Space Weather Effects in the Magnetosphere, Ionosphere and Thermosphere: What We Know and What Are Current Challenges

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Coronal Mass Ejections (CMEs) and Interplanetary CMEs(ICMEs): Solar Maximum

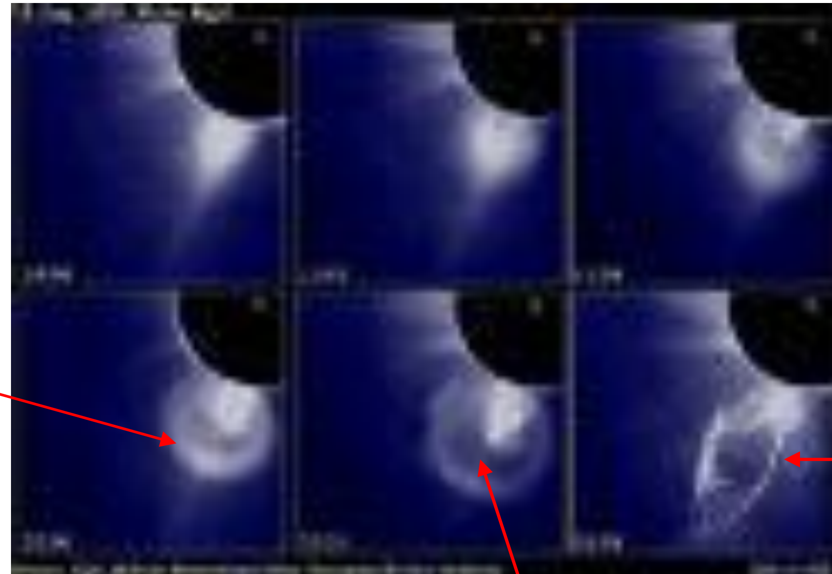
We distinguish between CMEs and ICMEs because what is observed at the Sun may not be exactly the same thing detected at 1 AU.

Typically the outer loops and filaments are not detected at 1 AU.

The magnetic cloud magnetic fields may be altered during passage from the Sun to the Earth?

A CME at the Sun

loop



High density filament

Iling and Hundhausen, 1986

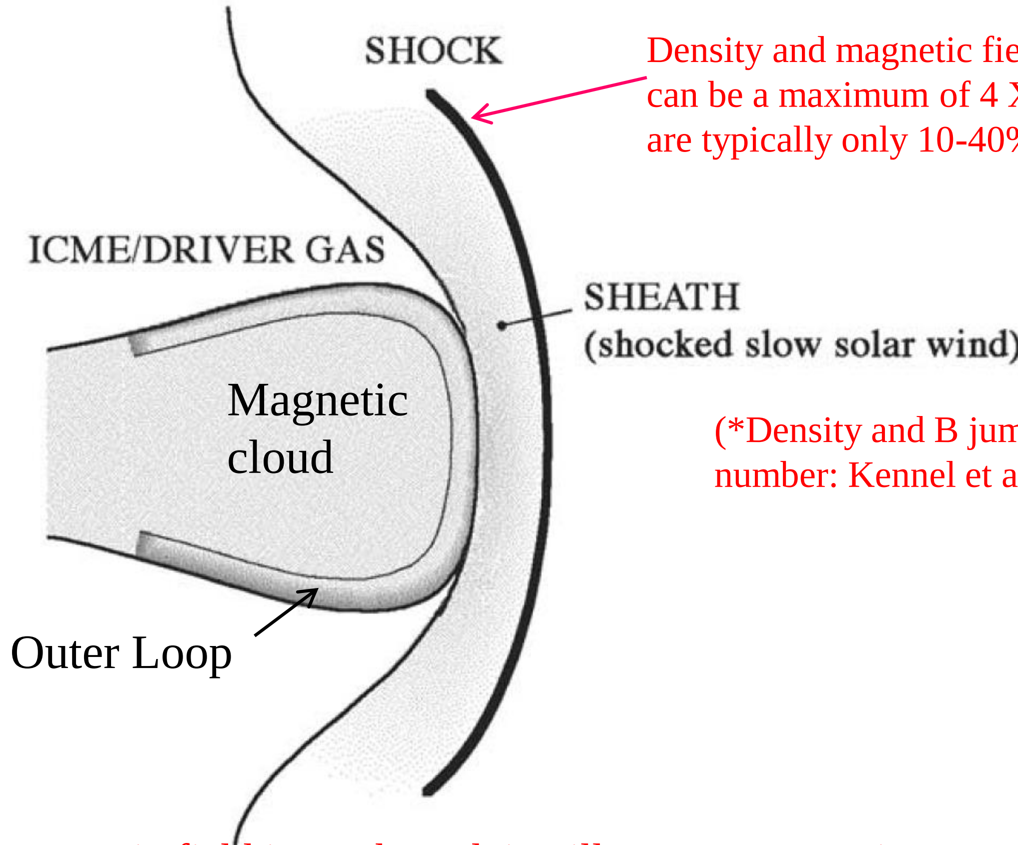
Dark region (Magnetic Cloud)

If the magnetic fields within magnetic clouds (MCs) are southward, they cause magnetic storms.

Intense solar flares are always accompanied with the release of CMEs. Very intense magnetic storms are always associated with intense flares.

Filaments can be geoeffective by causing solar wind ram pressure effects. However they are not detected too often at 1 AU. What happens to them? Solar Probe and Solar Orbiter may be able to answer this question. Data analysis.

A Second Region of Intense Magnetic Field is the Sheath: Interplanetary Space



Density and magnetic field magnitude jumps can be a maximum of 4 X*. Shock velocity jumps are typically only 10-40%.

(*Density and B jumps go like Mach number: Kennel et al. AGU mon. 1985)

If the sheath magnetic field is southward, it will cause a magnetic storm. Since this is compressed slow solar wind plasma (a different origin than MC plasma), it is high beta and the storm may have different properties than that of MC-caused events. Approximately half of magnetic storms with intensities Dst < -100 nT are caused by sheath fields. Forecasting these events are more challenging than MC storms.

Magnetic Storms at Earth are Caused by IMF Bs and Magnetic Reconnection

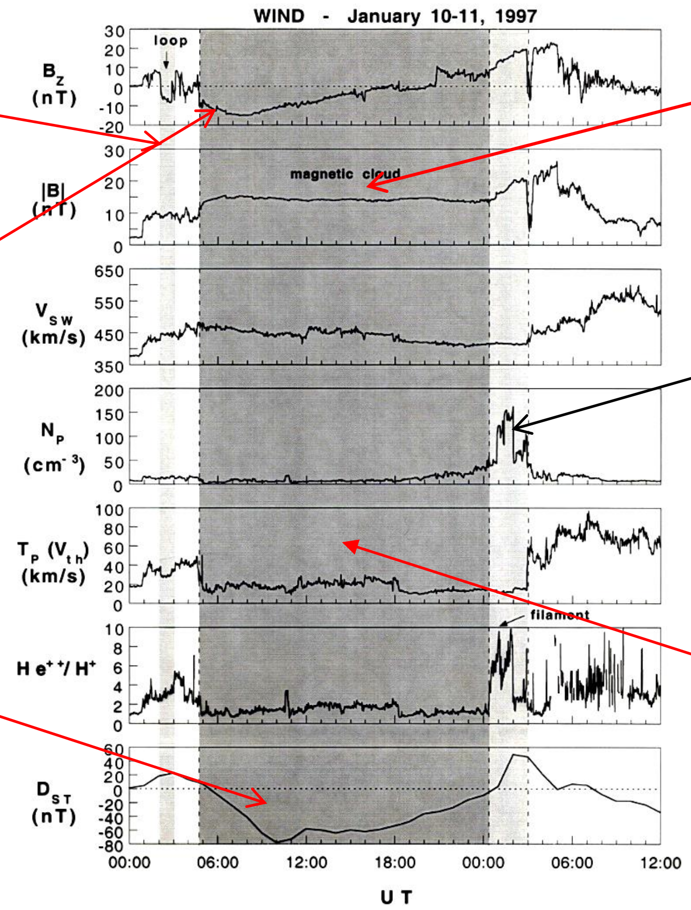
Coronal Loop?
(Tsurutani et al., 1998)

Southward B_z

Magnetic Cloud
(Burlaga et al. 1981)

Filament
(Burlaga et al., 1998)

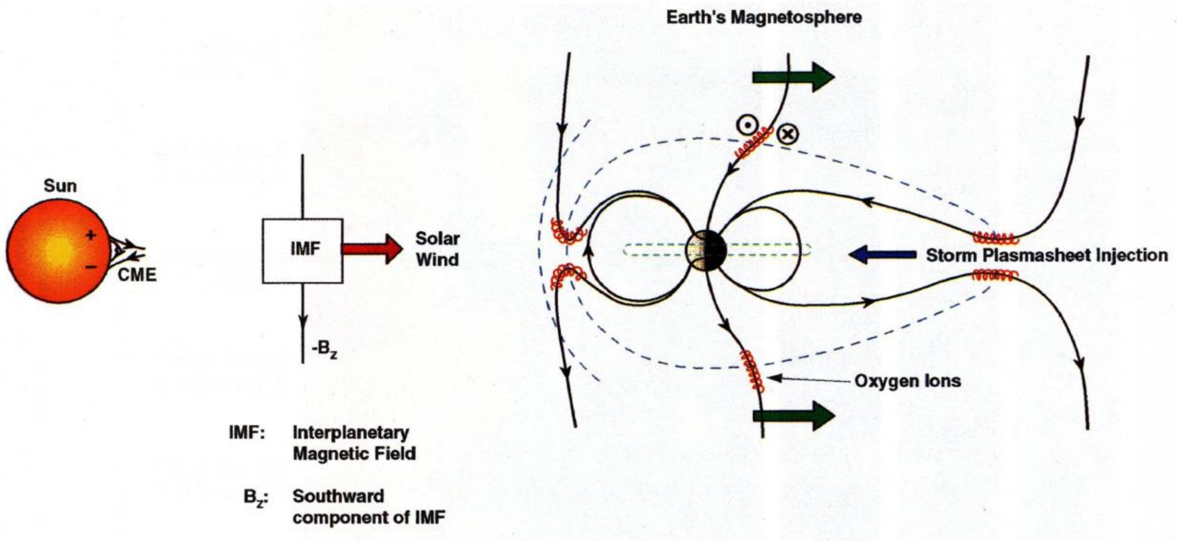
Magnetic storm
(main phase)



Magnetic cloud:
low β (β ≤ 10^{-1}), lack of discontinuities and waves

Tsurutani and Gonzalez, 1994

In this case the loop and filament were not geoeffective.



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

Echer et al. (2008) has shown that all 90 storms with Dst < -100 nT during SC 23 were caused by southward magnetic fields (no IMF By magnetic storms).

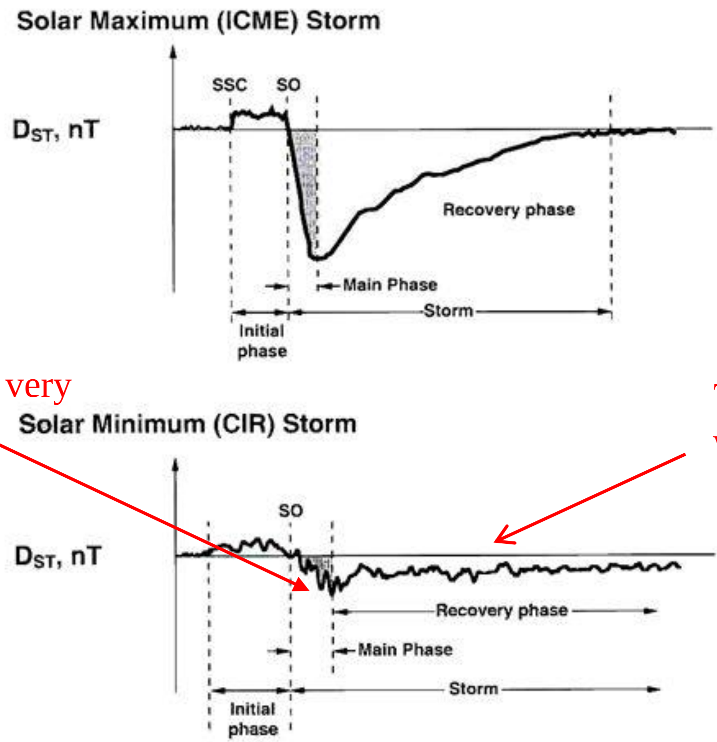
What Are the Fundamental Problems With ICME Magnetic Storm Forecasting?

The first main problem is predicting the IMF Bz at 1 AU. What is the CME magnetic field near the Sun (we do not know)? Can the CME magnetic fields be distorted during transit from the Sun to 1 AU? Perhaps data from the Parker Solar Probe, Solar Orbiter and ACE together can answer that question.

A second fundamental problem is with the accuracy of the codes in predicting the arrival time and features of the shock, sheath and ICME at 1AU. Dedicated NASA and NSF funding could aid in improving these data analyses and codes. So far there has NOT BEEN ANY emphasis placed on CODE VERIFICATION. It is known that during (solar) active periods, the predicted arrival times of an ICME can be off by days. No-one can predict the MC magnetic field yet.

CIR-Storms and High Intensity Long Duration Continuous AE Activity (HILDCAAs): Declining Phase Geomagnetic Activity

A Second Type of Magnetic Storm: CIRs



A CIR magnetic
Storm main phase has a very
different profile.

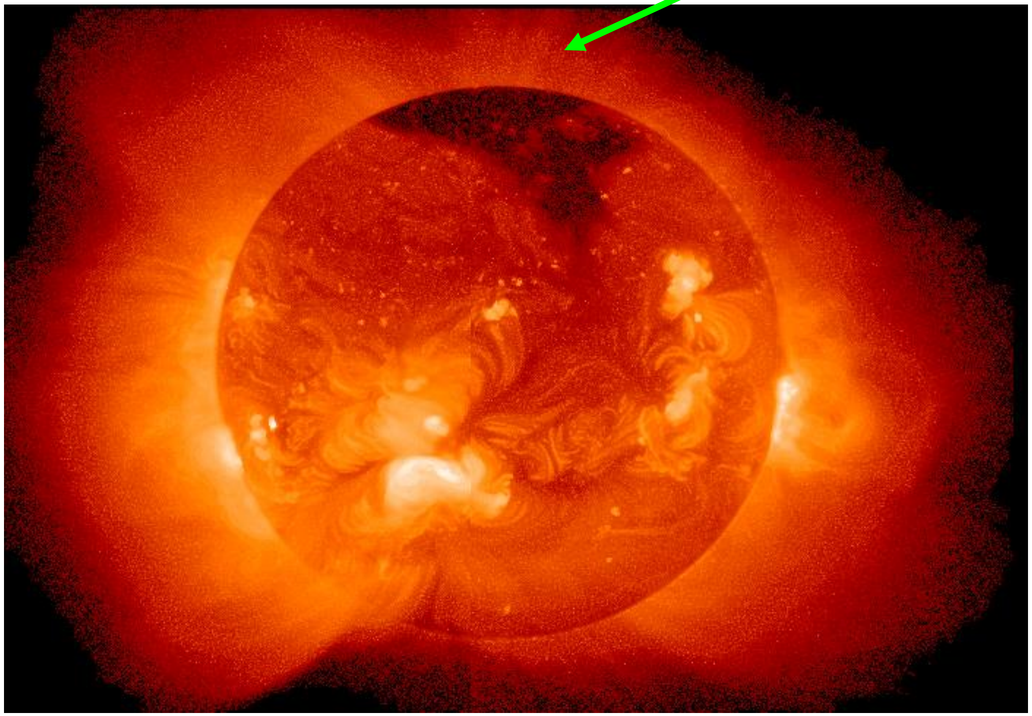
This “recovery phase” can last
weeks. This is called a HILDCAA

Tsurutani, 1991

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

During the Declining Phase of the Solar Cycle There Are Large Polar Coronal Holes

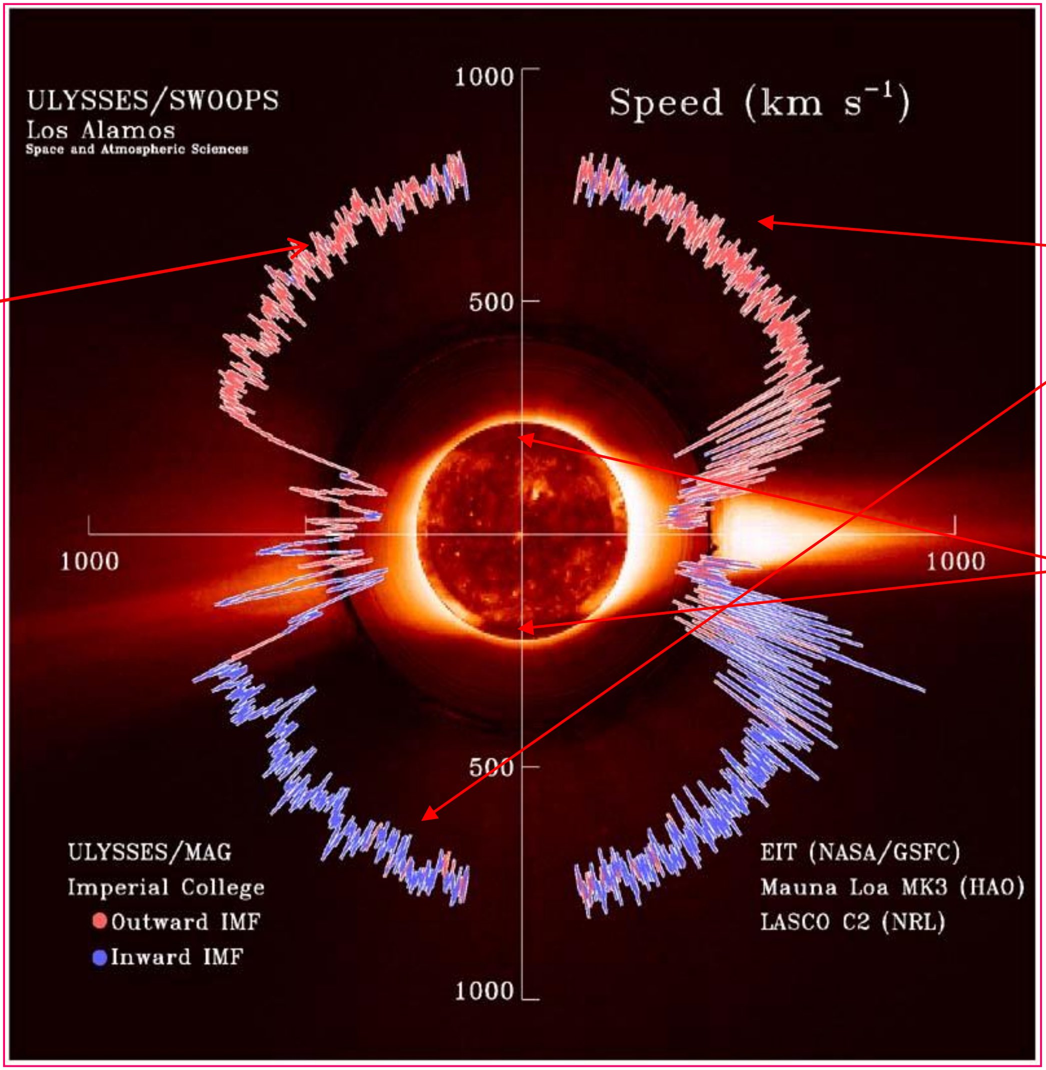
Coronal hole (CH)



The~27 day recurrent geomagnetic activity pattern was originally discovered in 1905 (Maunder 1905, 1906; Chree, 1911; Bartels, 1934)

High Speed Solar Wind With Vsw ~750 to 800 km/s Emanate from CHs

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



HSSs

Large polar coronal holes

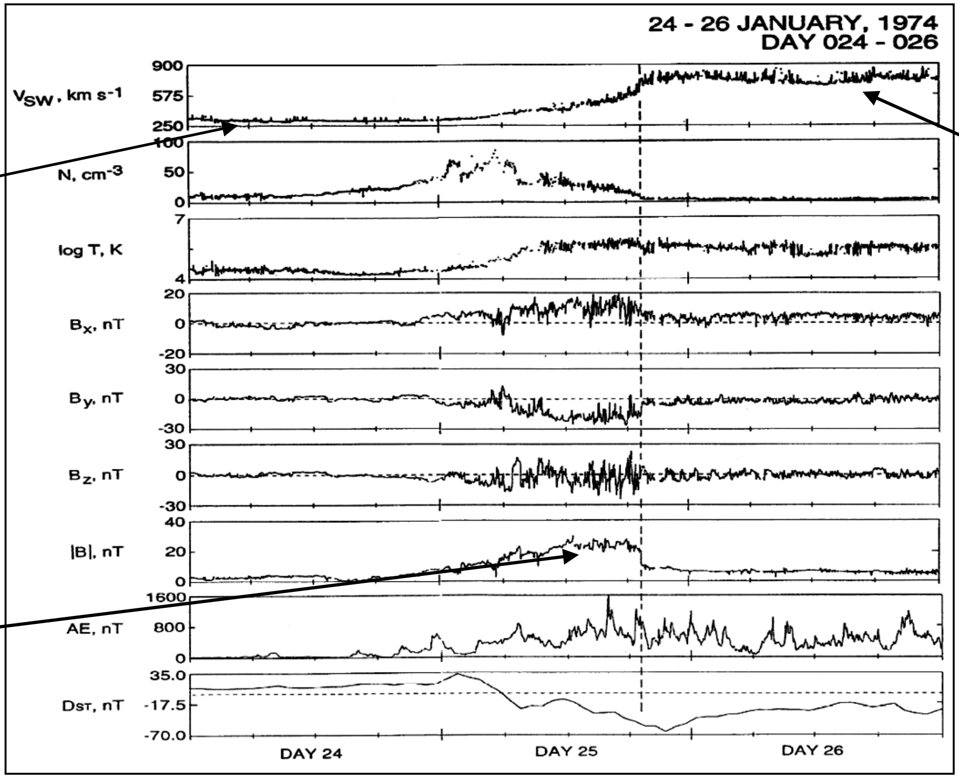
Phillips et al. GRL 1998; McComas et al. GRL 2003

