INTRODUCTION TO SPACE WEATHER

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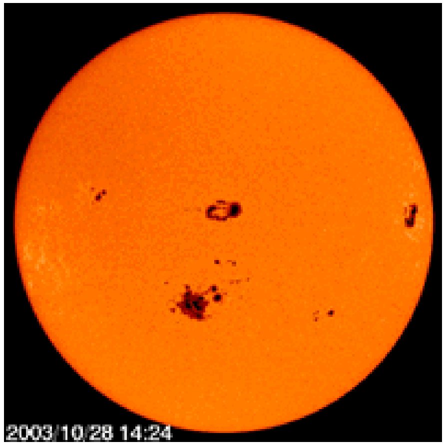
International Colloqium on Equatorial and Low Latitude Ionosphere
Lagos/ Nigeria 15-17 September 2020

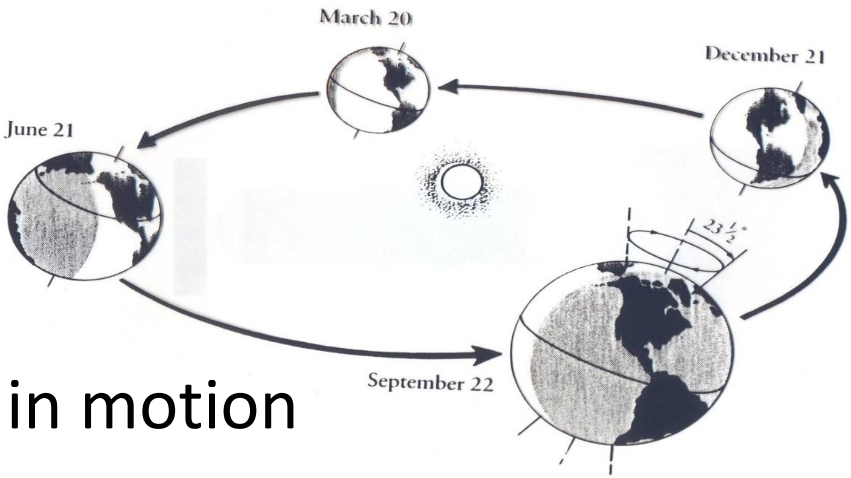
OUTLINES

- Sun and Earth two magnetic bodies in motion
- Emission from the Sun
- Sunspot cycle
- Solar Dynamo: the true solar cycle / solar indices
- Radiation channel regular
  - Ionosphere / Ionospheric dynamo
- Radiation channel disturbed
  - Solar flare
  - Solar Burst
- Particles channel
  - Regular solar wind
- Magnetic storms
  - CME and Coronal hole
  - Geomagnetic activity and solar wind
- Case studies of Space Weather events
  - Solar flare effect, Storm effect
  - Electrodynamics coupling between high and low latitudes
  - Equatorial ionosphere -> Magnetic quiet time, Coronal hole effect, CME effect
- Conclusion

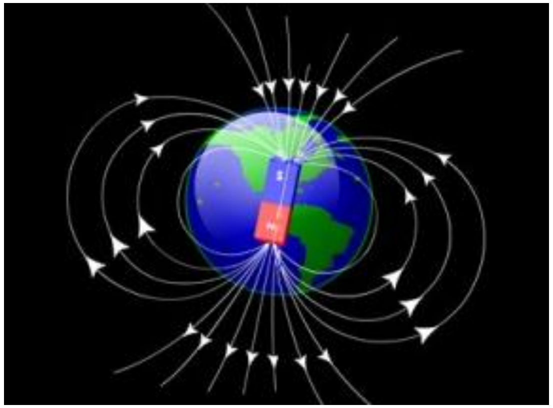
The Sun : a magnetic body in motion



Variability ~ 27 days

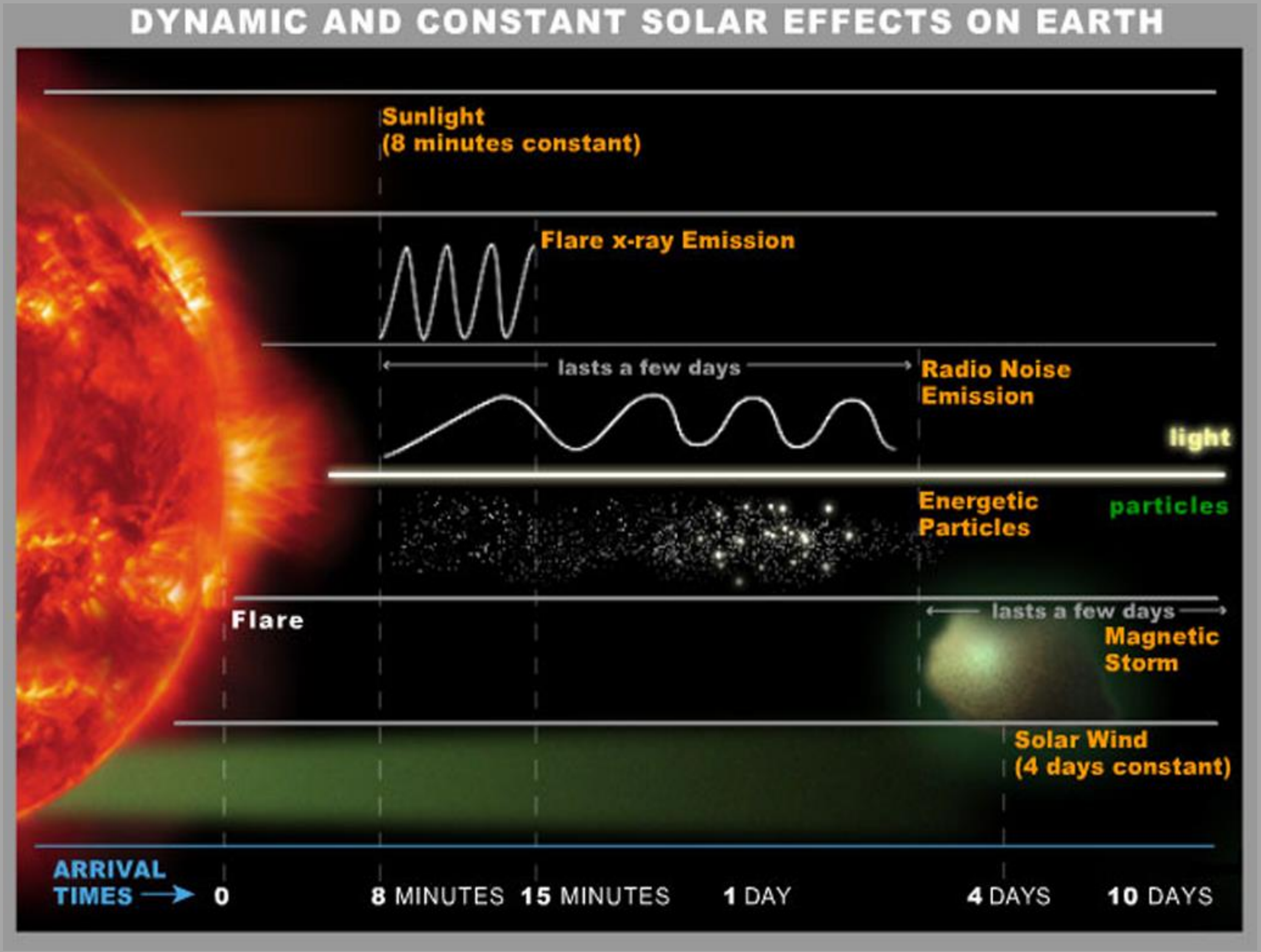


The Earth: a magnetic body in motion



Variability : diurnal , seasonal/annual

EMISSIONS FROM THE SUN



from Nasa website

Sunspot Cycle known since the middle age

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)

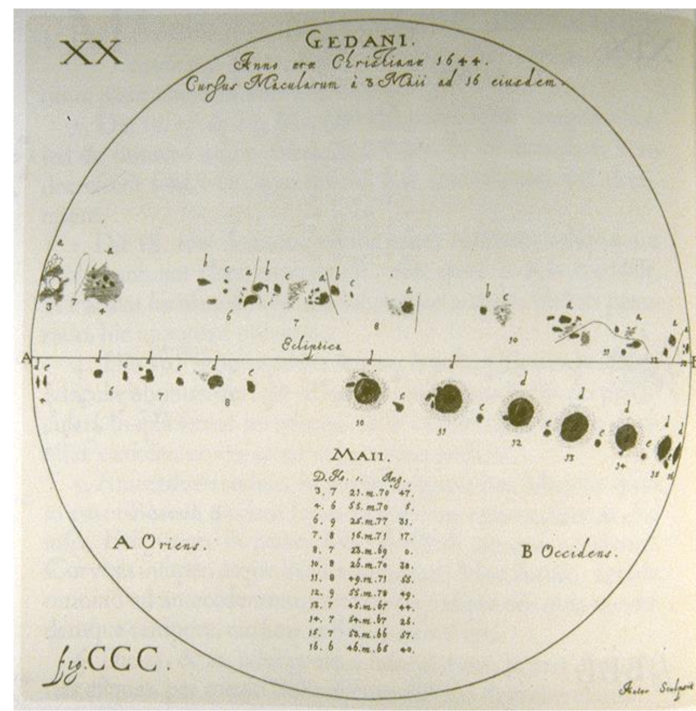
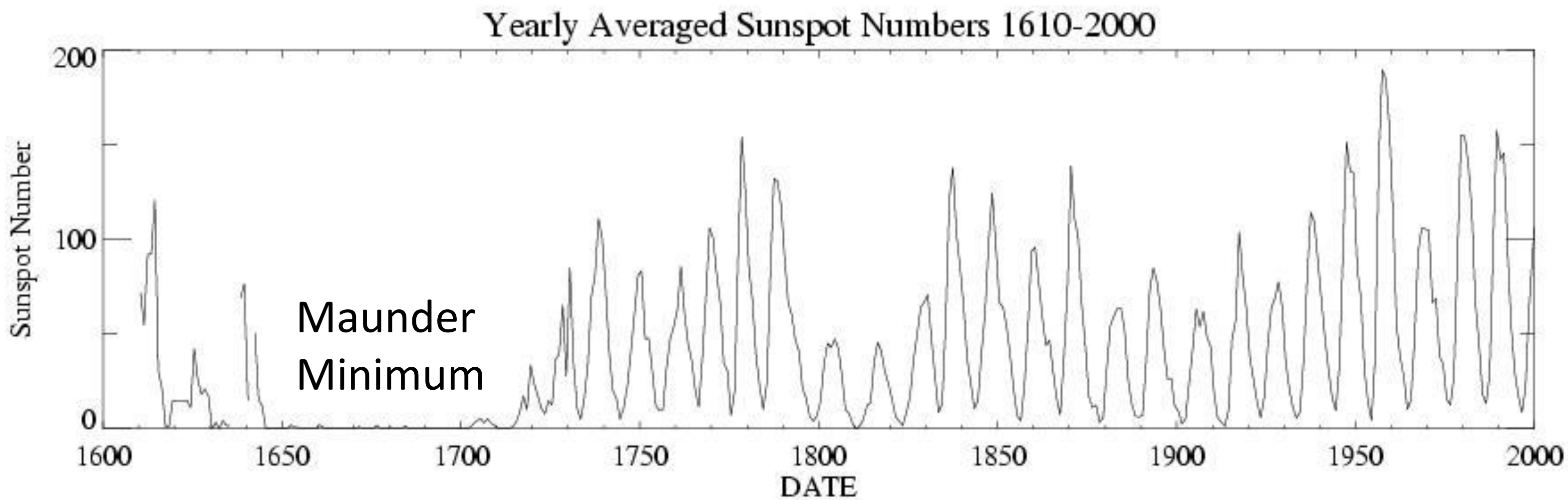


Figure of Father Scheiner

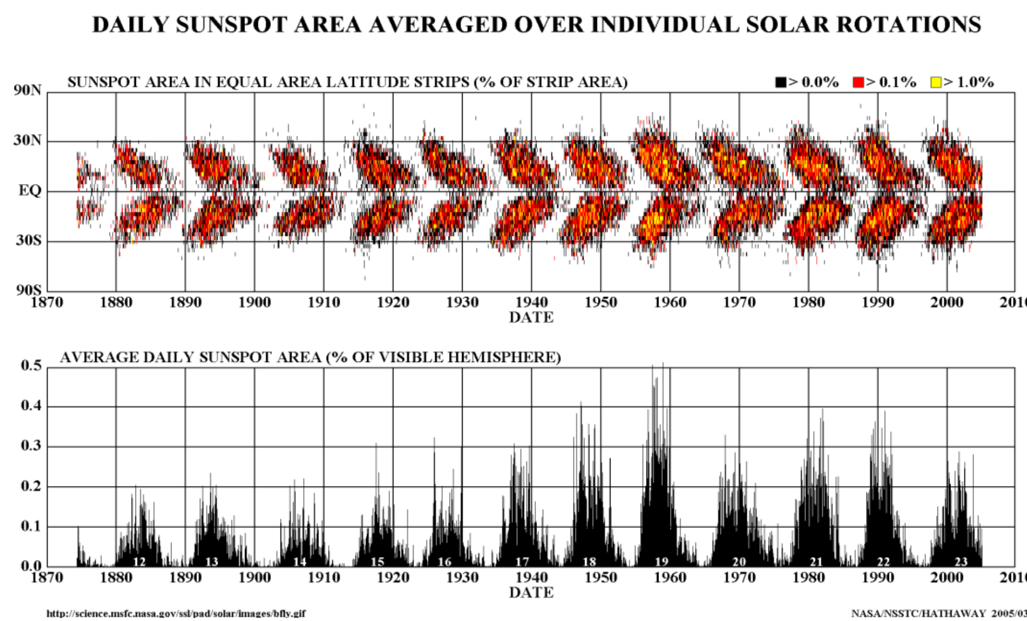
Motion of the sunspots

Scheiner : Priest Jesuit mathematician working at the university of Ingolstadt (near Augsburg)

SUN : Sunspot Cycle of 11 years : Heinrich Schwabe 1859

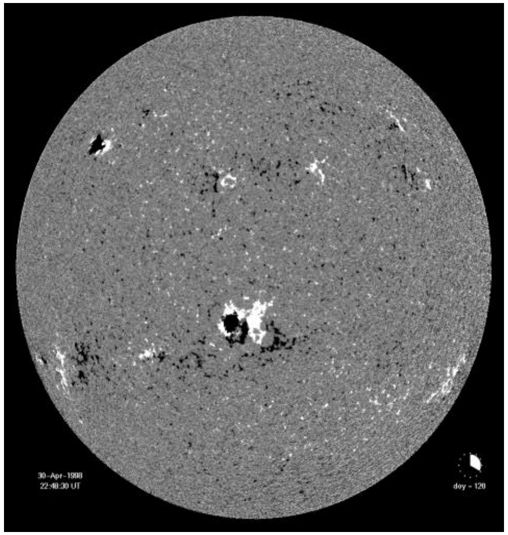


Legrand et al. 1990
On Maunder minimum

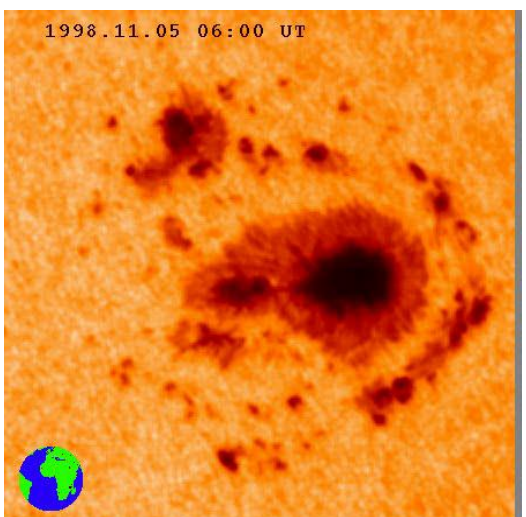


Legrand J.P., M. Le Goff, C. Mazaudier , On the climatic changes and the sunspot activity during the XVIIth century, Annales Geophysicae, 8 (10), 637-644,1990.

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

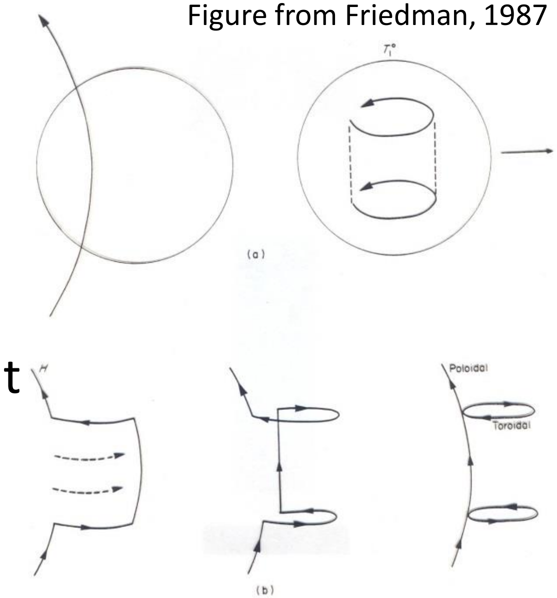


Figure from Friedman, 1987

Physical process : Dynamo

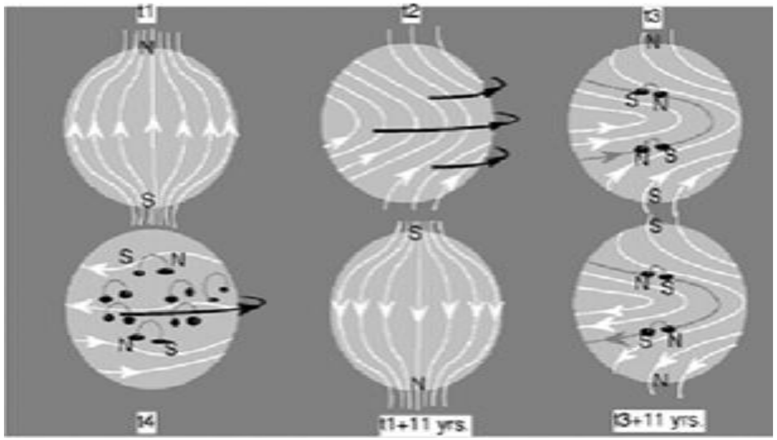
*The sun turns on itself.

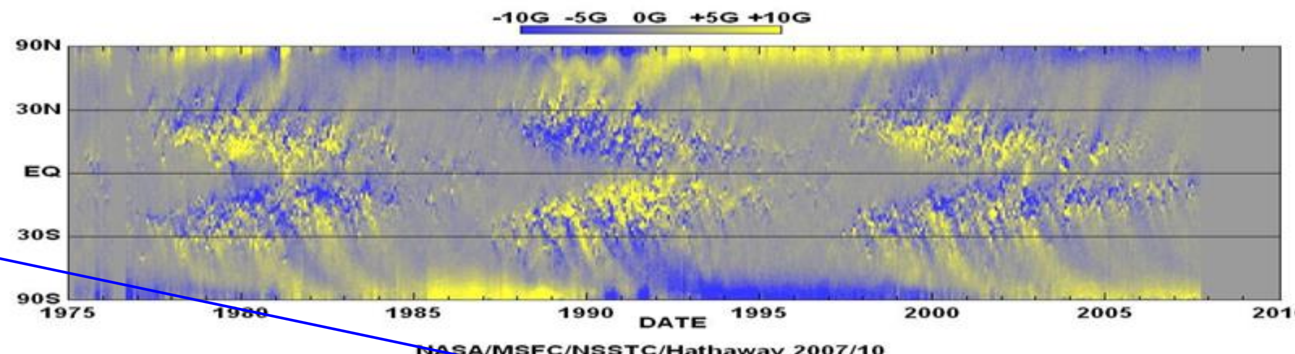
**Its rotation speed is faster at the equator than at the poles (~ 27 days against ~ 31 days).

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

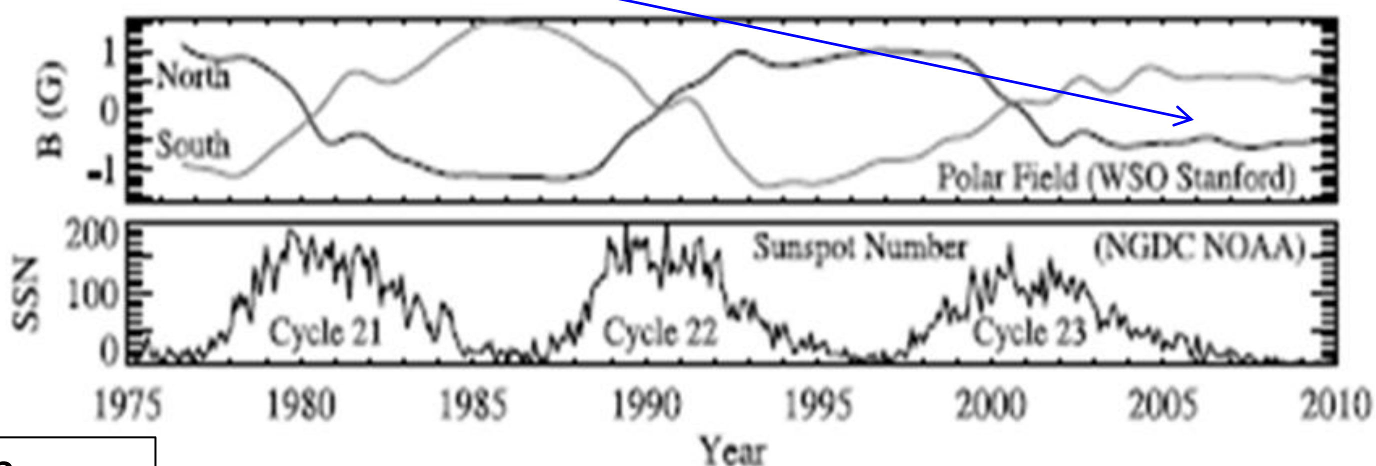
Solar Dynamo
the true solar cycle
by solar physicists

A sketch of the formation of sunspots and the 22-years sunspot cycle due to the differential rotion of plasma in the photosphere





decrease of the component of the poloidal solar magnetic field



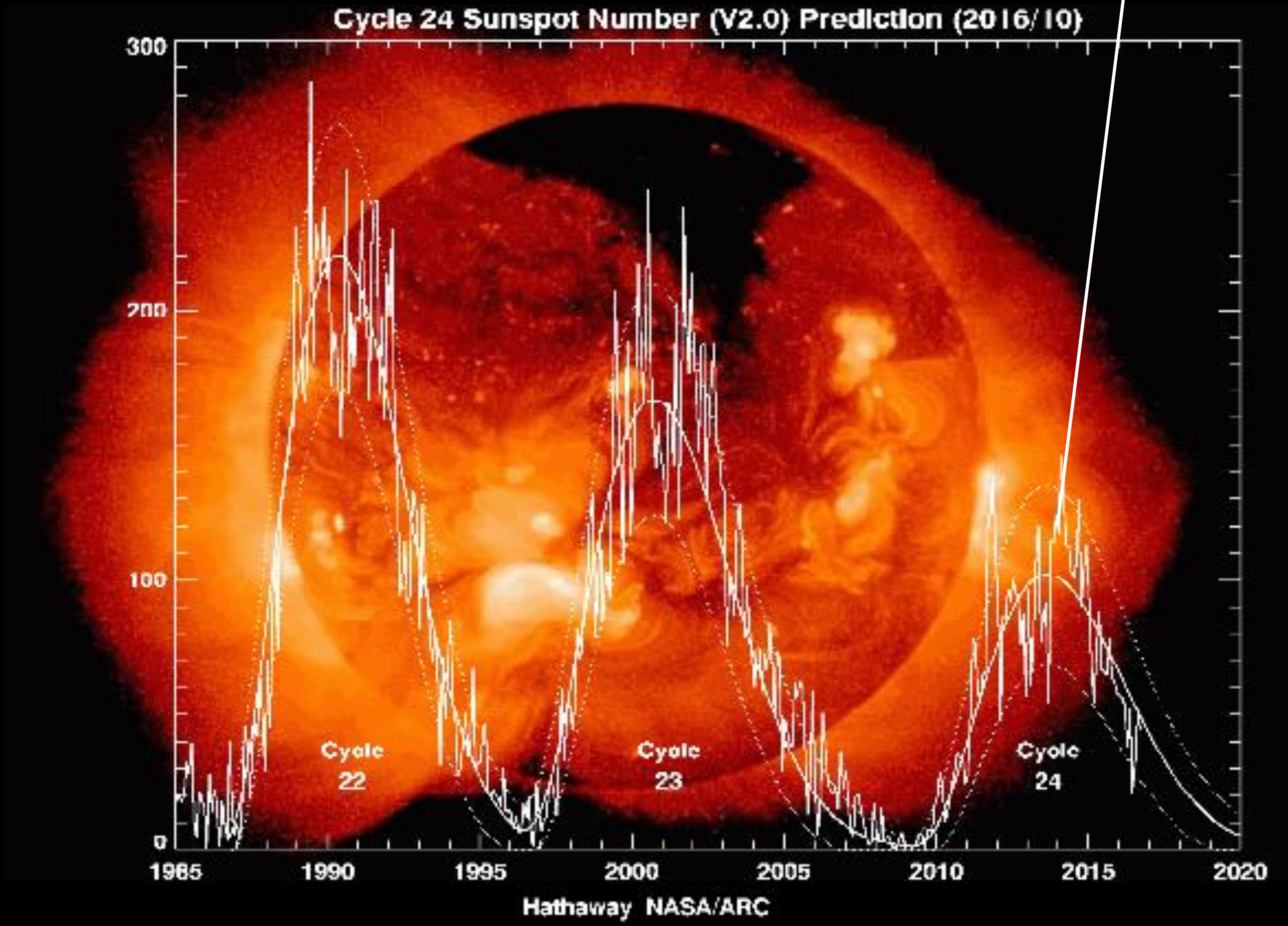
Liu et al., 2011

Variability ~ 11 and 22 years

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

Solar cycles 22-23-24

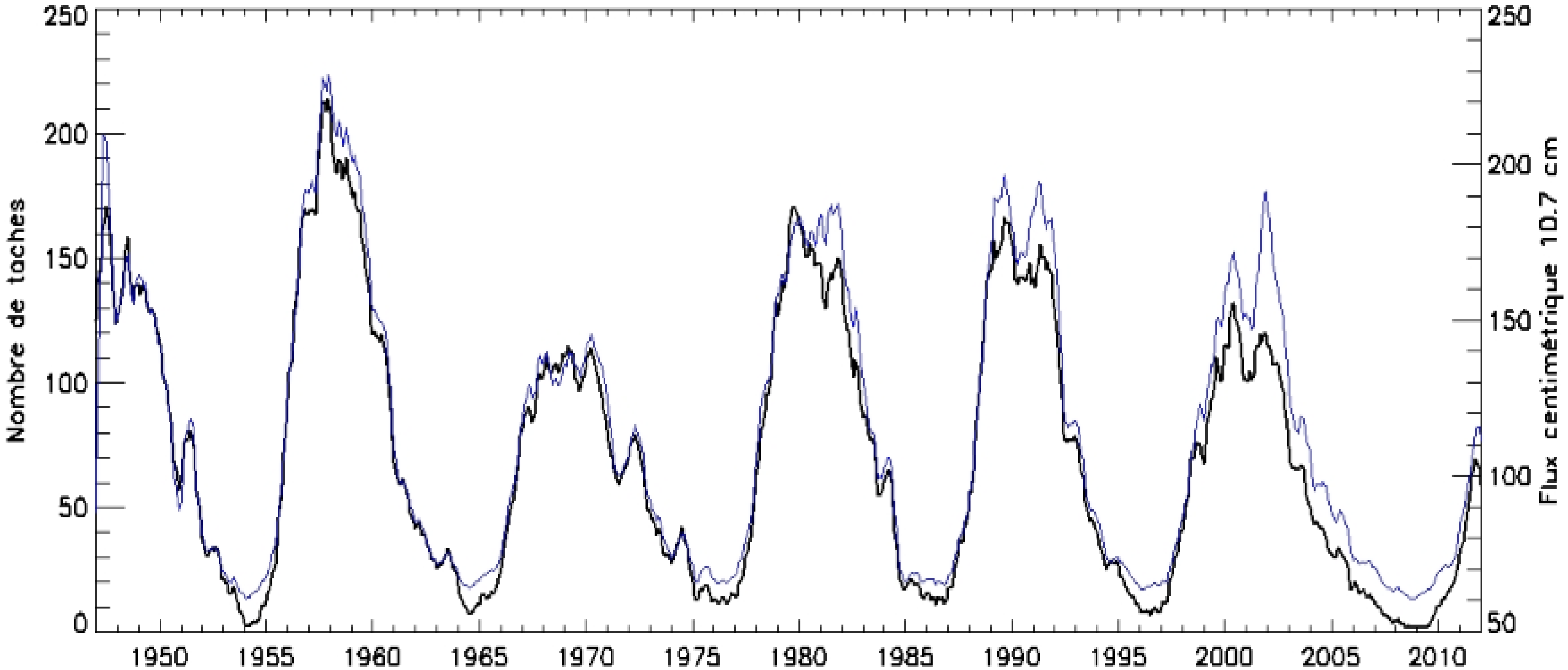
decrease of the sunspot due to the decrease of the poloidal component



The smallest sunpot cycle since the Space era

Solar indices used

Rz : sunspot number and F10.7cm : radio Flux at 10.7cm



F10.7 (station of Penticton/USA) et SSN (observatory of Brussels)

