SOLAR AND INTERPLANETARY PHENOMENA THAT CAUSE THE AURORA BOREALIS

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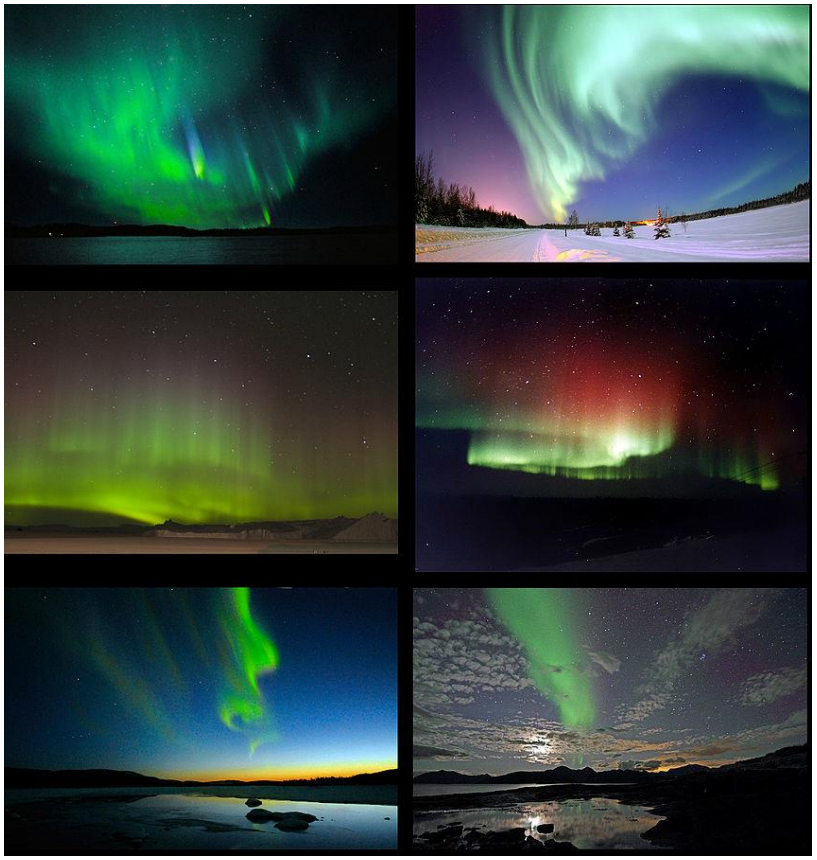
Aurora Borealis and Australis



Images of auroras from around the world, including those with rarer red and blue lights

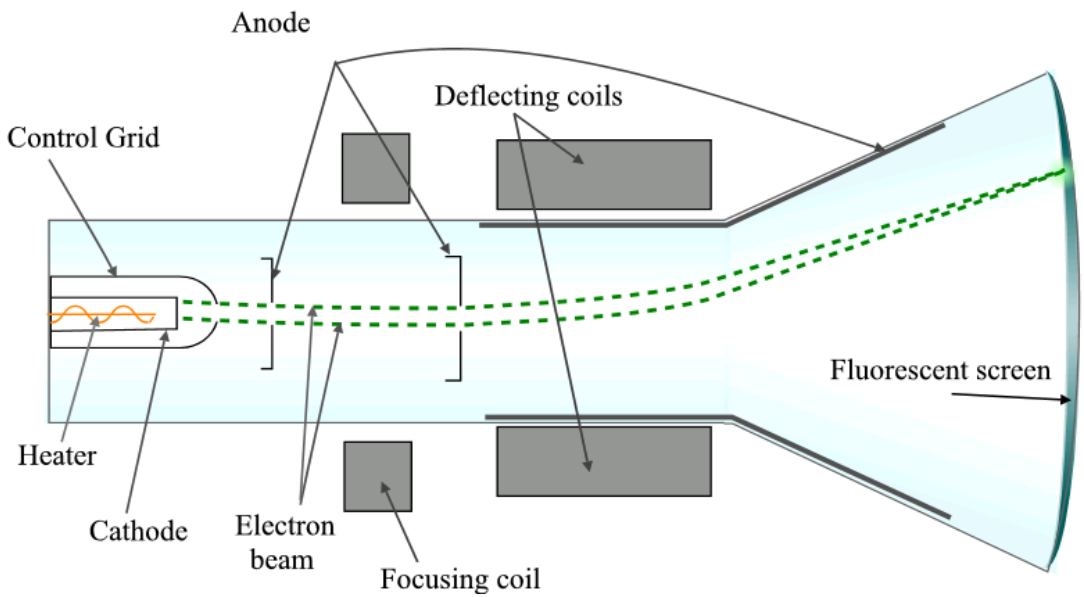
Where does the name “aurora borealis” or “northern lights” come from?

In 1619 Galileo gave it that name after the Roman goddess of dawn (Aurora, Latin: dawn, morning light) and the Greek name for the northern wind

Auroral Omens

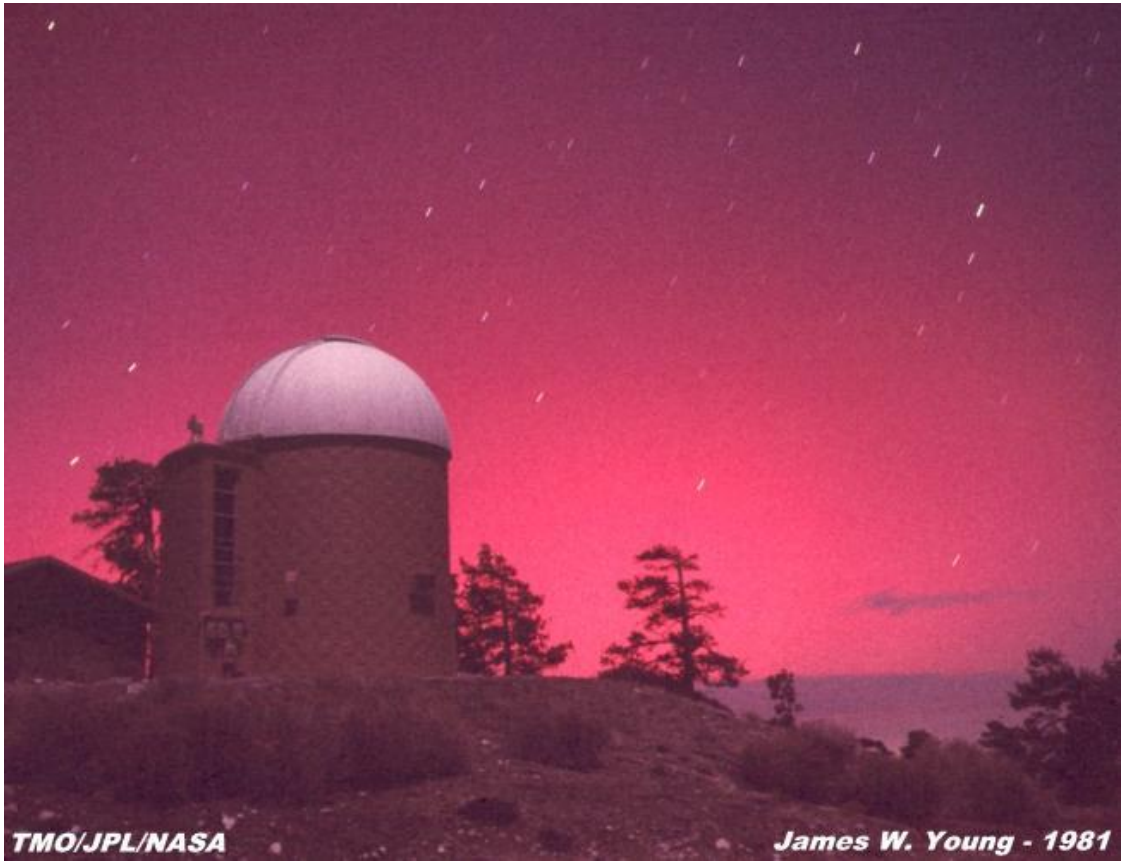
In Chinese and Japanese cultures it is believed that a child conceived under the northern lights will be blessed with good fortune and good looks.

A cathodic ray tube (CRT, the "old television screens") is made of an emitter of electrons called cathode, voltage/electric field accelerators and a fluorescent screen.



Red Auroras Over JPL's Table Mountain Observatory

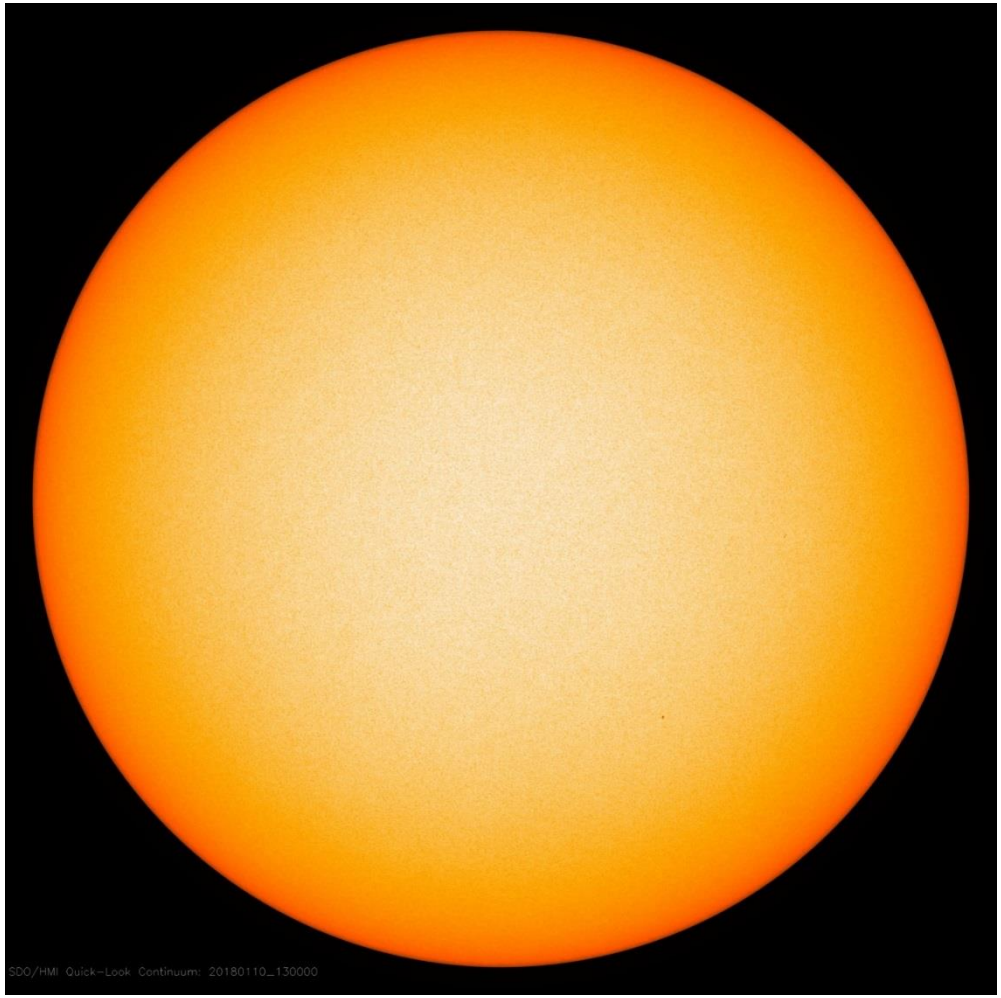
(Los Angeles, April 12, 1981)



Red Aurora Omens

Red auroras on the other hand are rare and terrifying as it was taken as an omen for war and bloodshed. Red auroras were seen over Europe before the French Revolution.

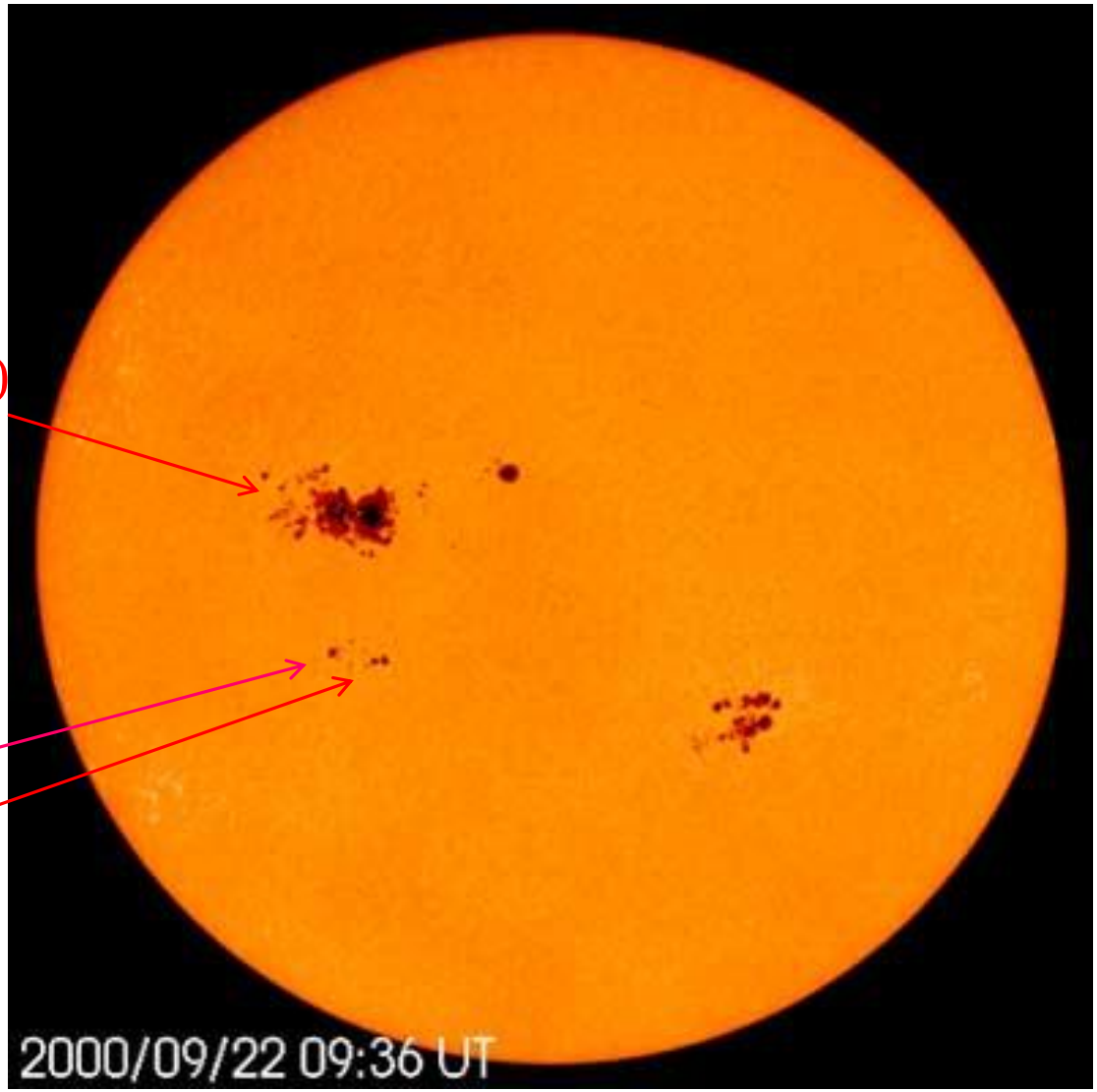
The Sun As Seen in Visible (White) Light in High Spatial Resolution (Processed to look orange)



Sunspots

Active region (AR)

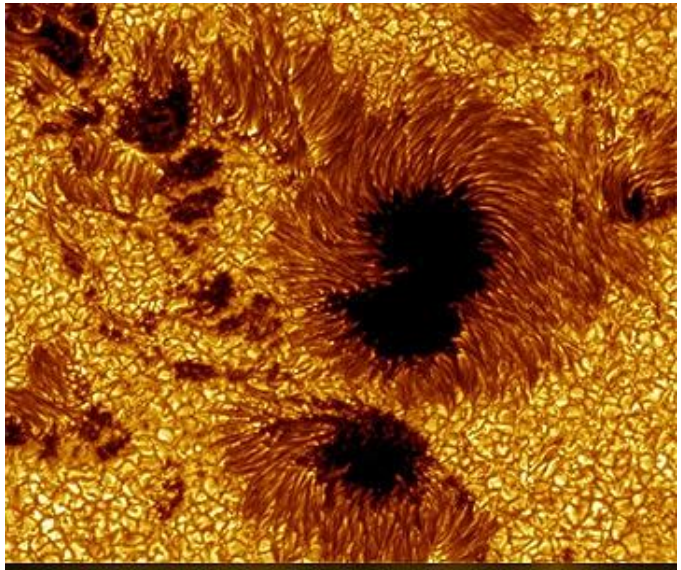
Sunspots:



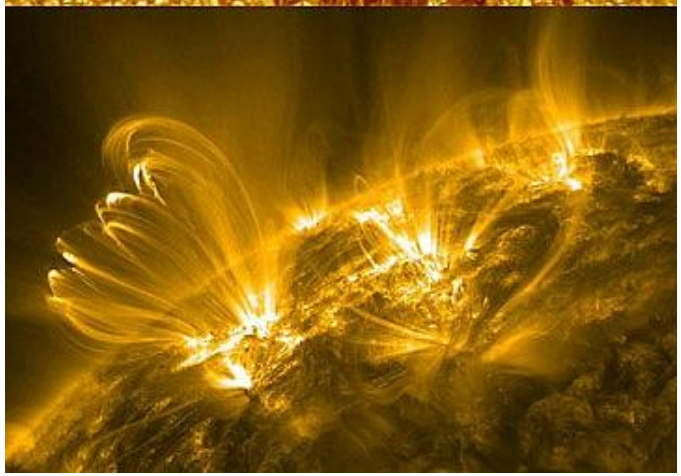
Sunspots reappear every ~27 days, thus the rotation period of the Sun

High Resolution Images of an Active Region

Frontal View

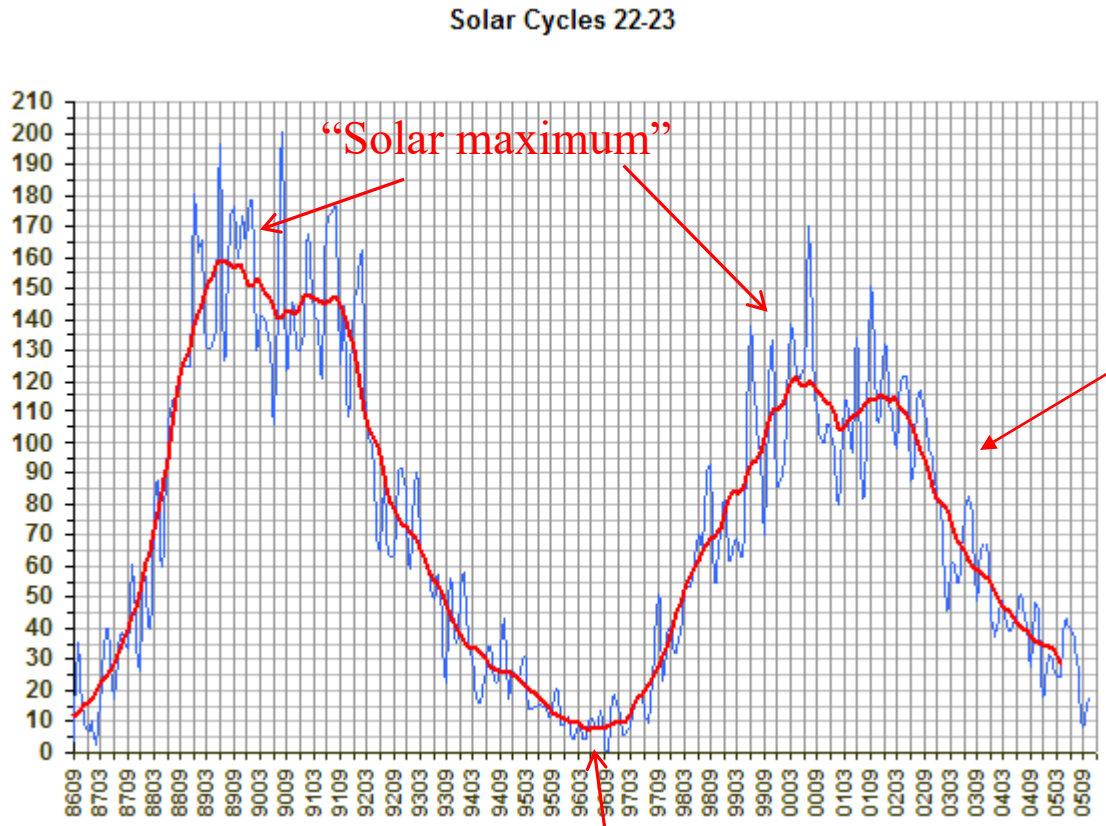


Side View

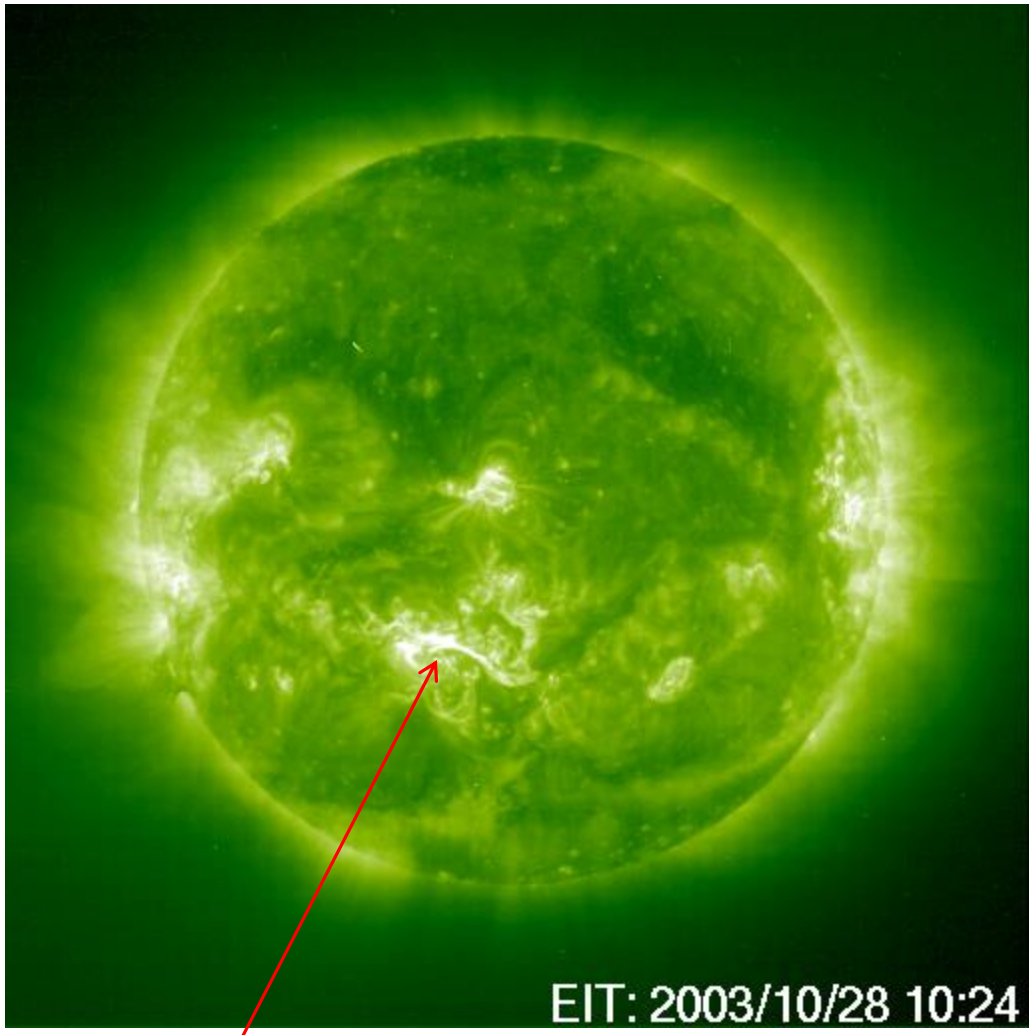


The “Solar Cycle”: ~11 Year Period (Actually ~ 22 Years)

Number of Sunspots

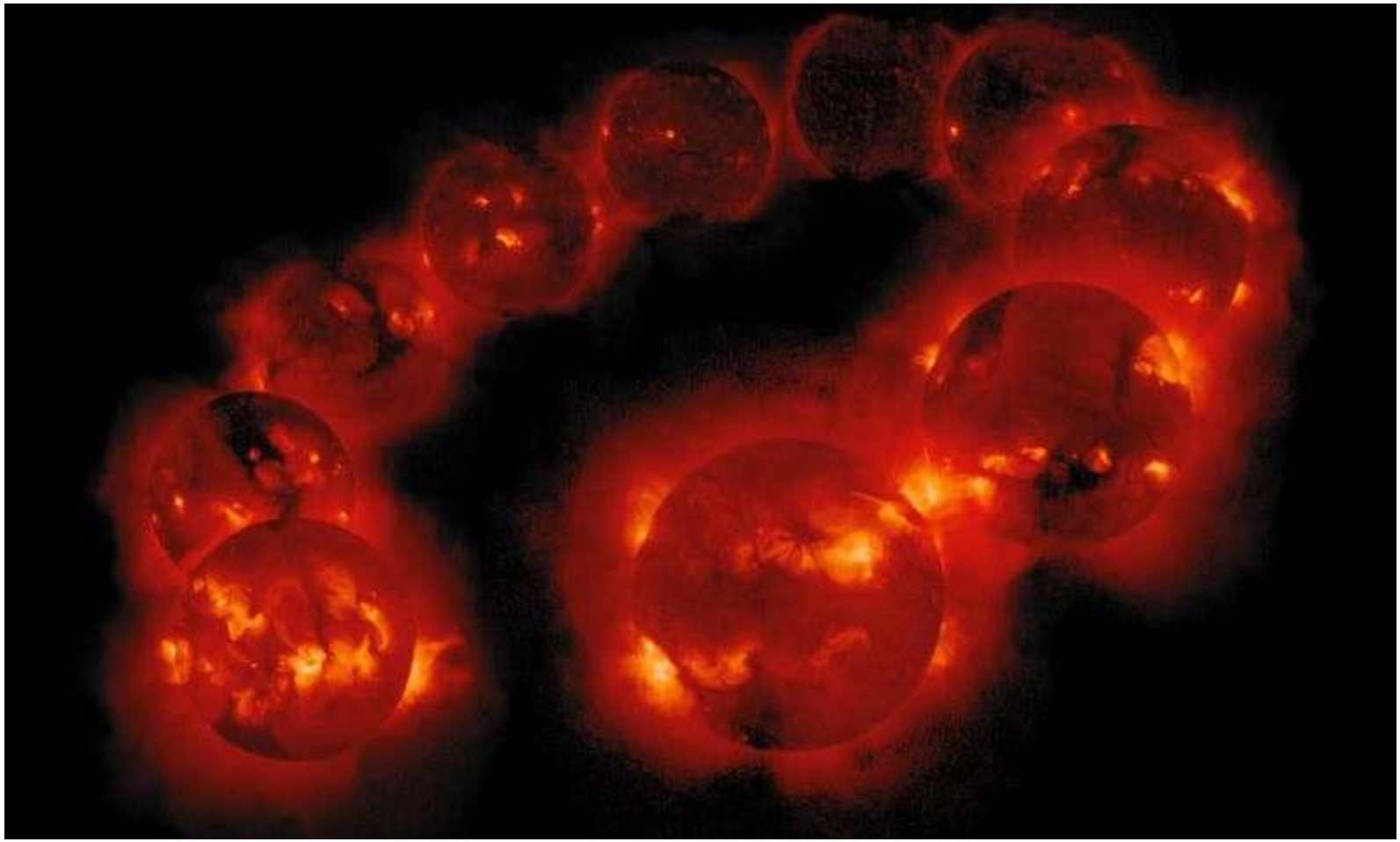


The Sun Viewed in Soft X-Rays During Solar Maximum

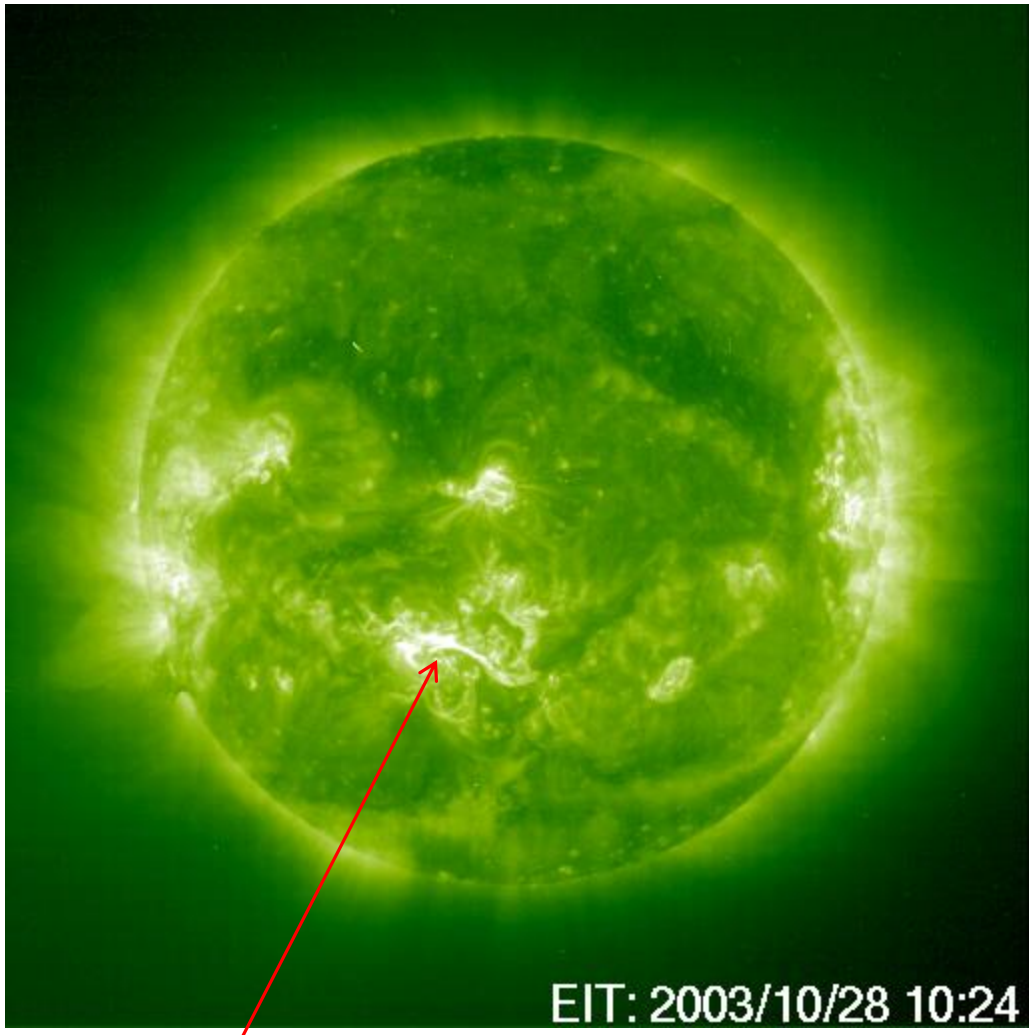


The Oct 28, 2003 Active Region and Solar Flare

Montage of images of solar activity between August 1991 and September 2001
Taken in soft X-rays