CIR Induced Storms Typically Don't Have SI$^+$s and Have Irregularly Shaped Main Phases

Slow speed stream

High speed stream

Corotating Interaction Region or CIR

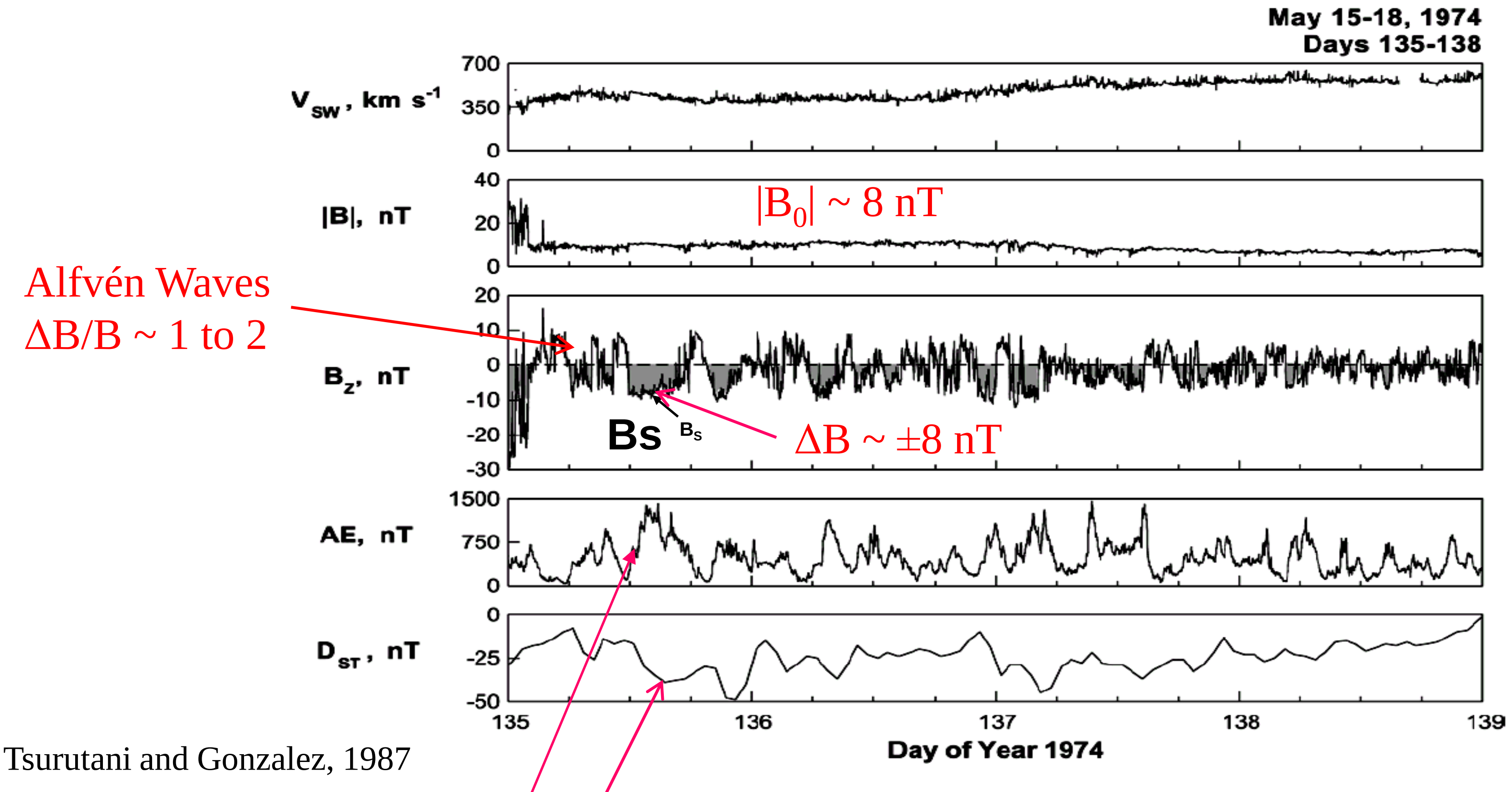


The irregularity of the profile of the storm main phase is due to the fluctuations in the IMF Bz component

Can one predict the variability of the IMF Bz in CIRs? This will be more difficult than predicting Bz for ICMEs. First of all what are the fluctuations, shock compressed interplanetary Alfven waves? Can one predict the properties of the upstream waves?

Knowing the location of a stable coronal hole, CIR generation and the propagation to 1 AU should be feasible. However again, little emphasis has been placed on code verification. Funding (and interplanetary observations) may help improve current capability.

HILDCAAs Are Caused by High Speed Stream Southward Magnetic Field Component of Alfvén Waves



Tsurutani and Gonzalez, 1987

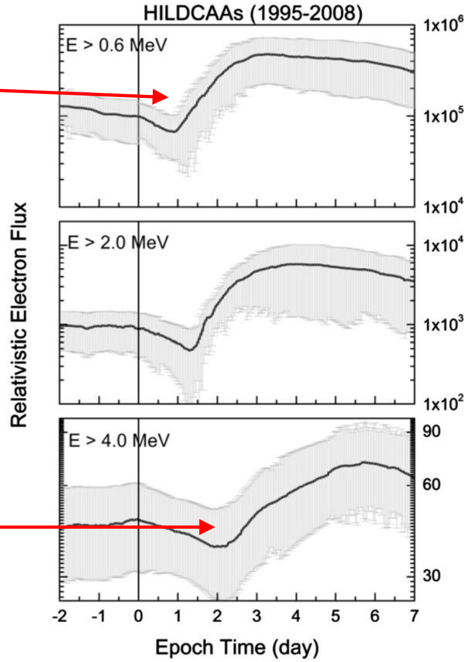
With IMF Bs increases, AE increases and Dst decreases
Averaged over time, HILDAAs pump more energy into the magnetosphere during the declining phase than ICMEs during solar maximum.

The Alfvénic fluctuations may be impossible to predict especially if some of the waves are generated near 1 AU upstream of the Earth.

Relativisitic Magnetospheric Electrons Are Accelerated/Created During HILDCAAs

E > 0.6 MeV electrons delayed by ~ 1 day

E >4.0 MeV electrons delayed by ~2 days



Hajra et al., 2015

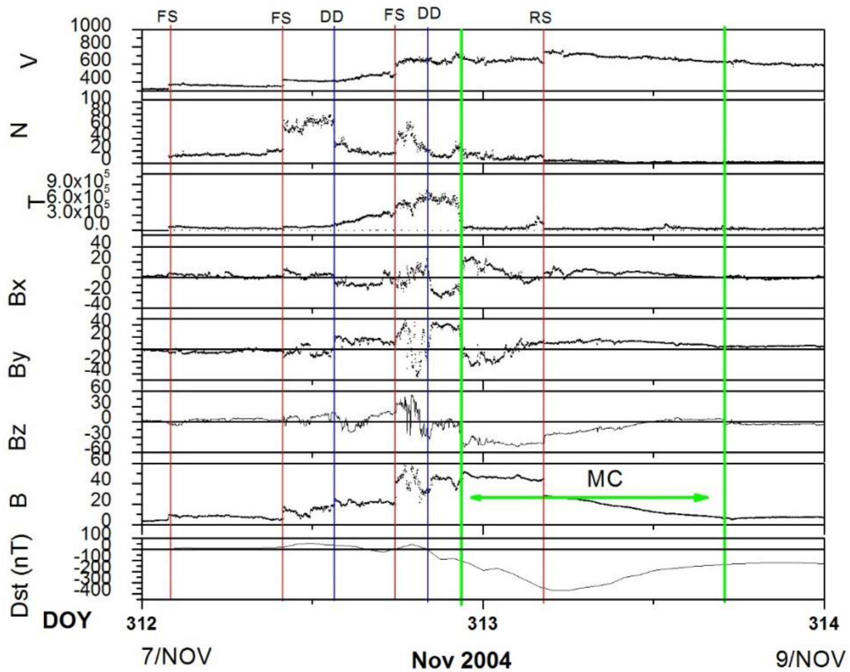
The accepted scenario is that substorm and injection events within HILDCAAs cause the convection of anisotropic plasmasheet electrons into the nightside magnetosphere. The anisotropic electrons generate electromagnetic chorus. The chorus accelerates the ~100 keV substorm electrons to ~0.6 MeV and the further bootstrapping occurs.

How high can this energy get, say with 1973-1975 type HILDCAAs?

Can the above relationship be used to predict the occurrence of relativistic electrons?

Interplanetary Shocks

Multiple Interplanetary Fast Forward Shocks Pump Up the Interplanetary Magnetic Field Magnitude



Tsurutani et al., 2008

Active Regions (ARs) on the Sun will have multiple flaring and multiple CME releases. The multiple shocks can pump up the interplanetary magnetic field to magnitudes higher than that of the MC.

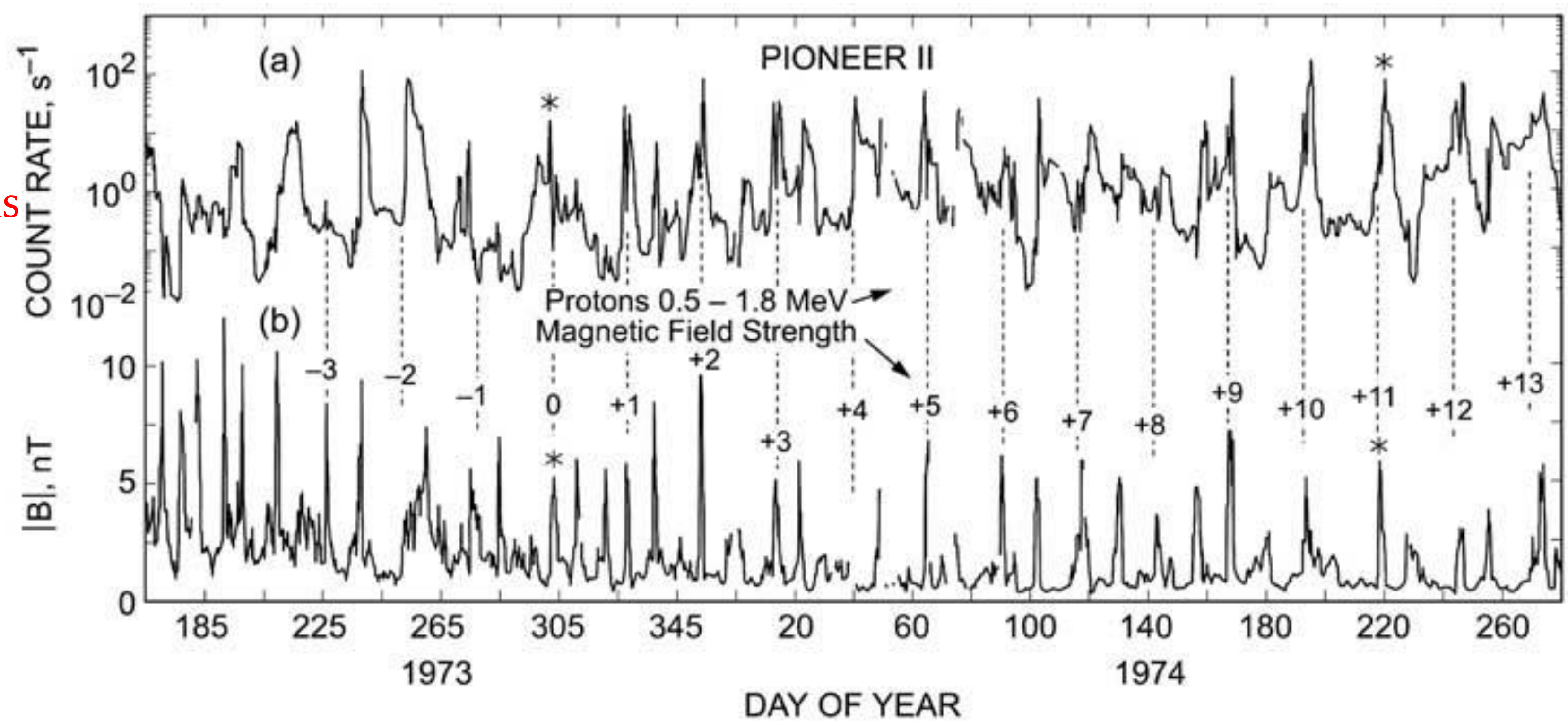
The high densities behind interplanetary shocks compress the Earth's magnetosphere. These events are detected on the ground as Sudden Impulses or SI^+s. In the above example, the three shocks cause SI^+s of ~15, 35 and 40 nT intensities. These are seen in the Dst/SYM-H trace.

Modeling of ICME propagation during AR flaring has so far not been successful. Data from Solar Orbiter and Parker Solar Probe will help.

Discovery of Shock Acceleration of ~ MeV Protons
(in the Outer Heliosphere)

~MeV protons

CIRs



Van Hollebeke, MacDonald, Trainor and Von Rosenvinge, JGR, 1978; Tsurutani, Smith, Simpson, Pyle, JGR 1982

The fast reverse shocks were more efficient in accelerating energetic particles

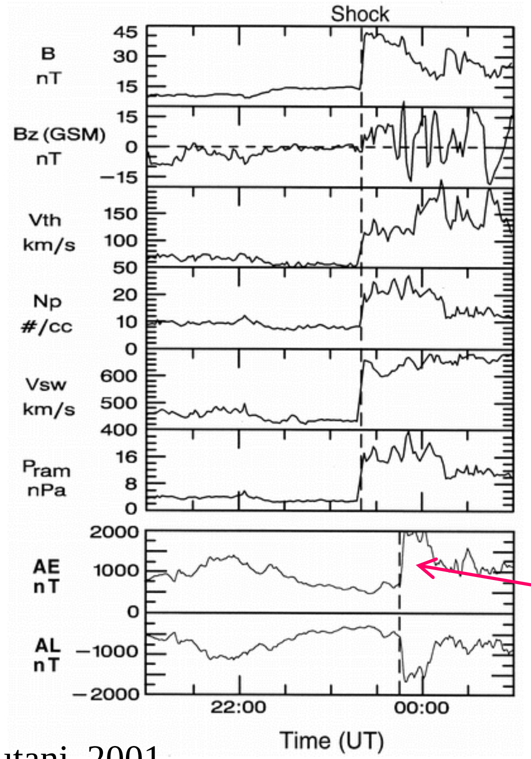
Can One Accurately Forecast Solar Flare Particle Fluences Today? If Not, What is Needed?

The biggest flare particle event was probably the August 1972 event. There was no magnetic storm caused by the MC. The biggest magnetic storm is the Carrington 1859 event. There is very little evidence of an energetic particle event. Thus the magnetic storm part of space weather is distinct from solar flare energetics.

The consensus is that the particle fluence depends on the upstream seed particles, the shock normal angle and the Mach number. Tsurutani and Lakhina (2014) have speculated that Mach nos. as large as 45 are possible*. Why haven't such large events been detected? The Parker Solar Probe and Solar Orbiter should be able to answer this question. Nonlinear dissipation effects should be studied.

*The largest detected is M = 28 (Riley et al ApJ, 819, 57, 2016)

Interplanetary Shock Powering A Dayside Aurora Event (and Triggering a Supersubstorm)



Zhou and Tsurutani, 2001

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

$\Delta N/N = 2.0$

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

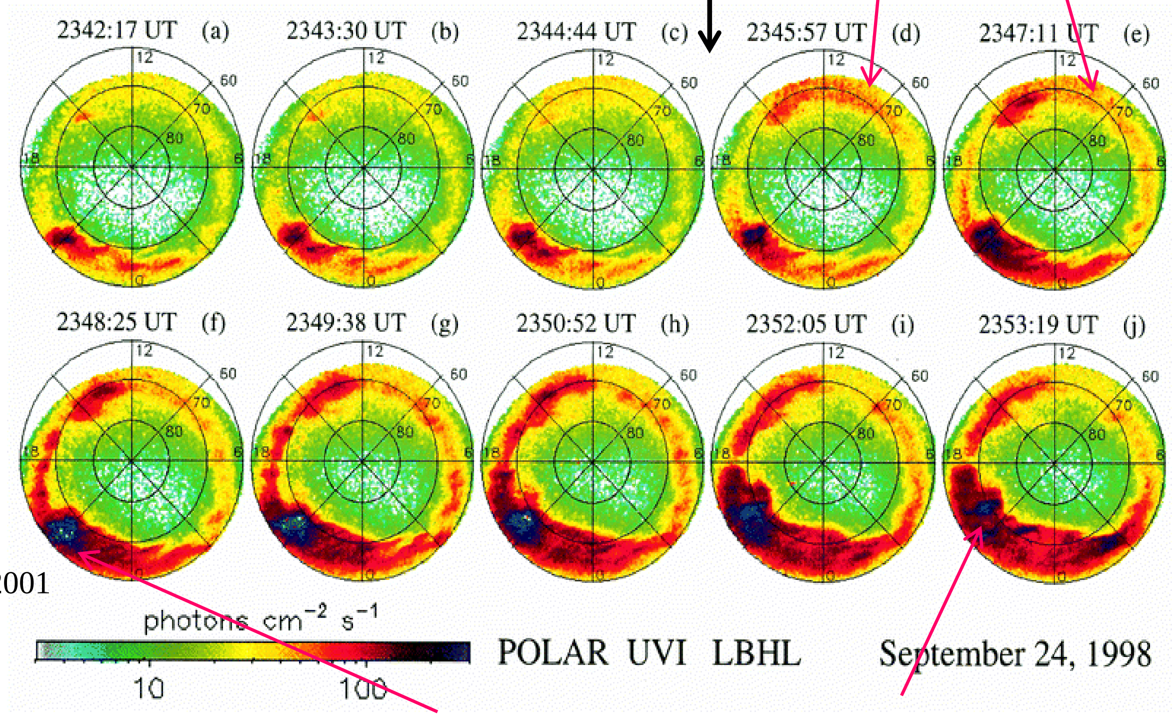
supersubstorm

The energy for the dayside aurora must be primarily from direct solar wind ram energy

Interplanetary Shocks Create Dayside Aurora AND Trigger Nightside Substorms

Dayside aurora: shock compression, involving nonadiabatic processes

Shock occurs here



Zhou and Tsurutani, 2001

Nightside supersubstorm

For the nightside supersubstorms where does the energy come from?
Recently stored tail energy? Long term tail energy? Solar wind ram energy? All three?

There Are Several Different Mechanisms for the Dayside Shock-Associated Auroras

1) Betatron acceleration (compression) of preexisting 10-100 keV electrons and protons, temperature instabilities and wave-particle interactions leading to diffuse aurora.

