SUN EARTH CONNECTIONS

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Eastern Africa Global Navigation Satellite Systems and Space Weather Capacity Building Workshop
online from June 21 to June 25

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
  - Regular and irregular magnetic field variations (Sq/Sr, EEJ, crochet related to Solar Flare)
- Sun Earth connections : particle channel
  - Solar wind, Solar wind-magnetosphere Dynamo
  - Magnetic storms produced by solar disturbance
  - CME : coronal Mass Ejection – HSSW : High Speed Solar Wind
  - Electric currents and key roal of auroral zone
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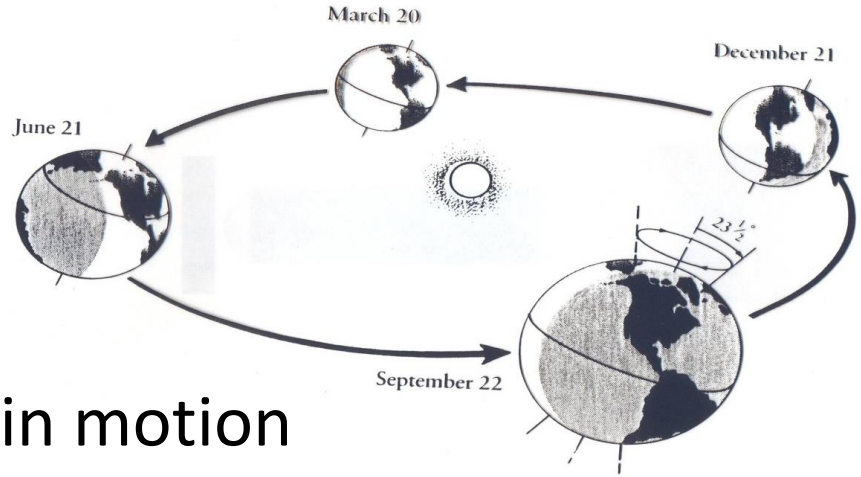
- Ionosphere : Electrodynamics coupling between high and low latitudes
  - Transmission of the magnetospheric electric field (PPEF)
  - Joule heating, thermal expansion of the atmosphere and disturbance Dynamo (DDEF)
  - Irregularities of equatorial plasma
- Conclusion

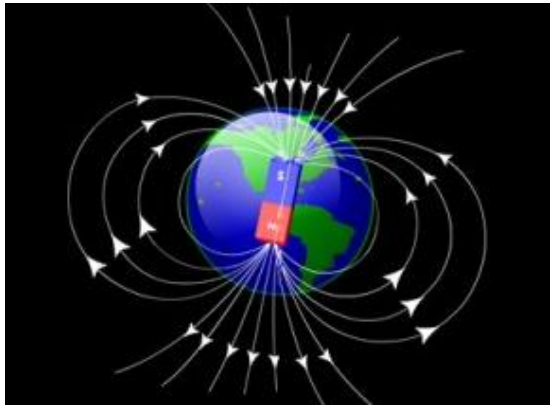
SUN EARTH CONNECTIONS : MOTIONS

The Sun : a magnetic body in motion

Variability ~ 27 days

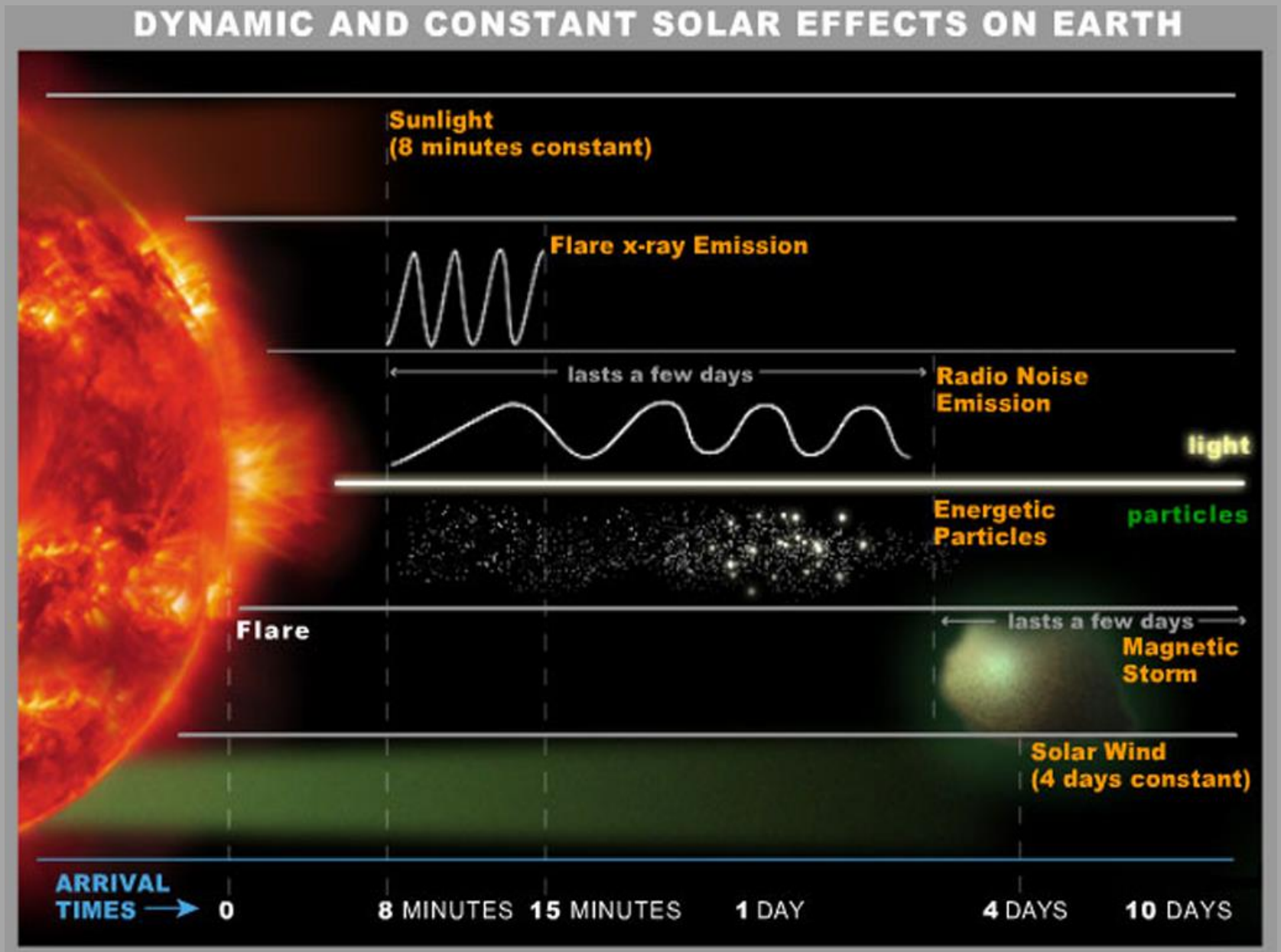


The Earth: a magnetic body in motion



Variability : diurnal , seasonal/annual

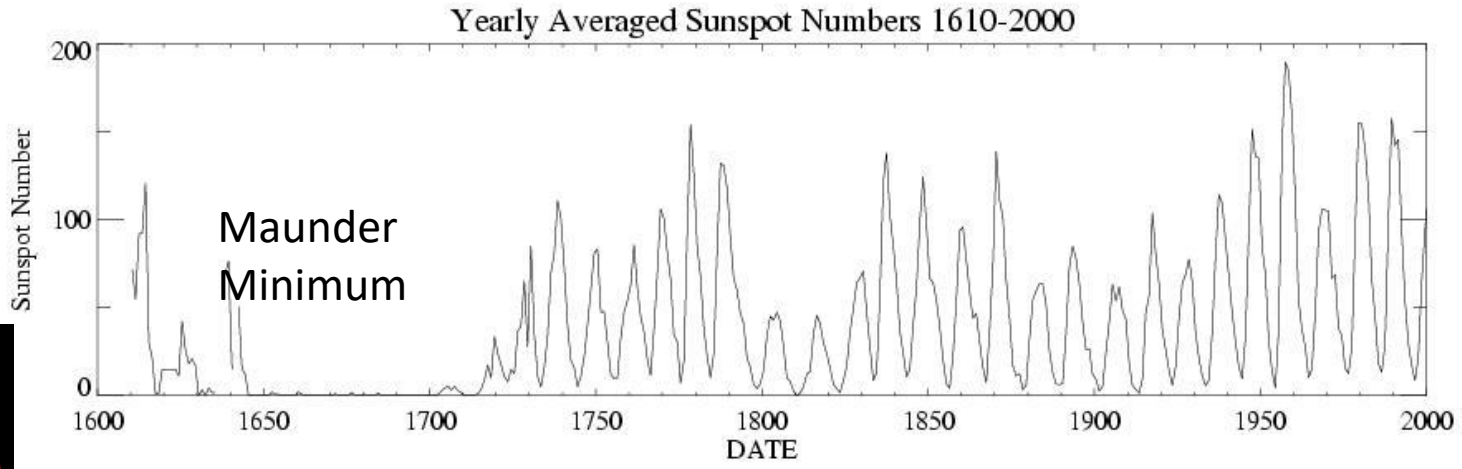
SUN EARTH CONNECTION : EMISSIONS FROM THE SUN

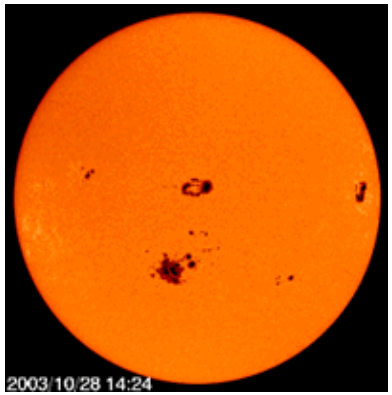


RADIATIONS PARTICLES

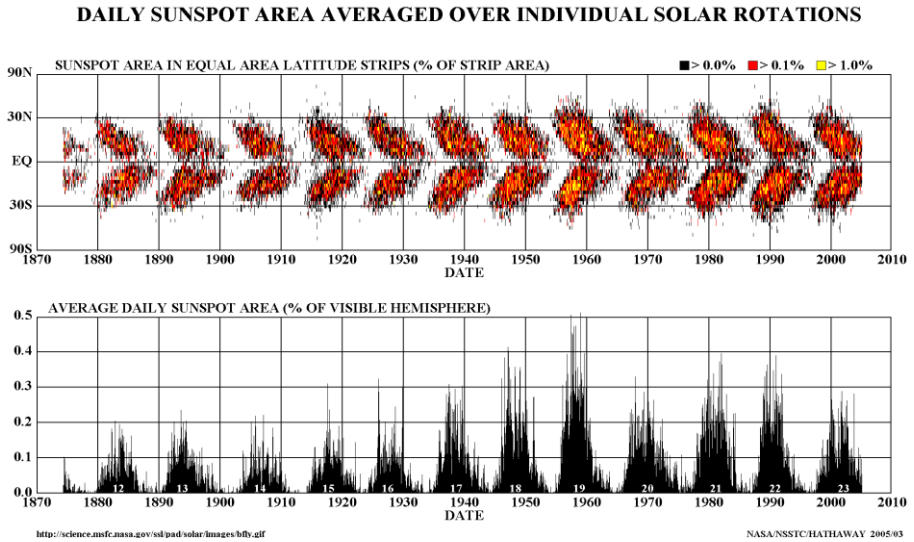
from Nasa website

SUN : THE SUNSPOT CYCLE





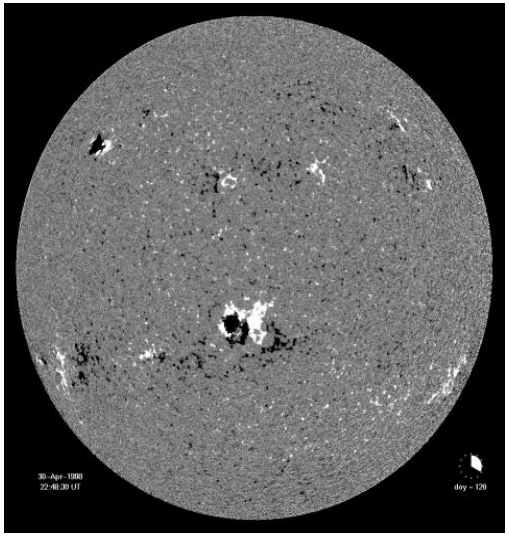
Sunspot Cycle of 11 years : Heinrich Schwabe 1859



Legrand et al. 1990
On Maunder minimum

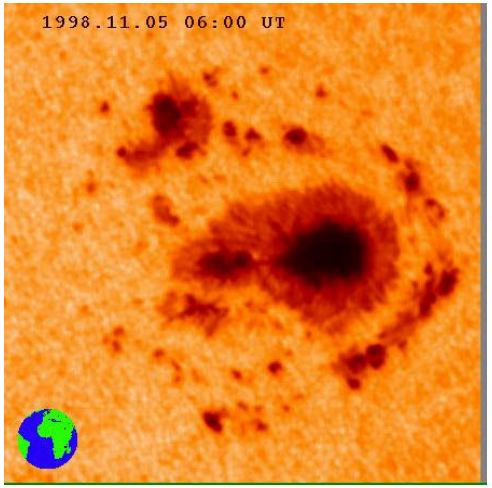
Legrand J.P., M. Le Goff, C. Mazaudier , On the climatic changes and the sunspot activity during the XVIIth century, Annales Geophysicae, 8 (10), 637-644,1990.

SUN : What is a sunspot ?



Magnetogram of the Sun

SOHO satellite data



Poloïdal component

~ 10 G

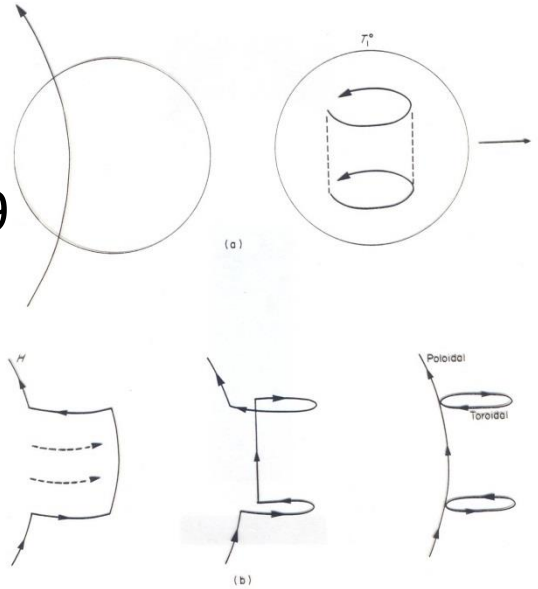
discovered by Hale 1919

Toroïdal component

Sunspot

~ 3-5 kG

Figure from Friedman, 1987



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).

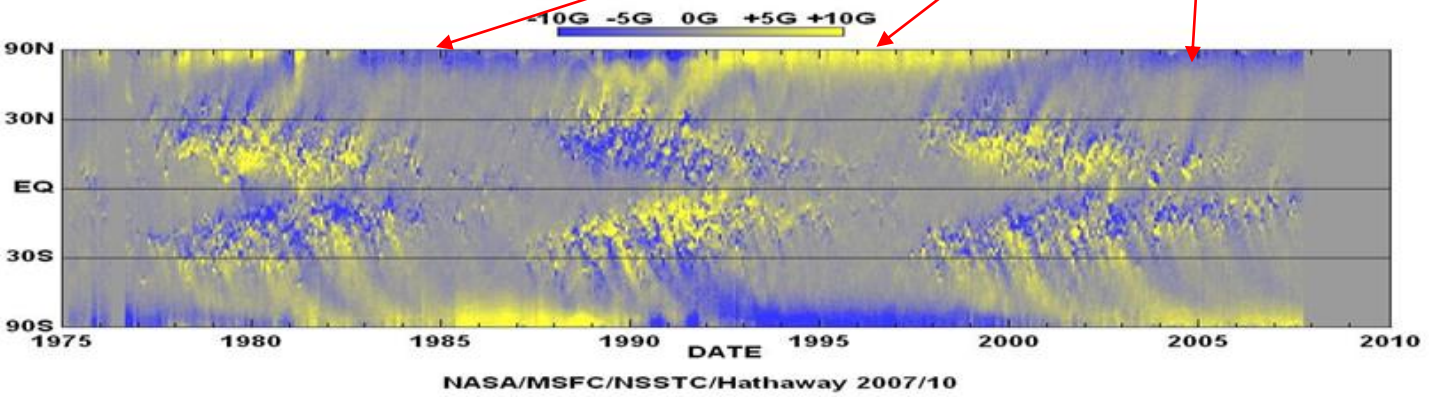
***This differential rotation twists the lines of the poloïdal magnetic field and generates magnetic loops called sunspots

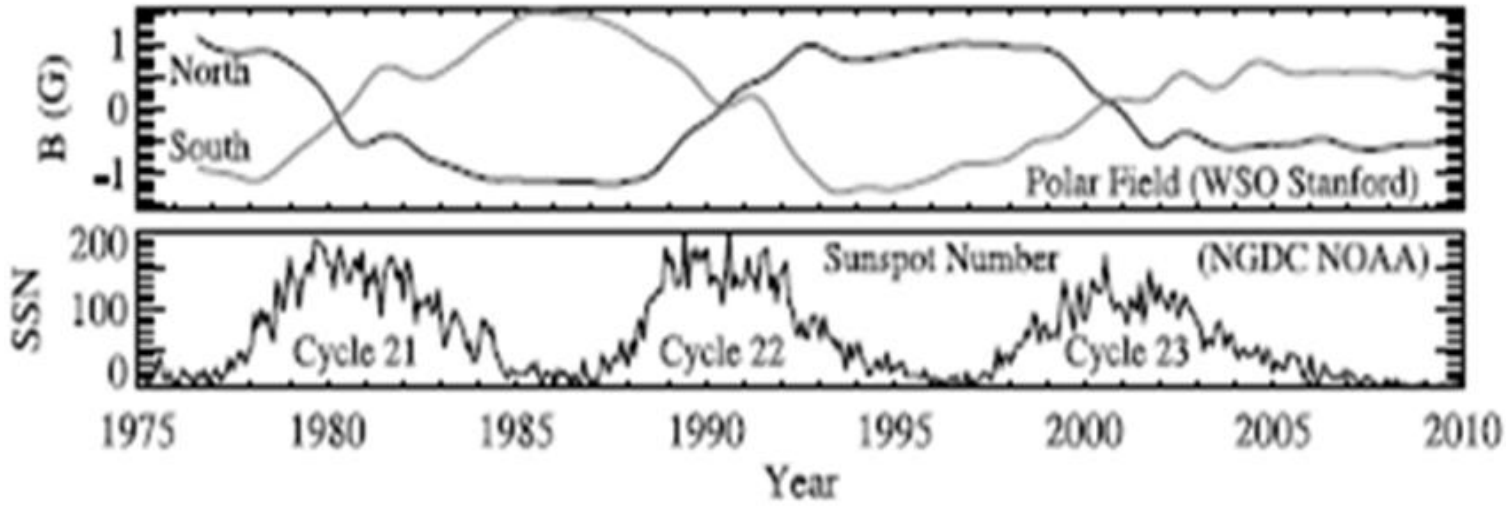
Solar Dynamo : the true solar cycle by solar physicists