The Sun Viewed in Soft X-Rays During Solar Maximum

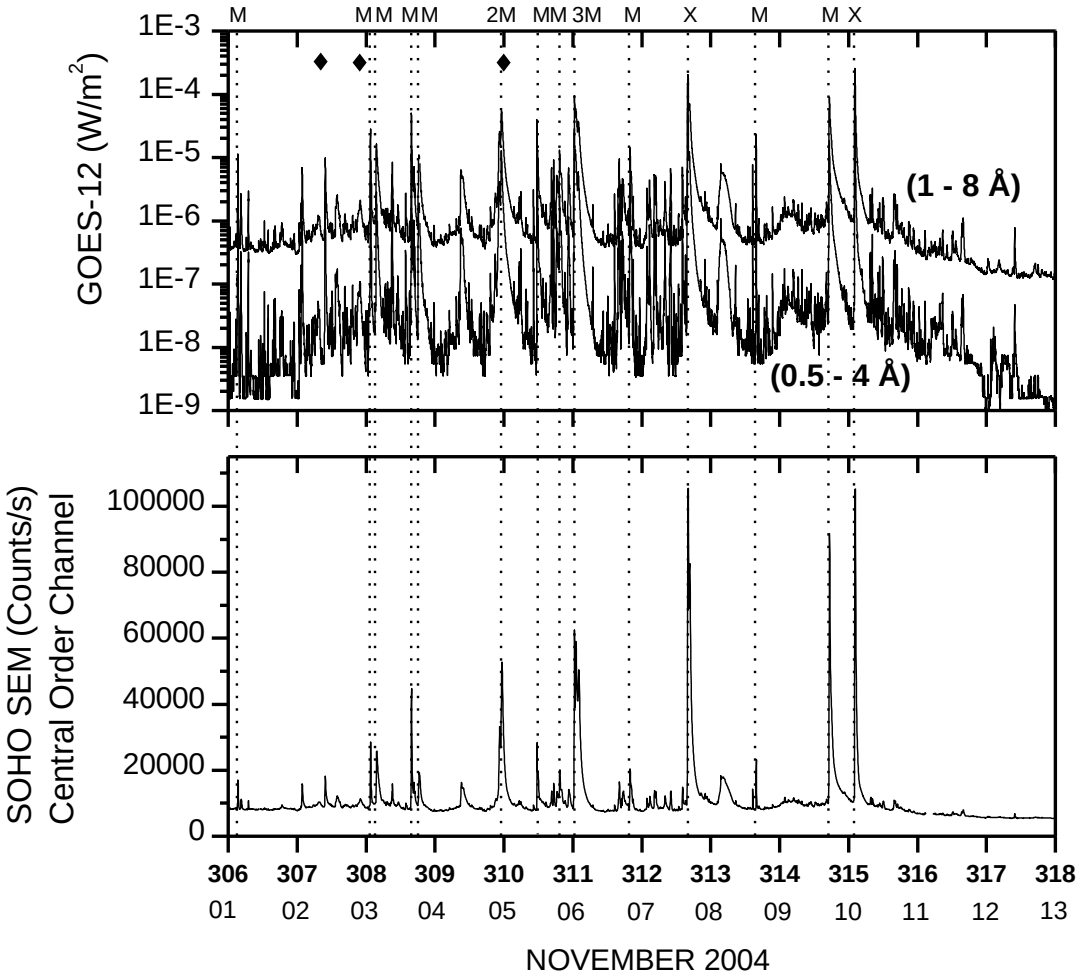


The Oct 28, 2003 Active Region and Solar Flare

Solar Flares From an Active Region (AR)

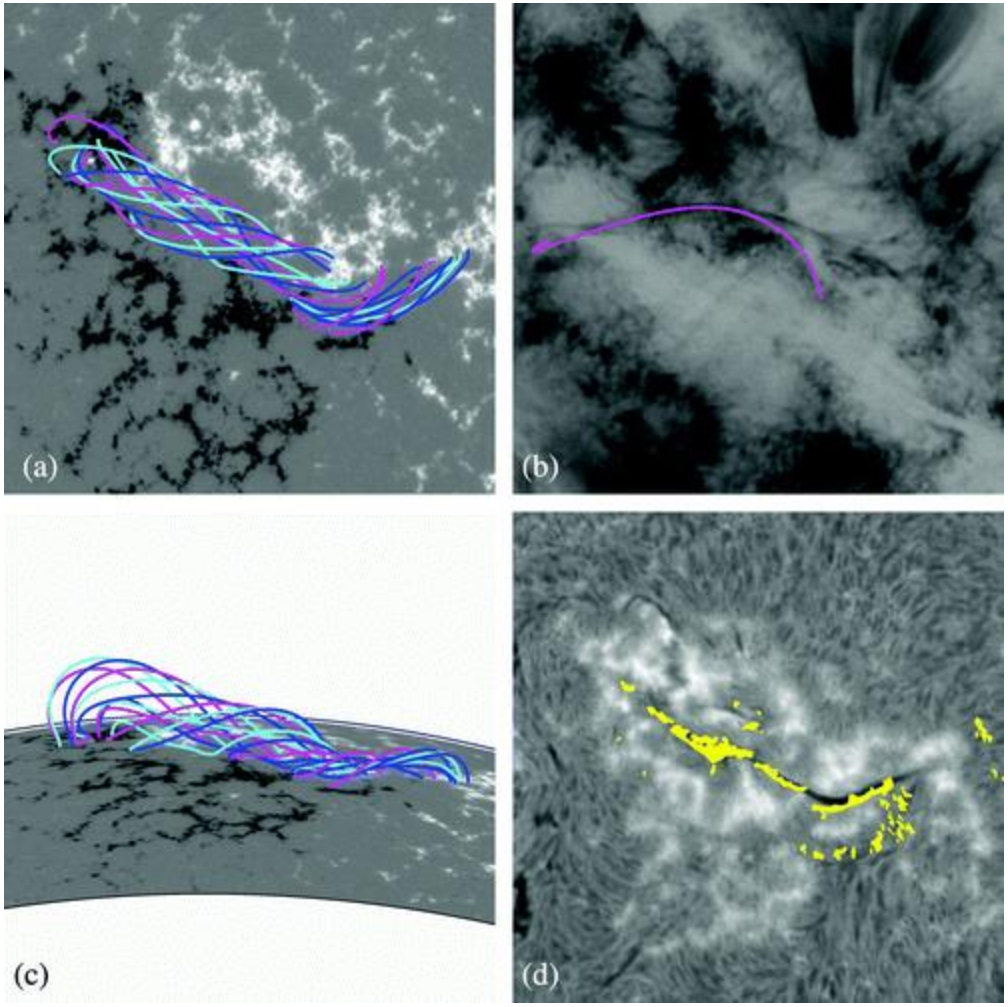
X-rays

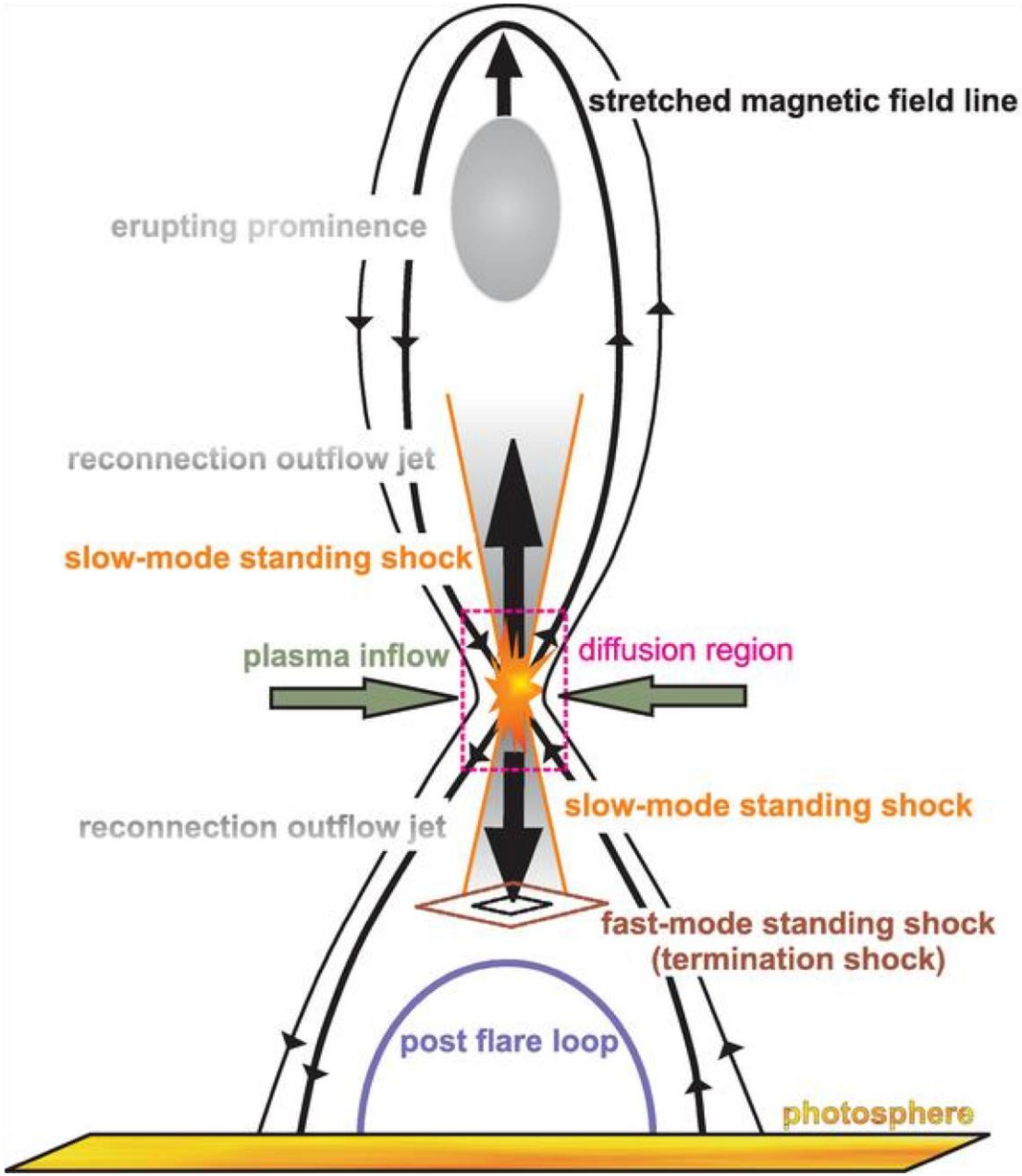
EUV wavelengths



Tsurutani et al. GRL, 2008

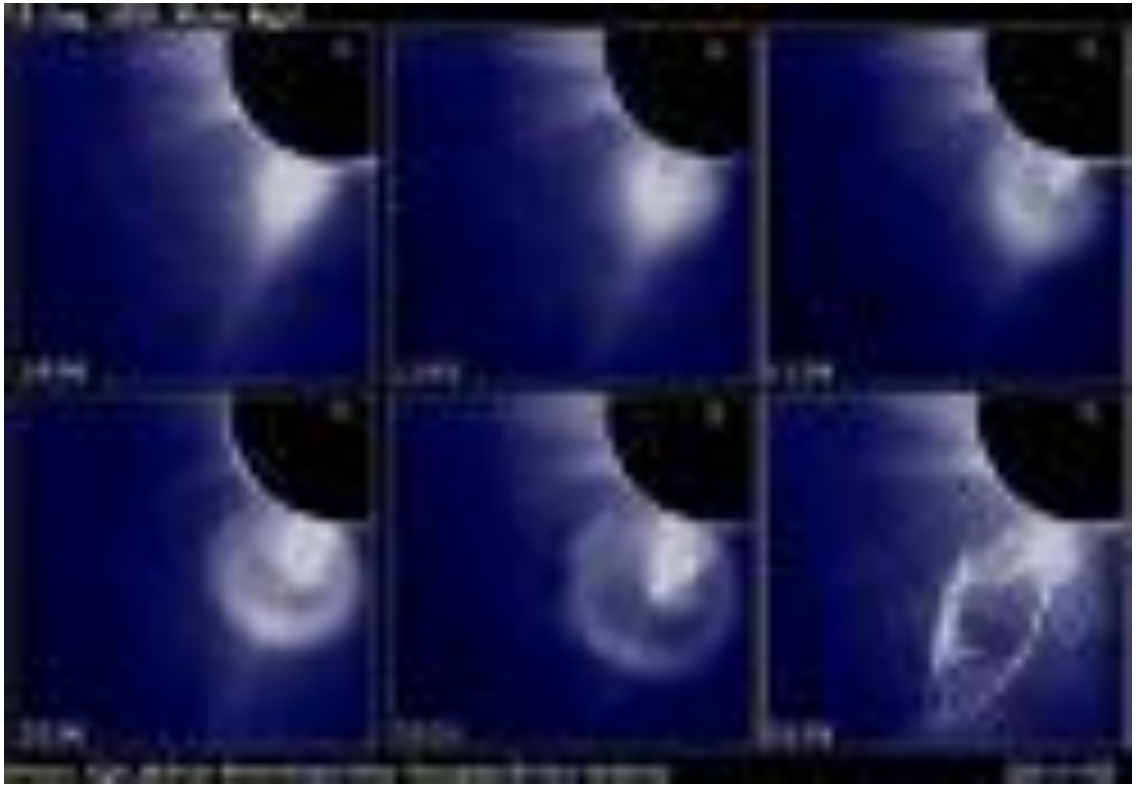
Twisted Magnetic Fields Lead to Magnetic Reconnection




stretched magnetic field line
erupting prominence
reconnection outflow jet
slow-mode standing shock
plasma inflow
diffusion region
slow-mode standing shock
reconnection outflow jet
fast-mode standing shock
(termination shock)
post flare loop
photosphere

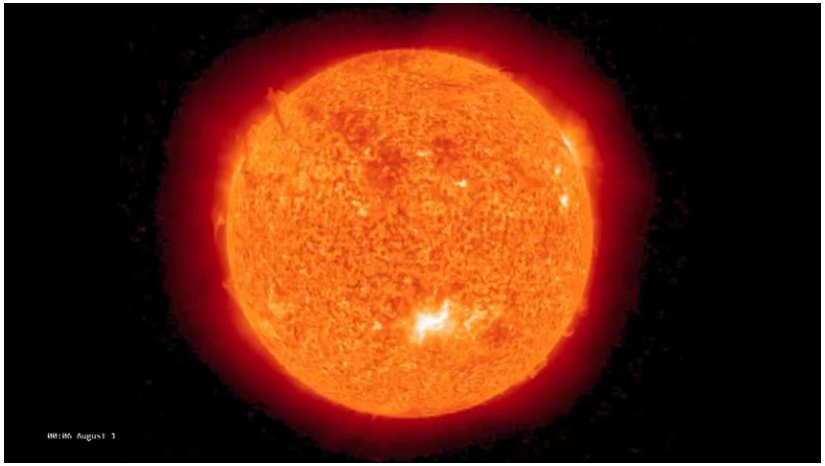
Intense Solar Flares Are (Almost) Always Accompanied with Coronal Mass Ejections (CMEs)

August 18, 1980

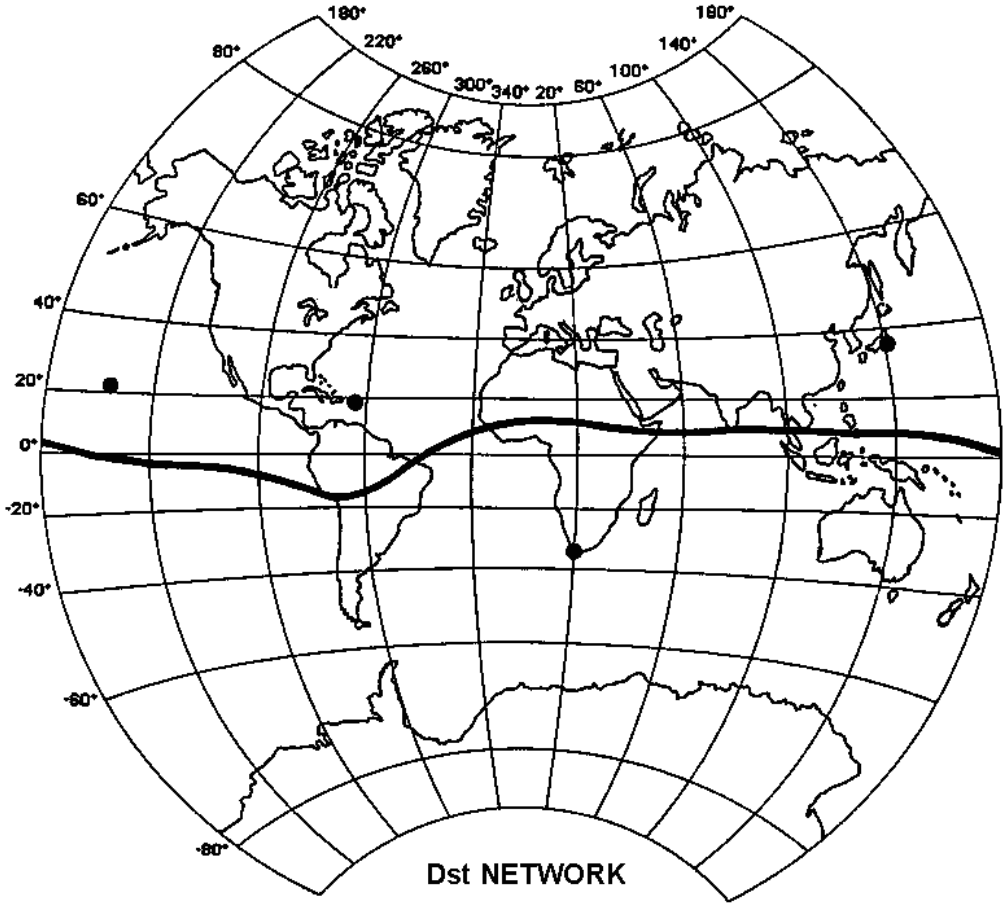


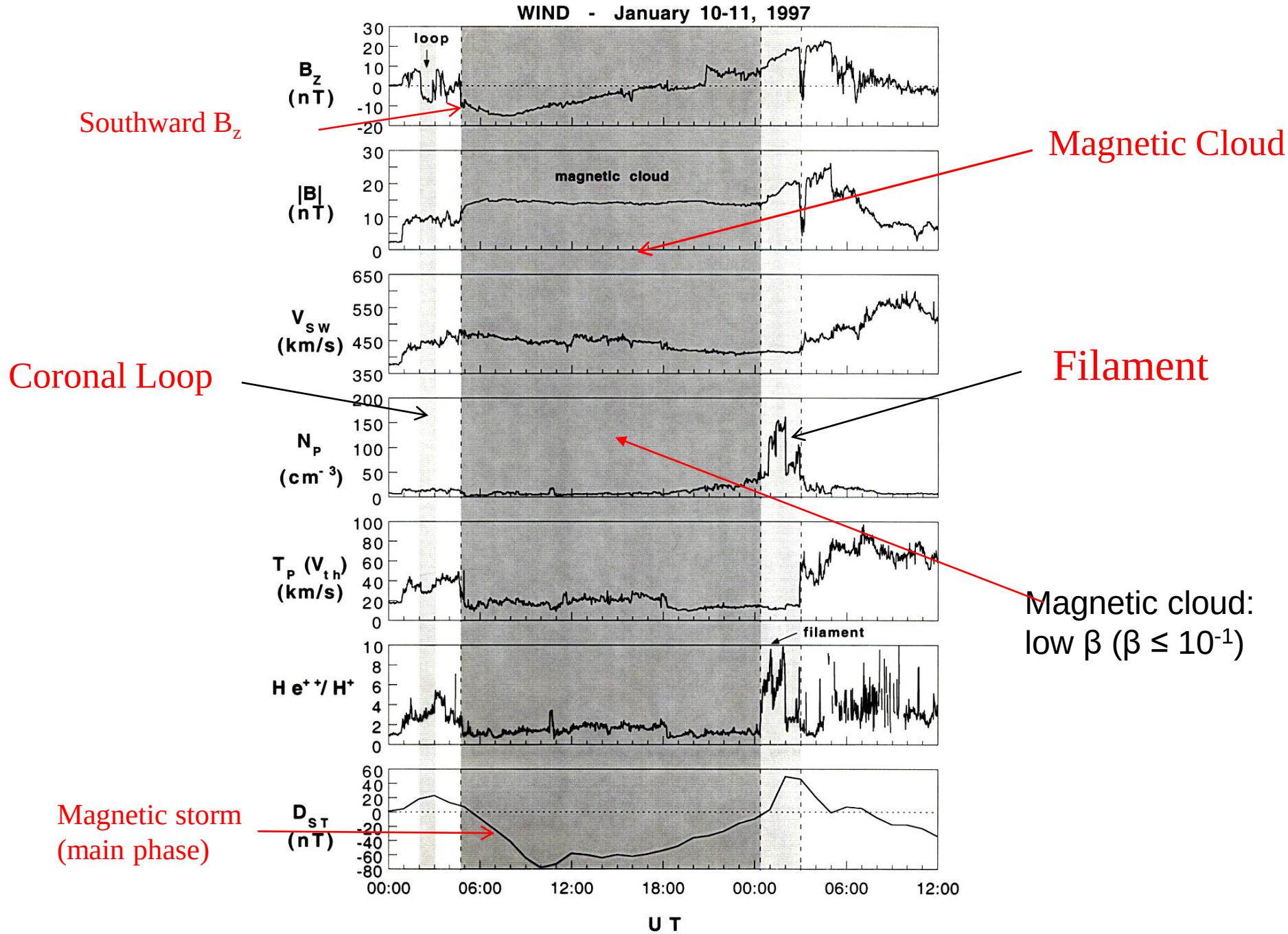
Courtesy of A.Hundhausen

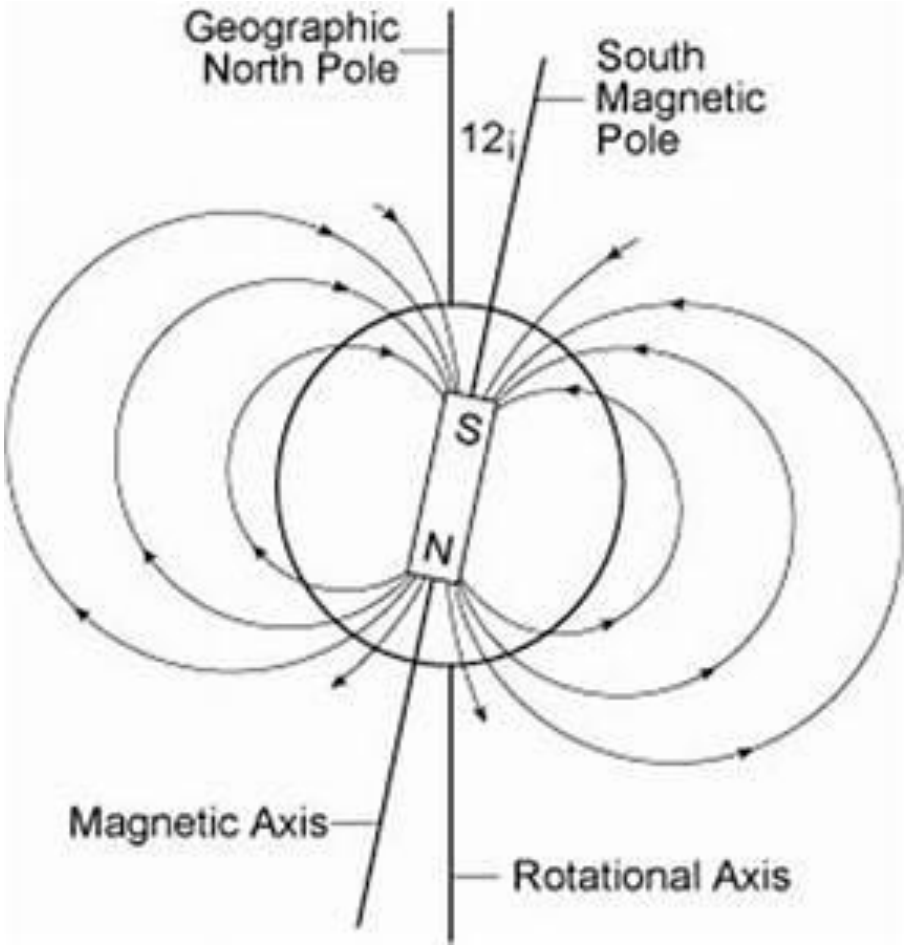
CMEs in August 2010.

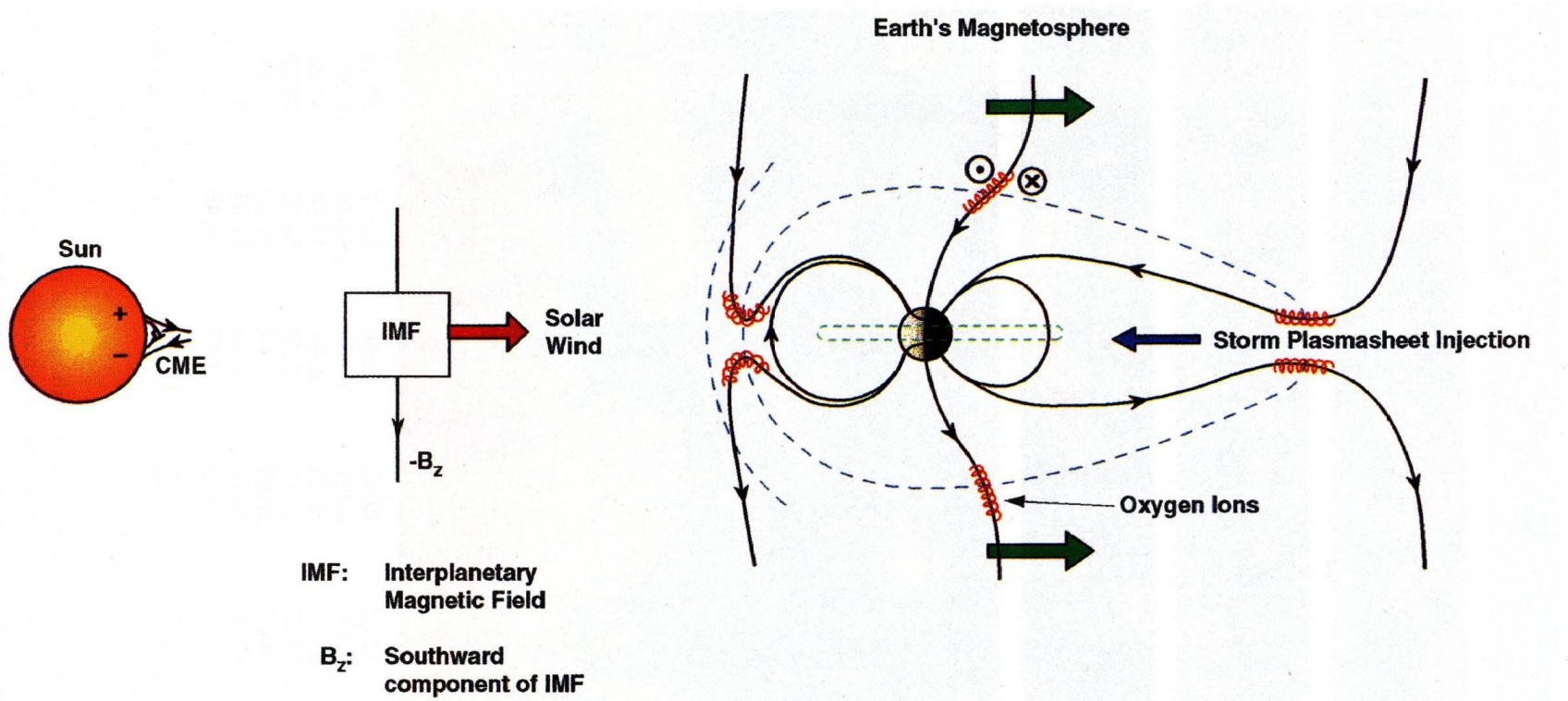


4 Magnetometer Ground Station Dst Index




WIND - January 10-11, 1997
loop
magnetic cloud
filament
B_z (nT)
|B| (nT)
V_{sw} (km/s)
N_p (cm^{-3})
T_p (V_{th}) (km/s)
He^{++}/H^+
D_{ST} (nT)
00:00
06:00
12:00
18:00
00:00
06:00
12:00
UT
Southward B_z
Magnetic Cloud
Coronal Loop
Filament
Magnetic cloud:
low β (β ≤ 10^{-1})
Magnetic storm
(main phase)

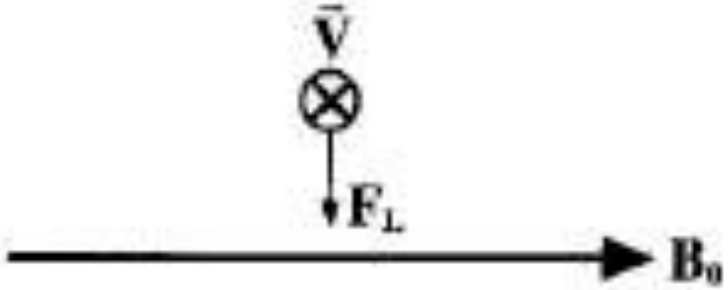

Geographic
North Pole
South
Magnetic
Pole
12¡
S
N
Magnetic Axis
Rotational Axis

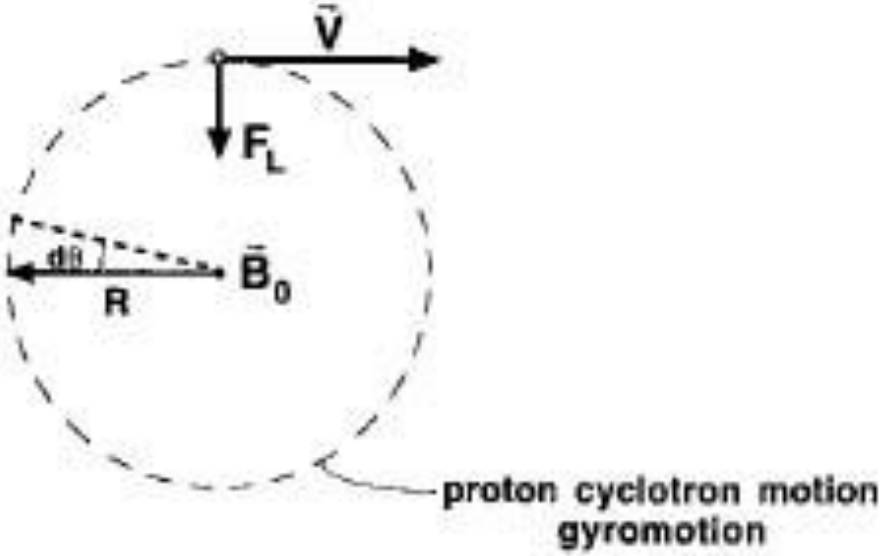


The principal cause of energy transfer from the solar wind to the magnetosphere during magnetic storms is magnetic reconnection (Dungey, Phys Rev. 1961)