2) Generation of Alfvén waves with ionospheric damping (Haerendel, 1994)

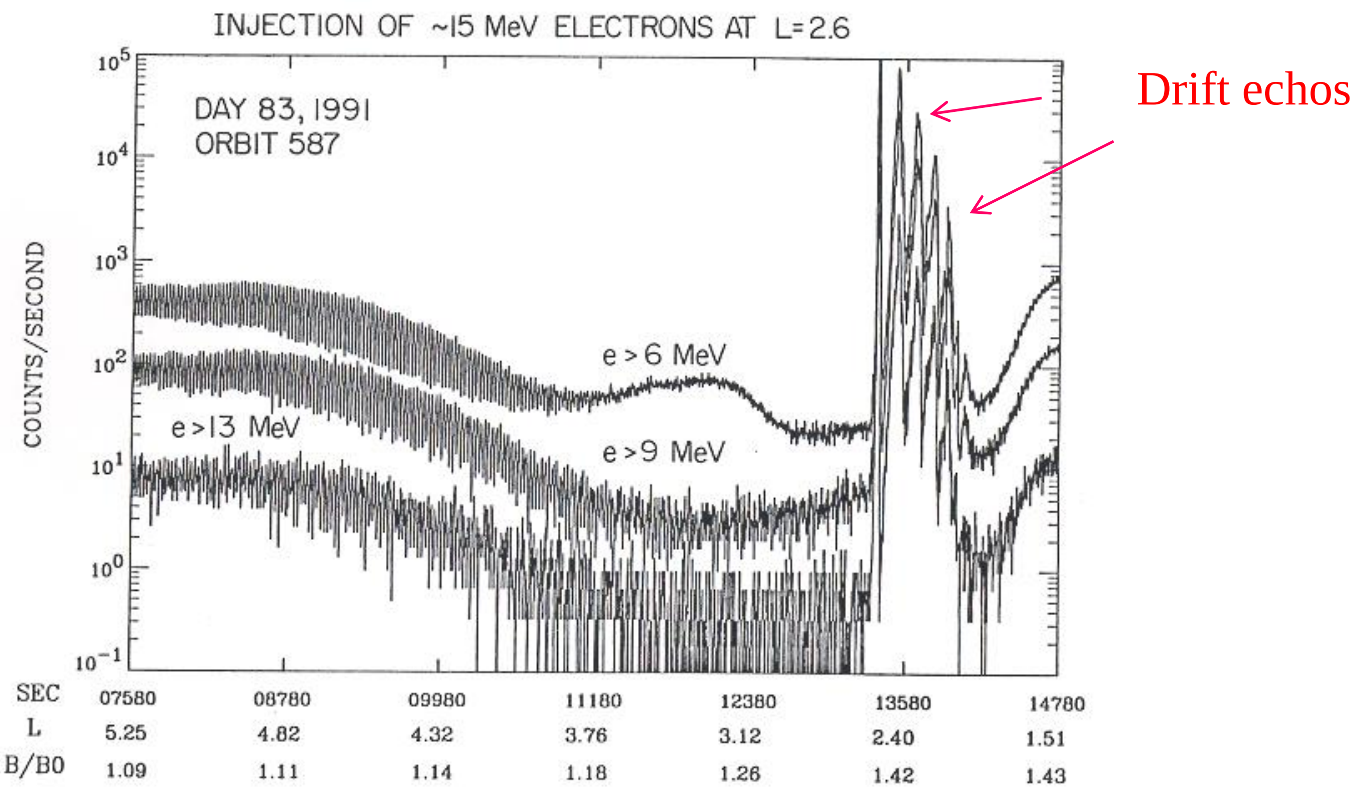
3) Field-aligned current generation.

Are double layers and monoenergetic electrons produced on the dayside during these events? If so this would be a 4^{th} mechanism.

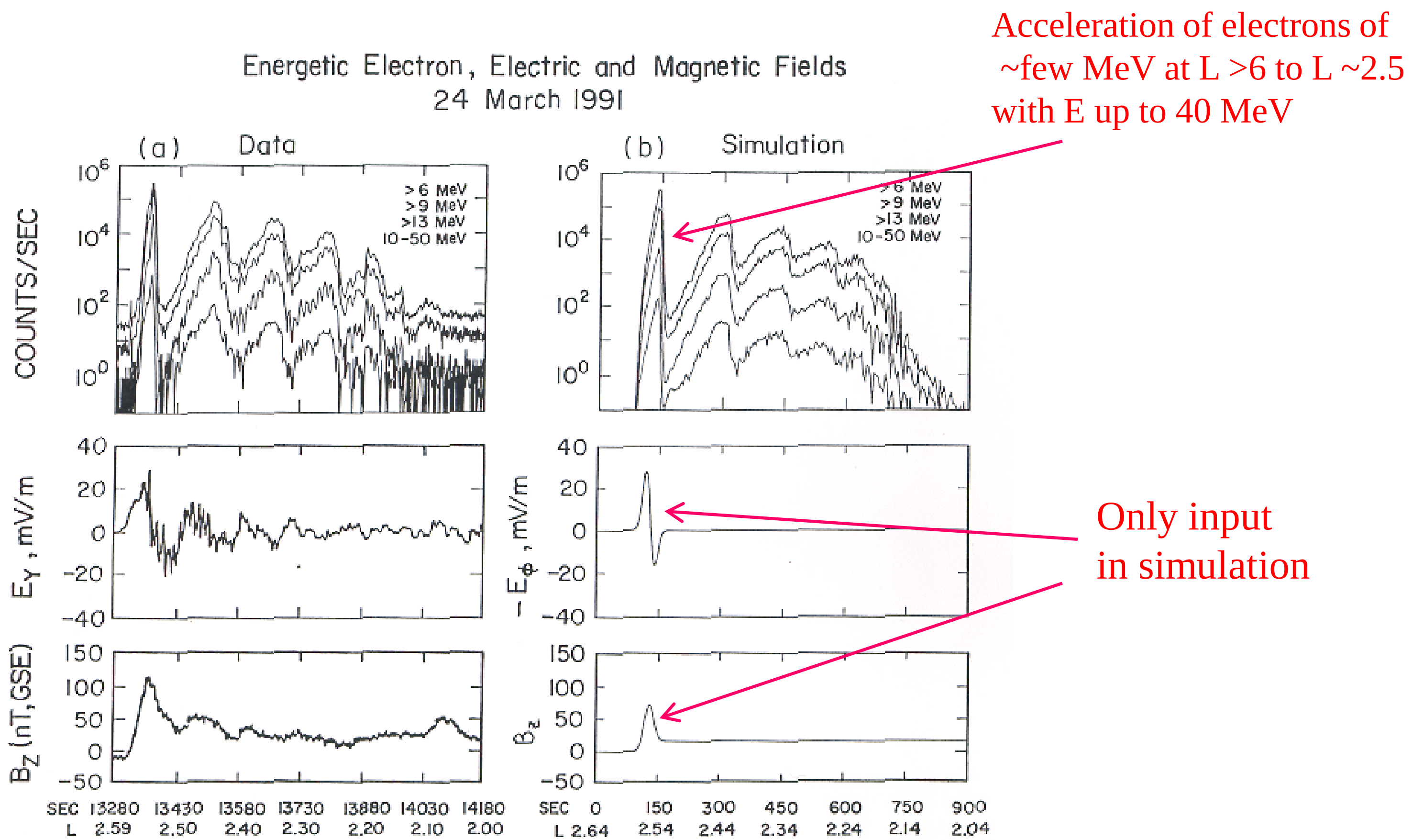
What are the relative energy inputs for the 4 above mechanisms?

Can ICON, GOLD and SWARM answer these questions?

Shock formation of a new radiation belt



Blake et al. 1992

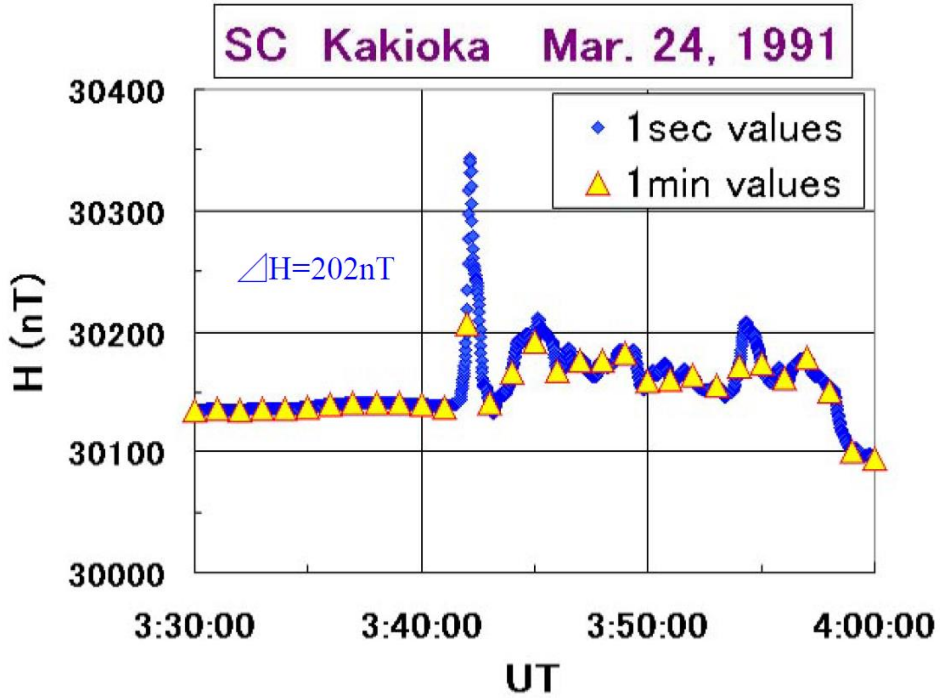


Li et al. 2003

The process conserves the first adiabatic invariant

What happens to the flux and spectra with larger shock events? How much larger can the magnetospheric electric field caused by the shock get?

The Second Largest SI^+ in Recorded History: Note Importance of 1s Data



T. Araki, 2012

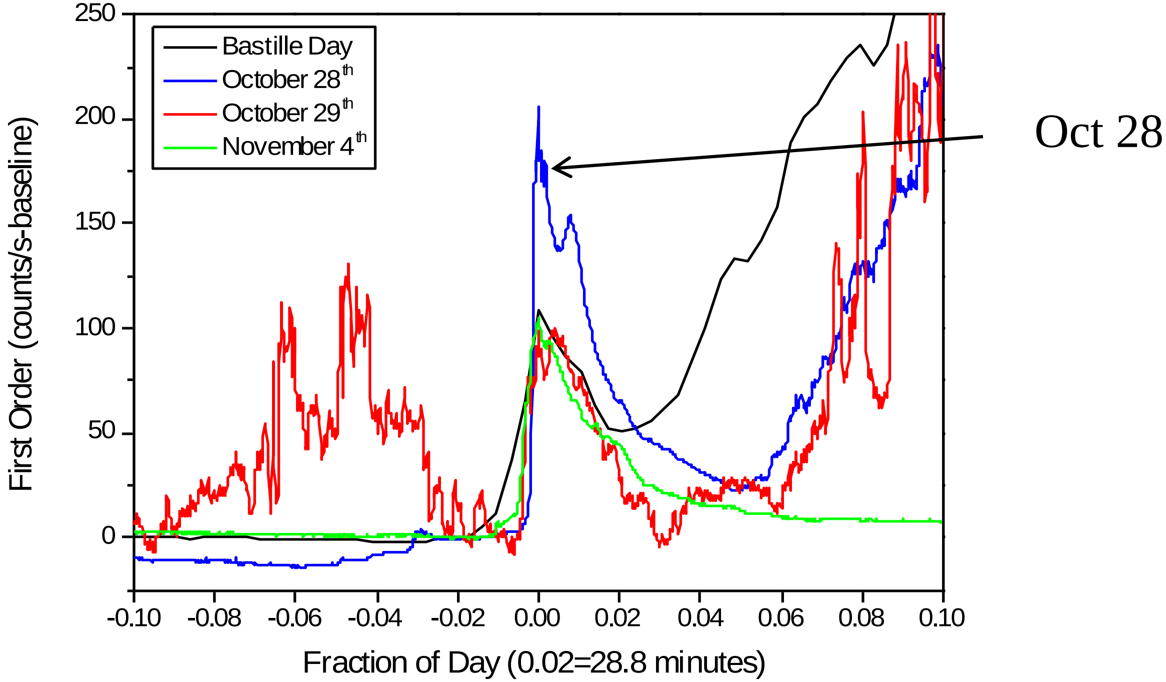
ΔP_R = MsNVs2 – $M_0 N V_0^2$

Unfortunately SW data not available. If V_{sw} jumps from 400 km/s to 1600 km/s, $\Delta P_R / P_R$ = 63 X!

Solar Flare Photons

Severe ionospheric disturbances

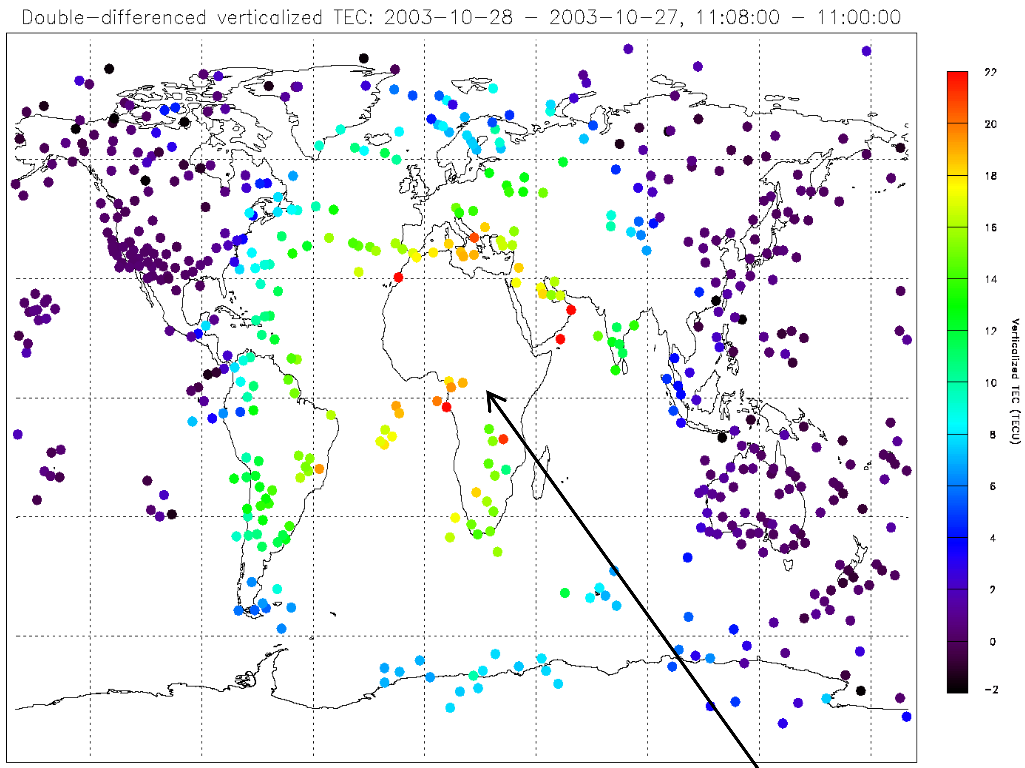
The Largest Solar EUV Flare in Recorded History: 28 October, 2003 (SOHO SEM 26-34 nm EUV)



Tsurutani et al., 2005

The November 4 flare was X-28, the largest in NOAA recorded history. In EUV flux the October 28 flare was larger by a factor of two. Is it possible that Oct 28 is the largest in X-rays as well? Thomson et al. (2004) have derived a value of X45.

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



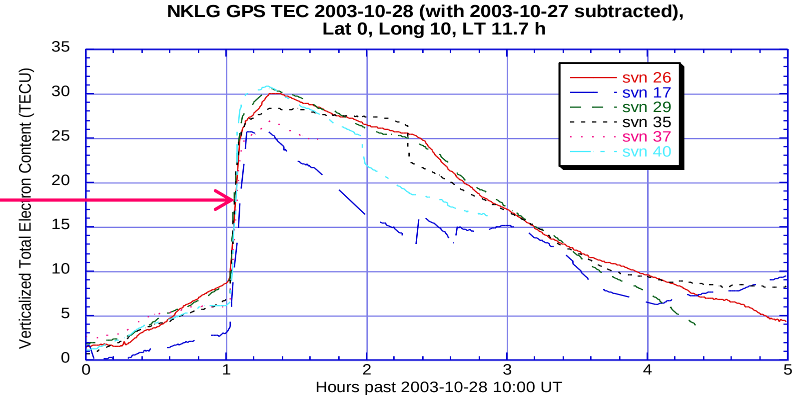
GRL 2005

Subsolar point

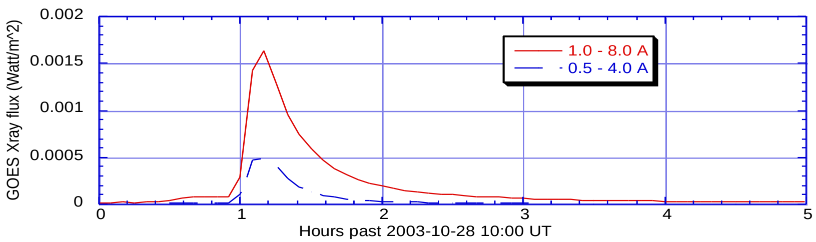
GPS is a relatively new technique for ionospheric physics. Ground based receiver networks and satellite constellations (COSMIC 1 and 2) can be used to help data analysis

Oct 28, 2003

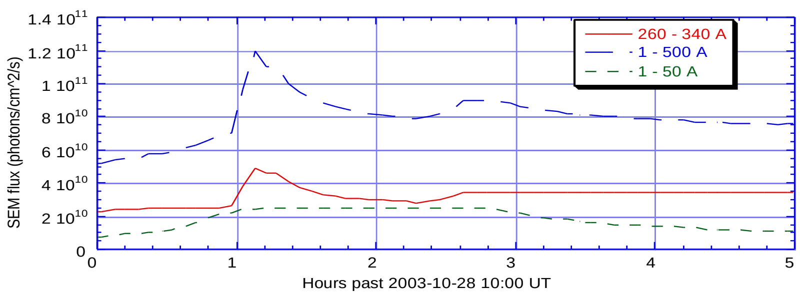
30% TEC jump



African ground station



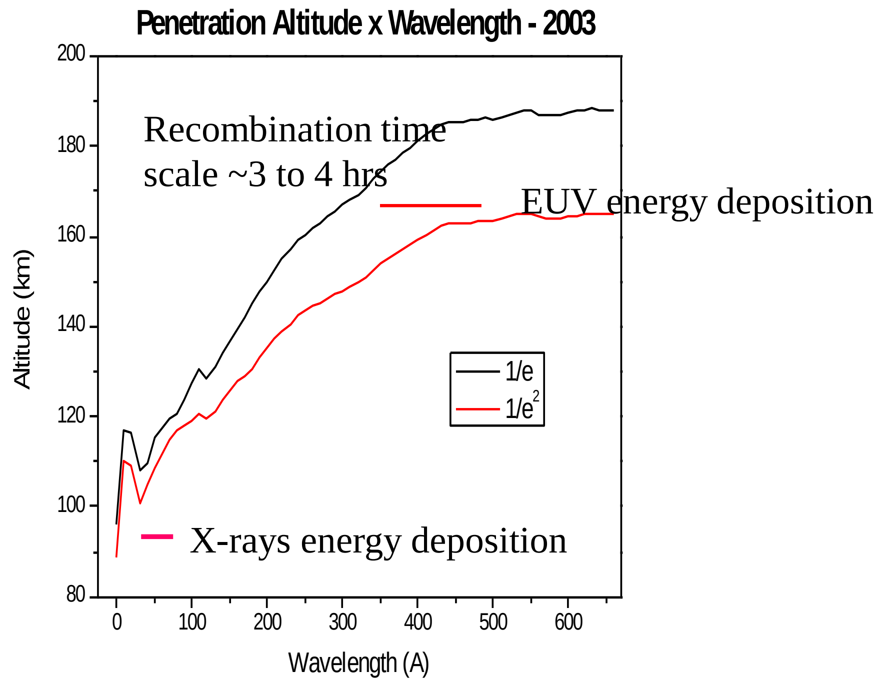
GOES X-rays



SOHO SEM EUV

Why does the ionospheric TEC effect last so long? What is the upper limit of flare intensities? Are their ionospheric effects different?

Why Does the Ionospheric TEC Last So Long After the Flare is Over?



Recombination time
Scale ~10s of mins

Model atmosphere for
Halloween Day events

Do the X-ray and EUV spectra of solar flares vary and why? Spectral variations will have profound influence on ionospheric effects.

Can GOLD, ICON and SWARM identify the ionization distribution in the dayside F region due to solar flares, giving more detailed information of TEC enhancement durations?

Can this information be used to work backwards and get the flare spectrum?

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

For substorms: Obayashi,1967; Nishida, 1968; Kelley et al. 1979, 2003.
In the last 10 years lots of work done on PPEFs during magnetic storms.