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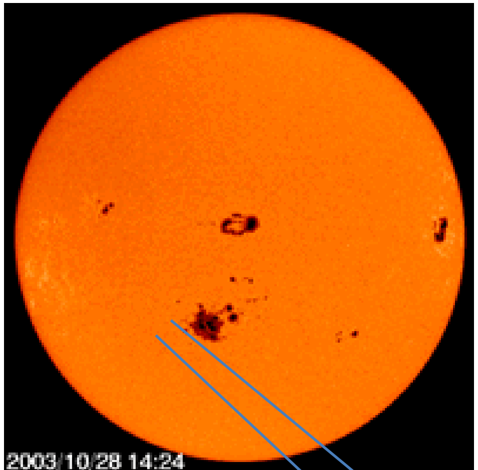
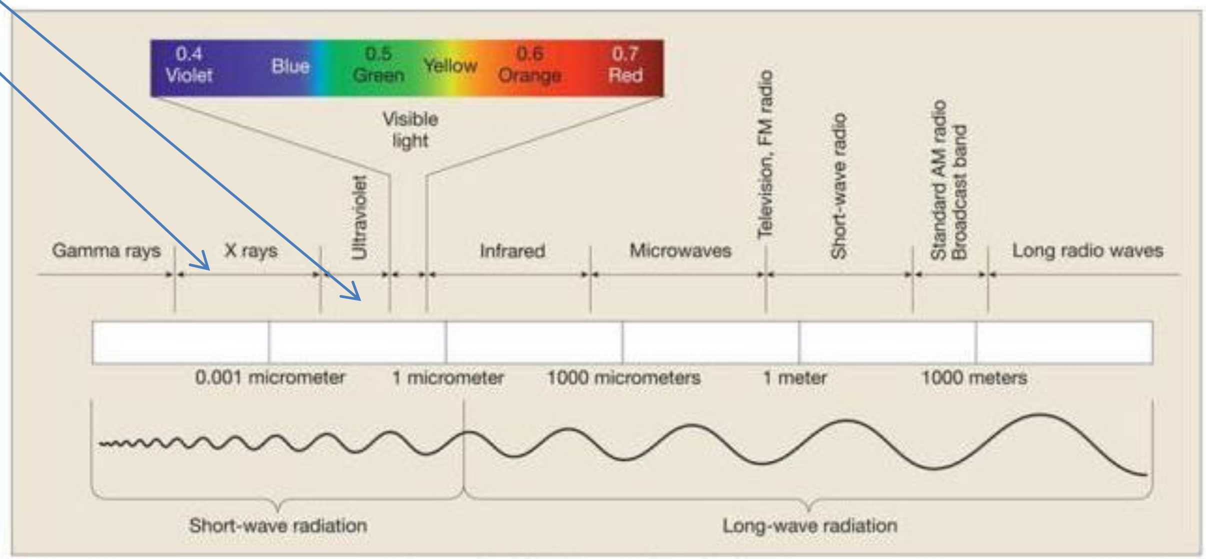
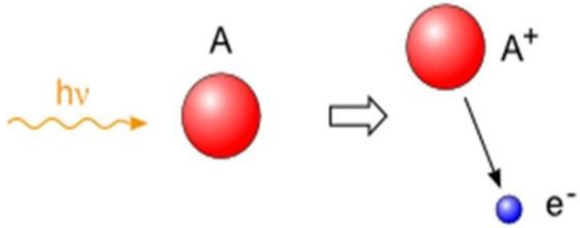


RADIATIONS Channel (LIGHT 8')

Regular

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





SUN and IONOSPHERE

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

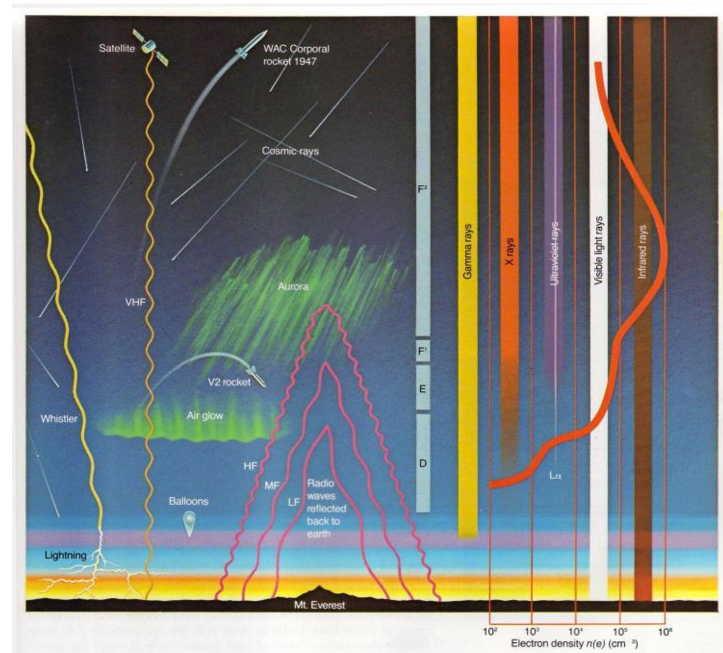
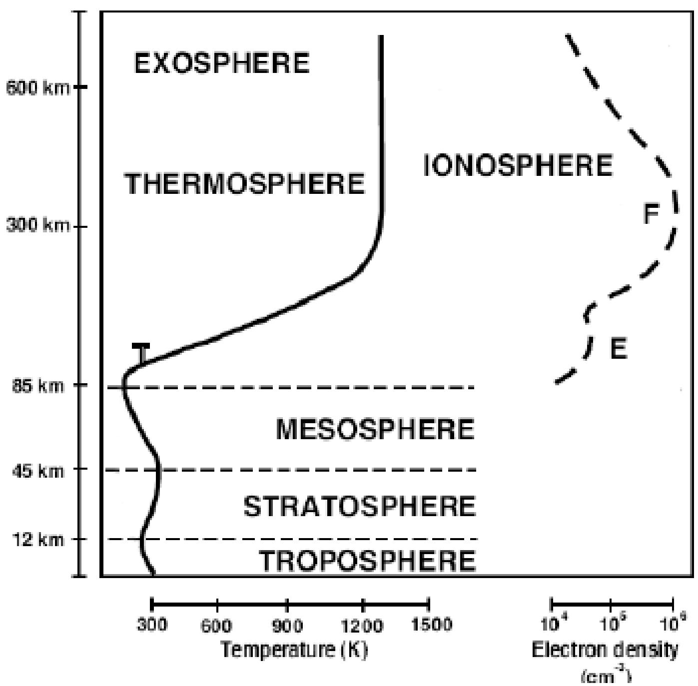


Figure from Friedman, 1987



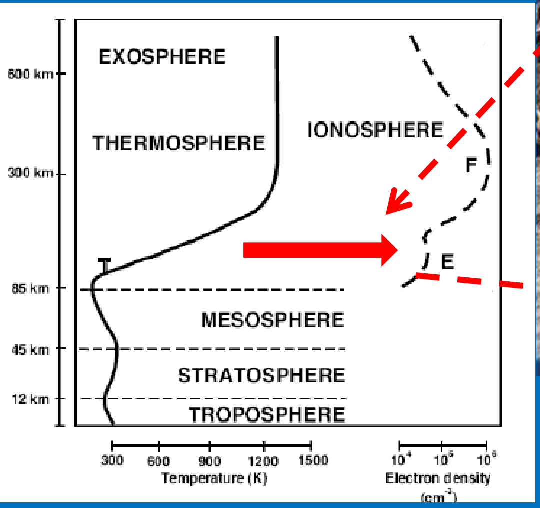
Ionosphere is a ionized part of the **atmosphere**
1 atom among 1 000 000

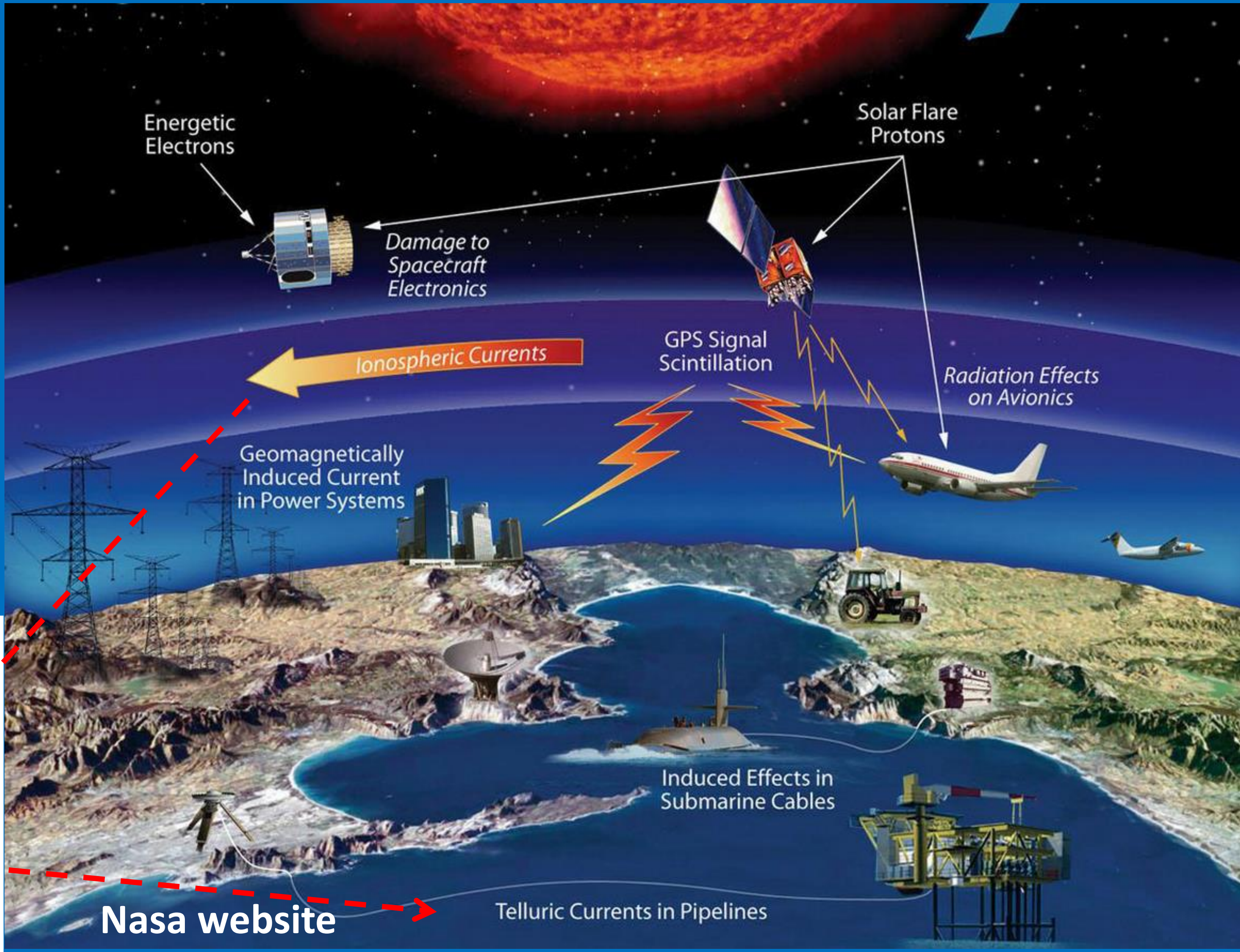
BOOKS : Risbheth and Gariott, 1969
Kelley ,2009

Between the Sun and the Earth : the IONOSPHERE
Ionosphere is a ionized layer around the Earth (from ~ 50 km up to 800 km)
The ionosphere is the largest source of perturbations for GNSS signals and source of GIC

Dynamo layer ~ 90-160km
Ionospheric dynamo

$$\vec{J} = N_e e(\vec{V_i} - \vec{V_e})$$





Nasa website

[ionospheric dynamo –Richmond, 1995]

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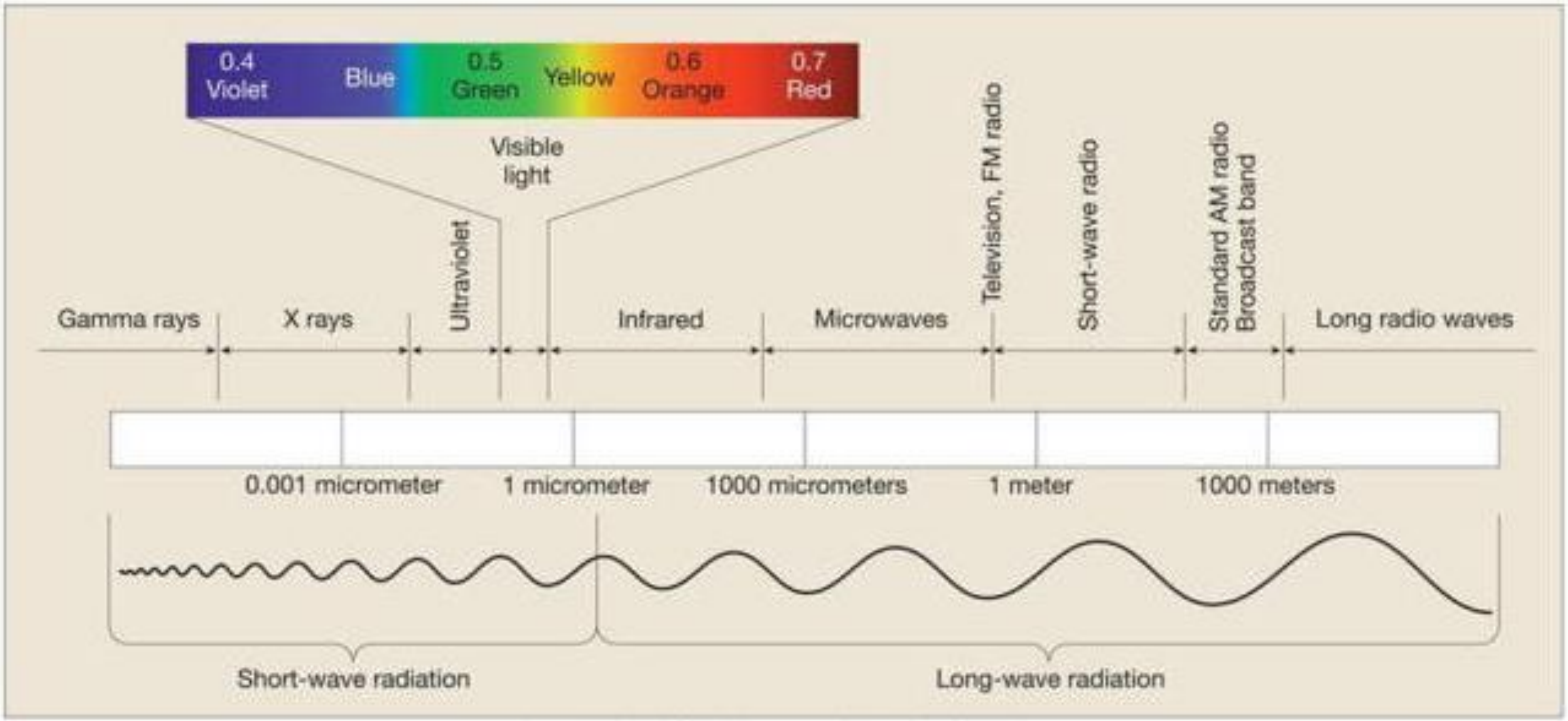
SOLAR RADIATIONS DISTURBED [8’]



SOLAR FLARE
extra radiations mainly X ray

SOLAR BURST
extra radio waves

SOLAR FLARE (8′)

Disturbed 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

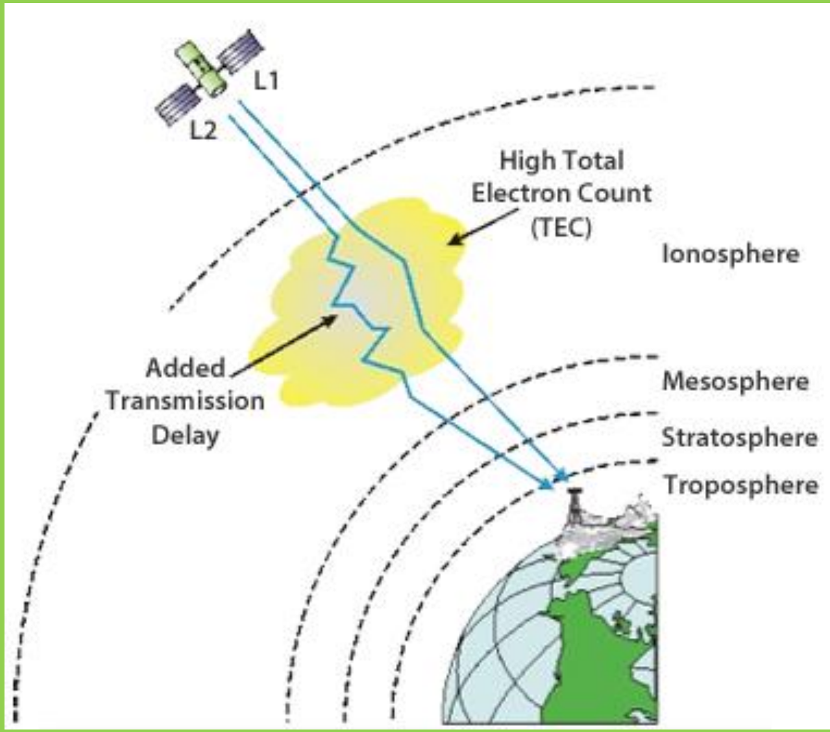
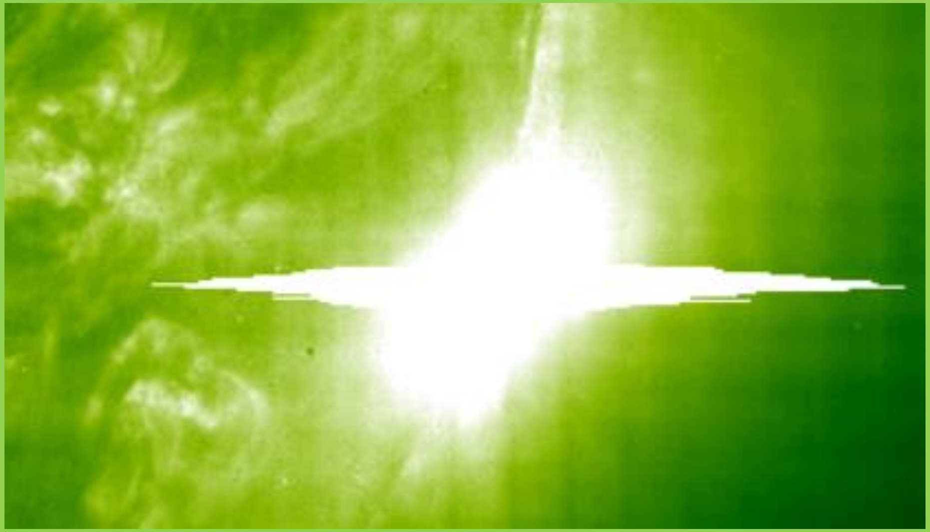


Figure from http://reflexions.ulg.ac.be



SOHO data

The Sweden Case: Airplanes disappear from radars due to "solar storm"

Posted by Adonai on November 05, 2015 in categories Featured articles, Geomagnetic storms, Solar activity

Follow @TheWatchers_

Radio Bursts : extra radio emission + Solar Flare: extra X ray

"The **2015 Nov. 4th** event was a radio burst **[15.30 to 16.30 LT]** exceeding everything before. It was so strong that neither GPS nor radar nor communication nor instrument landing system did work properly. All these receivers were completely saturated by the radio radiation, instruments went blind. "

from Christian Monstein

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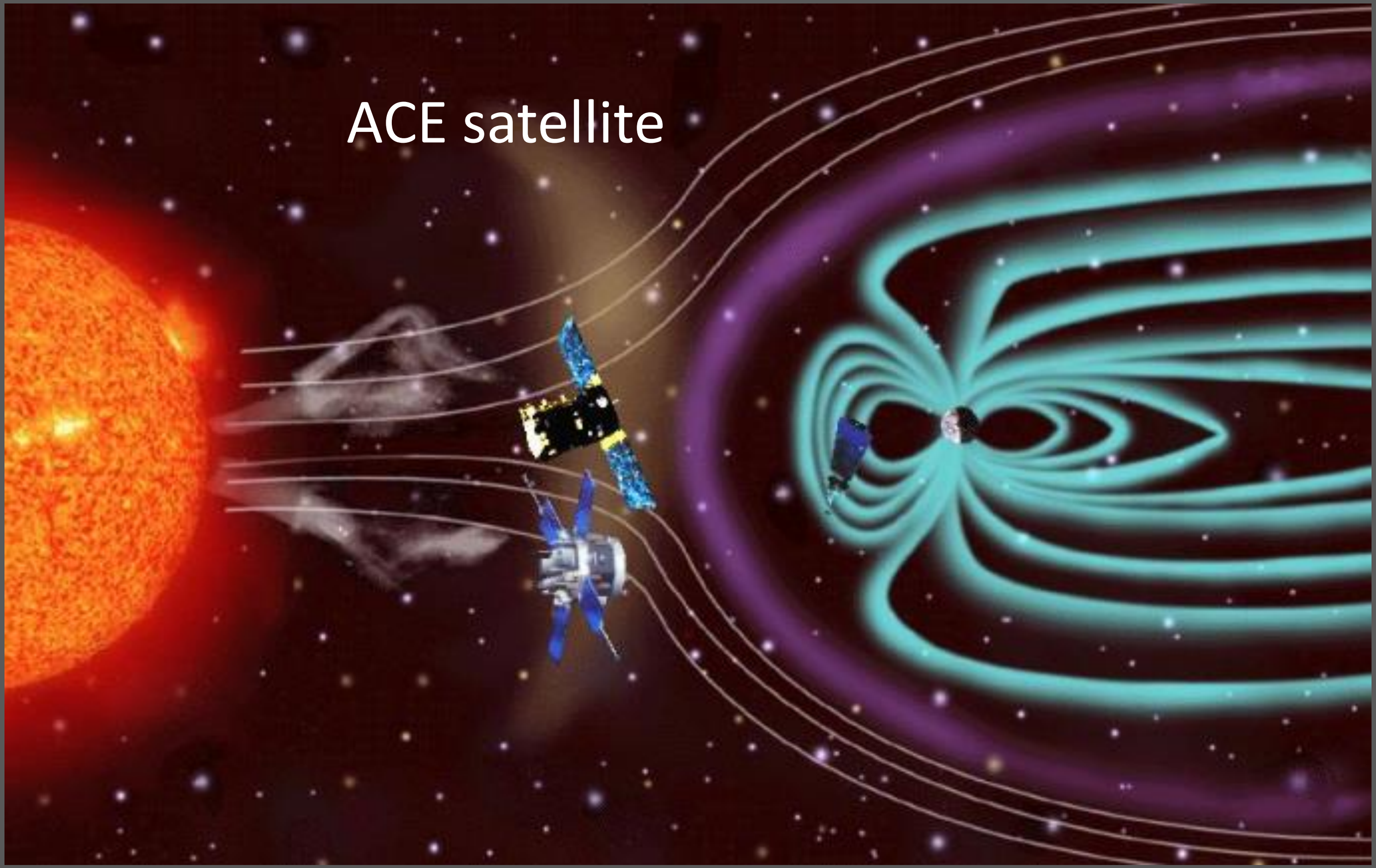
FROM THE SUN TO THE EARTH
SOLAR WIND /PARTICLES[1-4 days]

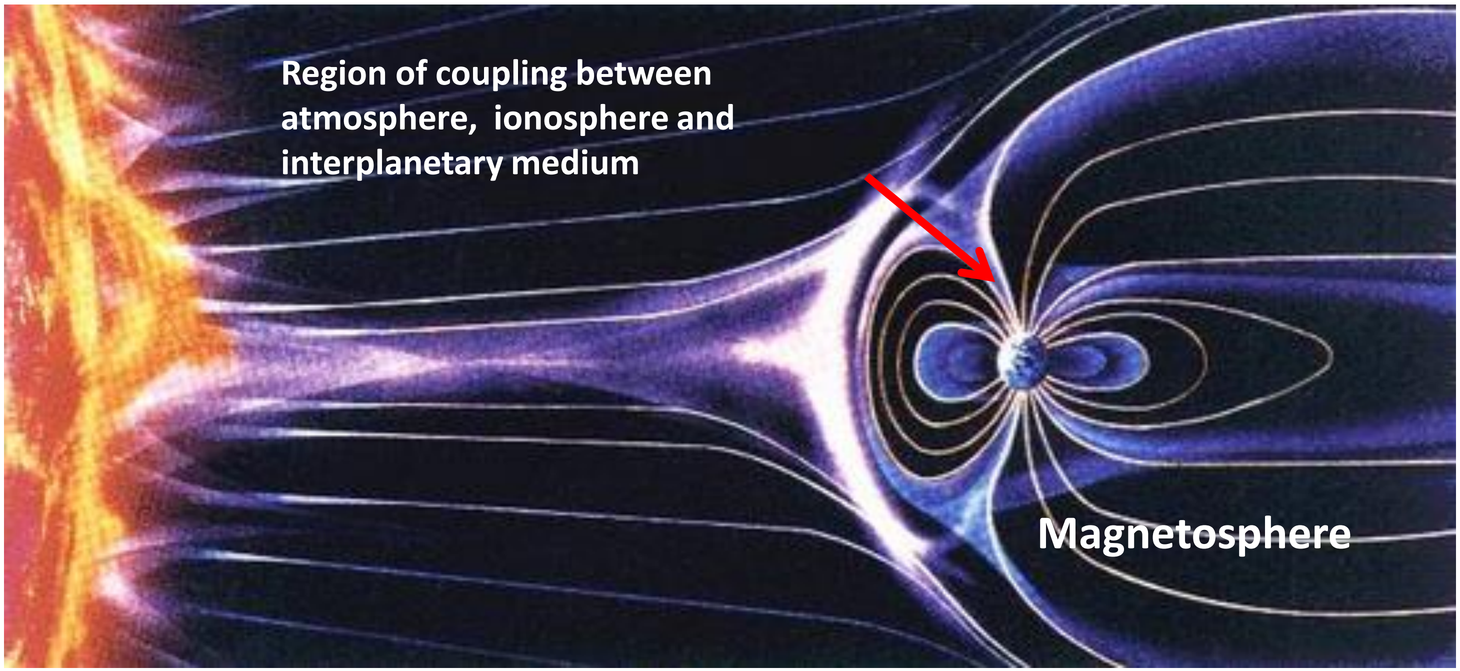


The solar wind carries part of the solar magnetic field towards the Earth : Interplanetary Magnetic Field, IMF.

