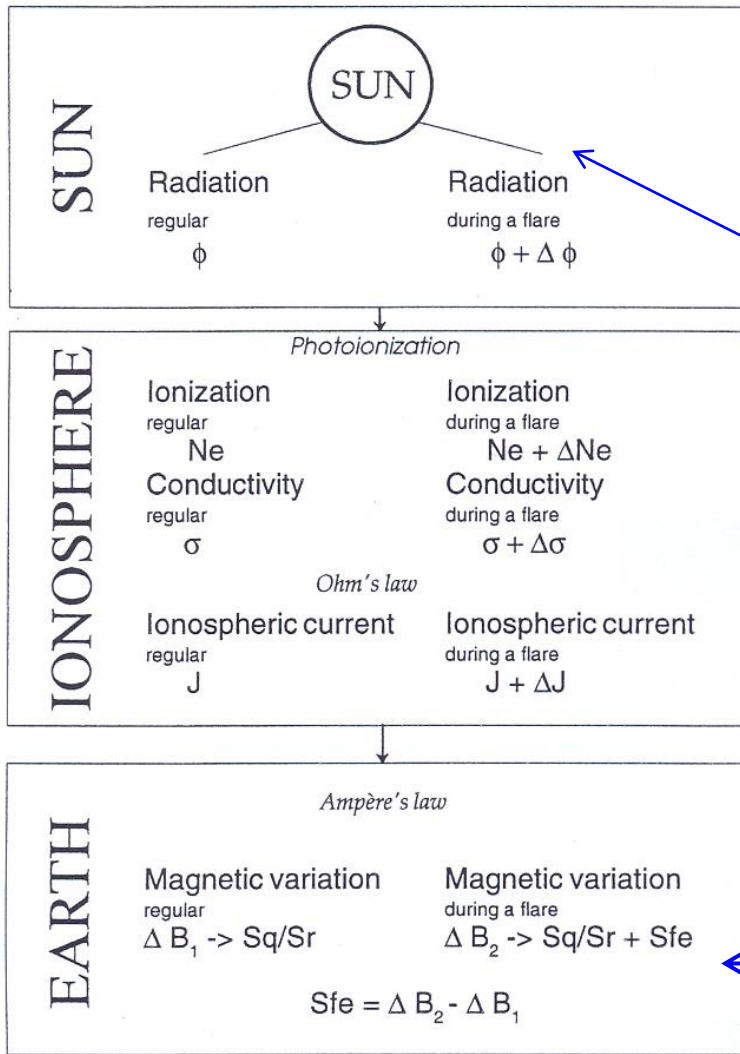


Big solar flare of November 2003



SOHO data

SUN EARTH CONNECTIONS : DISTURBED MAGNETIC VARIATIONS



Magnetic variation : crochet

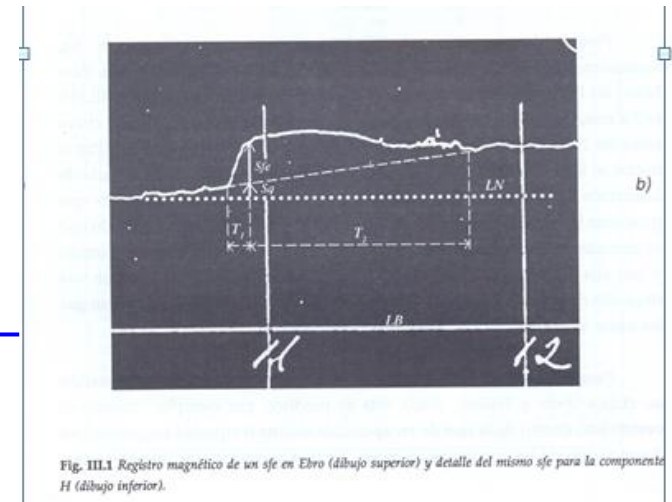


Fig. III.1 Registro magnético de un sfe en Ebro (dibujo superior) y detalle del mismo sfe para la componente H (dibujo inferior).

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.

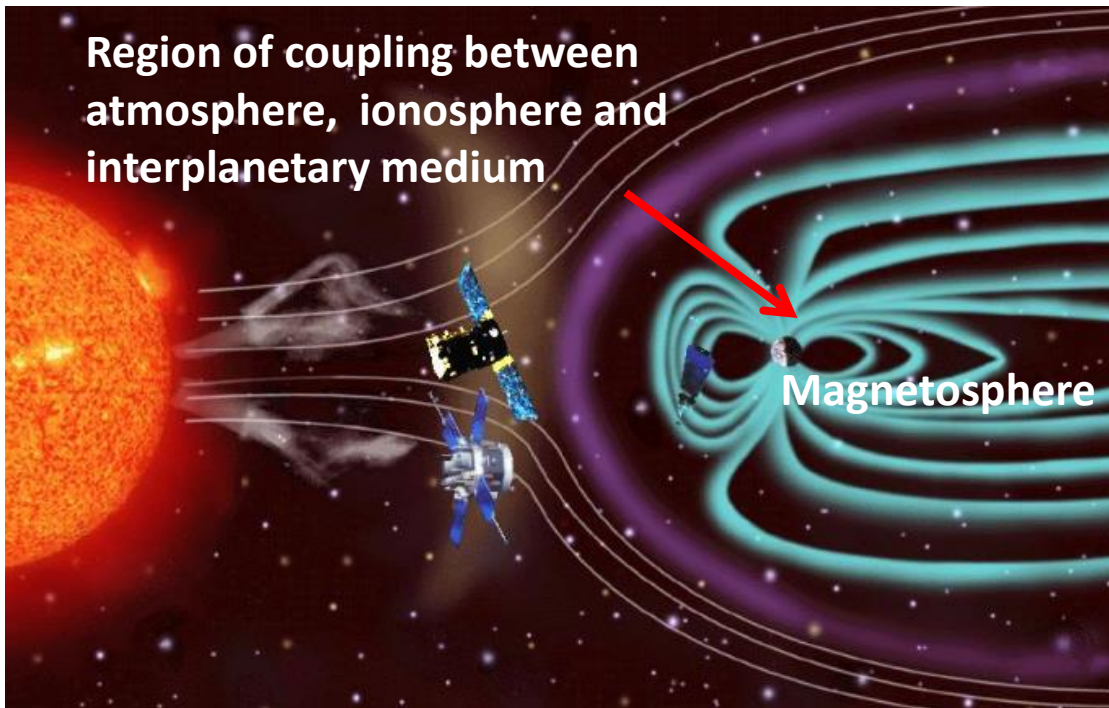
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SUN EARTH CONNECTIONS : PARTICLES Channel :

Regular solar wind : $V \sim 350-400\text{km/s}$, Time $\sim 2-3$ 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. It 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

INTERACTION BETWEEN THE SOLAR WIND and THE MAGNETOSPHERE

Physical processes : Reconnection and Dynamo

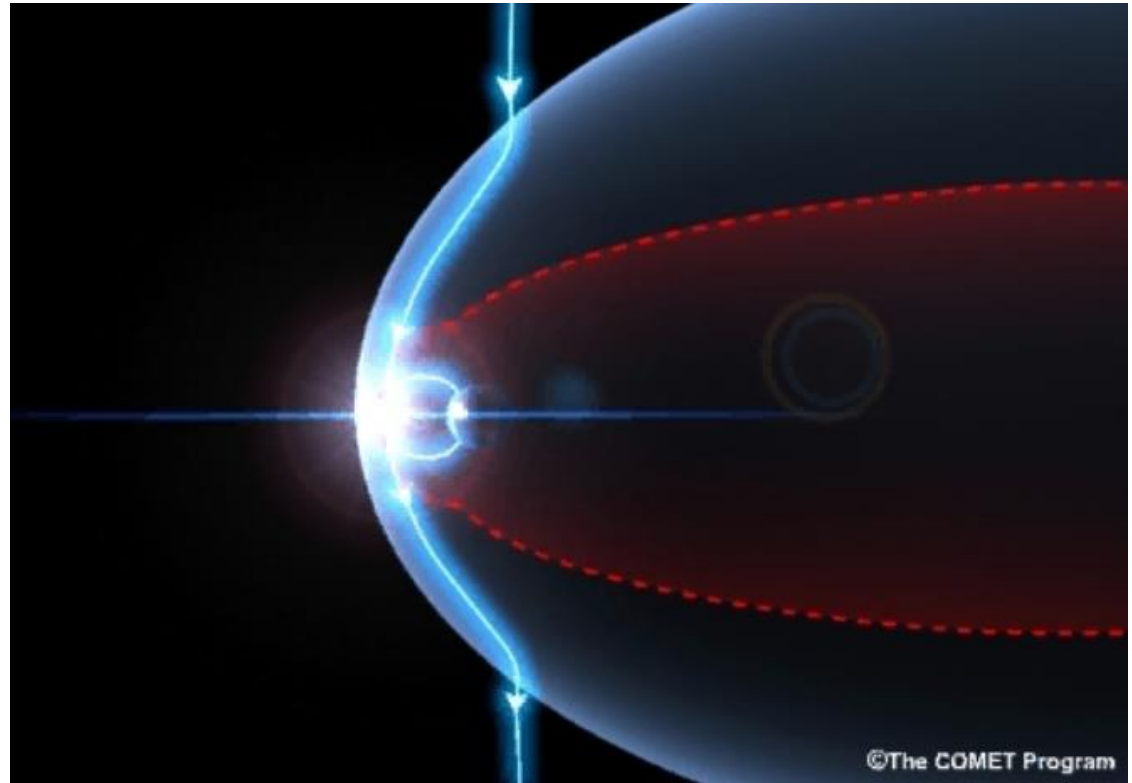
If the Interplanetary Magnetic Field , IMF field is opposite to the terrestrial magnetic field, i.e directed toward the South, there is reconnection between the IMF and the Earth's magnetic field and **there is a magnetic storm**