Equatorial Ionospheric Anomalies (EIAs): Normally Located at ± 10°

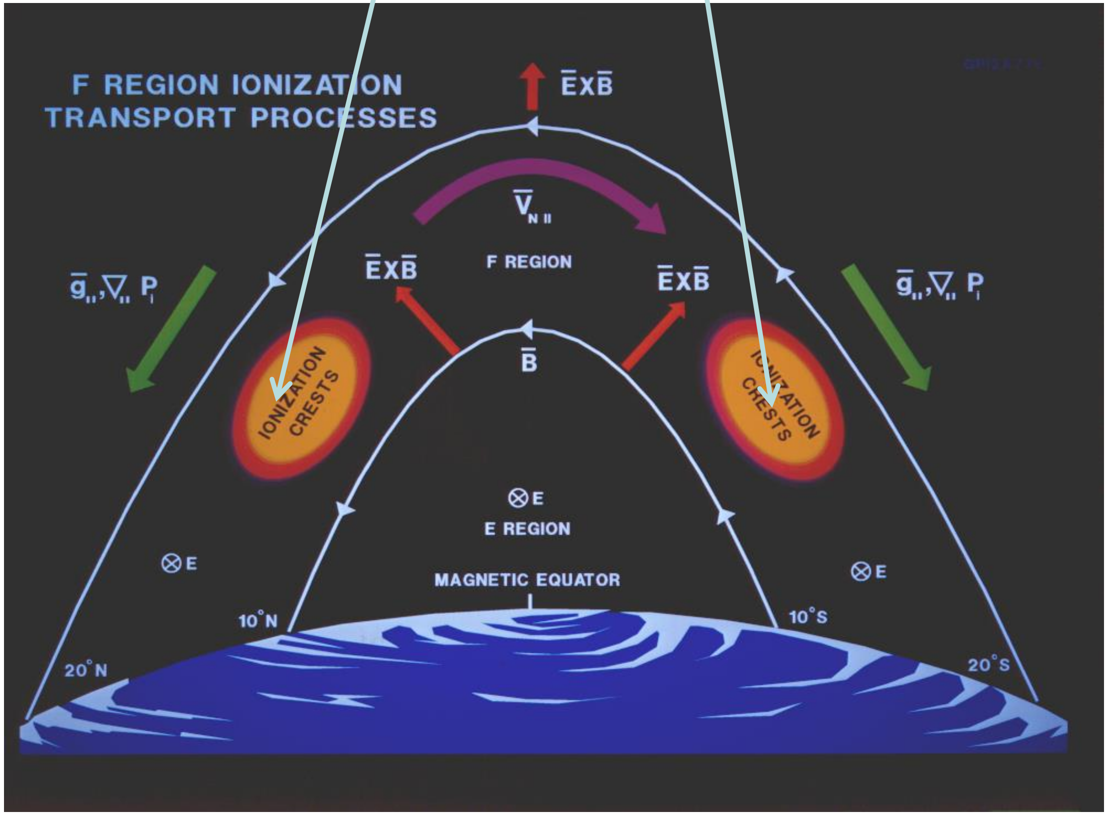
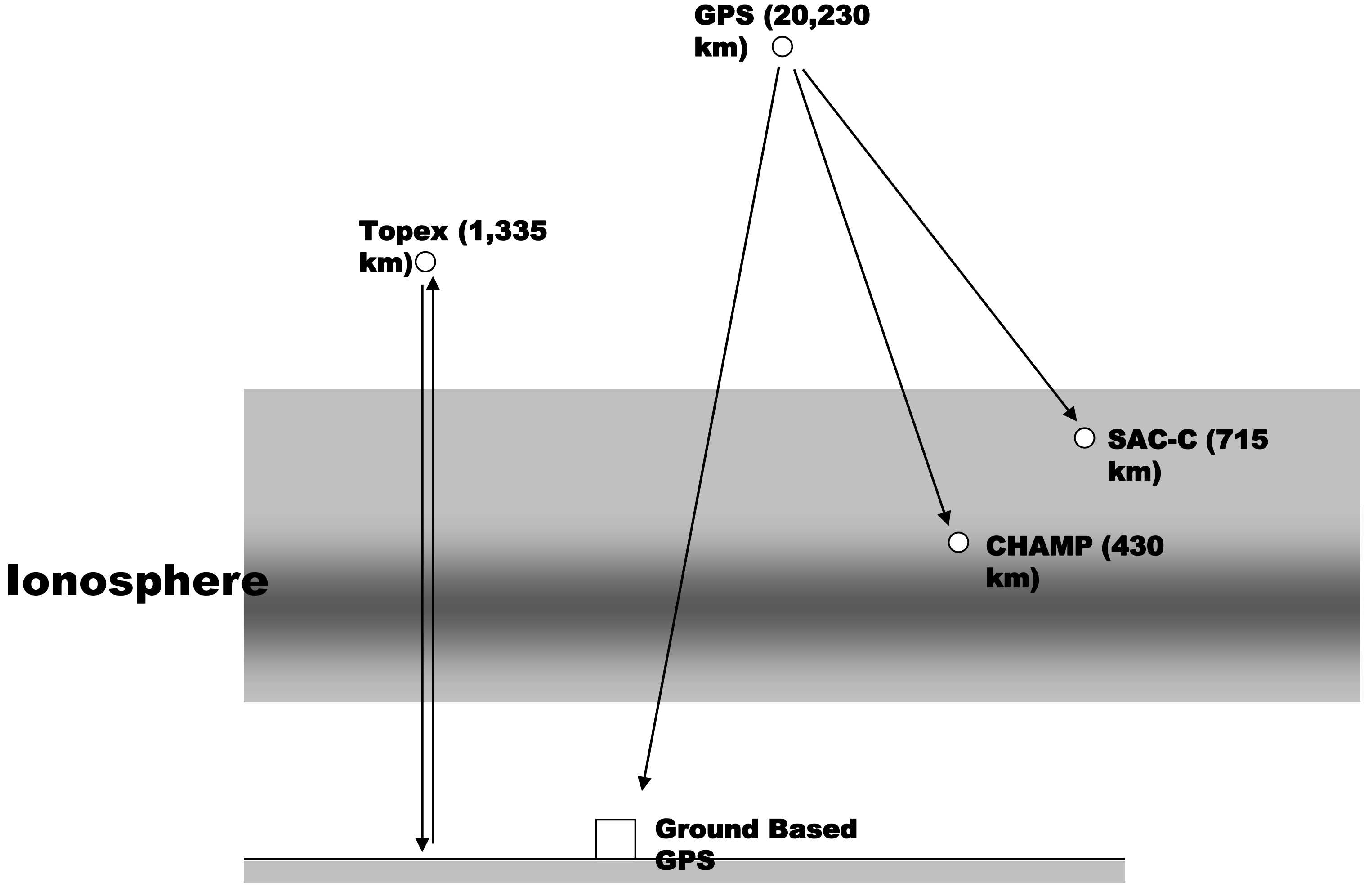


Figure from Anderson et al., 1996

EIAs: Namba and Maeda, 1939, Appleton,1946

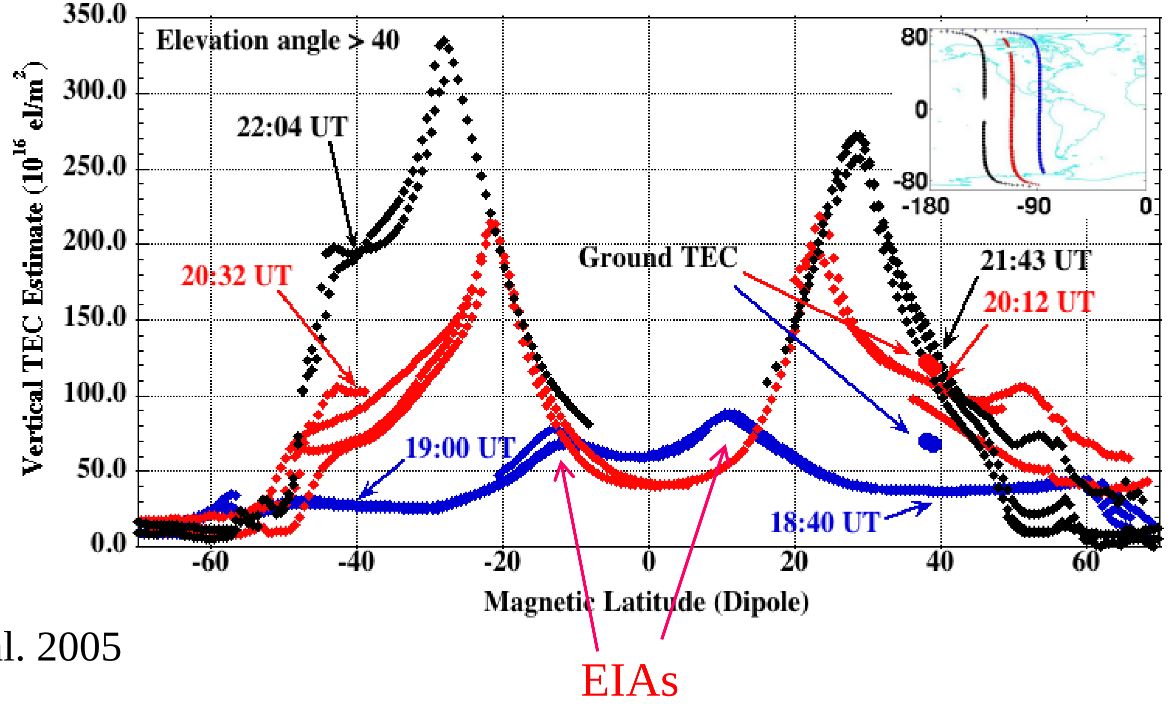
Ground-Based GPS Receivers Can Be Used to Get Ionospheric TEC Along Ray Path



Tsurutani et al. JGR 2004

PPEF Effects on Dayside Ionosphere During Halloween 30 October Superstorm Called "Dayside Superfountain Effect"

CHAMP Altitude: ~430 km)



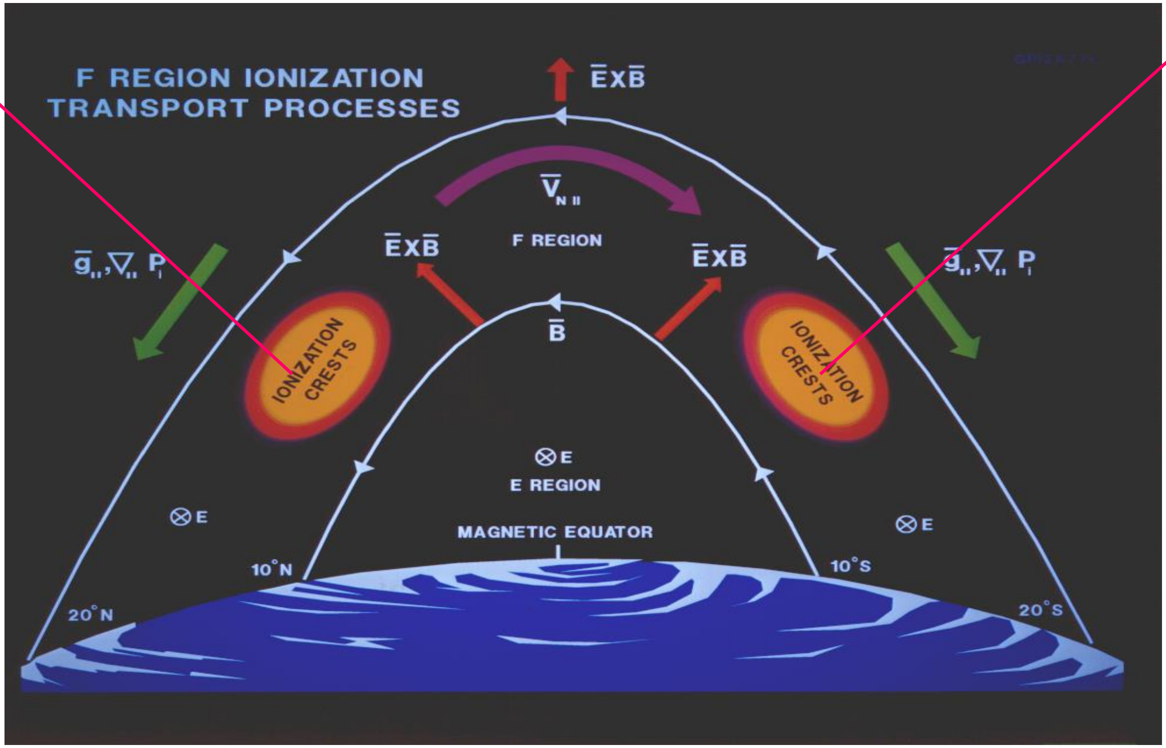
Mannucci et al. 2005

The dayside superfountain effect is present during almost all large magnetic storms.
However the magnitude of the effect varies. Why?

Mechanism for Uplift and Higher Latitudes of EIAs

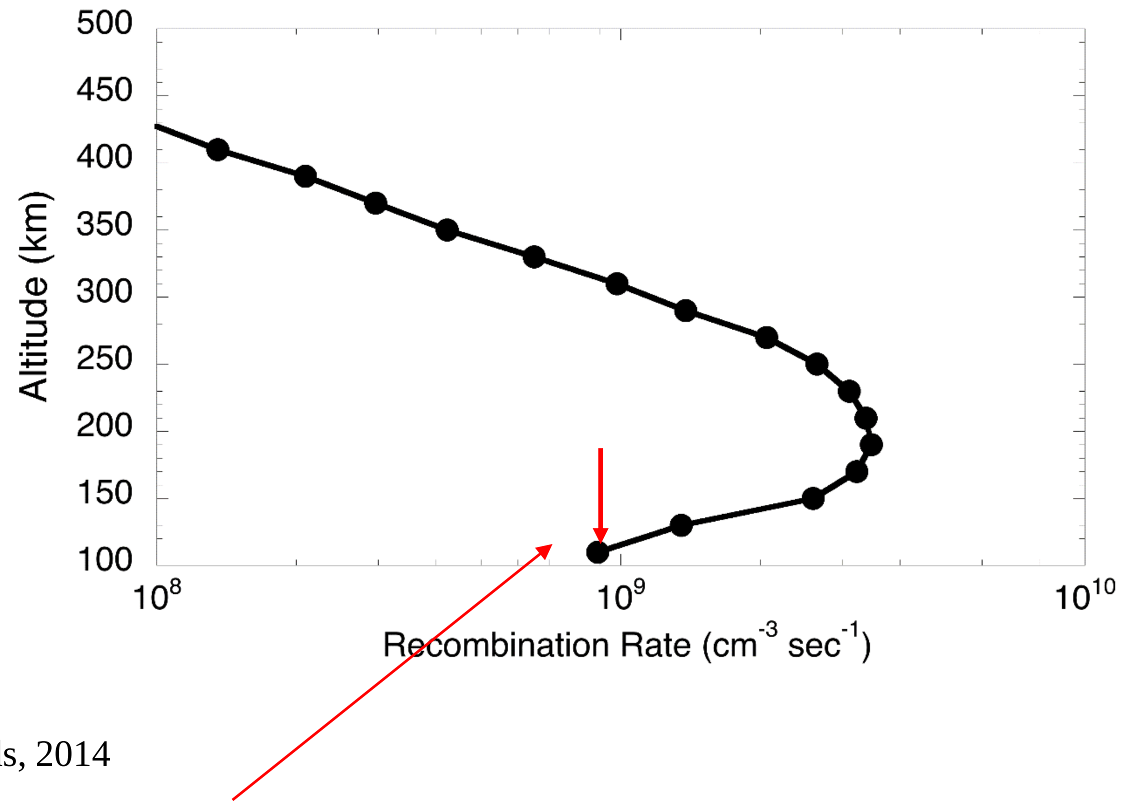
E x B

E x B



Although the PPEF lifts the F-Region ionosphere upward and to higher latitudes, why does TEC increase?

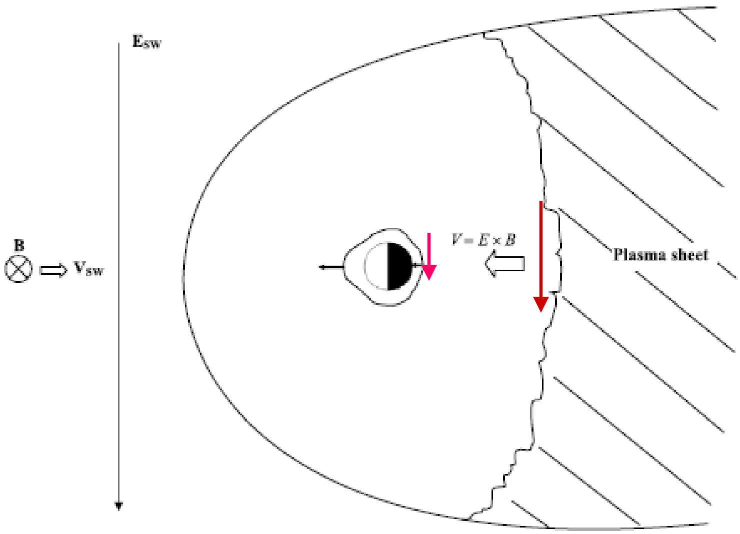
The Answer is that When The Ionospheric Plasma is at High Altitudes The Recombination Time is Longer, Thus the Plasma is Stable



Richards, 2014

Solar photoionization creates a new ionosphere at lower altitudes

PPEFs Have Global Consequences



Tsurutani et al. 2003, 2008; Mannucci et al. 2005, 2008

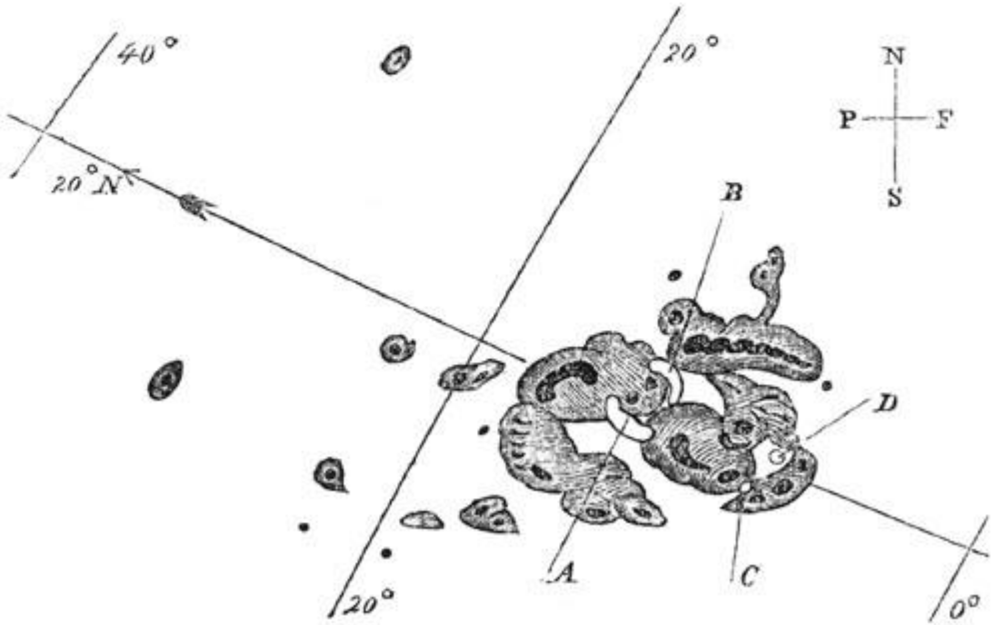
PPEFs Cause the Dayside Superfountain effect. There is nightside ionospheric suppression as well (due to downward convection and recombination).

This simple schematic divides day and night. What is the variation of the PPEF magnitude with LT? Again, ICON, GOLD and SWARM could be used to answer this question.

The September 1-2, 1859 Carrington Superstorm:

Ionospheric Effects

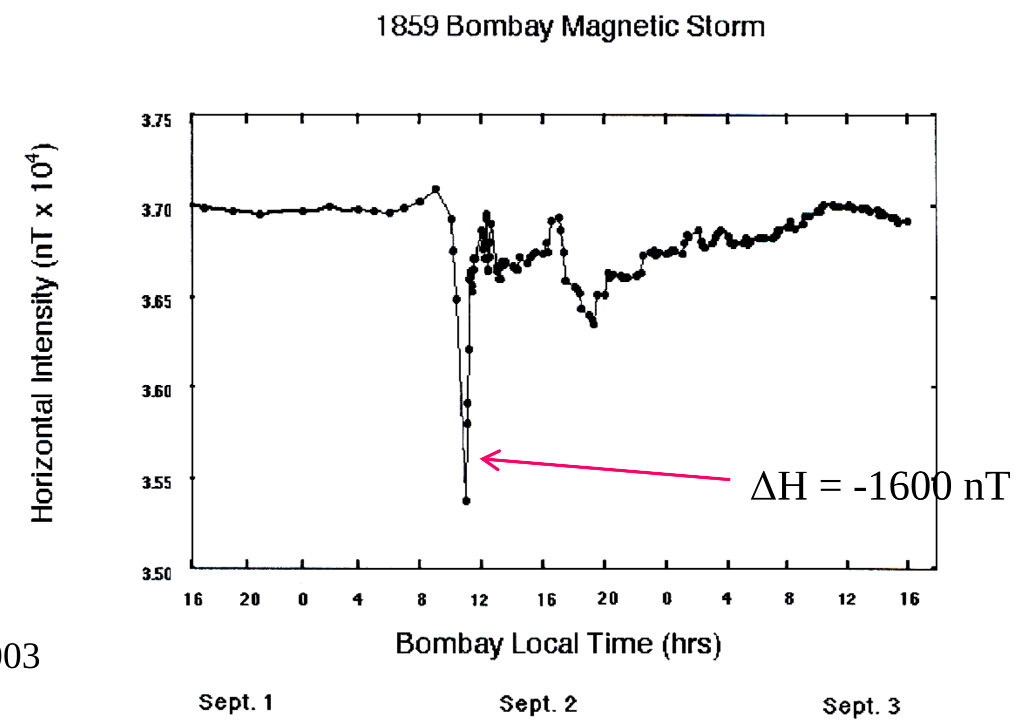
The R. Carrington Hand-Drawing of the Solar Active Region (AR) during the Carrington Optical Flare Event of Sept 1, 1859



Carrington, 1859

The AR caused multiple flaring over a week duration

The Carrington Magnetic Storm of 1-2 September 1859



Tsurutani et al 2003

This is the biggest magnetic storm in recorded history.