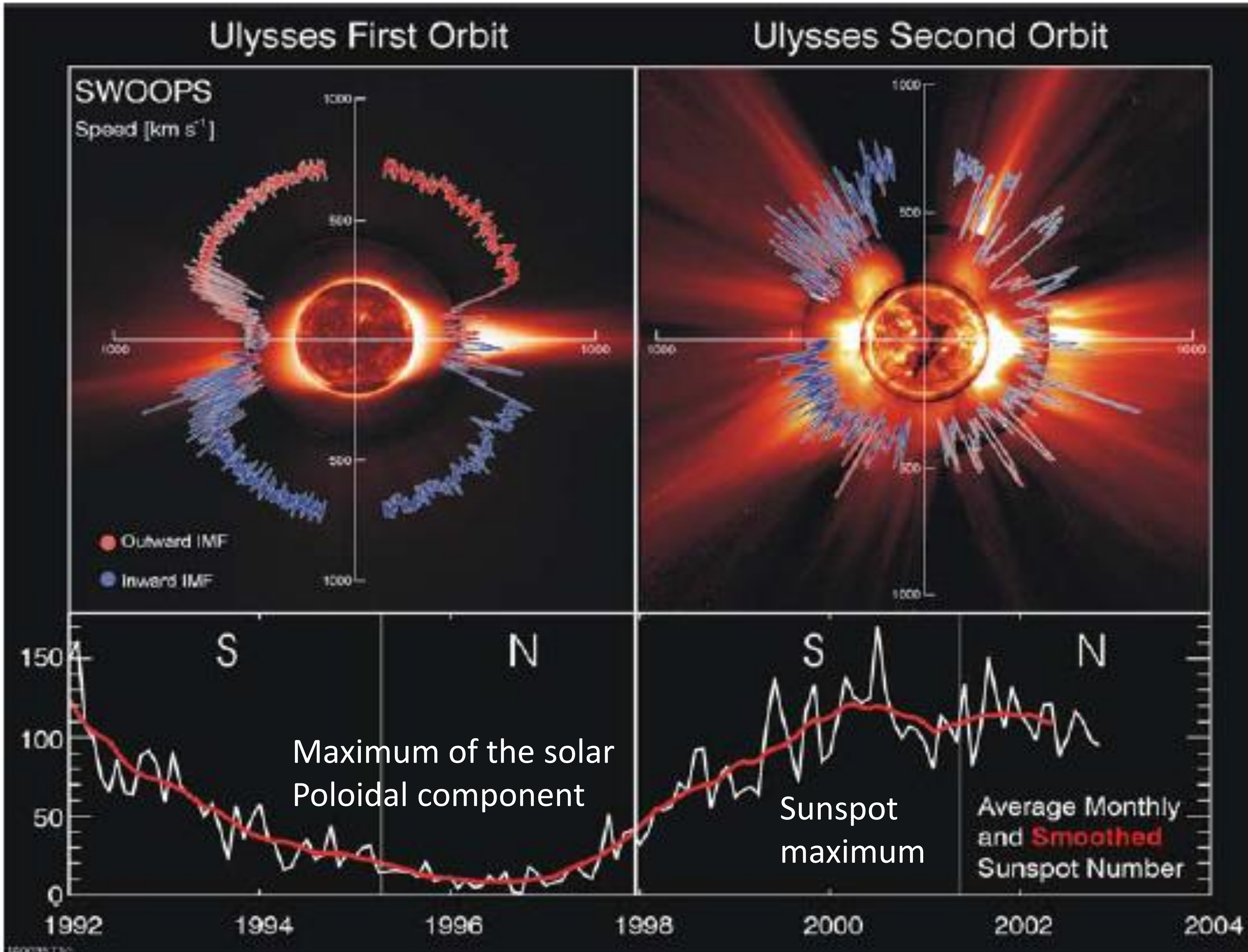
PARTICLES Channel

Regular solar wind : V ~ 350-400km/s
Time ~ 2-3 days

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



Ulysses First Orbit
Ulysses Second Orbit
SWOOPS
Speed [km s-1]
1000
500
1000
1000
500
1000
Outward IMF
Inward IMF
1000
500
1000
1000
500
1000
S
N
S
N
150
100
50
0
1992
1994
1996
1998
2000
2002
2004
Maximum of the solar
Poloidal component
Sunspot
maximum
Average Monthly
and Smoothed
Sunspot Number

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INTERACTION BETWEEN THE SOLAR WIND and THE MAGNETOSPHERE

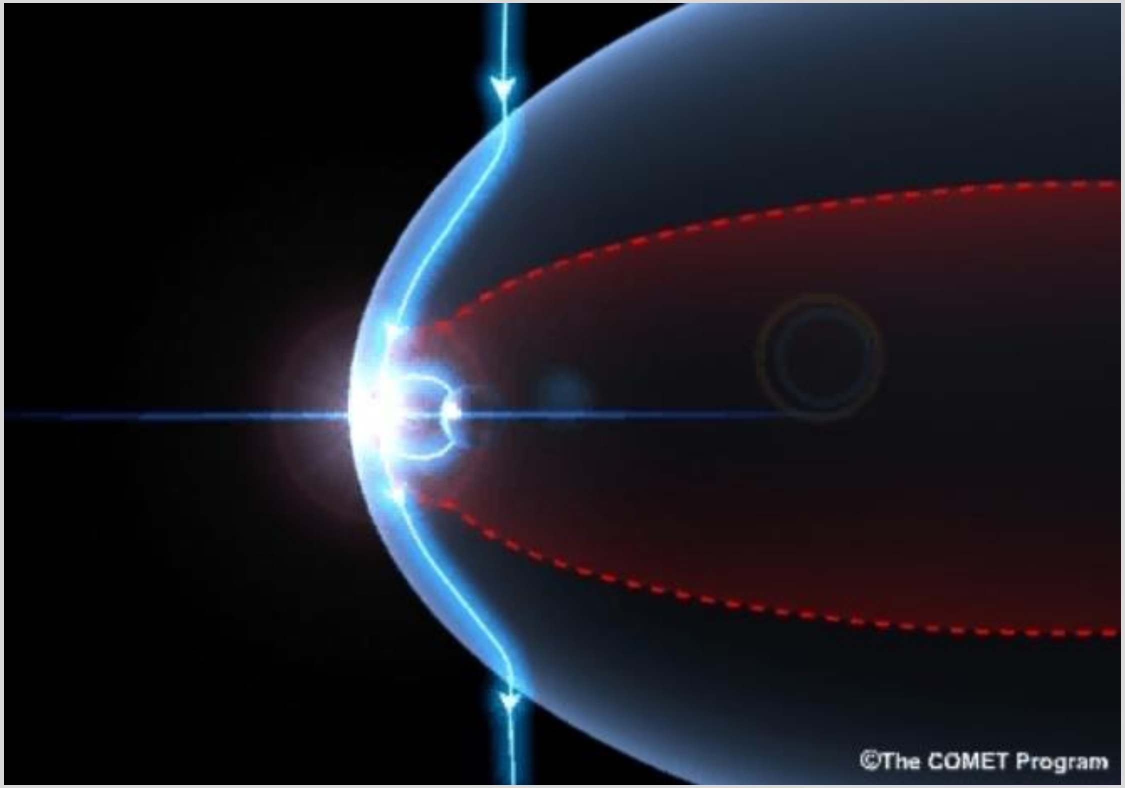
Physical processes : Reconnection and Dynamo

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

Omniweb data base
$E_y = - V_x . B_z$

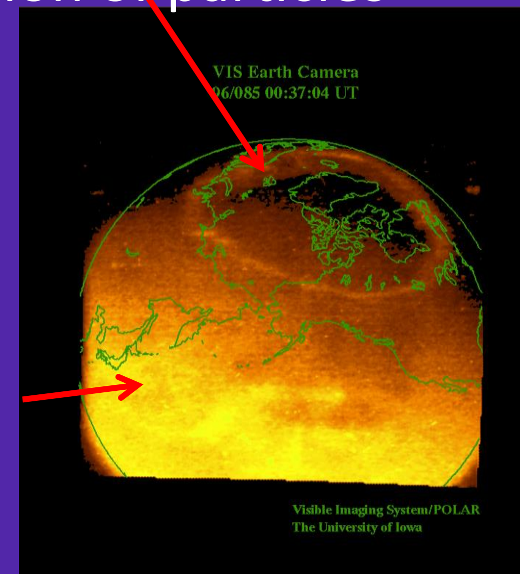


Solar wind – Magnetosphere Dynamo : E=VsxB
movement is converted into electrical energy

AURORA : THE MOST SPECTACULAR PHENOMENON OF SPACE WEATHER

Regular auroral oval due
to precipitation of particles

Dayside
regular solar
radiation
photo ionisation



Physical processes : precipitation and ionization

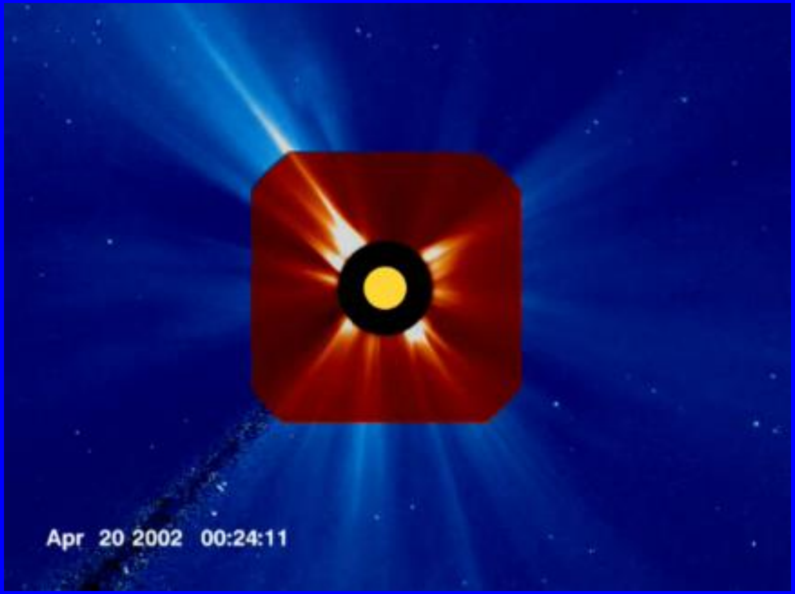
The particles follow the lines of the earth's magnetic field and rush to the atmosphere where they ionize the atmosphere.

There is an increase in electronic density and TEC

CORONAL MASS EJECTION
CME : billions tons of matter ejected from the sun

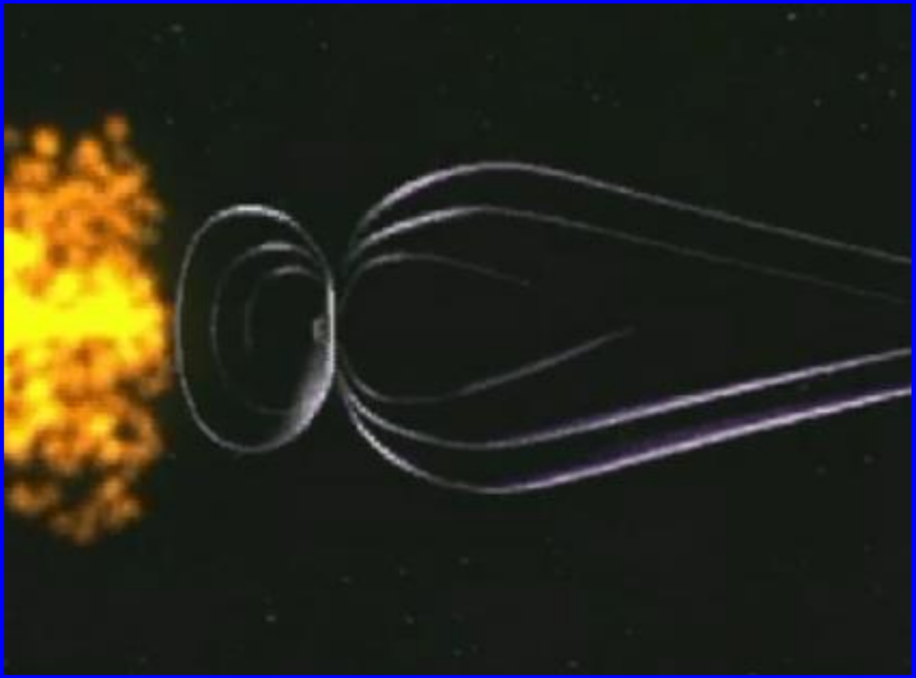
Near the sun

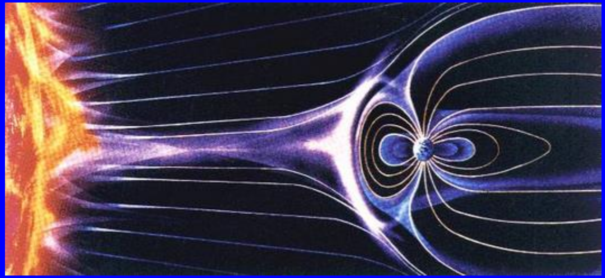
SOHO satellite data



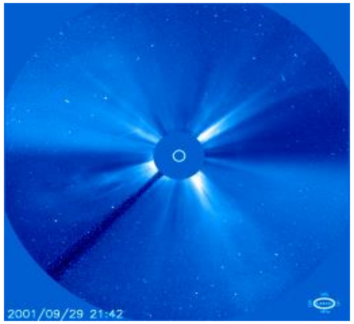
From the Sun to the Earth

Movie from the NASA





CME produce magnetic storms
if the IMF inside the CME is southward

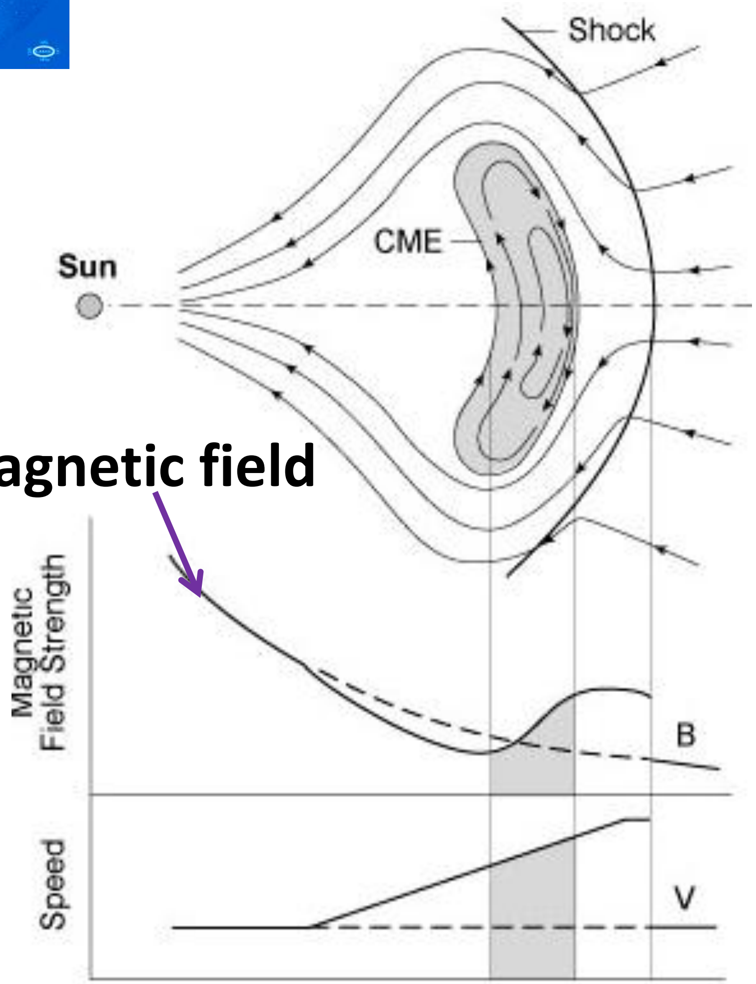


Interplanetary CME Shocks

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

A fast coronal mass ejection CME pushes an interplanetary shock wave

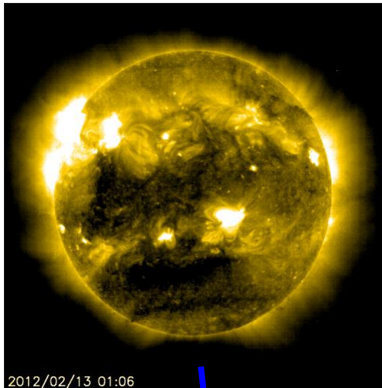
Strong magnetic field

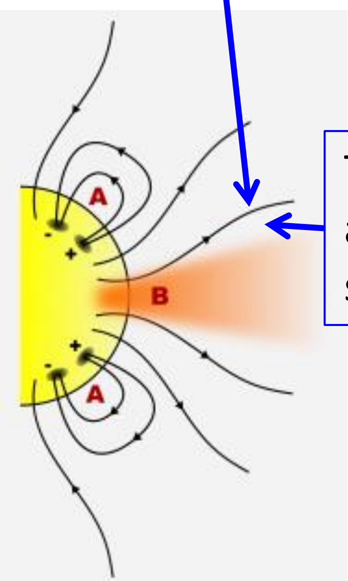


Increases of solar wind speed V and magnetic field strenght B by the interplanetary shock wave in front f the CME

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

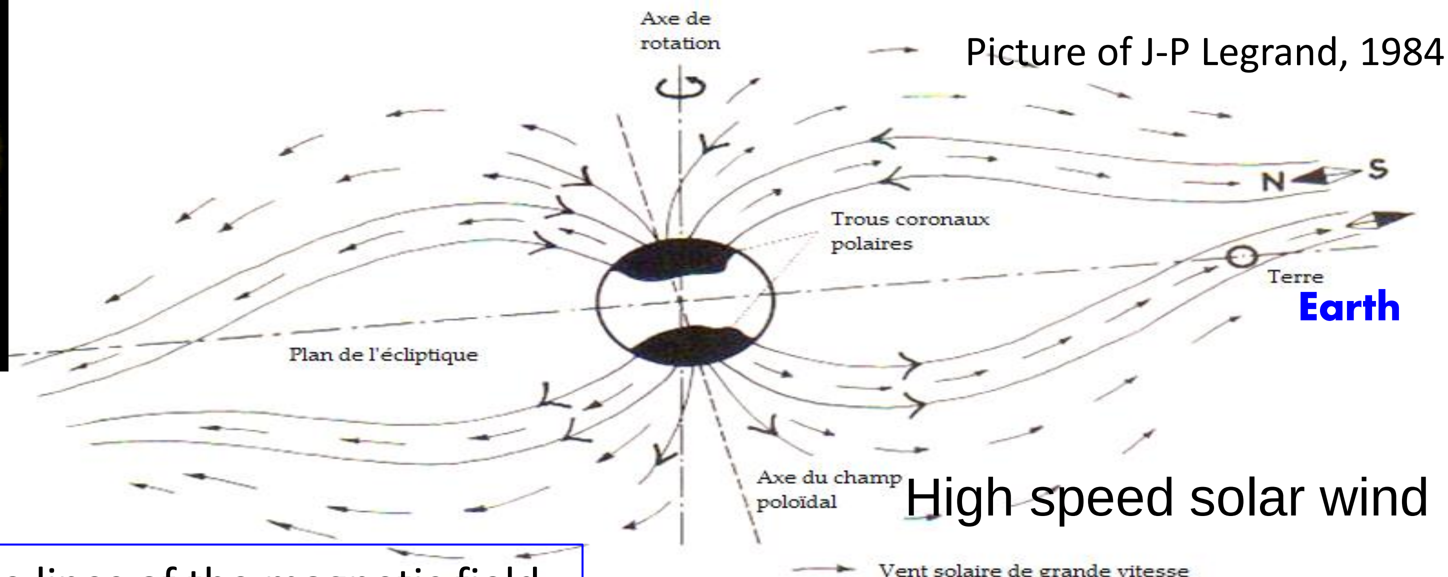
CORONAL HOLE – reccurrent geomagnetic activity

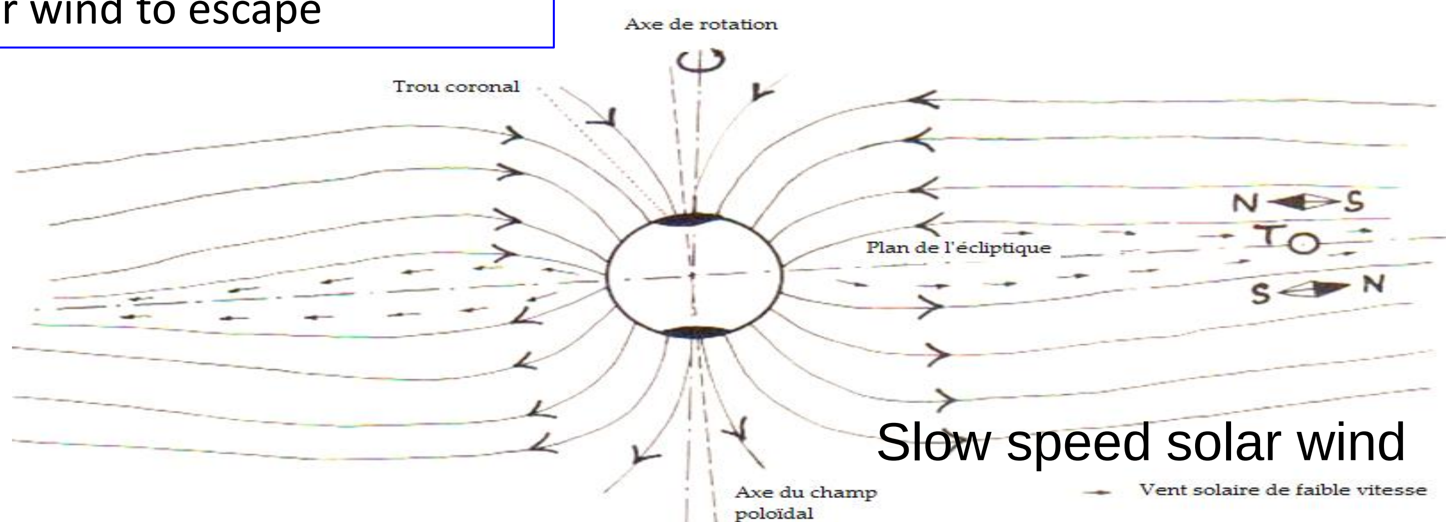




The lines of the magnetic field are open .This allows for the solar wind to escape

Picture of J-P Legrand, 1984





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

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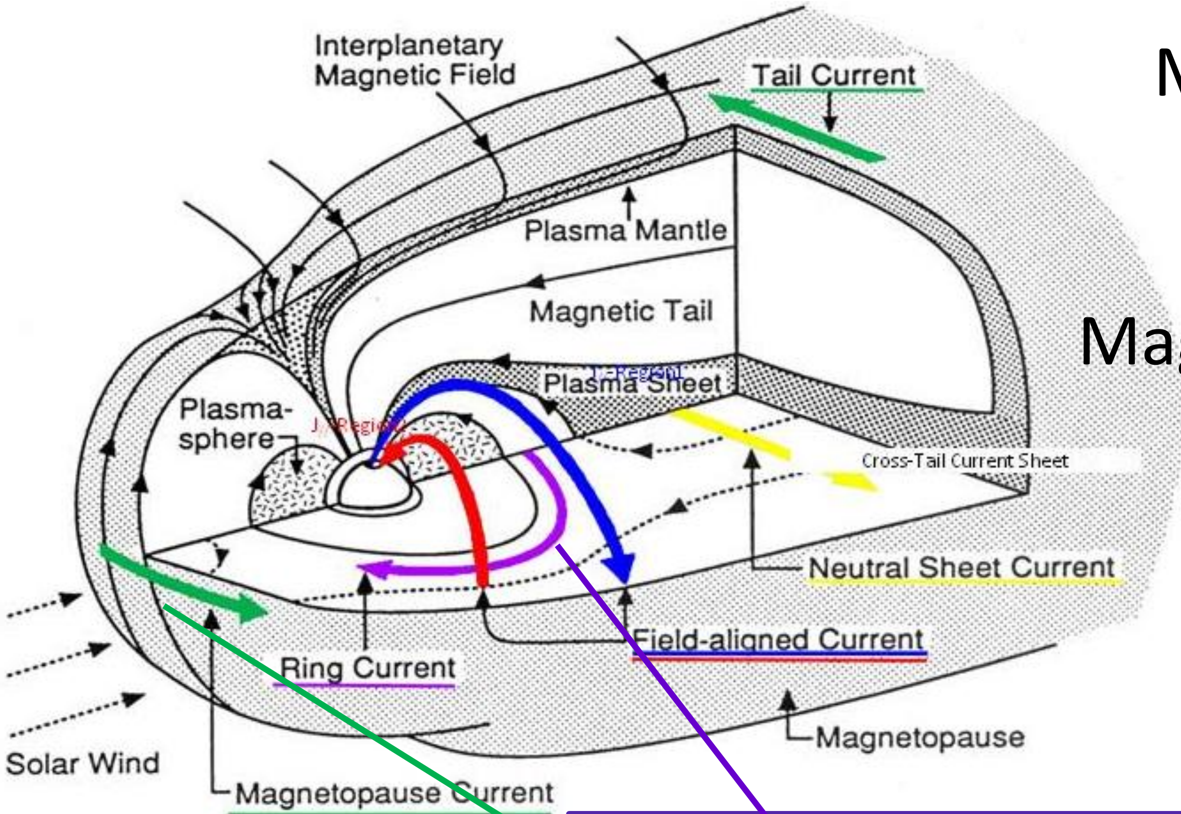
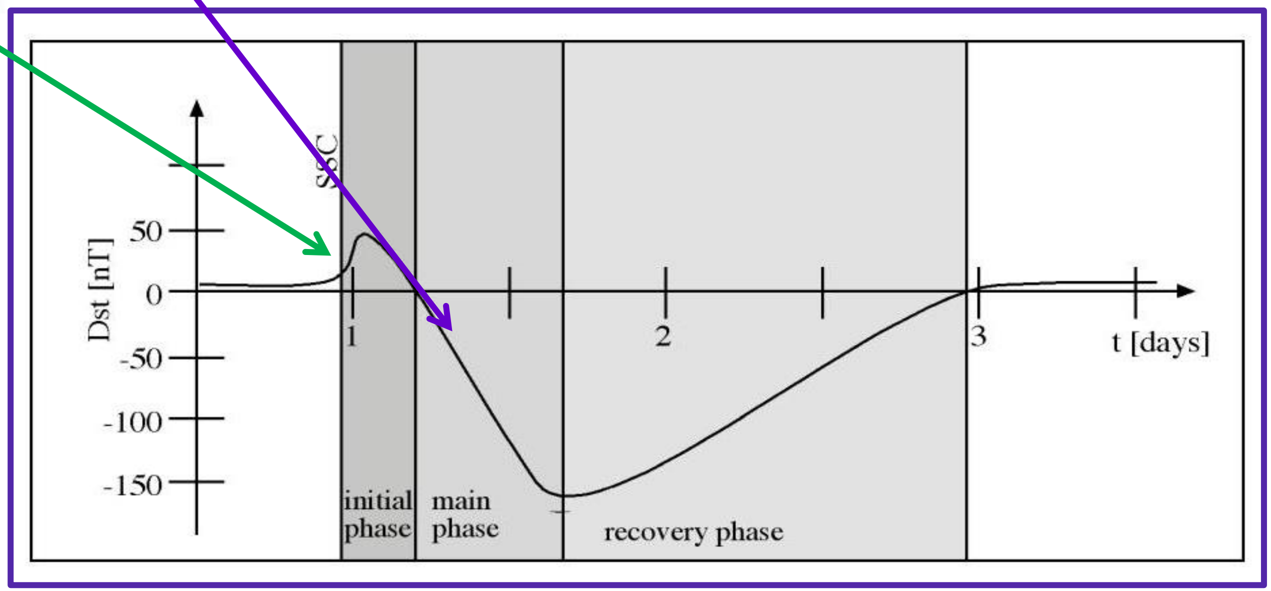
MAGNETOSPHERE
Electric currents

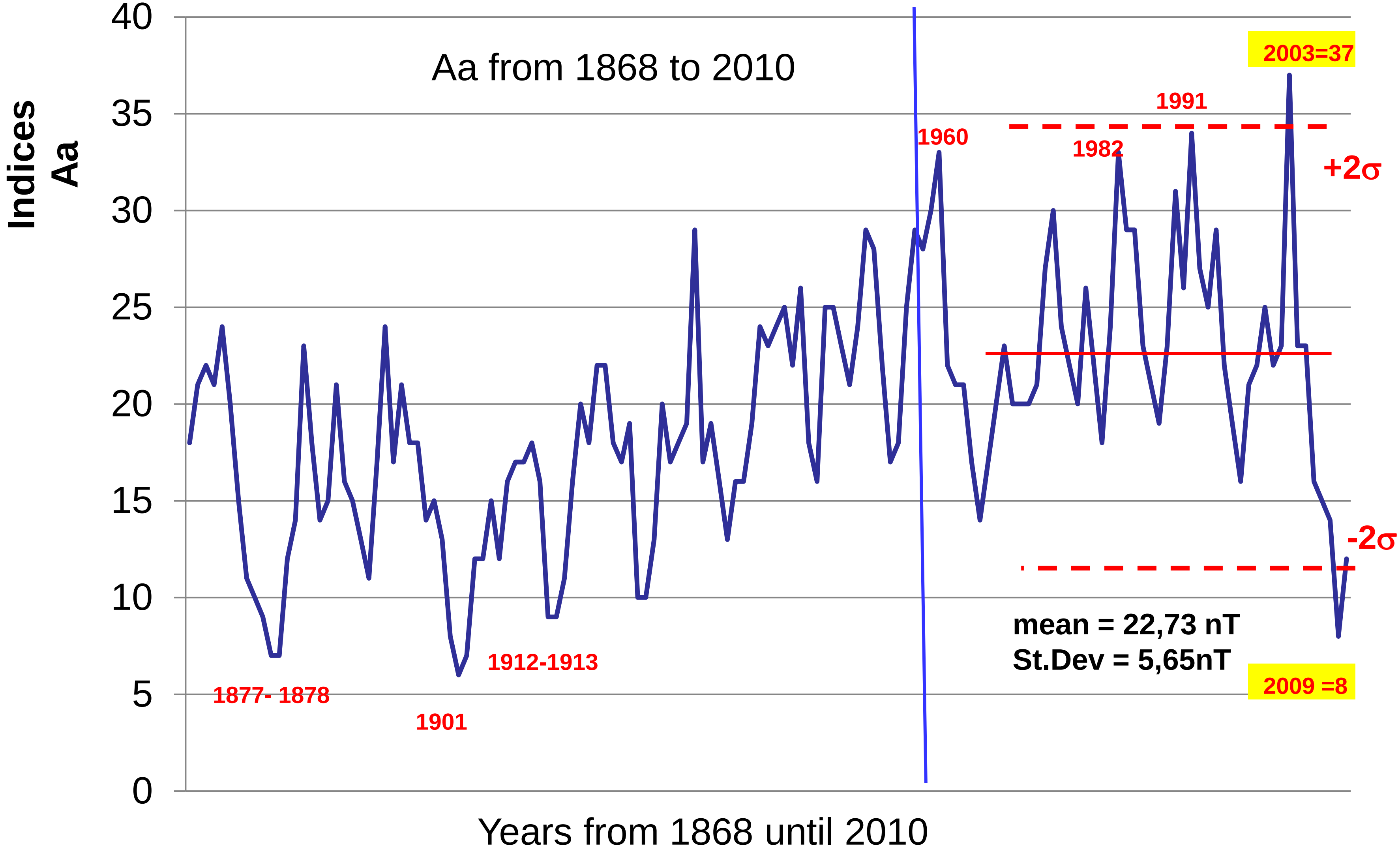
Magnetic storm indices

Dst, SYM-H *





GEOMAGNETIC ACTIVITY



Zerbo, J-L., C. Amory-Mazaudier, F. Ouattara, Geomagnetism during solar cycle 23: Characteristics, 2012, J. Adv Res http://dx.doi.org/10.1016/j.jare.2012.08.010

Pixel diagram of the daily mean Aa magnetic indices

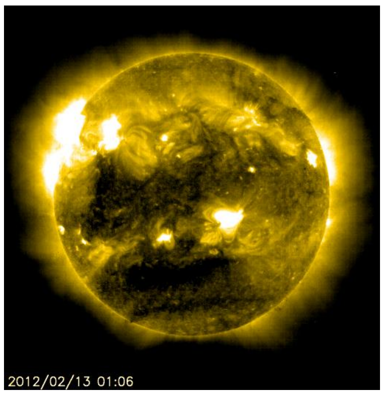
YEAR 2003

Solar rotations

01-janv	2003																							14	12	40	29	17	8	12	8
07-janv	17	8	12	8	7	28	17	19	14	18	13	8	16	29	41	30	33	37	32	32	46	39	23	20	34	47	31	28	81	35	52
03-févr	28	81	35	52	27	32	27	30	33	29	18	26	14	37	39	32	23	46	24	32	25	22	22	14	10	30	52	37	31	23	36
02-mars	37	31	23	36	52	33	48	26	20	20	30	21	16	26	43	49	49	57	41	22	47	49	28	38	12	7	16	46	42	53	57
29-mars	46	42	53	57	54	29	44	32	57	43	16	12	38	39	41	25	17	19	30	29	58	46	37	16	24	43	42	33	46	49	35
25-avr	33	46	49	35	31	29	34	56	64	27	22	11	25	50	61	65	55	49	381	41	41	46	39	16	15	17	22	21	45	48	31
22-mai	21	45	48	31	44	31	31	52	50	122	75	39	35	60	44	37	23	25	40	53	46	37	26	13	15	46	37	63	71	81	23
18-juin	63	71	81	23	23	45	27	37	44	35	34	50	62	41	33	14	26	29	37	32	17	28	5	7	15	66	61	27	26	51	74
15-juil	27	26	51	74	37	32	50	32	11	11	16	15	15	44	35	29	59	49	52	61	38	27	21	12	46	52	52	28	21	18	45
11-août	28	21	18	45	28	29	23	16	40	110	24	26	78	70	59	33	37	24	19	29	28	23	14	23	20	29	44	31	17	7	11
07-sept	31	17	7	11	40	36	27	18	17	9	11	58	90	72	54	42	34	33	29	55	50	29	9	8	7	10	18	16	28	11	12
04-oct	16	28	11	12	20	32	15	13	6	3	9	31	80	64	47	50	41	53	50	66	55	12	59	36	23	17	43	299	230	179	41
31-oct	299	230	179	41	31	24	55	13	32	15	20	51	48	78	48	76	57	62	61	53	46	24	228	59	46	40	27	27	16	11	11
27-nov	27	16	11	11	11	29	17	14	9	13	66	39	29	65	54	67	64	43	45	48	38	19	14	7	4	39	45	35	15	17	12
24-déc	35	15	17	12	15	21	25	11	15	39																					

aa (nT)
100
60
40
30
20
10

Equatorial coronal hole



Pixel diagram of the daily mean solar wind

01-janv	2003																							403	370	496	574	432	397	358	288
07-janv	432	397	358	288	288	426	434	402	396	385	404	341	337	394	551	655	673	587	642	687	743	676	505	445	428	482	516	539	513	483	580
03-févr	539	513	483	580	568	489	494	505	459	439	401	376	385	500	569	632	625	604	545	644	595	579	583	484	423	429	549	461	422	402	399
02-mars	461	422	402	399	506	482	515	473	420	402	400	422	444	462	578	624	680	720	777	707	695	688	627	613	551	415	385	474	488	428	541
29-mars	474	488	428	541	560	526	495	459	483	491	459	373	423	432	630	659	591	500	522	579	718	708	625	596	529	549	562	501	495	540	446
25-avr	501	495	540	446	482	449	508	587	630	578	506	414	525	695	712	759	786	626	620	675	721	743	668	593	516	427	428	421	446	491	473
22-mai	421	446	491	473	495	536	471	524	687	678	676	700	606	724	797	782	601	620	650	746	684	694	641	526	425	514	544	512	500	546	563
18-juin	512	500	546	563	538	531	525	501	542	561	580	691	703	743	762	636	510	540	737	742	640	570	468	424	355	387	621	562	499	569	586
15-juil	562	499	569	586	617	617	559	632	490	448	446	402	326	397	680	649	747	764	795	799	735	630	527	444	495	539	706	688	614	575	657
11-août	688	614	575	657	537	476	370		560	513	423	413	609	752	752	618	628	535	473	430	488	549	439	439	521	490	612	642	587	470	409
07-sept	642	587	470	409	540	649	642	600	520	417	364	422	678	770	714	675	581	565	488	606	692	582	460	381	321	307	282	344	468	465	394
04-oct	344	468	465	394	483	548	568	567	453	388	344	351	461	598	514	464	407	451	422	319	412	465	536	543	478	485	685	522	907	918	665
31-oct	522	907	918	665	523	521	629	529	461	465	427	525	534	696	683	662	624	649	728	732	687	529	554	514	514	539	530	576	491	461	394
27-nov	576	491	461	394	347	456	418	420	340	318	428	473	411	507	661	723	772	701	727	708	686	550	413	362	301	380	481	554	512	429	394
24-déc	554	512	429	394	371	460	506	535	348	381																					