Key parameters for Space Weather

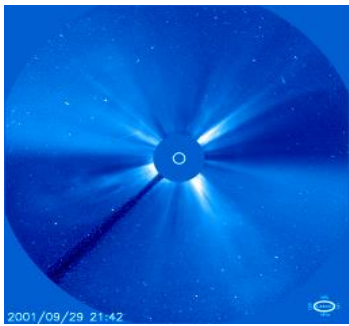
B_z IMF

V_s : solar wind speed

$$E_y = - V_x \cdot B_z$$

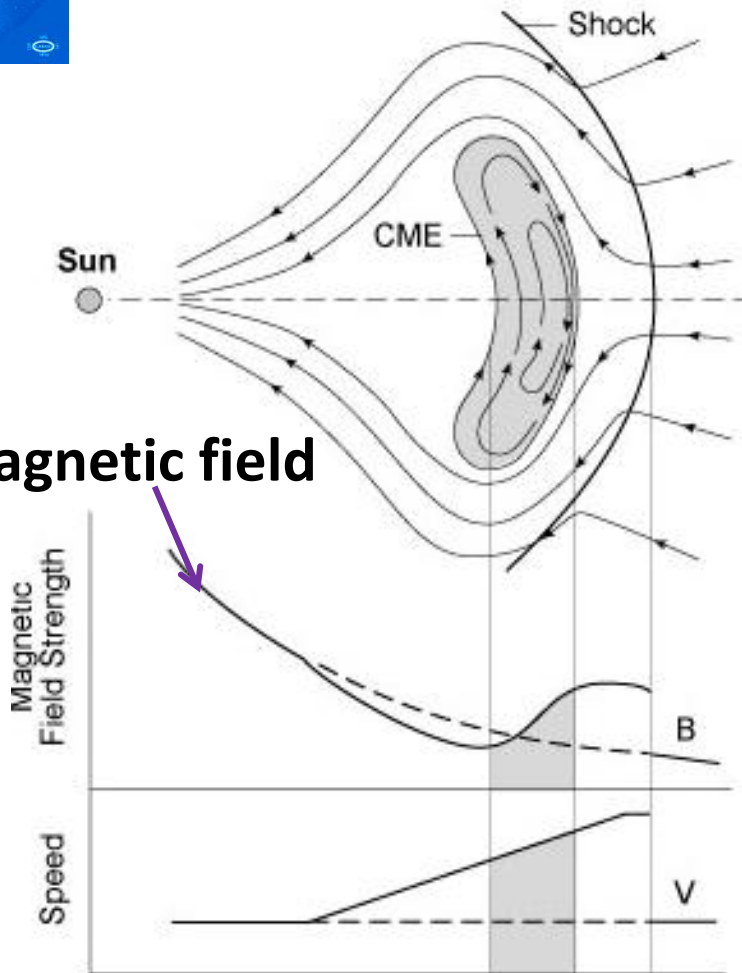


**Solar wind – Magnetosphere Dynamo : $E = V_s \times B$
movement is converted into electrical energy**



Interplanetary CME Shocks

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

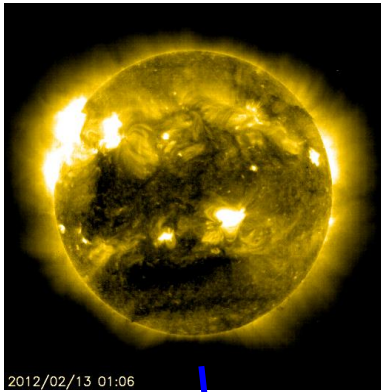


A fast coronal mass ejection CME pushes an interplanetary shock wave

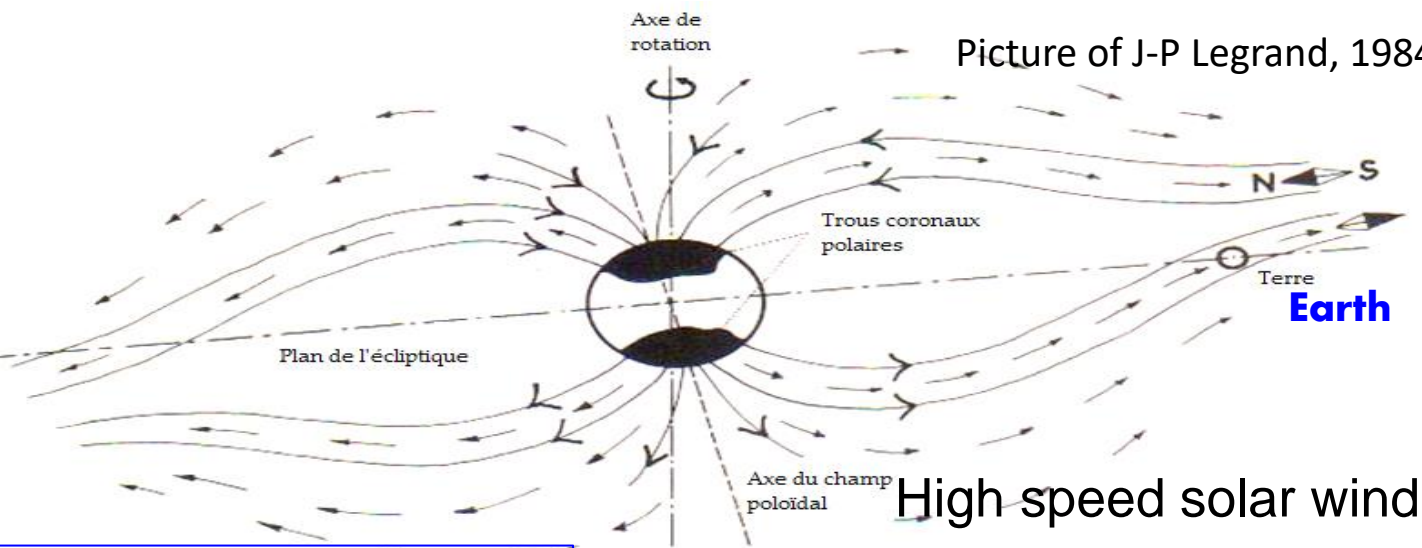
Increases of solar wind speed V and magnetic field strength B by the interplanetary shock wave in front of the CME