How much larger can magnetic storms become? Partially answered in Tsurutani and Lakhina, 2014.
Why is the recovery phase of such short duration? A possible answer is provided in Tsurutani et al. 2018.

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:**

[illegible]

Where and are radial distance and azimuthal angle measured counterclockwise from solar direction (M – dipole moment - particle charge and magnetic moment)

Derived a: Dst ~ -1760 nT and a E_{mag} ~ 20 mV/m

What Was The Dayside Superfountain Effect During The Carrington Storm?

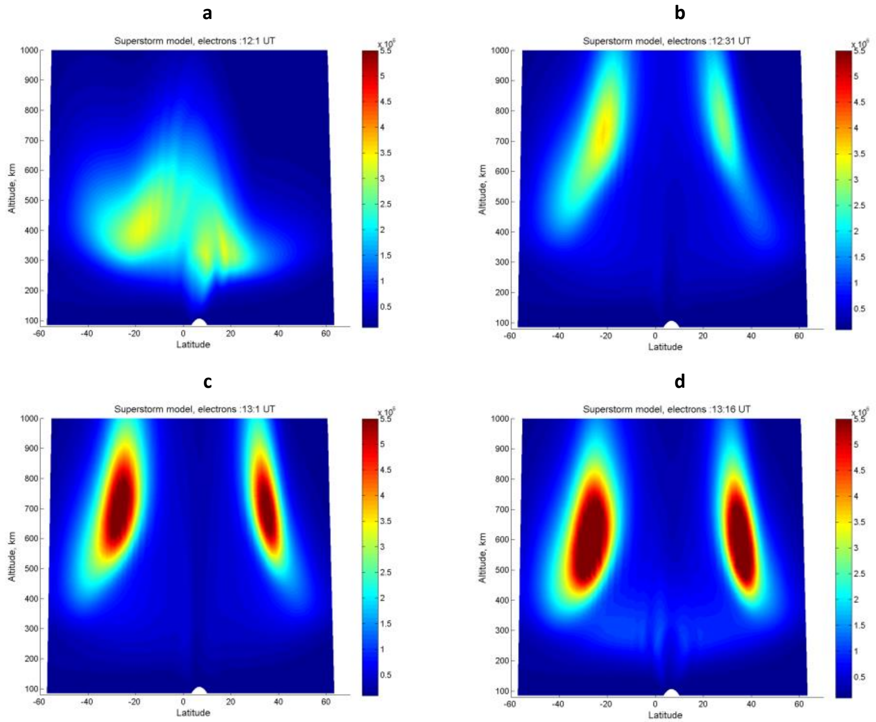
Huba et al. 2002 SAMI-2 code

Quiet

30 min after
PPEF applied

1 hr after
PPEF applied

15 min after
PPEF terminated



Tsurutani et al. 2012

Although the Daytime Superfountain Effect will convect oxygen ions up to satellite altitudes, what about neutrals (through ion-neutral collisions)? This problem has not been solved yet. Gravity waves will be launched by this process.

At altitudes of ~700 to 1000 km the O^+ densities will be 300 X quiet-time neutral densities.

These much higher densities will increase drag substantially for LEO satellites.

But again, how much will neutral densities increase? What will the total ion plus neutral densities become? GOLD, ICON, SWARM

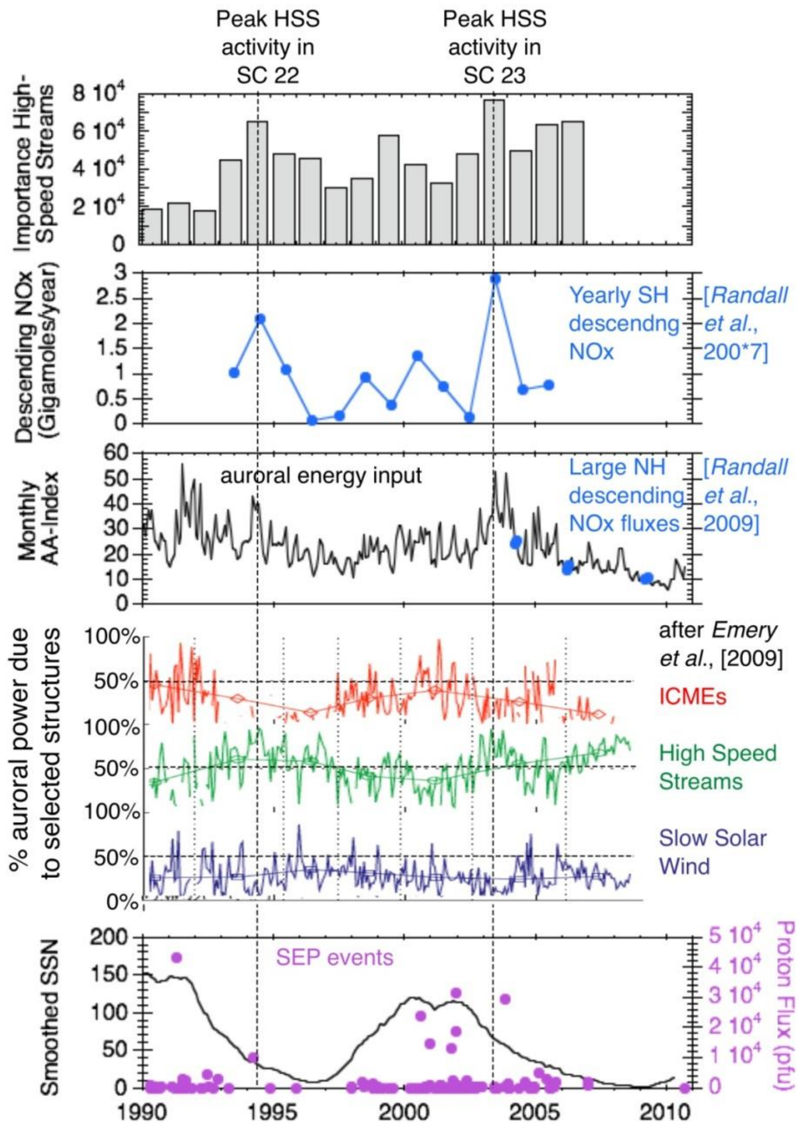
HILDCAA ~10-100 keV Electron Precipitation Effects

HSS peaks
In SC22 and 23

Peaks in NOx
descent

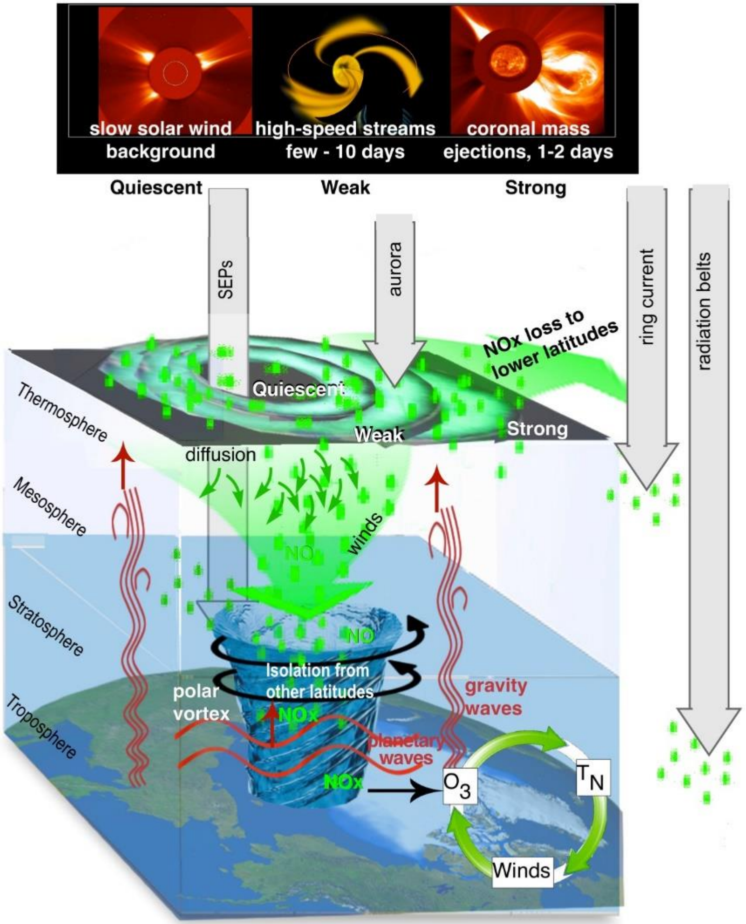
Peaks in auroral
energy input

Declining phase
of SCs



Kozyra et al., 2012

Polar Cap Ozone Destruction

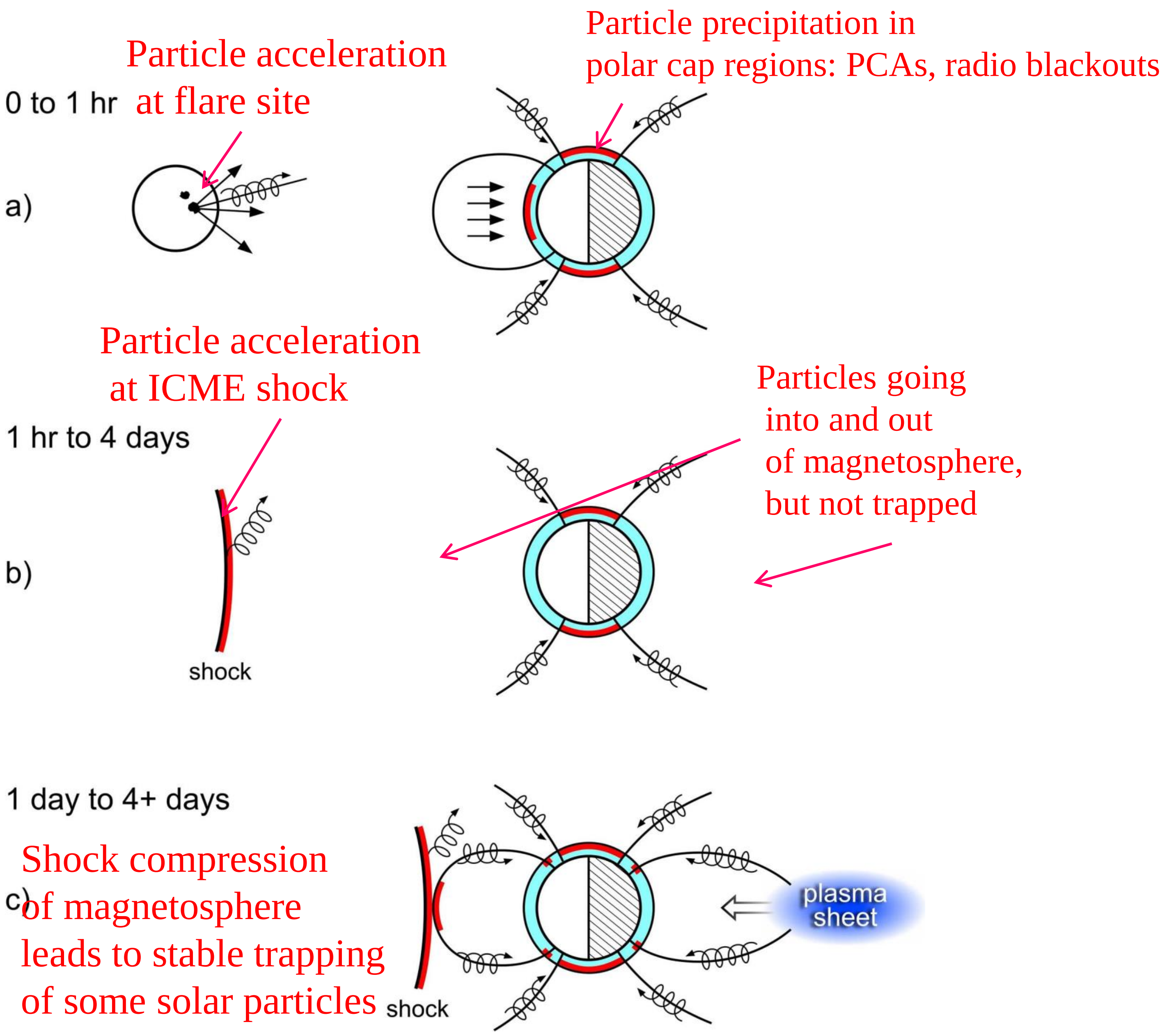


Kozyra et al. 2015

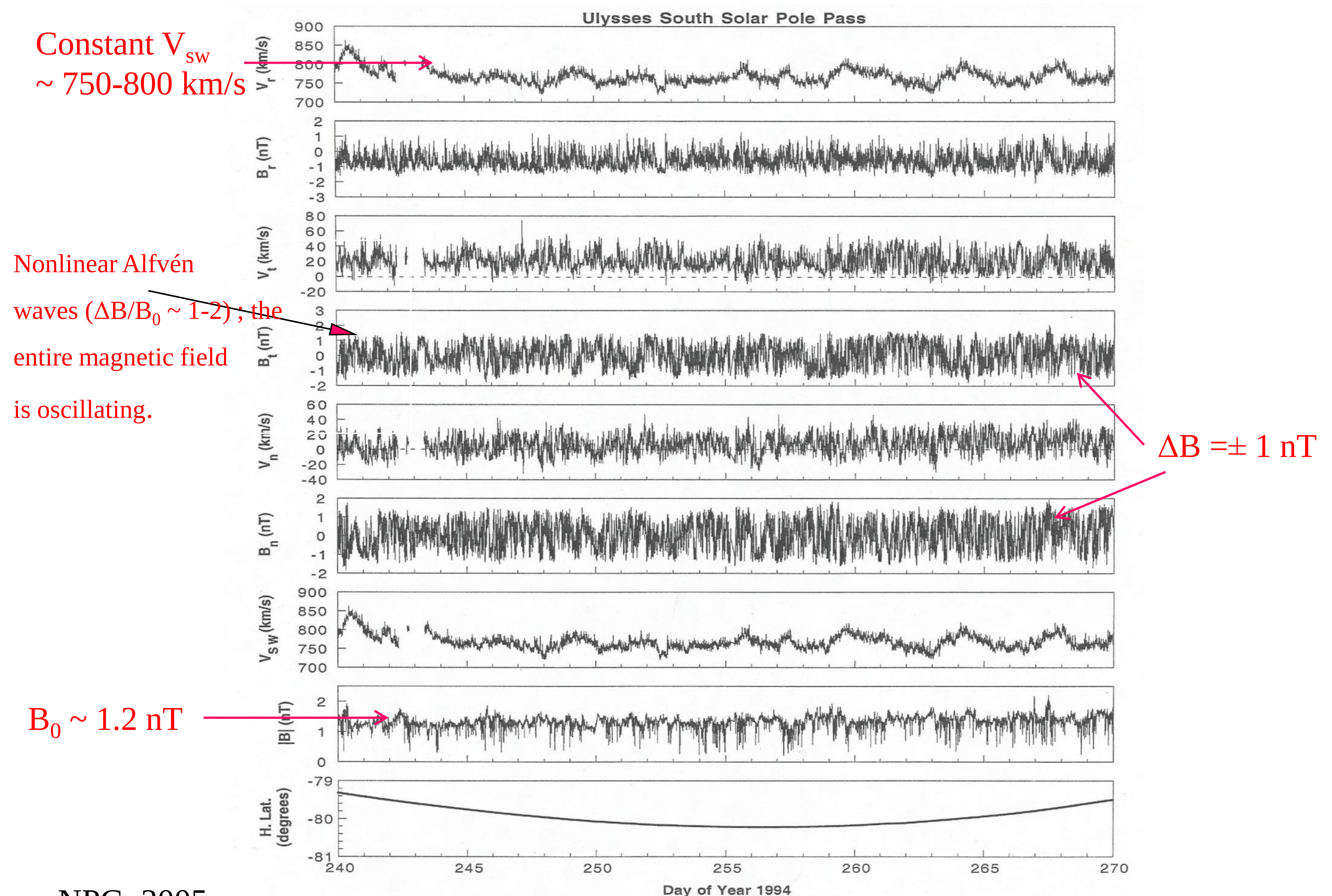
If the NOx is entrained in a polar vortex, the molecules will diffuse in altitude downward with the destruction of ozone months later.

Thank You for Your Attention

bruce.tsurutani@jpl.nasa.gov

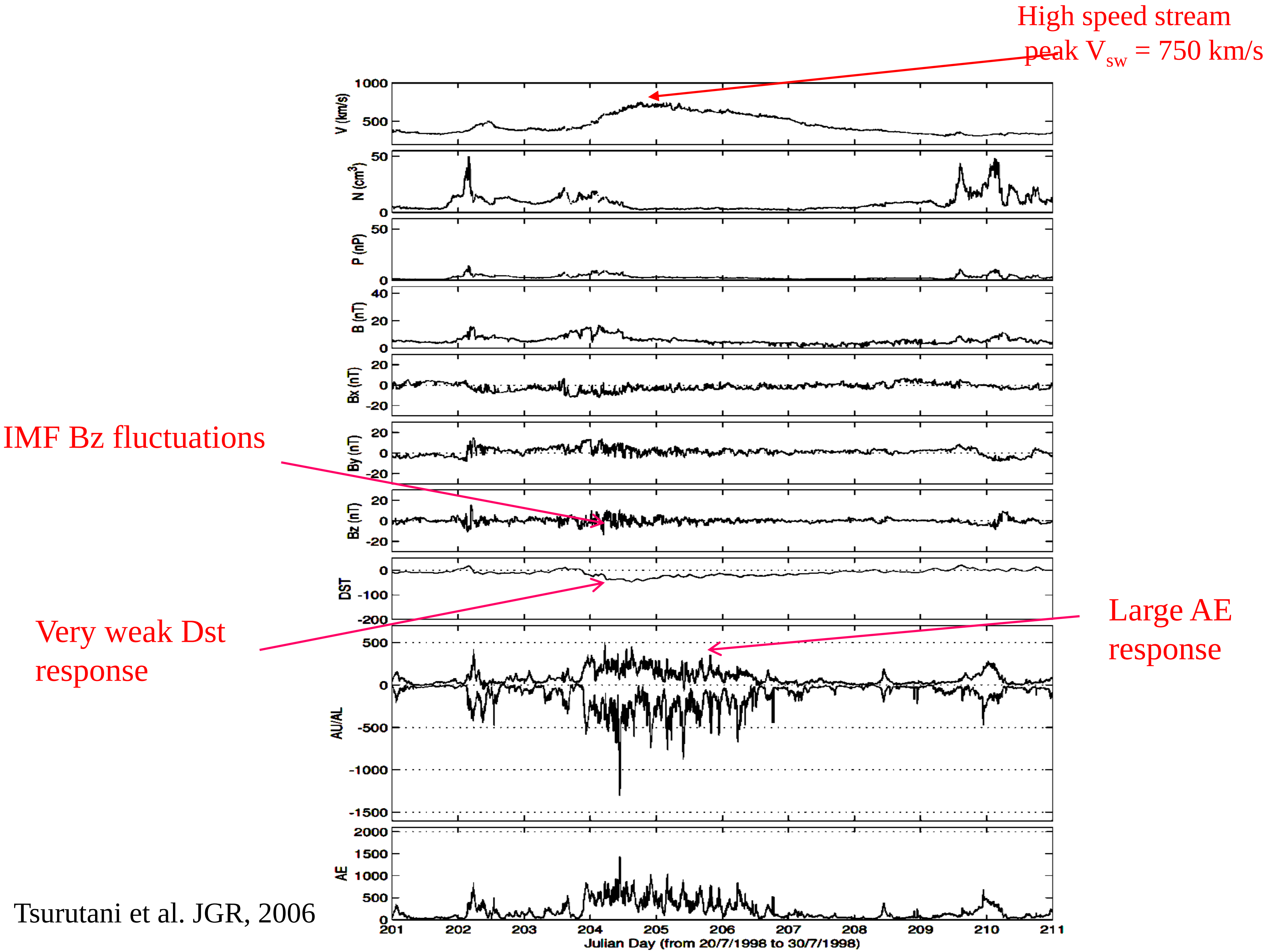


Tsurutani et al. RS 2008



Ulysses South Solar Pole Pass
Constant V_{sw}
~ 750-800 km/s
Nonlinear Alfvén waves ($\Delta B/B_0$ ~ 1-2) ; the entire magnetic field is oscillating.
$\Delta B = \pm$ 1 nT
B_0 ~ 1.2 nT
V_r (km/s)
B_r (nT)
V_t (km/s)
B_t (nT)
V_n (km/s)
B_n (nT)
V_{SW} (km/s)
|B| (nT)
H. Lat. (degrees)
Day of Year 1994