V (Km/s)
650
600
550
500
450
350
0

Mayaud 1971,1973
Legrand and Simon, 1989
Zerbo et al., 2012

YEAR 2009

Most magnetic quiet year since 1901

Pixel diagram of the daily mean Aa magnetic indices

01-Janua	2009																												16	10	21
02-Janua	28	16	10	21	10	11	7	5	7	13	11	3	2	11	13	13	9	6	6	19	9	9	5	5	4	8	29	9	5	7	9
29-Janua	9	5	7	9	14	5	3	9	28	12	3	5	3	5	5	6	8	5	36	25	8	3	7	4	11	7	9	13	12	6	6
25-Febru	13	12	6	6	22	10	6	4	17	14	5	4	2	15	3	8	8	15	32	19	14	11	6	4	10	7	21	9	3	16	17
24-March	9	3	16	17	10	11	5	5	8	5	6	3	4	4	7	5	5	13	28	17	21	12	7	4	8	9	10	15	9	6	6
20-April	15	9	6	6	7	3	11	8	5	6	4	7	4	5	7	4	6	4	13	15	21	12	6	8	3	4	14	4	8	3	4
17-May	4	8	3	4	6	10	7	10	8	5	2	5	2	11	9	6	5	3	3	8	9	8	5	9	4	4	6	4	2	6	9
13-June	4	2	6	9	6	6	4	5	3	8	13	4	7	32	14	5	9	22	15	8	4	4	6	5	8	5	8	7	10	14	6
10-July	7	10	14	6	5	18	13	7	3	2	3	2	11	7	39	13	9	7	5	7	6	4	8	9	7	5	11	7	11	22	13
06-Augus	7	11	22	13	5	12	6	5	6	6	4	3	3	4	4	16	22	16	9	8	3	5	6	12	4	2	37	9	6	5	10
02-Septe	9	6	5	10	14	4	7	3	3	4	5	8	4	10	10	10	11	10	5	2	9	13	5	2	3	3	7	13	19	2	11
29-Septe	13	19	2	11	3	3	3	11	4	3	2	4	5	4	18	3	7	3	14	5	2	4	5	2	3	28	18	20	11	7	6
26-Octob	20	11	7	6	6	11	16	5	8	8	3	3	2	3	3	18	6	3	2	3	4	13	12	4	3	5	5	5	18	9	2
22-Noven	5	18	9	2	18	13	14	4	7	3	3	2	3	2	2	9	6	7	2	2	3	2	8	7	12	3	10	7	7	4	5
19-Decen	7	7	4	5	10	11	12	8	12	10	8	6	5	4	6																

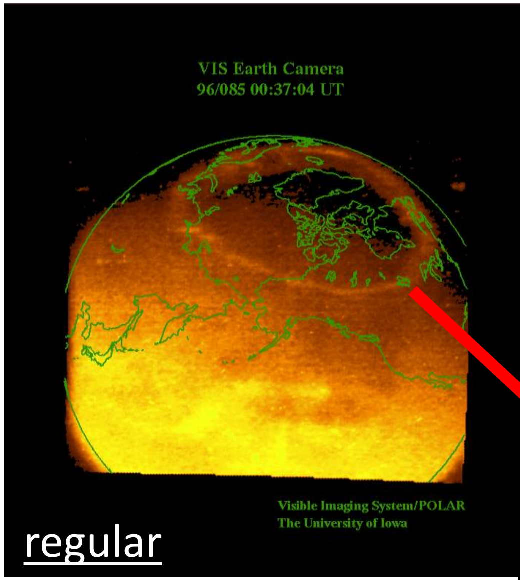
aa (nT): 100, 60, 40, 30, 20, 10

Pixel diagram of the daily mean solar wind

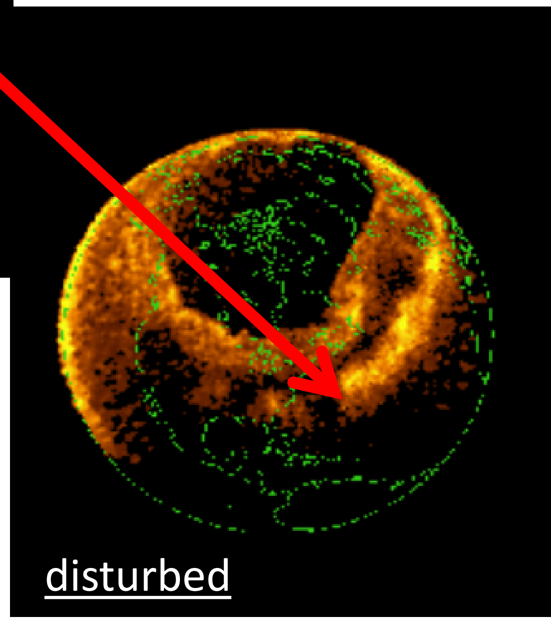
01-janv	2009																												456	424	513
02-janv	485	456	424	513	459	420	369	323	315	366	378	343	309	303	334	343	378	350	355	434	433	409	341	311	301	294	350	368	359	397	373
29-janv	368	359	397	373	444	394	360	329	357	359	317	316	313	311	294	310	332	310	459	558	475	406	333	311	331	373	431	444	434	418	402
25-févr	444	434	418	402	567	555	437	359	350	362	363	362	336	402	377	325	335	359	503	547	500	423	379	343	307	335	402	419	390	422	478
24-mars	419	390	422	478	454	419	401	420	414	384	384	350	325	293	286	362	391	357	340	453	506	525	496	413	346	318	348	421	493	467	445
20-avr	421	493	467	445	428	392	361	387	408	384	361	336	331	321	310	312	343	363	341	385	451	490	480	412	392	343	313	350	352	363	337
17-mai	350	352	363	337	307	290	301	340	367	368	356	331	312	290	379	382	355	323	316	302	305	314	312	311	338	348	310	346	329	292	288
13-juin	346	329	292	288	316	308	311	301	303	314	319	330	299	269	339	473	427	399	386	517	487	417	375	357	344	346	342	339	321	325	416
10-juil	339	321	325	416	433	383	390	520	457	383	338	300	288	311	319	411	495	548	486	415	400	398	379	352	379	408	362	375	349	374	459
06-août	375	349	374	459	470	426	368	345	354	338	316	293	272	290	330	358	482	503	505	469	382	335	359	369	364	336	398	431	388	345	357
02-sept	431	388	345	357	459	418	384	351	321	303	303	300	301	307	384	425	454	442	405	346	331	418	409	339	301	289	306	333	326	318	344
29-sept	333	326	318	344	342	336	324	360	378	337	288	279	289	265	381	379	350	333	373	395	329	307	307	292	283	345	384	387	416	390	370
26-oct	387	416	390	370	357	363	361	333	348	331	321	288	298	285	266	352	386	351	308	286	285	323	348	332	320	305	335	384	497	506	409
22-nov	384	497	506	409	392	434	396	348	343	328	294	266	274	256	254	282	387	341	311	297	280	266	280	268	273	285	313	362	411	406	372
19-déc	362	411	406	372	350	341	346	389	326	391	371	339	311	279	279																

V (Km/s): 650, 600, 550, 500, 450, 350, 0

MAGNETIC STORMS/Ionospheric electric currents

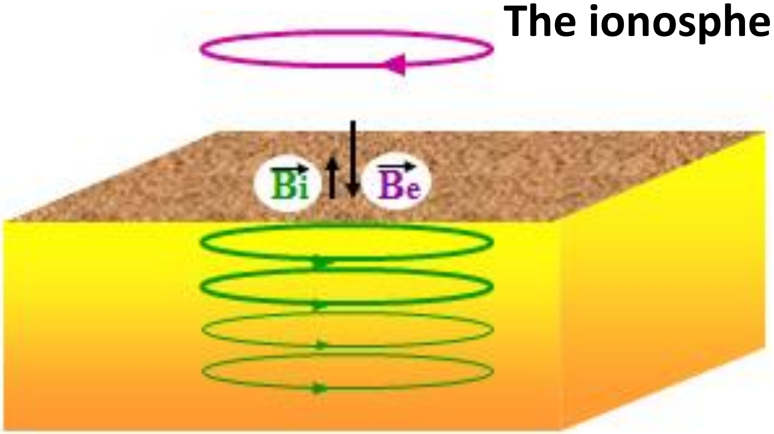


The auroral oval extends toward middle latitudes
the auroral ionospheric electric currents strongly affects low latitudes

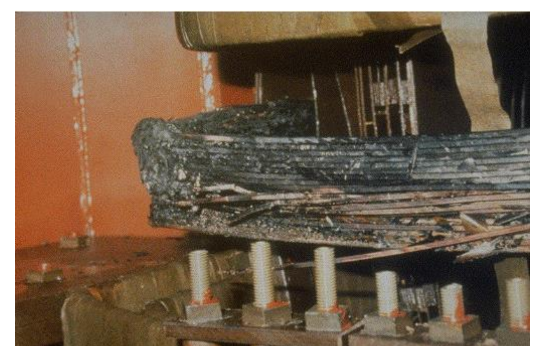


March 13, 1989 - The Quebec Blackout Storm - Most newspapers that reported this event considered the spectacular aurora to be the most newsworthy aspect of the storm. Seen as far south as Florida and Cuba, the vast majority of people in the Northern Hemisphere had never seen such a spectacle in recent 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

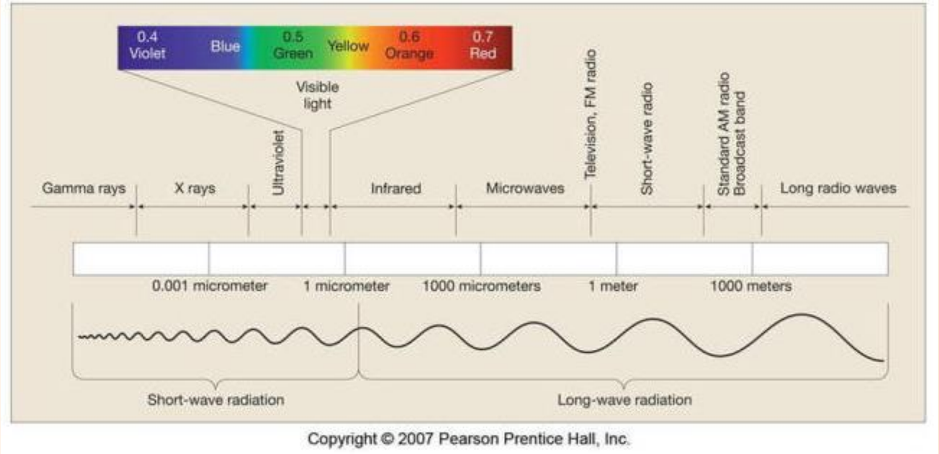


Transformer damaged

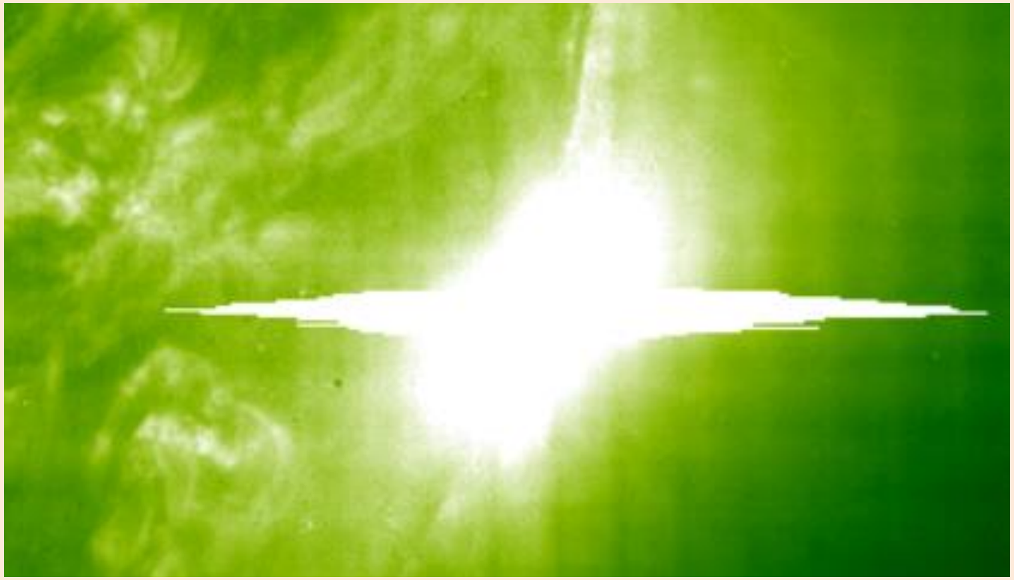
OUTLINES

- Sun and Earth two magnetic bodies in motion
- Emission from the Sun
- Sunspot cycle
- Solar Dynamo: the true solar cycle / solar indices
- Radiation channel regular
  - Ionosphere / Ionospheric dynamo
- Radiation channel disturbed
  - Solar flare
  - Solar Burst
- Particles channel
  - Regular solar wind
- Magnetic storms
  - CME and Coronal hole
  - Geomagnetic activity and solar wind
- Case studies of Space Weather events
  - Solar flare effect, Storm effect
  - Electrodynamics coupling between high and low latitudes
  - Equatorial ionosphere -> Magnetic quiet time, Coronal hole effect, CME effect
- Conclusion

Radiation channel

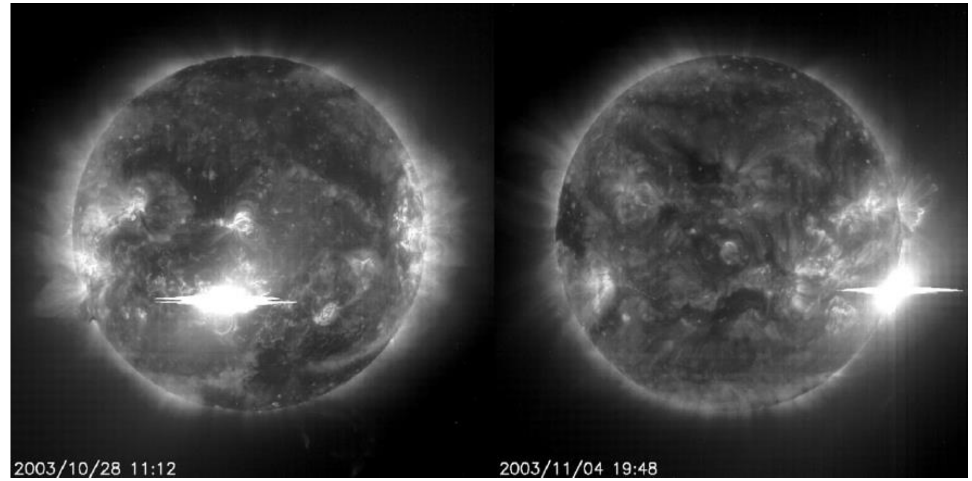


Case studies : solar flare, <u>no interaction with the magnetosphere</u>



SOLAR FLARES

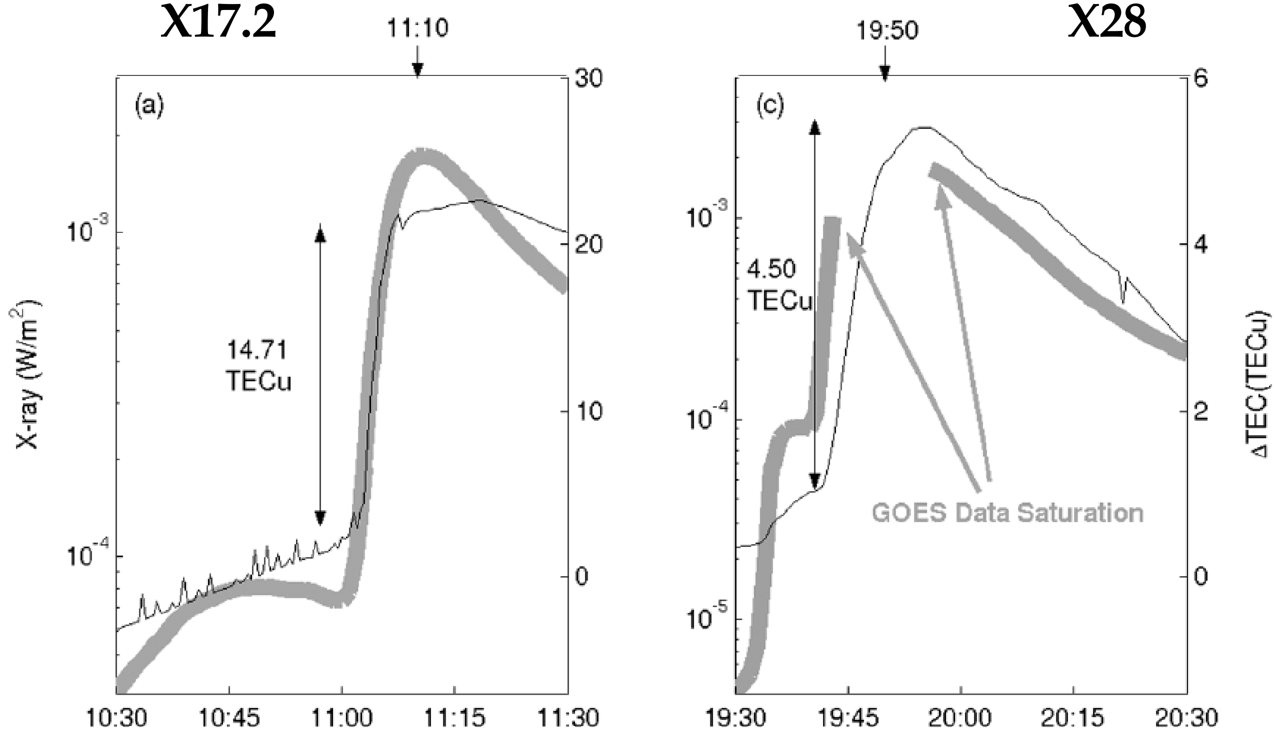
2003/10/28 : 11h12 2003/11/04 : 19h48



SOHO Extreme ultraviolet Imaging Telescope (EIT) of the fourth largest (1) and the largest solar flare (2)

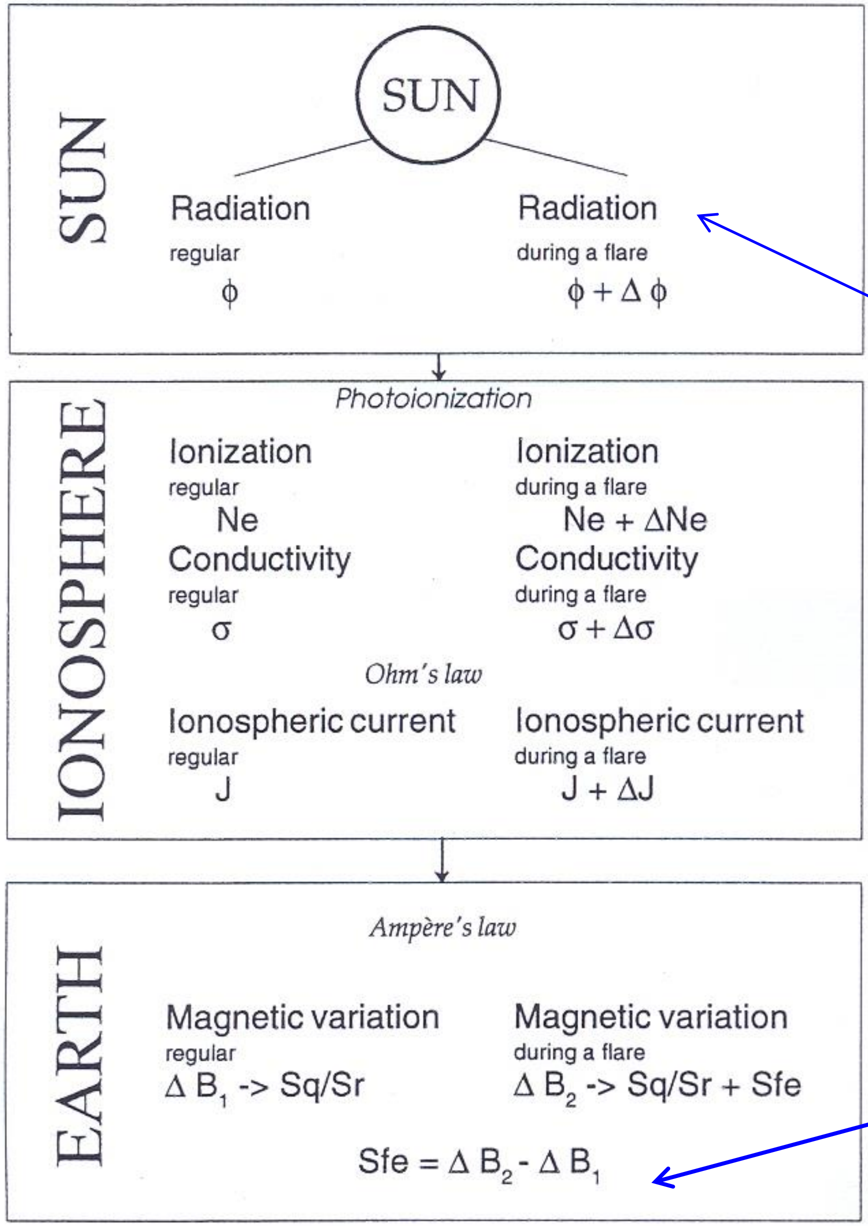
03301 03308

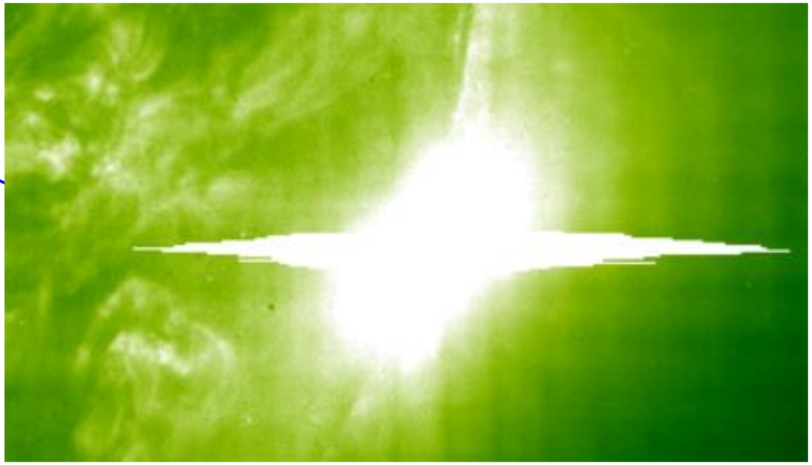
X17.2 **X28**



Liu et al, 2006,
JGR, vol 111, A05308

Observatory of Ebre -J.J Curto PhD 1992 and Curto et al., JGR 1994





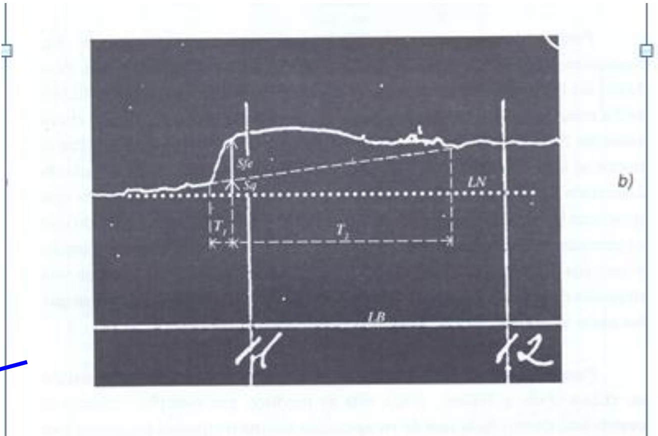


Fig. III.1 *Registro magnético de un sfe en Ebro (dibujo superior) y detalle del mismo sfe para la componente H (dibujo inferior).*

Magnetic variation : crochet

Ionospheric dynamo

Dynamo layer 90-160km

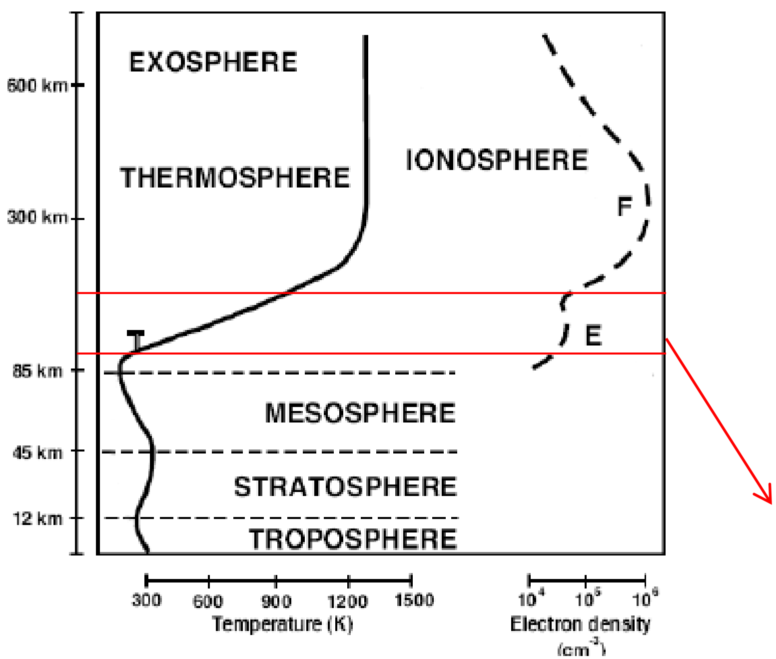


Table 1. Main Processes and Related Models Used.

	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., C. Amory-Mazaudier, J. M. Torta, M. Menvielle, "Study of Solar Flare Effects at Ebre : 2. Unidimensional physical integrated model, J. of Geophys. Research, A, 12 23289-23296,1994.