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

CORONAL HOLE – recurrent geomagnetic activity

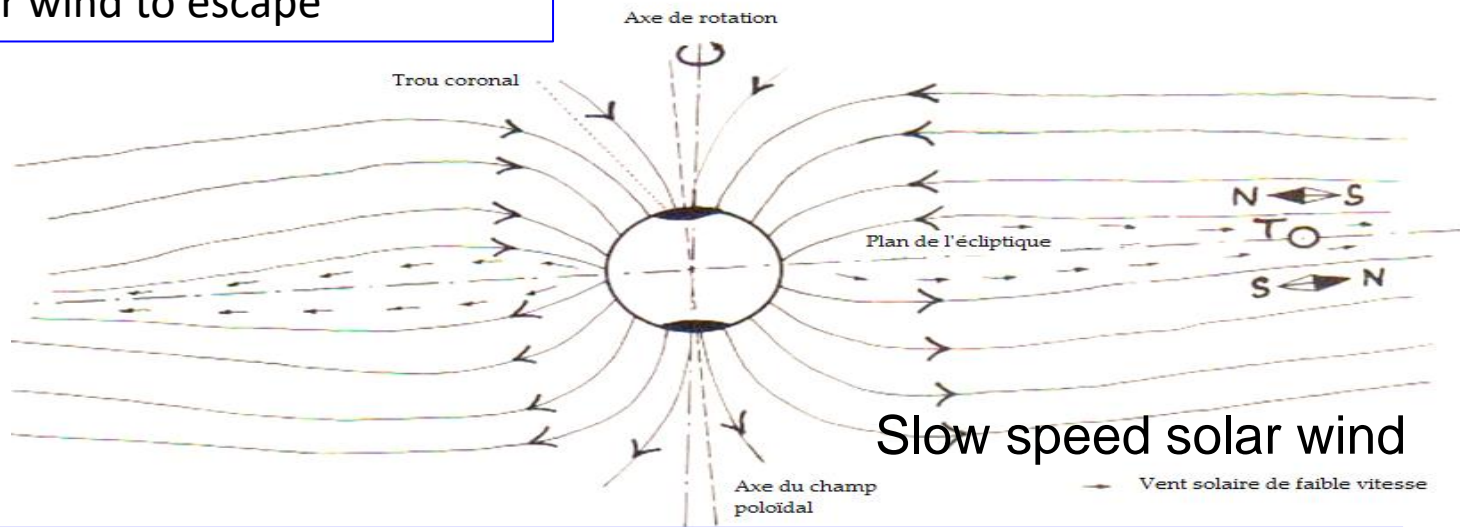
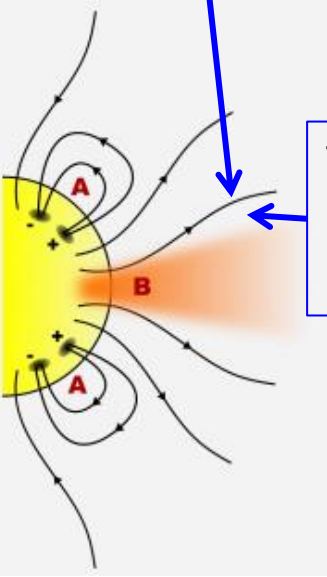


Picture of J-P Legrand, 1984



High speed solar wind

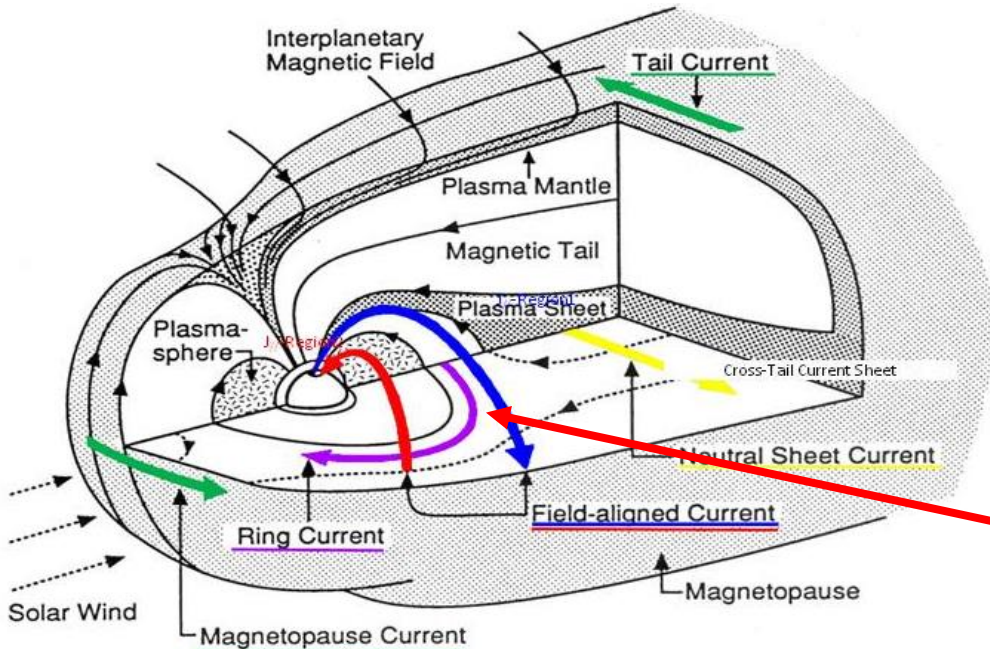
The lines of the magnetic field are open. This allows for the solar wind to escape



Slow speed solar wind

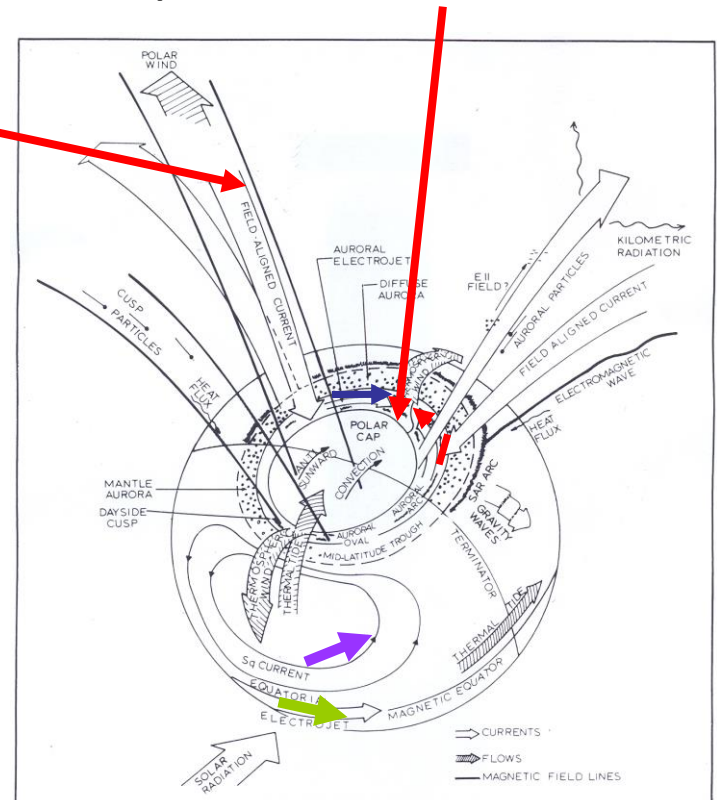
Maximum occurrence during the declining and minimum phases of solar sunspot cycle

SUN EARTH CONNECTIONS ELECTRIC CURRENTS

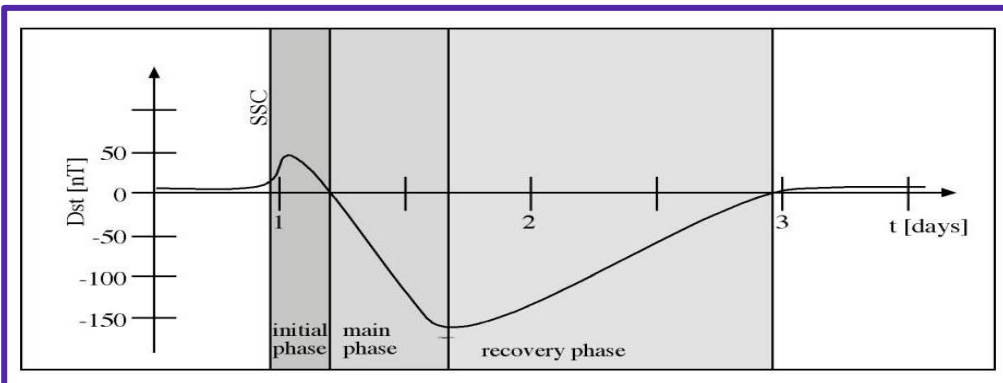


AURORAL ZONE

- * Field aligned electric currents
- * Precipitation
- * Convection electric field
- * Ionospheric electric currents