Lorentz Force

$$\bar{F} = \frac{q}{c}\left(\bar{V} \times \bar{B}_0\right)$$

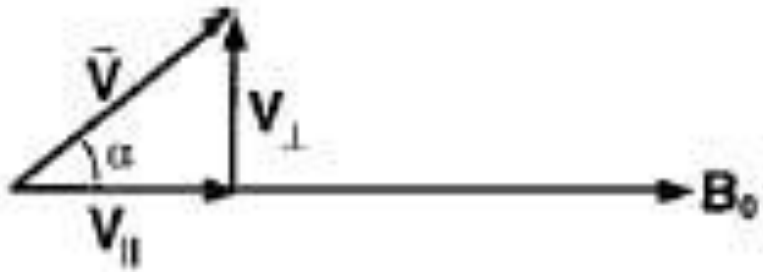




$mV^2/r = q\,\mathbf{v} \times \mathbf{B}/c$

$r = mvc/qB = pc/eB$

$\Omega = d\theta/dt = V/r = eB/mc$



$$\sin\alpha = \frac{V_\perp}{V}$$

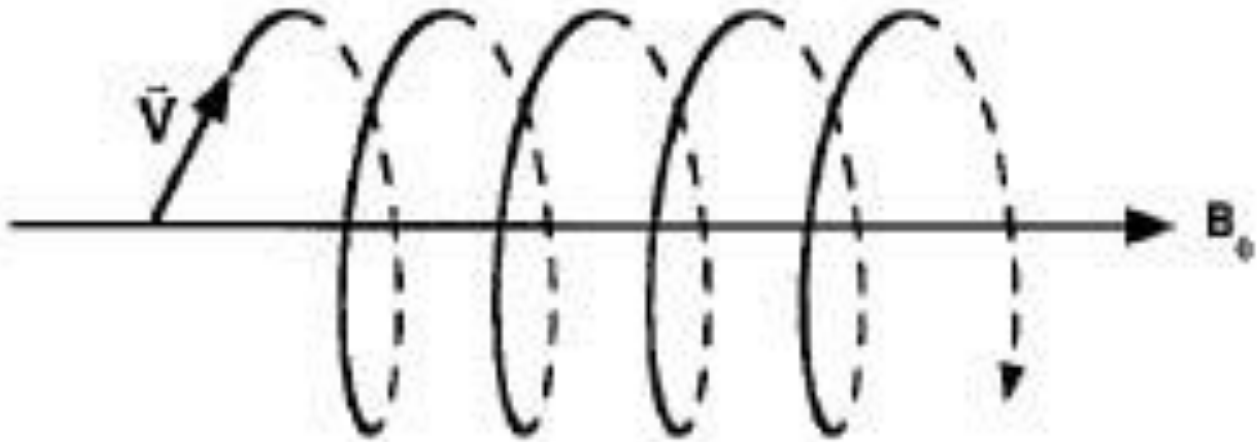
α is the “pitch angle”

$$\mathbf{V} = V_{\parallel}\mathbf{b} + \mathbf{V}_\perp$$

$$E_T = \tfrac{1}{2} mV^2 = \tfrac{1}{2} m\,(V_{\parallel}\mathbf{b} + \mathbf{V}_\perp)\,.\,(V_{\parallel}\mathbf{b} + V_\perp)$$

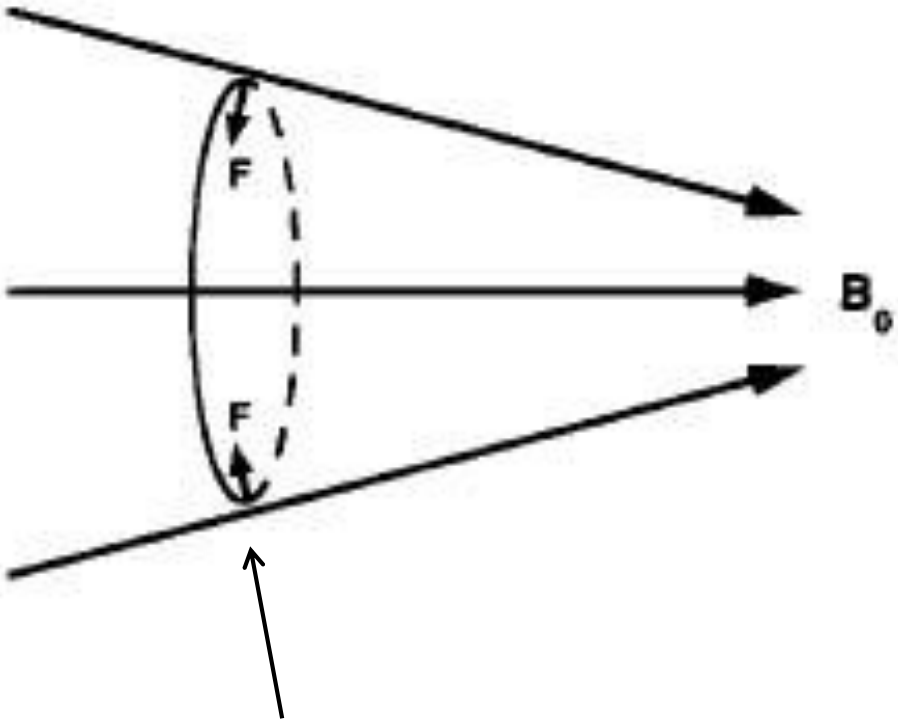
$$= \tfrac{1}{2} mV_{\parallel}^2 + \tfrac{1}{2} mV_\perp^2 = E_{\parallel} + E_\perp$$

Particle Gyromotion



Particles move in a corkscrew motion about the magnetic field

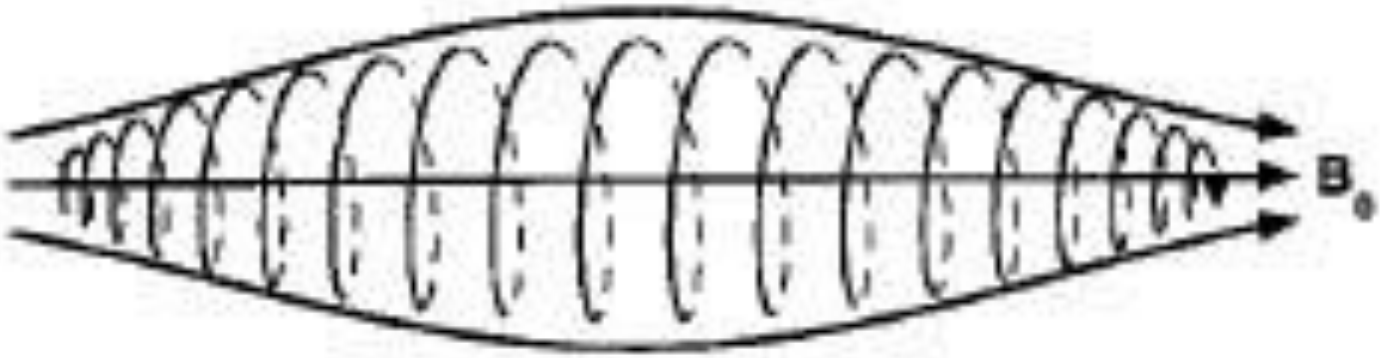
Particle Motion in a Magnetic Field Gradient



Magnetic Mirror : $E_{\perp} = E_{Total}$

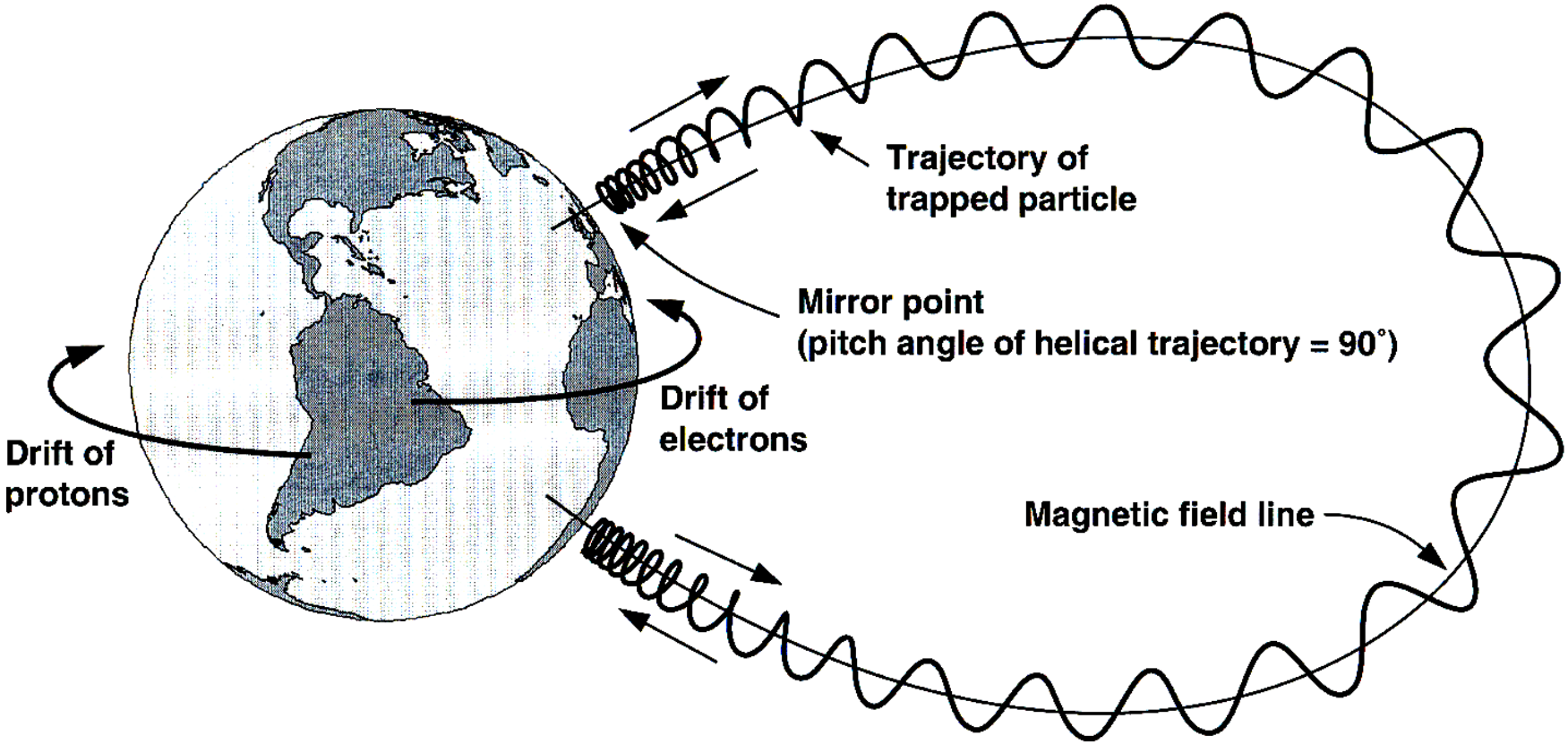
Magnetic Bottle

Plasma Confinement



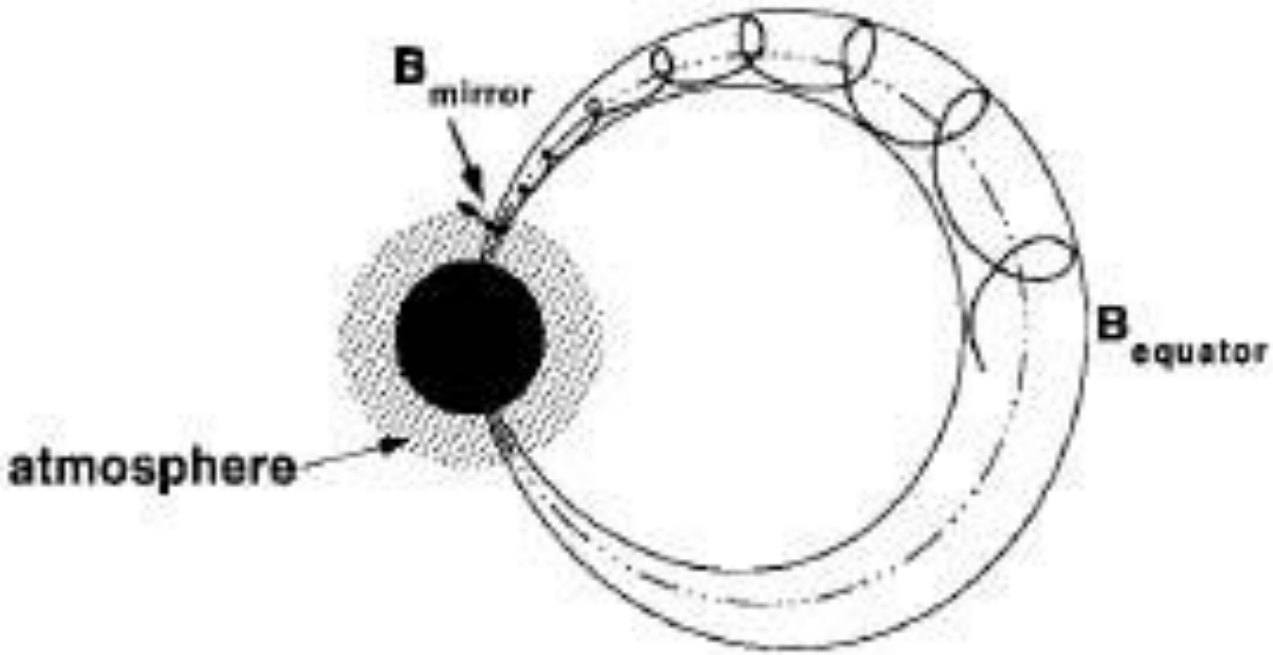
$\mu = E_\perp/B$ = constant (Hannes Alfvén: first adiabatic invariant)

Formation of an Enhanced 30-300 keV Ring Current (Protons And Electrons)



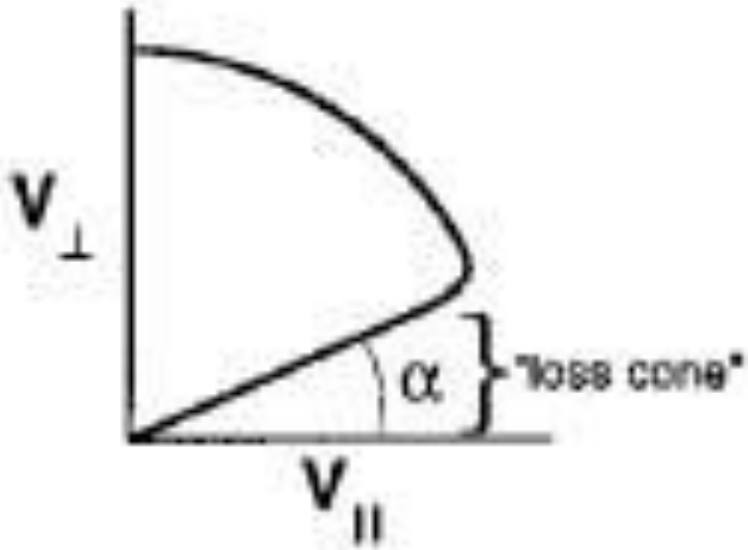
The decrease of the horizontal component of the Earth's surface field (Dst or SYM-H) is caused by the diamagnetic ring current, which is intensified during storms. The total field decrease is linearly proportional to the total particle energy.

Earth's Radiation Belts



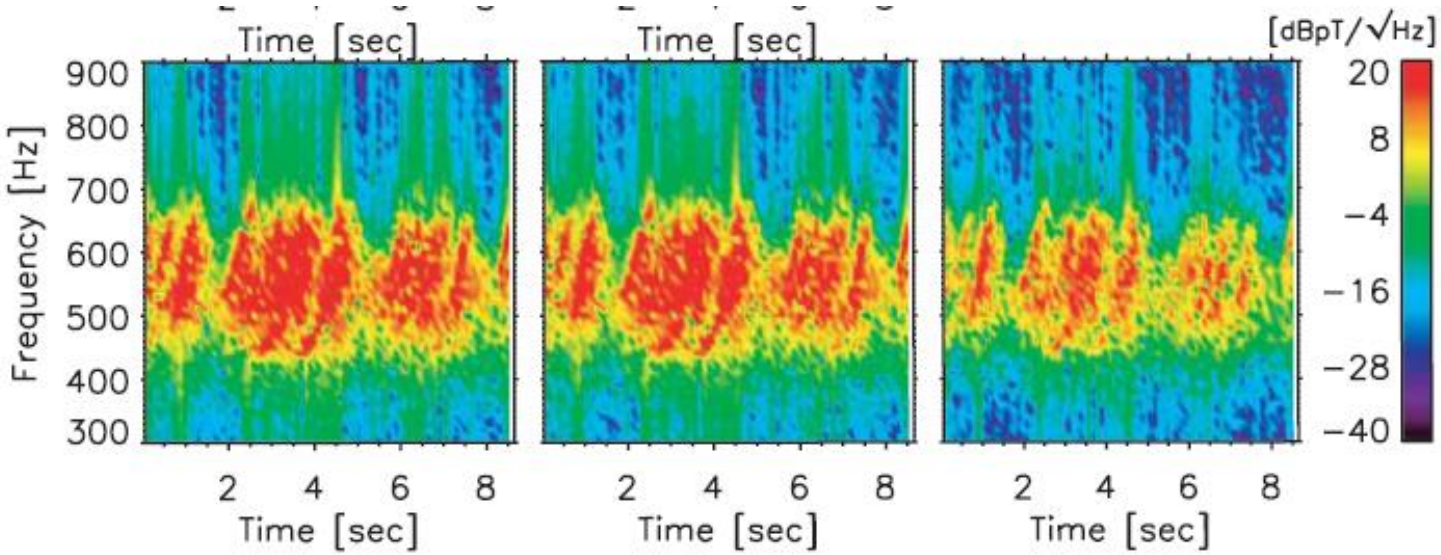
Auroras

Loss Cone

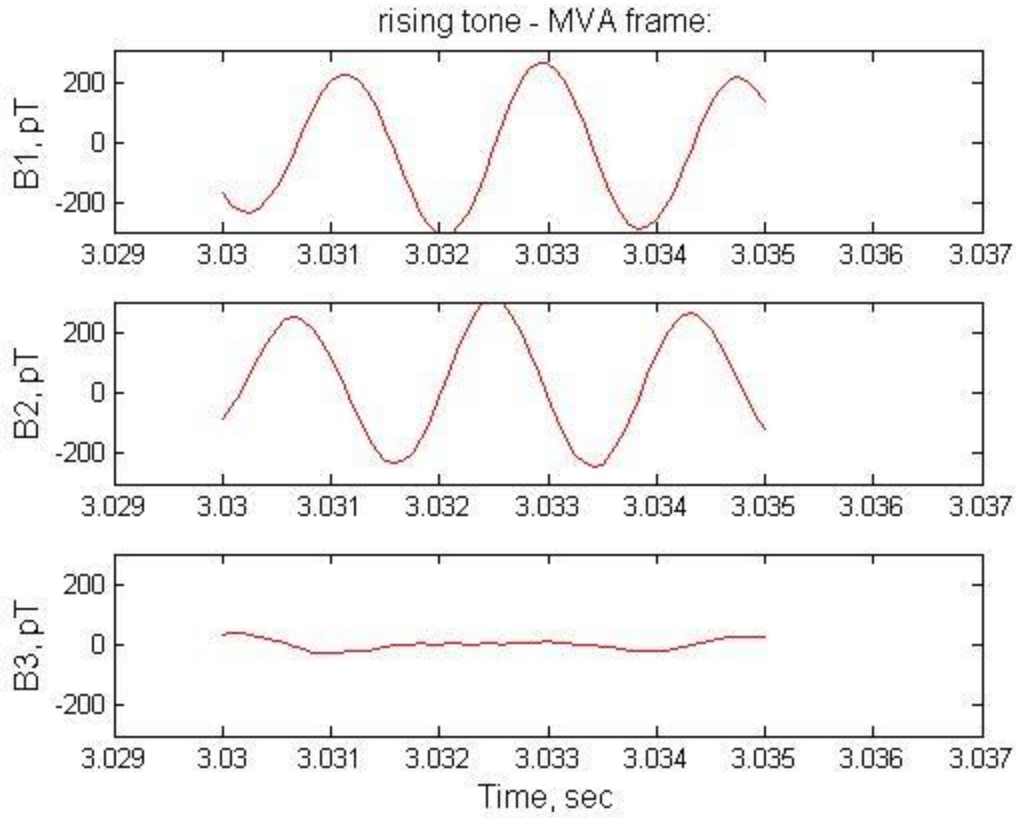


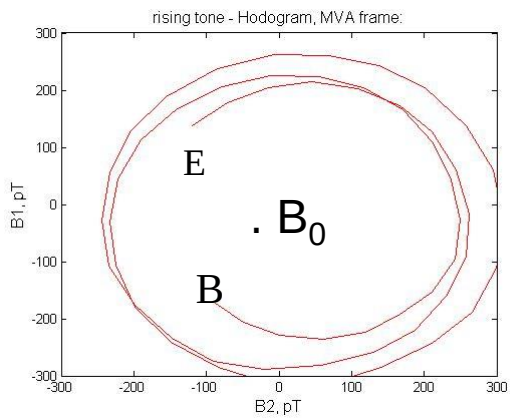
Pitch angle distribution at magnetic equator

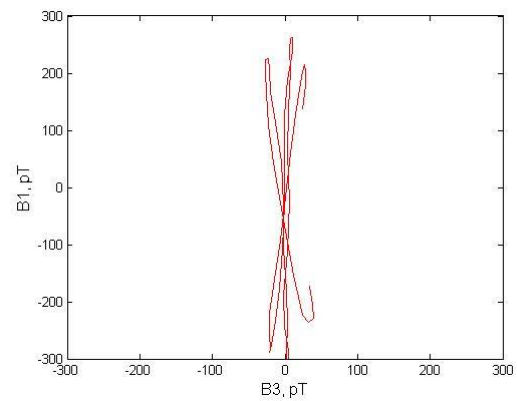
Electromagnetic “Whistler Mode” Chorus



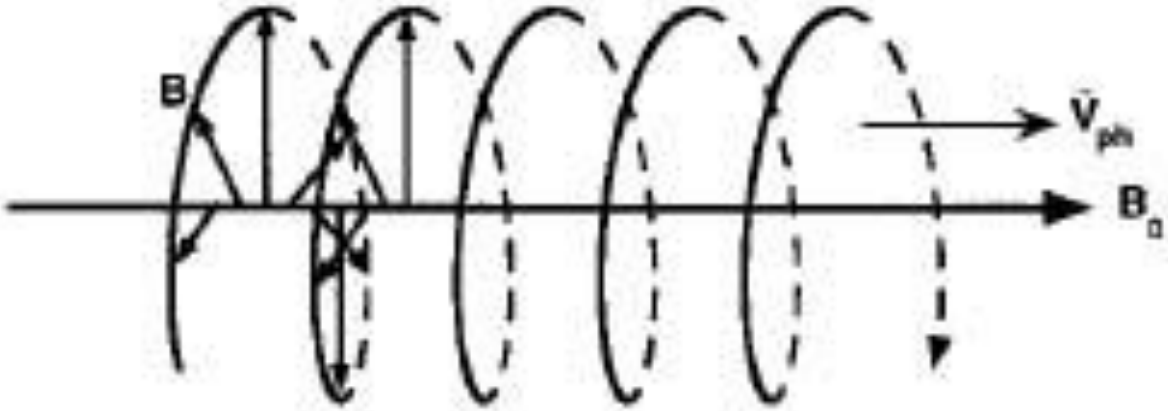
Tsurutani et al. 2009


rising tone - MVA frame:
B1, pT
B2, pT
B3, pT
200
0
-200
3.029
3.03
3.031
3.032
3.033
3.034
3.035
3.036
3.037
Time, sec


rising tone - Hodogram, MVA frame:
E
. B0
B
B1, pT
B2, pT
300
200
100
0
-100
-200
-300

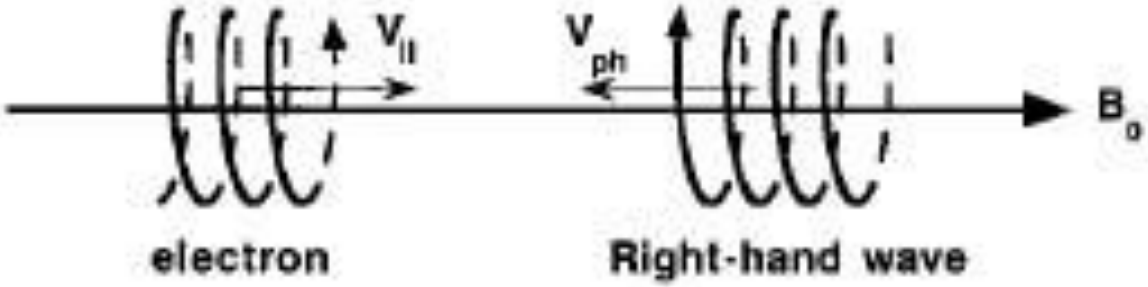

B1, pT
B3, pT
300
200
100
0
-100
-200
-300

Right-Hand Polarized Waves



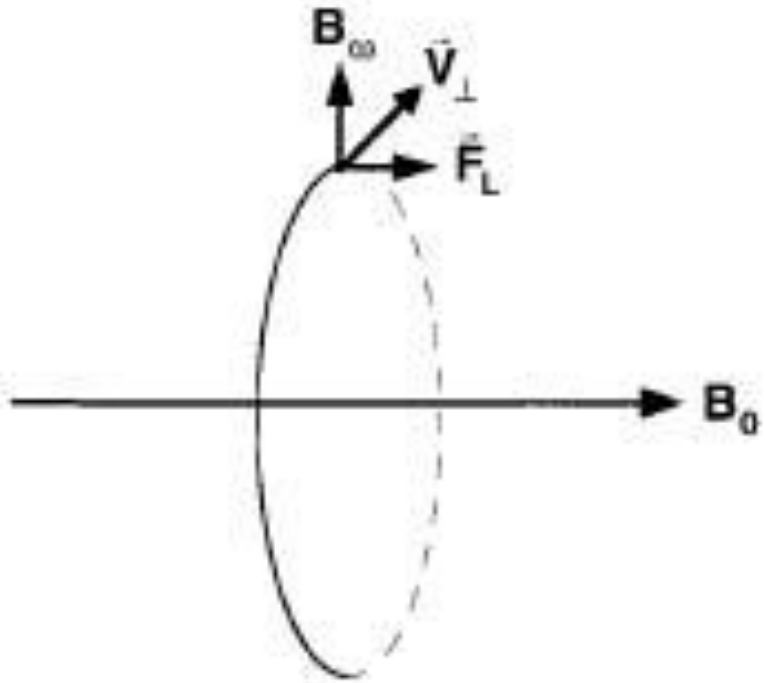
Whistler mode (high ω)
Magnetosonic mode (low ω)

Normal Cyclotron Resonance

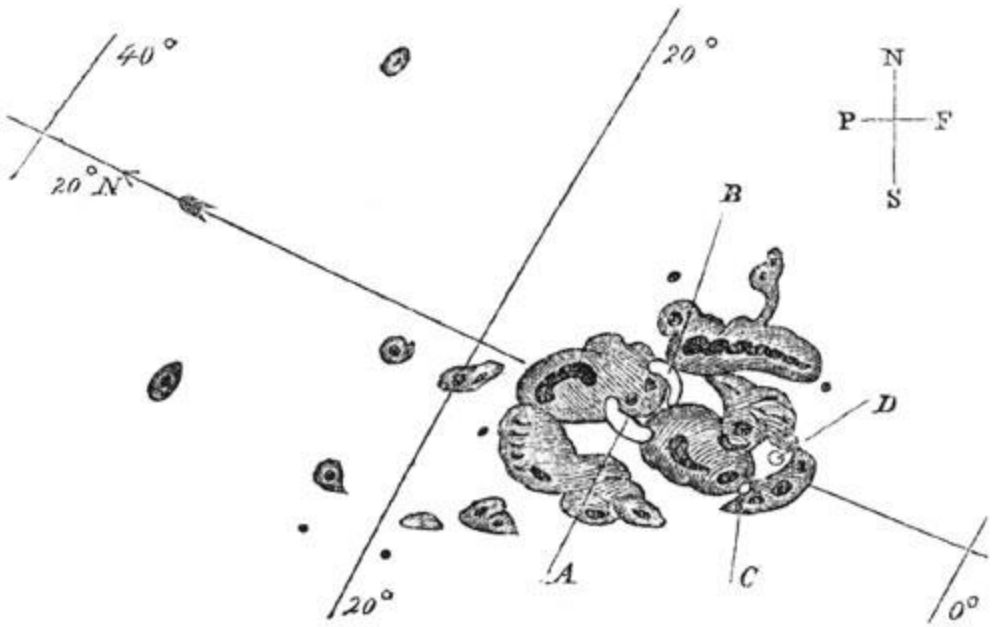


$$\omega + k_{ll} V_{ll} = \Omega^{-}$$

Wave-Particle (Cyclotron) Interaction



The September 1, 1859 “Carrington” Solar Flare



Famous hand drawn by R. Carrington: clearly what we now call an “active region”.

AR caused multiple flaring and continuous geomagnetic activity over a week duration

Carrington MNRS, 1859

“Description of a Singular Appearance seen in the Sun on September 1, 1859”

By R.C. Carrington, Esq. ***(MNRA, 20, 13, 1859)***

“Mr. Carrington exhibited at the November meeting of the Society and pointed out that a moderate but very marked disturbance took place at about 11:20 AM, September 1st, of short duration; and that towards four hours after midnight there commenced a great magnetic storm, …….”
“While contemporary occurrence may deserve nothing, he would not have it supposed that he even leans towards hastily connecting them. “One swallow does not make a summer”. “

Carrington gave us gave us information to determine the average speed of the CME. It was not “politically correct” to relate solar and geomagnetic phenomena at the time (due to Lord Kelvin) .