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





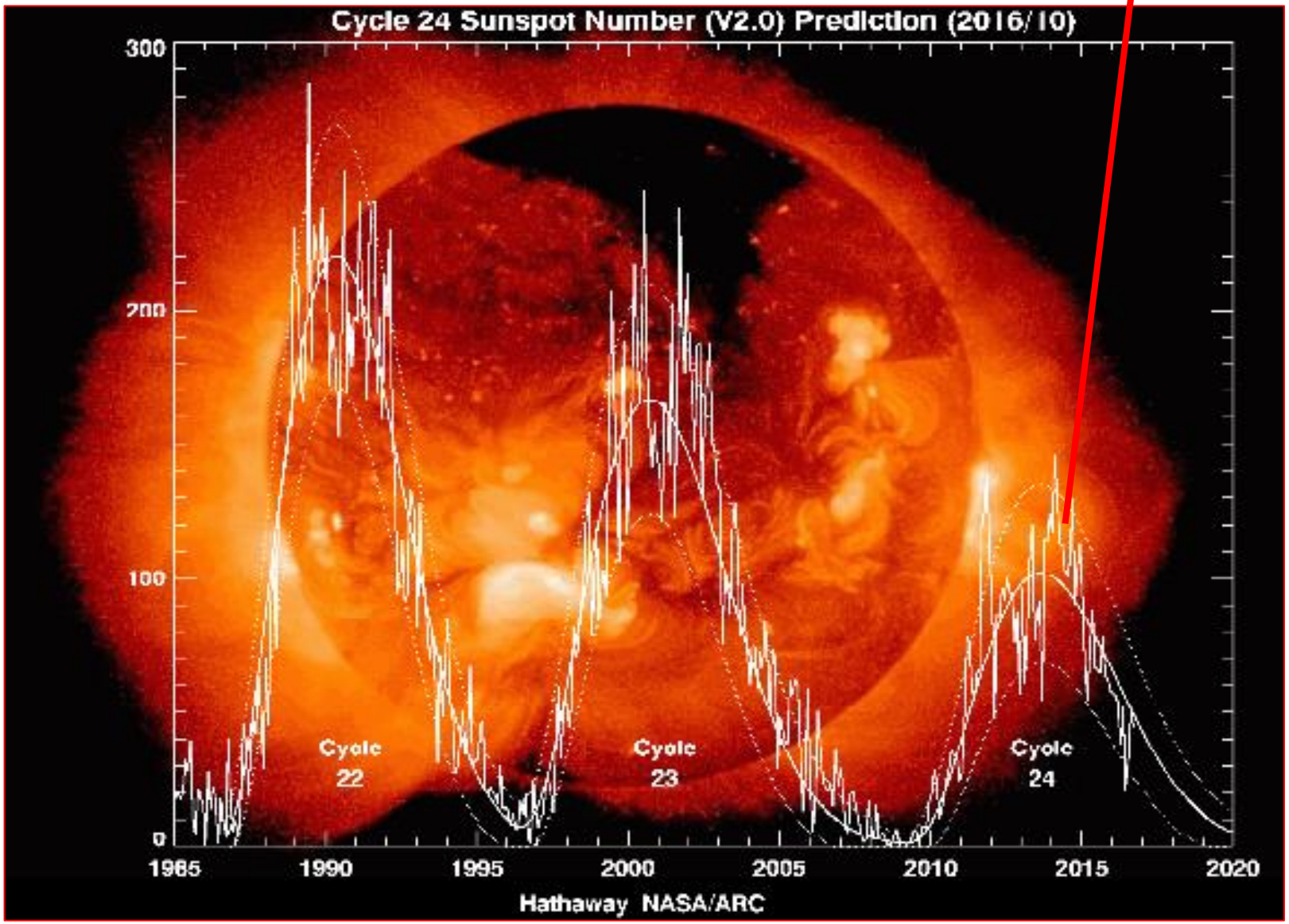
Variability ~ 11 and 22 years

Liu et al., 2011

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

Solar cycles 22-23-24

decrease of the sunspot due to the decrease of the poloidal component



smallest sunpot cycle since the Space era (1957)

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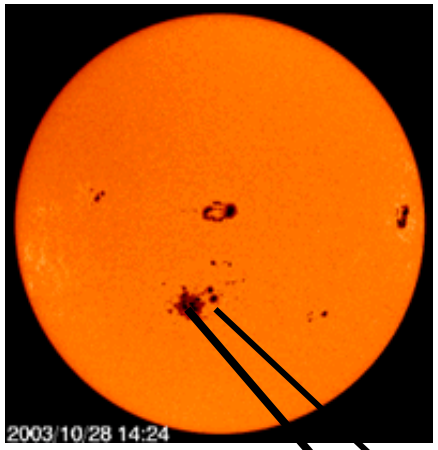
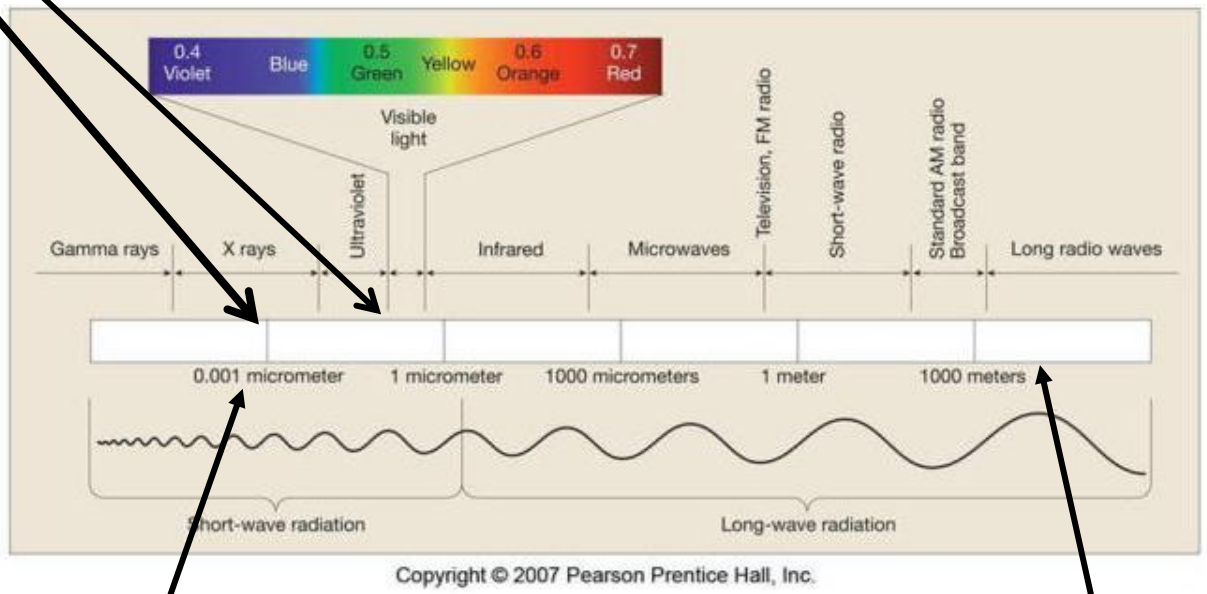


SUN : RADIATIONS Channel **(REGULAR)**
Speed of Light

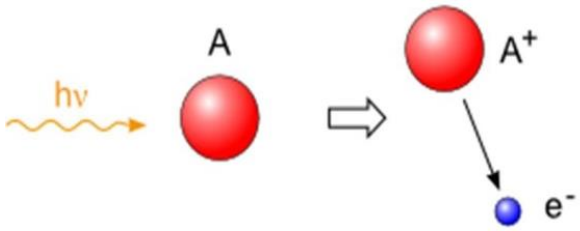
around sunspots => emissions of EUV, UV, X rays



SOLAR FLARE
Extra X rays

SOLAR BURST
Extra Radio waves

RADIATIONS Channel **(Disturbed)**

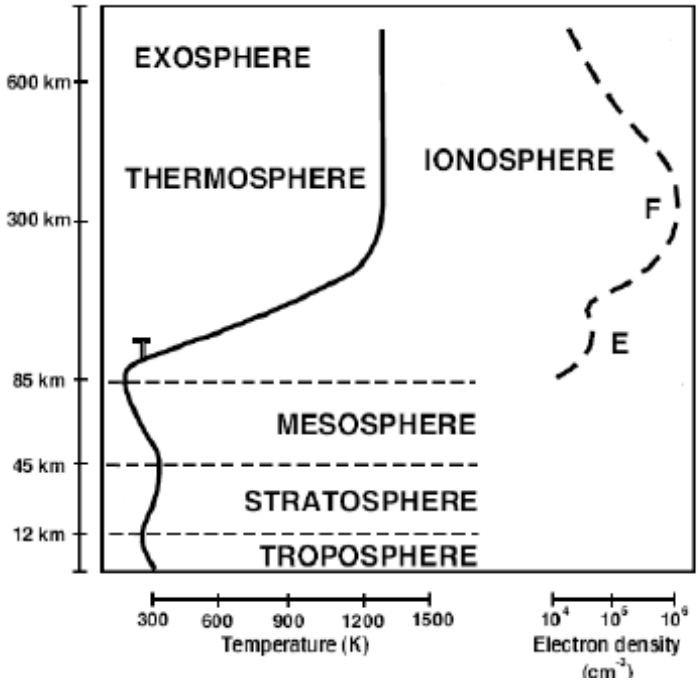


SUN EARTH CONNECTIONS

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



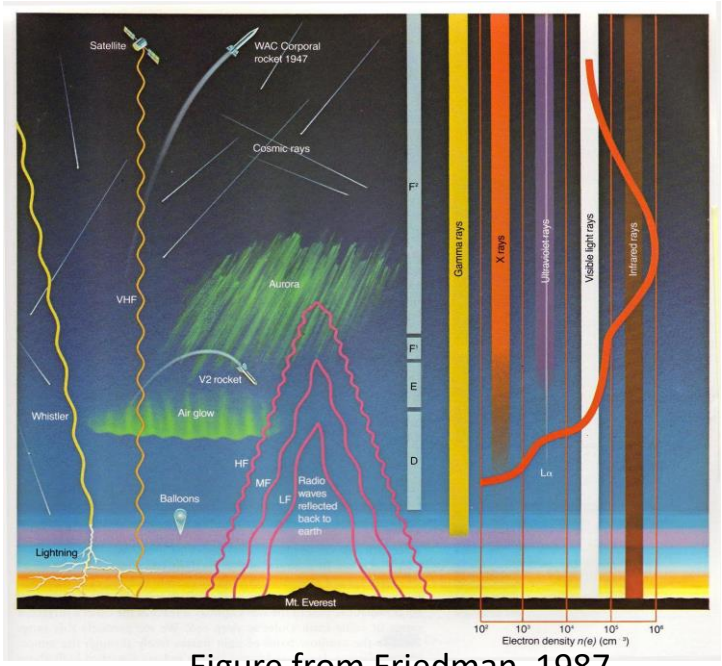


Figure from Friedman, 1987

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

1 atom among 1 000 000

BOOKS : Risbheth and Gariott, 1969

Friedman, 1987, Kelley ,2009

SUN EARTH CONNECTIONS : THE IONOSPHERE

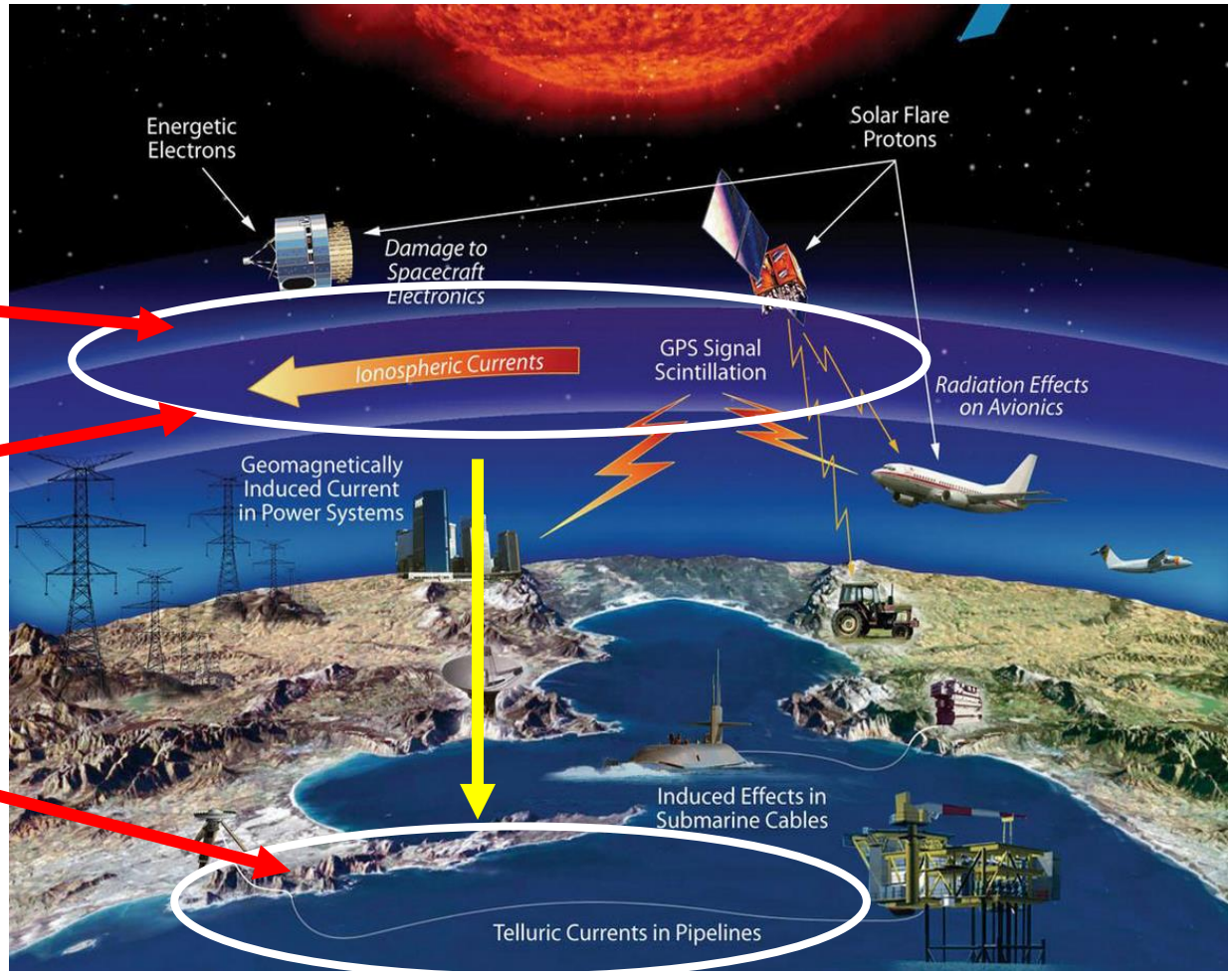
The ionosphere is a ionized layer around the Earth (from ~ 50 km up to 800 km).
Ionospheric electric currents are at the origin of variations of the Earth's magnetic field and Ground Induced Electric Currents (GIC)
The ionosphere is the largest source of perturbations for GNSS

Regular and irregular variations

1) Ionization

2) Ionospheric Electric current

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

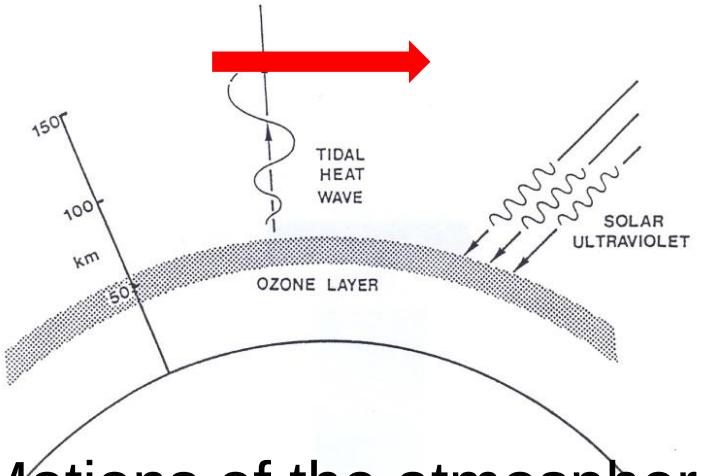


Nasa website

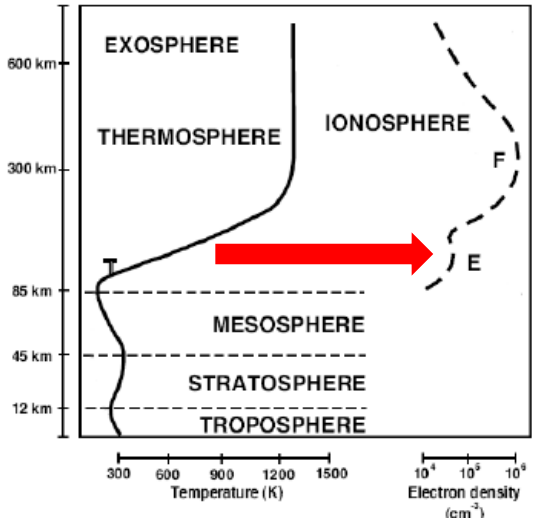
Ionosphere due to photoionisation => Earth's magnetic field