MAGNETOSPHERE Electric currents



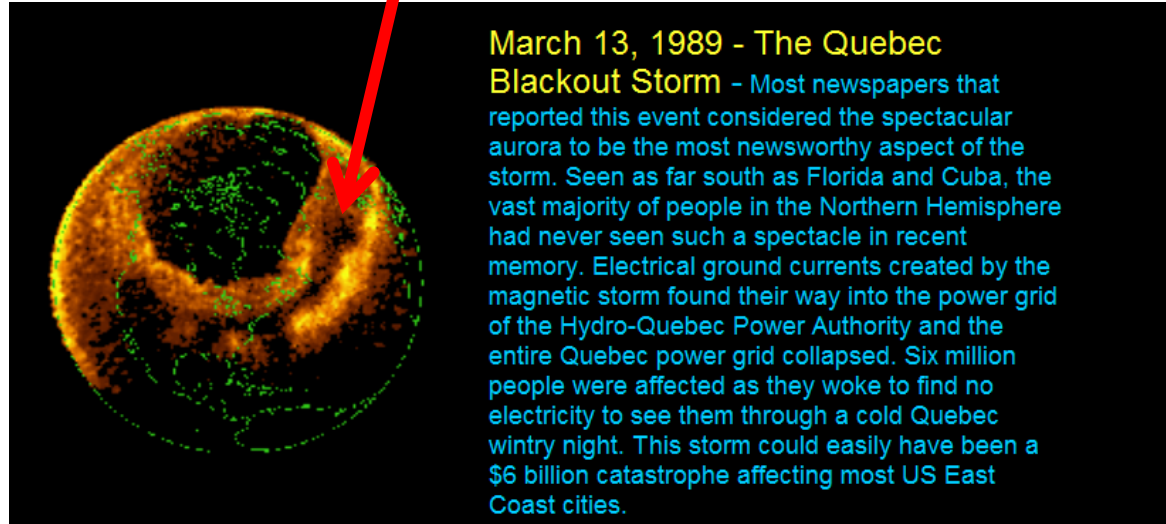
Magnetic storm indices Dst, SYM-H *



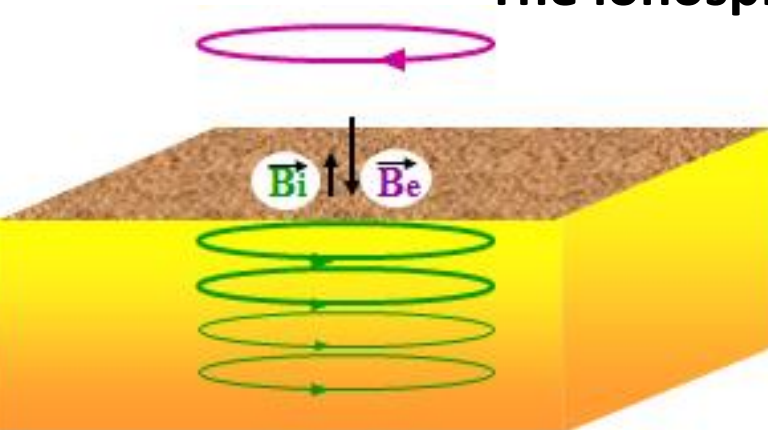
The auroral oval extends toward middle latitudes the auroral ionospheric electric currents strongly affects low latitudes

MAGNETIC STORMS

Ionospheric electric currents



The ionospheric electric currents induce telluric currents



Power failure



Transformer damaged³¹

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SUN-EARTH CONNECTIONS

coupling between high and low latitudes

- 1 Transmission of an **electric field PPEF**
- 2.a Thermal expansion of the atmosphere
 - **Changes in pressure, temperature, motions and composition of the Atmosphere**
- 2.b Transmission of a disturbance **electric field dynamo DDEF, by the disturbed atmospheric motions in the dynamo layer**

COUPLING between AURORAL and EQUATORIAL regions ELECTRIC FIELD ALONE

Prompt penetration of the magnetospheric convection electric field [PPEF]

Nishida, A. (1968), Geomagnetic DP2 fluctuations and associated phenomena, *J. Geophys. Res.*, 73, 1795–1803, doi: 10.1029/JA073i005p01795

The electric field of magnetospheric convection is transmitted to the whole ionosphere
=> simultaneity of the disturbances from auroral to equatorial latitudes

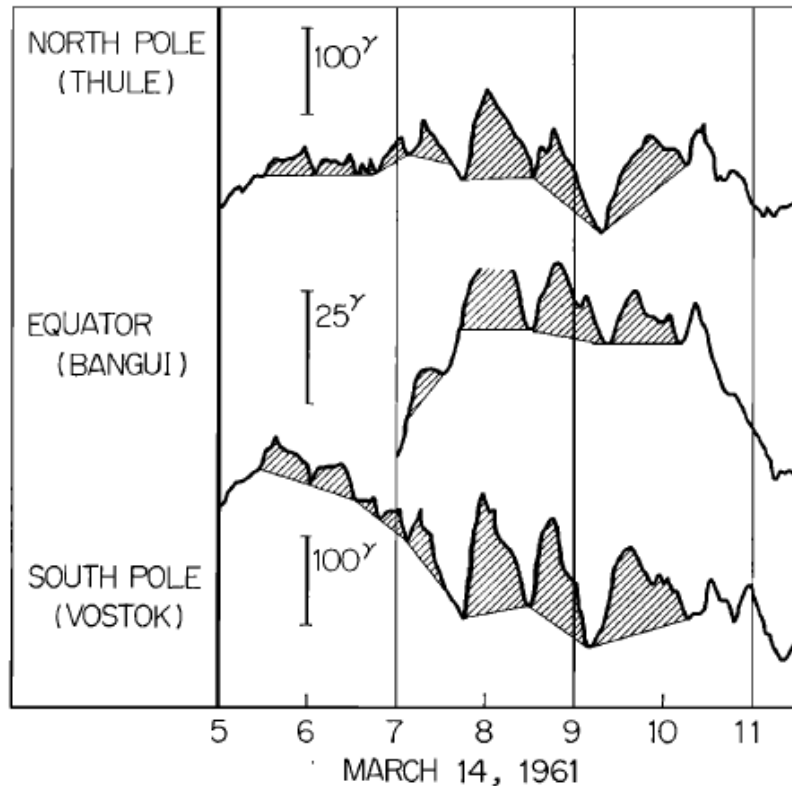
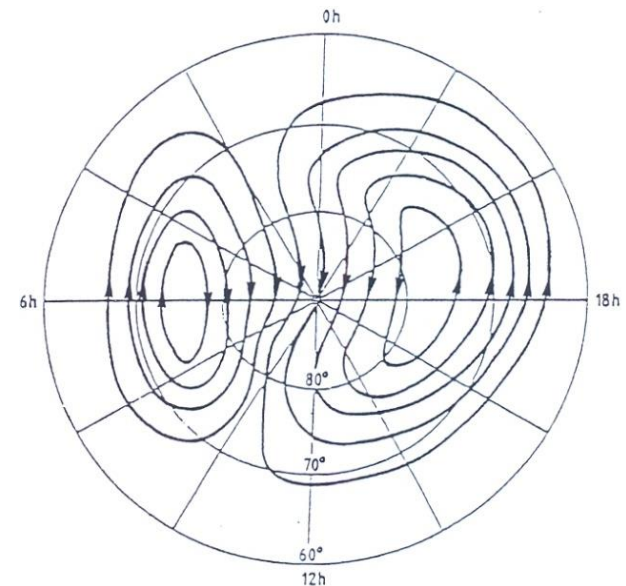


Fig. 1. Train of $D_p 2$ fluctuations (shaded). Geomagnetic latitudes of these stations are 88.9 (Thule), 05.0 (Bangui), and -89.1 (Vostok).



Magnetic signature : DP2

COUPLING between AURORAL and EQUATORIAL regions

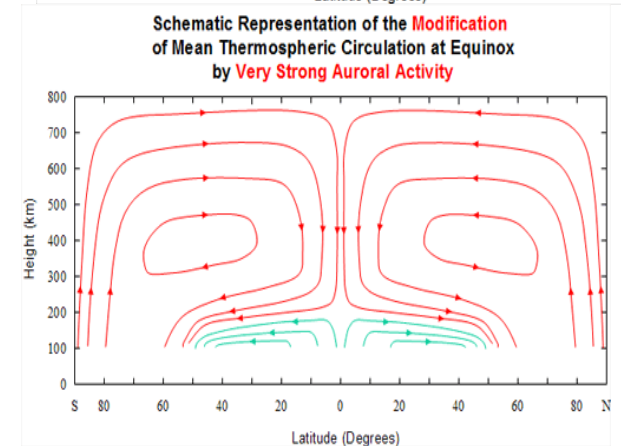
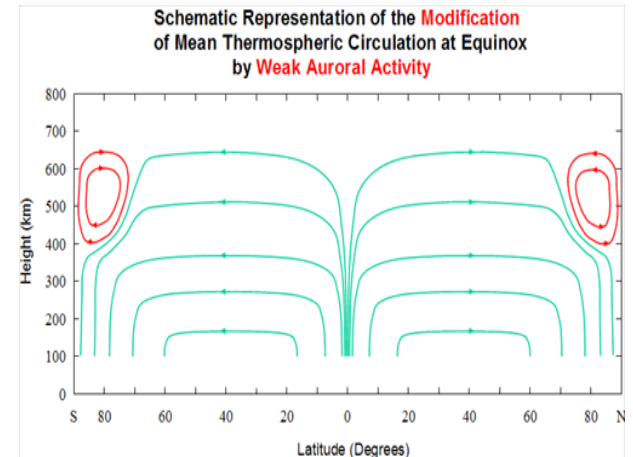
Storm winds and ionospheric disturbance dynamo

=> delay between the auroral and equatorial regions DDEF

Auroral electrojets



Joule heating most effective



Blanc, M., and A. D. Richmond (1980), The ionospheric disturbance dynamo, *J. Geophys. Res.*, 85(A4), 1669–1686, doi: 10.1029/JA85iA04p01669.