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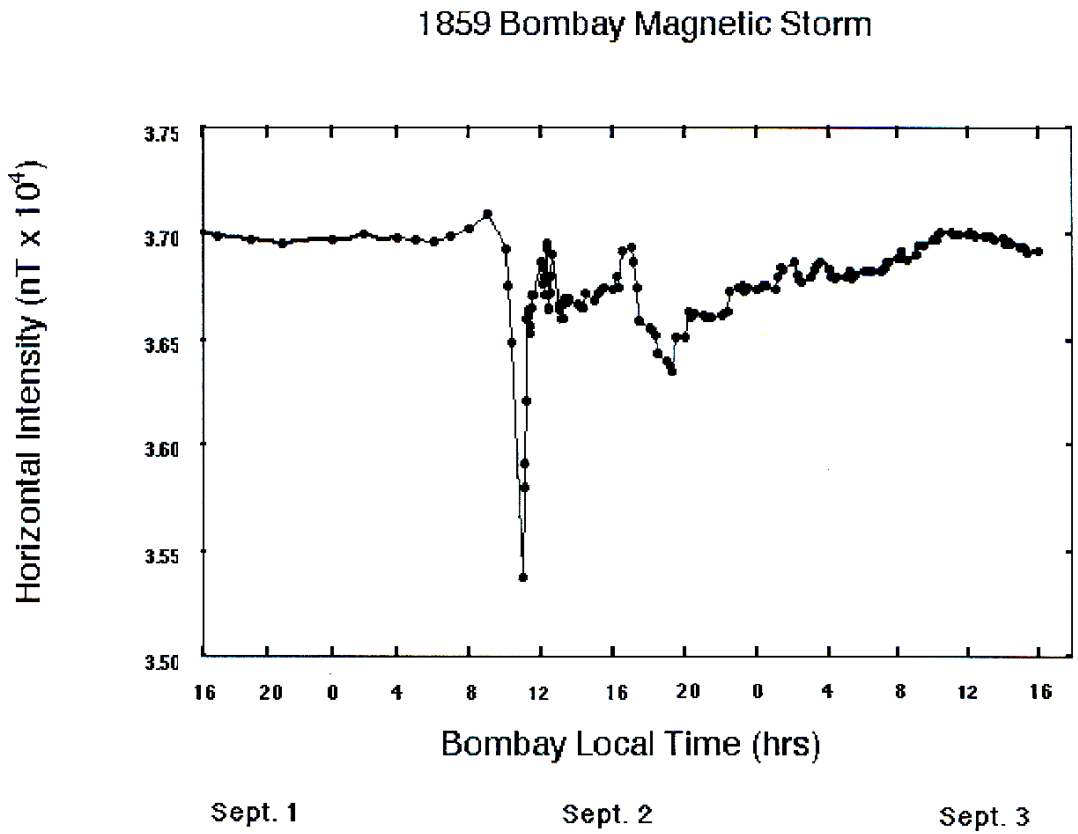
Auroras During the Magnetic Storm of 1-2 September 1859

D.S. Kimball* (*University of Alaska internal report*), 1960

“Red glows were reported as visible from within 23° of the geomagnetic equator in both north and south hemispheres during the display of September 1-2”

*Kimball was a colleague of Sydney Chapman. He was not a permanent employee of the University of Alaska, but came there for summers (from the east coast) to enjoy the Alaskan (summer) weather (S.-I. Akasofu, personal comm., 2001).



*Measurements taken from a Grubb magnetometer. The magnetometer was "high technology" at the time. The manual for calibration does not have a sketch of it, probably because the British wanted to keep it secret (a copy of the calibration information can be found at the Royal Society, London).

Tsurutani, Gonzalez, Lakhina and Alex, JGR, 2003

Grubb Magnetometer Calibration

Royal Society, Revised Instructions for the Use of the Magnetic Meteorological Observations and for Magnetic Surveys, Comm. of Phys. and Meteorol., R. Soc., London, 1842.

The magnetometer was “high technology” at the time. The manual for calibration does not have a sketch of it, probably because the British wanted to keep it secret (a copy of the calibration information can be found at the Royal Society, London).

Modern day knowledge plus older observations allowed us to estimate the magnetic storm strength

From a plasmapause location of L=1.3 (auroral data: *Kimball*, *1960*), we can estimate the magnetospheric electric field.

The electric potential (*Volland, 1973; Stern, 1975; Nishida, 1978*) for charged particles is:

Where r and Ψ are radial distance and azimuthal angle measured counterclockwise from solar direction

M dipole moment, q and μ- particle charge and magnetic moment.

The magnetospheric electric field is estimated to be ~20 mV/m. The interplanetary electric field has been estimated to have been ~160 to 200 mV/m*.

Extreme Magnetic Storm of September 1-2, 1859

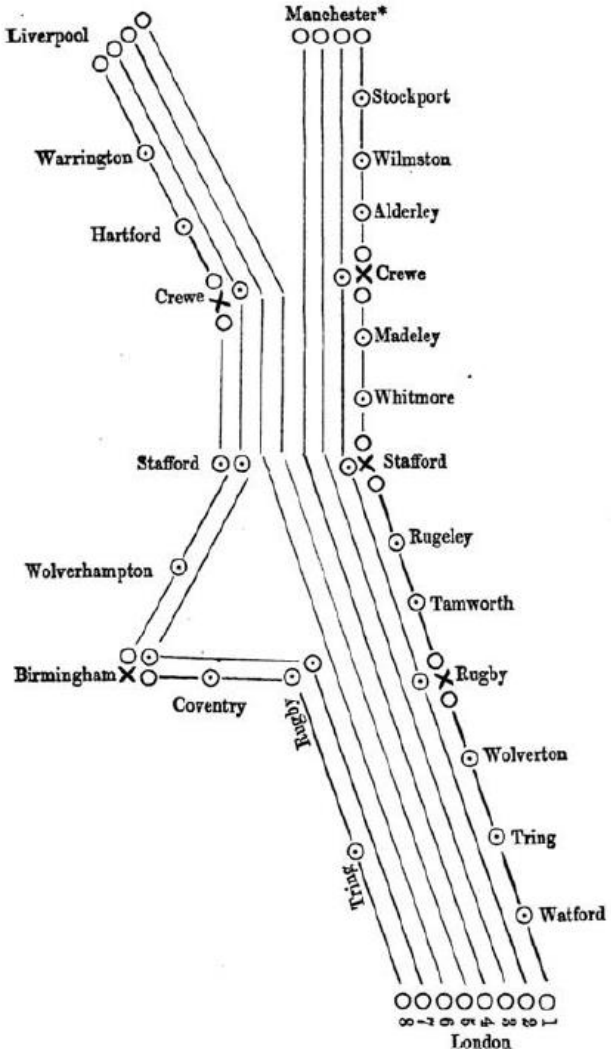
Dst is estimated to be ~ -1760 nT, consistent with the Colaba 11 am response of $\Delta H = -1600 \pm 10$ nT.

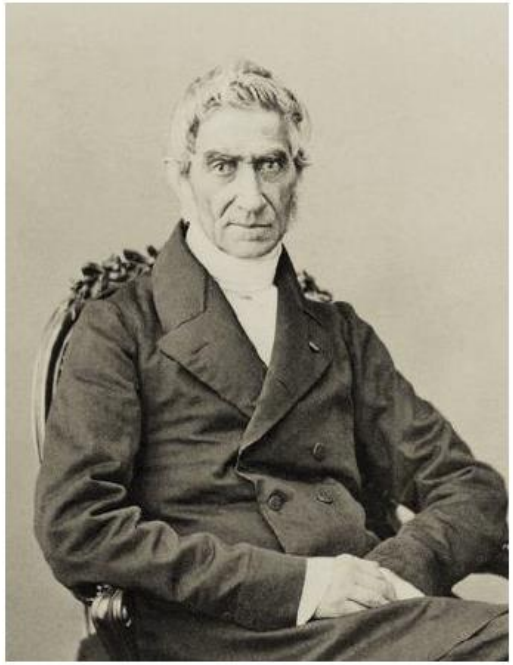
The storm was the most intense in recorded history. Auroras were seen at Hawaii and Santiago, Chile.

The Carrington storm was larger than anything that we have experienced in our lifetimes*.

What Happened During the 1859 Carrington Magnetic Storm?

The electrical telegraph





The Wheatstone telegraph system was operational in England in 1840 and was tested for network science at the Brussels Observatory in the same year by Quetelet and Gauss. In 1859, the Morse design was dominating.

US observations

An extensive compilation by Edgar Loomis, record of low latitude observations and electrical effects.

THE AURORA BOREALIS.

THE BRILLIANT DISPLAY ON SUNDAY NIGHT.

PHENOMENA CONNECTED WITH THE EVENT

Mr. Meriam's Observations on the Au-
rora—E. M. Picks Up a Piece
of the Auroral Light.

The Aurora as Seen Elsewhere—Remarkabl
Electrical Effects.

N.Y. times title, August 30, 1859.

US telegraph: what God has wrought!

US telegraph lines would follow the railway network. They were already long and the rocky character of the soil would lead to strong ground induced currents.

The line between Portland and Boston shut down batteries and transmitted on ground induced currents.

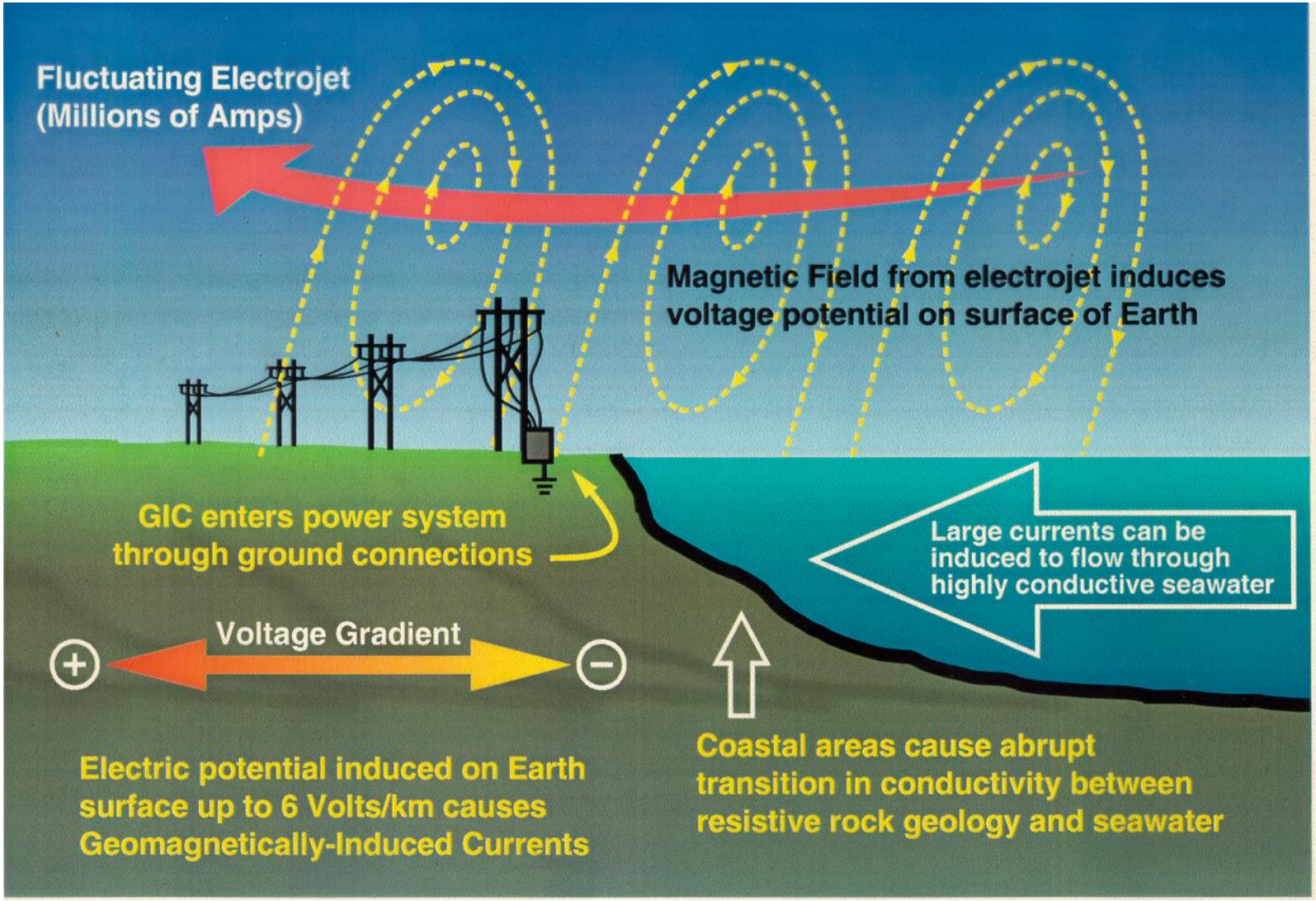
At least two stations had dangerous sparks and fires.

The Times of India reported the following in an article entitled “The Aurora Borealis” on Tuesday, 6 February 1872:

Will it surprise our readers to learn that the Aurora Borealis was plainly visible in Bombay on Sunday last? Such was indeed the case and its effects were felt too. After sunset on Sunday, the Aurora was slightly visible, and constantly kept changing colour, becoming deep violet, when it was intense about 3 O’clock on Monday morning. It was distinctly visible until sunrise on Monday. The influence of this atmospheric disturbance was unpleasant both for our person and our correspondence. The cold was unpleasantly keen, and all telegraphic communication was stopped for some hours. Both before and after its height, the aurora affected the working of both sections of the, section running east and west and the other North and South. At 8 O’clock yesterday morning the magnetic disturbance in the telegraph offices was very strong. The extent of this disturbance may be gathered from the fact that all the lines to England in connection with the British-Indian Submarine cable were affected for hours and so were the Government lines. At Aden, Aurora was brilliant in the extreme.

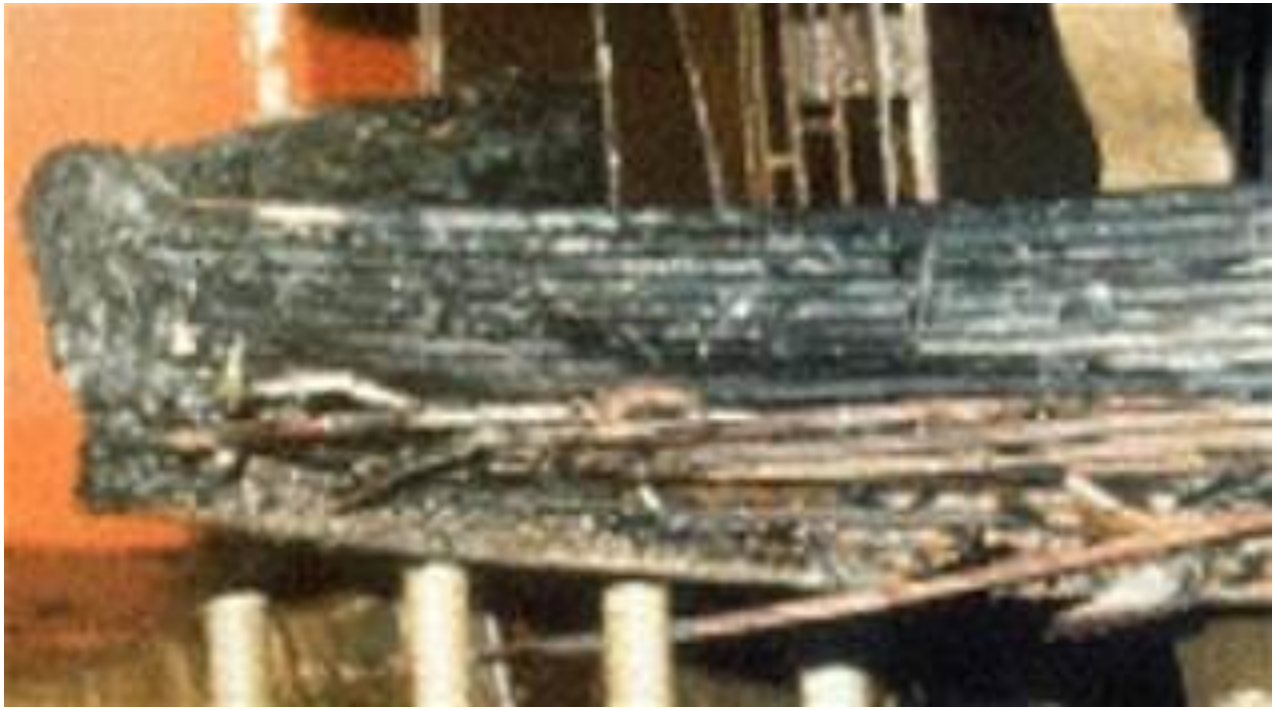
A More Recent Magnetic Storm in 1989 (Dst = -589 nT)

- The Quebec, Canada power system was down for ~9 hrs.
- The New Salem New Jersey (U.S.) nuclear system went down.
- The U.S. eastern seaboard grid almost went down.


Fluctuating Electrojet
(Millions of Amps)
Magnetic Field from electrojet induces voltage potential on surface of Earth
GIC enters power system through ground connections
Large currents can be induced to flow through highly conductive seawater
Voltage Gradient
+
−
Electric potential induced on Earth surface up to 6 Volts/km causes Geomagnetically-Induced Currents
Coastal areas cause abrupt transition in conductivity between resistive rock geology and seawater

New Salem, New Jersey Nuclear Power Plant Transformer

Copper Bus Rated at 2000 Amperes



What Would Happen if the Carrington Storm Happened Today?

- One or more of the four U.S. power grids would be significantly damaged (until transformer replacement)
- Likely satellite radiation damage
- Radiation hazards to human in space

Thank You for Your Attention

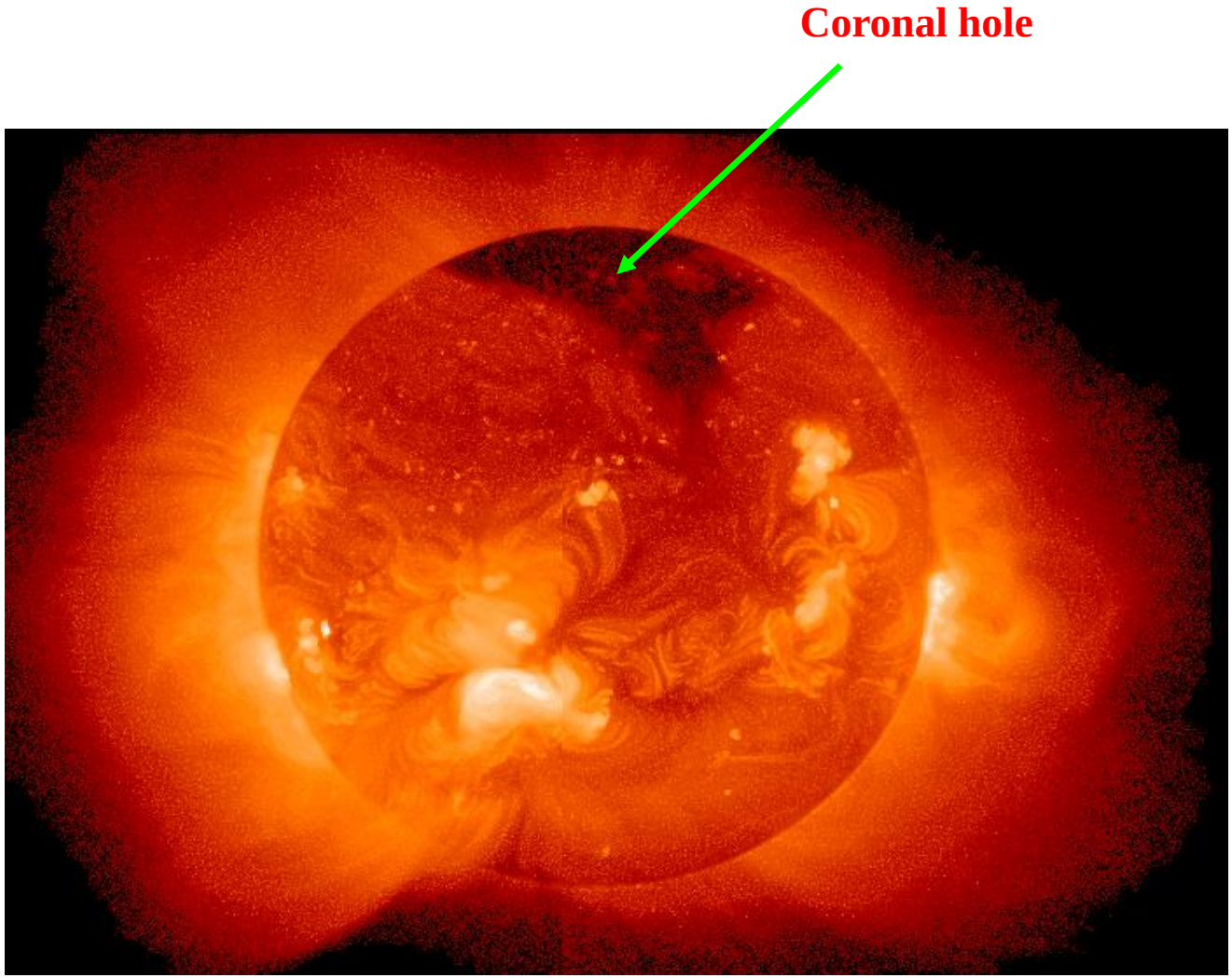
bruce.tsurutani@jpl.nasa.gov

Backup Slides

What About Other Parts of the Solar Cycle?
Does Nothing Happen Then?

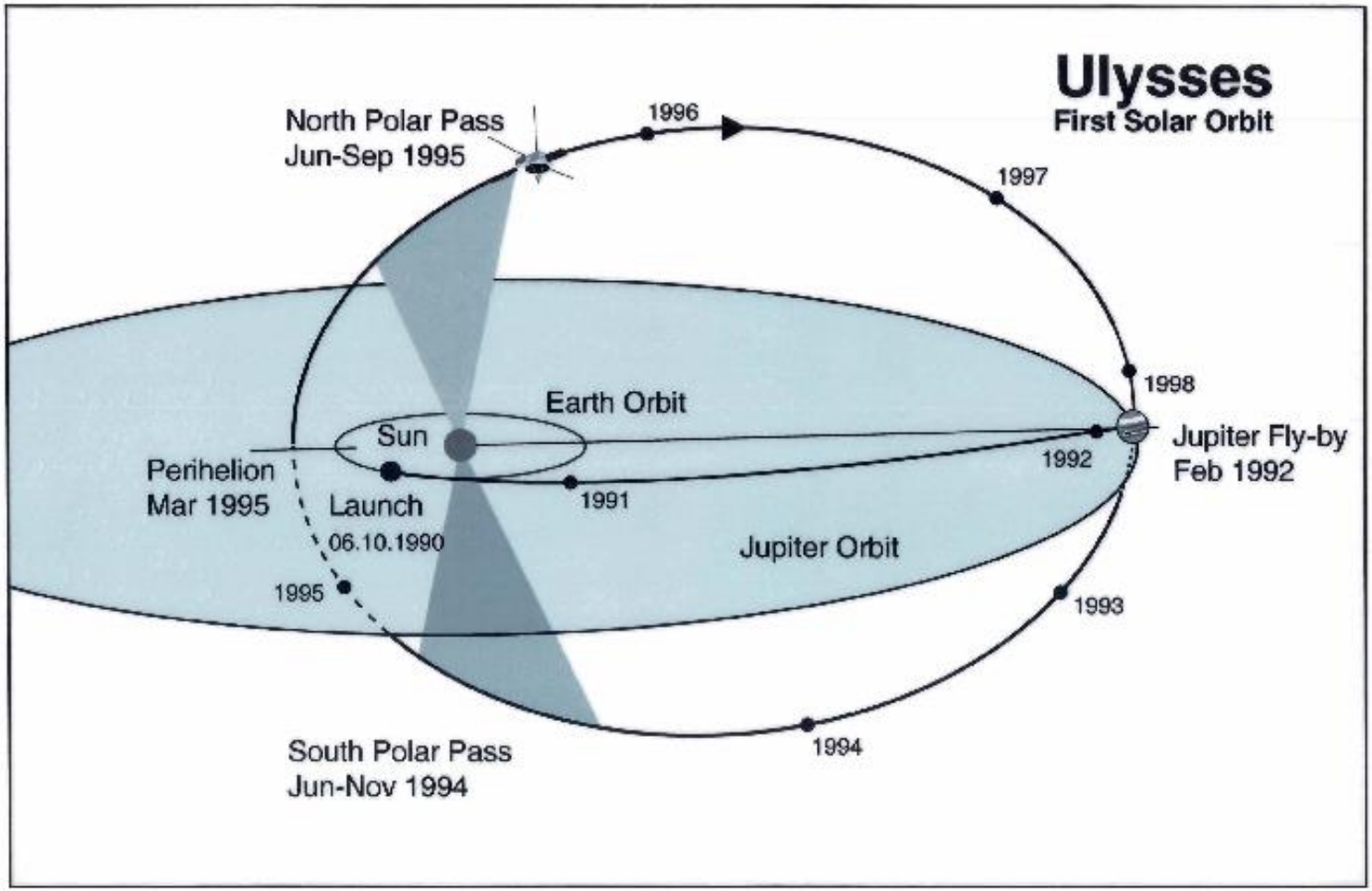
Coronal Hole High Speed Solar Wind Streams: Declining Phase of Solar Cycle

DECLINING PHASE OF SOLAR CYCLE



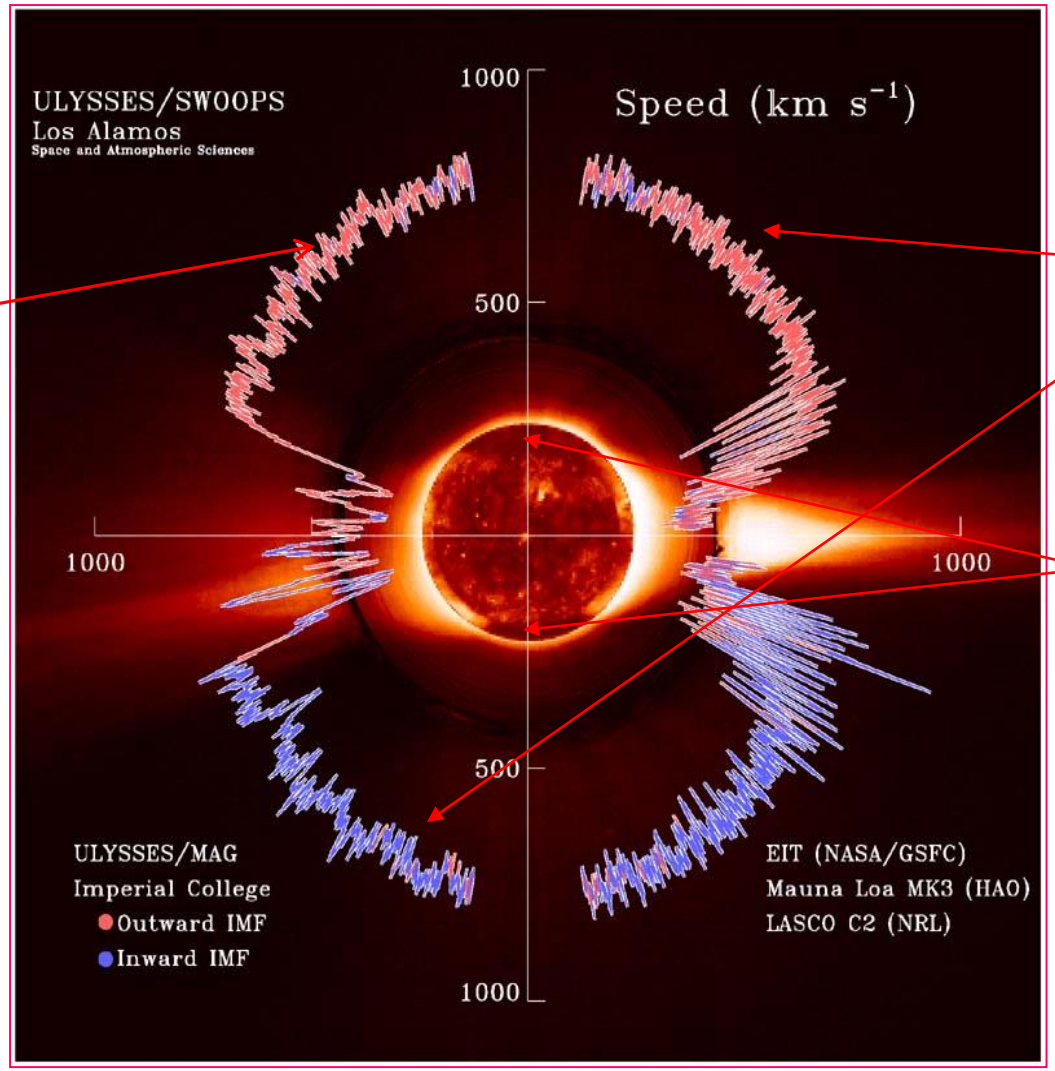
Maunder 1905, 1906; Chree, 1911; Bartels, 1934: ~27 day recurrent geomagnetic activity

The Ulysses Mission over the Solar Poles



Ulysses Observations of the Solar Wind During the Declining Phase of the Solar Cycle