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

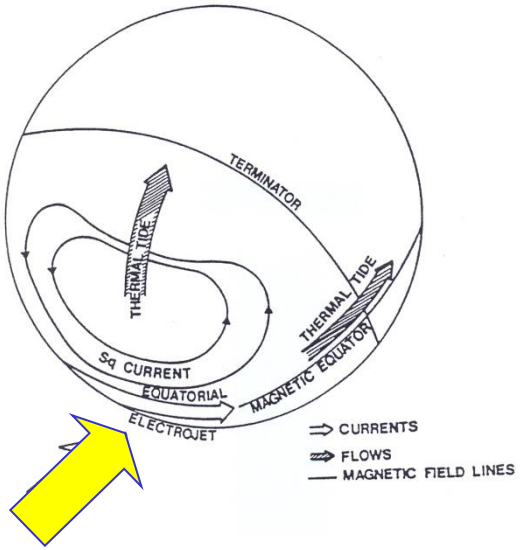
Ionospheric electric currents
90km<h<150km
J = Ne. e (Vi- Ve)



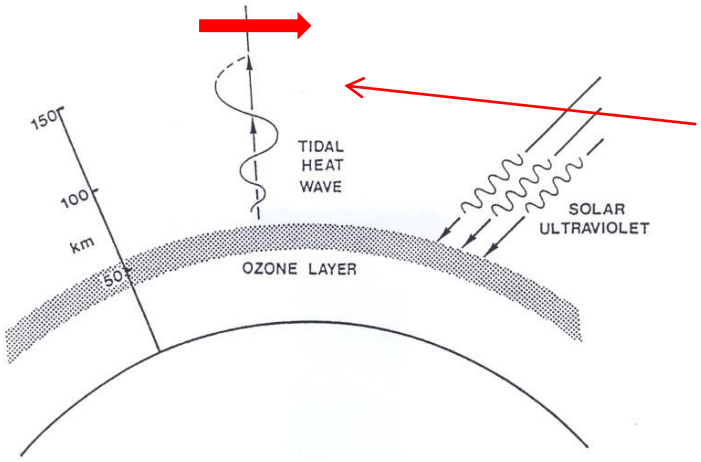
Motions of the atmosphere



Regular variations of the Earth's magnetic field

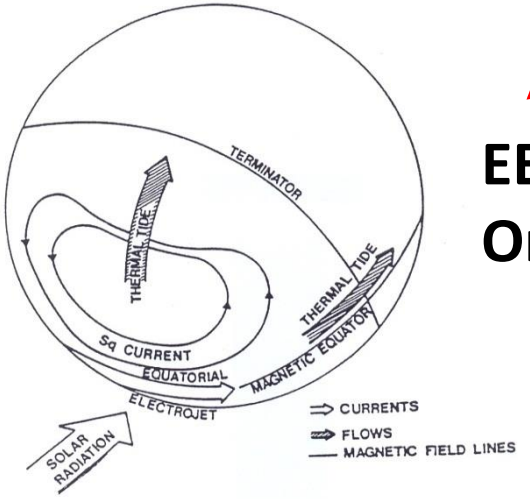


IONOSPHERIC DYNAMO / MOTION OF ATMOSPHERIC WINDS

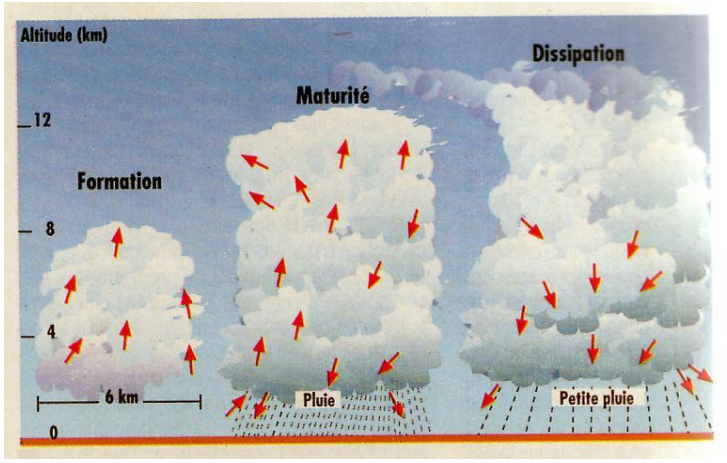


Stratosphere Atmospheric Tides , Evans 1978

Diurnal process
E Region of the Ionosphere
Electric currents system (90km< h< 150km)
Equivalent Electric currents from magnetic variations



EEJ-Sq/S_R
On the dayside

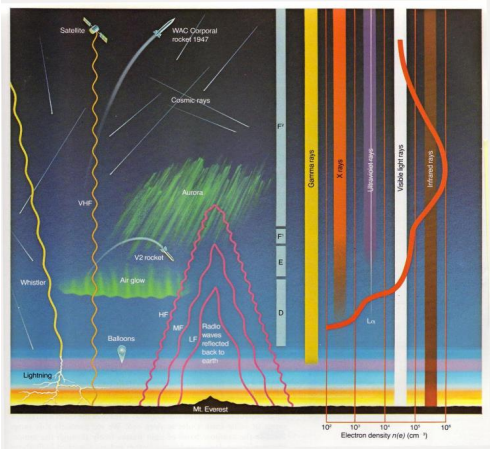


Deep convection in the troposphere
non migrating tides

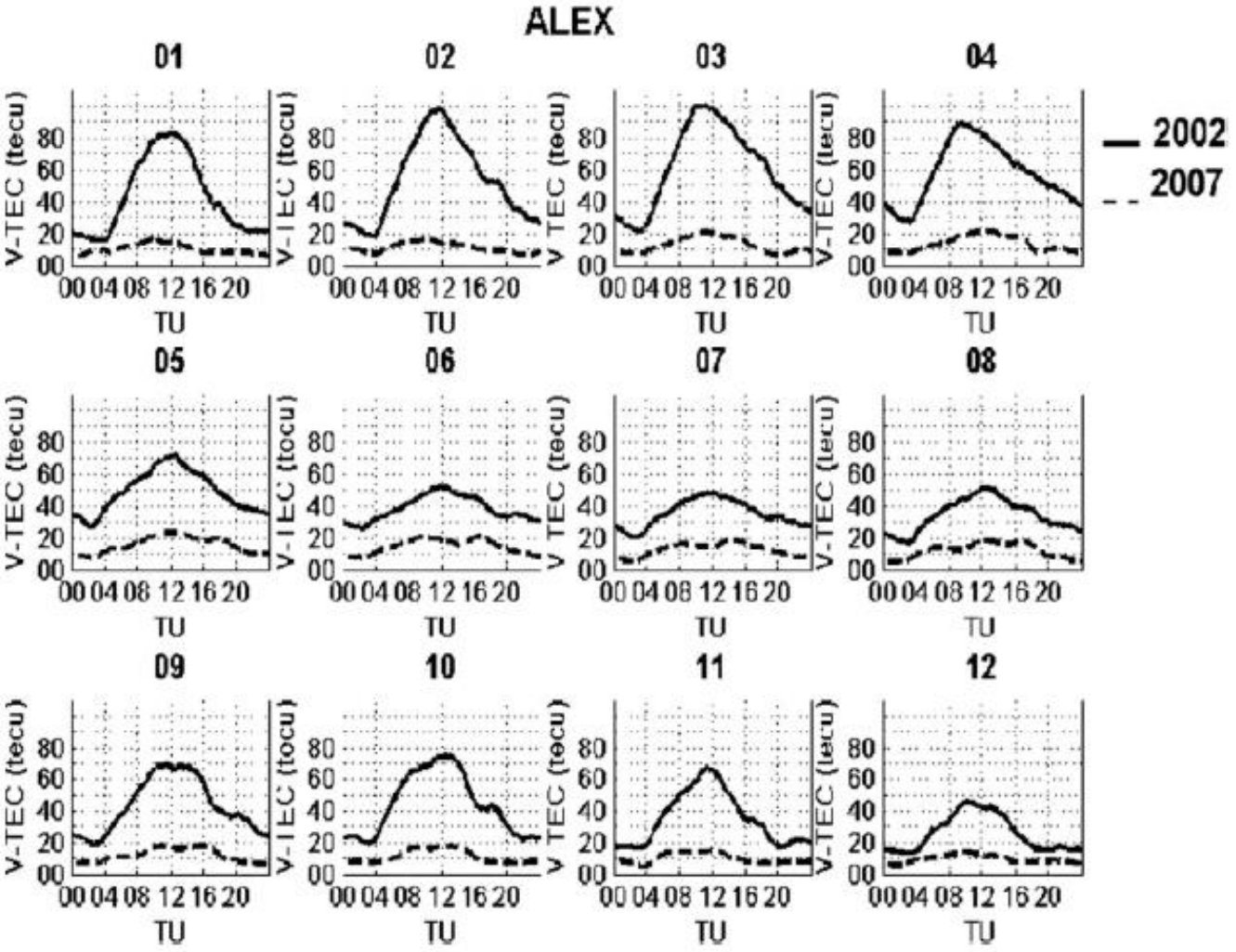
Vertical coupling
Stratosphere , troposphere
Atmospheric electricity
Earthquake
Etc…

Field to investigate

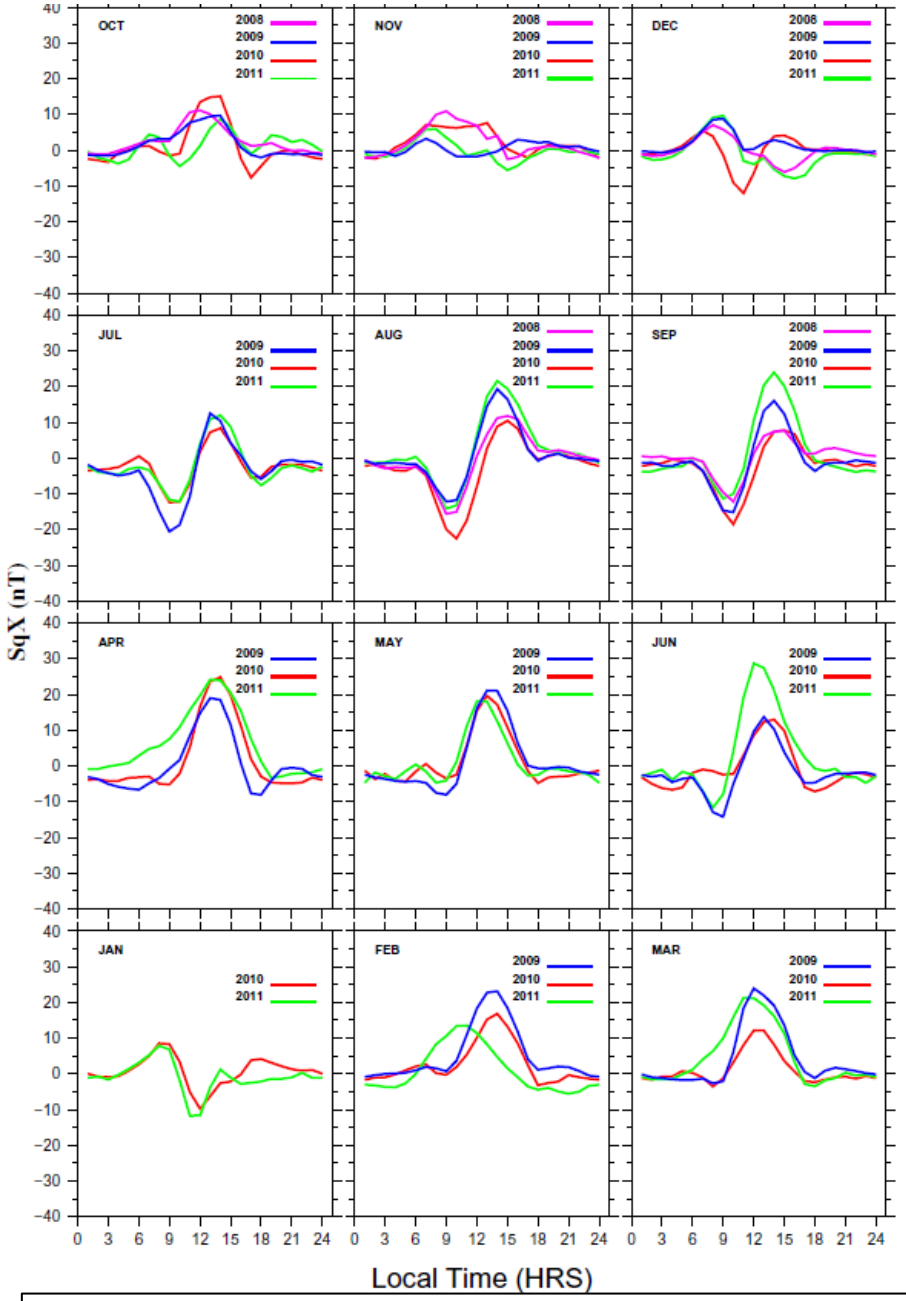
Diurnal variations of VTEC for 2 years 2002 and 2007
2002 : maximum of sunspot cycle 23, 2007 : minimum of sunspot cycle 23



Regular Solar Radiations
UV, EUV, X rays

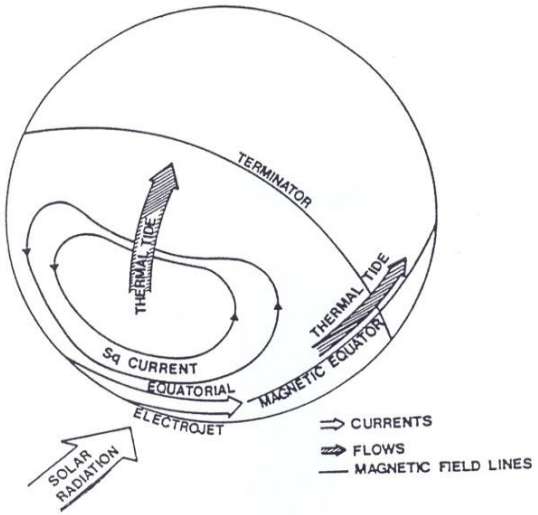


Shimeis, A., C. Amory-Mazaudier, R.Fleury ,A.M. Mahrous,A. F.Hassan, 2014, Transient Variations of Vertical Total Electron Content over Some African Stations from 2002 to 2012, Advances in Space Research 54, 2159-2171



Study of the Sq in Africa

MEDEA in ALGERIA,



Anad, F. et al. ,Sq solar variation at Médéa Observatory (Algeria), from 2008 to 2011, in Advances and Space Research, doi10.1026/j.asr. 2016.06029.

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.

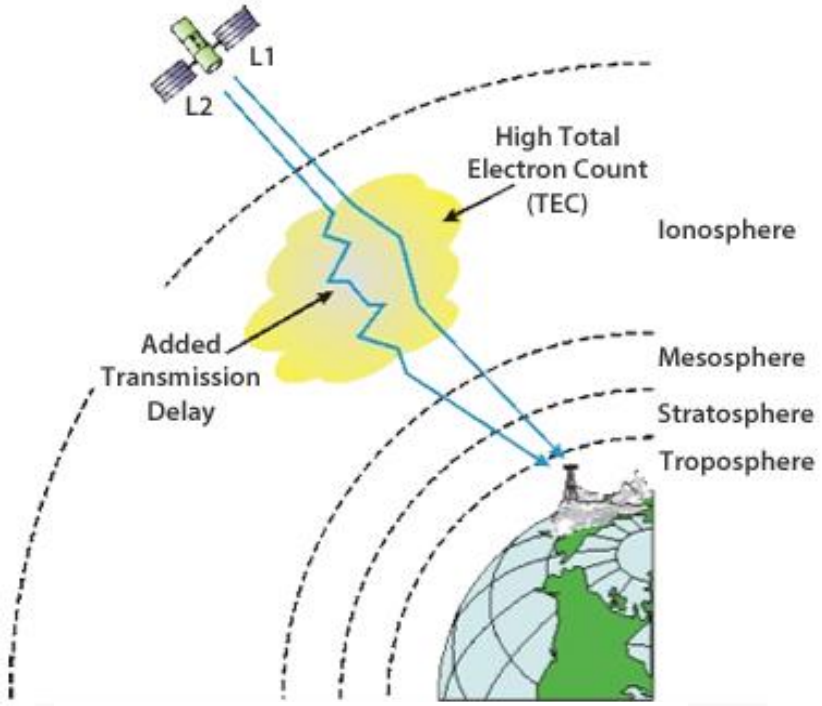
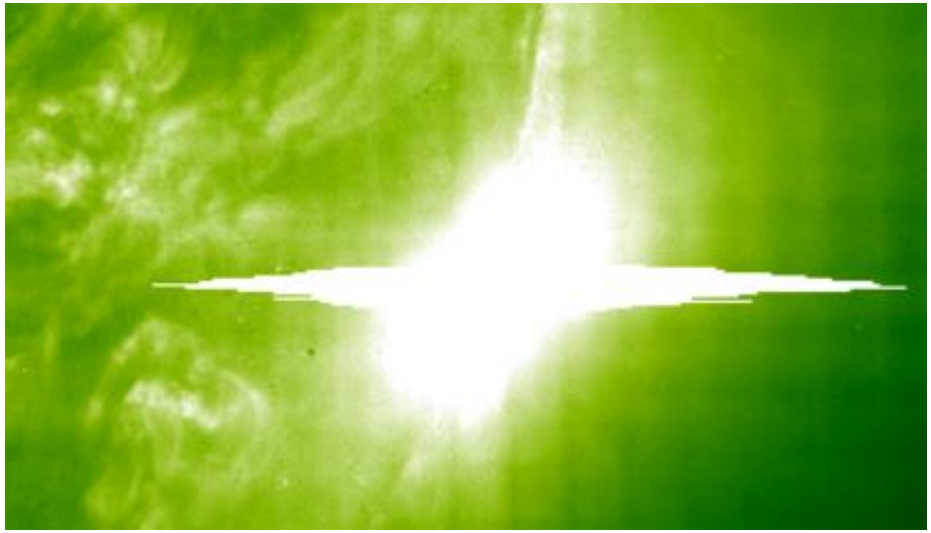
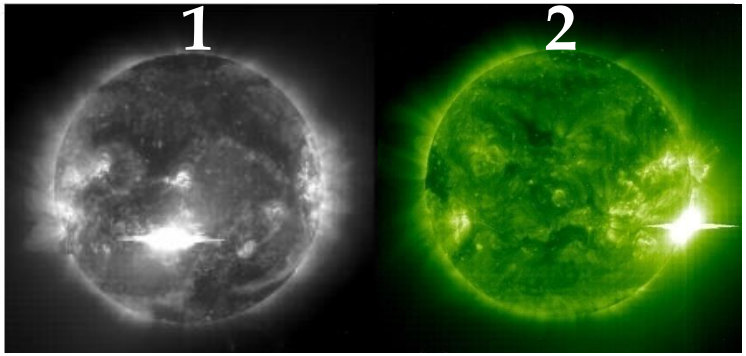