1 : the solar flare
Radiation on the Sun

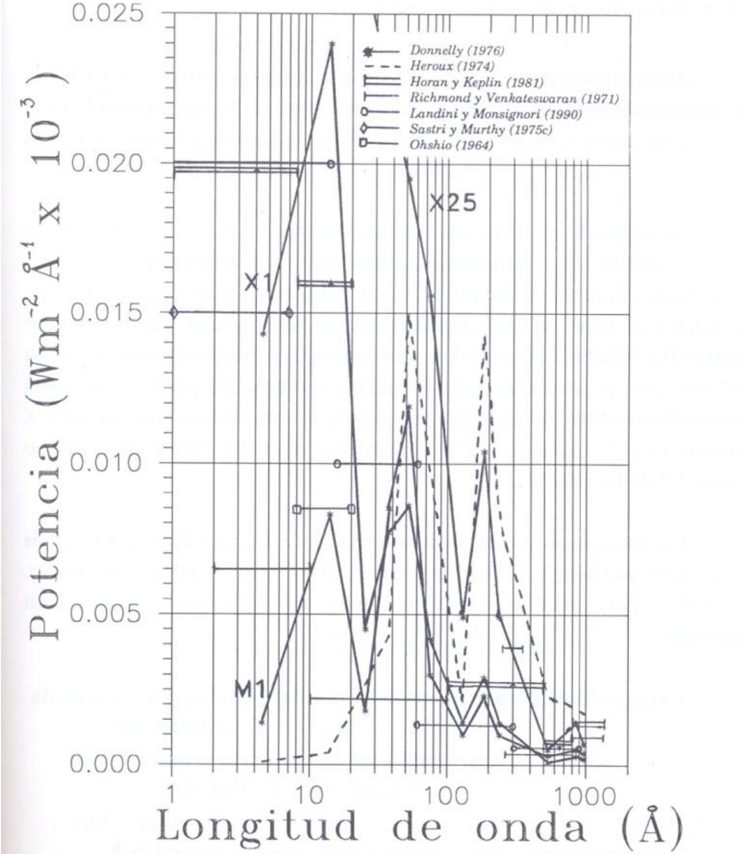


Fig. VI.2 *Valores de la potencia espectral para los distintos modelos de radiación emitida durante una fulguración solar.*

2.: Ionosphere
Increase of ionization

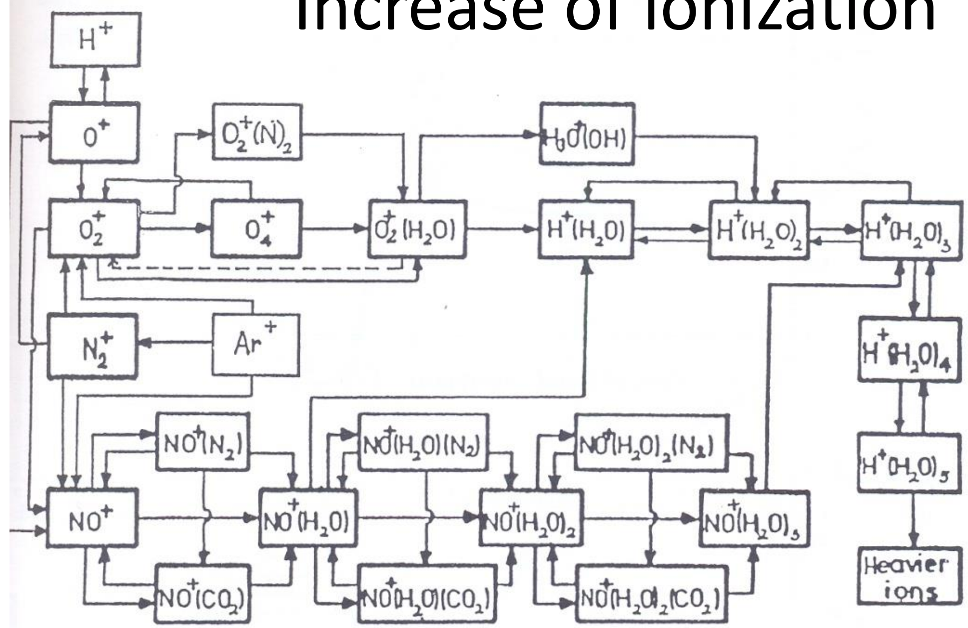


Fig. VI.4 *Esquema de las reacciones químicas principales en el cálculo de los iones positivos. De Dymek (1989).*

From Curto 's PhD 1992
Curto et al., 1994

3 :Ionosphere ; increase of the electric current density

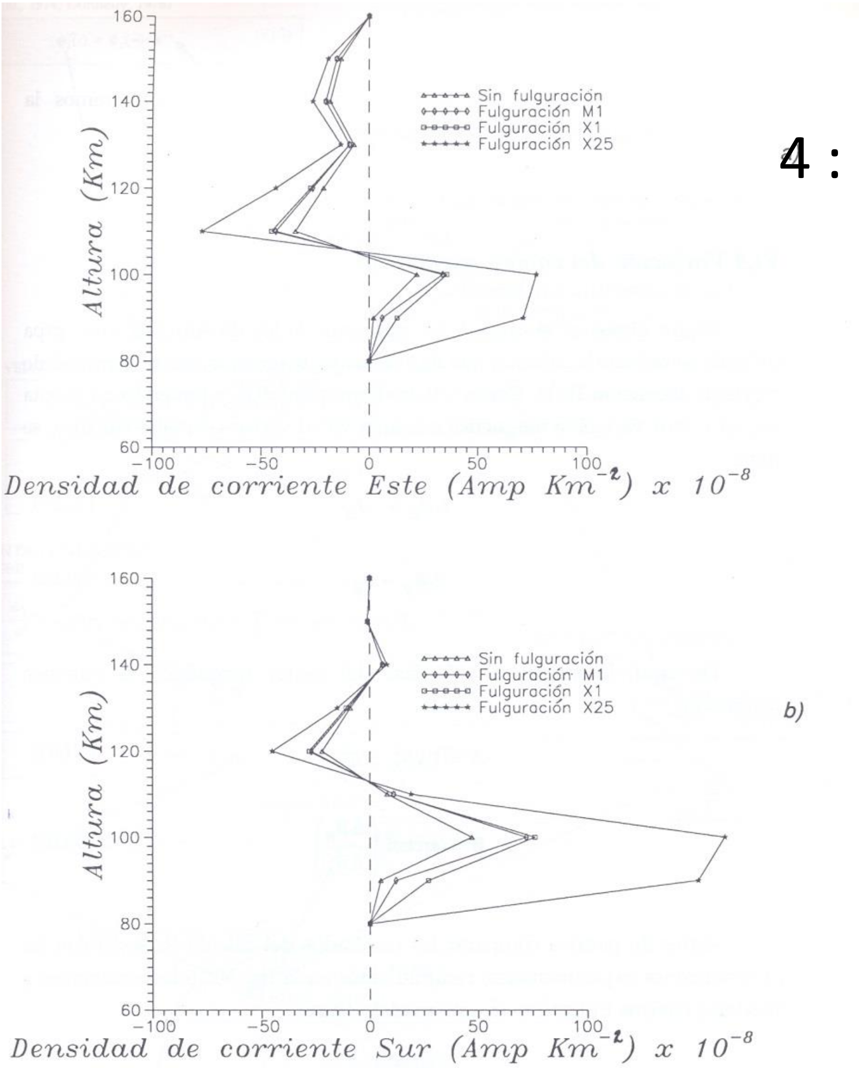
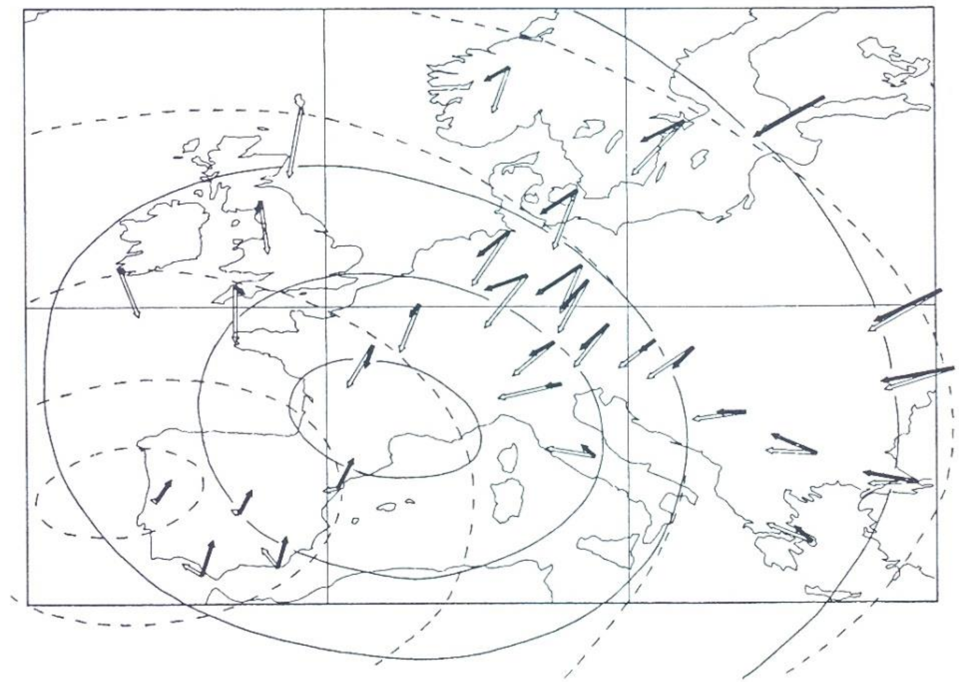


Fig. VI.15 *Densidad de corriente Este (a) y Sur (b) para cada uno de los tipos de fulguración para un día equinoccial medio a las 11 horas locales (en nuestra latitud).*

4 : Magnetic signature of the solar flare
Solar flare -> black arrows



Curto et al., JGR, 1994

Induction Effects of Geomagnetic Disturbances in the Geo-electric Field Variations at Low-latitude

V. Doumbia, et al., 2017,
Ann. Geophys., 35, 1-13.

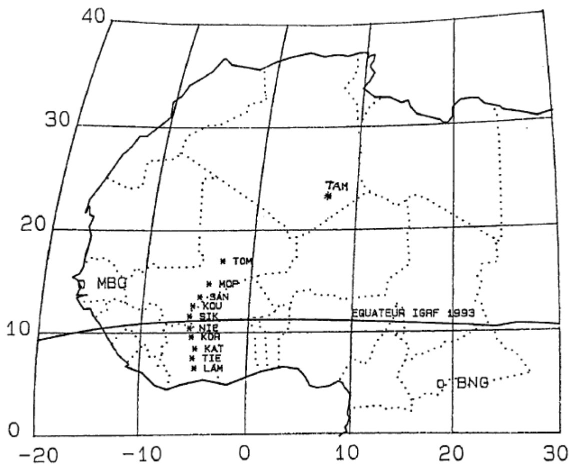
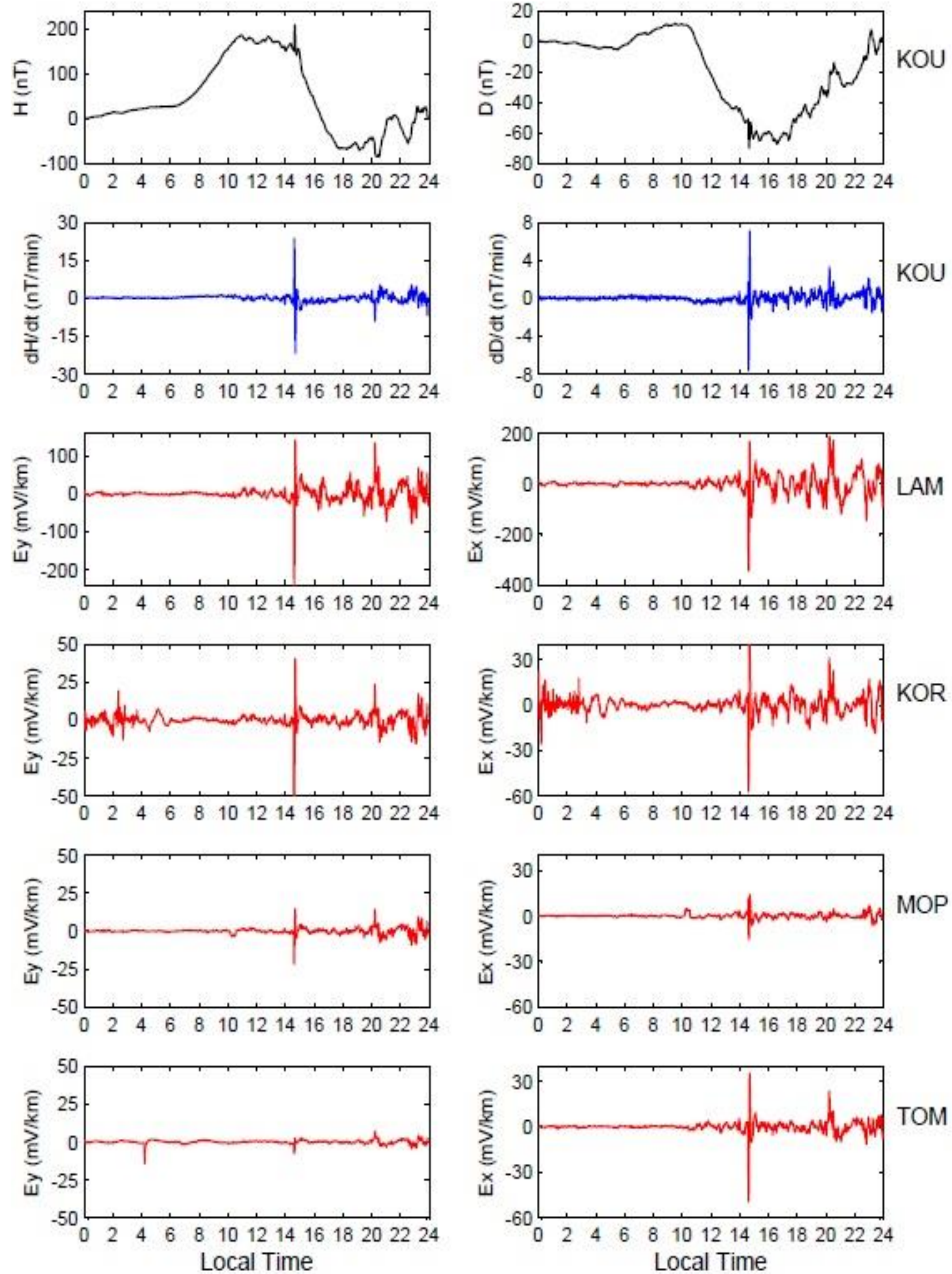


Fig. 1. Experimentation sites of the African sector during the IEEY project.

Magneto telluric station



OUTLINES

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  - Solar Burst
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  - Solar flare effect, Storm effect
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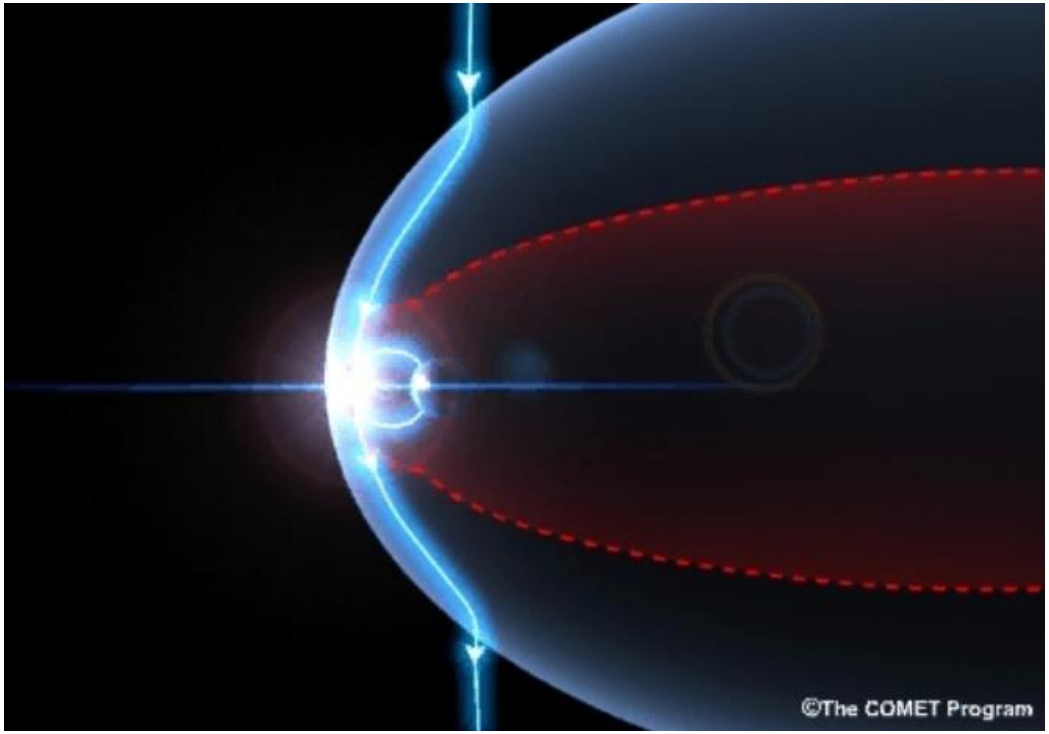
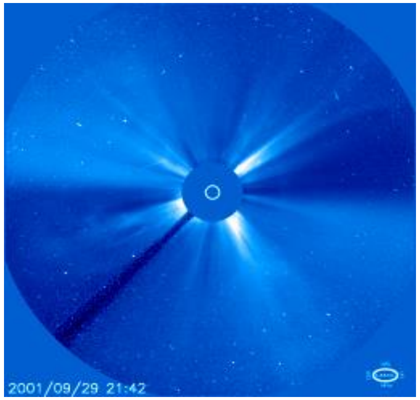
- Conclusion

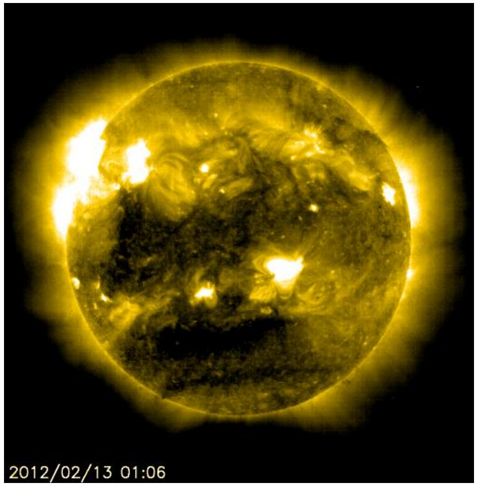


CME

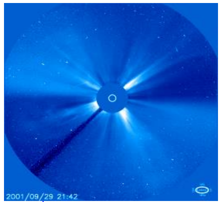


Magnetic Storms

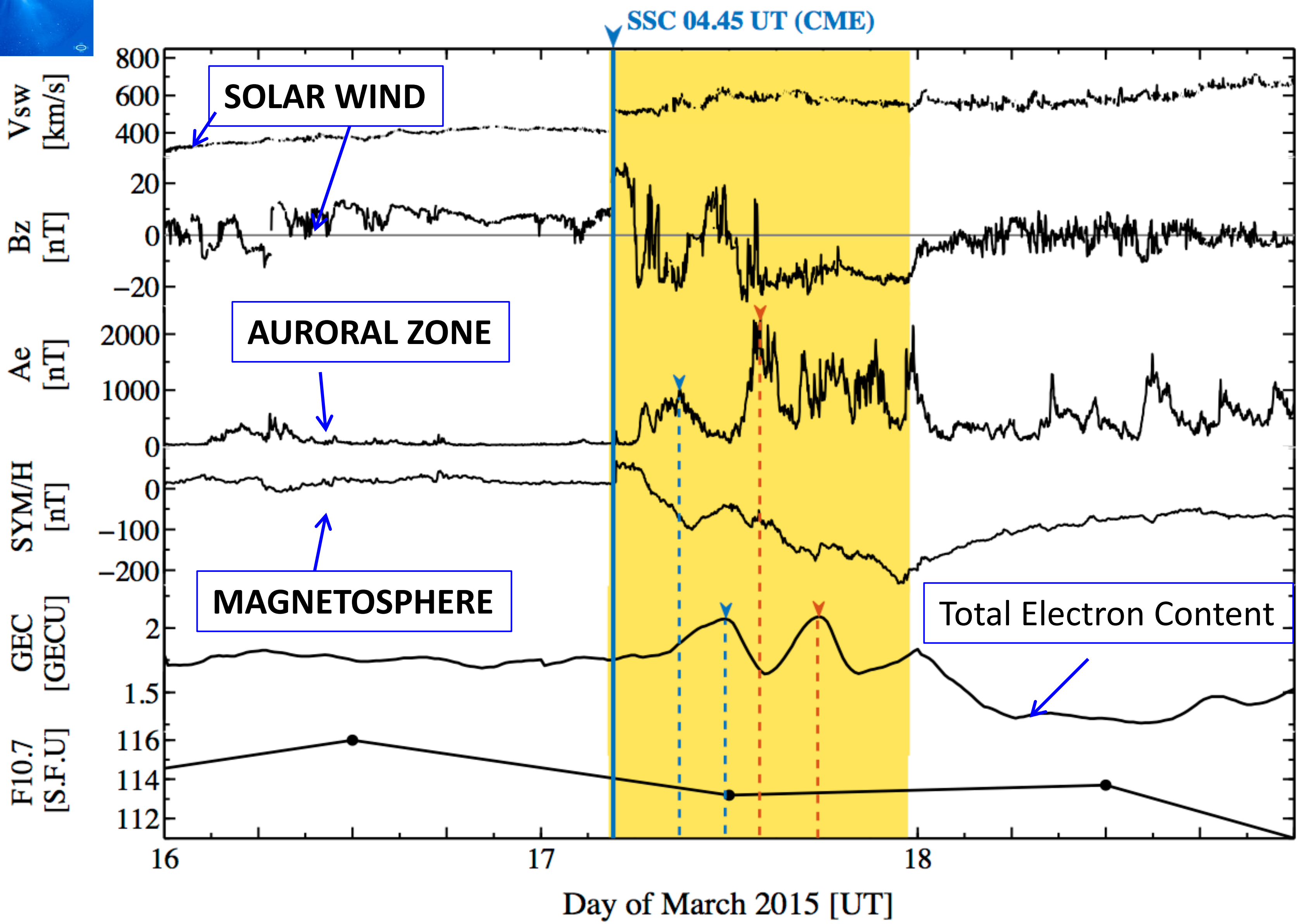
Coronal hole



GLOBAL CONTEXT OF THE MAGNETIC STORM OF St PATRICK's DAY

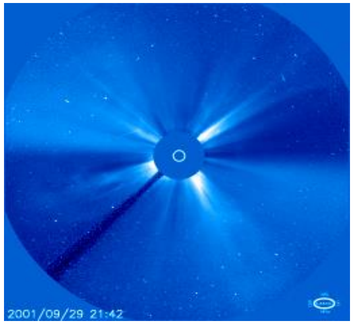


SUN



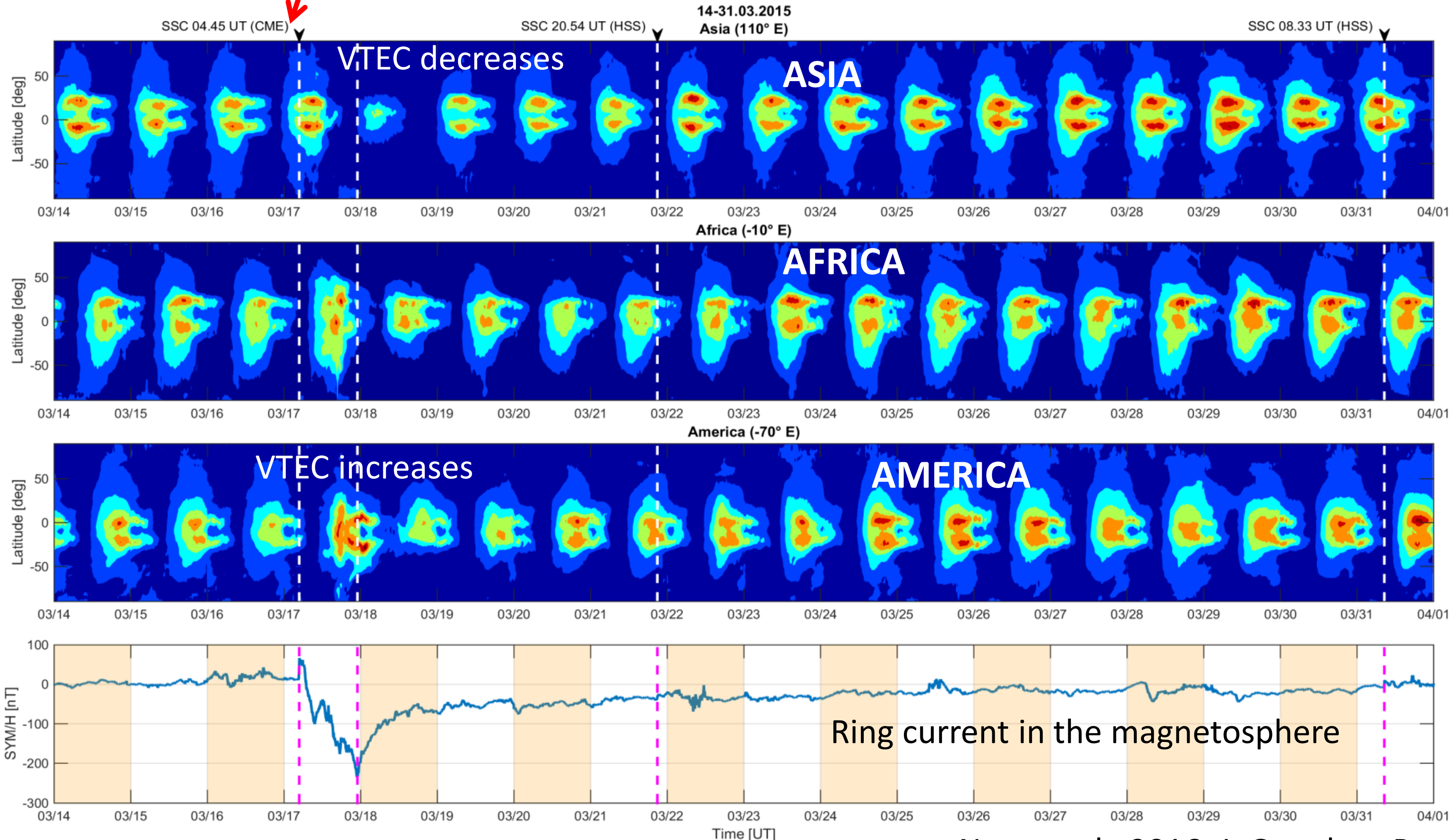
Nava,, et al., "Middle and low latitude ionosphere response to 2015 St. Patrick's Day geomagnetic storm", J. Geophys. Res. Space Physics,121, 3421–3438, doi:10.1002/ 2015JA022299.

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)

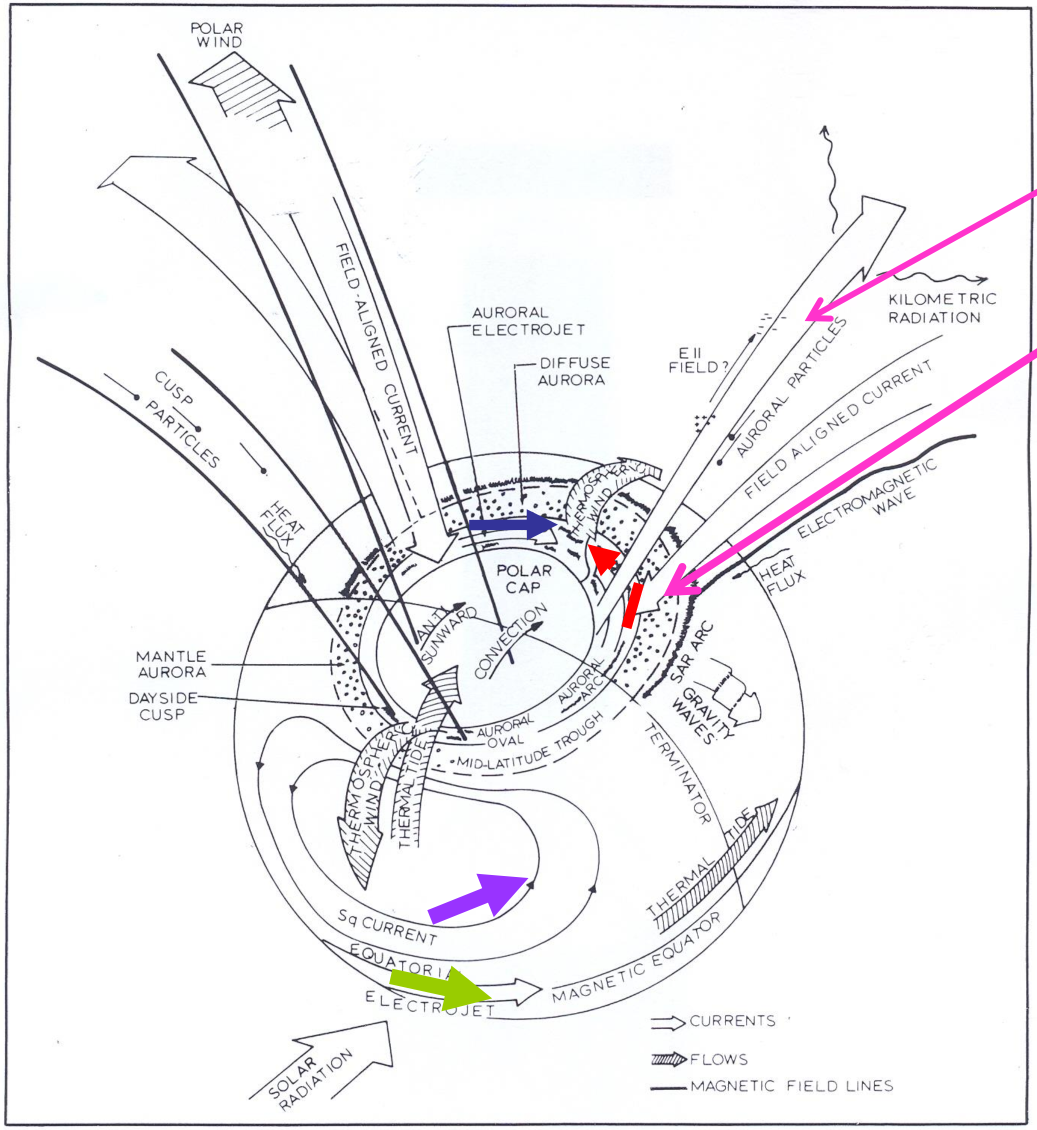


Nava et al., 2016, J. Geophys. Res.