V_{sw} a constant 750-800 km/s



HSSs

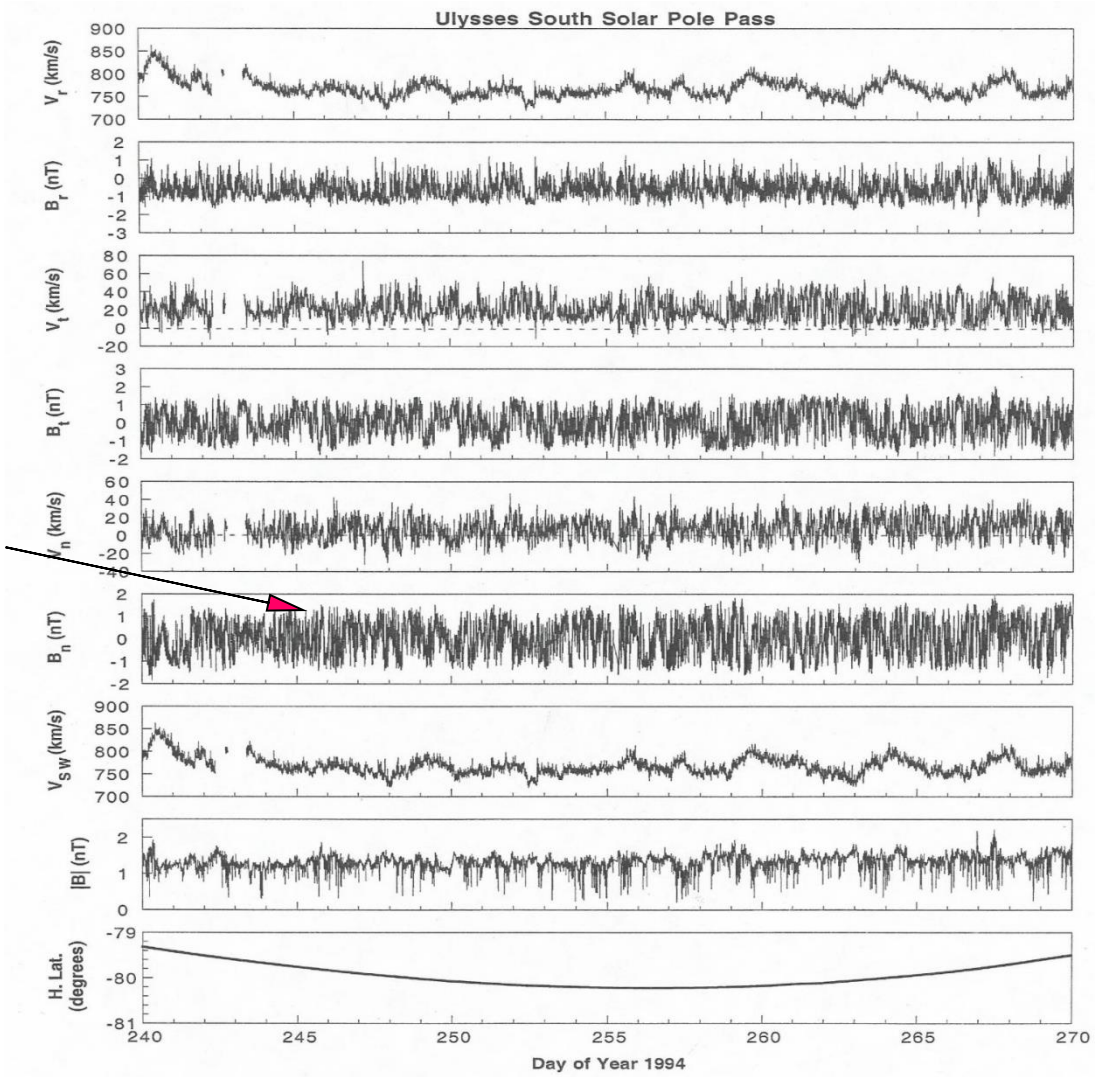
Large polar coronal holes

Phillips et al. GRL 1998; McComas et al. GRL 2003

The High Speed Solar Wind is Filled With Alfven Waves

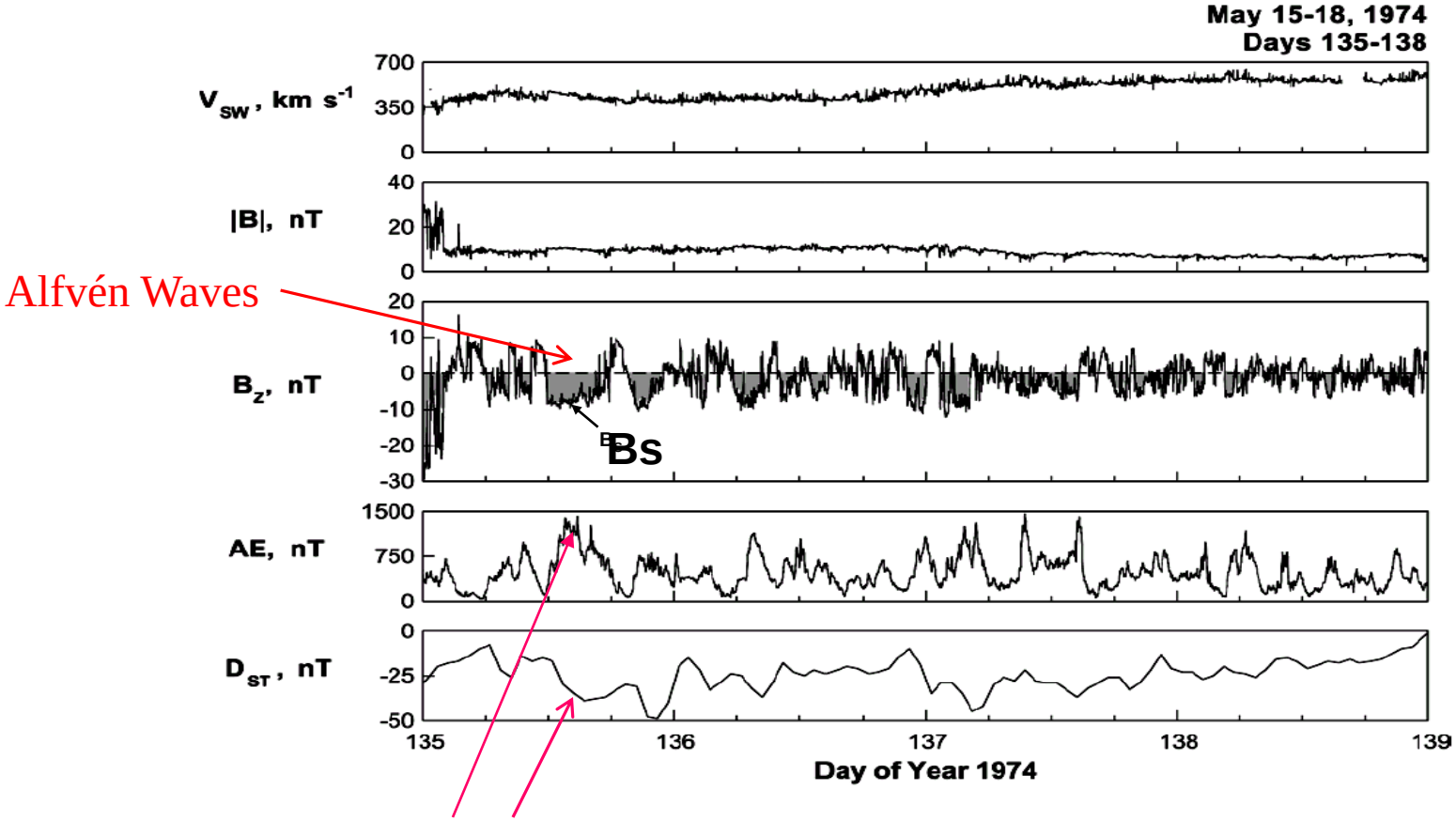
(Hannes Alfven received a Nobel Prize in physics for predicting these waves)

Nonlinear Alfvén waves; the entire magnetic field is oscillating.



NPG, 2005

Magnetic Reconnection Associated with Southward Component of Alfvén Waves

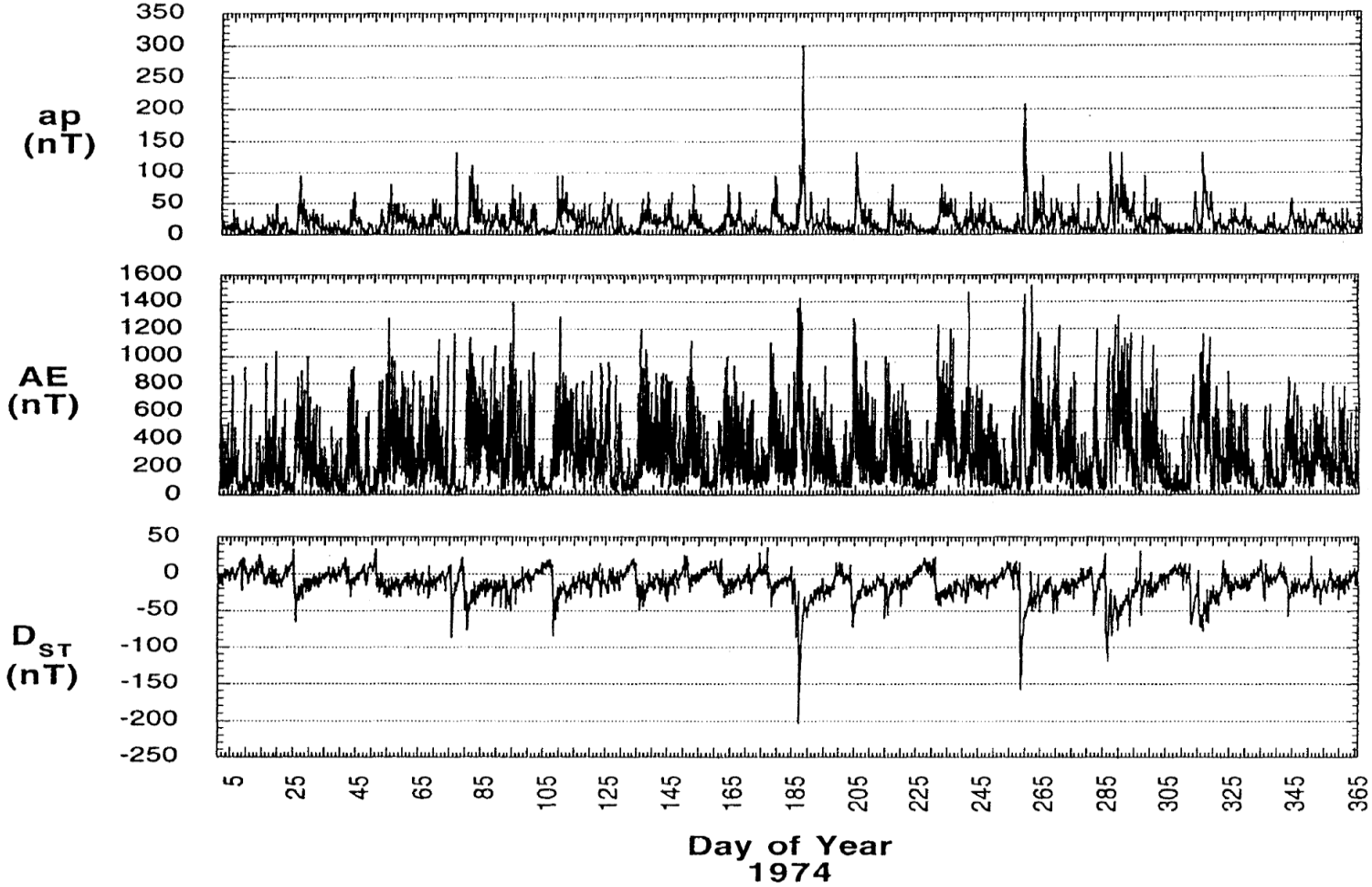


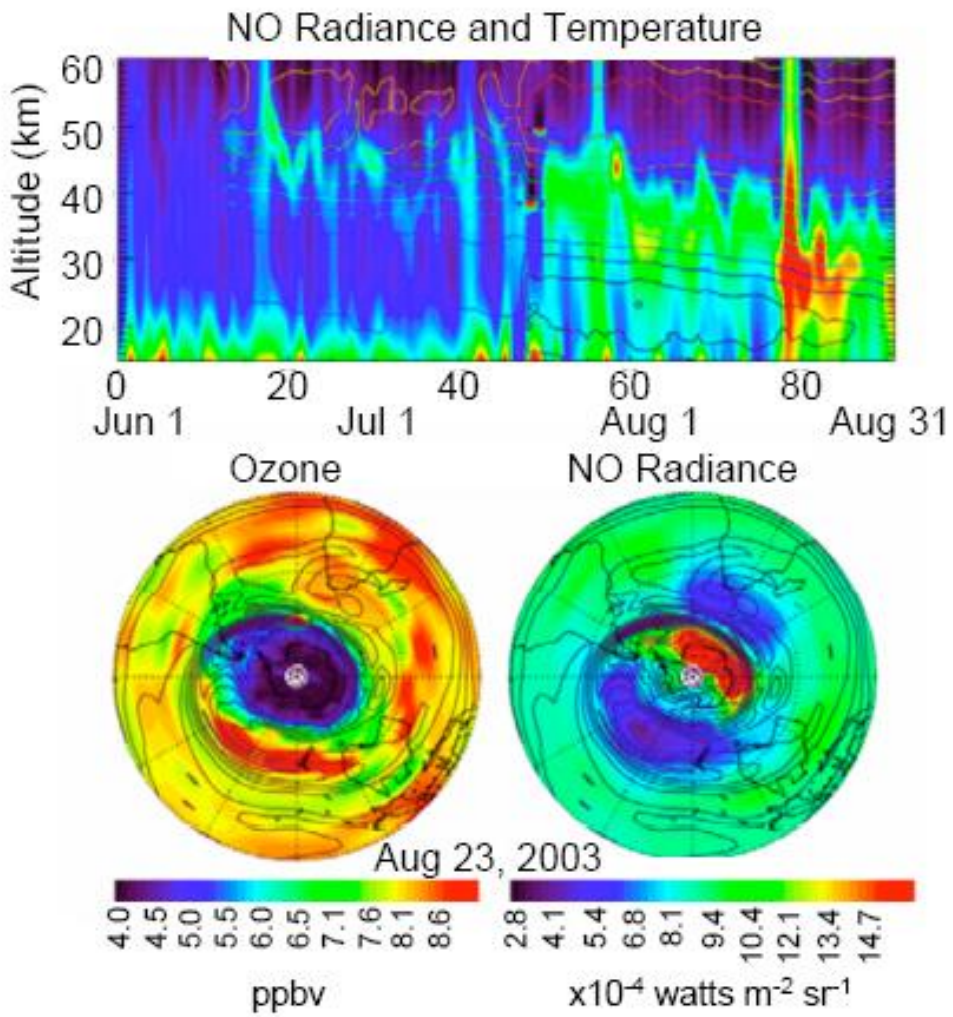
Earth ionospheric auroral electrojet (AE) increases. Called HILDCAAs

Tsurutani and Gonzalez, 1987

HILDCAAs Throughout 1973-1975

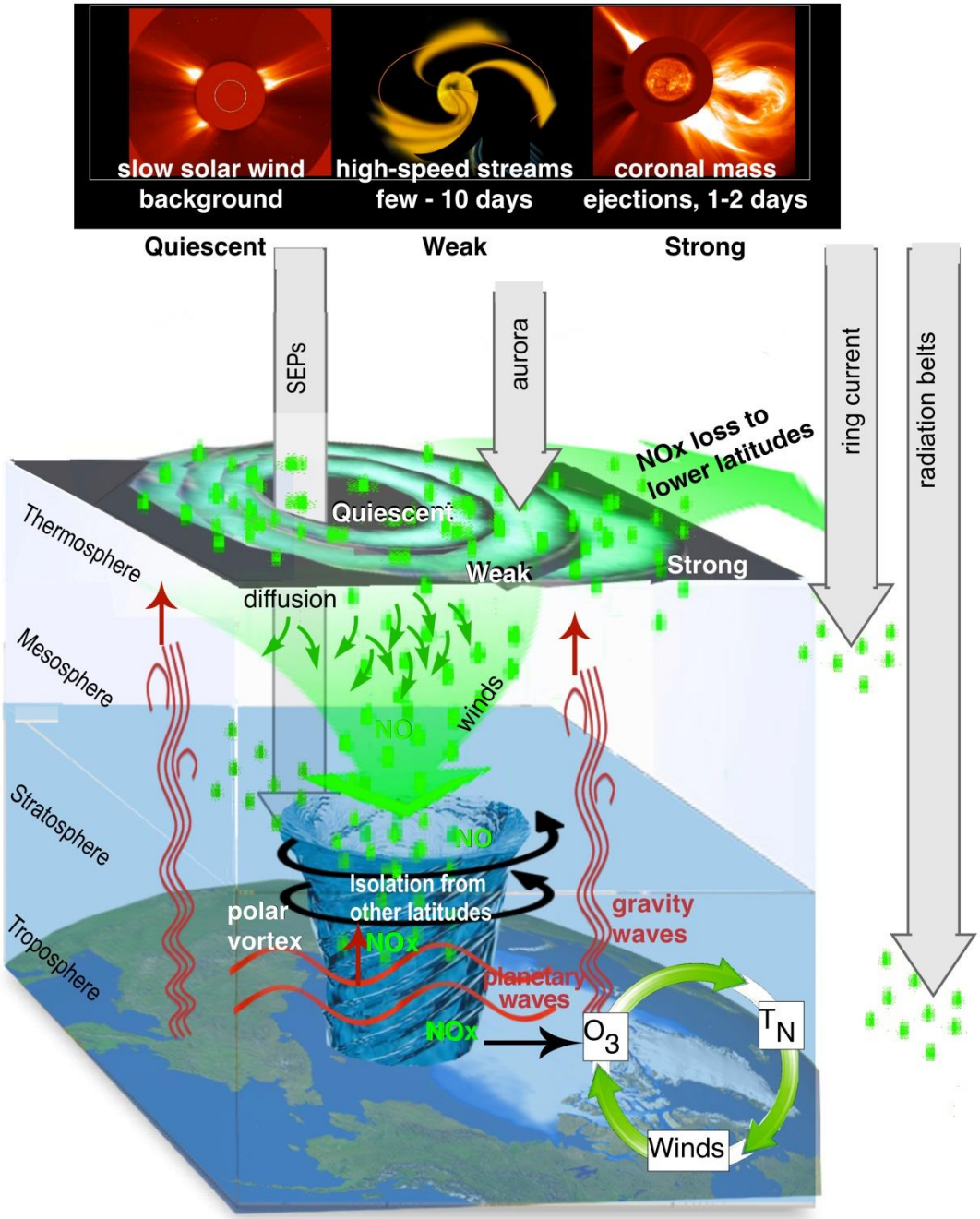
(all caused by interplanetary Alfven waves and magnetic reconnection)

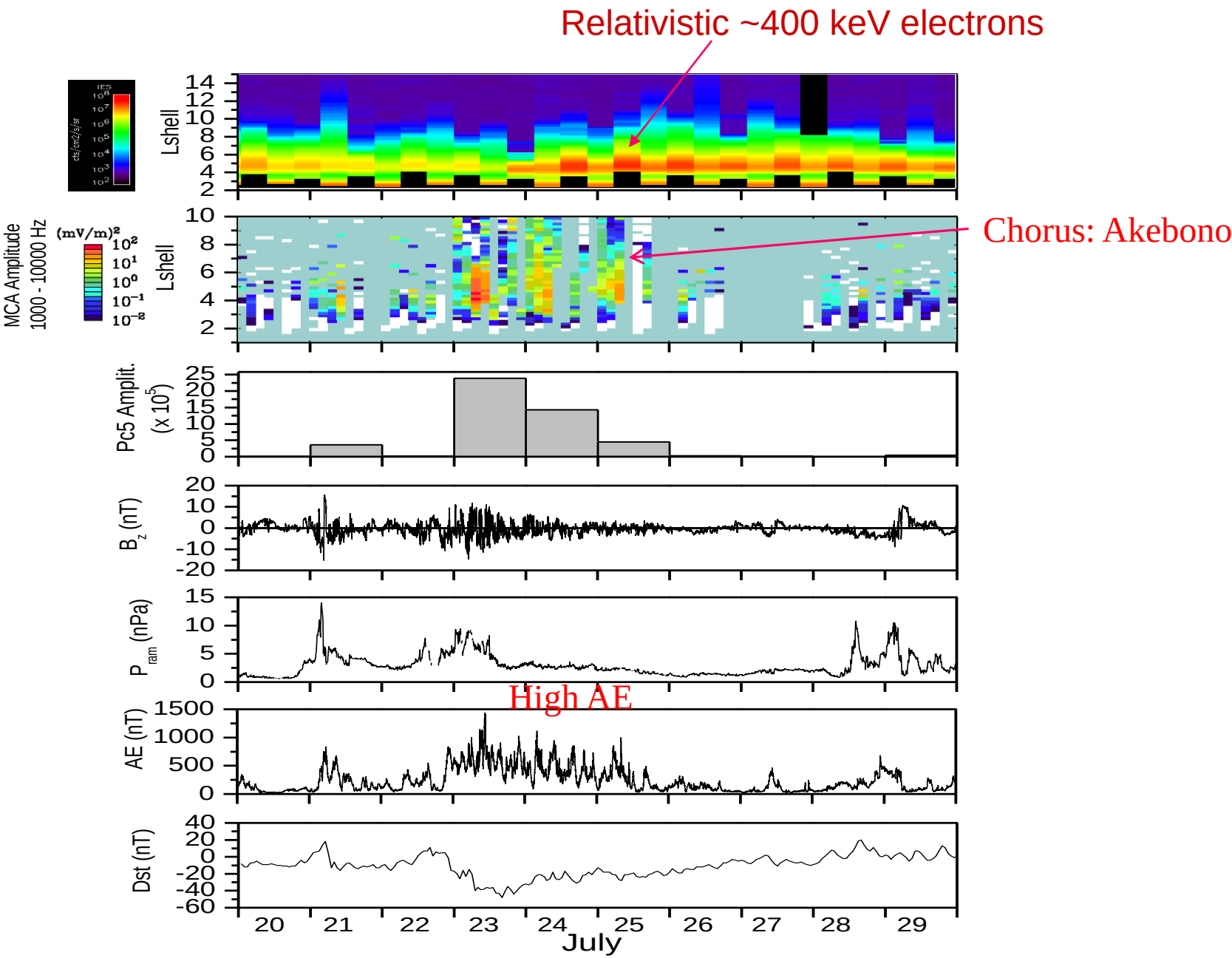




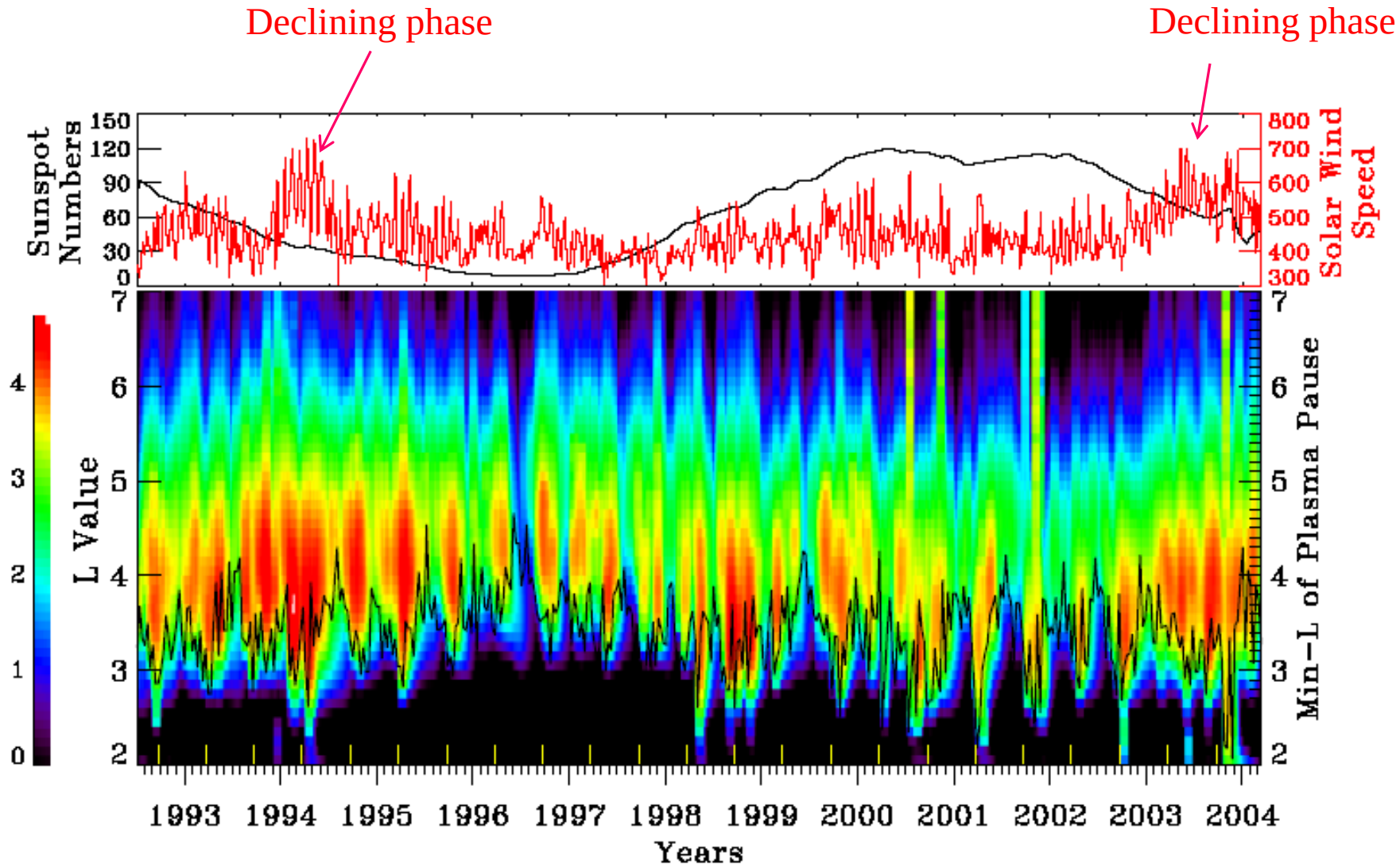
HIDCAA electron precipitation causes NOx formation at low altitudes . Polar vortex causes entrainment of catalytic molecules which lead to the destruction of ozone

Kozyra et al., AGU, 2006


slow solar wind
background
high-speed streams
few - 10 days
coronal mass
ejections, 1-2 days
Quiescent
Weak
Strong
SEPs
aurora
ring current
radiation belts
NOx loss to
lower latitudes
Quiescent
Weak
Strong
Thermosphere
Mesosphere
Stratosphere
Troposphere
diffusion
winds
NO
NO
Isolation from
other latitudes
polar
vortex
NOx
NOx
gravity
waves
planetary
waves
O_3
T_N
Winds


Relativistic ~400 keV electrons
Chorus: Akebono
High AE
Lshell
MCA Amplitude
1000 - 10000 Hz
(mV/m)²
Pc5 Amplit.
(x 10⁵)
B_z (nT)
P_ram (nPa)
AE (nT)
Dst (nT)
20
21
22
23
24
25
26
27
28
29
July

Solar Cycle of SAMPEX 2-6 MeV Electrons

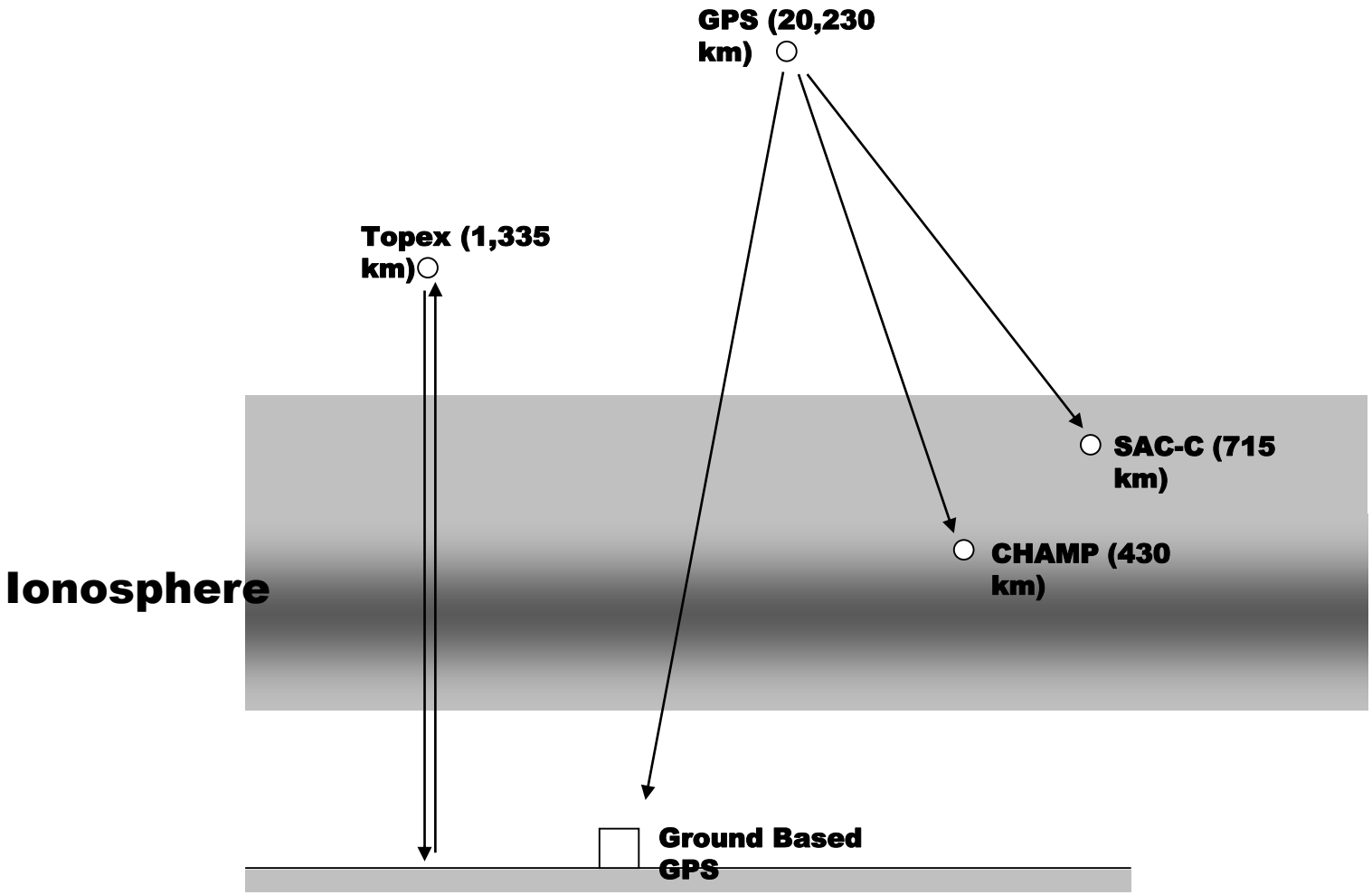


Li et al., GRL, 2006

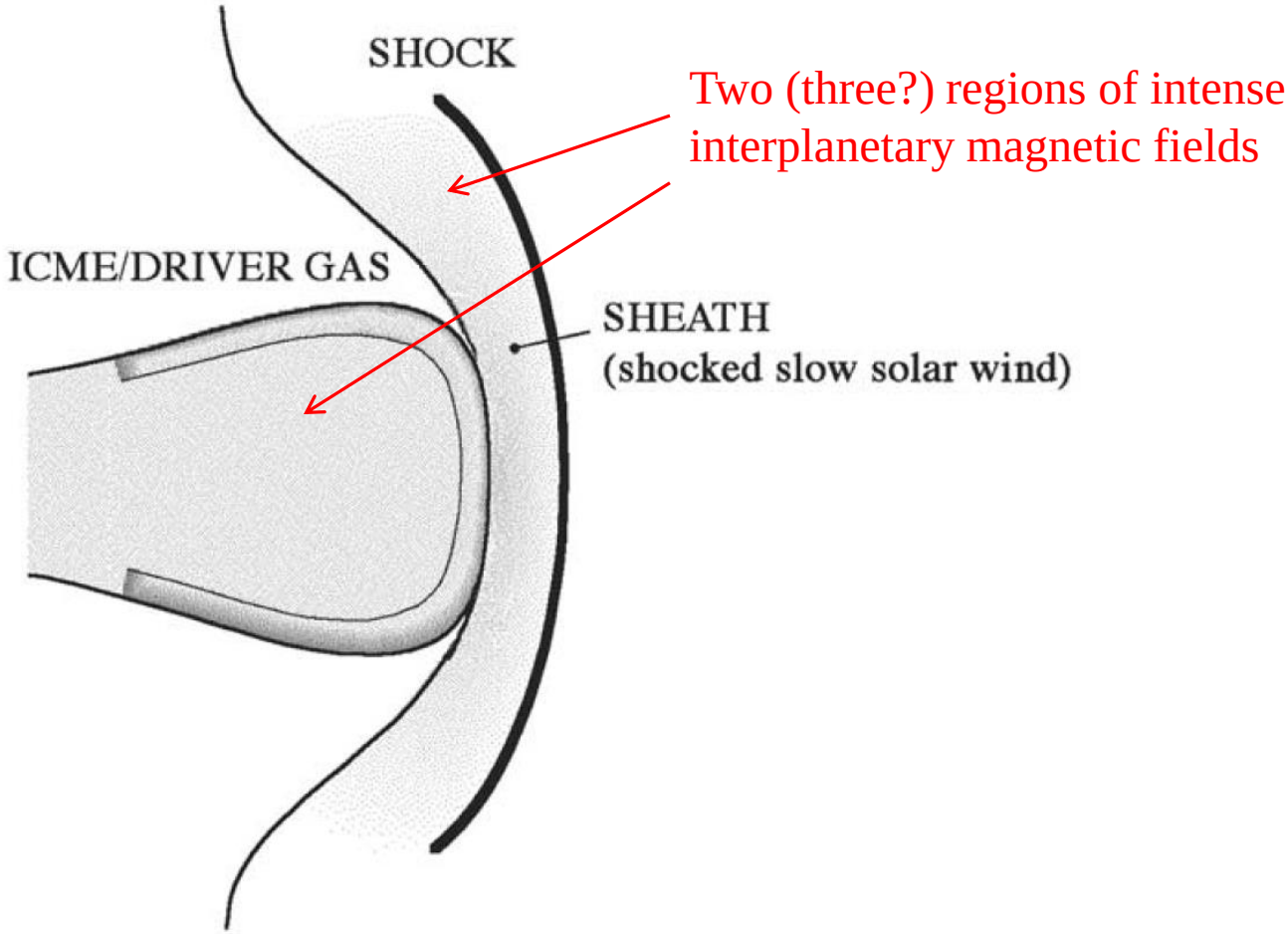
The Relativistic Electrons Have Been Called “Killer” Electrons