Thermal expansion of the atmosphere: Travelling Atmospheric disturbance (TAD's) => disturbed TEC [Theory Fuller Rowell et al., (1994), (1996)]

24/08/2005

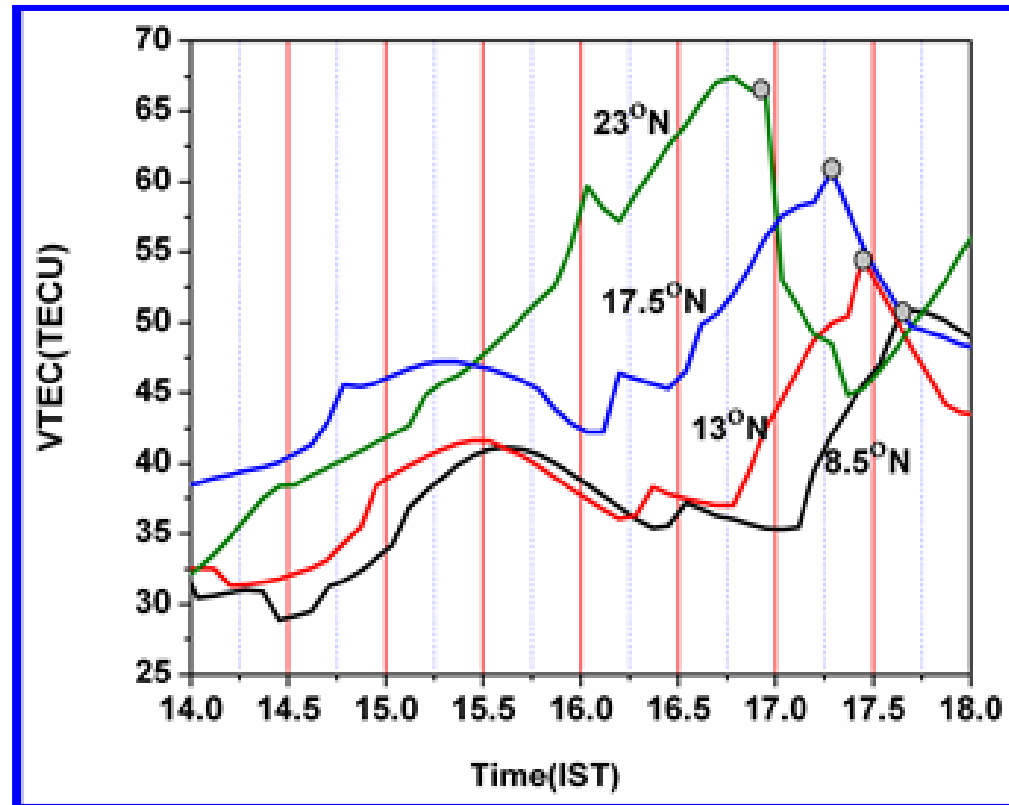
SSC : 13.00 UT

Main Phase : 16 00 UT

INDIA

77-78°E meridian

V~750m/s



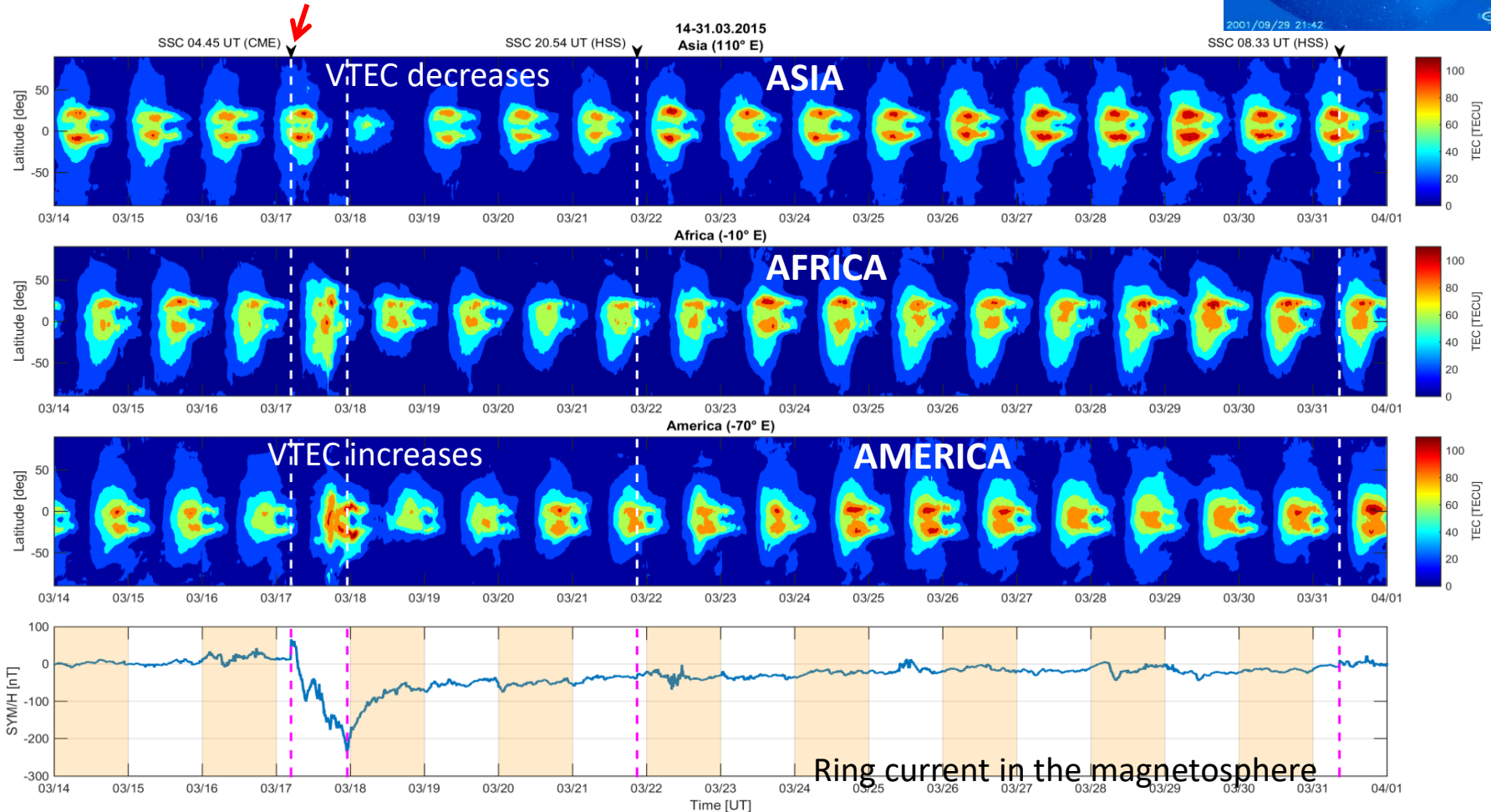
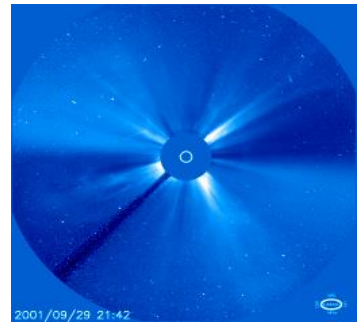
A time delay in the VTEC variations over the different latitudes indicates a propagation of TAD's Velocity 750m/s

Sreeja et al., JGR vol 114, A12307, 2009

MAGNETIC STORM of St PATRICK'S DAY : MAPS of VTEC

Variations near the magnetic Equator due to a CME (~200 GPS stations)