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

AURORAL ZONE : Ionospheric electric currents



Field aligned current

Auroral electrojets

Precipitation of particles

Electric field

Auroral

Middle latitudes

Equatorial latitudes

COUPLING between AURORAL and EQUATORIAL regions
ELECTRIC FIELD ALONE

Prompt penetration of the magnetospheric convection electric field [PPEF]

Observations Nishida et al., (1966 Nishida) et al., (1968)

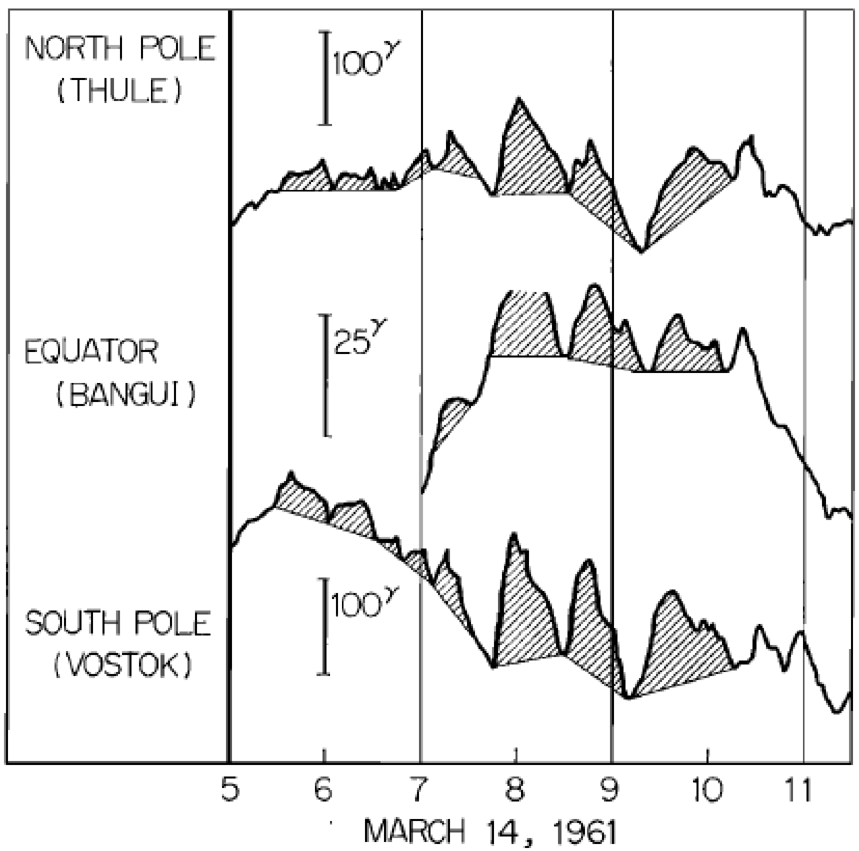
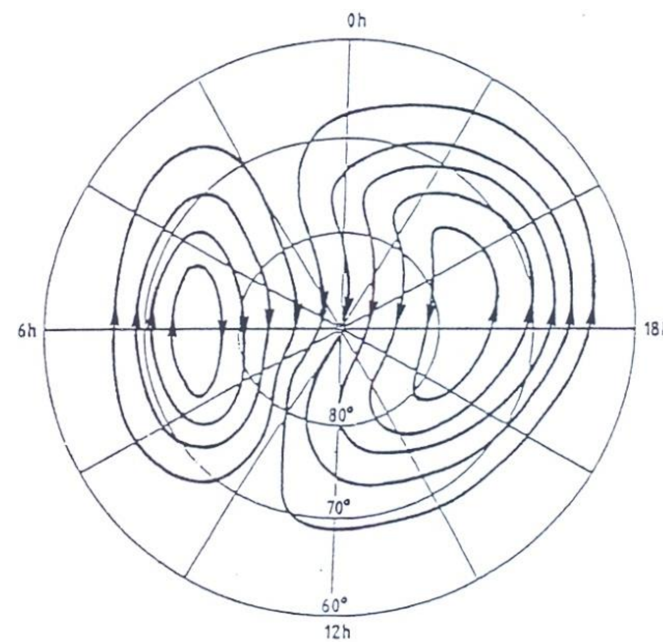


Fig. 1. Train of D_P 2 fluctuations (shaded). Geomagnetic latitudes of these stations are 88.9 (Thule), 05.0 (Bangui), and −89.1 (Vostok).

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

=> simultaneity of the disturbances from auroral to equatorial latitudes



Magnetic signature : DP2

Penetration of the magnetospheric convection electric field to the equator , Kikuchi et al., 2000, JGR, Vol 105, N° A10, 23251-23261

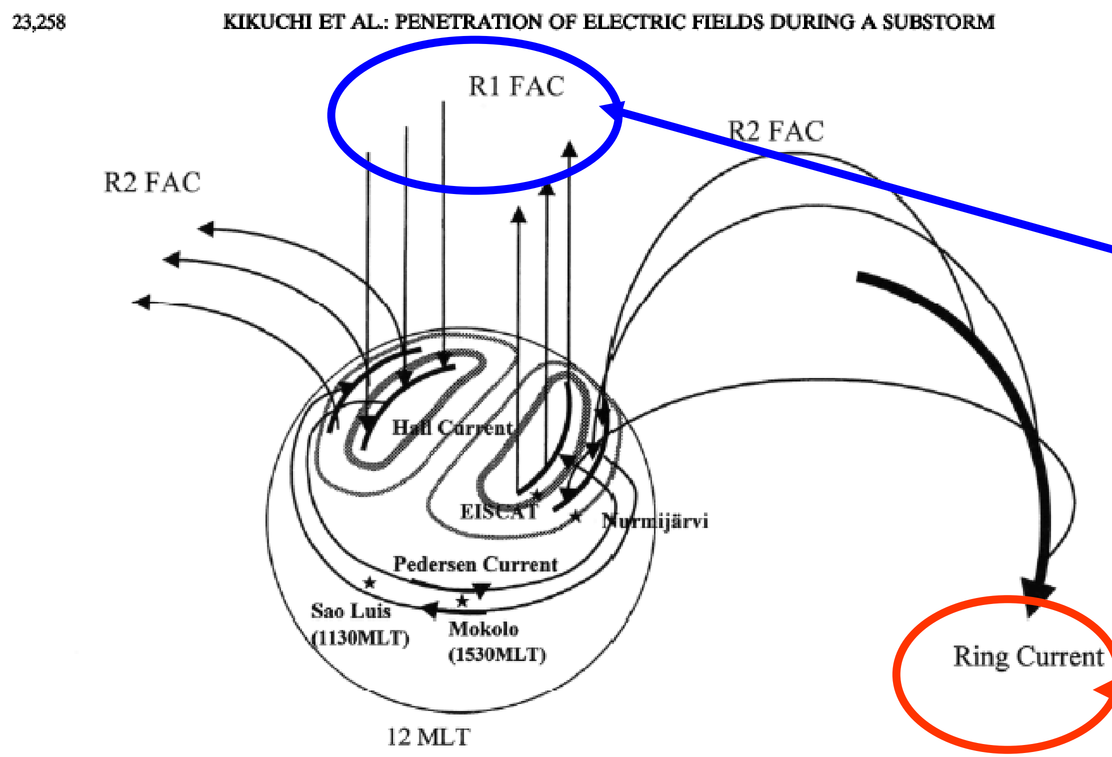


Figure 7. Schematic picture of Region 1 (R1) and Region 2 (R2) field-aligned currents (FACs) with locations of EISCAT, Nurmijärvi, and equatorial (Sao Luis and Mokolo) stations. The dominant electric field associated with R1 FACs is northward in the high-latitude afternoon sector and eastward at the daytime dip equator. The R2 FACs enhance the northward electric field at EISCAT but reduce this component at the Nurmijärvi and equatorial stations. The electric fields drive ionospheric Hall currents at high latitudes and Pedersen currents at the dip equator. The Hall currents are closed circuits in the ionosphere, while the Pedersen currents are connected to the R1 and R2 FACs. The magnetic local time of the equatorial stations corresponds to the peak of the negative bay at 1440 UT.

Direct process

DDP

No shielding

Loaded driven process/RC

Shielding or Overshielding

PPEF

Electrodynamic coupling of high and low latitudes observations on May, 27, 1993

Kobéa et al. 2000, JGR, Vol 105, A10, 22979-22989

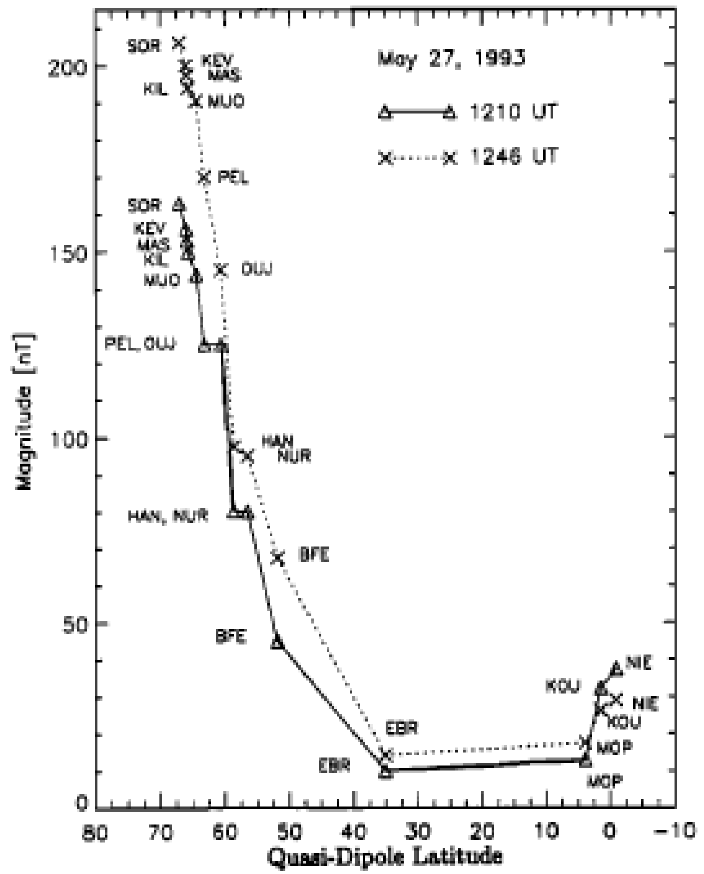


Figure 4. Latitudinal profile of the fluctuations at 1210 and 1246 UT extending to the equator, in the longitudinal sector ranging from 65° to 120° magnetic longitude including IMAGE and the West African network.

Overshielding related to R2 Fac
Peymirat et al., JGR 2000
TIEGCM

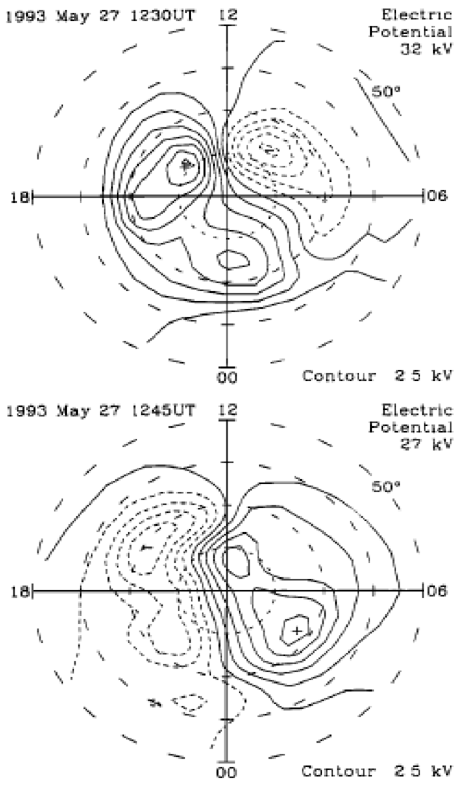
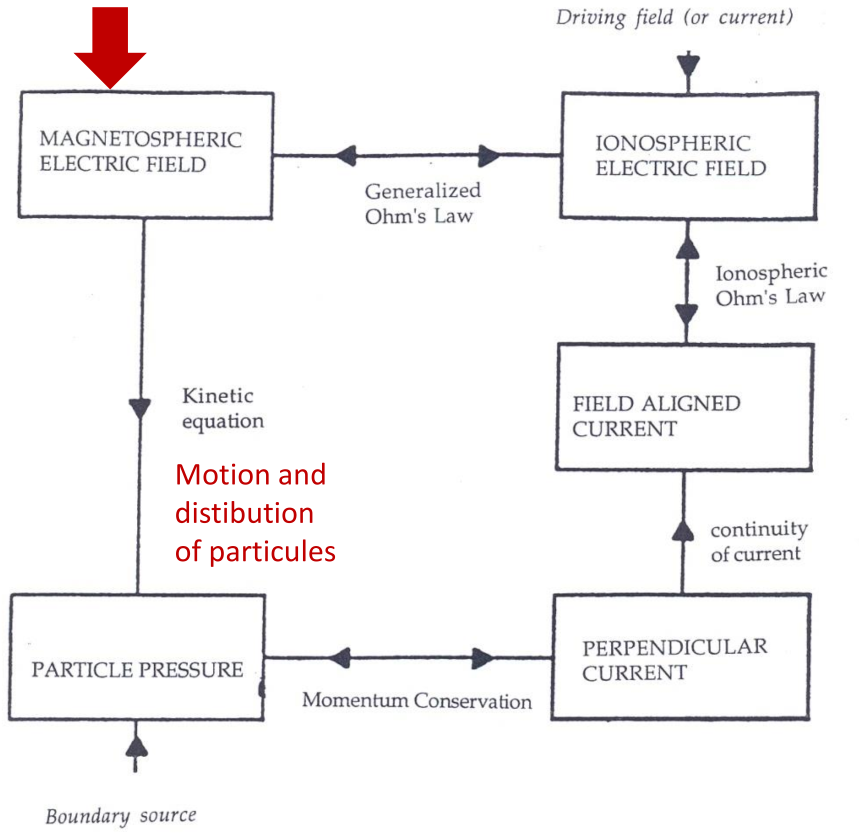


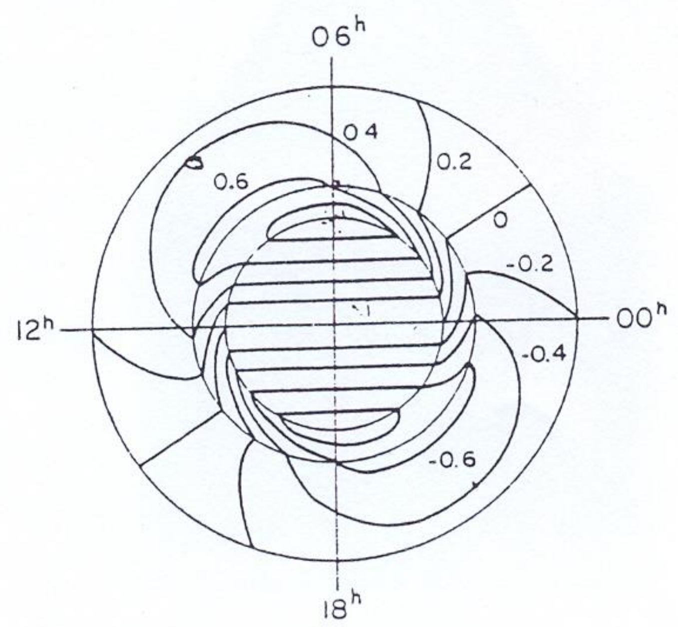
Figure 6. Electric potentials at 1230 and 1245 UT on May 27, 1993, with a 2-hour running mean subtracted to emphasize the fluctuations. The contour interval is 2.5 kV.

Richmond and Kamide, 1988 AMIE
JGR vol 83 n°A6, 5741-5759

First mathematical convection model

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





Equipotential contours in the ionosphere (enhanced auroral conductivies)

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

PPEF

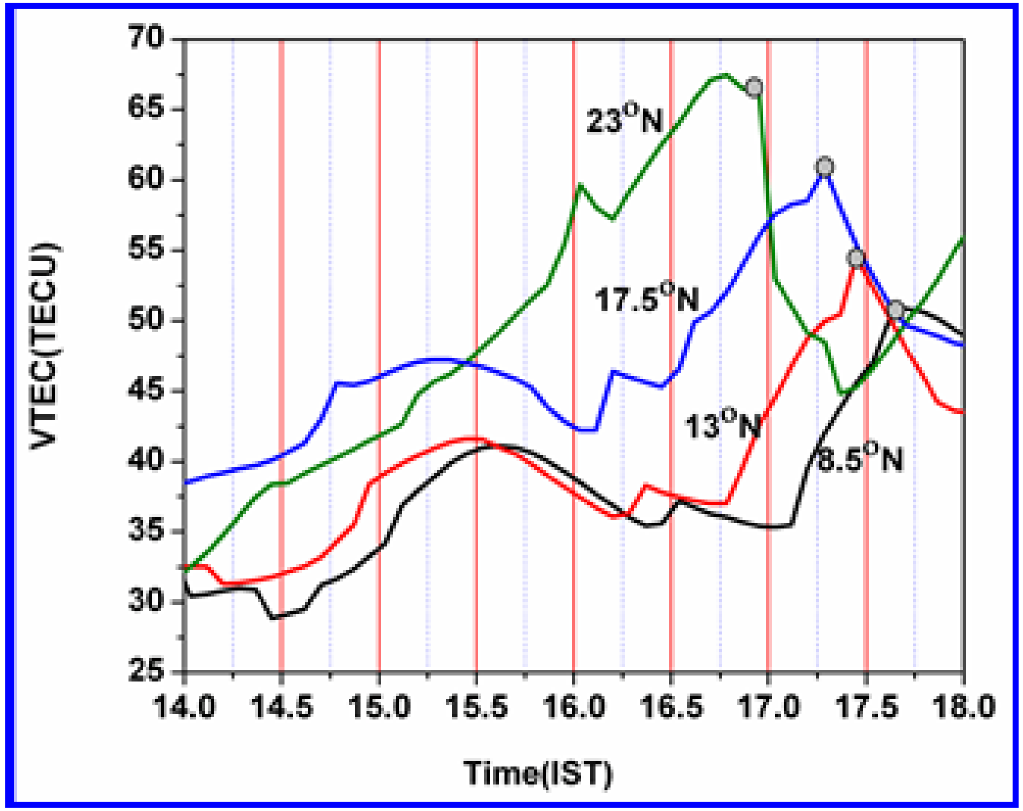
Thermal expansion of the atmosphere: Travelling Atmospheric disturbance (TAD's) => disturbed TEC [Theory Fuller Rowell et al., (1994), (1996)]

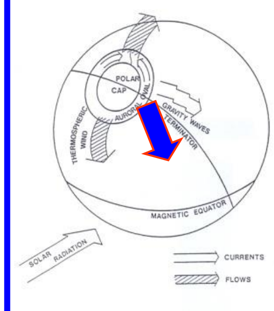
24/08/2005

SSC : 13.00 UT
Main Phase : 16 00 UT

INDIA
77-78°E meridian

V~750m/s

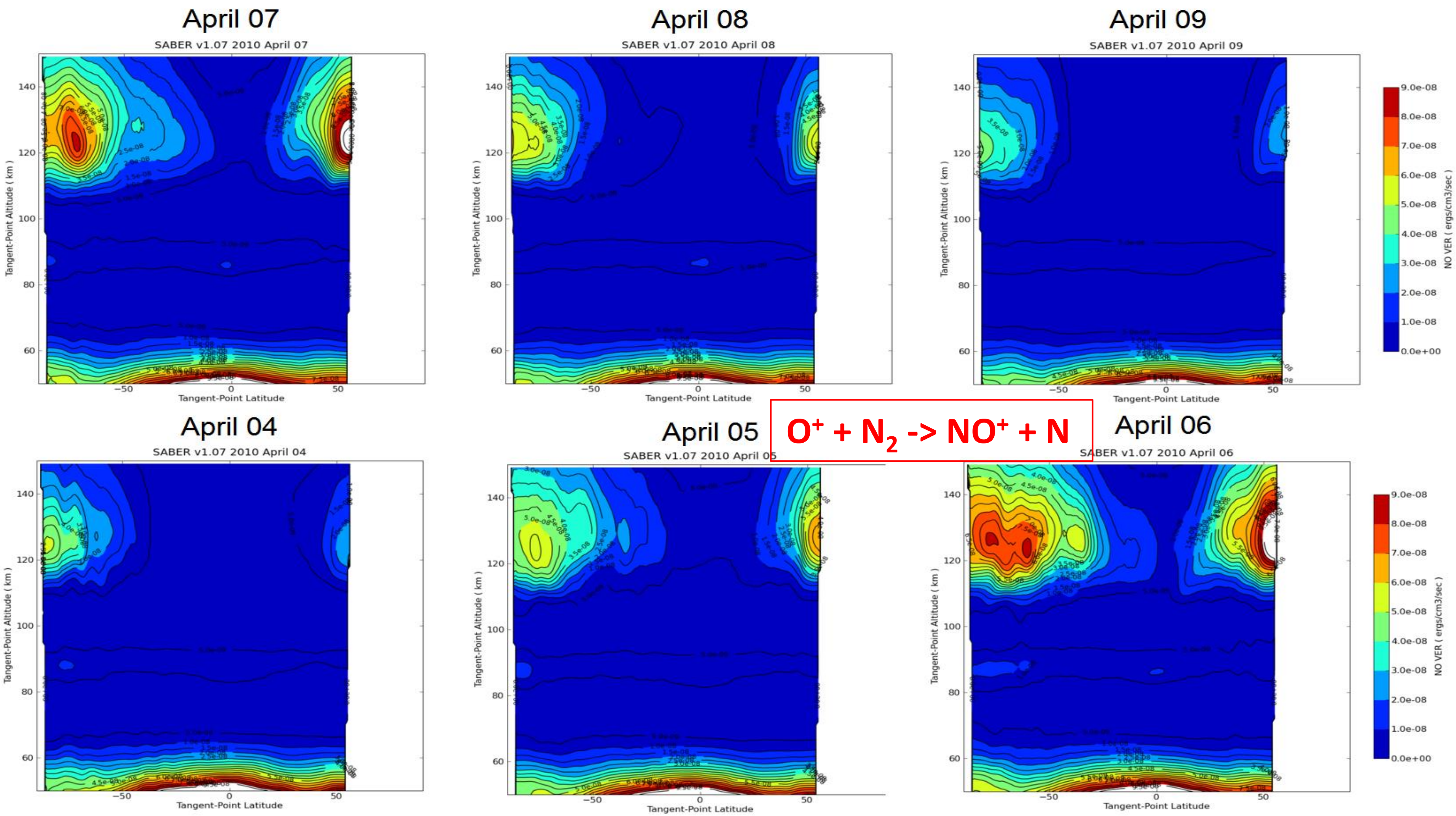




A time delay in the VTEC variations over the different latitudes indicates a propagation of TAD's Velocity 750m/s

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

DURING STORMS => THERMAL EXPANSION OF THE ATMOSPHERE MOLECULAR MASS TRANSPORT ⇔ CHANGE IN COMPOSITION



NO+(v) volume emission rate (VER) along the geographical latitude on x-axis with altitude (y-axes) for each day of the geomagnetic storm of 05 April 2010 measured by SABER.

Shimeis et al., Advances in Space Research,Volume 55, Issue 9, pp 2239-2247, 2015.

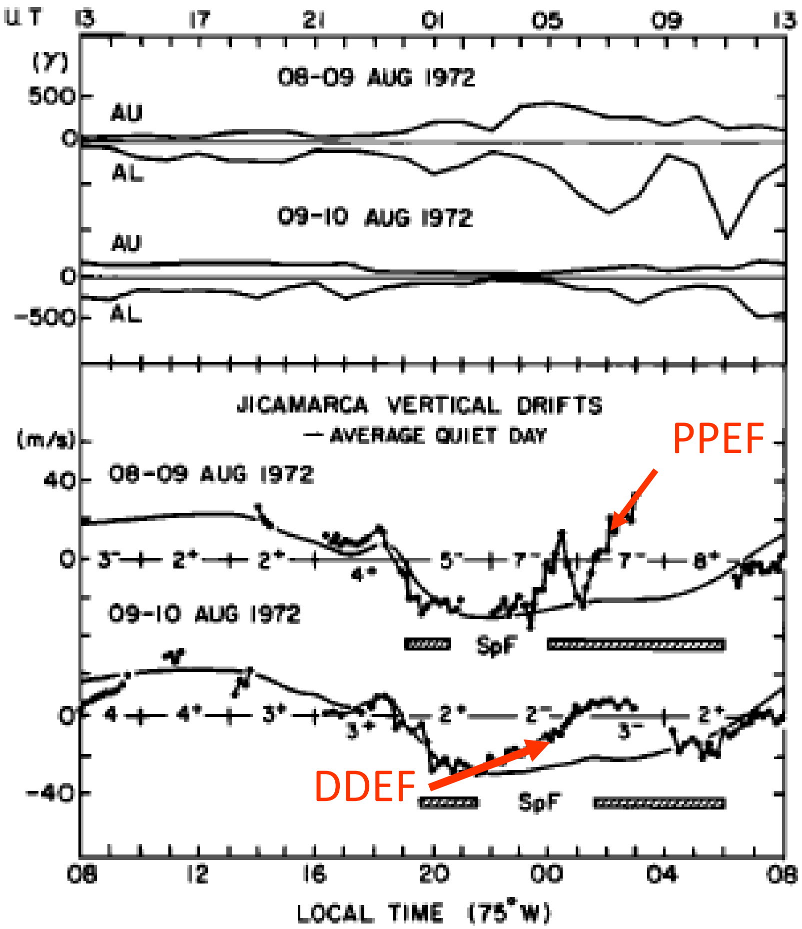


Figure 1. Auroral electrojet indices and F-region vertical drifts at Jicamarca on August 8-10, 1972. The solid curves in the lower panel show the average quiet time diurnal variation. Deviations from this pattern beginning at 2300 LT on August 8 are due to direct penetration effects, whereas the slower deviations starting at 2200 LT on August 9 are due to the disturbance dynamo.

Equatorial Disturbance Dynamo Electric Fields

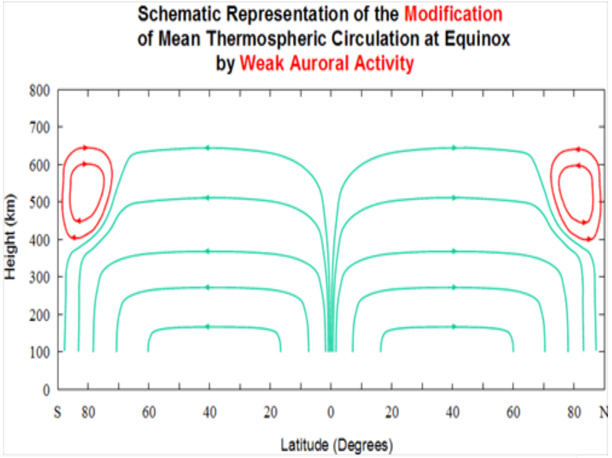
Fejer et al., 1983

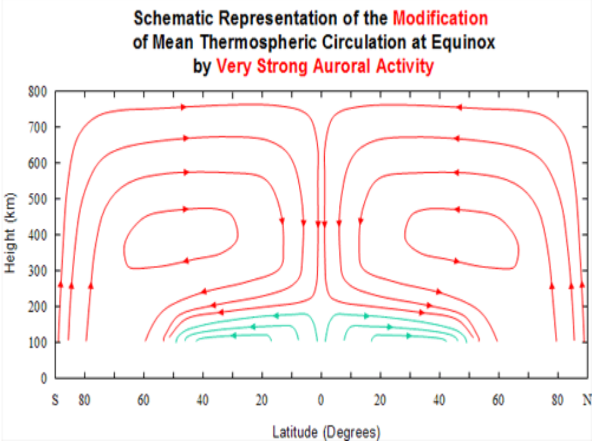
GRL, Vol 10, N°7, 537-540

Mayaud, JGR 1980
Comment on the Ionospheric Disturbance dynamo

Blanc JGR 1983
Magnetospheric convection Effects at midlatitudes
1. Sai nt-Santin Observations
Vol 88, P. 211

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

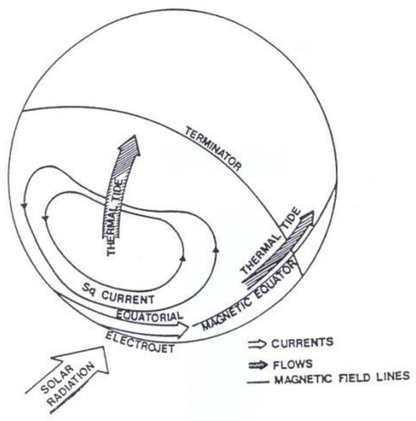
↓

+ ΔV_n → ΔE_{dyn} → ΔJ → ΔB

Gravity waves, HADLEY convection cell etc…

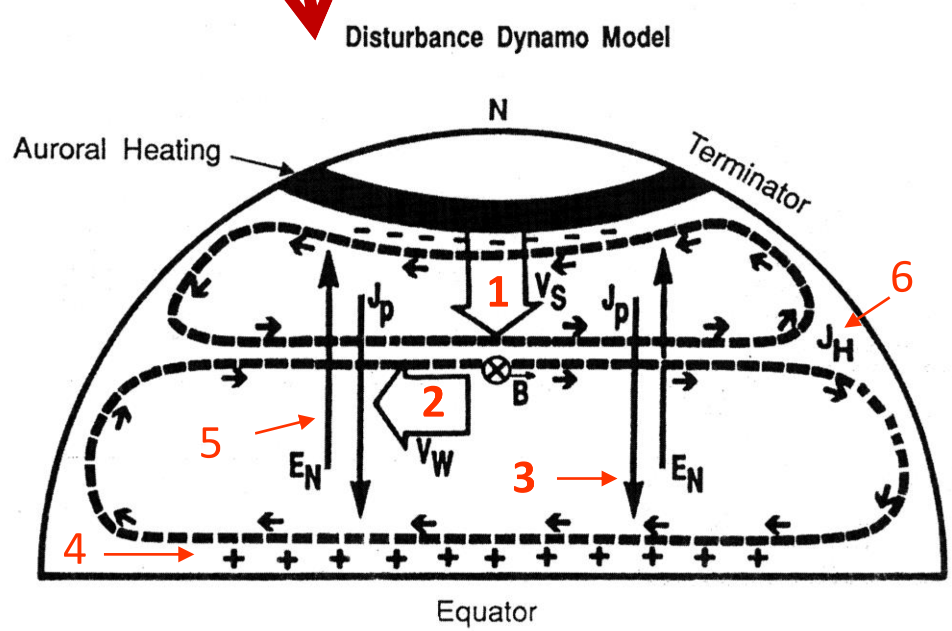
The Ionospheric Disturbance Dynamo => disturbed electric current

JGR,85, 1669-1686, 1980 Blanc and Richmond

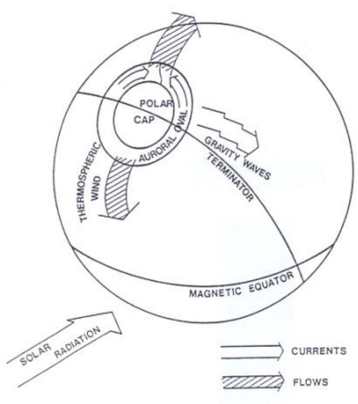


Regular wind

Mazaudier and Venkateswaran, 1990
Annales Geophysicae, 8, (7-8), 511-518



Storm wind



Richmond and Matshushita, JGR, 1975 vol 80, N°19, 2839-2850
Thermospheric response to a magnetic storm

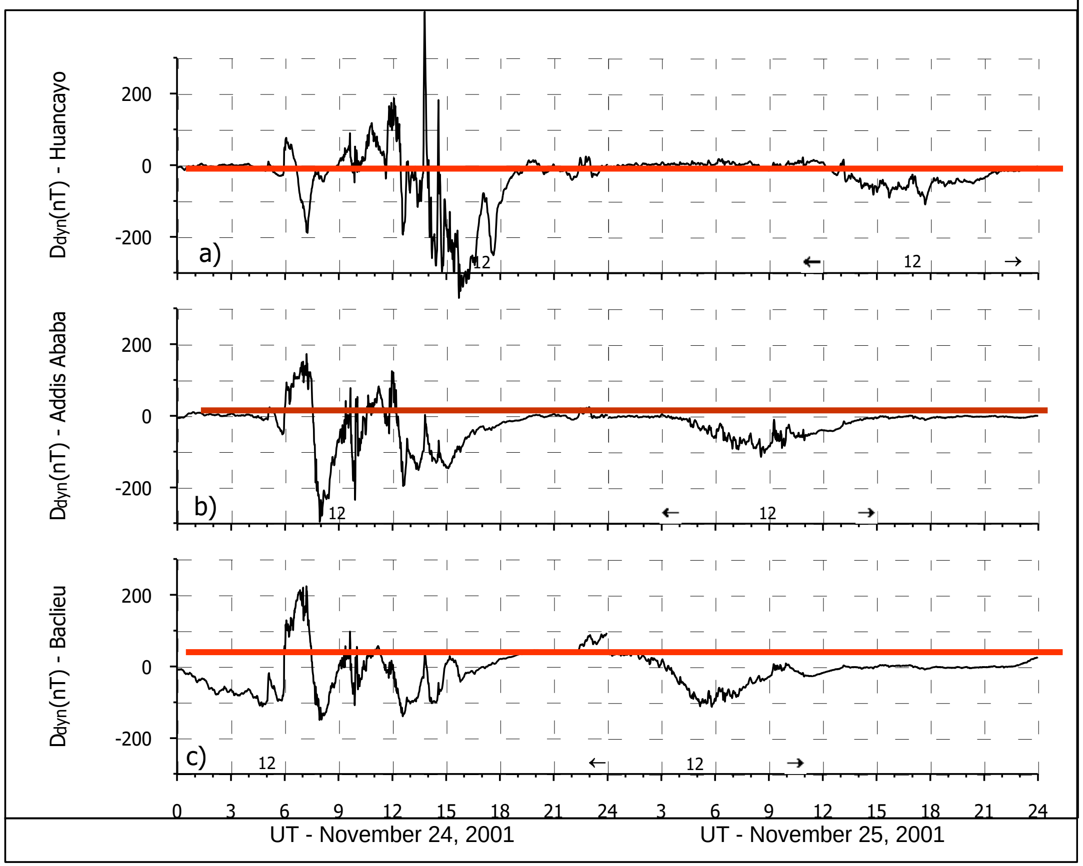
DDEF

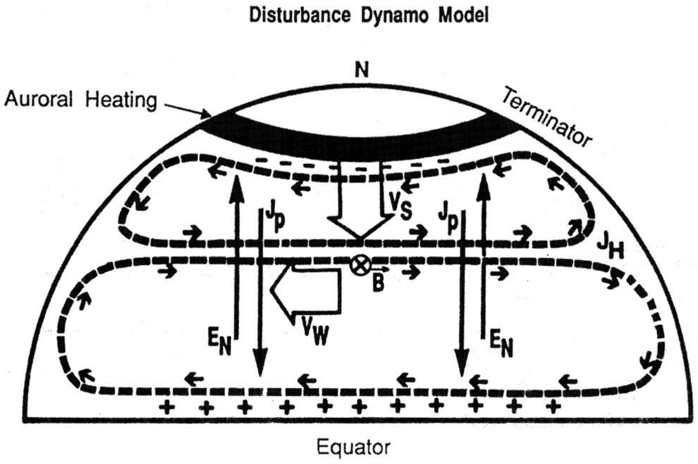
Magnetic signature of the Ionospheric disturbance dynamo

Le Huy and Amory-Mazaudier, 2005

Simple case $\Delta H = S_R + \text{SYM-H} + D_{dyn}$

Figure 9.