- Earth orbiting satellites could be damaged by these penetrating particles

Ground-Based GPS Receivers Can Be Used to Get Ionospheric TEC Along Ray Path

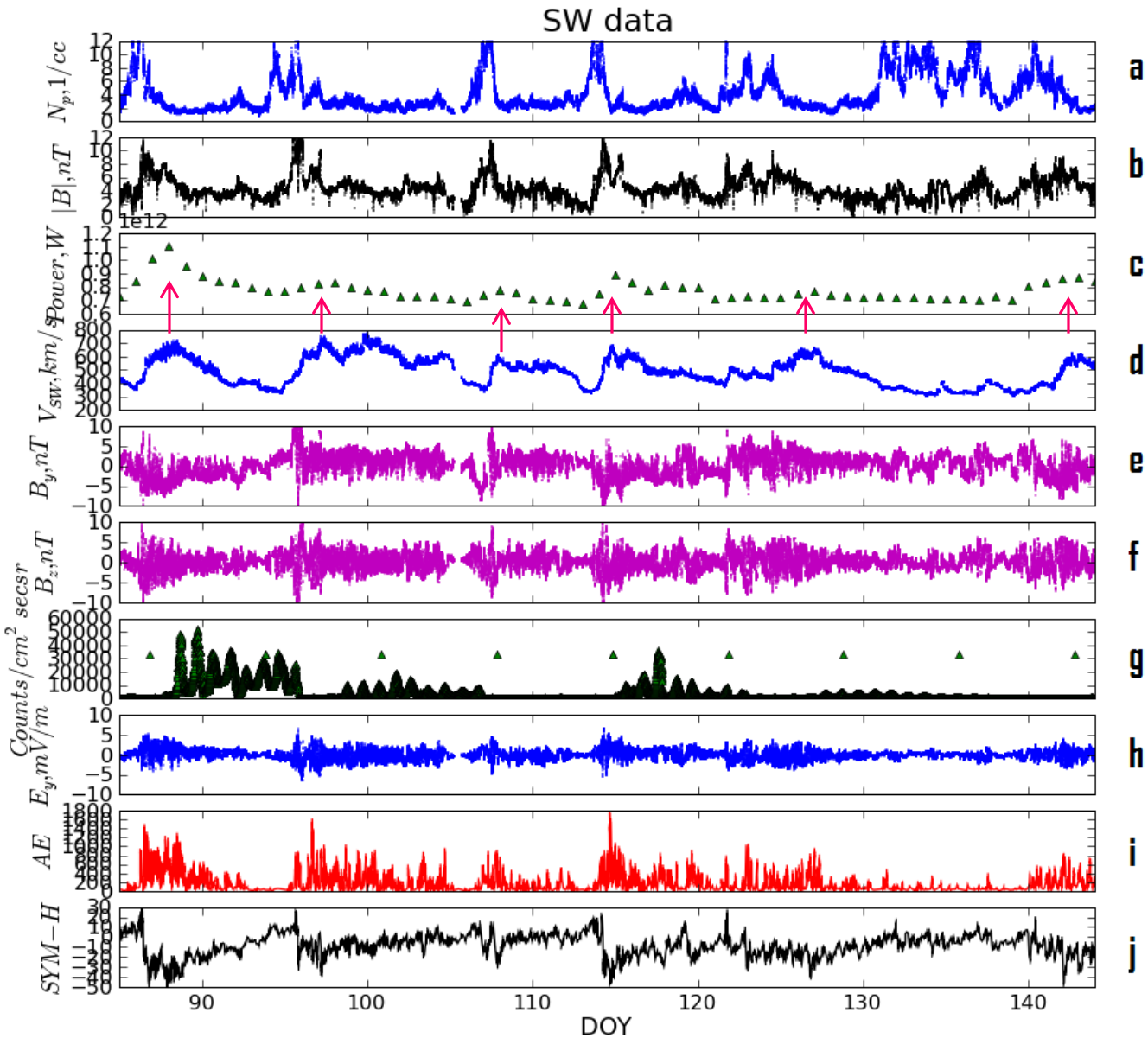


Tsurutani et al. JGR 2004



Shock compression can raise magnetic field magnitudes (and densities) by a maximum of 4 X (Kennel et al. AGU, 1985)

WHI INTERVAL



Atmos. Rad. Power has a HSS dependence

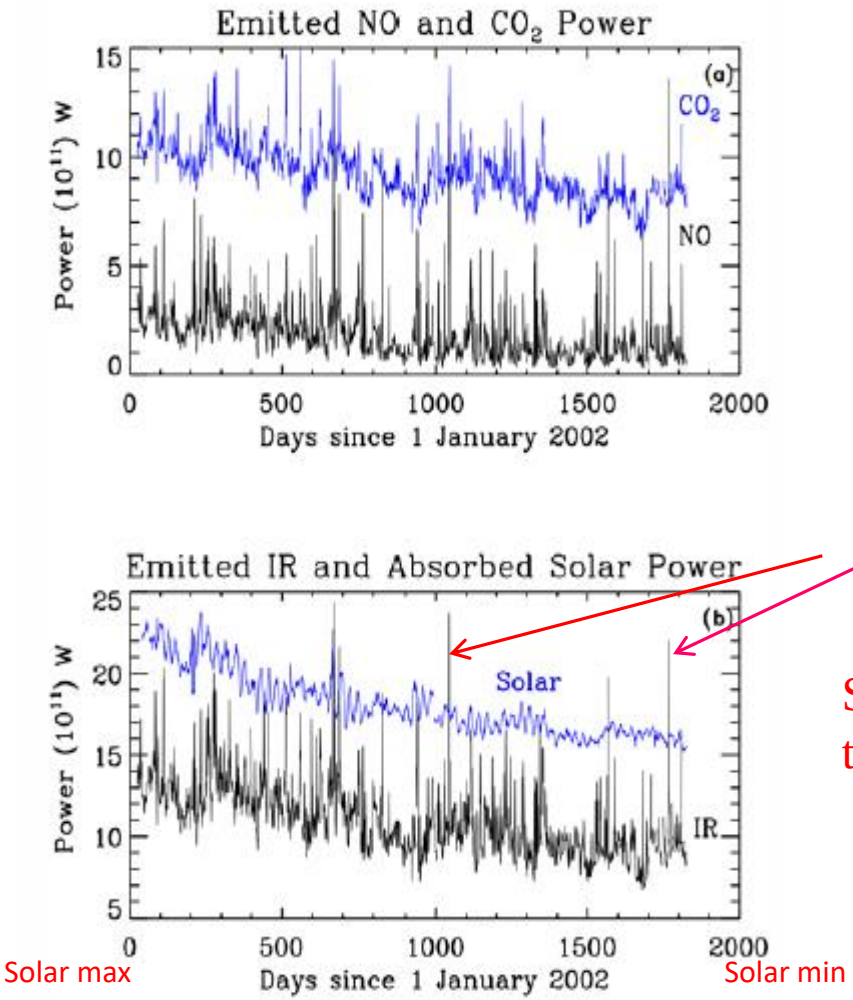
HSS

Relativistic electrons

HILDCAAs

2008

Verkhoglyadova et al., JGR 2011



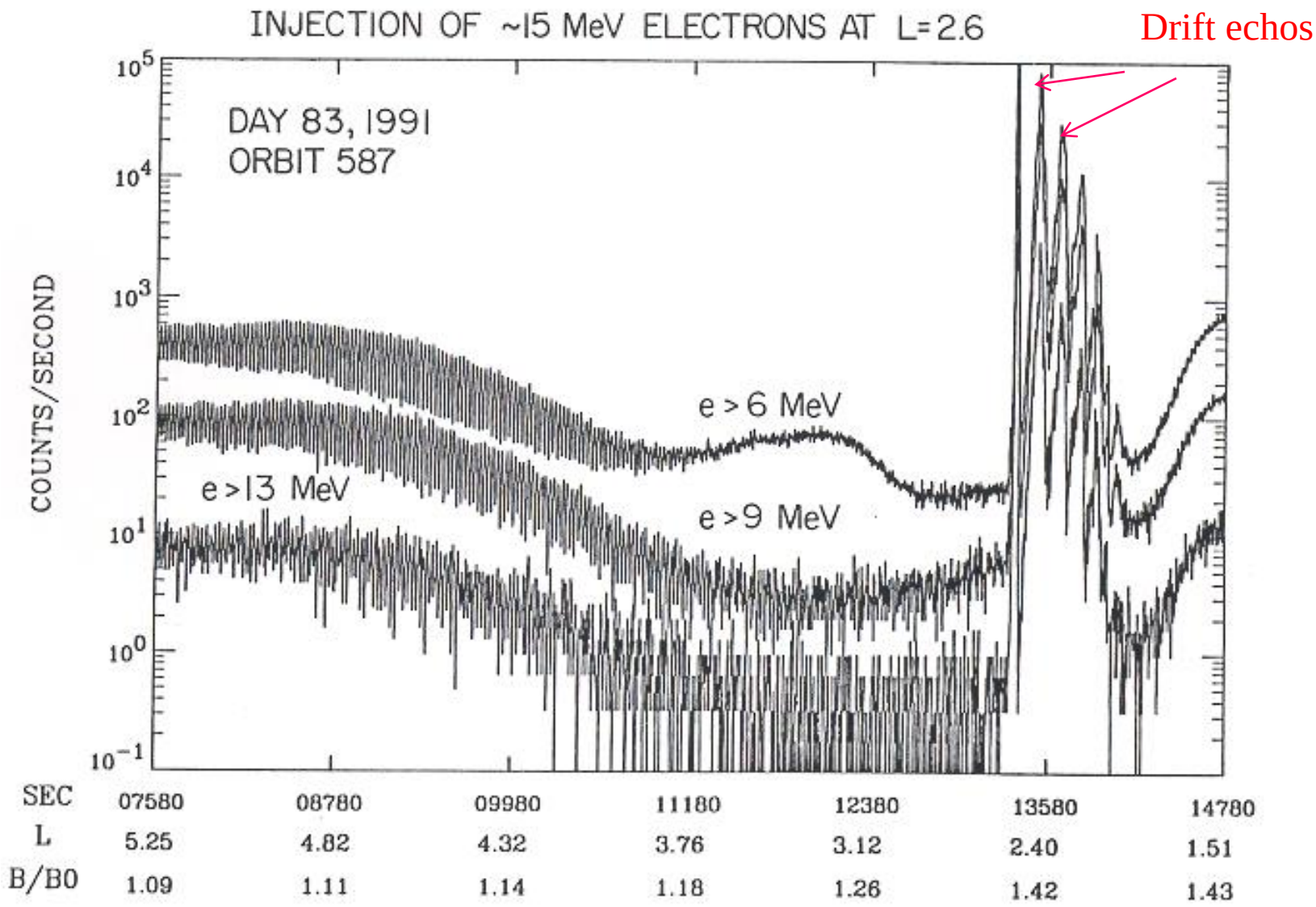
Thermospheric irradiated power (SABER/ TIMED)

Anomalous spikes where radiated power is higher than solar input power

Solar irradiance decline since Jan 2002 plus thermospheric irradiance decline

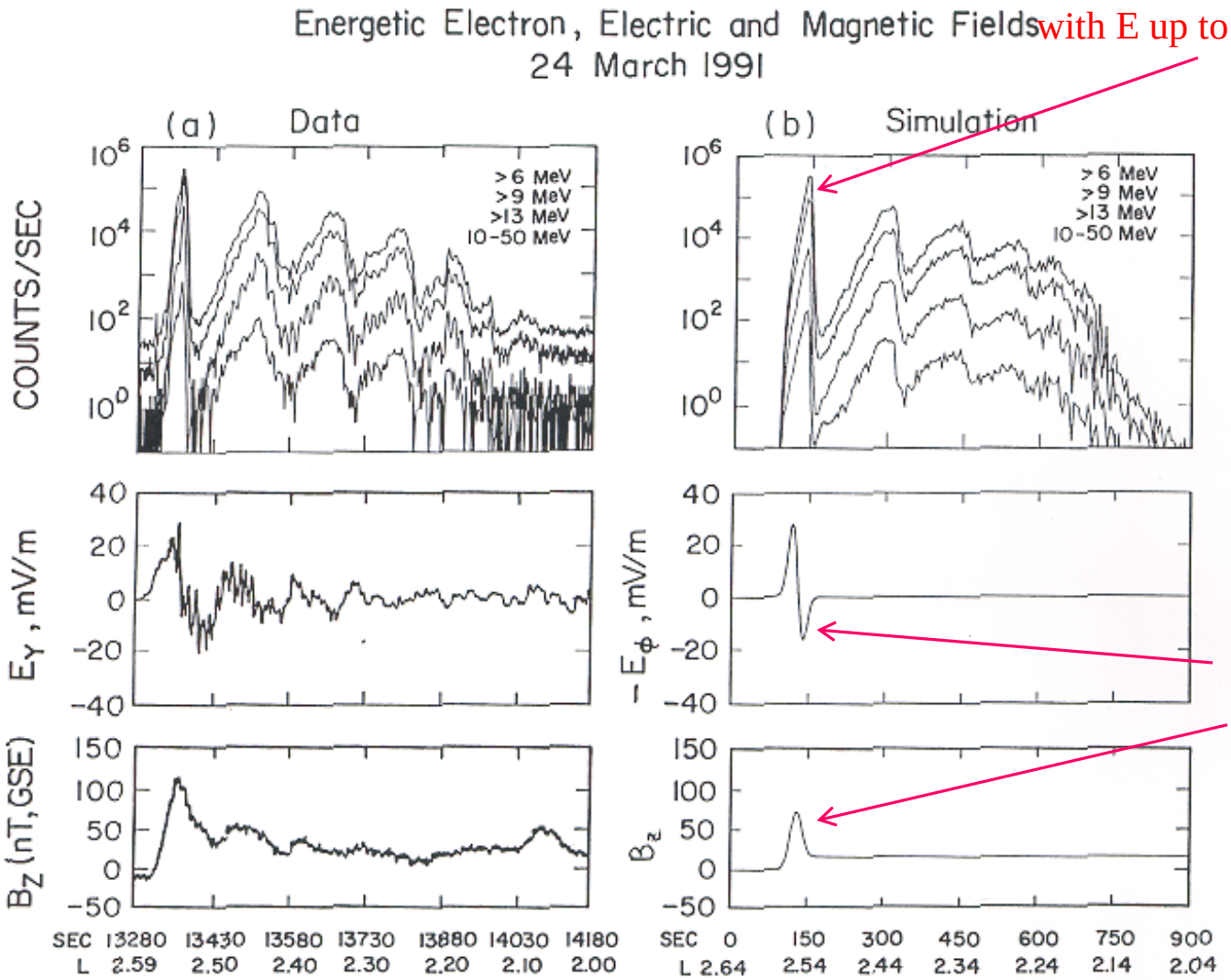
Figure 1. (a) Time series of daily global radiated power from the thermosphere (100–200 km) from NO and CO_2 from January 2002 through December 2006. (b) Time series of daily global absorbed solar power (0 to 175 nm) and radiated infrared (IR) power (CO_2 plus NO) in the thermosphere from January 2002 through December 2006.

Mlynczak et al, GRL, 2008



Blake et al., GRL 1992

Acceleration of electrons of ~few MeV at L >6 to L ~2.5 with E up to 40 MeV

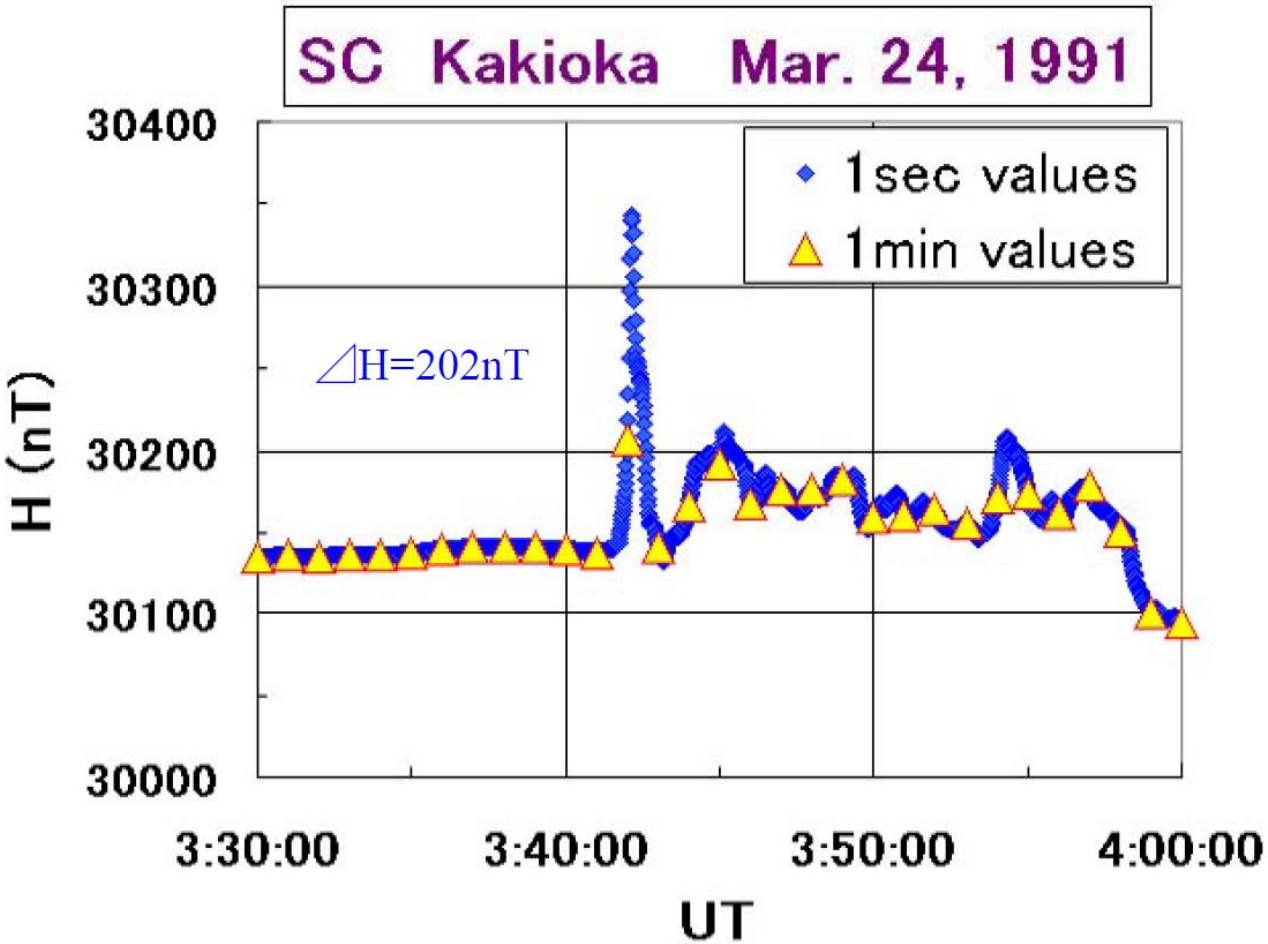


Only input in simulation

Process conserves first adiabatic invariant

Li et al. GRL 2003

The Second Largest SI$^+$ in Recorded History: Note importance of 1 s data

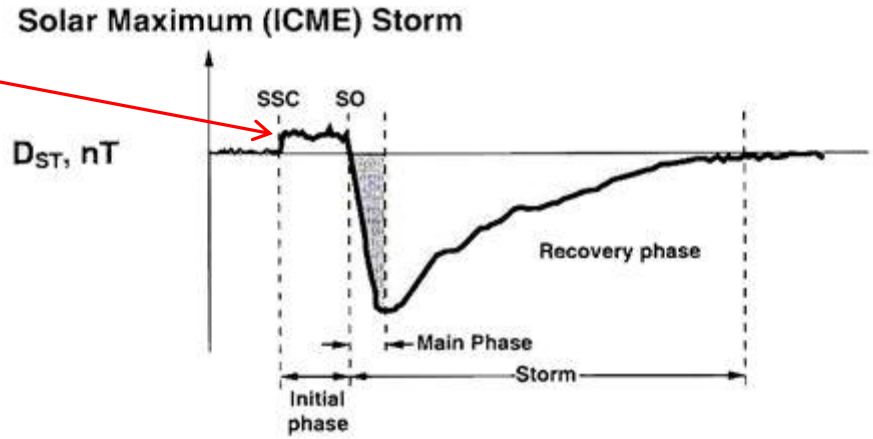


$$\Delta P_R = M_s V_s^2 - M_0 V_0^2$$

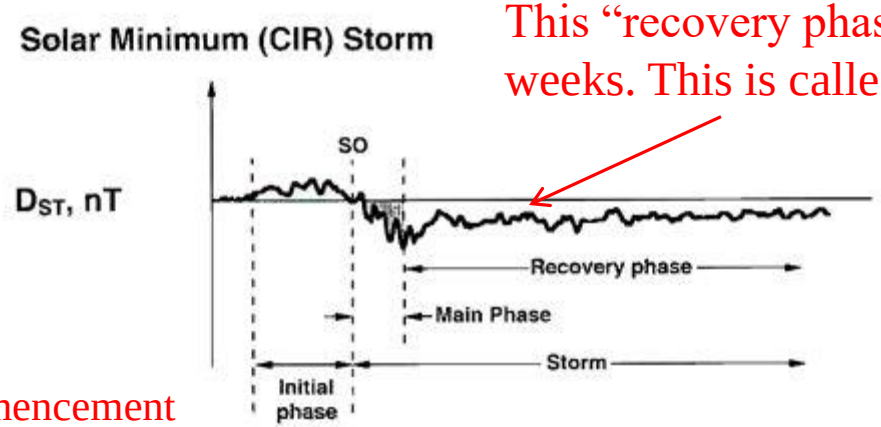
T. Araki, 2012

Unfortunately SW data not available. If V_{sw} jumps from 400 km/s to 1600 km/s, $\Delta P_R/P_R$ = 64 X!

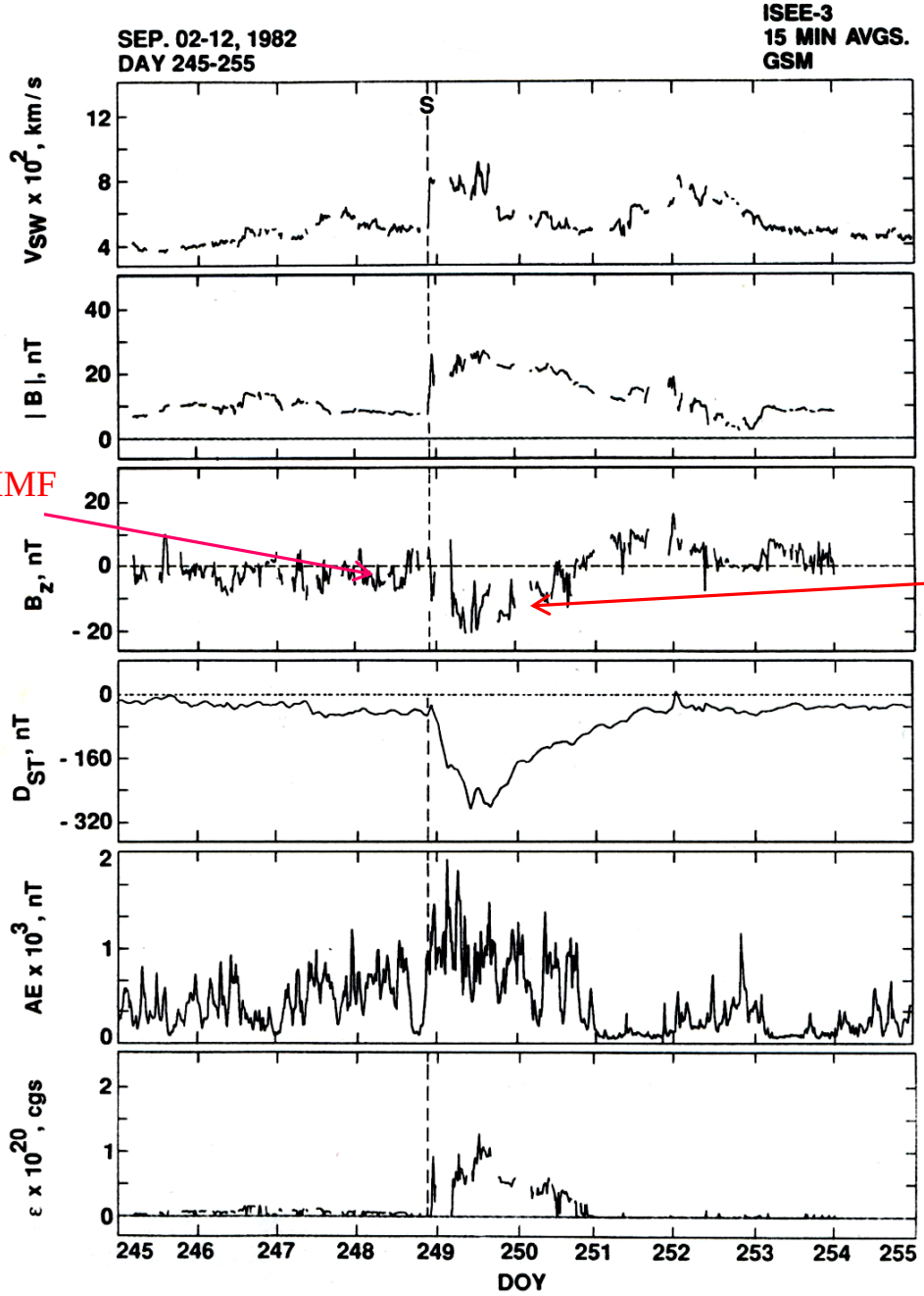
The SSC (or SI^+) is cause by a shock ram pressure



This "recovery phase" can last weeks. This is called a HILDCAA



SSC = storm sudden commencement
SI^+ = sudden impulse
CIR = corotating interaction region
Initial phase = positive Dst interval
Main phase = negative Dst interval from 0 to peak value
HILDCAA = High Intensity Long Duration Continuous AE Activity: Tsurutani, 1991