Figure from http://reflexions.ulg.ac.be

Big solar flare of November 2003



SOHO data

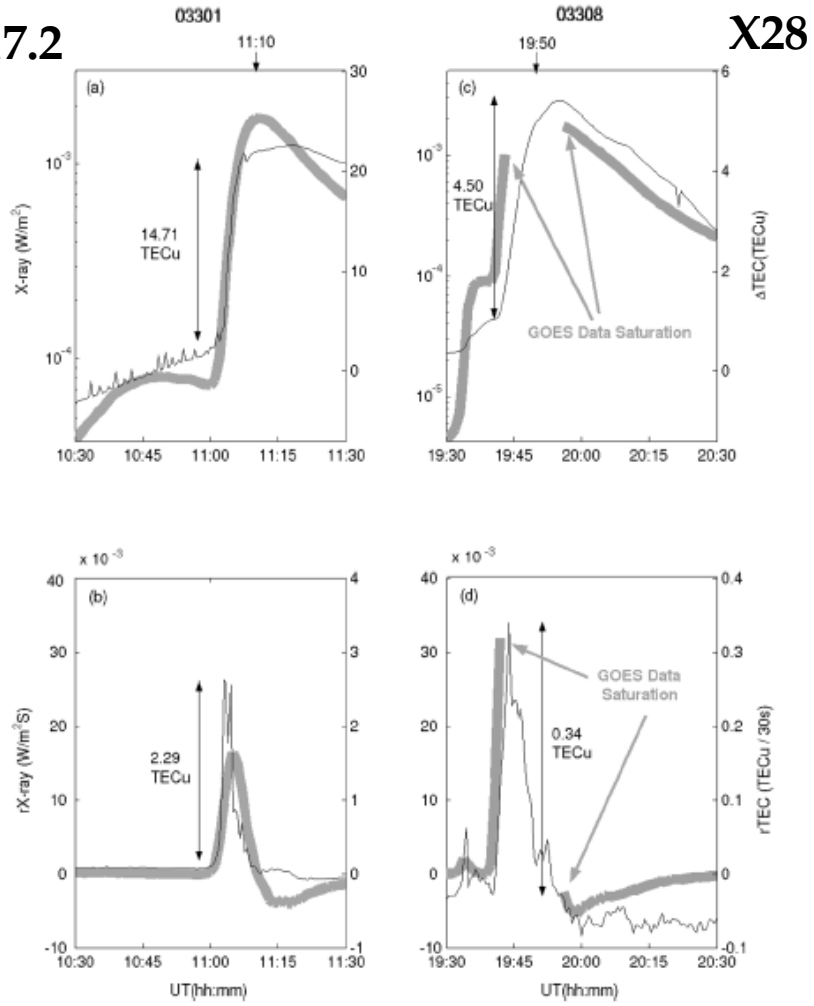


2003/10/28 : 11h12
2003/11/04 : 19h48
SOHO Extreme ultraviolet Imaging telescope (EIT) of the fourth largest (1) and the largest solar flare (2)

SOLAR FLARES AFFECT TEC

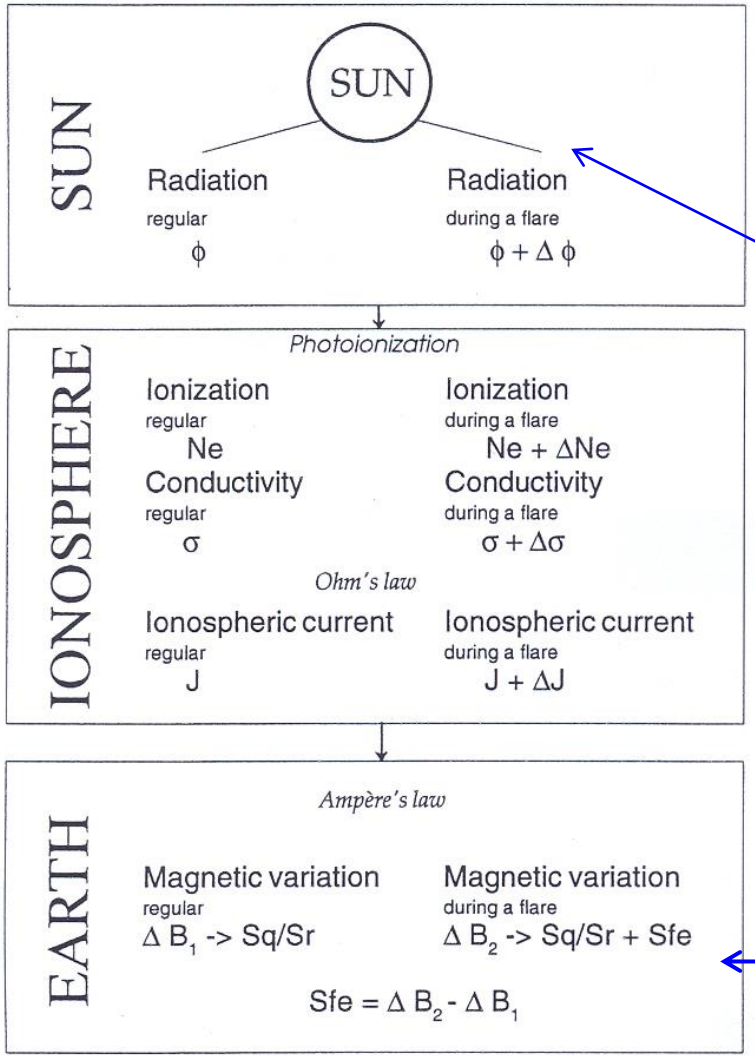
2003/10/28 : 11h12 **2003/11/04 : 19h48**

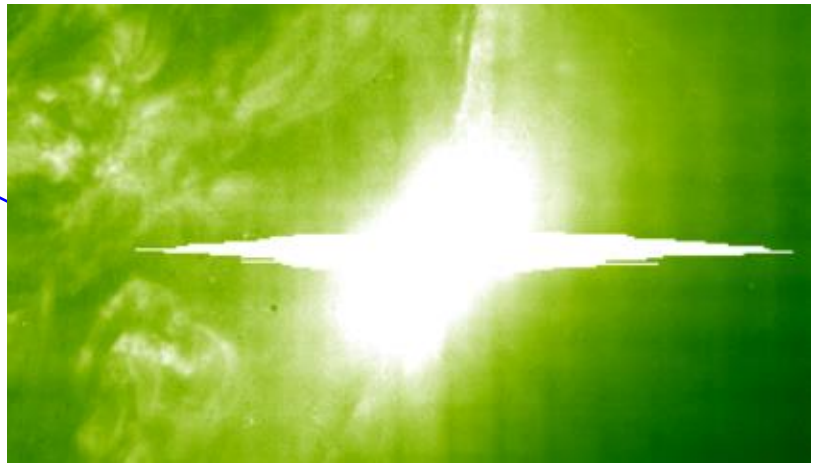
X17.2 **X28**



Liu et al, 2006, Solar flare signatures of the ionospheric GPS total electron content, JGR, vol 111, A05308

SUN EARTH CONNECTIONS : DISTURBED MAGNETIC VARIATIONS





Magnetic variation : crochet

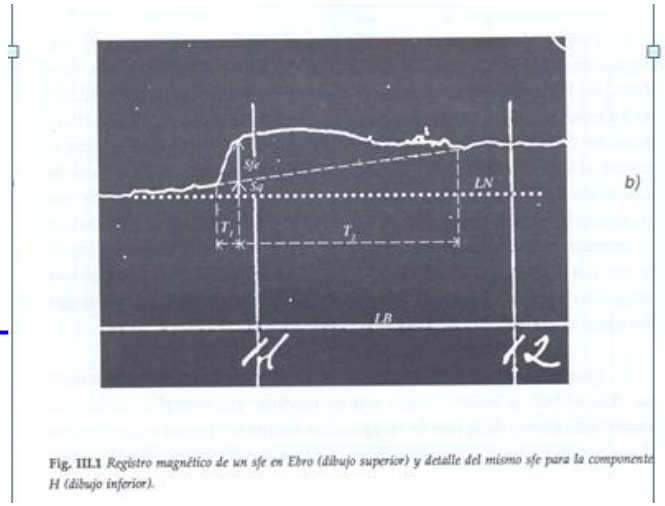


Fig. III.1 *Registro magnético de un sfe en Ebro (dibujo superior) y detalle del mismo sfe para la componente H (dibujo inferior).*

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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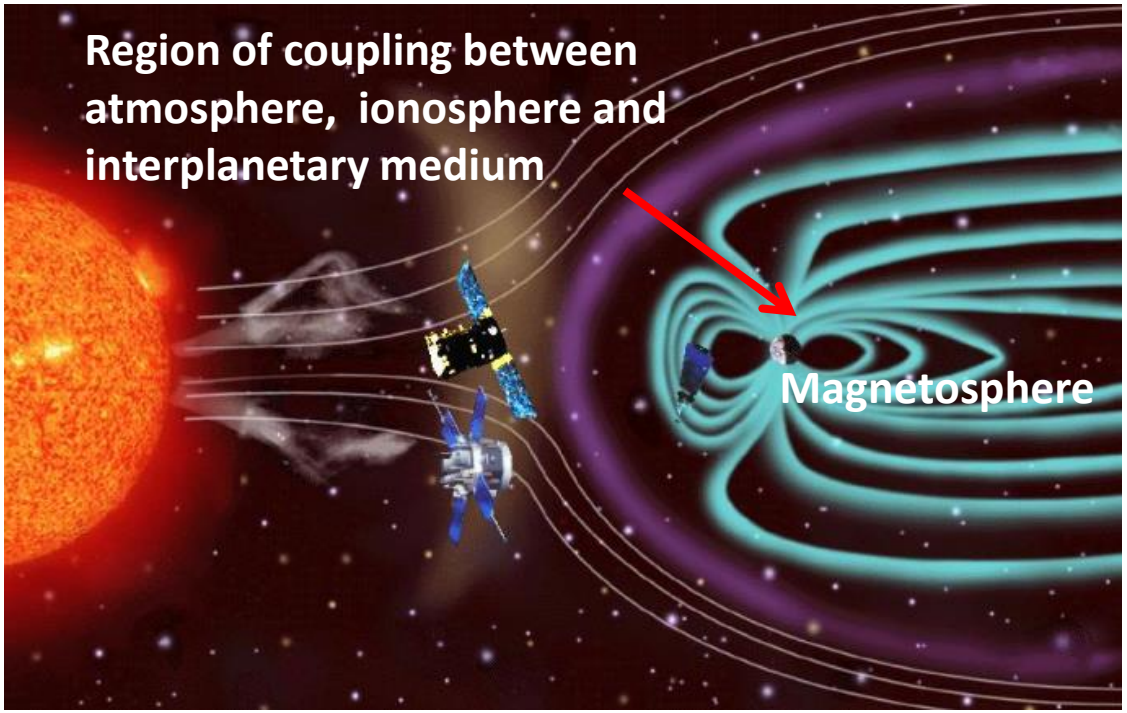
SUN EARTH CONNECTIONS : PARTICLES Channel :

Regular solar wind : V ~ 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

INTERACTION BETWEEN THE SOLAR WIND and THE MAGNETOSPHERE

Physical processes : Reconnection and Dynamo

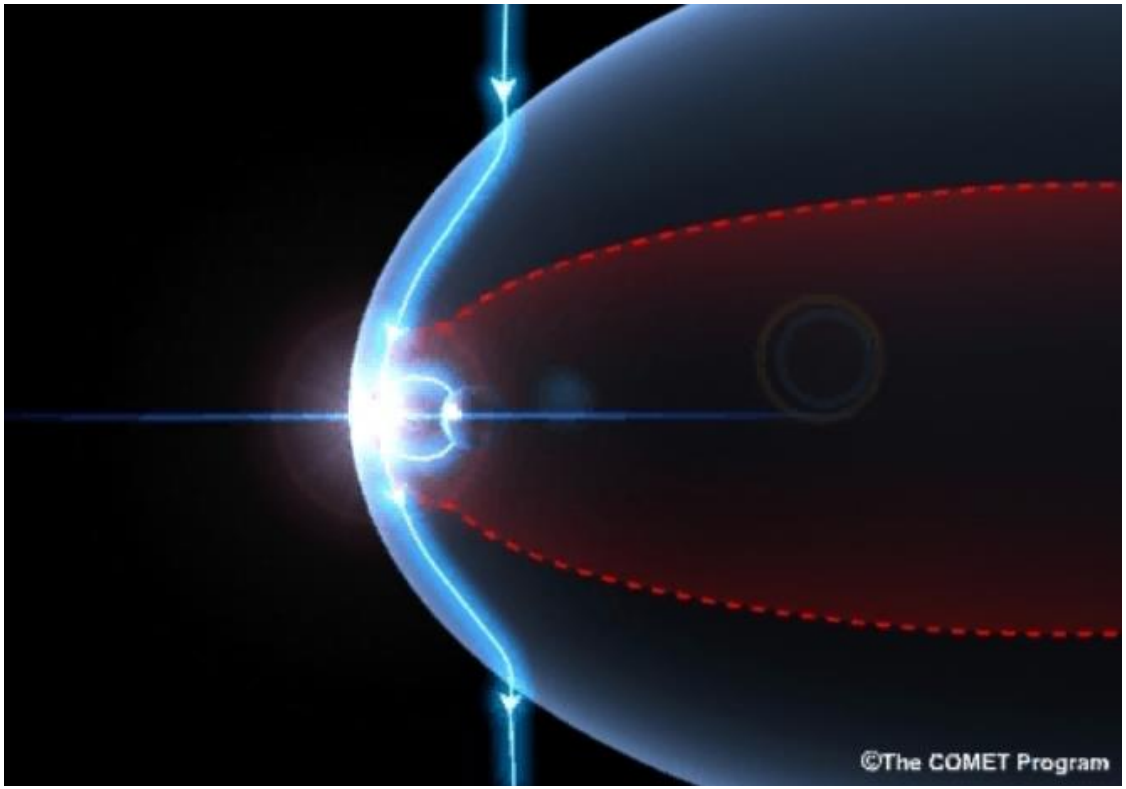
If the Interplanetary Magnetic Field , IMF field is opposite to the terrestrial magnetic field, i.e directed toward the South, there is reconnection between the IMF and the Earth's magnetic field and **there is a magnetic storm**

Key parameters for Space Weather

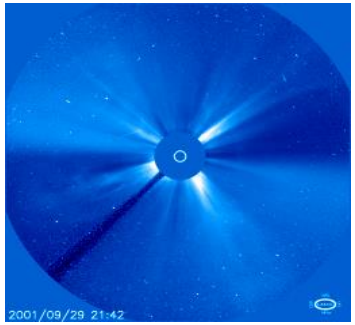
B_z IMF

Vs : solar wind speed

$E_y = - V_x . B_z$

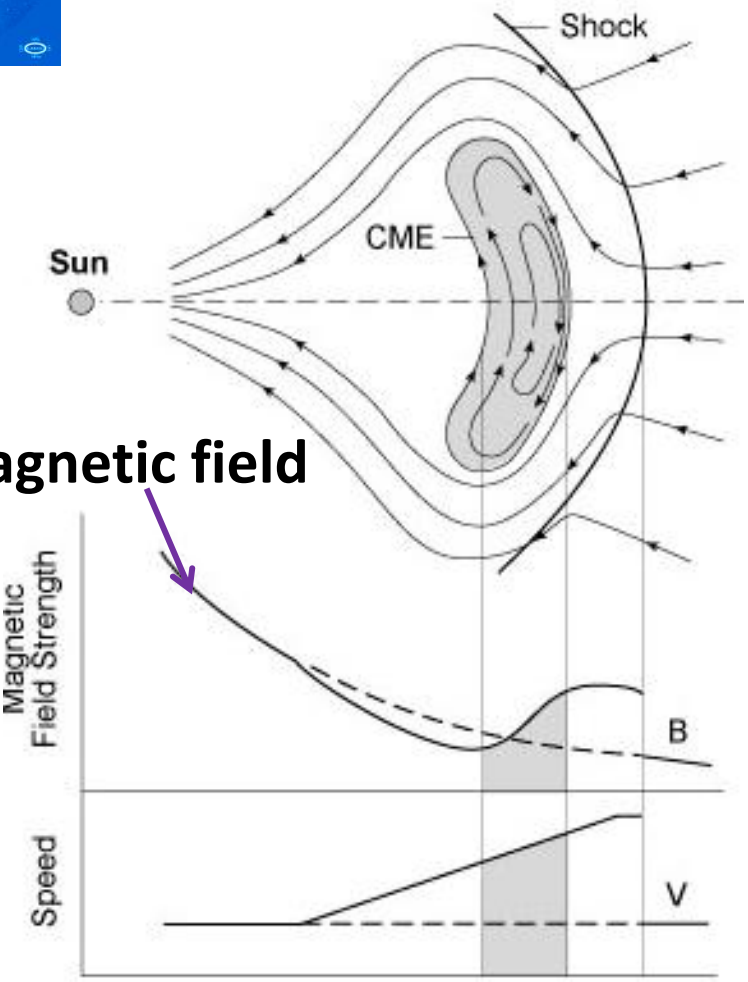


Solar wind – Magnetosphere Dynamo : E=VsxB movement is converted into electrical energy



Interplanetary CME Shocks

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



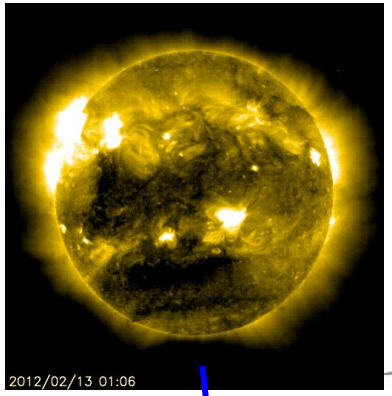
A fast coronal mass ejection CME pushes an interplanetary shock wave