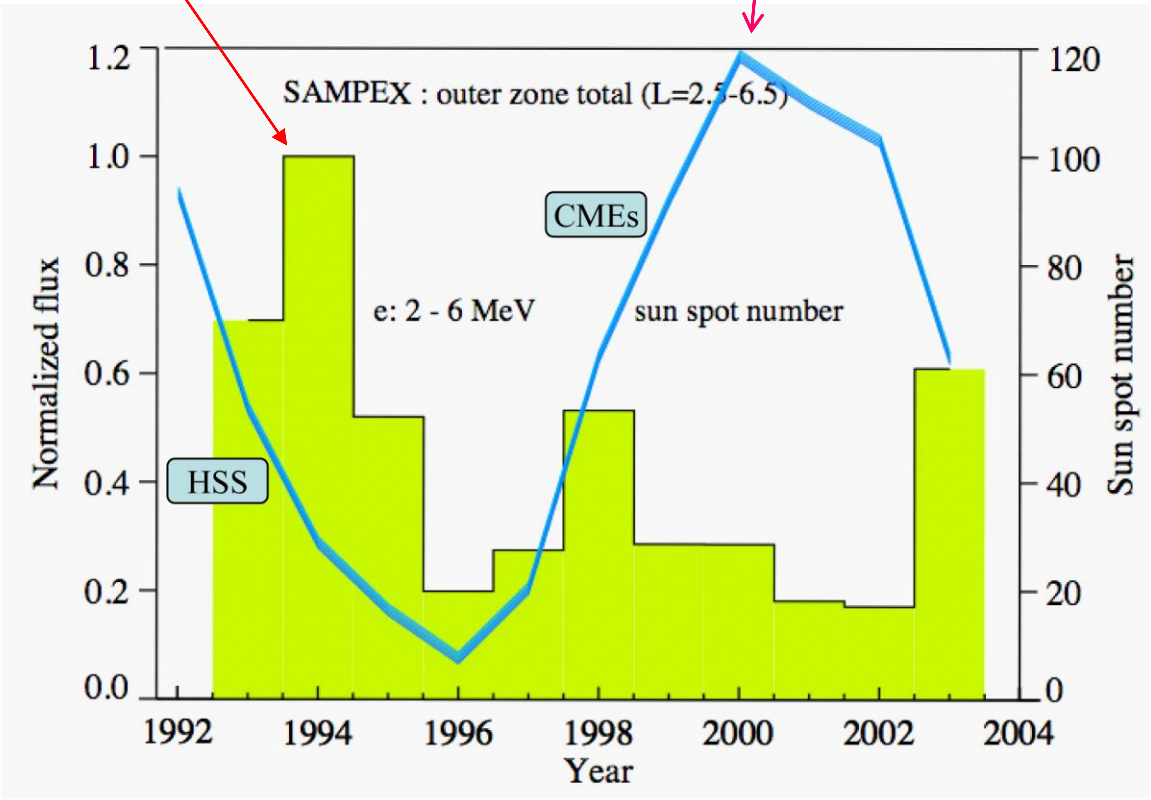
NPG, 2005



Tsurutani et al. JGR, 2006

2-6 MeV electron peak occurrence occurs in solar cycle declining phase when HSSs dominate

Low 2-6 MeV electron flux



D. Baker, 2006

Scenario: 1) ~30 keV electrons injected by B_s of interplanetary Alfvén waves, 2) chorus generated by anisotropic electrons, 3) ~2.5 MeV relativistic electrons accelerated by chorus

Electrons

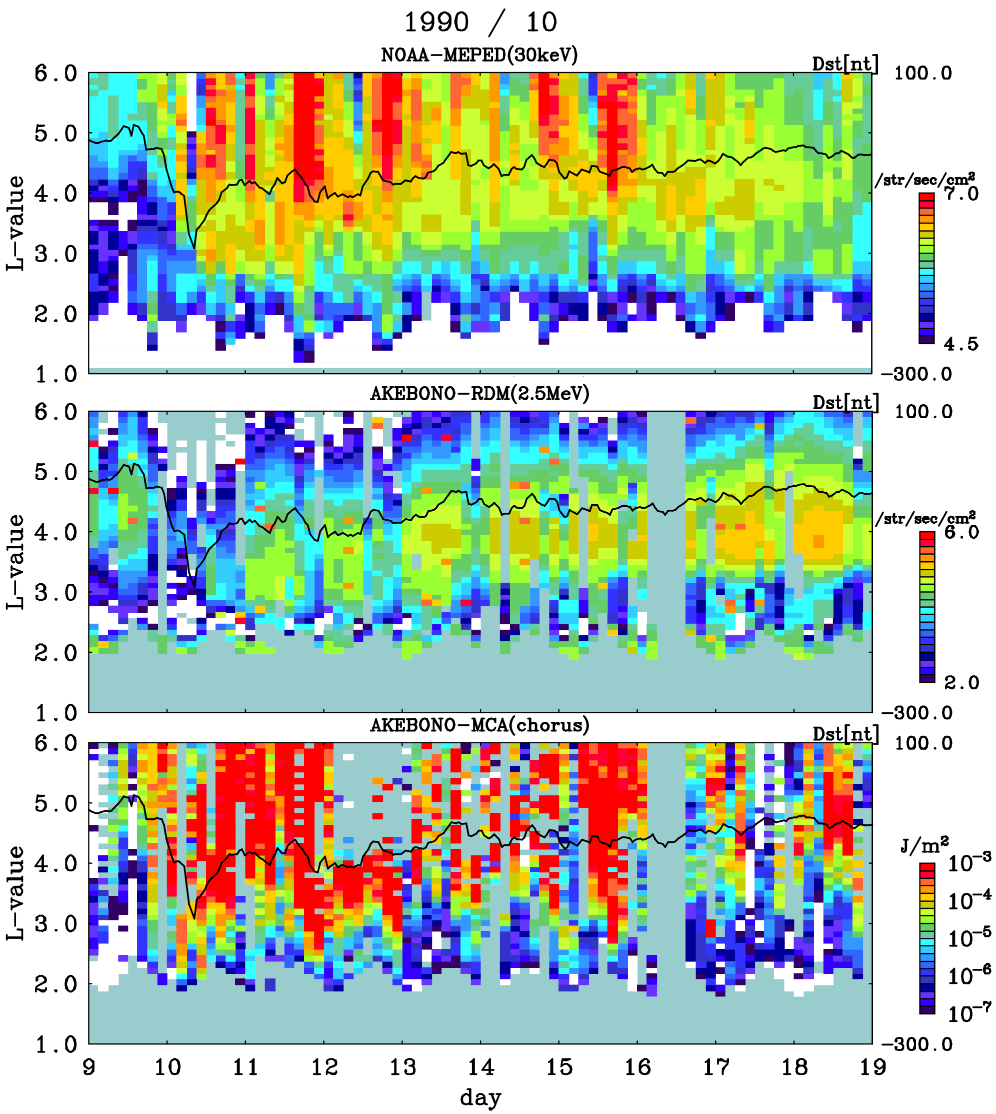
(30keV)

Electrons

(2.5Mev)

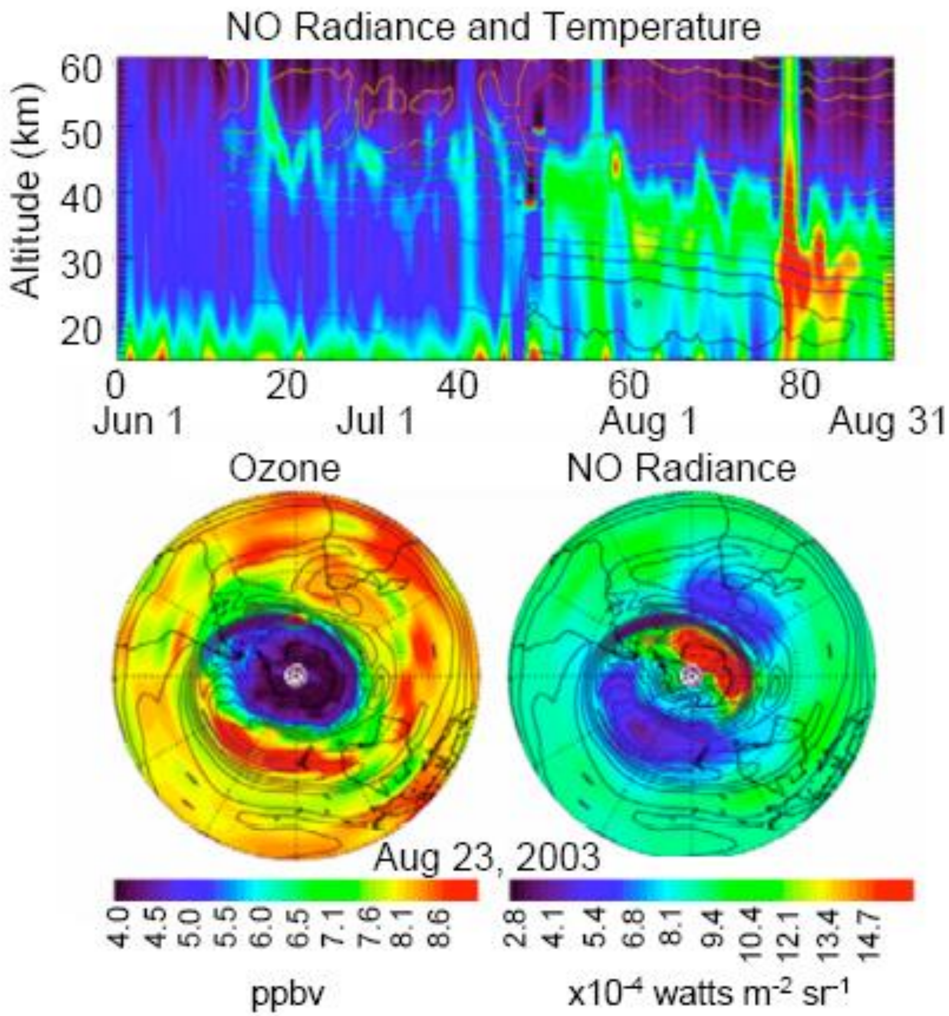
VLF wave

(1-10kHz)



Kasahara et al., 2006

~ 9 day event



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

Kozyra et al., AGU, 2006

~7 and 9 day periodicities in Vsw, Kp and atmospheric density (at CHAMP altitudes—400 km)

Solar wind speed

Kp

Thermospheric density

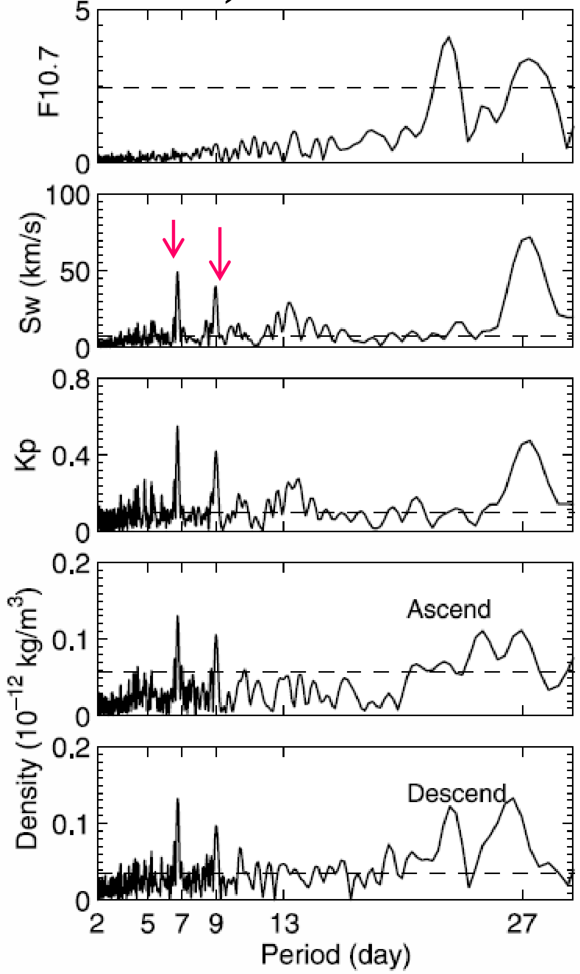
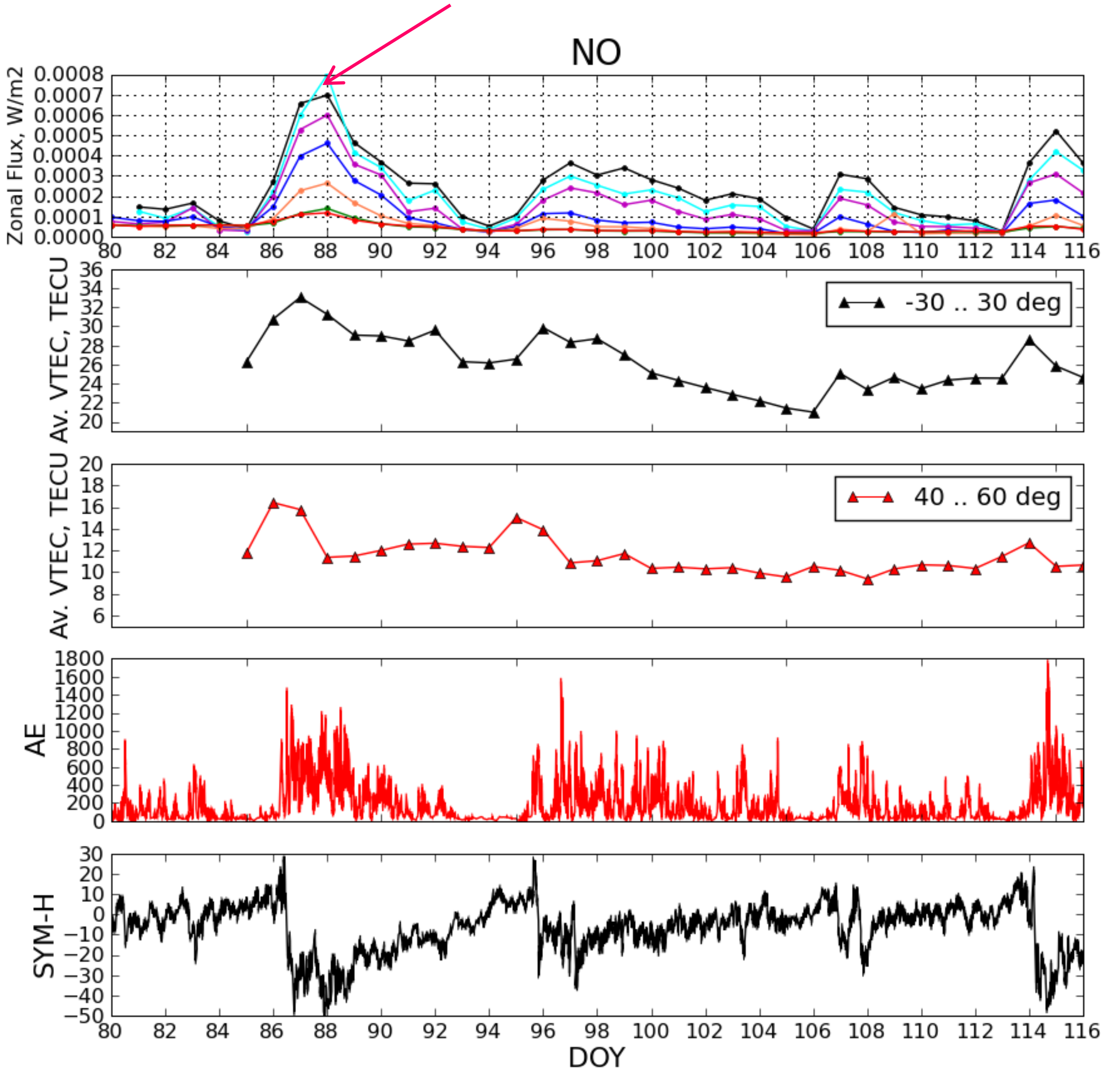


Figure 2. Lomb-Scargle spectral amplitudes of the time series shown in Figure 1. The dashed lines denote the 95% significance level.

~ ±20-30% effect

Thayer et al, JGR 2008; Lei et al GRL 2008

Radiation highest in auroral zone



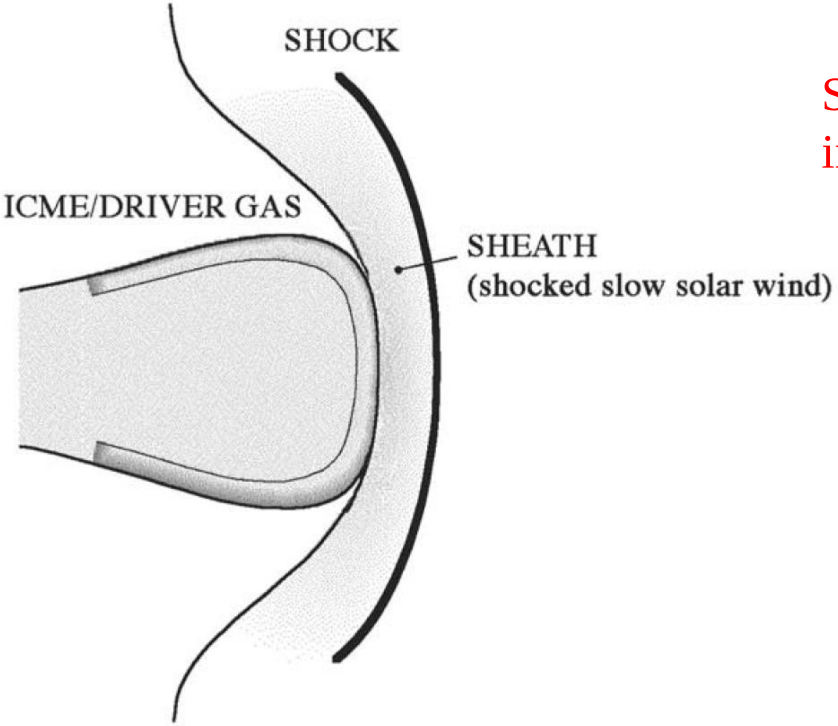
Irradiated
Zonal flux

TEC, low latitudes
(12-14 LT). Enhancements
caused by PPEFs or with
disturbance dynamos?