Ionospheric disturbance dynamo
Westward deviation
$\Delta H < 0$

Regular ionospheric dynamo
Eastward electrojet
$\Delta H > 0$

For selected events

Signature of the ionospheric disturbance dynamo: Ddyn

Le Huy and Amory-Mazaudier, Journal of Geophys. Research, Vol. 110, A10301, October 2005

Blanc and Richmond, 1980

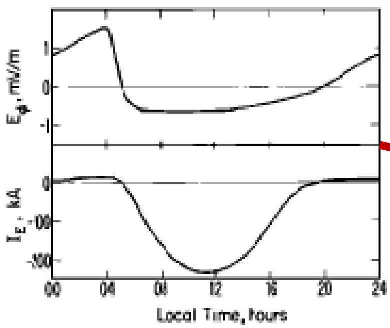


Fig. 9. Local time distributions of the equatorial electrojet parameters E_ϕ, eastward electrostatic field, and I_E, total eastward current flow between +10° and -10° magnetic latitude. Both are basically reversed from their observed normal quiet-day variation.

2. Criteria for the Selection of Cases and Data Analysis

2.1. Criteria

[10] Our purpose being to study the sole ionospheric disturbance dynamo process, we must point out that only daytime signatures can be inferred from the data. Here are the criteria for the selection of the period of observation: (1) daytime period => to study the dynamo action in the E region, (2) period immediately after a storm => there is Joule heating in auroral regions during the period preceding our selected period, (3) no auroral electrojet => there is no penetration of the magnetospheric convection electric field during our selected period.

Simple case : a very quiet day after a storm

Biot and Savard 'law

$$\Delta H = S_R + D_{magnetosphere} + D_{ionosphere}$$

A10301 HUY AND AMORY-MAZAUDIER: MAGNETIC SIGNATURE OF IONOSPHERIC DISTURBANCE DYNAMO A10301

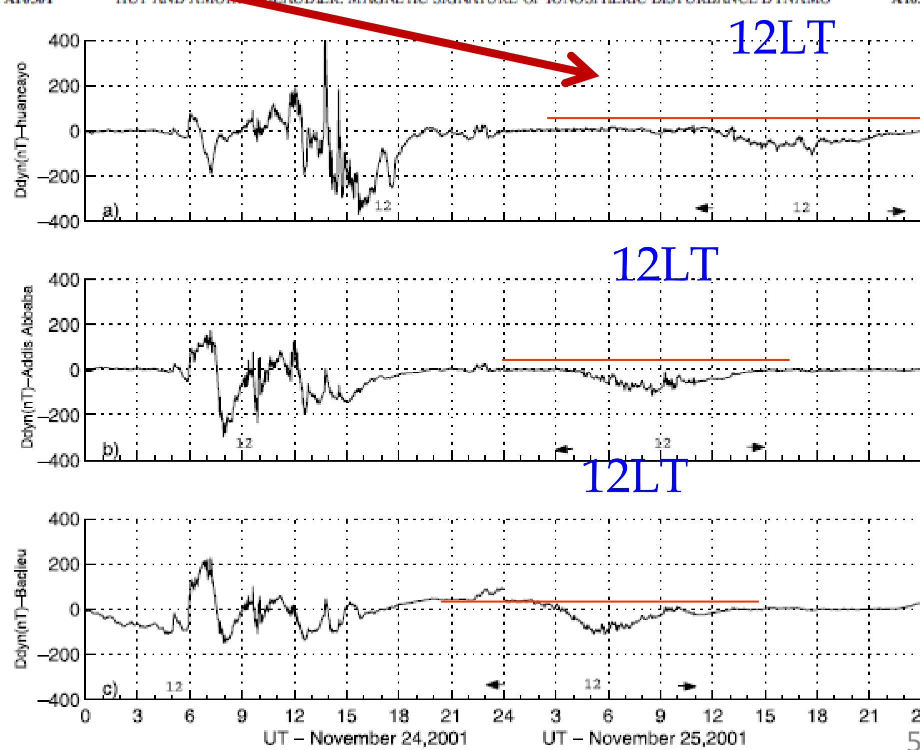
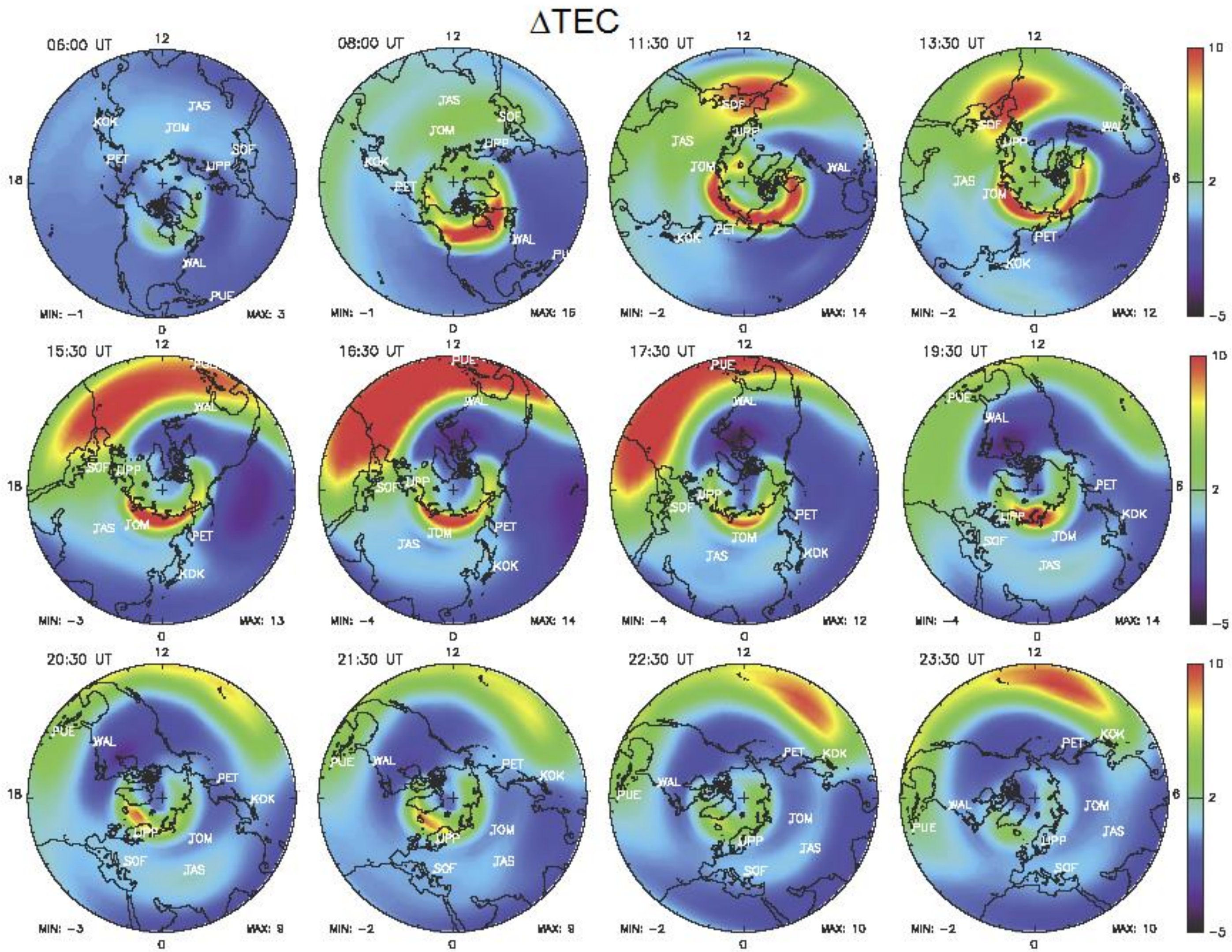


Figure 9. Same as Figure 4 for the sixth storm event on 24 and 25 November 2001.

Storm simulation

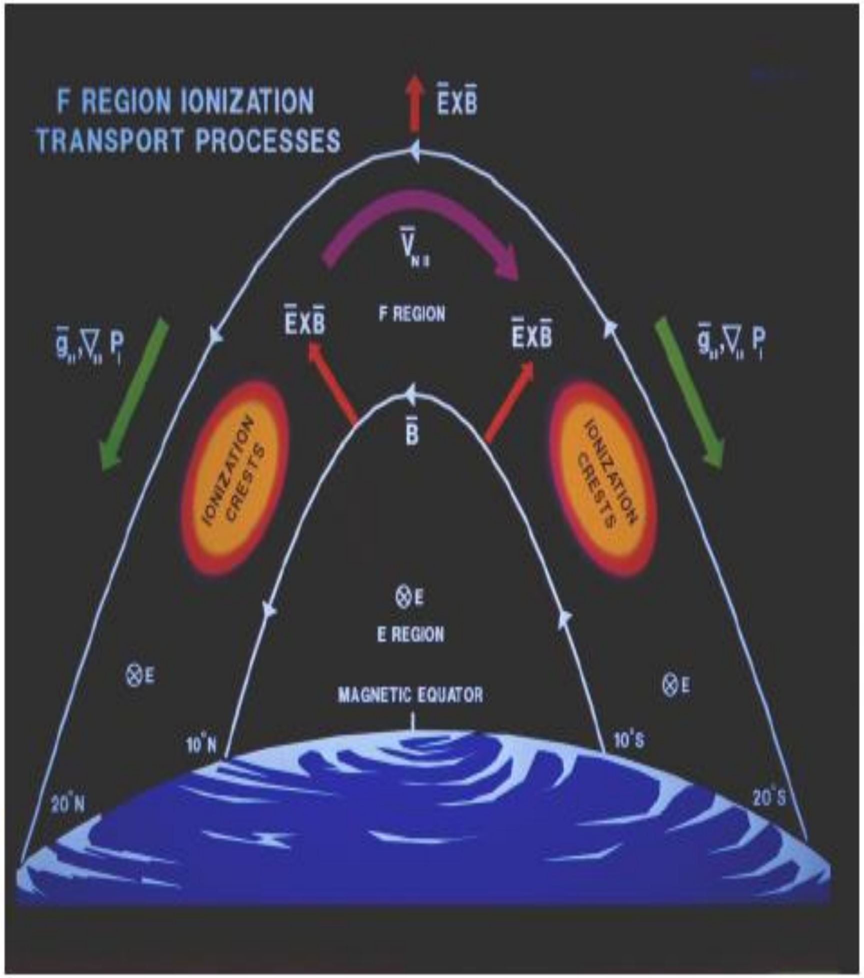


Lu, G., A.D. Richmond, R.G. Roble, and B.A. Emery, Coexistence of ionospheric positive and negative storm phases under northern winter conditions: A case study, J. Geophys. Res., 106, 24,493-24,504, 2001.

OUTLINES

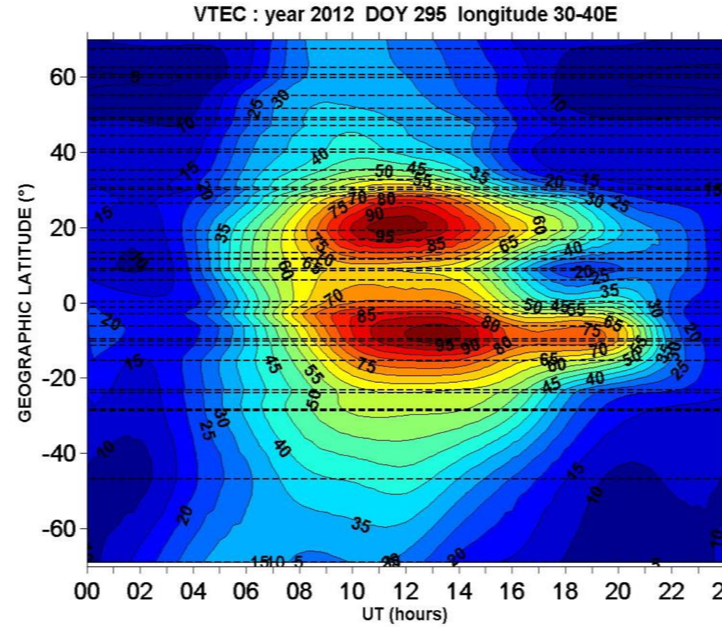
- Sun and Earth two magnetic bodies in motion
- Emission from the Sun
- Sunspot cycle
- Solar Dynamo: the true solar cycle / solar indices
- Radiation channel regular
  - Ionosphere / Ionospheric dynamo
- Radiation channel disturbed
  - Solar flare
  - Solar Burst
- Particles channel
  - Regular solar wind
- Magnetic storms
  - CME and Coronal hole
  - Geomagnetic activity and solar wind
- Case studies of Space Weather events
  - Solar flare effect, Storm effect
  - Electrodynamics coupling between high and low latitudes
  - Equatorial ionosphere -> Magnetic quiet time, Coronal hole effect, CME effect
- Conclusion

Features of the Equatorial Ionosphere

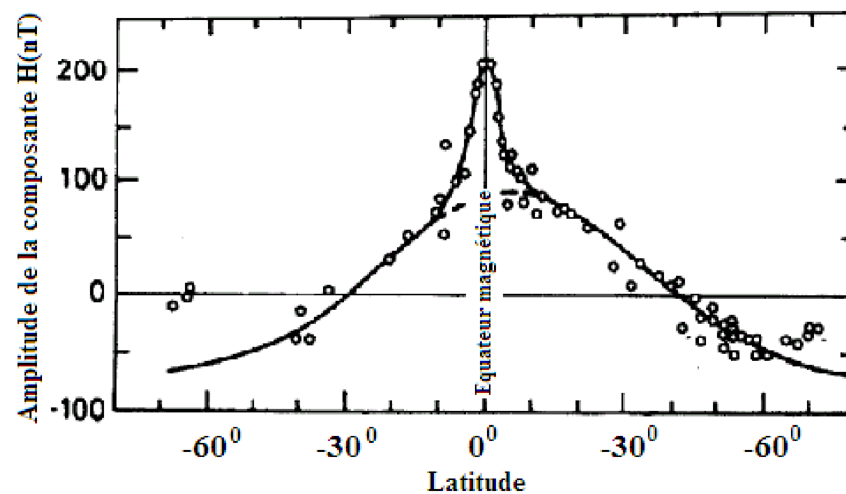


Equatorial Fountain

Eastward electric field => moves up
Westward electric field => moves down



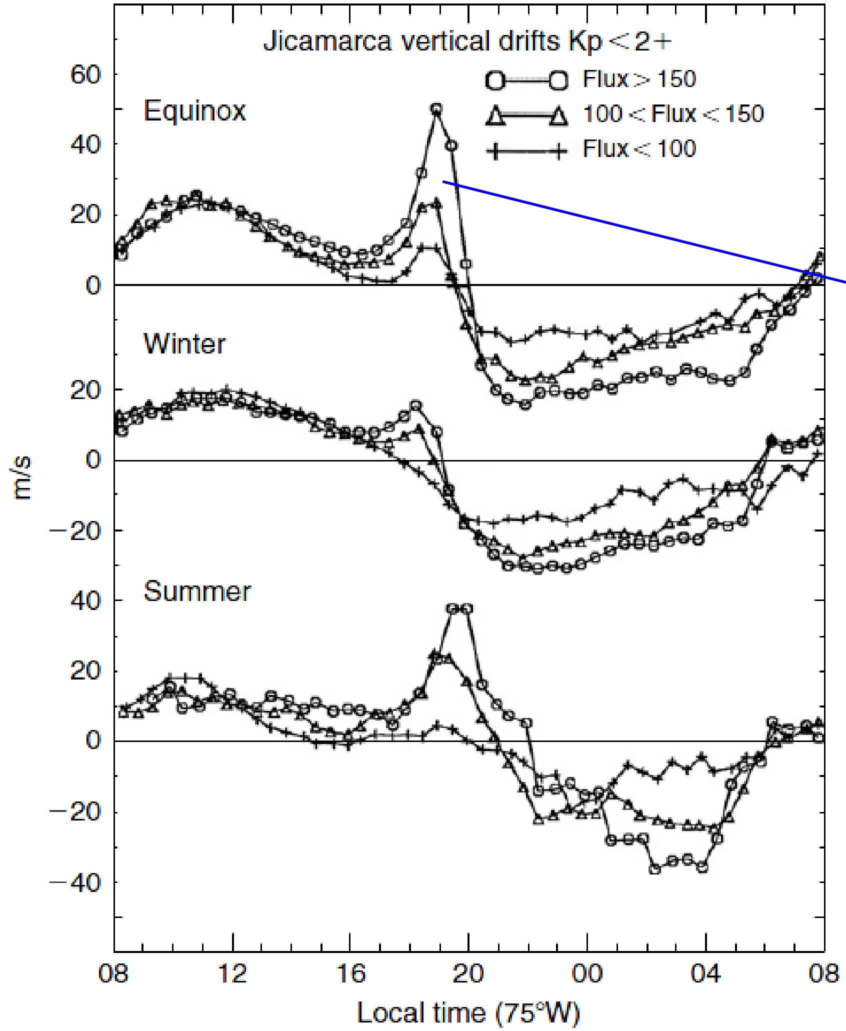
VTEC map in East AFRICA
Amory-Mazaudier et Fleury, 2013

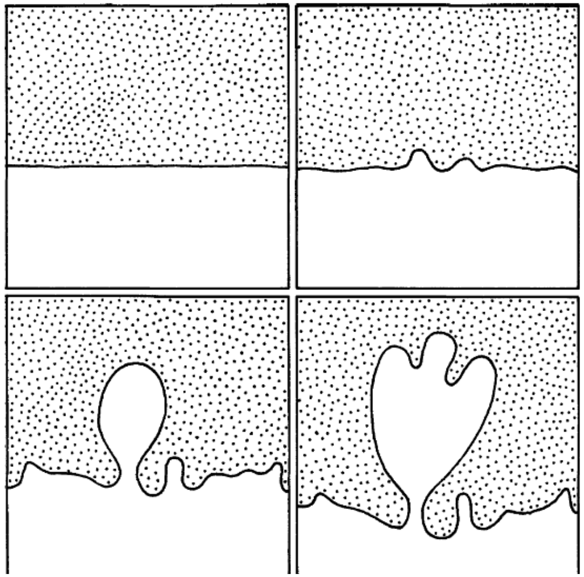


The Equatorial Electrojet

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, 2009)

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., 1991)

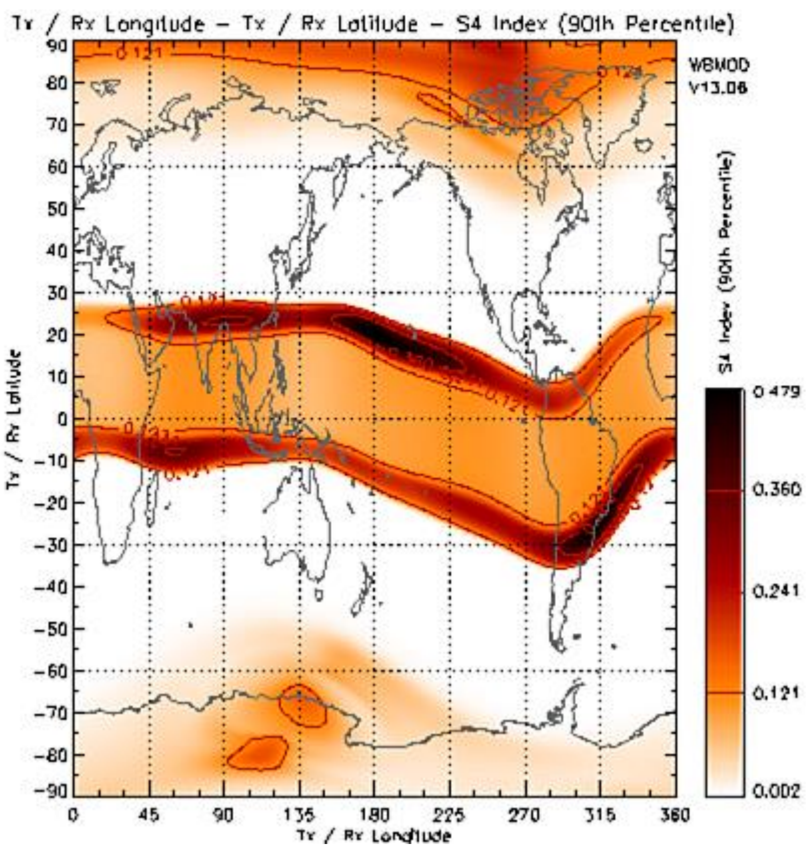
Scintillations a regular phenomenon

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

<u>Physical Process :</u> Instabilities in Plasma

Indice of scintillation

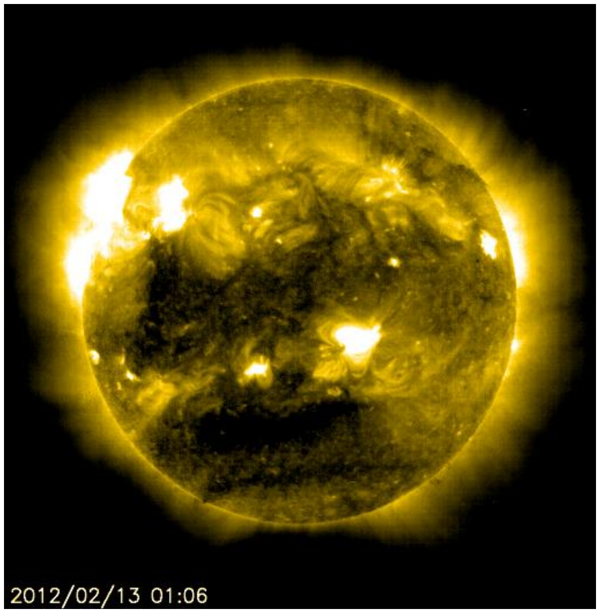
$$s4 = \sqrt{\frac{<I^2> - <I>^2}{<I>^2}}$$



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

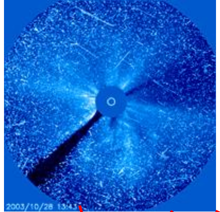
"Ionospheric scintillation is primarily an equatorial and high-latitude ionospheric phenomenon, although it can (and does) occur at lower intensity at all latitudes.
Ionospheric scintillation generally peaks in the sub-equatorial anomaly regions, located on average ~15° either side of the geomagnetic equator."