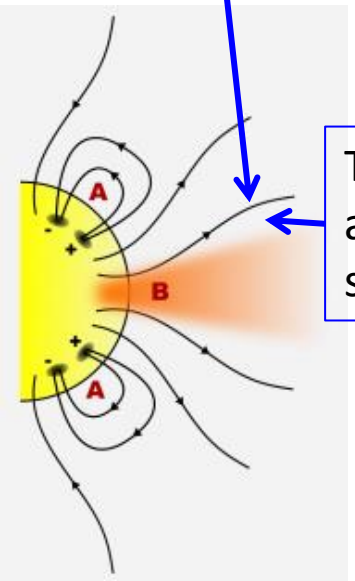
Strong magnetic field

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

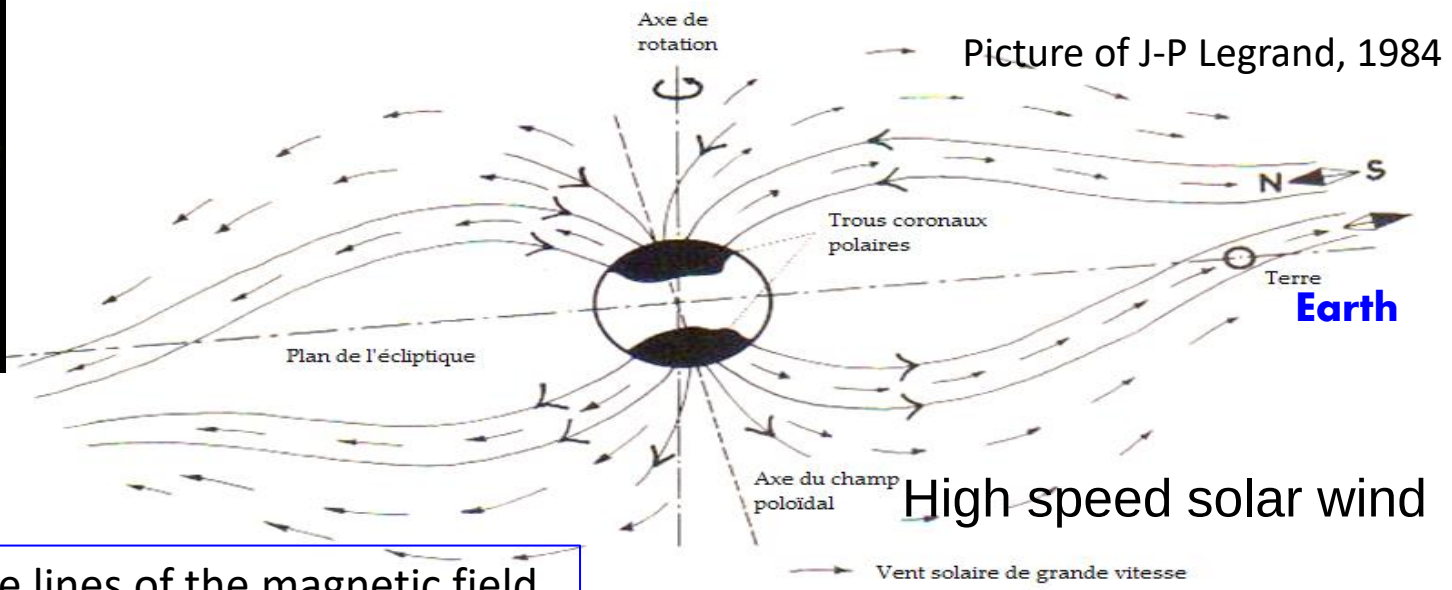
Maximum occurrence of CME during the maximum of the solar sunspot cycle

CORONAL HOLE – reccurrent geomagnetic activity



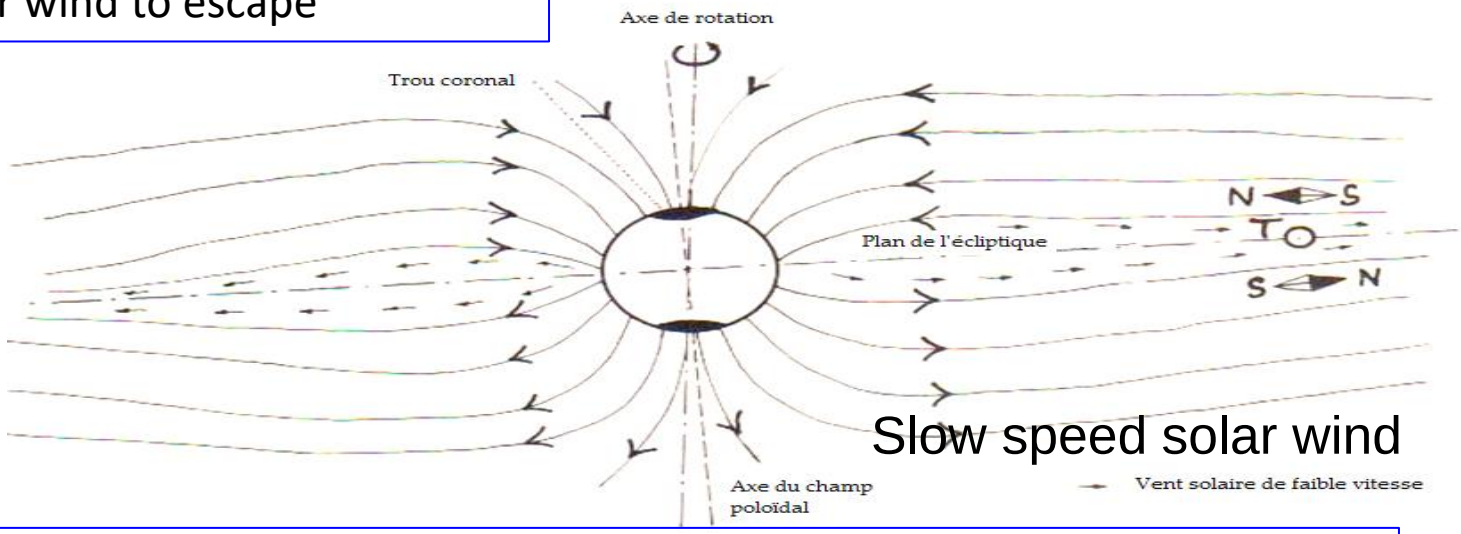


The lines of the magnetic field are open .This allows for the solar wind to escape



Picture of J-P Legrand, 1984

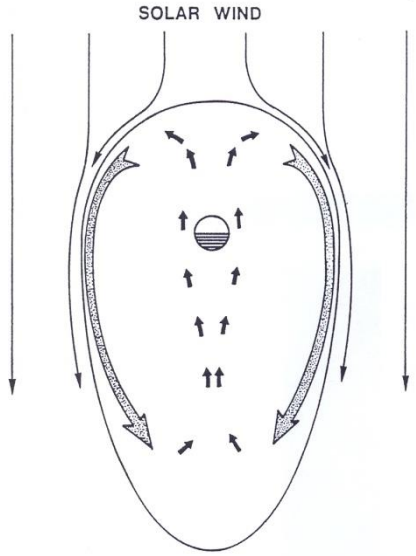
High speed solar wind



Slow speed solar wind

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

Dynamo solar wind /magnetosphere / Theory and Observations
Solar wind + interplanetary magnetic field



This process is based on a closed magnetosphere

<u>Viscous interaction between the solar wind and the magnetosphere</u> Axford and Hines, 1961

The interplanetary magnetic field is transmitted to the magnetosphere

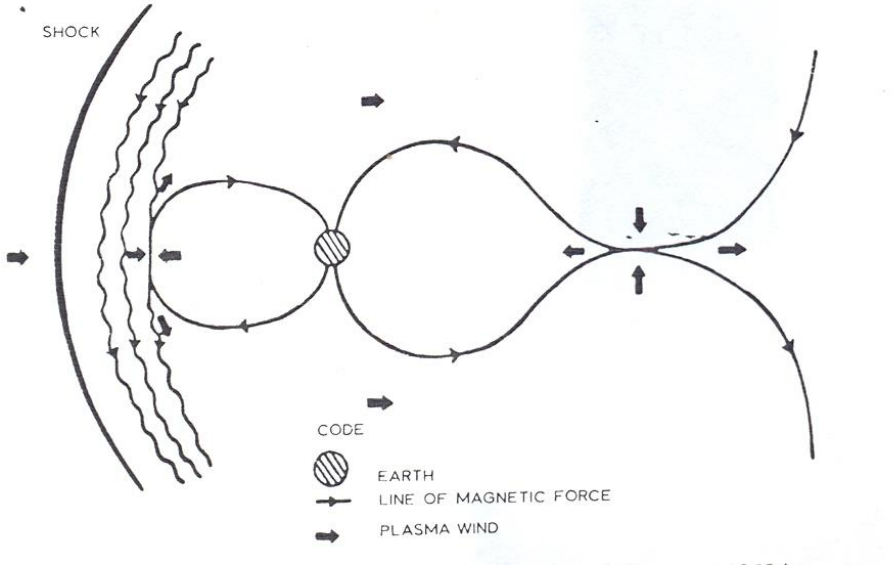
$E = -Vsx\ Bi \Rightarrow Ey = -VxBz$

<u>Reconnection Dungey 1961</u>

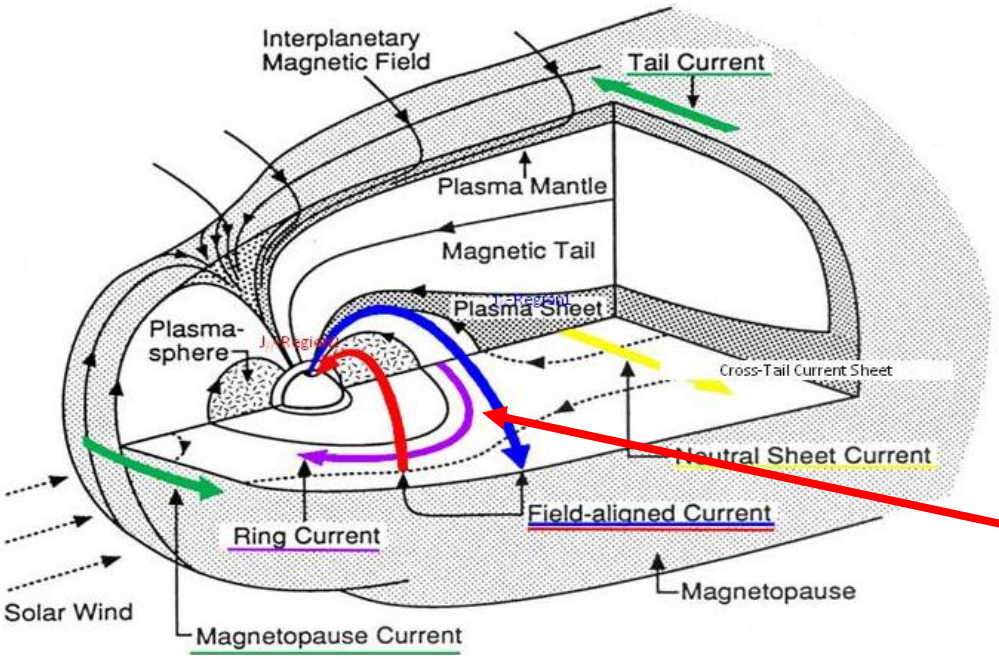
Connexion between the interplanetary and the earth magnetic fields

These 2 processes lead to motion of the particules inside the magnetosphere

Magnetospheric convection



SUN EARTH CONNECTIONS ELECTRIC CURRENTS



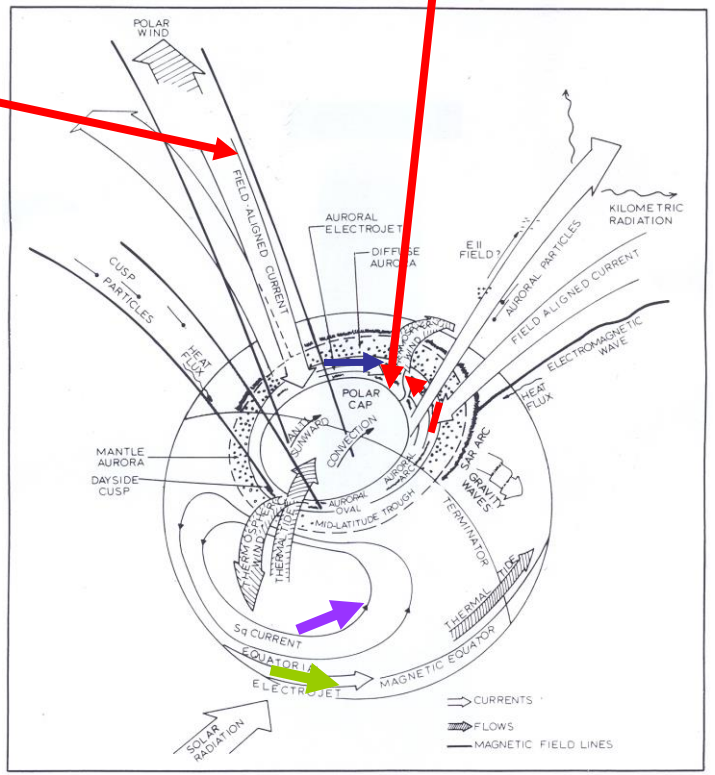
AURORAL ZONE

*Field aligned electric currents

*Precipitation

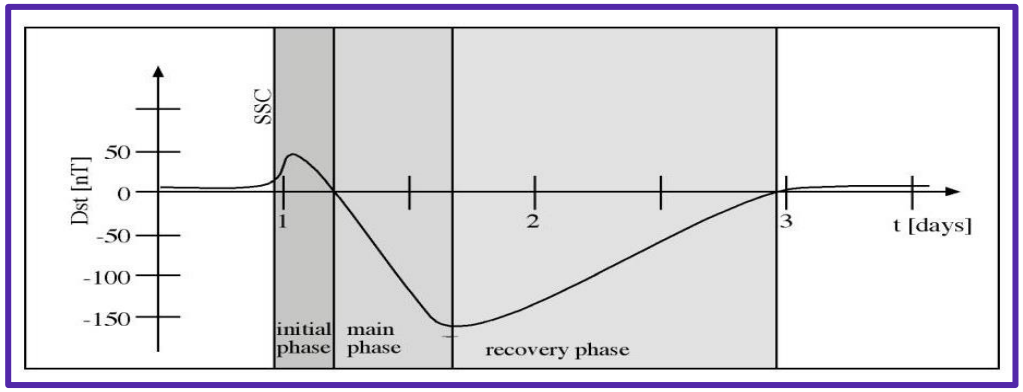
*Convection electric field

* Ionospheric electric currents



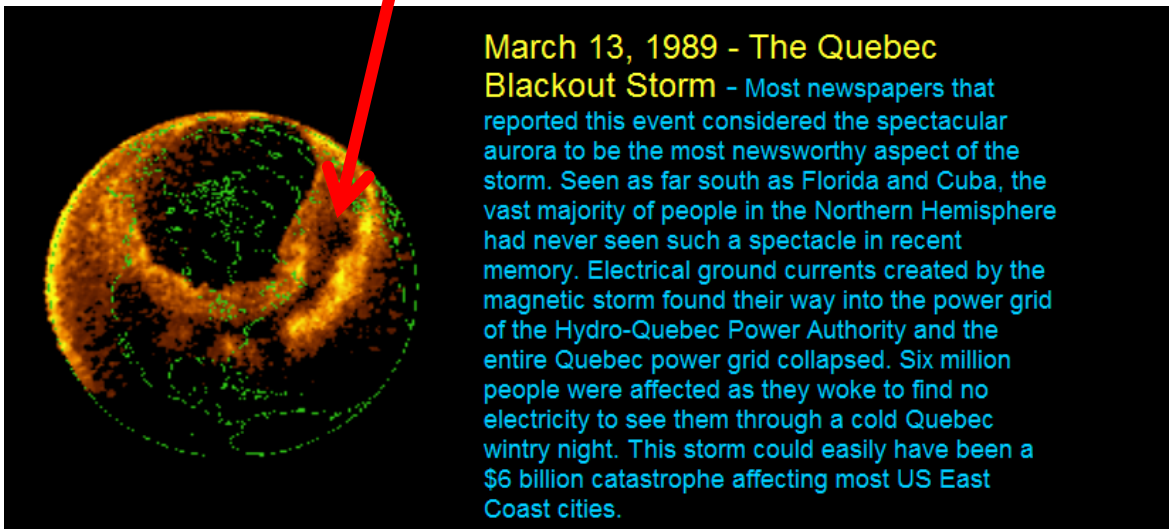
MAGNETOSPHERE

Electric currents



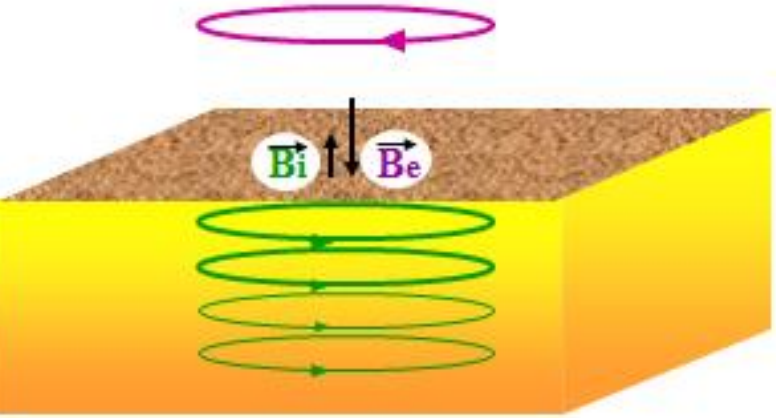
Magnetic storm indices Dst, SYM-H *

MAGNETIC STORMS
Ionospheric electric currents



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

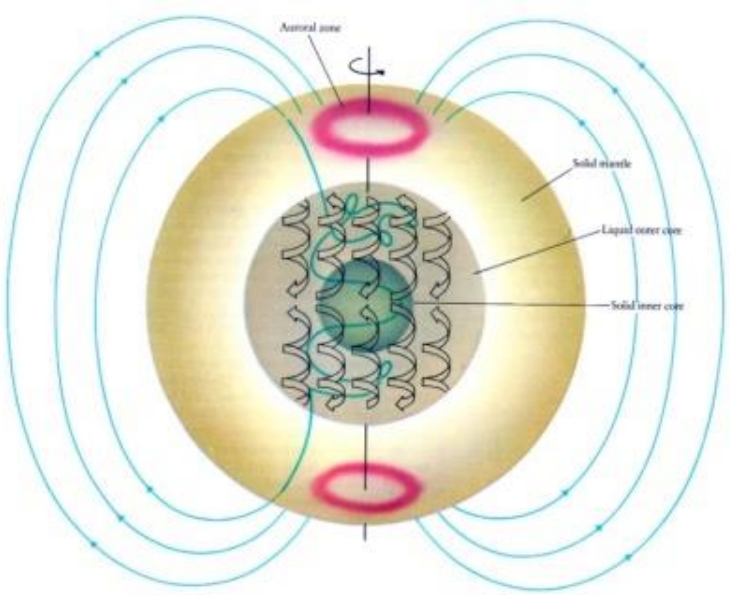
The ionospheric electric currents induce telluric currents