TEC, mid latitudes
(12-14 LT)

Verkhoglyadova et al. JGR 2011

Fast ICMEs Will Create An Upstream Shock and Sheath

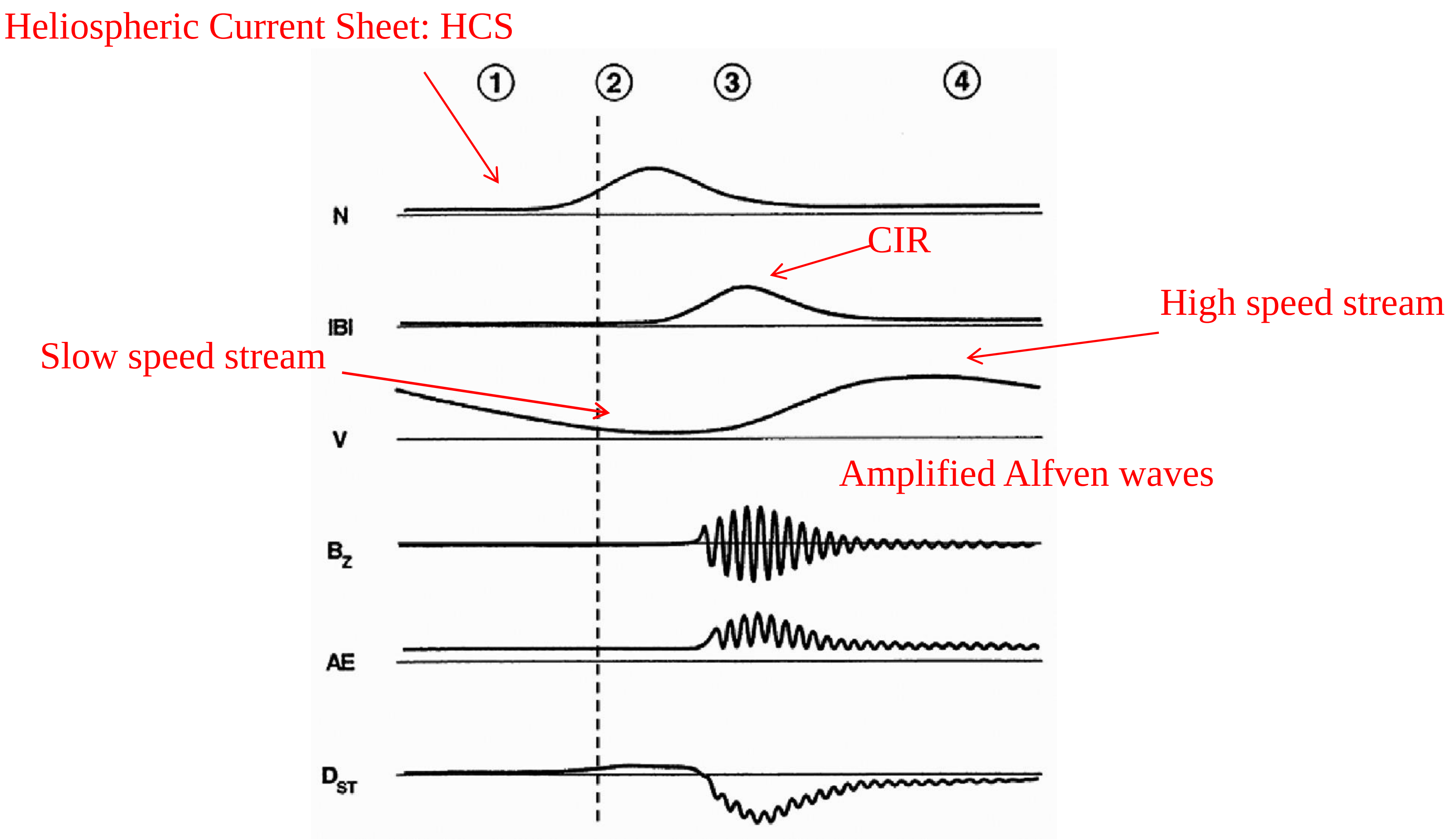


Sheaths are another region of intense interplanetary magnetic fields

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

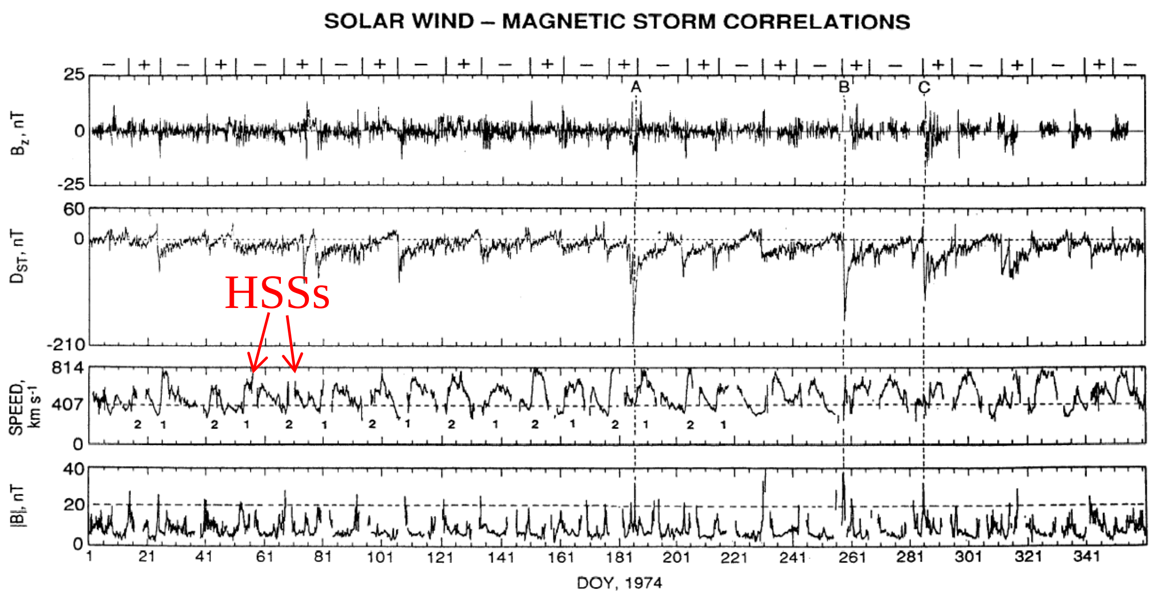
If both the MC and sheath fields are southward, a double storm occurs at Earth. However the storms will have different properties.

A Schematic of Interplanetary Phenomena and Geomagnetic Activity



Tsurutani et al., 1995, 2006

Two High Speed Streams (HSSs) Per Solar Rotation during 1973-5

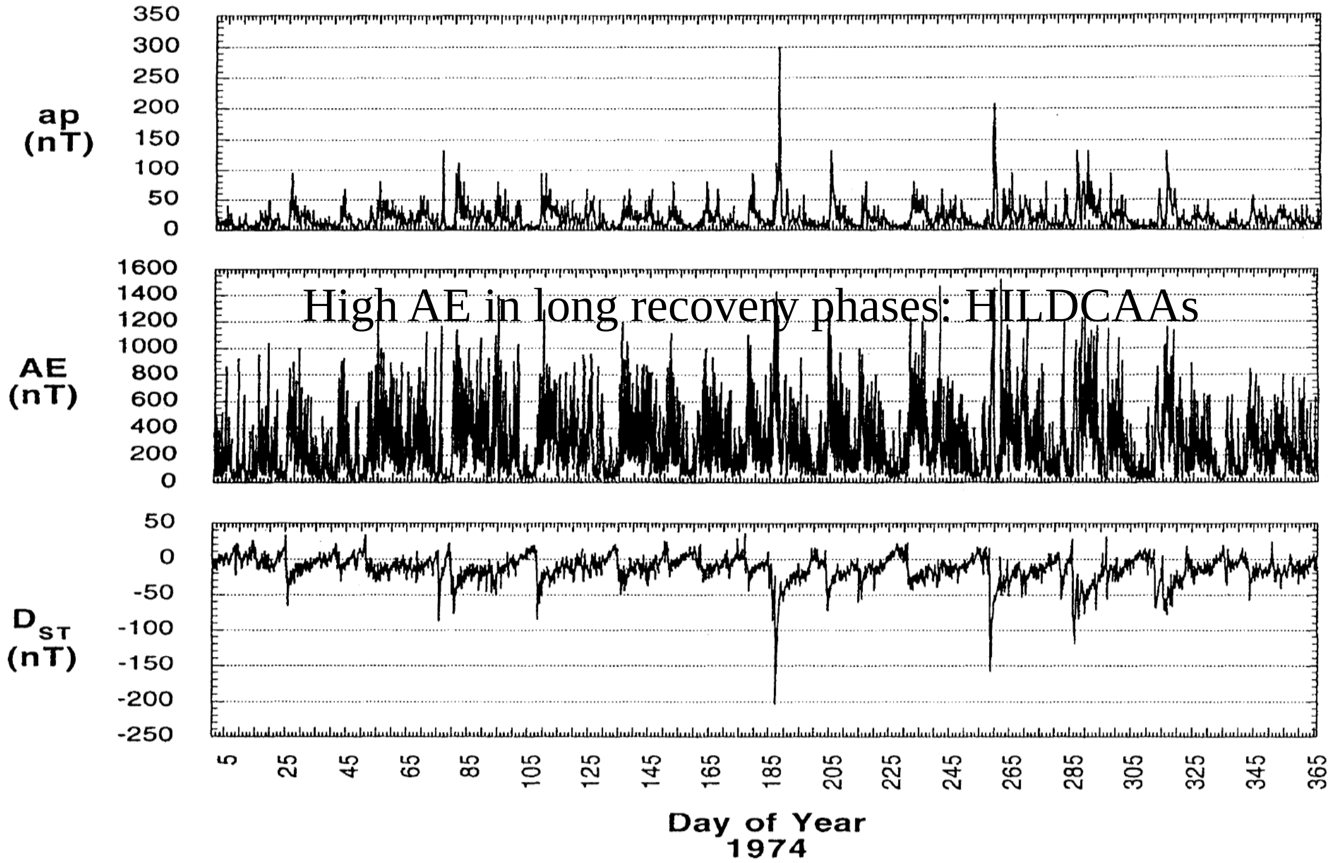


Tsurutani et al. 1995

In this extreme case the two HSSs came from the northern and southern polar cap coronal holes (CHs).

The related geomagnetivity does not seem to depend on the location of the CHs? However see solar minimum (discussed later)

HILDCAAs During An Exception Period: 1973-1975

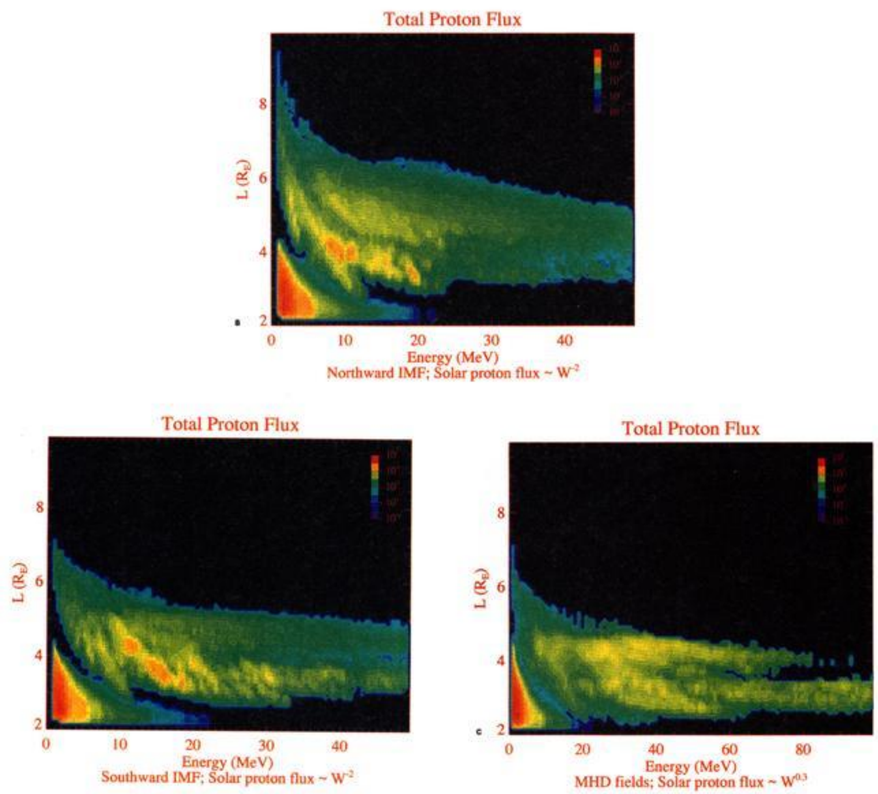


Because of HILDCAAs created by Alfvén waves present in HSSs, the overall energy input into the magnetosphere is higher during the declining phase than during solar maximum

ICME Shock Magnetospheric Particle Acceleration

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

Modeling to Simulate Observations

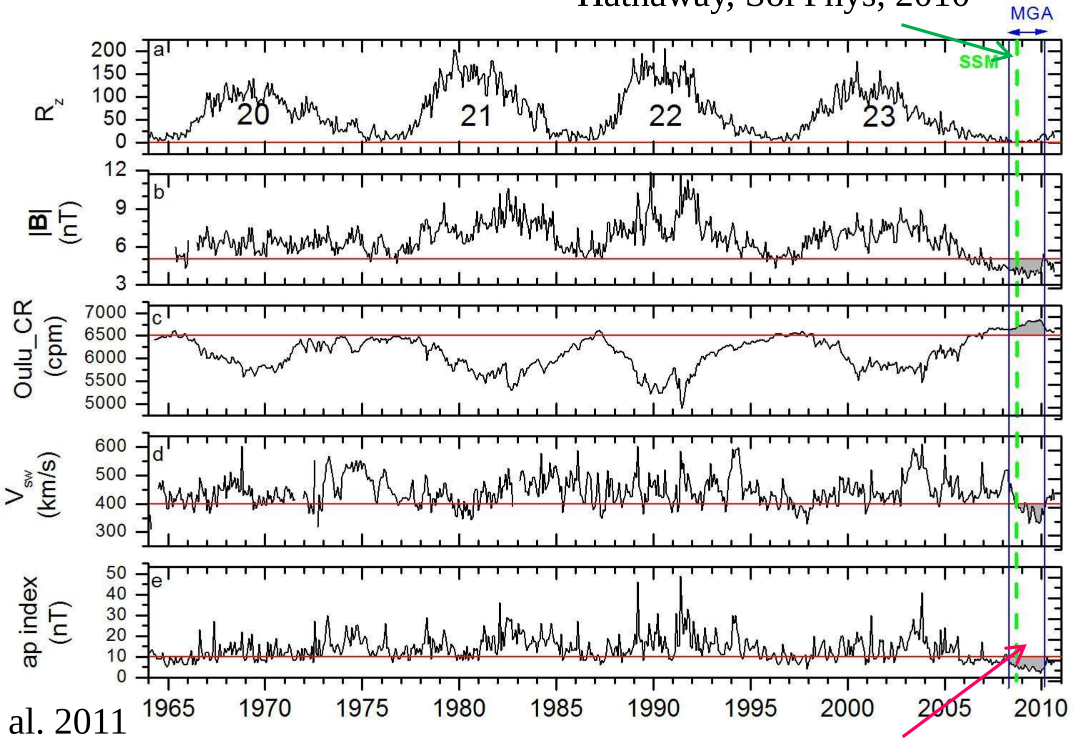


From Hudson et al.,1997. Panel a) northward IMF, b) southward IMF and Vsw = 1000 km/s, c) Southward IMF, Vsw = 1400 km/s and $W^{-0.3}$ solar proton power law weighting.

Solar Minimum: Extreme Geomagnetic Quiet

Although the Official Sunspot Minimum was in 2008, There was an Extremely Low Geomagnetic Activity Ap Index Closer to 2010

Official Sunspot Min: 2008
Hathaway, Sol Phys, 2010



Minimum in Geomagnetic Activity

Low int. Mag. fields

High Oulu CR fluxes

Low V_{sw}

Low ap

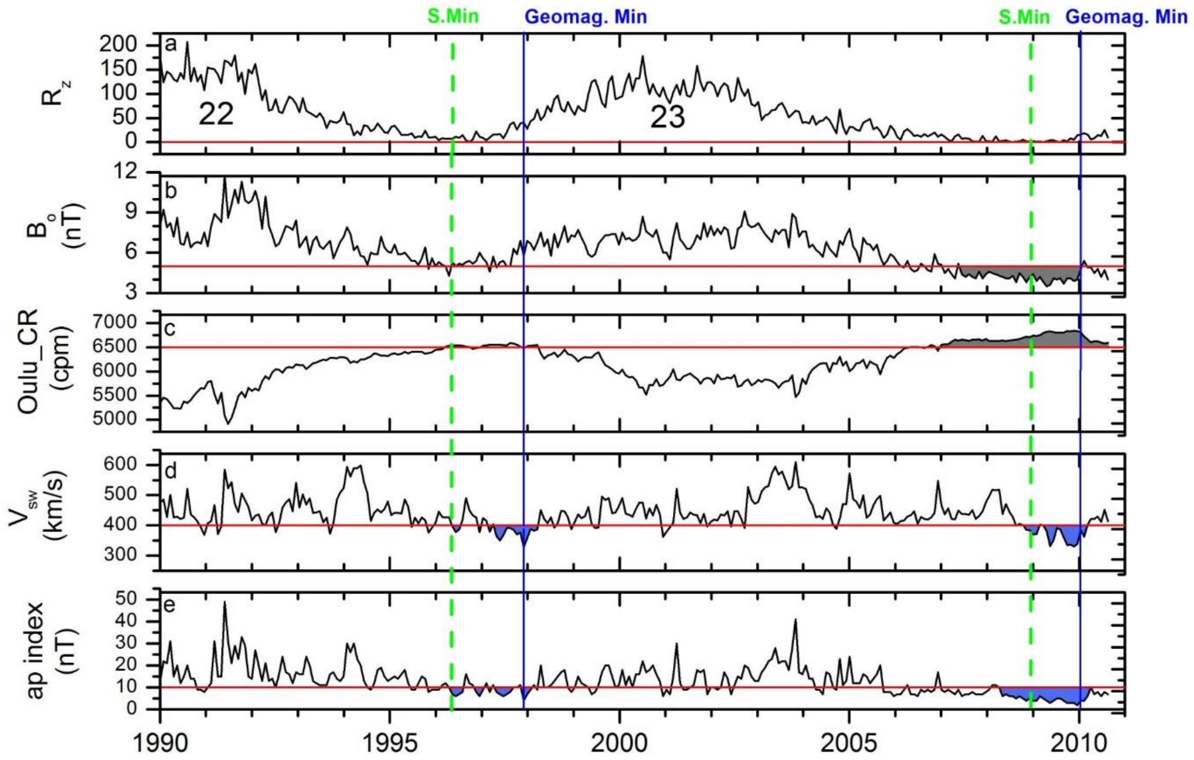
Tsurutani et al. 2011

An alltime minimum in Ap indices

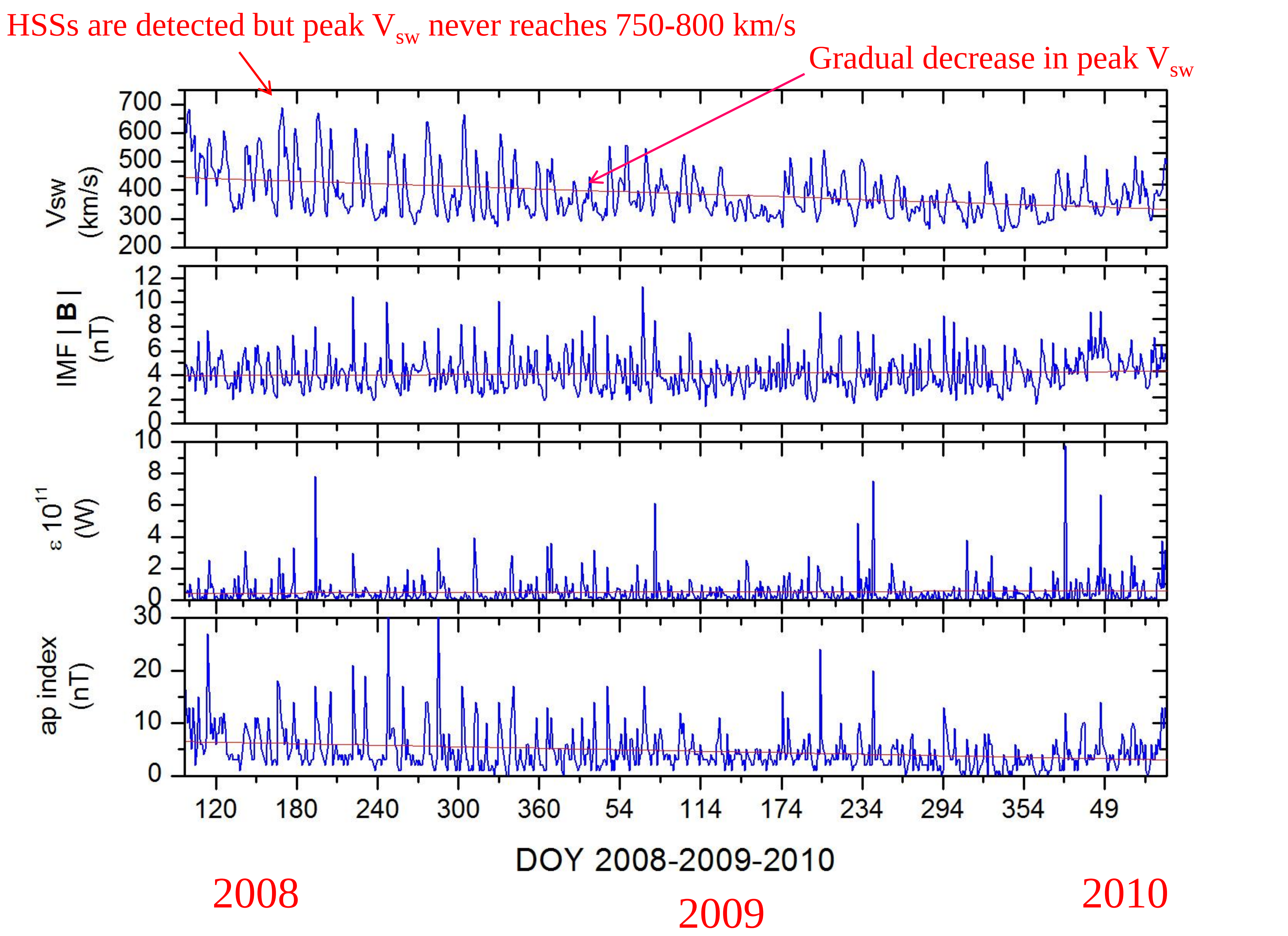
What is the cause of this extremely low geomagnetic activity?

The question is partially answered by the low Vsw and B characteristics, but what causes those low solar wind values?