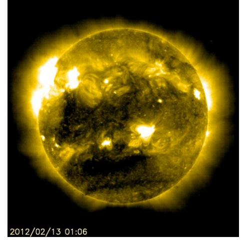
Effect of a high speed solar wind due to a coronal hole



some solar perturbations inhibit the scintillations and facilitate radio transmissions

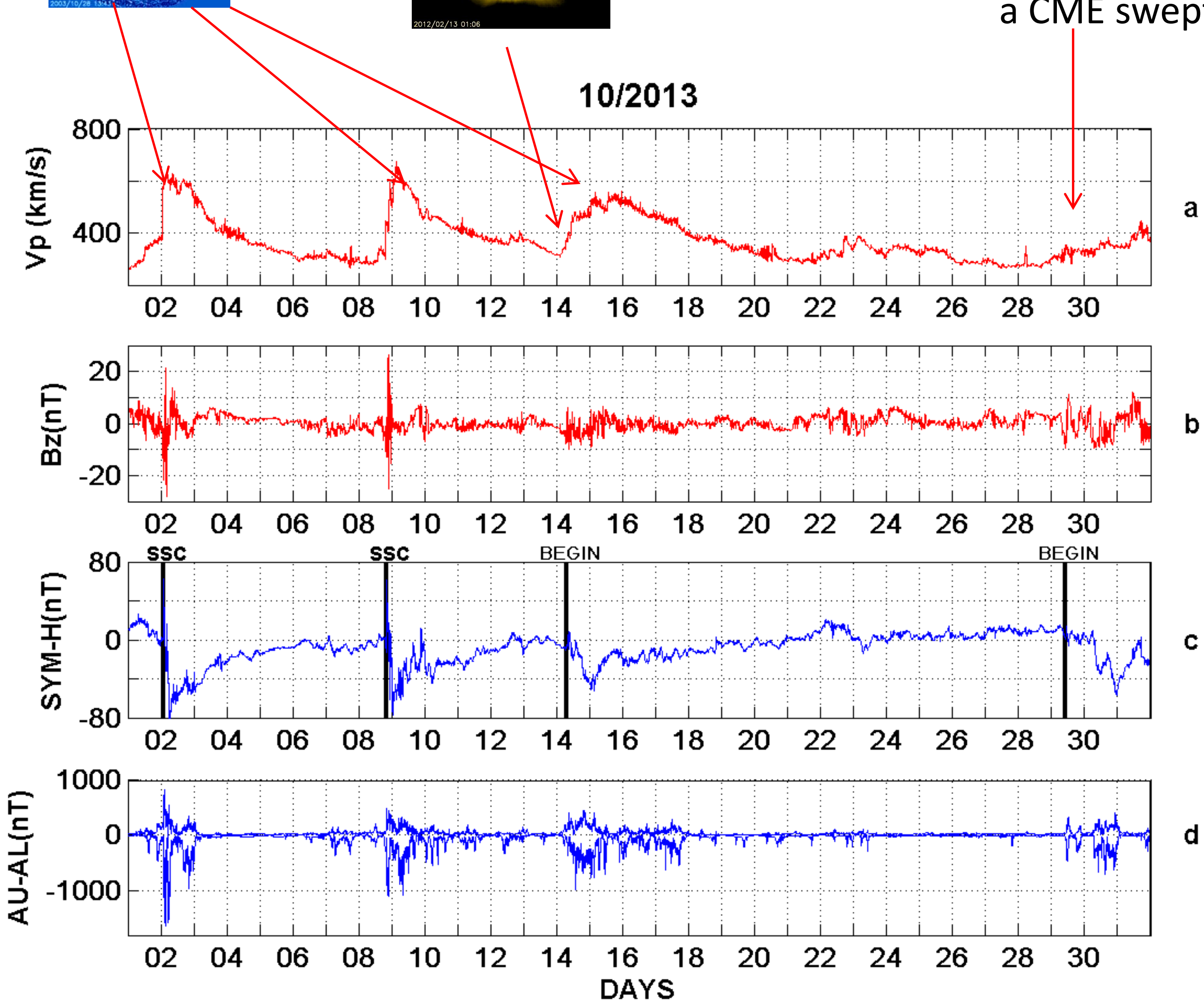
Azzouzi, I, Migoya-Orué, Y, Amory Mazaudier, C, Fleury,R, Radicella, S.M ,Touzani, A, Signatures of solar event at middle and low latitudes in the Europe-African sector, during geomagnetic storms, October 2013, ***Advances in Space Research,*** **doi: http://dx.doi.org/10.1016/j.asr.2015.06.010**



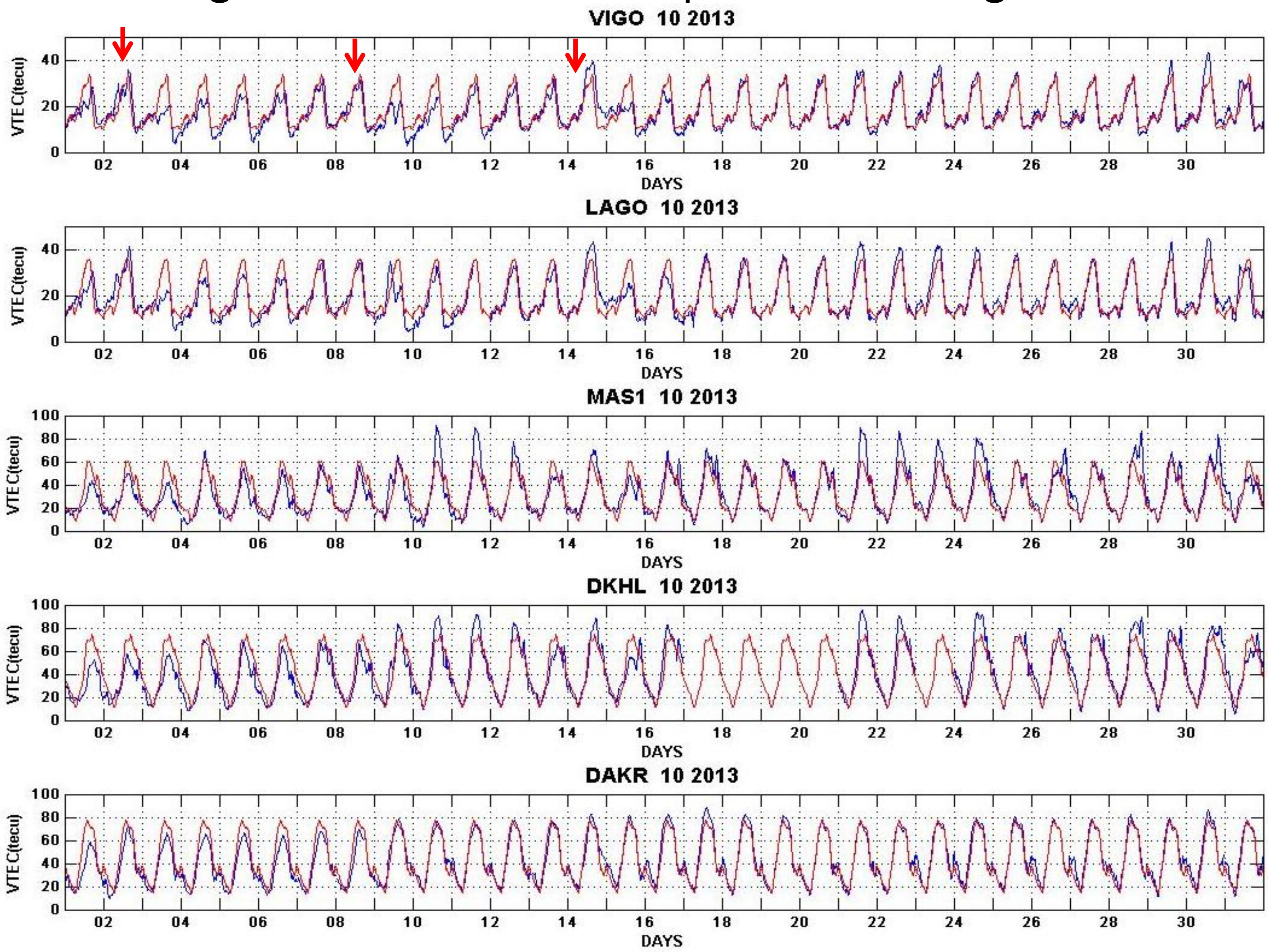


Azzouzi et al., 2015

a CME swept the Earth

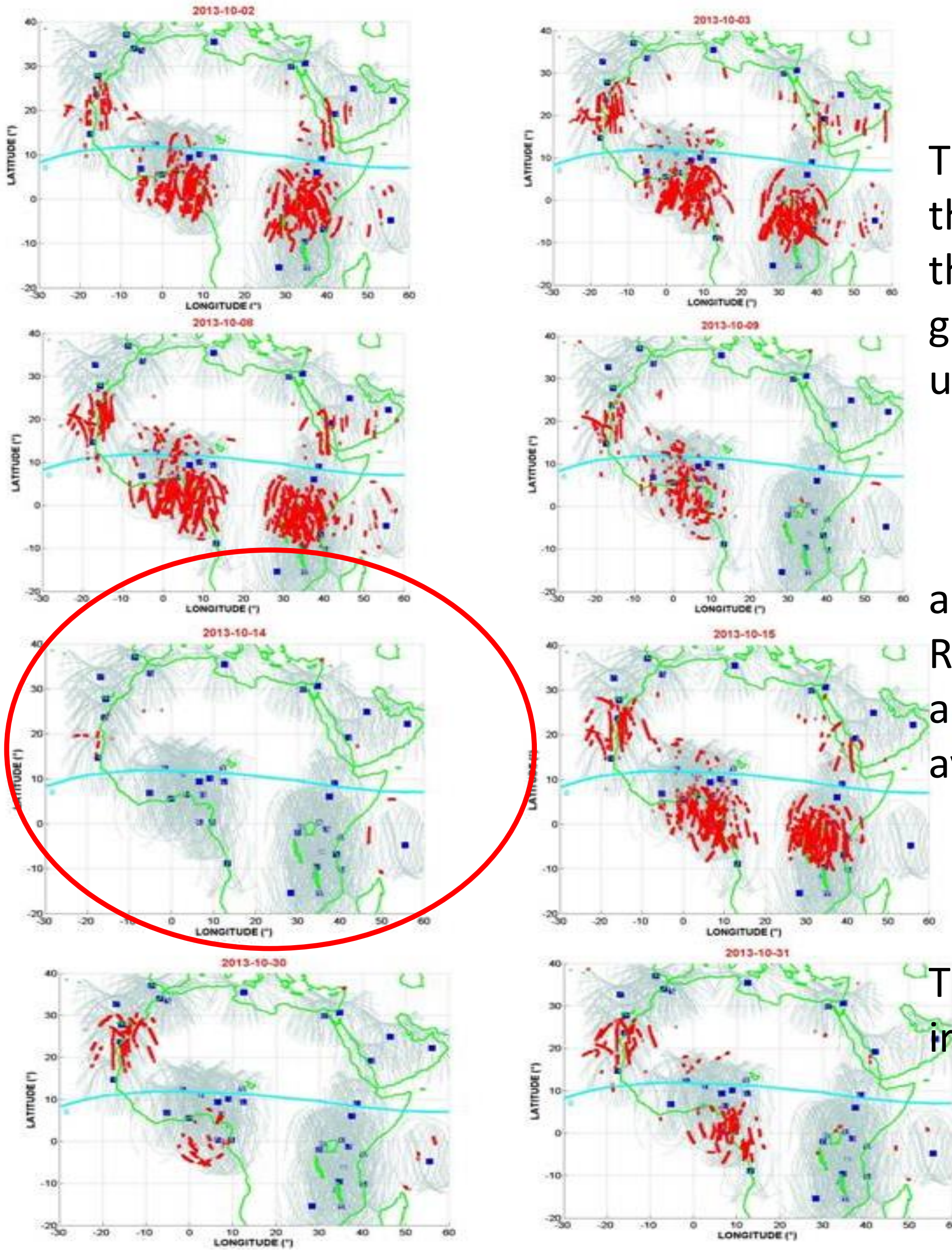


VTEC along the West-African Europe sector during October 2013.



Azzouzi et al., 2015

Maps of ROTI index



The ROTI index is calculated according to the development of Pi et al. (1977). From the 30s Rinex files, we calculate the gradient of STEC (ROT for Rate of TEC) in unit of tecu/mn

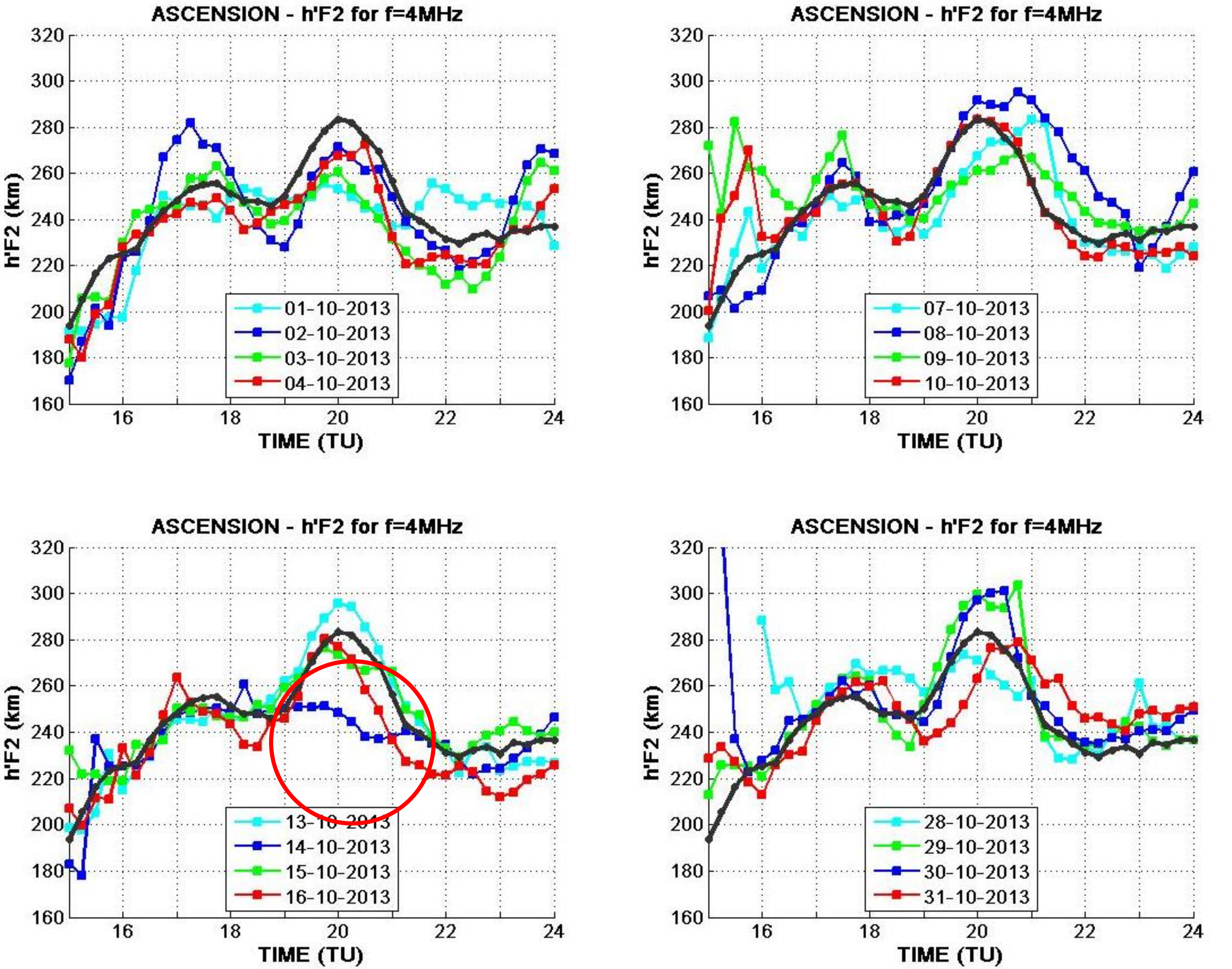
$$\mathbf{rot} = \frac{STEC_{k+1} - STEC_k}{time_{k+1} - time_k} * 60$$

and then the ROTI index which is RMS of ROT values with a time span of 10 mn and only for data above 20° elevation to avoid the influence of multi paths.

$$\mathbf{roti} = \sqrt{\langle \mathbf{rot}^2 \rangle - \langle \mathbf{rot} \rangle^2}$$

The ROTI is use to get information of irregularities in the F-region.

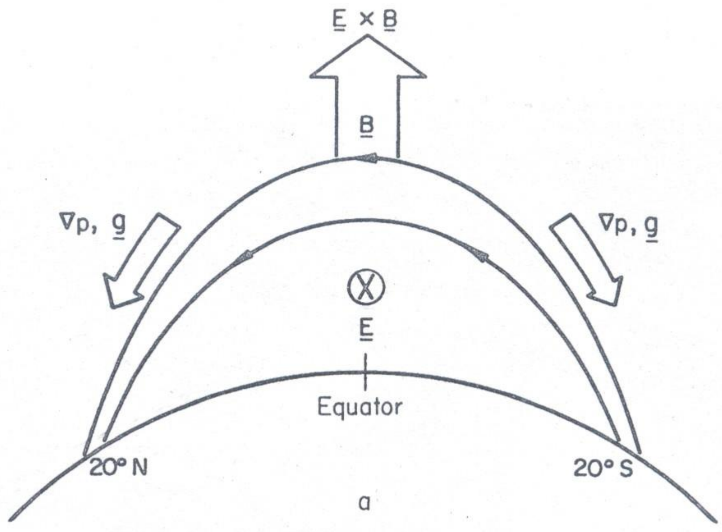
Azzouzi et al., 2015

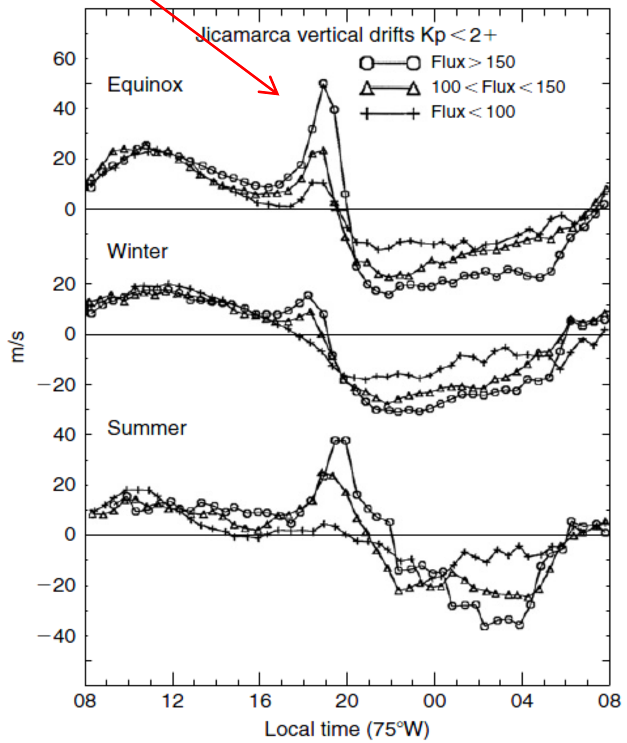


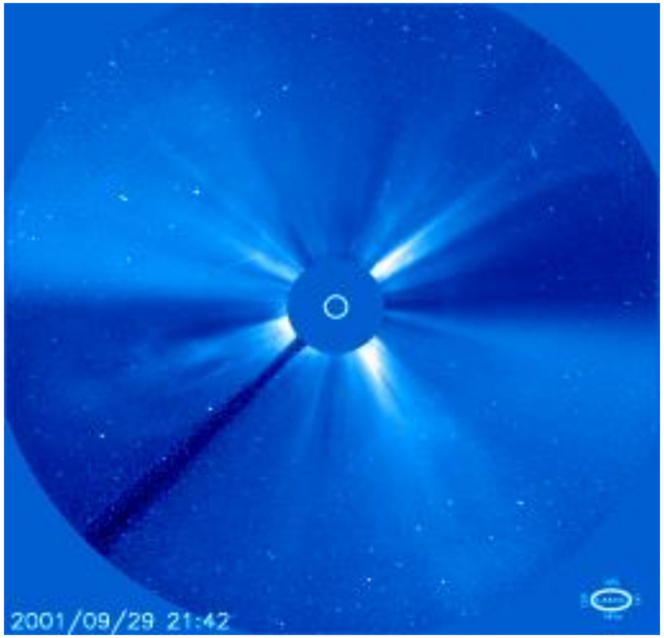
Azzouzi et al., 2015

Eastward electric field => moves up
Westward electric field => moves down

PRE : Pre Reversal Enhancement of Ey



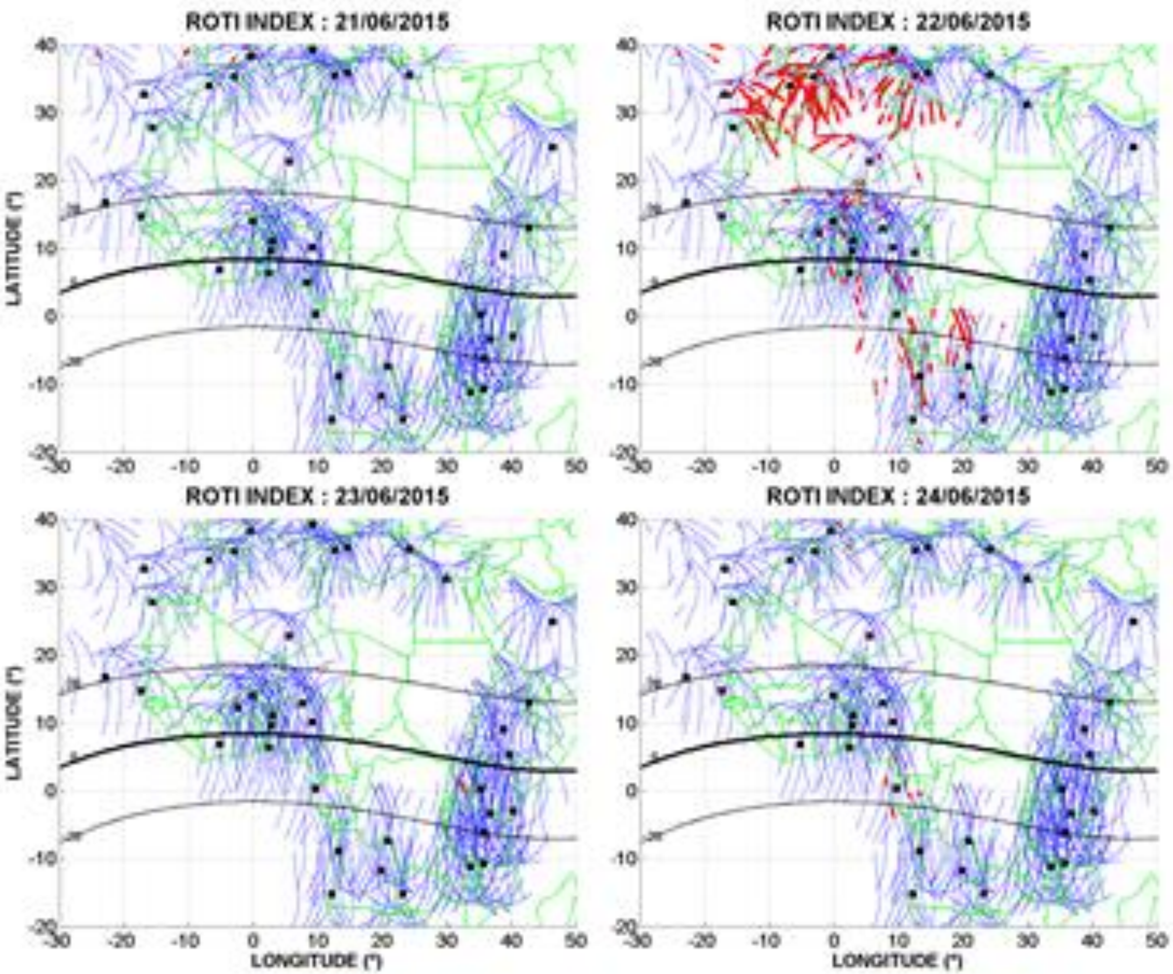




Effect of CME

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

Kashcheyev, A., Y. Migoya-Orué, C. Amory-Mazaudier, R. Fleury, B. Nava, K. Alazo-Cuartas and S.M. Radicella, "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

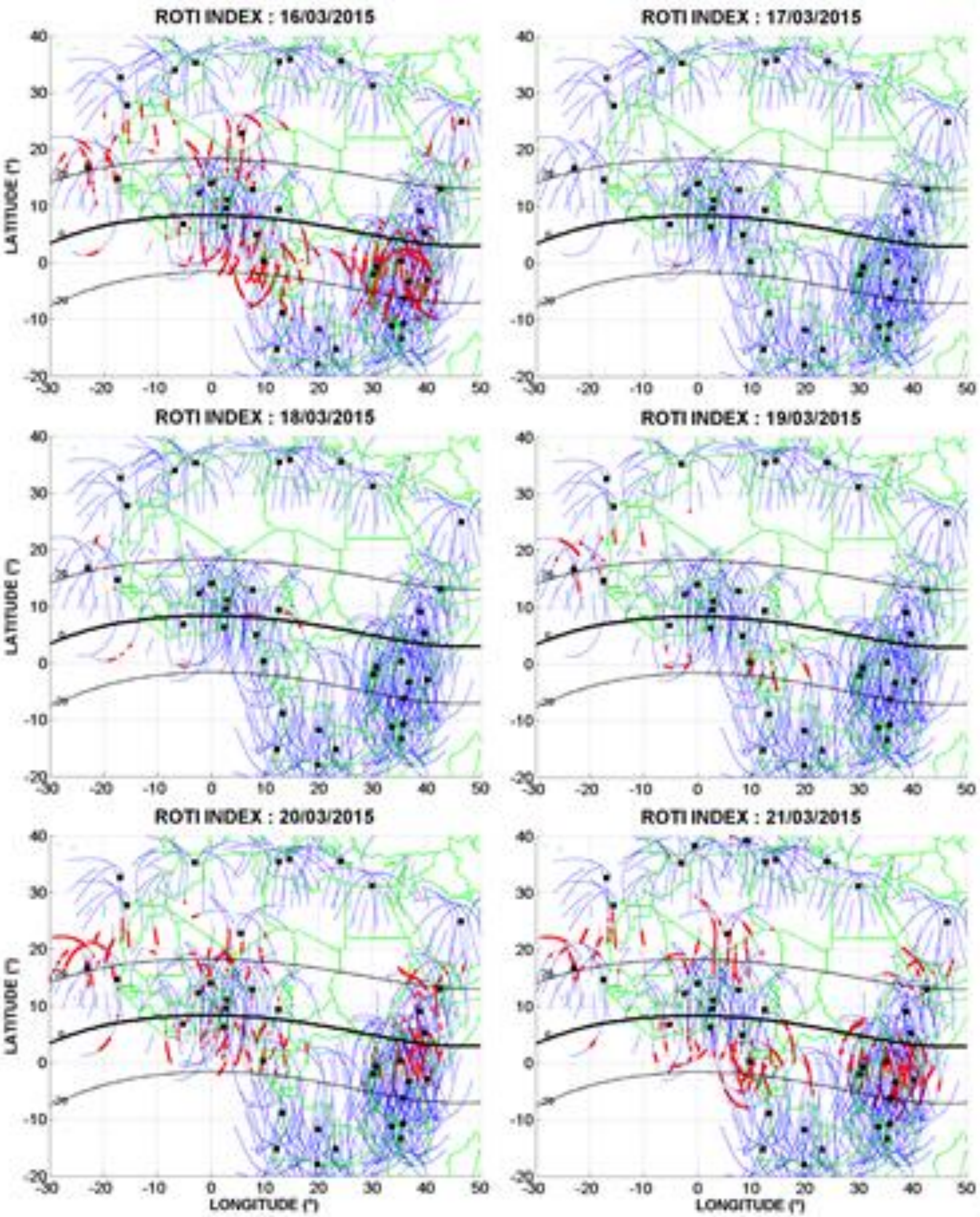
$$rot = \frac{STEC_{k+1} - STEC_k}{time_{k+1} - time_k} * 60$$

Dst < -200 nT
Storm started at 18.33 UT

Increase of scintillations

PPEF effect
short duration

Kashcheyev, A et al;, 2018



Storm March 17, 2015 equinox

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

Dst < -200 nT

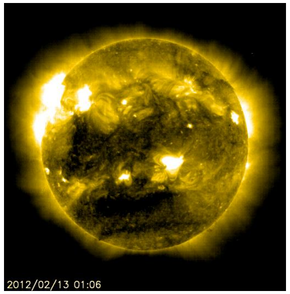
Storm started at 04.45 UT

Inhibition of scintillations over the whole earth during several days

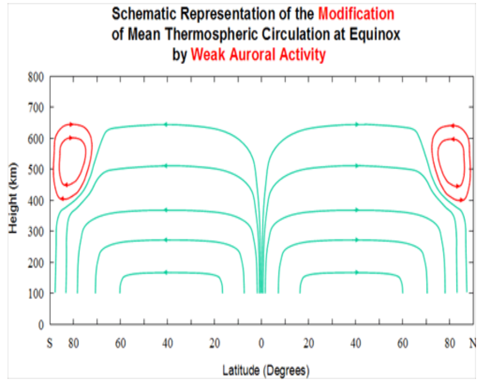
DDEF effect long duration

Model of Fejer et al., (2008) – PPEF and DDEF

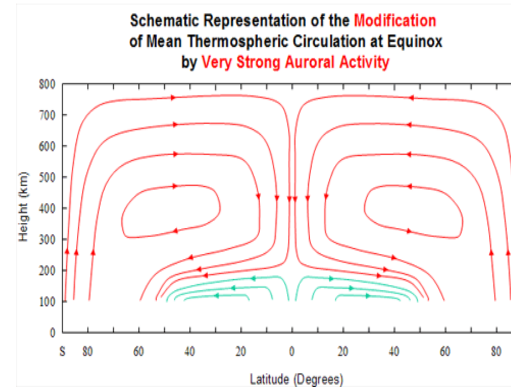
DDEF is a westward electric field which inhibits the regular eastward electric field at the time of the PRE

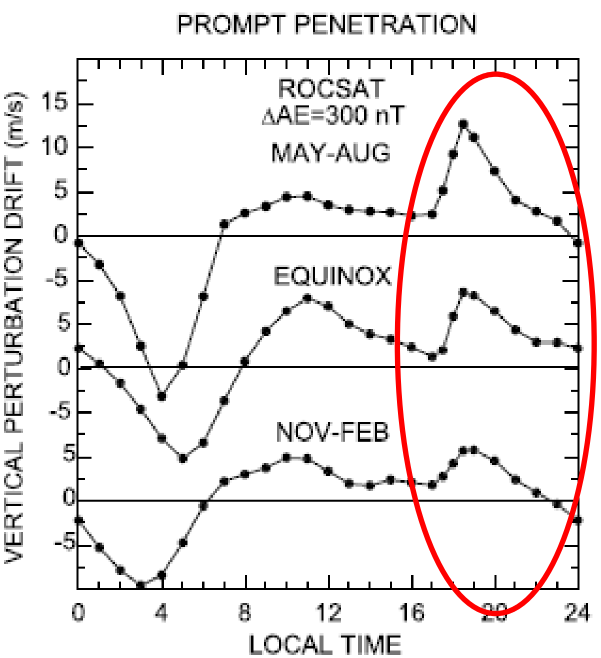


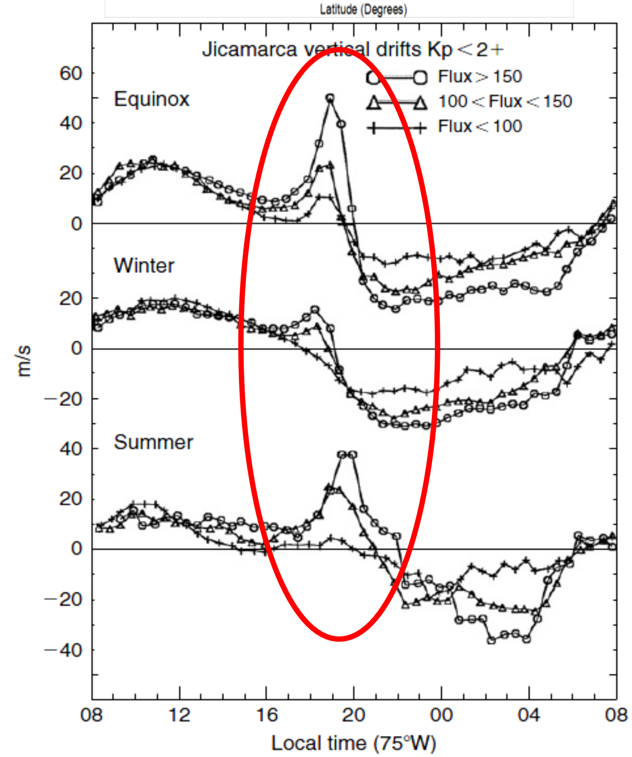
Weak auroral activity

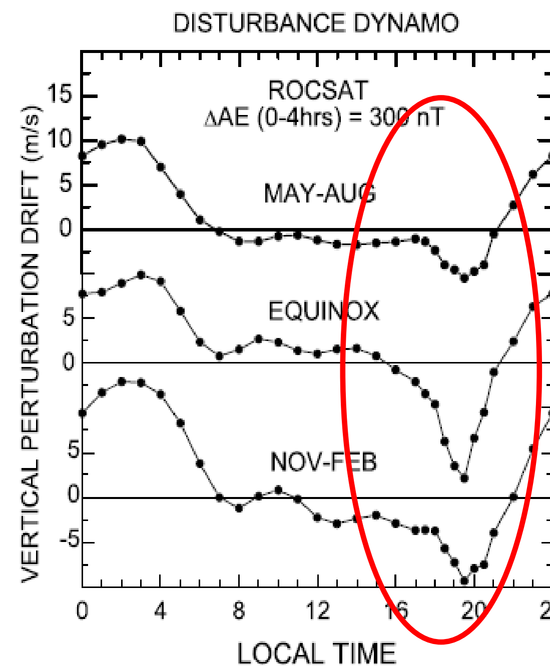


Auroral activity









PPEF

DDEF

Conclusion

- Space Weather is a new scientific discipline connecting physics from the Sun to the Earth
- All the case studies presented in this talk are from PhD students
- There are many data sets and many subjects to do with data available on the web
- More than 80% of the data are not analyzed

Thank you