Impact of a CME (solar event, on March 15 ~ 04.45 - 02.00UT)

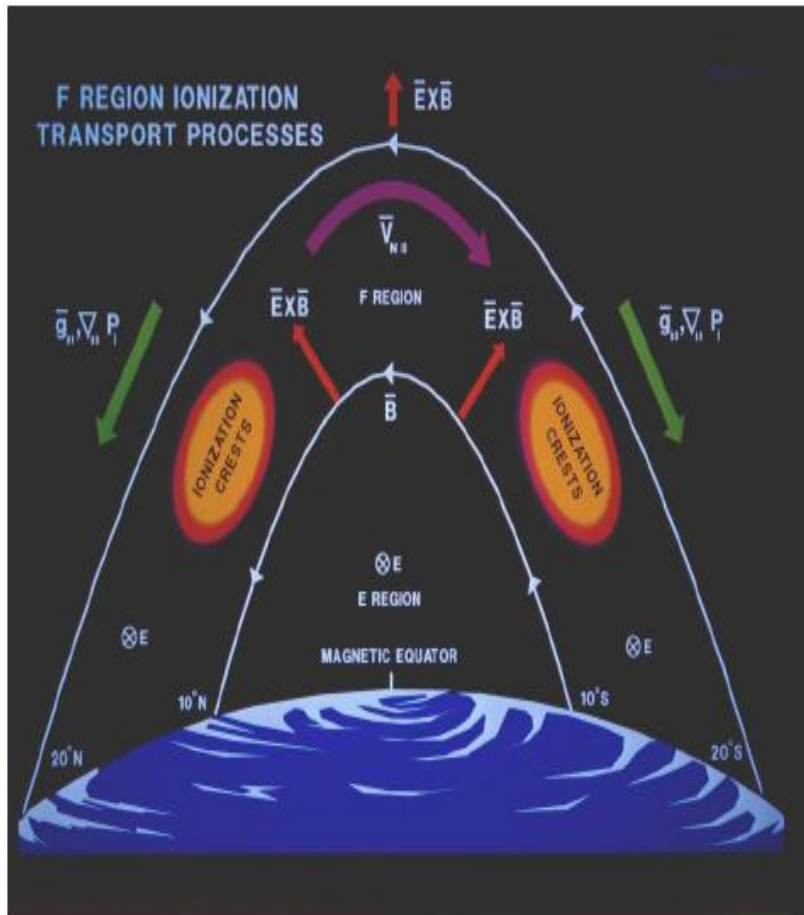


Nava,, et al., "Middle and low latitude ionosphere response to 2015 St. Patrick's Day geomagnetic storm", J. Geophys. Res. Space Physics,121, 3421–3438, doi:10.1002/ 2015JA022299.

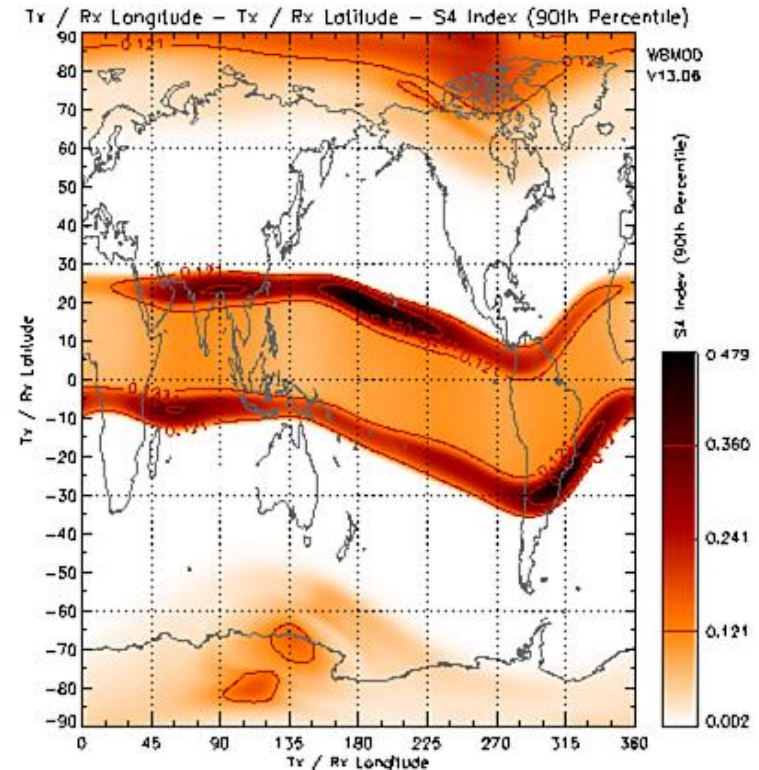
Scintillations a regular phenomenon

Ionospheric scintillation is the rapid modification of radio waves caused by small scale structures in the ionosphere

Physical Process : Instabilities in Plasma

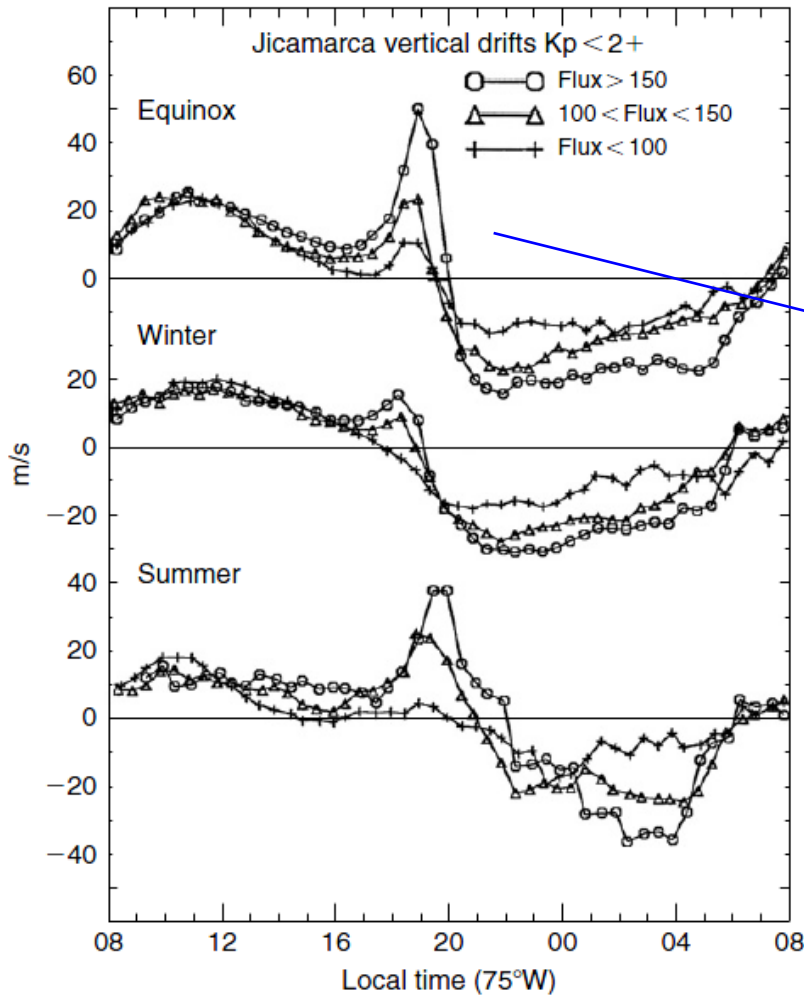


Equatorial Fountain

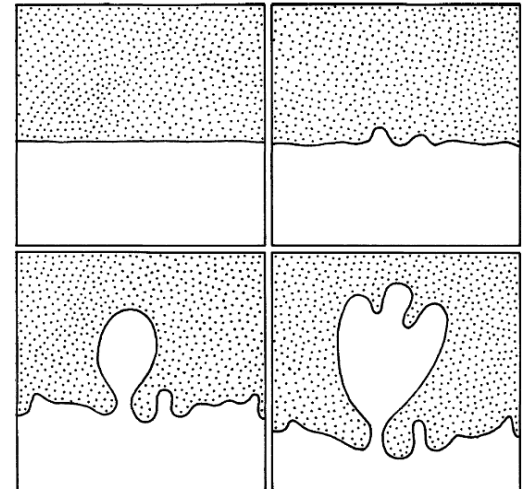


Scintillation index at GPS L1 (1575.42 MHz)
assuming constant local time 23.00 at all longitudes
(from <http://www.sws.bom.gov.au>)