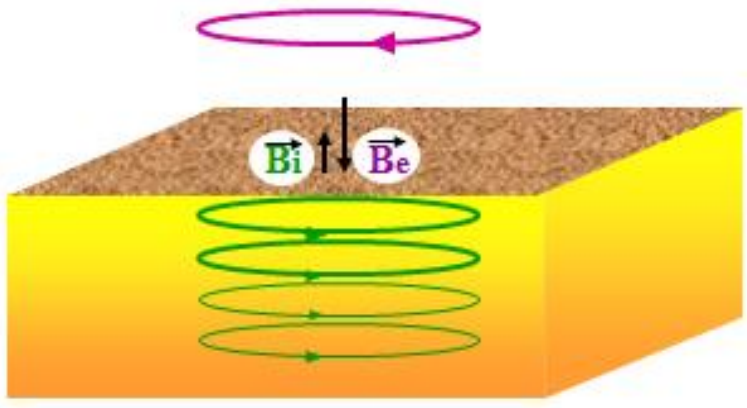
Power failure

Transformer damaged

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)
(~ 10-20 nT)

Be = external field related to Ionosphere and magnetosphere
(10nT to 2000nT)

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 electrical currents of the SUN-EARTH system

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
  - Regular and irregular magnetic field variations (Sq/Sr, EEJ, crochet related to Solar Flare)
- Sun Earth connections : particle channel
  - Solar wind, Solar wind-magnetosphere Dynamo
  - Magnetic storms produced by solar disturbance
  - CME : coronal Mass Ejection – HSSW : High Speed Solar Wind
  - Electric currents and key roal of auroral zone
  - Earth's dynamo
- Ionosphere : Electrodynamics coupling between high and low latitudes
  - Transmission of the magnetospheric electric field (PPEF)
  - Joule heating, thermal expansion of the atmosphere and disturbance Dynamo (DDEF)
  - Irregularities of equatorial plasma
- Conclusion

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

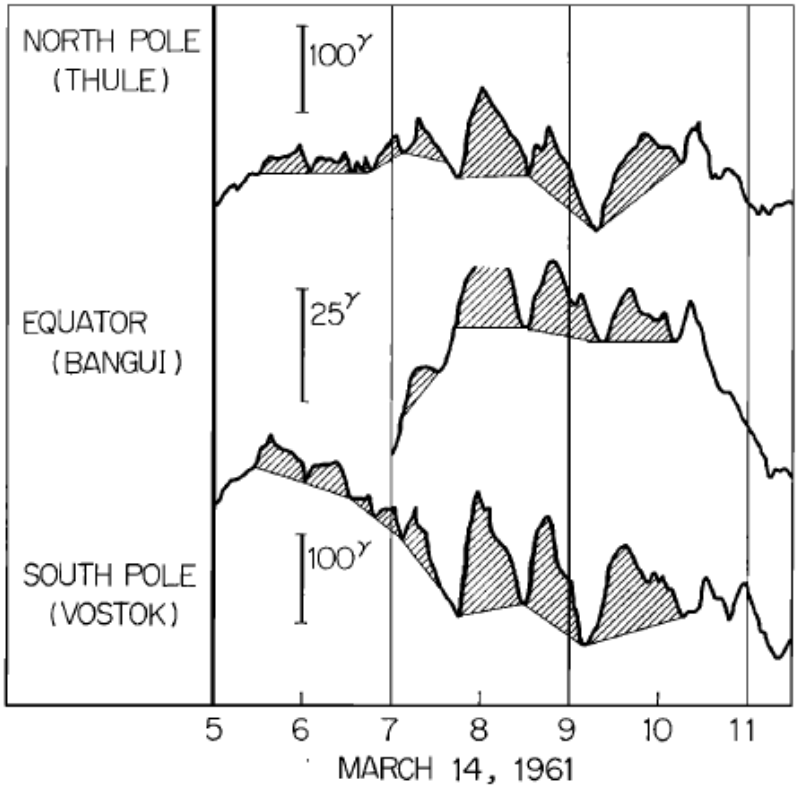
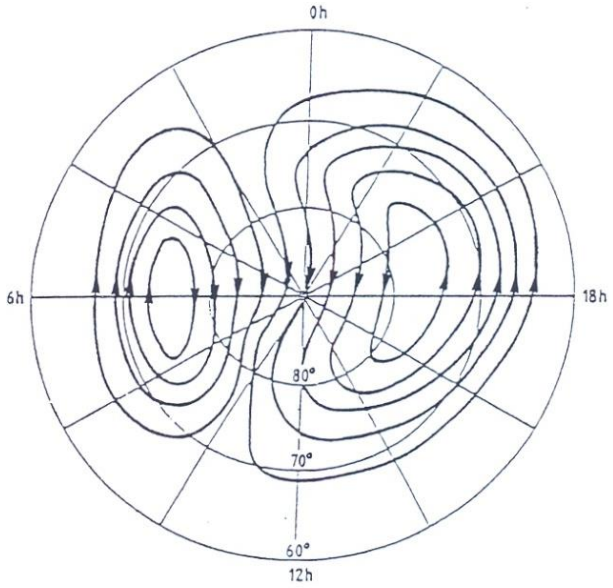


Fig. 1. Train of D_P 2 fluctuations (shaded). Geomagnetic latitudes of these stations are 88.9 (Thule), 05.0 (Bangui), and −89.1 (Vostok).

The electric field of magnetospheric convection is transmitted to the whole ionosphere

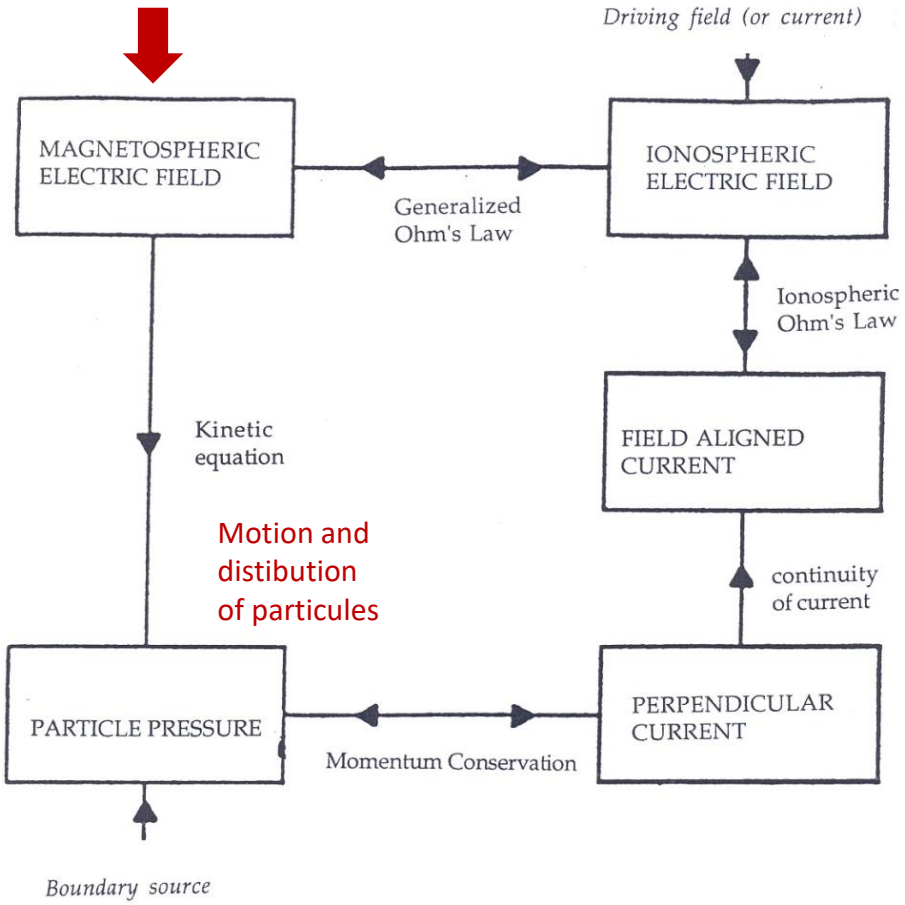
=> simultaneity of the disturbances from auroral to equatorial latitudes

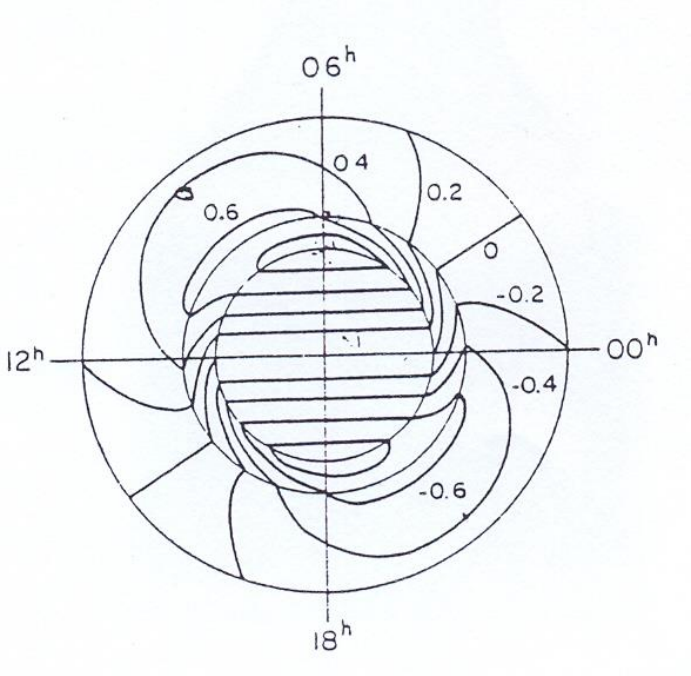


Magnetic signature : DP2

First mathematical convection model

Outlines of the self consitent calculation : calcultated quantities are in boxes,
Lines joining boxes are labeled with the physical principle



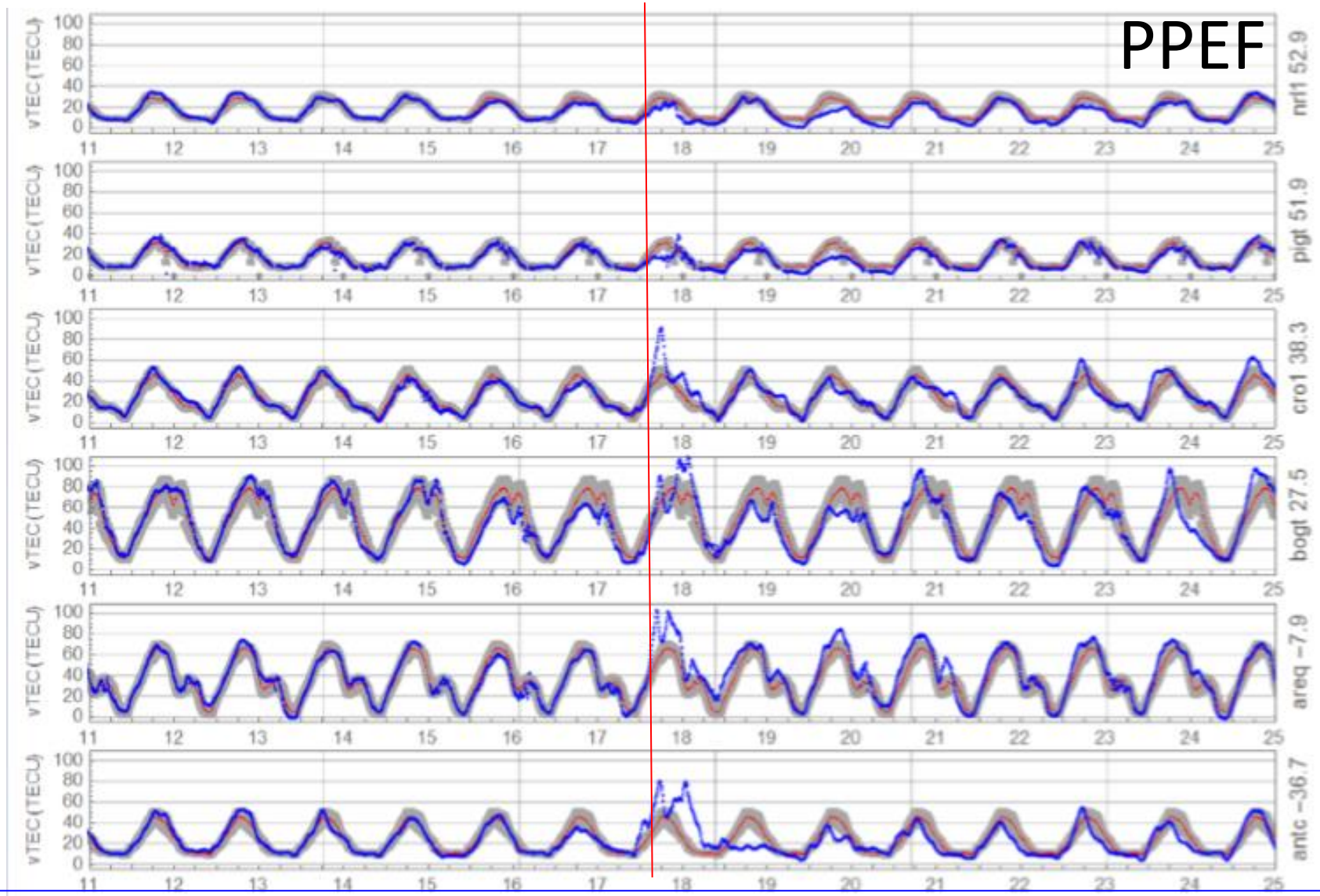


Equipotential contours in the ionosphere
(enhanced auroral conductivies)

Vasyliunas V. M., Mathematical Models of Magnetospheric Convection and its coupling to the ionosphere 1970, Mc Cormac book

PPEF

VTEC in the AMERICAN SECTOR DURING MARCH 2015



"Middle and low latitude ionosphere response to 2015 St. Patrick's Day geomagnetic storm", Nava, B., J. Rodríguez-Zuluaga, K. Alazo-Cuartas, A. Kashcheyev, Y. Migoya-Orué, S.M. Radicella, C. Amory-Mazaudier, R. Fleury, 2016, J. Geophys. Res. Space Physics,121, 3421–3438, doi:10.1002/ 2015JA022299.

COUPLING between AURORAL and EQUATORIAL regions
Storm winds and ionospheric disturbance dynamo
=> delay between the auroral and equatorial regions DDEF

Auroral electrojets

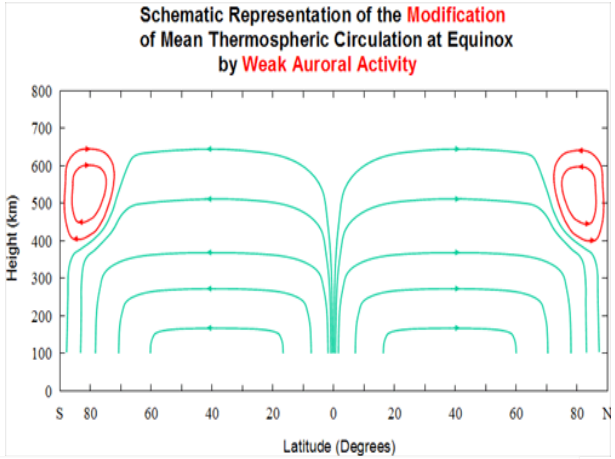
↓

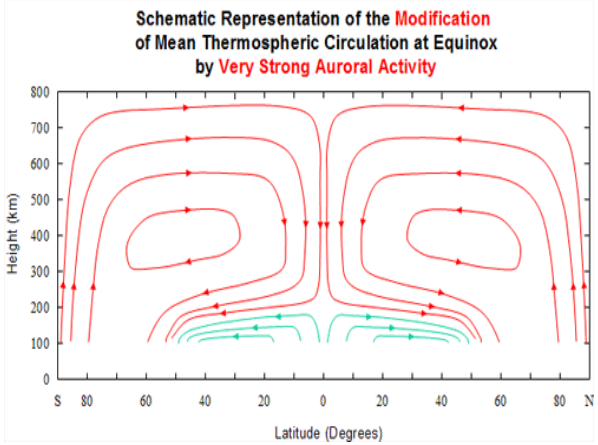
Joule heating most effective

↓

$+\Delta Vn \longrightarrow \Delta E_{dyn} \longrightarrow \Delta J \longrightarrow \Delta B$

Gravity waves, HADLEY convection cell etc…





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

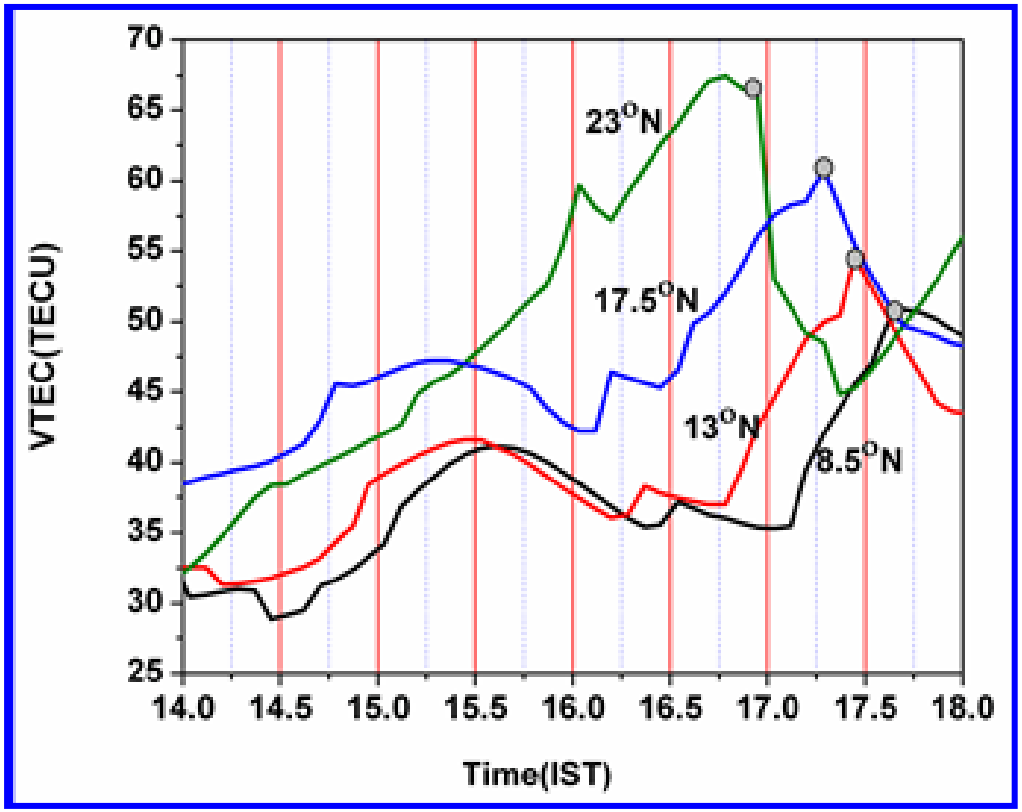
Thermal expansion of the atmosphere: Travelling Atmospheric disturbance (TAD's) => disturbed TEC [Theory Fuller Rowell et al., (1994), (1996)]