Preexiting southward IMF

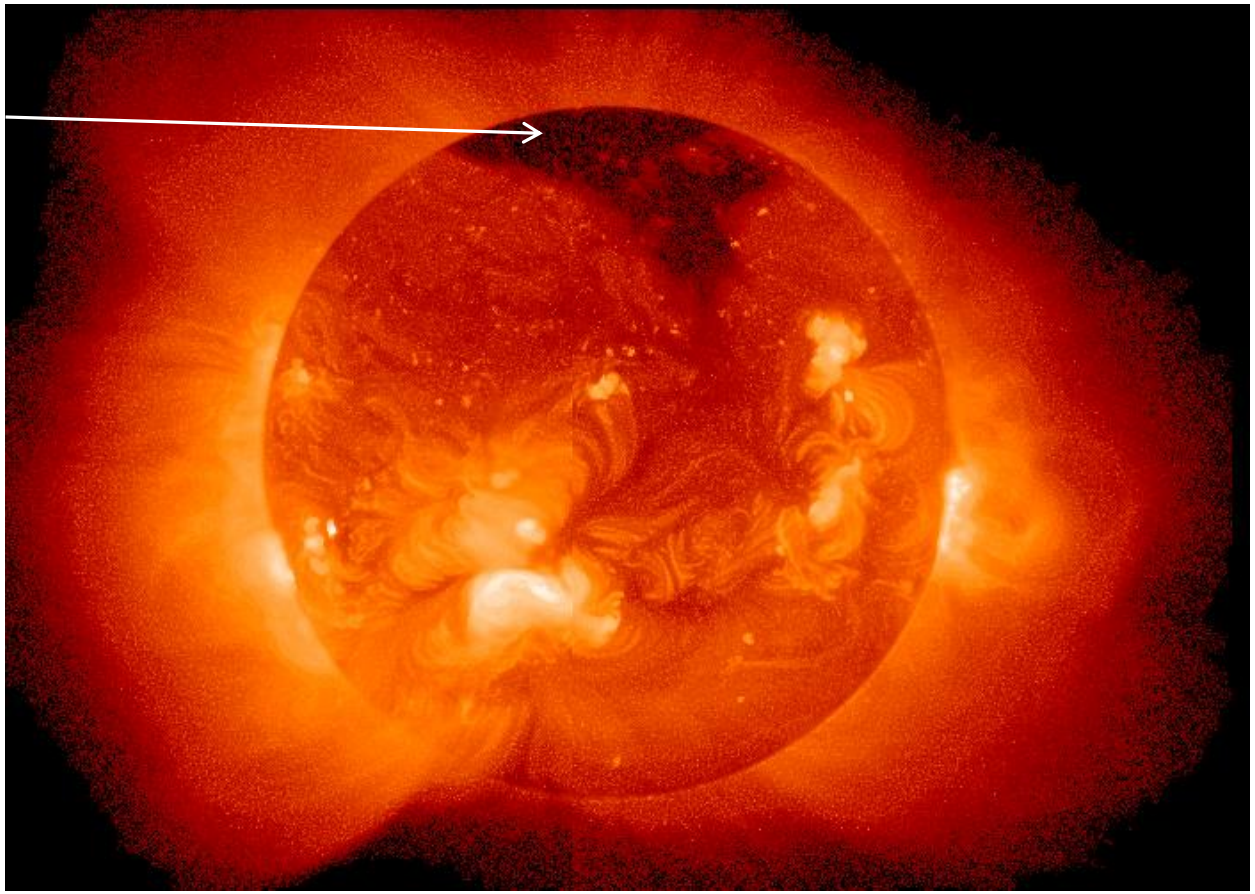
Sheath Fields Causing Storm

Shock compression of Southward fields

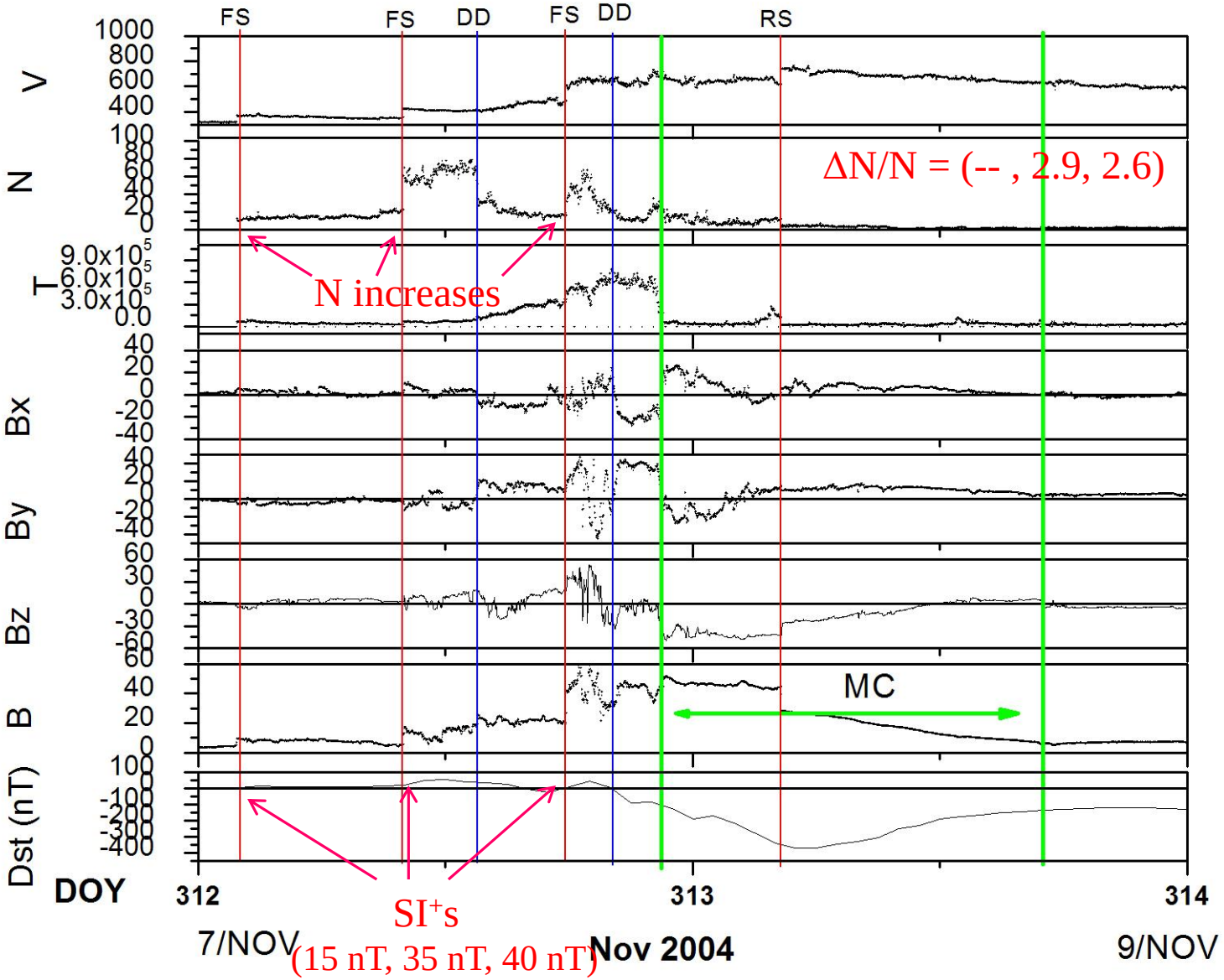
Tsurutani et al. JGR 1988

The Sun Viewed in Soft X-Rays During the Declining Phase

Coronal Hole



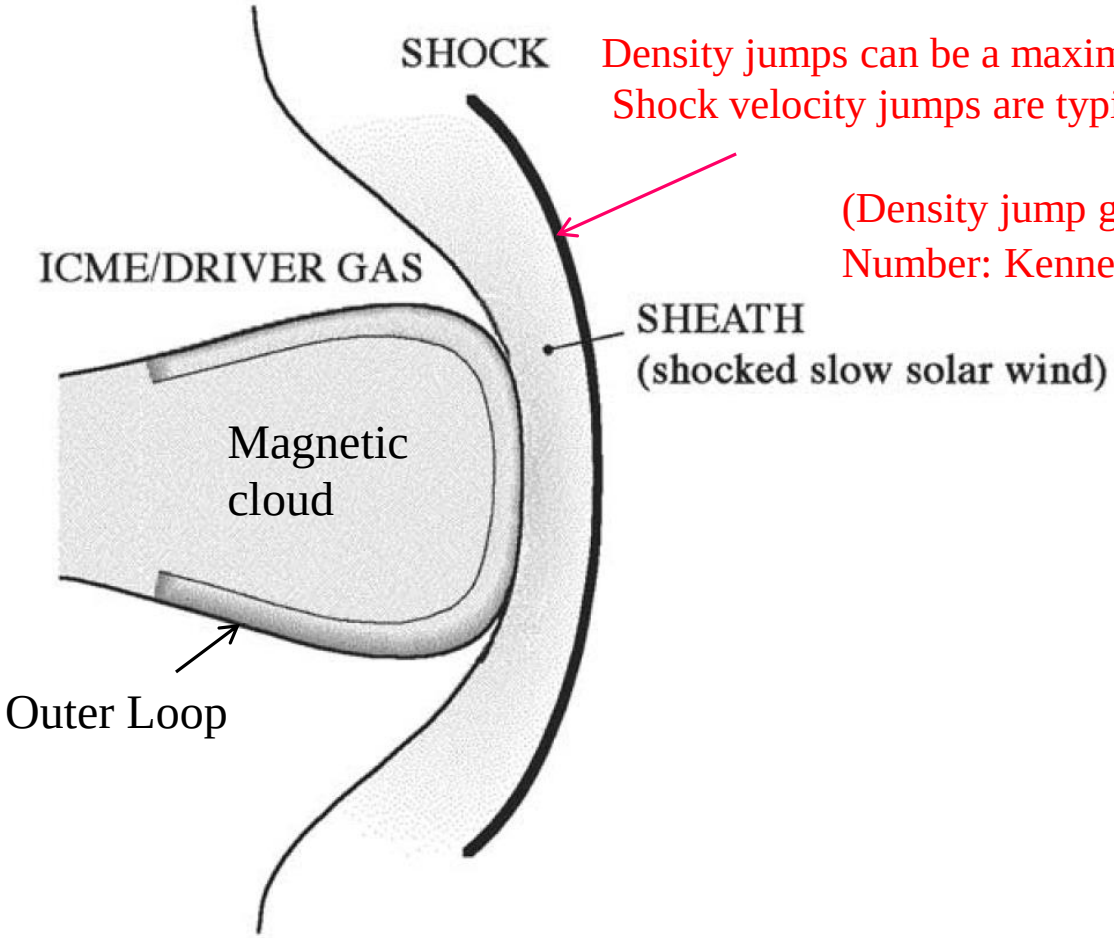
Active Regions Are Associated with Multiple Flaring/Multiple CME Releases



Tsurutani et al., 2008 GRL

Other Solar Wind Energy Transfer Mechanism besides Magnetic Reconnection: ICME Shocks

Leads to solar wind energy transfer directly to the magnetosphere (and also release of stored energy)

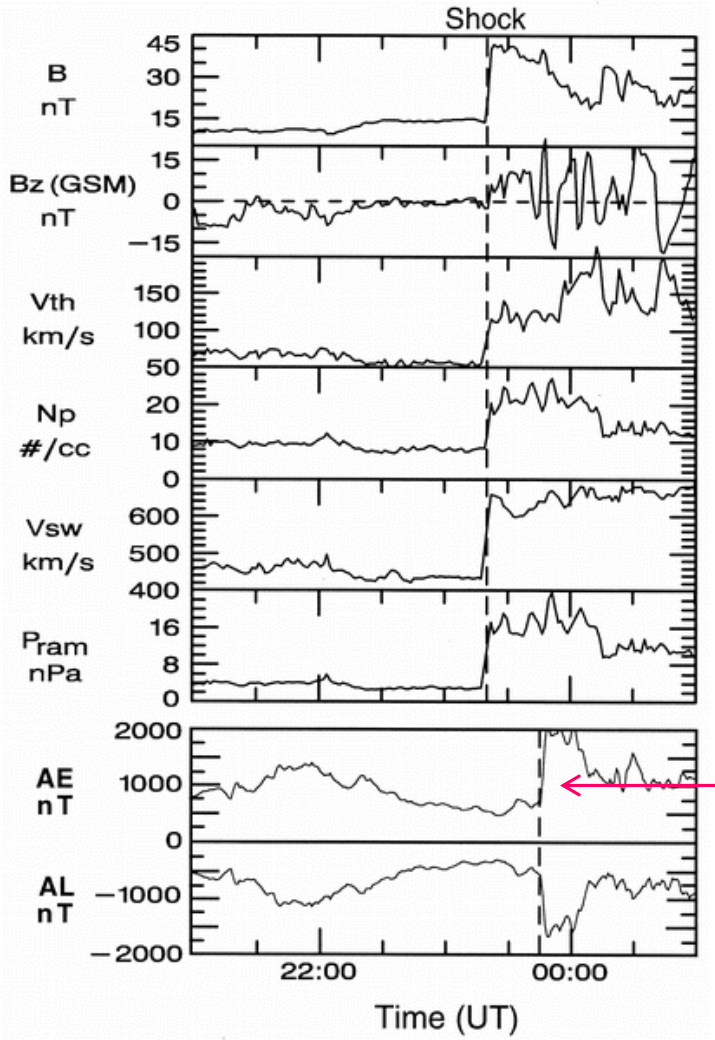


Density jumps can be a maximum of 4 X*;
Shock velocity jumps are typically only 10-40%

(Density jump go like Mach Number: Kennel et al. AGU 1985)

Ram Pressure = MV^2; $\Delta P_R = M_s V_s^2 - M_0 V_0^2$

Dayside Aurora Powered by an Interplanetary Shock (and a Supersubstorm Triggered by the Shock)



$\Delta N/N = 2.0$

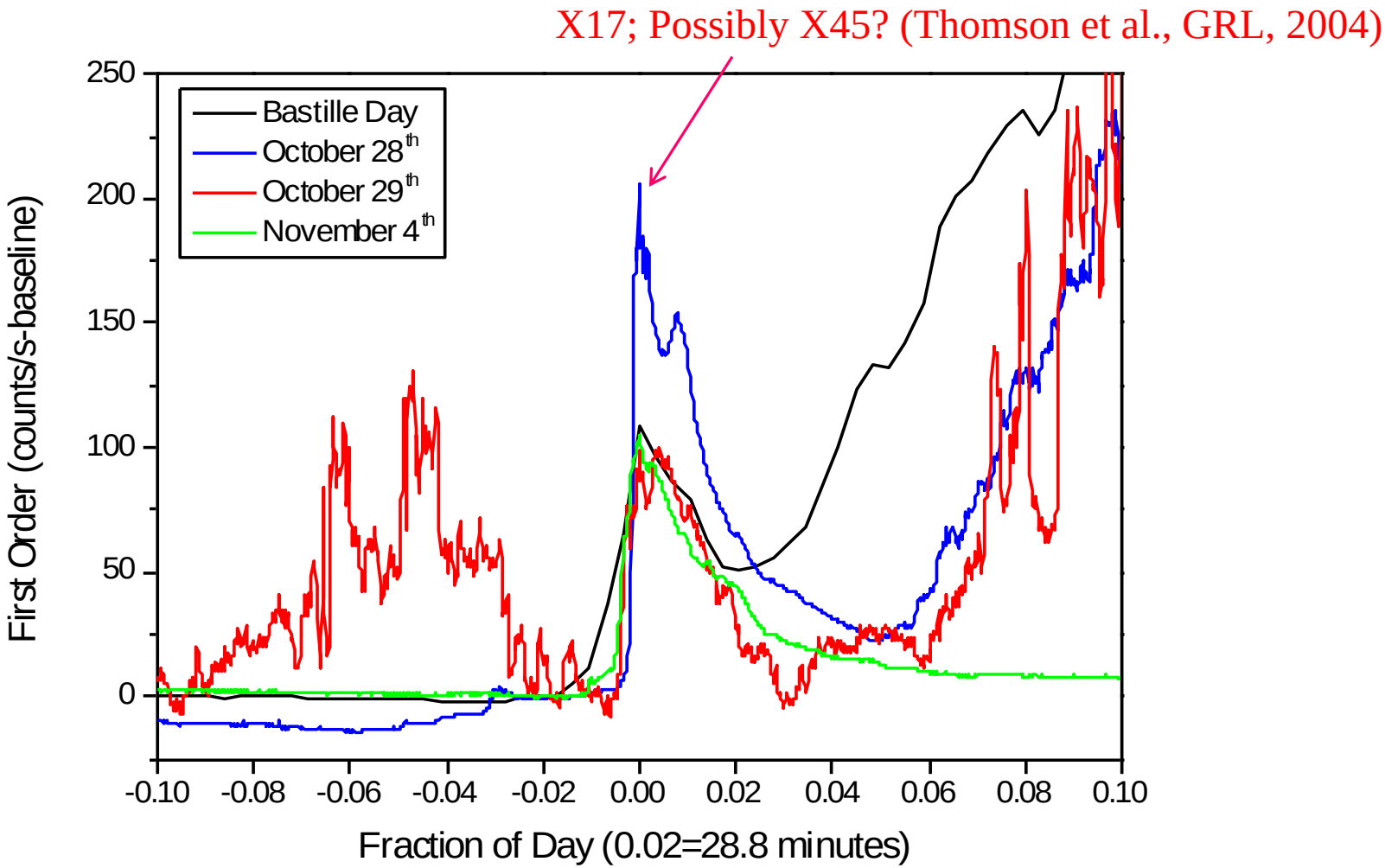
$\Delta V_{sw}/ V_{sw} = 0.45$

$\Delta P_{ram} = \sim 4.0$

supersubstorm

JGR 2001

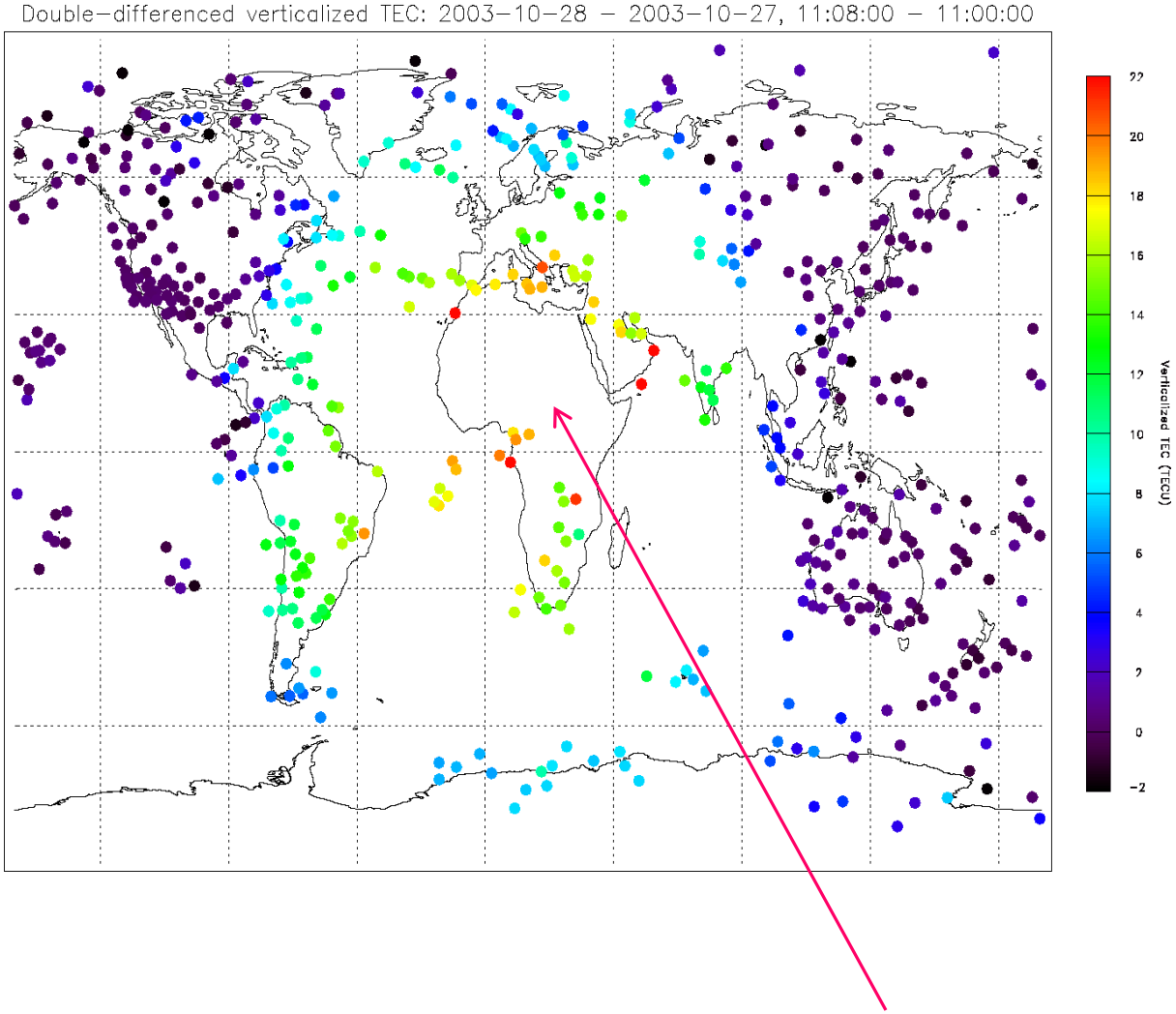
28 October, 2003: SOHO SEM EUV Photons



Tsurutani et al GRL 2005

Delta-TEC from Ground GPS Receivers for 28 October 28, 2003

GPS: a New Technique for Ionospheric Physics

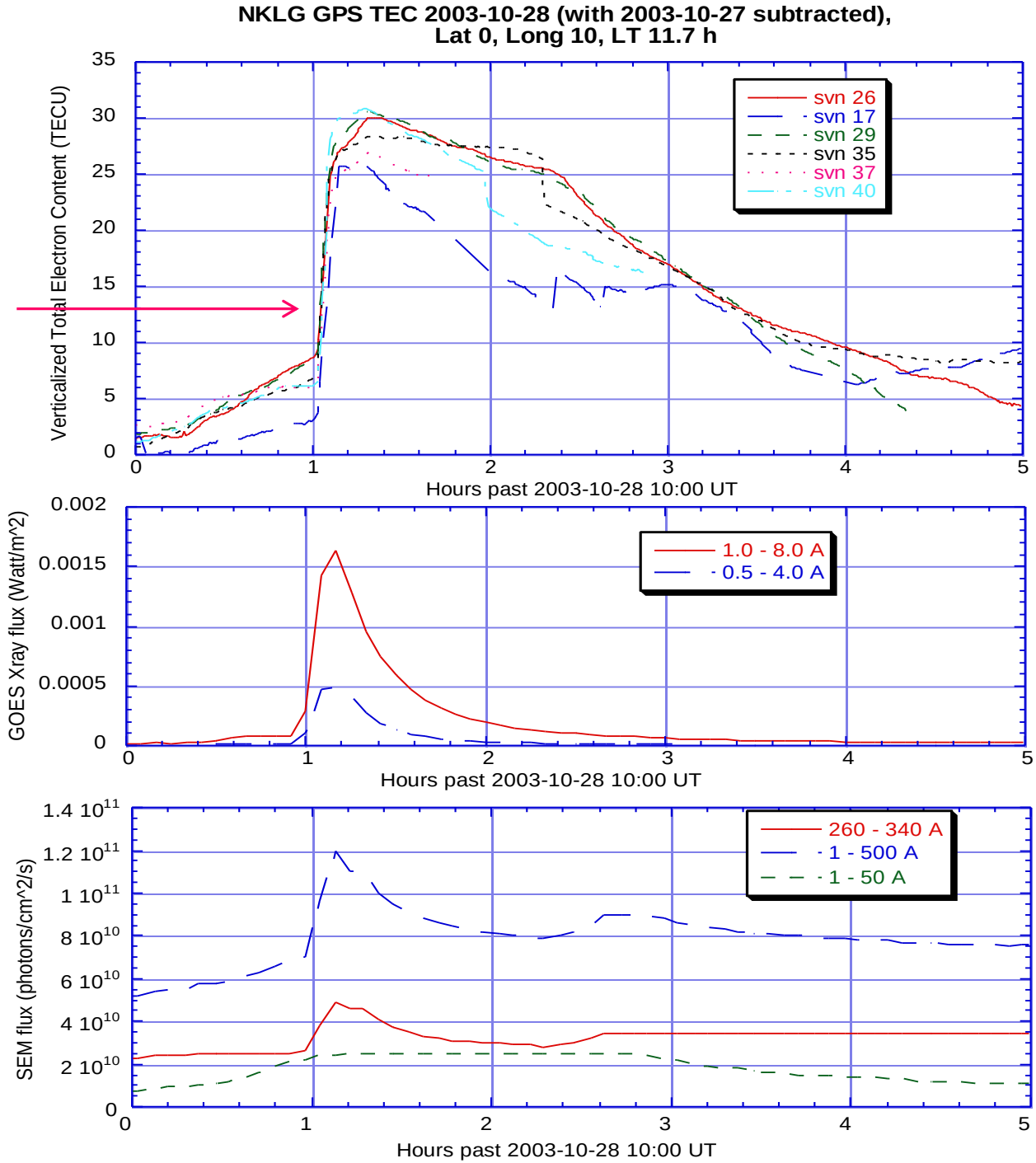


Tsurutani et al., GRL 2005

Subsolar point

Oct 28, 2003

30% TEC jump



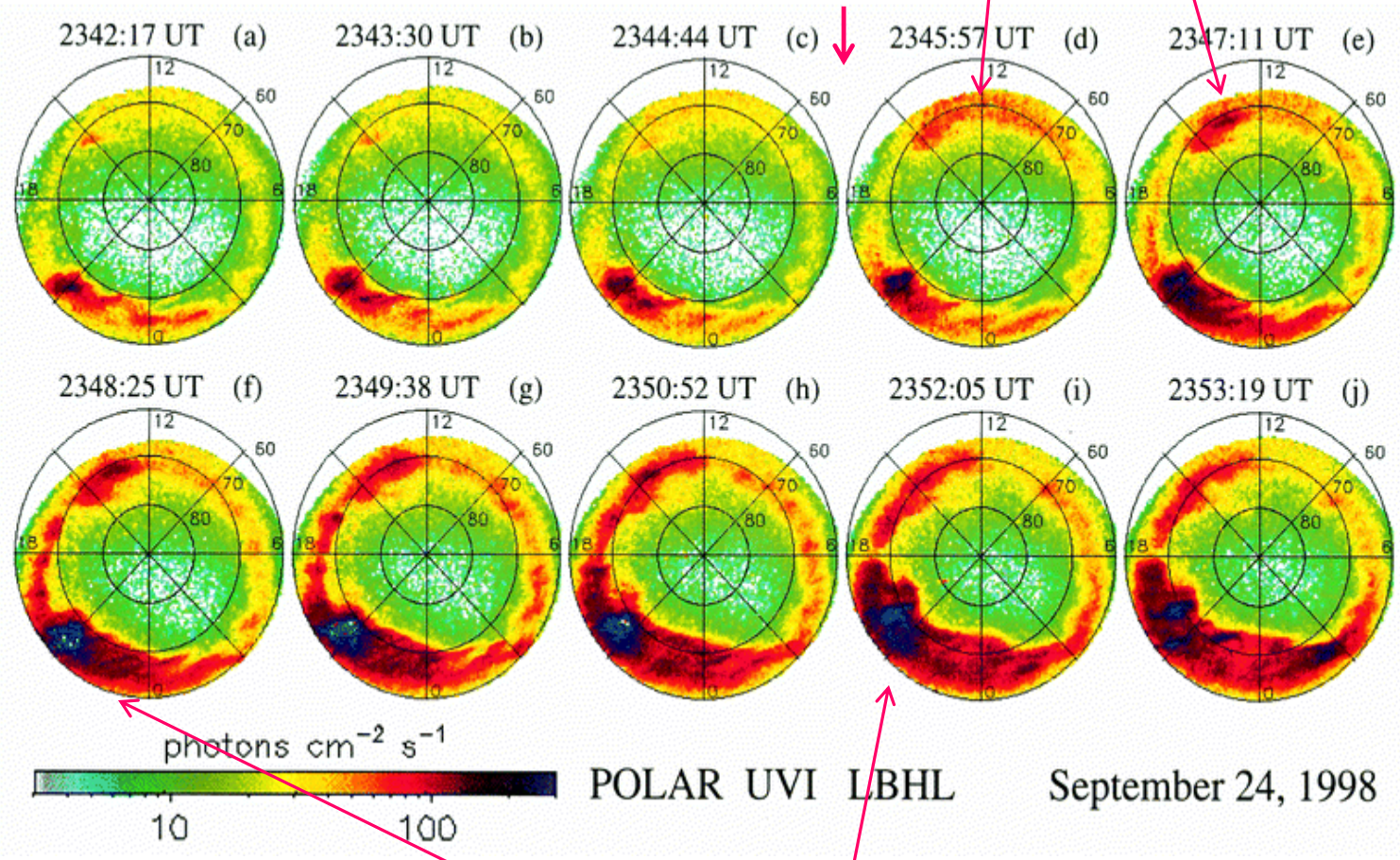
African ground station

GOES X-rays

SOHO SEM EUV

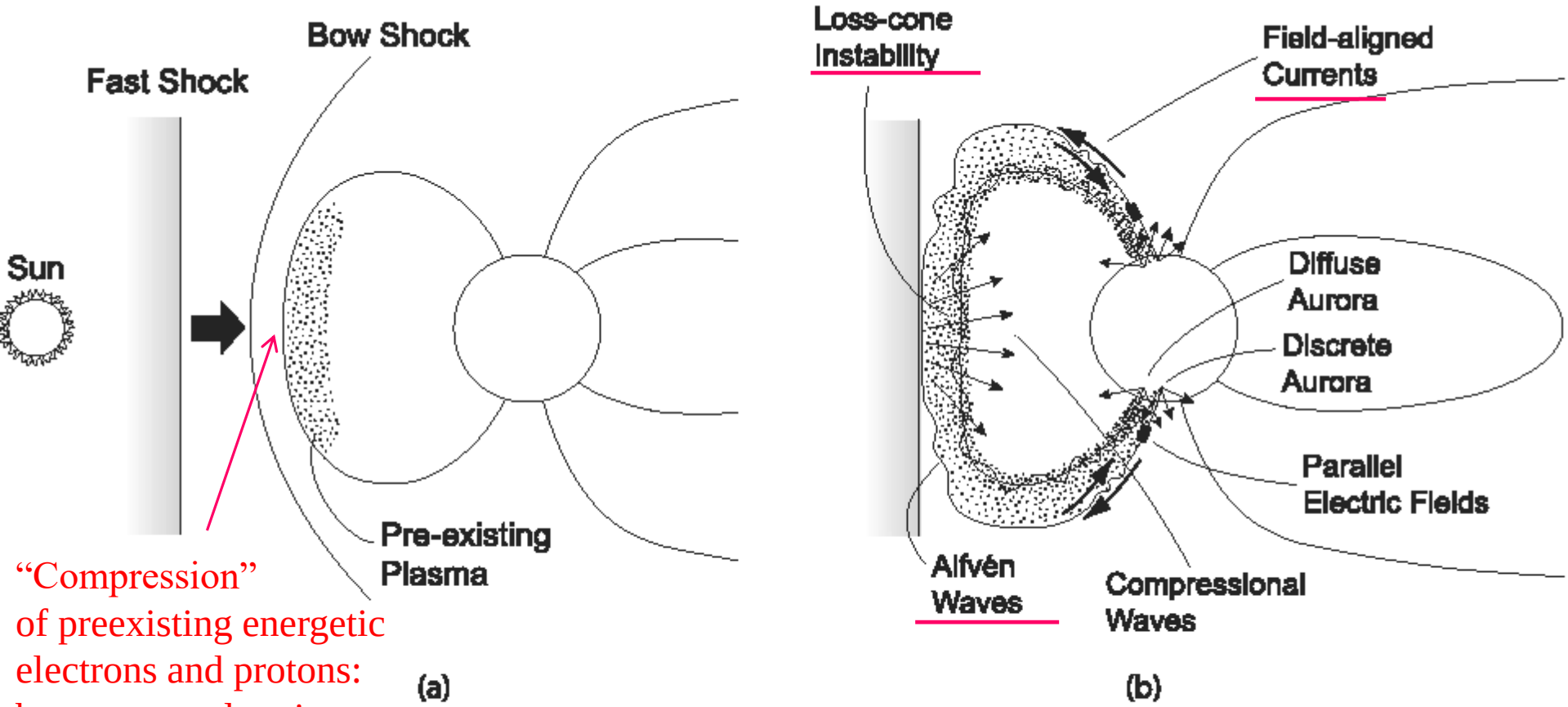
Dayside aurora: shock compression, involving nonadiabatic processes

Shock occurs here



JGR, 2001

Nightside supersubstorm: release of stored energy



"Compression" of preexisting energetic electrons and protons: betatron acceleration

Figure from Zhou et al. JGR, 2003: all three processes are dissipative mechanisms!