PRE : Pre Reversal Enhancement



Equatorial Plasma Bubbles



Sequential diagram, from photos, of the development of a Rayleigh Taylor instability. The heaviest fluid [... ..], over a lighter and more transparent fluid
[Kelley, M.C., \(1989\), the Earth Ionosphere, ed. Academic Press, San Diego.](#)

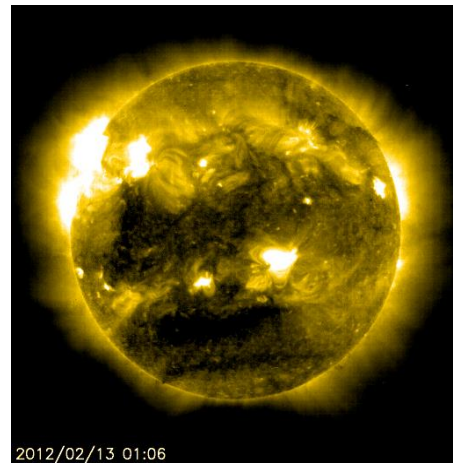
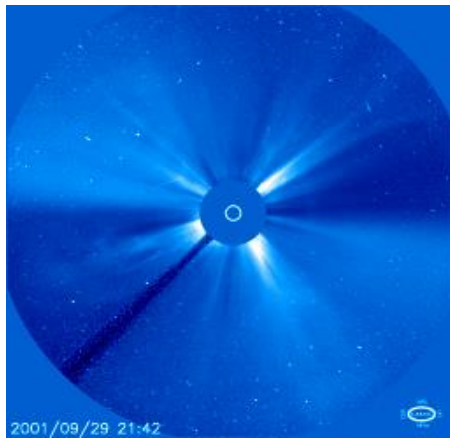
Average vertical plasma velocities at Jicamarca during the equinox (March-April, September-October), winter (May-August), summer (November-February) for 3 solar flux values

[Fejer, et al., Average vertical and zonal F region drifts over Jicamarca, Journal of Geophys. Res, Vol. 96, N° A8, page 13901-13906, 1991](#)

SUN EARTH CONNECTIONS

some solar perturbations inhibit or increase the irregularities and as consequence the scintillations

Effect of CME (and Magnetic cloud)
or Coronal Hole (High Speed Solar Wind HSSW)
2 cases of CME + HSSW (March and June 2015)



Kashcheyev et al., "Multi-variable comprehensive analysis of two great geomagnetic storms of 2015", *Journal of Geophysical Research: Space Physics*, 123.

<https://doi.org/10.1029/2017JA024900>

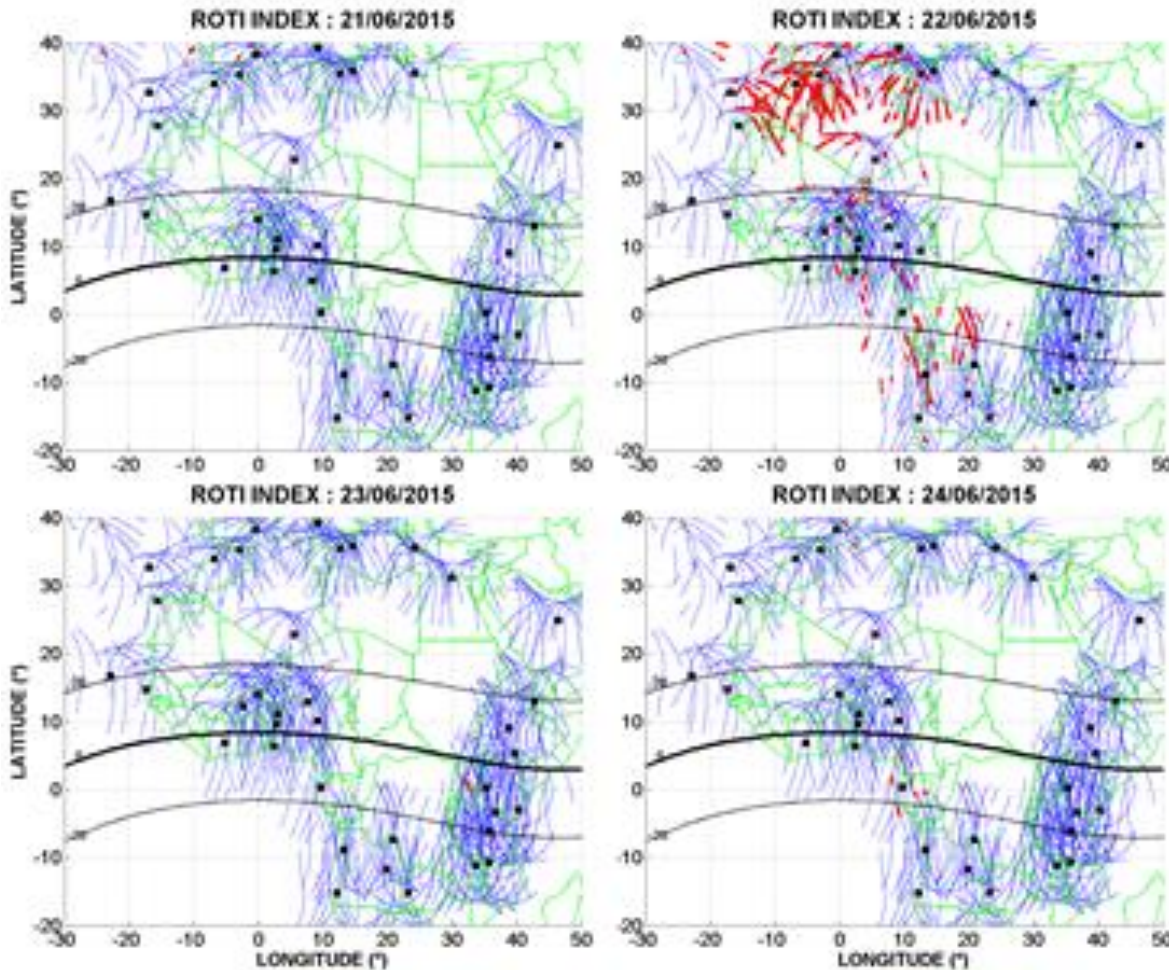
Storm June 22, 2015 solstice

$$\text{rot} = \frac{STEC_{k+1} - STEC_k}{time_{k+1} - time_k} * 60$$

Dst < -200 nT

Storm started at 18.33 UT

Increase of scintillations at
the beginning of the storm
Short duration



It is the effect of the penetration of the magnetospheric electric field (PPEF), just at the time of the Pre reversal enhancement of the Eastward ionospheric electric field