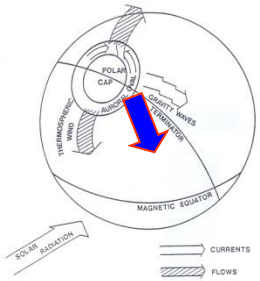
24/08/2005

SSC : 13.00 UT
Main Phase : 16 00 UT

INDIA
77-78°E meridian

V~750m/s





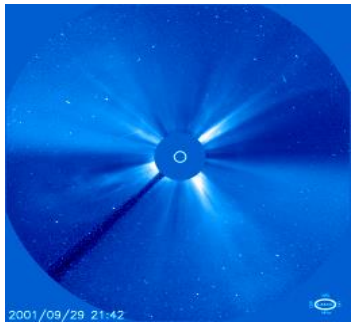
A time delay in the VTEC variations over the different latitudes indicates a propagation of TAD's Velocity 750m/s

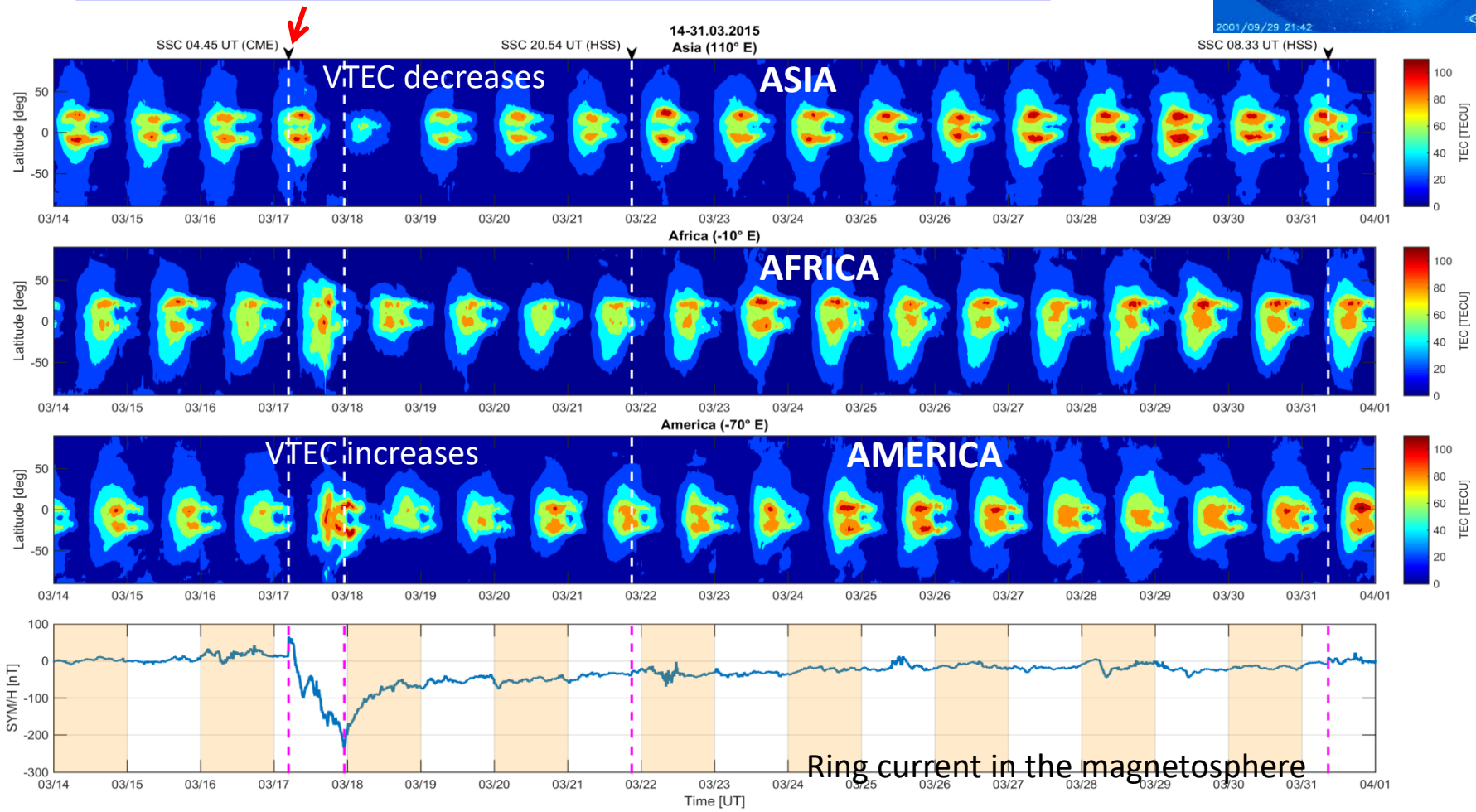
Sreeja et al., JGR vol 114, A12307, 2009

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

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

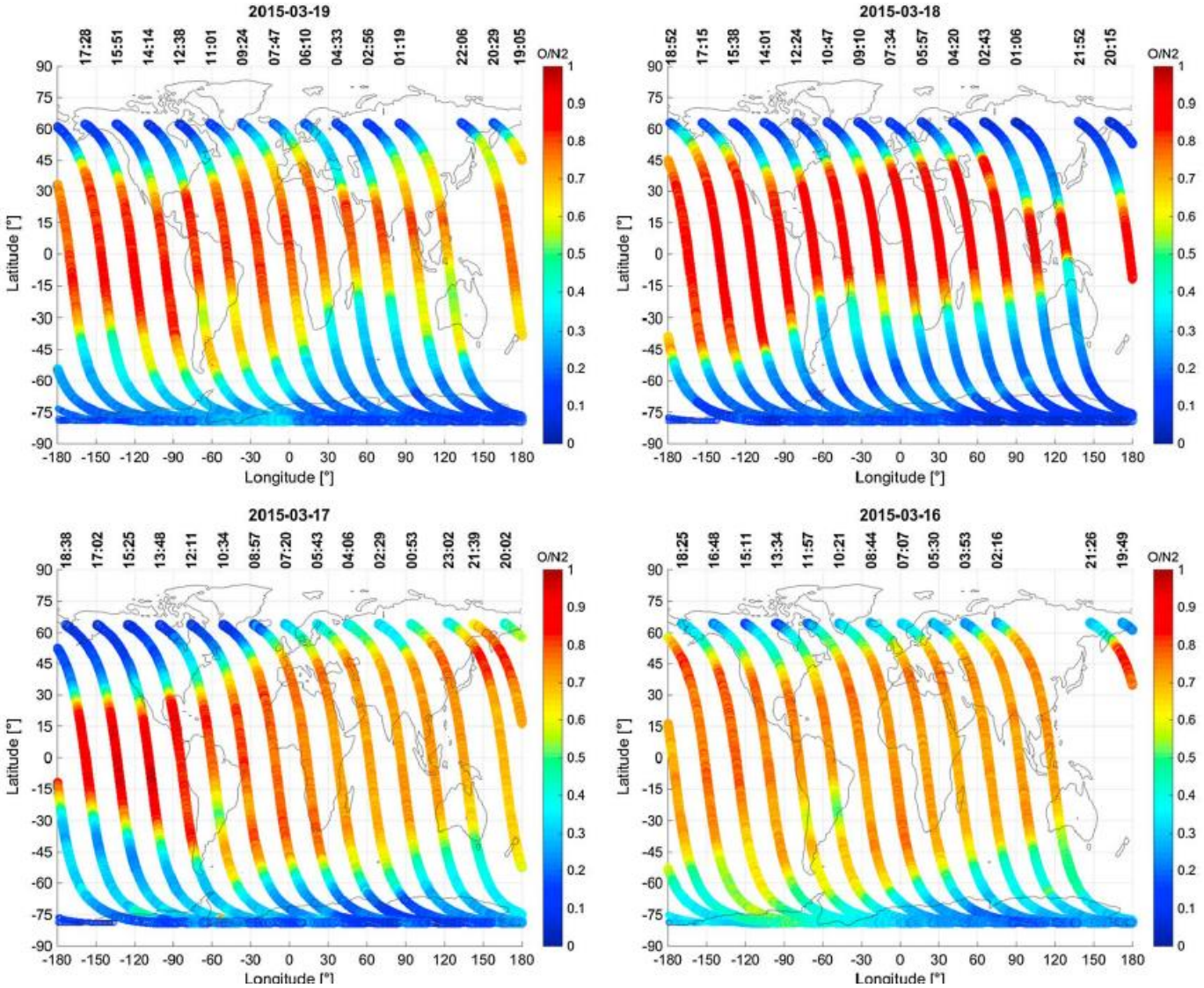
Impact of a CME (solar event, SSC on March 17 ~ 04.45UT)





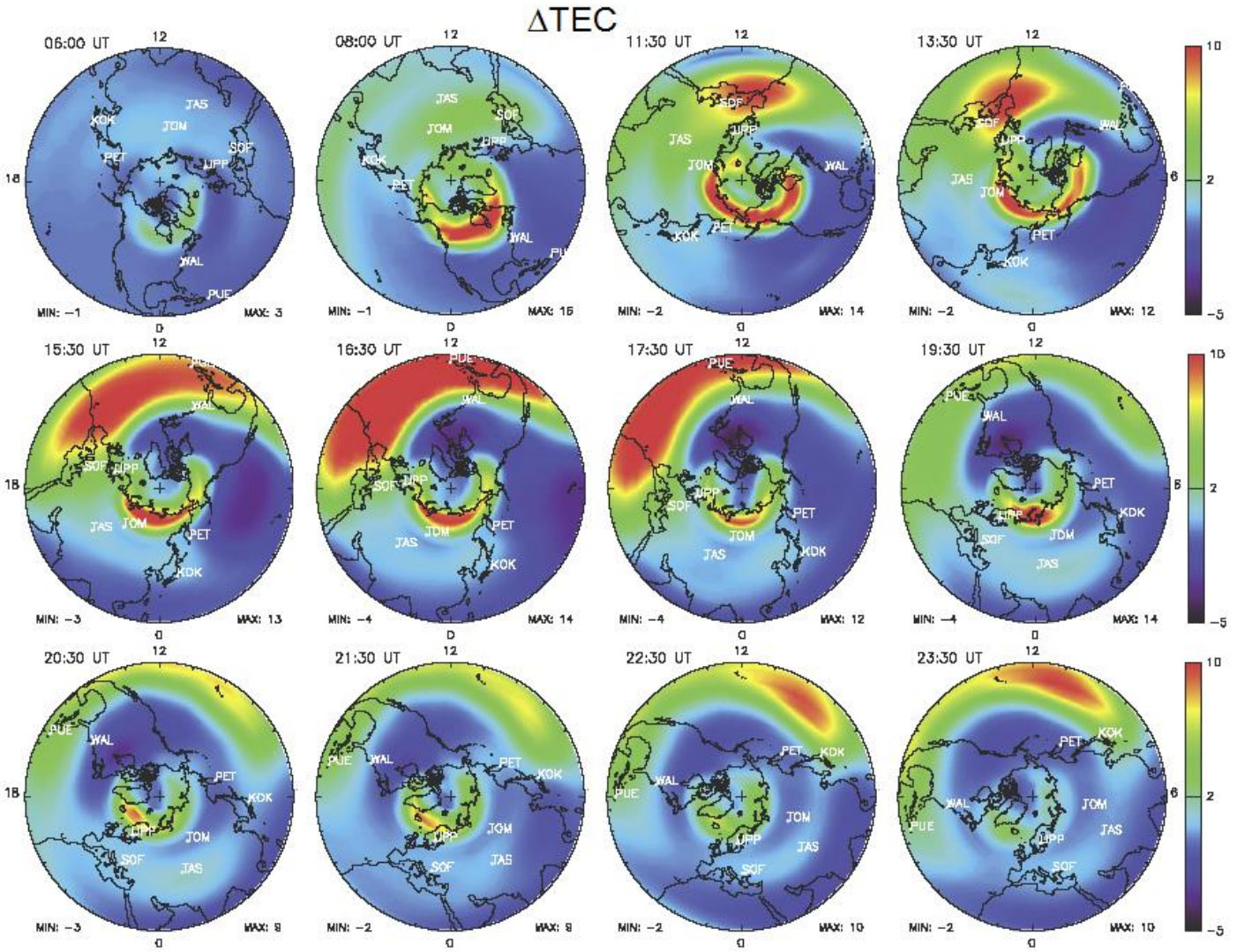
Nava,, et al., "Middle and low latitude ionosphere response to 2015 St. Patrick's Day geomagnetic storm", J. Geophys. Res. Space Physics,121, 3421–3438, doi:10.1002/ 2015JA022299.

Maps of [O/N_2] from GUVI for 4 days MARCH 16 to MARCH 19, 2015



Nava, B., J. Rodríguez-Zuluaga, K. Alazo-Cuartas, A. Kashcheyev, Y. Migoya-Orué, S.M. Radicella, C. Amory-Mazaudier, R. Fleury, 2016, 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.

Storm simulation

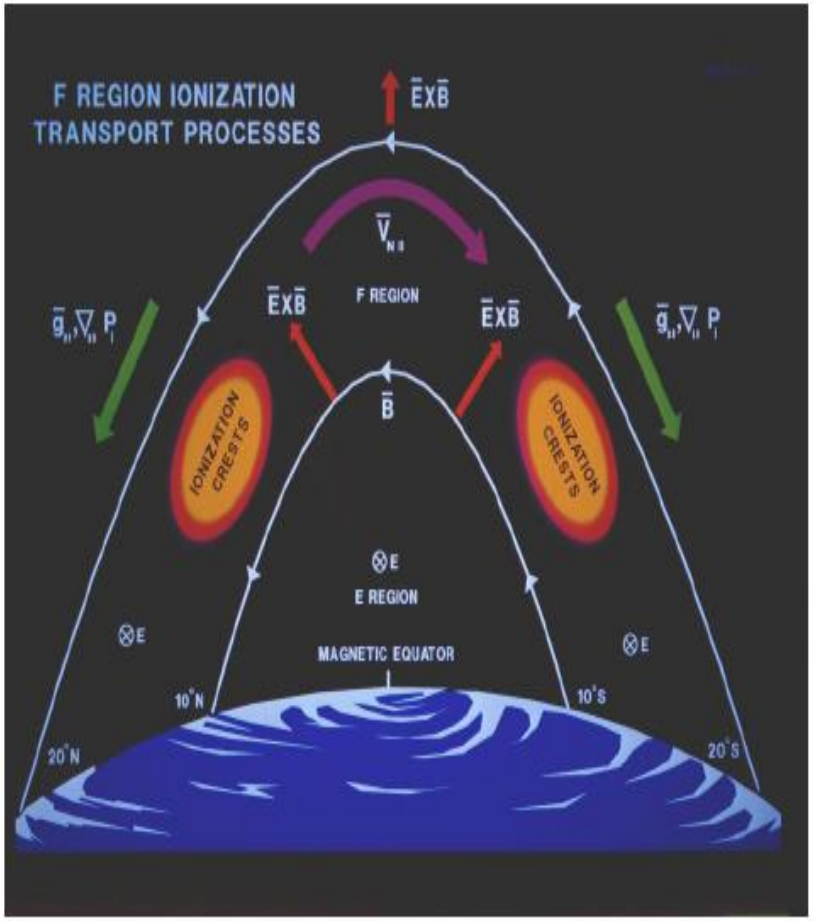


Lu, G., A.D. Richmond, R.G. Roble, and B.A. Emery, Coexistence of ionospheric positive and negative storm phases under northern winter conditions: A case study, J. Geophys. Res., 106, 24,493-24,504, 2001.