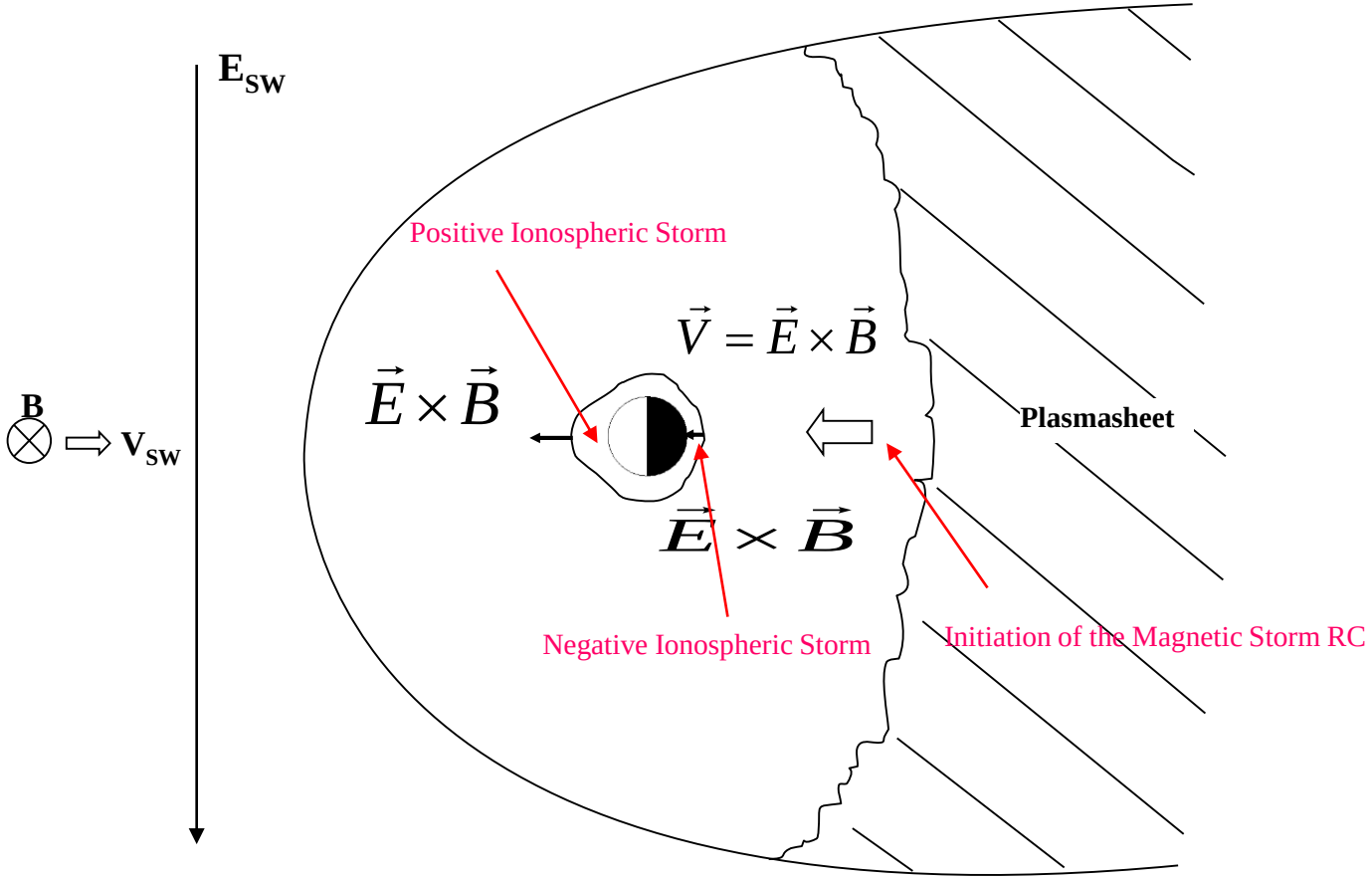
Alfvén waves from Haerendel, Ap.J. Suppl. 1994

Electron and proton auroras after shocks: Liou et al. GRL 2002; Zhou et al., JGR, 2003; Zhang et al JGR 2002; Hubert et al. GRL, 2003; Fuselier et al. JGR 2004; Jeurant et al., JGR 2004; Zhou et al. JGR, 2009

Storm-Time Prompt Penetrating Electric Fields (PPEFs): Ionospheric Effects

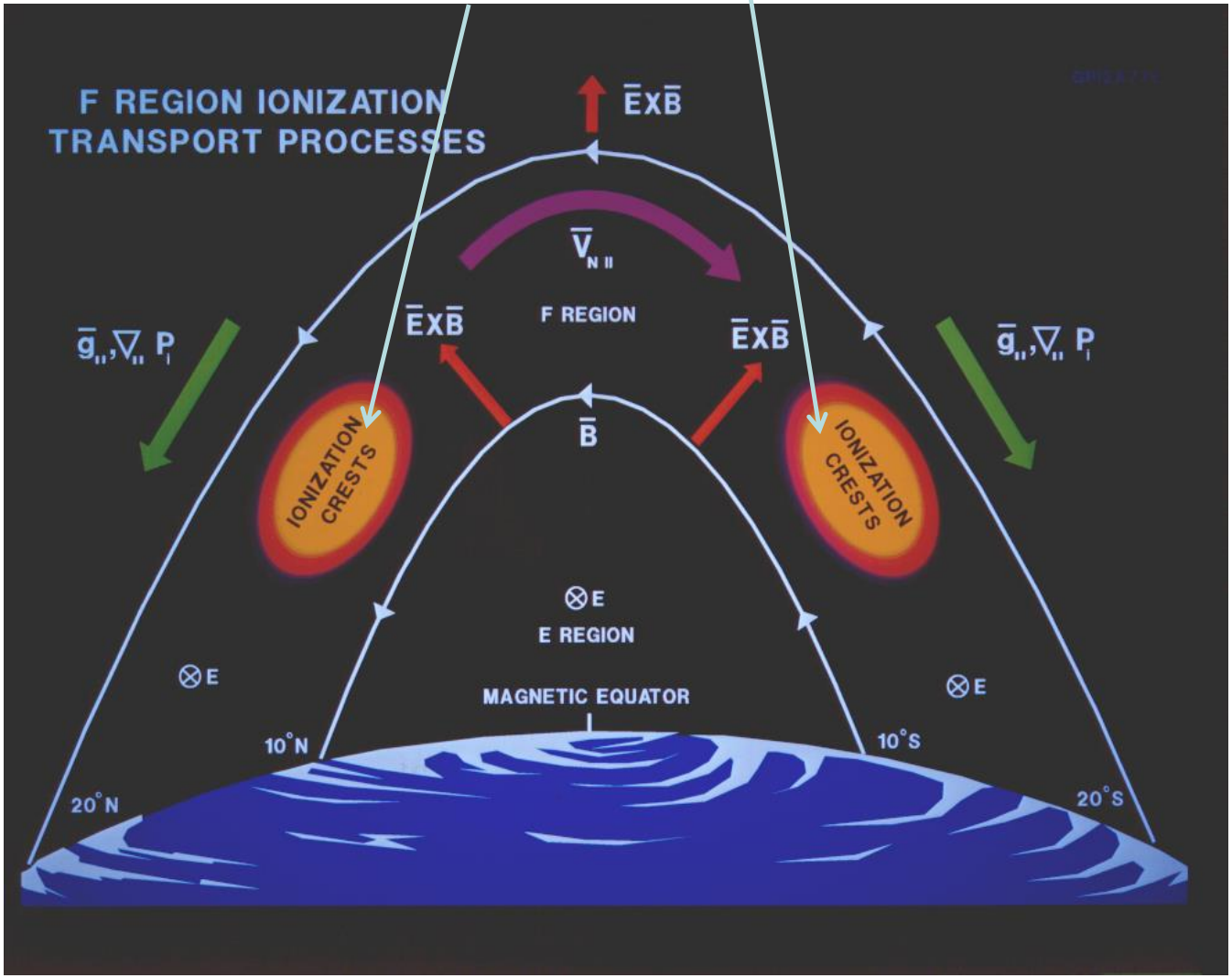
For substorms: Kelley et al. GRL 1979, 2003, Obayashi STP1967, Nishida, JGR 1968
In last 10 years lots of work on PPEFs in magnetic storms.

Prompt Penetration Electric Fields(PPEFs) and Their Effects: A Global Scenario



Tsurutani et al., JGR, 2004

Equatorial Ionospheric Anomalies (EIAs) normally located at ± 10°

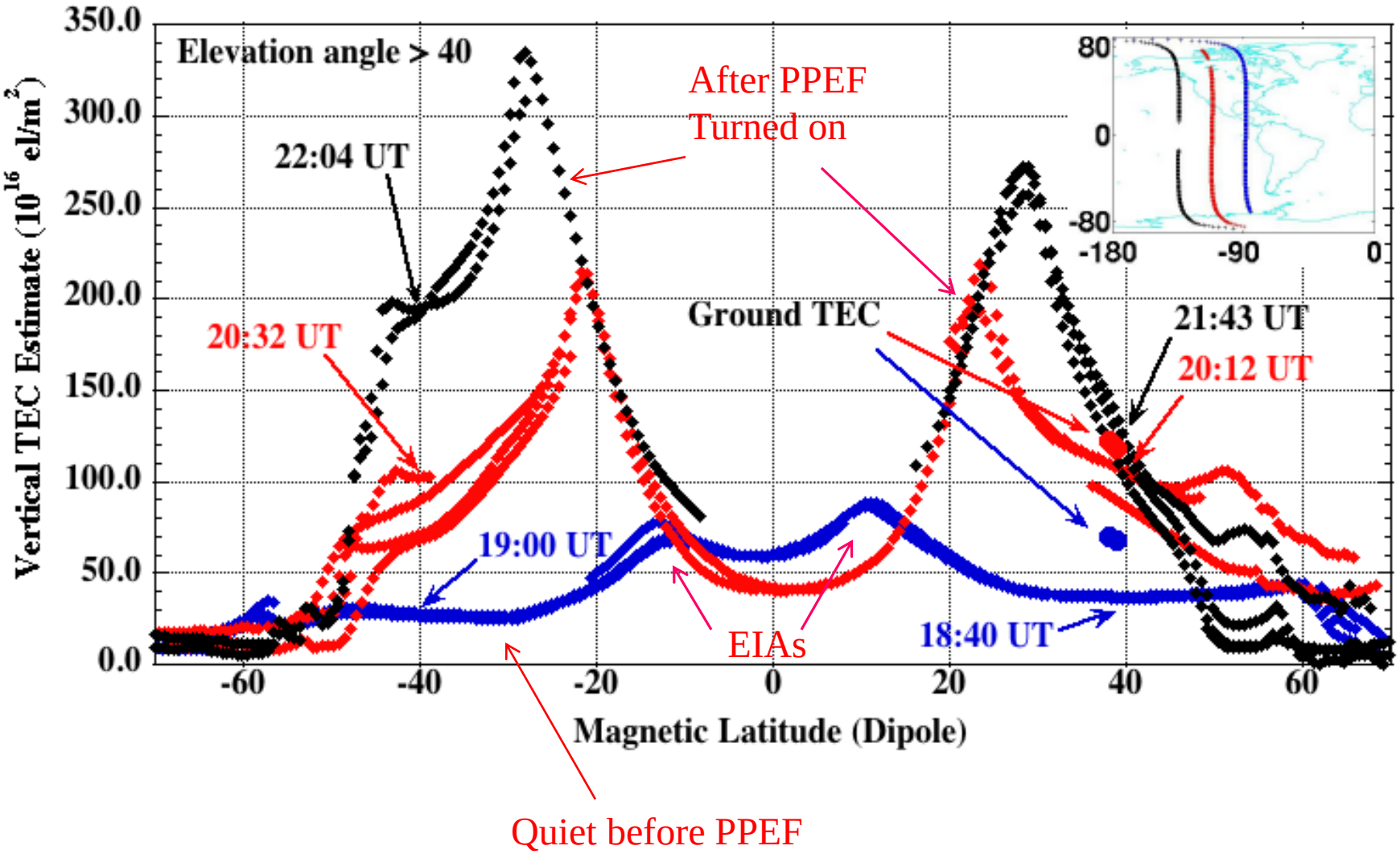


EIAs: Namba and Maeda, RWP 1939, Appleton, Nature 1946

Figure from Anderson et al., 1996

CHAMP TEC (Altitude: ~400 km)

Halloween 30 Oct, 2003 Superstorm

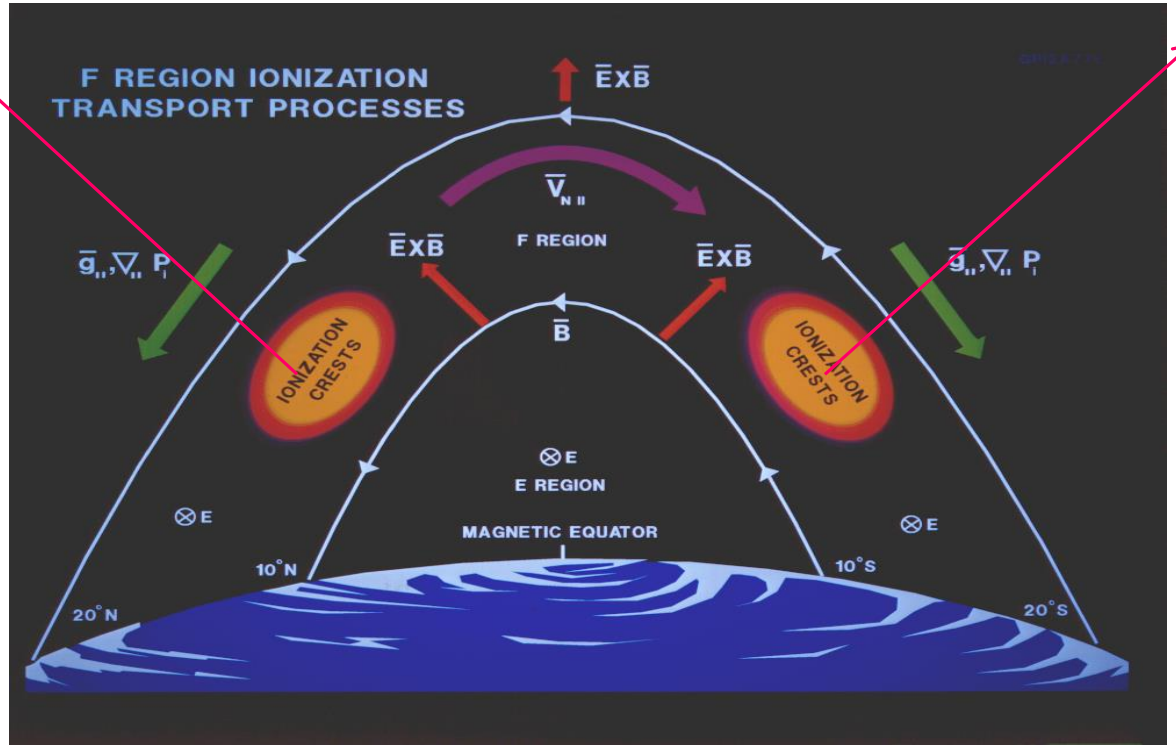


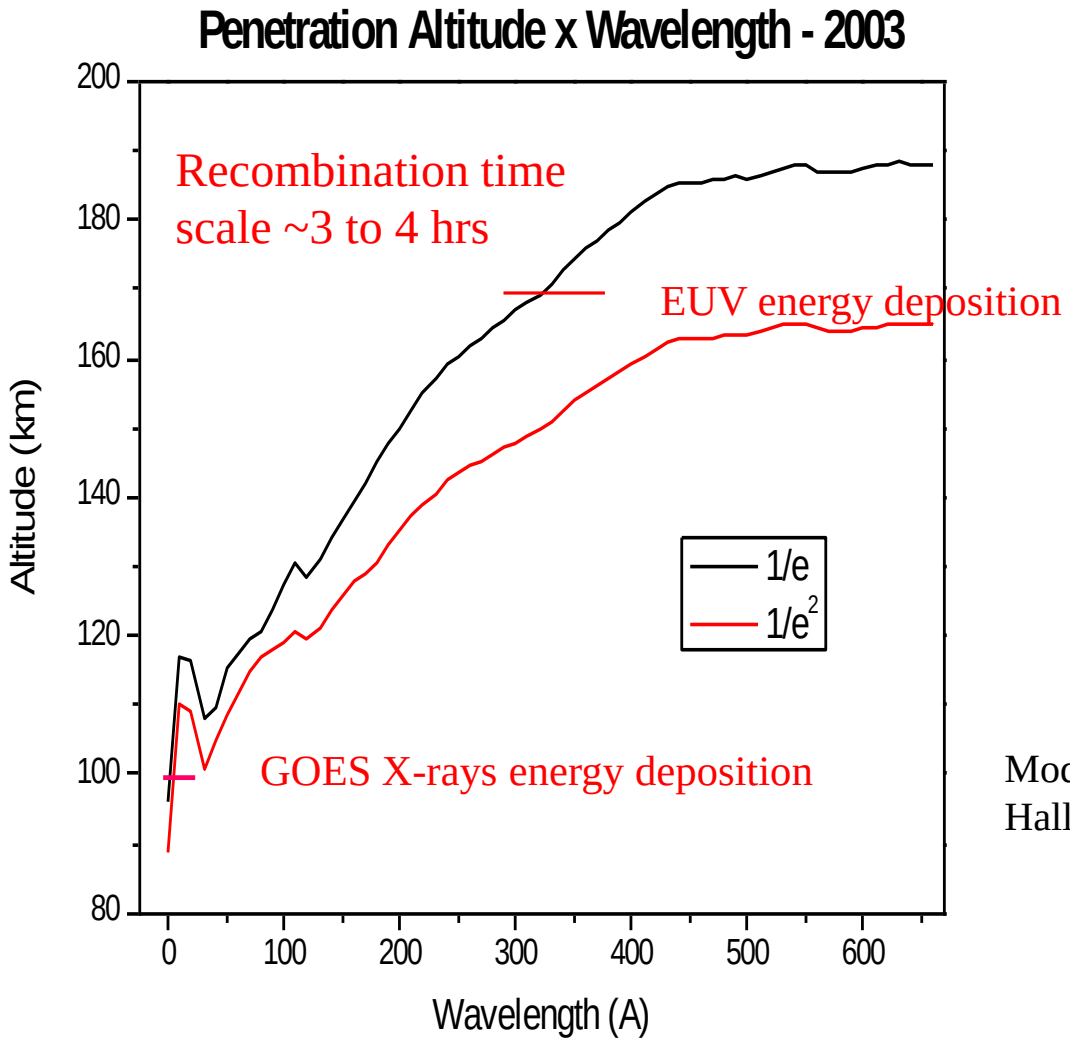
Mannucci et al., GRL 2005

Mechanism for Uplift and Higher Latitudes of EIAs

E x B

E x B





Recombination time
Scale ~10s of mins

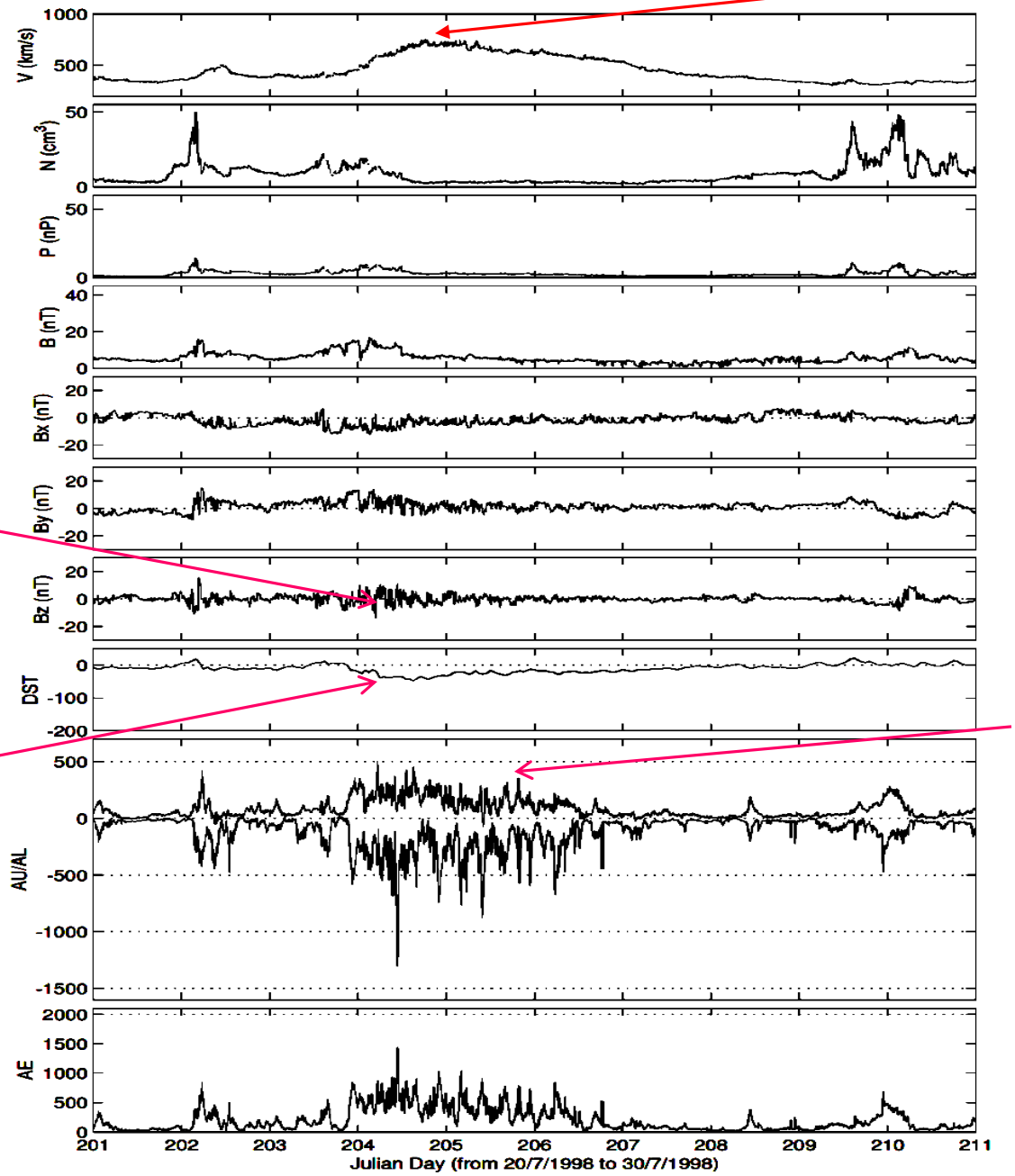
Model atmosphere for
Halloween Day events

High speed stream
peak V_{sw} = 750 km/s

IMF Bz fluctuations

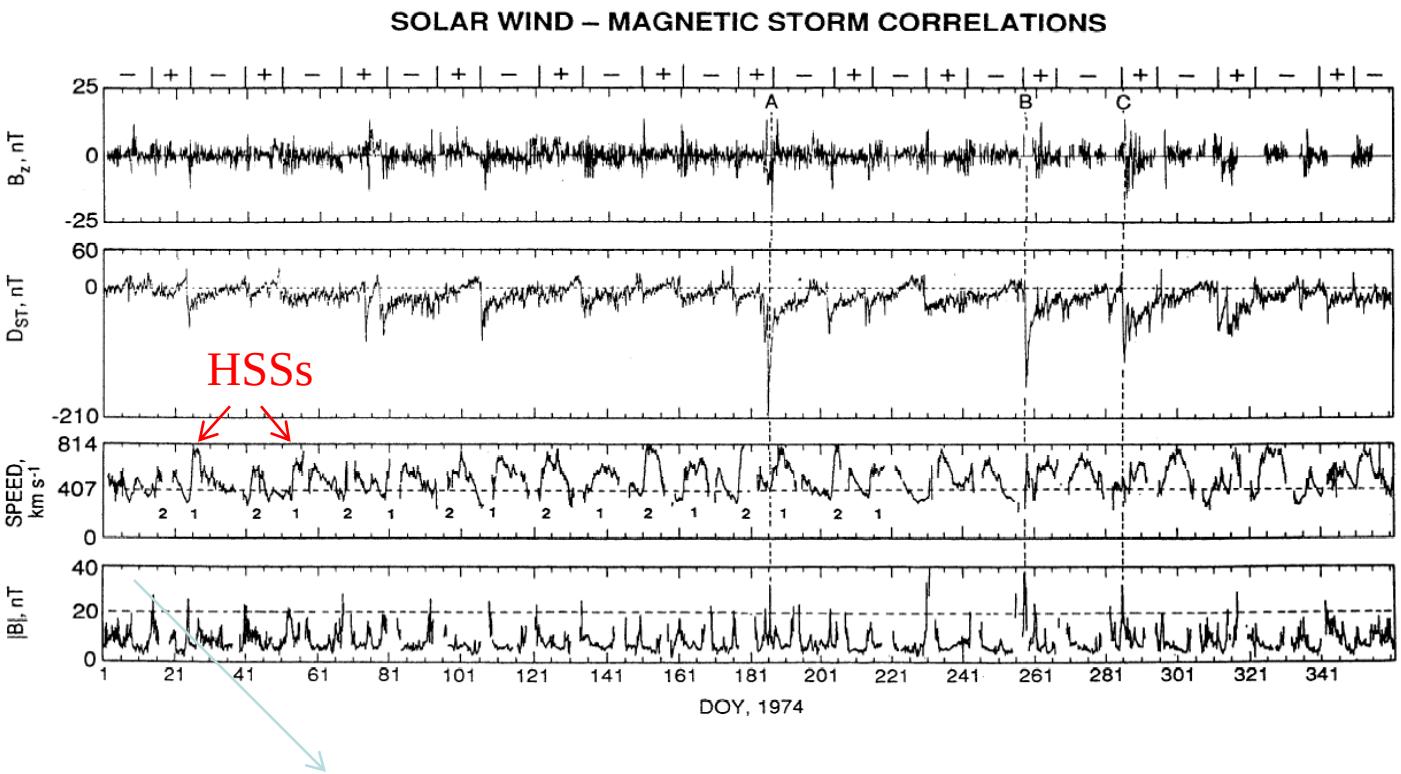
Very weak Dst response

Large AE response



Tsurutani et al. JGR, 2006

High Speed Streams (HSSs) during 1974



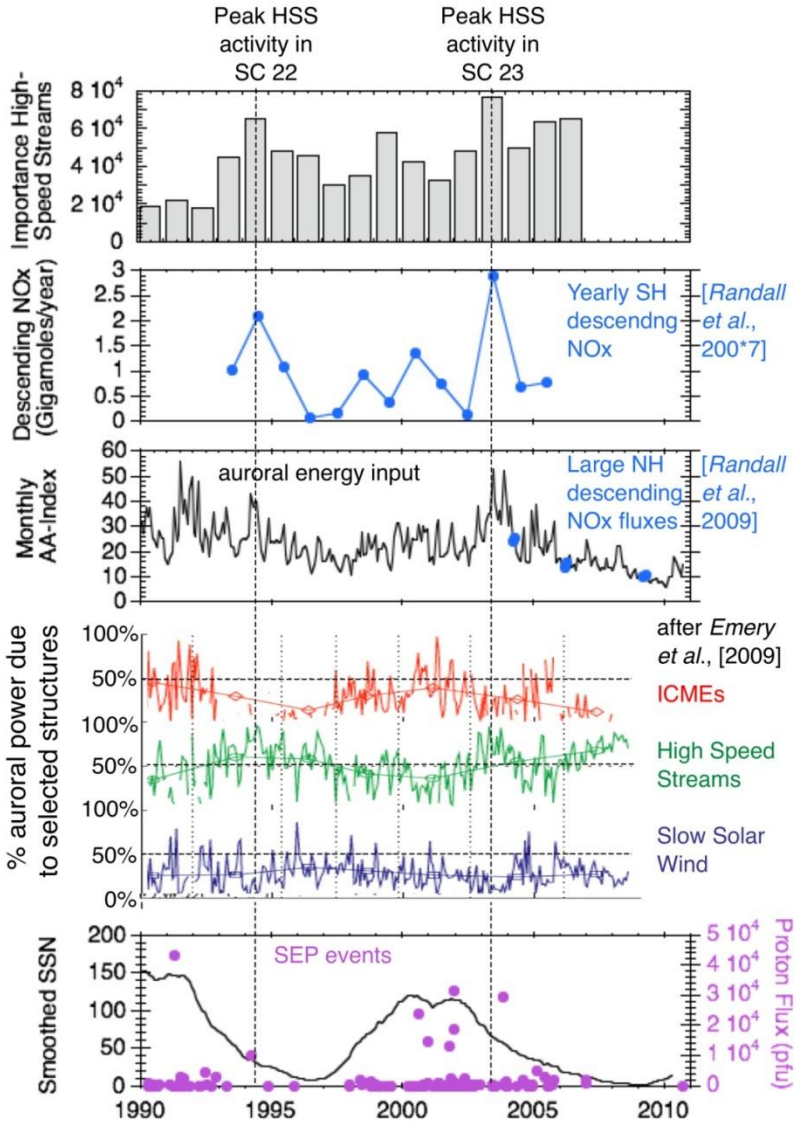
Tsurutani et al. JGR 1995

HSS peaks
In SC22 and 23

Peaks in NOx descent

Peaks in auroral energy input

Declining phase of SCs



Kozyra et al., 2012

SUMMARY: SOLAR MINIMUM

- An all-time Ap minimum (2009) was detected ~6 months to 1 year after the sunspot minimum of SC23 (2008).

- The cause was the disappearance of equatorial coronal holes and appearance of midlatitude coronal holes on the Sun. The high speed streams coming from the latter holes had weaker V_{sw} and IMF Bs at the Earth's latitude.

SUMMARY, SOLAR MAX: ICMEs

- Intense IMF Bs (sheath or magnetic cloud) will generate major magnetic storms (by magnetic reconnection). Auroral energy deposition will descend to middle latitudes.

- Shock impingement onto the magnetosphere can cause significant energy input (and also release of stored energy) into the magnetosphere.

- Magnetic storm PPEFs cause dayside TEC enhancement and the transport of ionospheric plasma from the equator to middle latitudes.

SUMMARY, DECLINING PHASE: HIGH SPEED STREAMS

- CIRs typically create only weak magnetic storms (Dst > -100 nT).

- Bs from interplanetary Alfvén waves causes the continuous/sporadic injection of plasmasheet plasma causing long duration CIR storm “recovery phases”. Relativistic electrons are accelerated in this process.

- Auroral zone NOx entrained by a polar vortex may diffuse downward to lower altitudes, leading to ozone depletion.

- Strong atmospheric heating is associated with HSSs.