Storm March 17, 2015 equinox

$$\text{rot} = \frac{STEC_{k+1} - STEC_k}{time_{k+1} - time_k} * 60$$

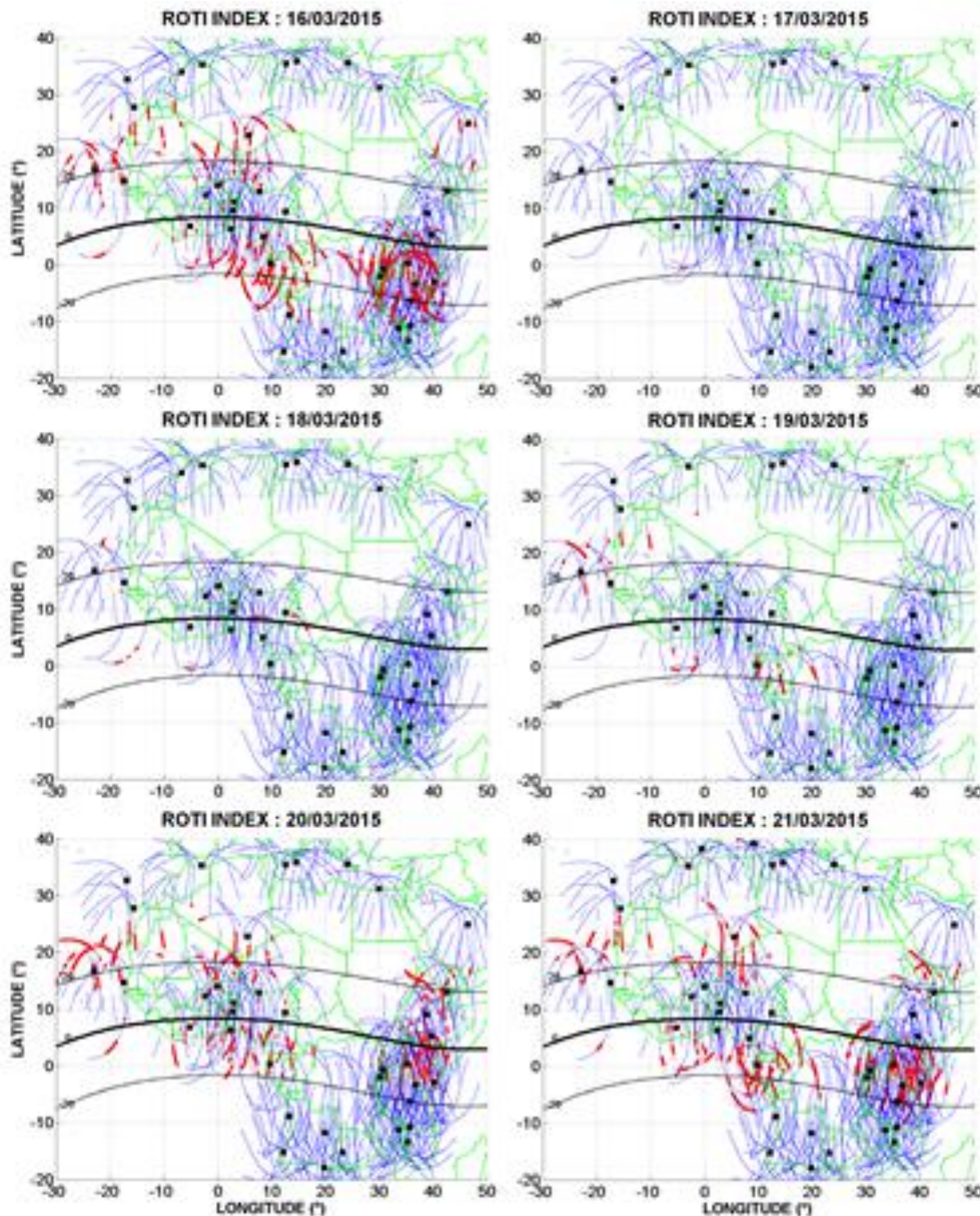
Dst < -200 nT

Storm started at 04.45 UT

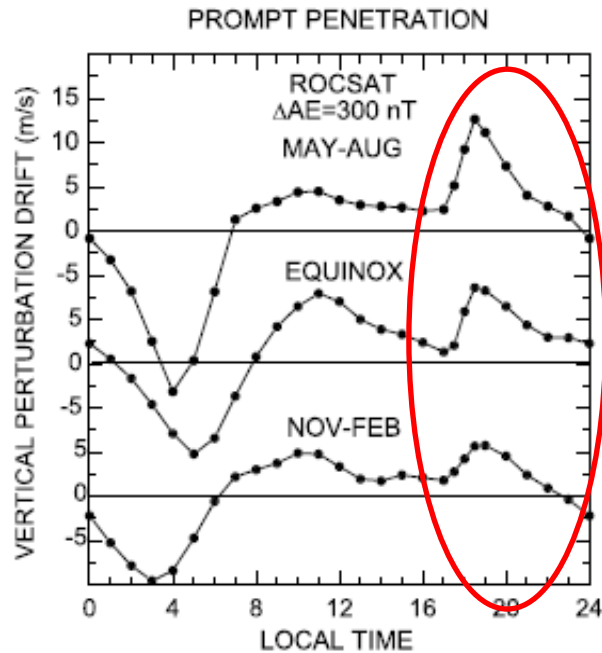
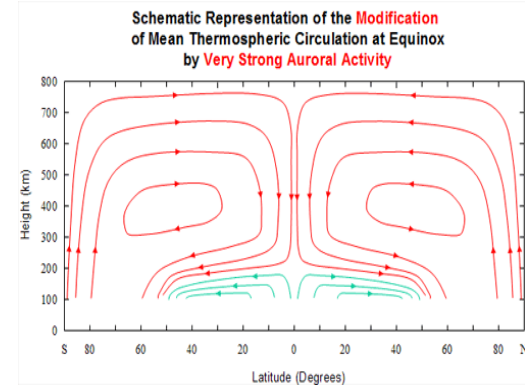
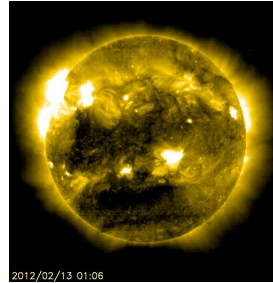
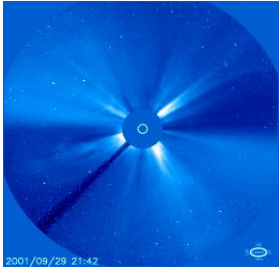
Inhibition of scintillations
over the whole earth during
several days du to the
disturbance dynamo (DDEF)
effect

long duration

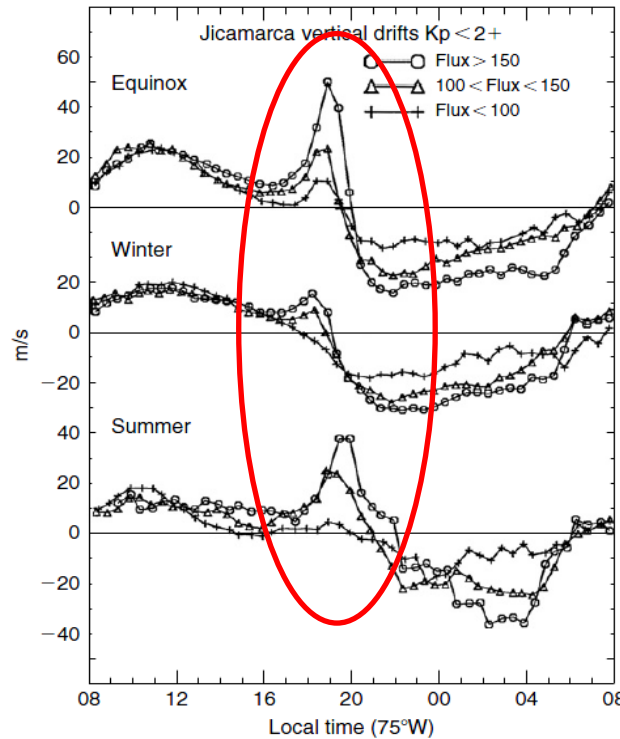
Kashcheyev, A et al., 2018



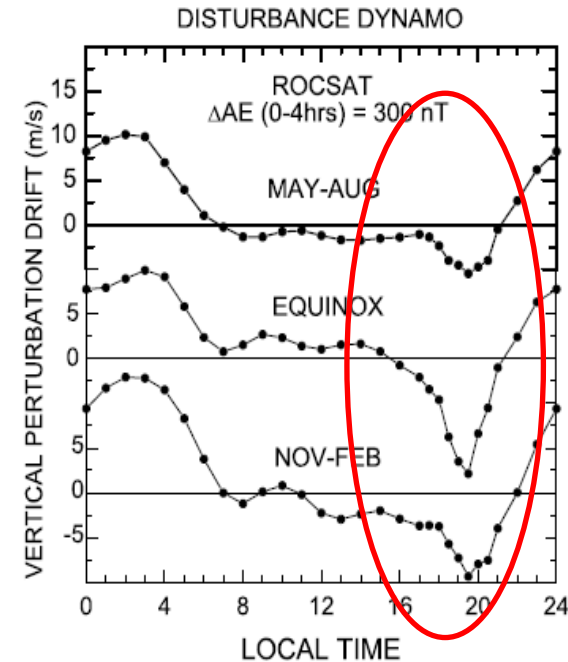
Fejer, B. G., Jensen, J. W., & Su, S.-Y. (2008). Seasonal and longitudinal dependence of equatorial disturbance vertical plasma drifts. *Geophysical Research Letters*, 35, L20106. <https://doi.org/10.1029/2008GL035584>



PPEF: disturbance



REGULAR



DDEF :disturbance

Conclusion

For the study of Sun-Earth connections you have to know:

- the state of the sun: calm or disturbed
- is there a disturbance of the sun ?
- what is this disturbance (radiation channel or particle channel)
- the state at Earth: level of the magnetic activity : calm or disturbed
- It is necessary to know the calm level of the ionosphere if you want to study the effect of a solar disturbance
- It is necessary to know the active processes in the ionosphere: regular physical processes or disturbed physical processes related to storm (thermal expansion of atmosphere, PPEF or DDEF)

For this you have to use

- Many data sets available on the web
 - satellite data for the sun, solar wind, magnetosphere and thermosphere,
 - GNSS data , ionosonde and radar data etc...
 - magnetic data
 - many magnetic or solar indices
 - Etc...