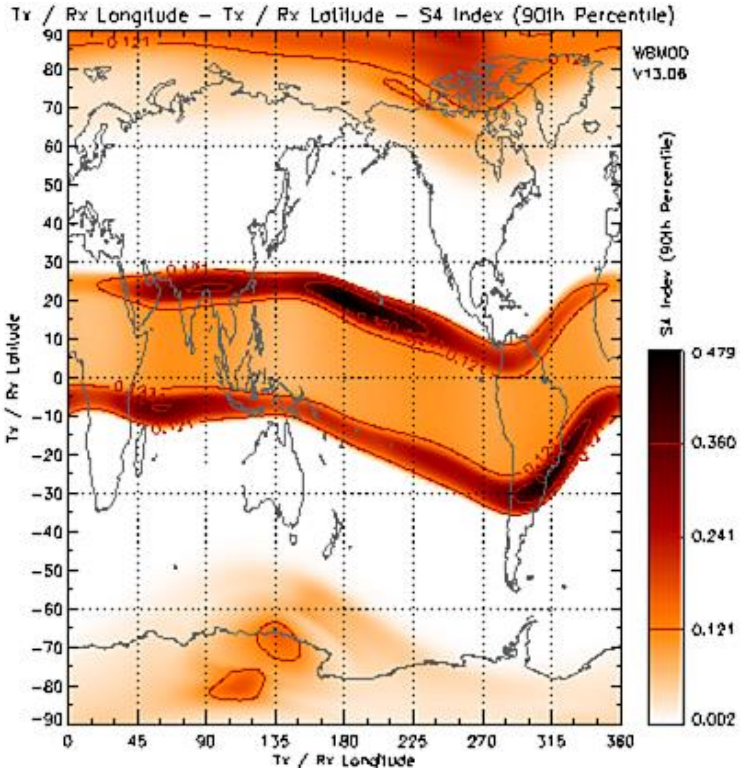
Scintillations a regular phenomenon

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

P**hysical Process : Instabilities in Plasma**

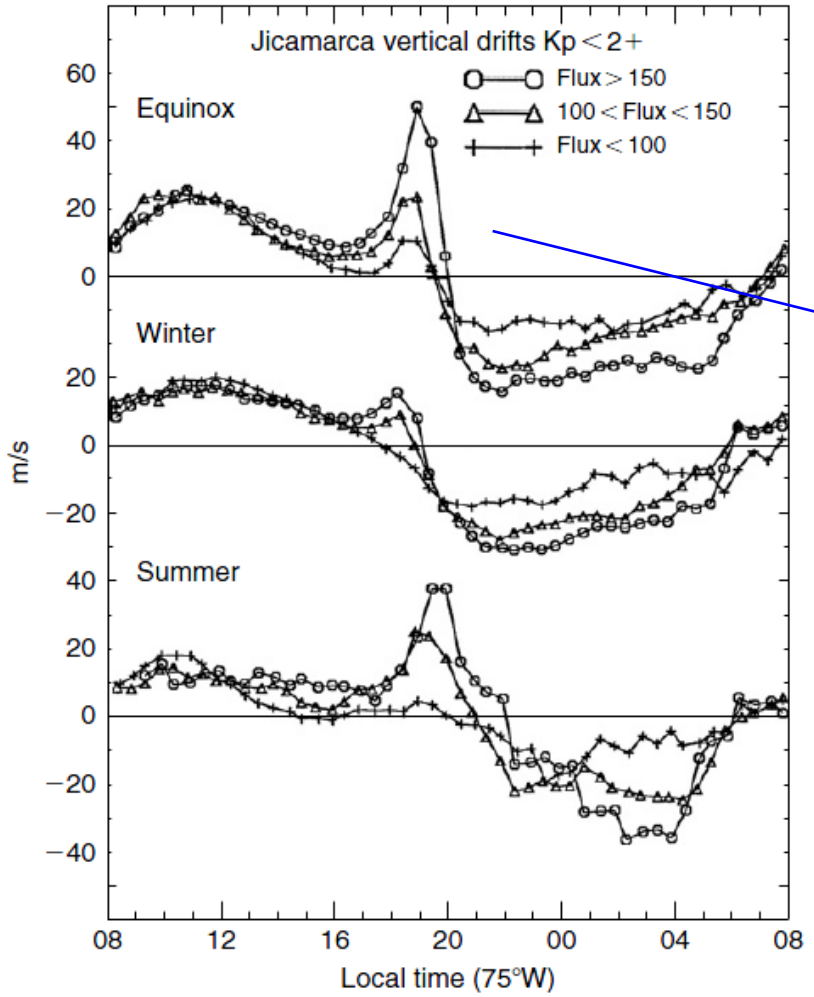


Equatorial Fountain

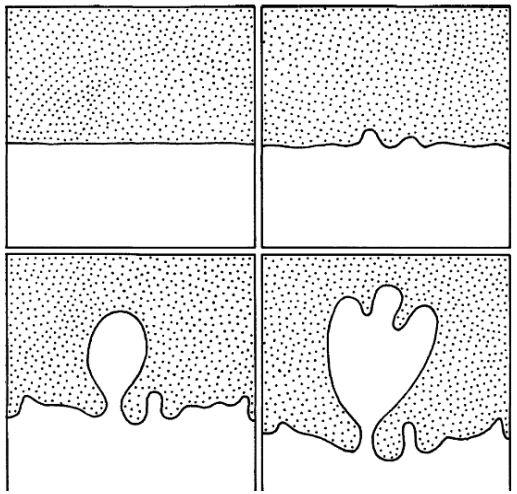


Scintillation index at GPS L1 (1575.42 MHz) assuming constant local time 23.00 at all longitudes (from http://www.sws.bom.gov.au)

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.

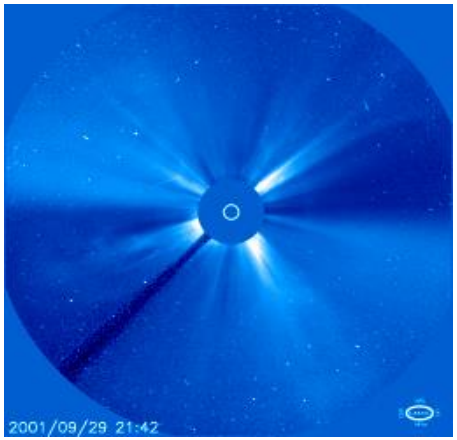
Average vertical plasma velocities at Jicamarca during the equinox (March-April, September-October), winter (May-August), summer (November-February) for 3 solar flux values

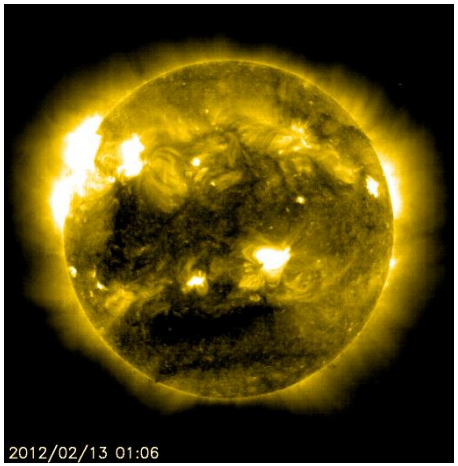
Fejer, et al., Average vertical and zonal F region drifts over Jicamarca, Journal of Geophys. Res, Vol. 96, N° A8, page 13901-13906, 1991

SUN EARTH CONNECTIONS

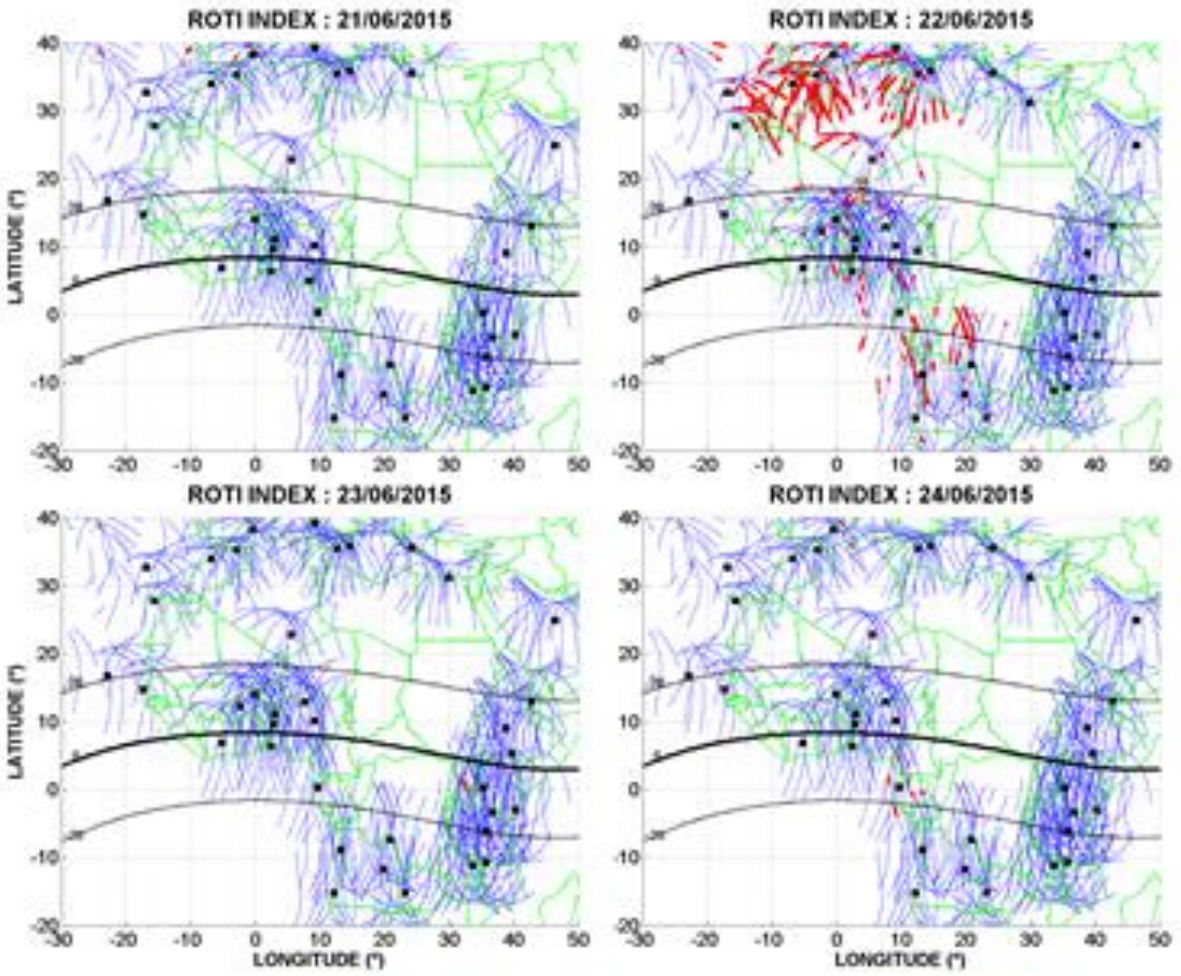
some solar perturbations inhibit or increase the irregularities and as consequence the scintillations

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

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

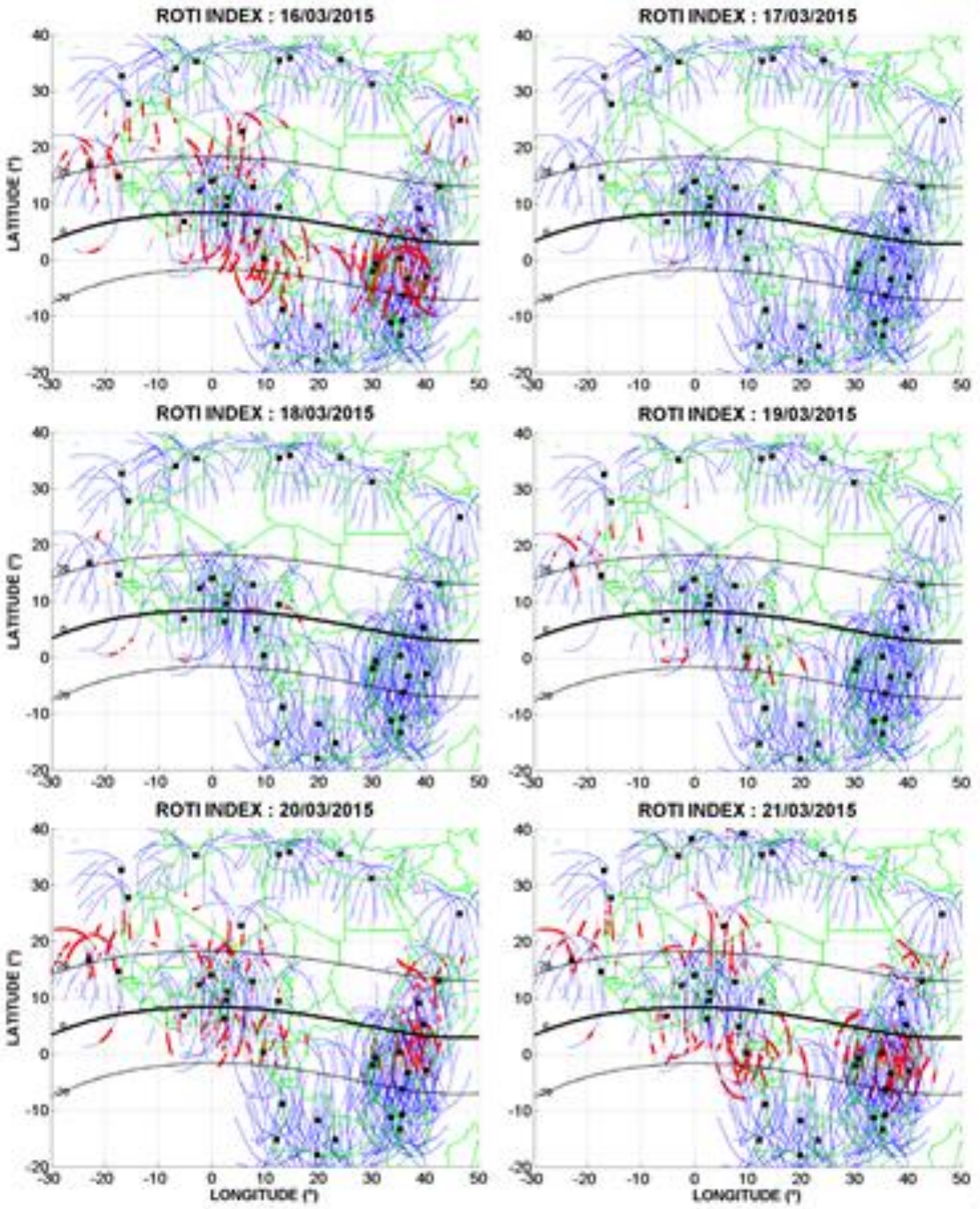
Dst < -200 nT

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

Kashcheyev, A et al., 2018



Storm March 17, 2015 equinox

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

Dst < -200 nT

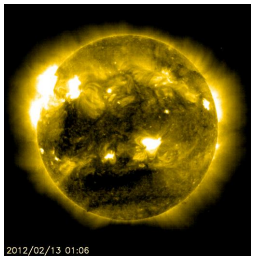
Storm started at 04.45 UT

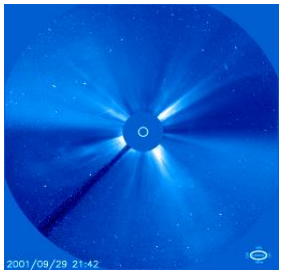
Inhibition of scintillations over the whole Earth during several days due to the disturbance dynamo (DDEF) effect

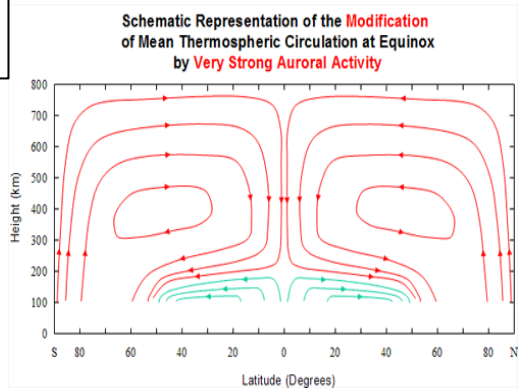
long duration

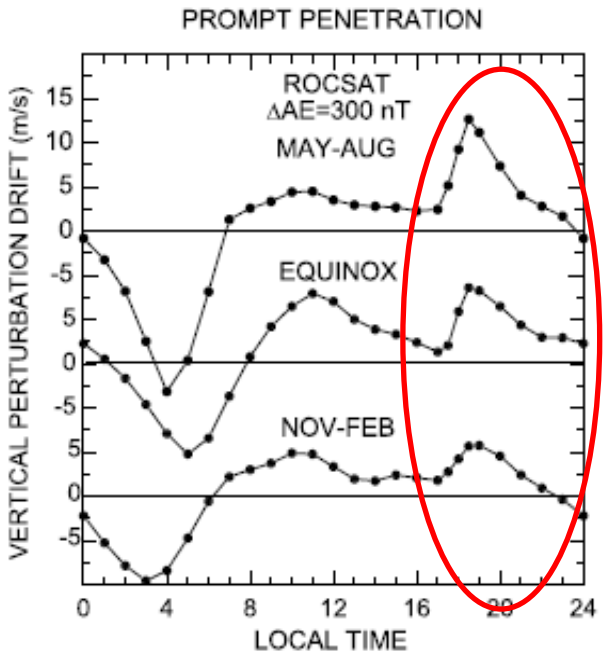
Kashcheyev, A et al., 2018

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

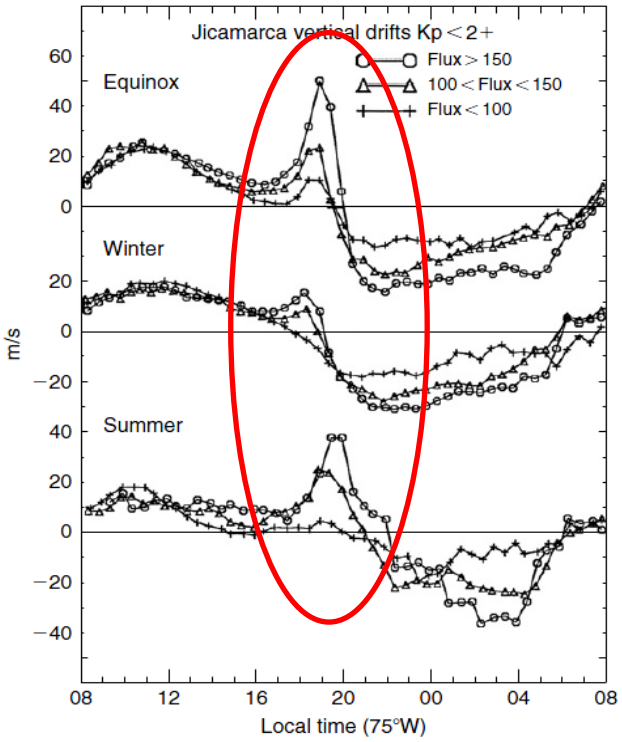




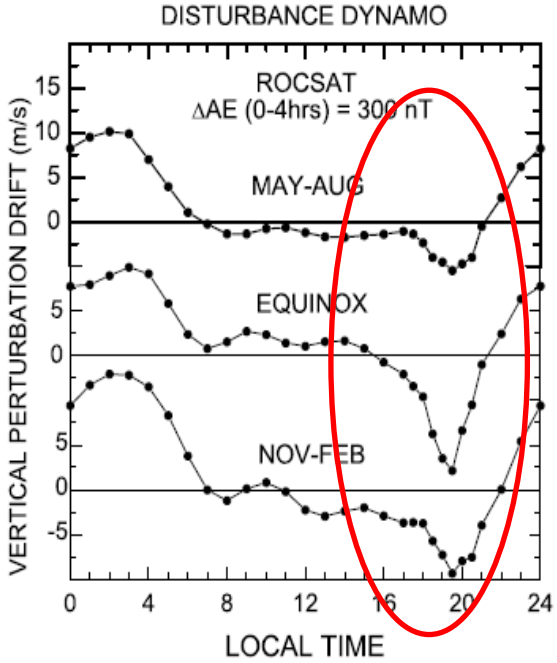




PPEF: disturbance



REGULAR



DDEF :disturbance

Conclusion

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

- the state of the sun: quiet 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 : quiet or disturbed
- It is necessary to know the quiet 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…