The Same Geomagnetic Activity Effects and Interplanetary Phenomena Are Noted in the Previous Solar Minimum With A Similar Lag from the Sunspot Minimum

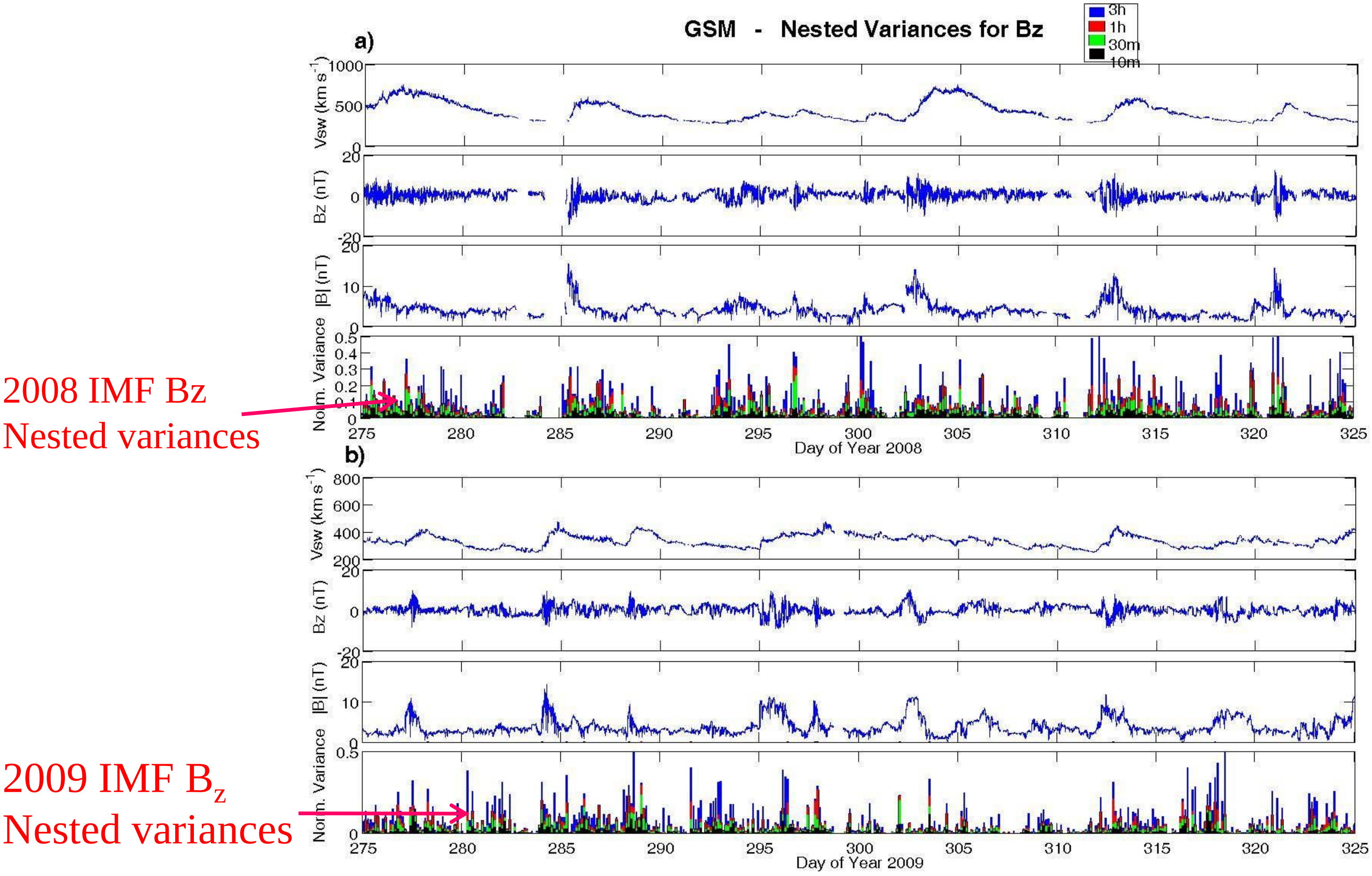


The minima in geomagnetic activity (MGAs) are delayed from the sunspot minima by 6 to 12 months



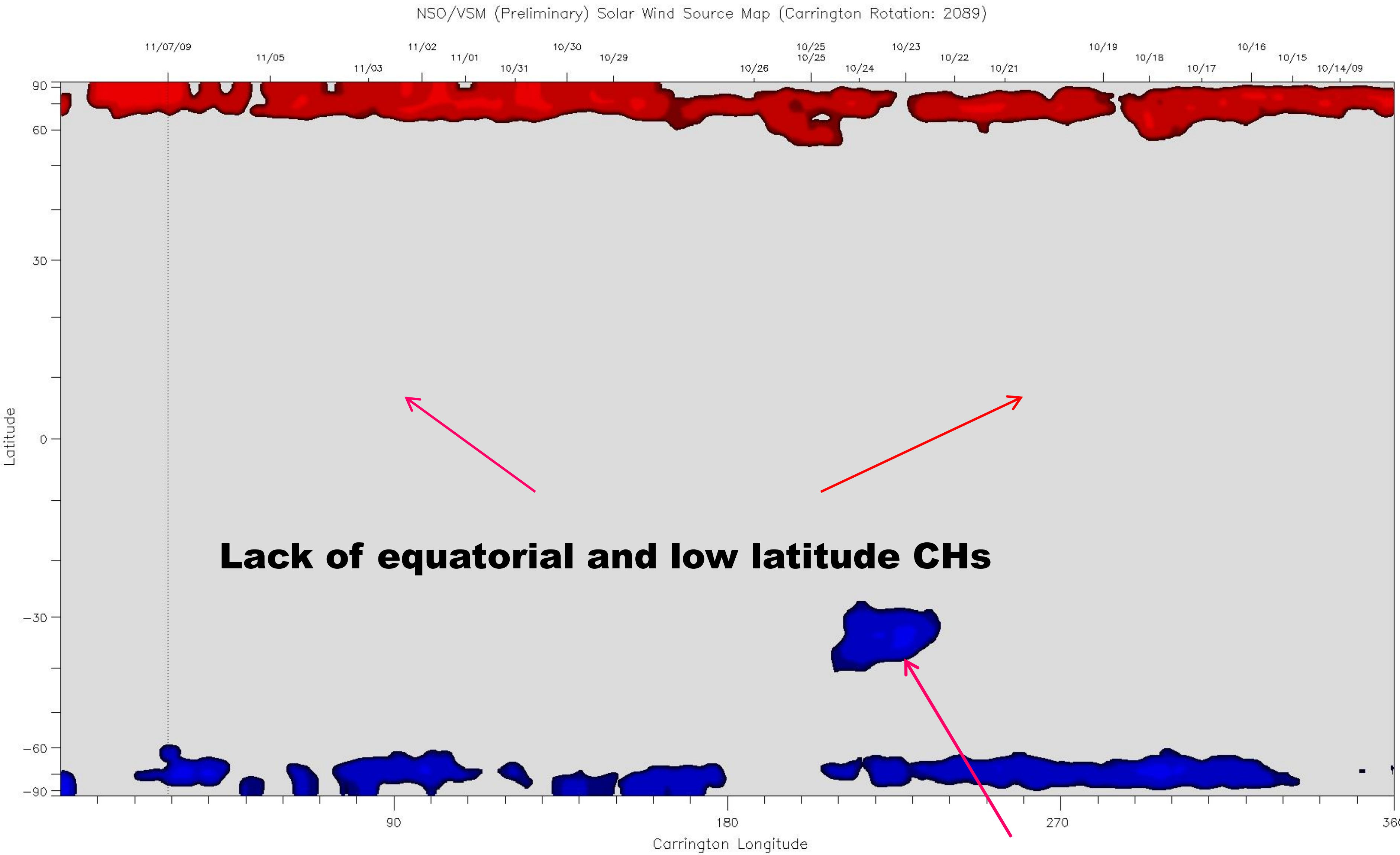
HSSs are detected but peak V_{sw} never reaches 750-800 km/s
Gradual decrease in peak V_{sw}
Vsw (km/s)
IMF | B | (nT)
ε 10^11 (W)
ap index (nT)
120 180 240 300 360 54 114 174 234 294 354 49
DOY 2008-2009-2010
2008
2009
2010

The interplanetary Alfvénic wave intensities in 2009 was much less than that in 2008



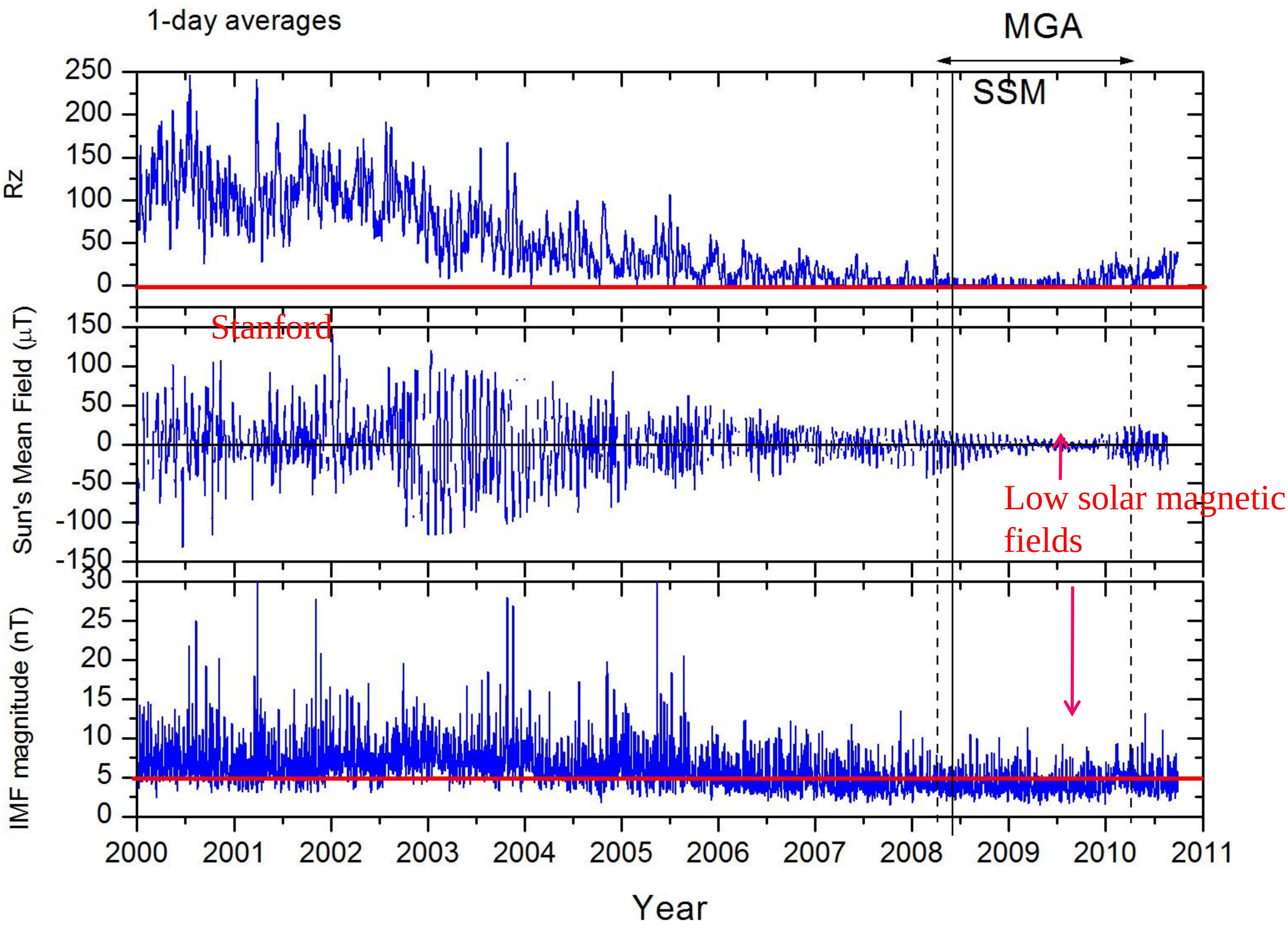
AG, 2011

NSO Coronal Maps: Nov 2009



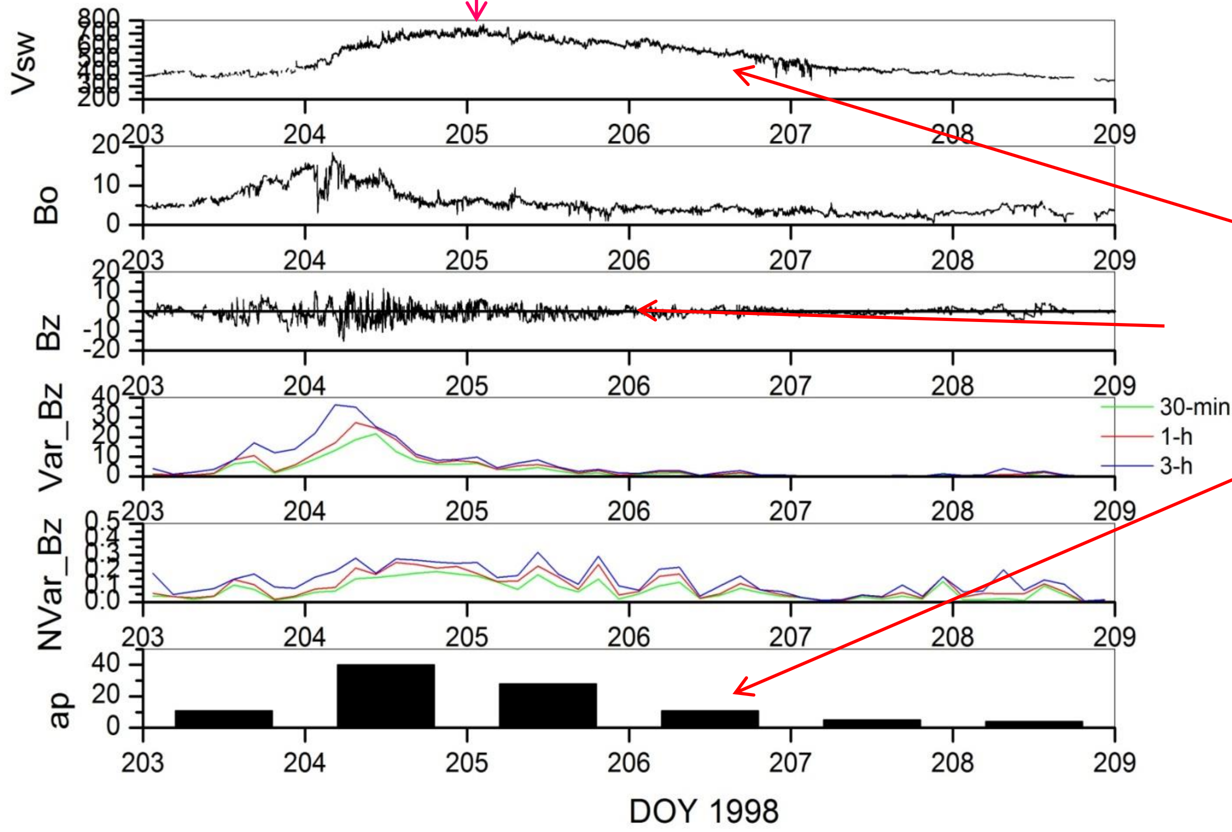
Midlat. Coronal Hole

de Toma, Sol Phys. 2011 (WHI study)


1-day averages
MGA
SSM
Rz
250
200
150
100
50
0
Stanford
Sun's Mean Field (μT)
150
100
50
0
-50
-100
-150
Low solar magnetic fields
IMF magnitude (nT)
30
25
20
15
10
5
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
Year

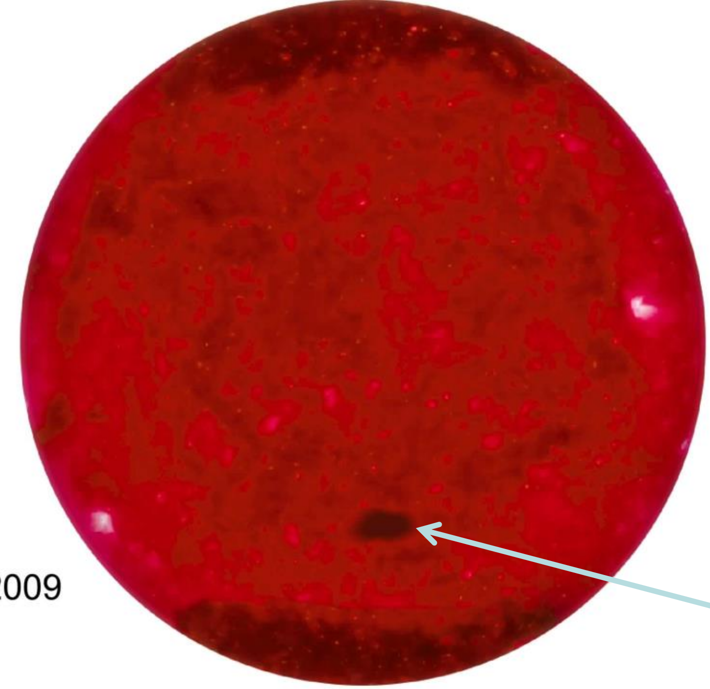
The Same High Speed Stream Shown Earlier: 1998

Peak V_{sw} ~750 km/s



Tapering off of IMF Bz fluctuations (and ap) with gradually decreasing V_{sw}

At the "wings" of HSSs, the Alfven wave amplitudes taper off

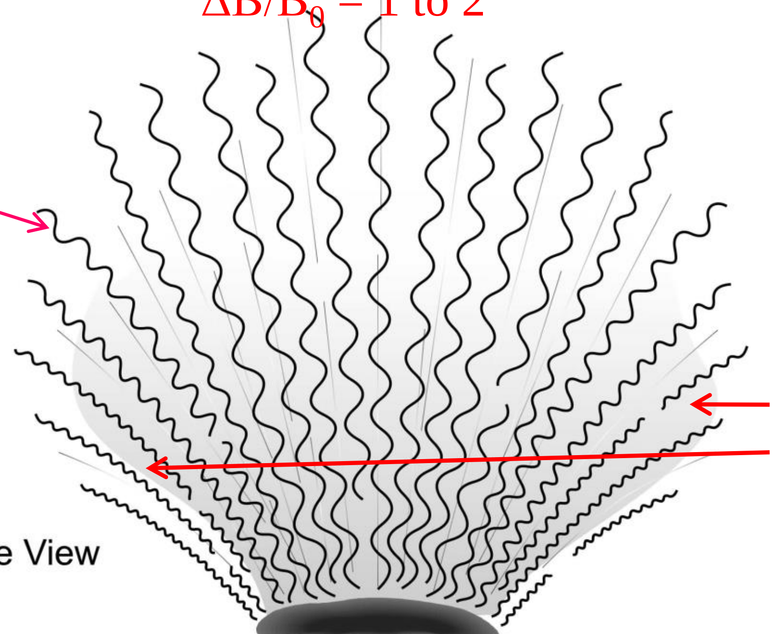


Isolated midlatitude coronal hole

V_{sw} = 750-800 km/s
$\Delta B/B_0$ = 1 to 2

Blowup of isolated coronal hole

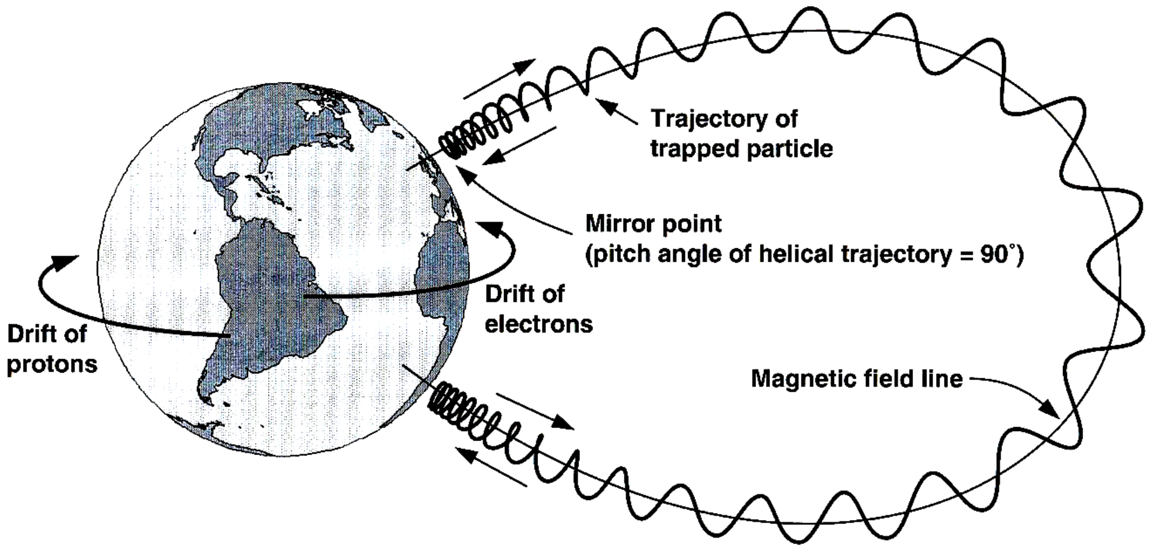
V_{sw} = 450-600 km/s
$\Delta B/B_0$ = 0.2 to 0.3



Note effects of superradial expansion: lower peak speeds and lower Alfvén wave amplitudes

AG 2011

Formation of an Enhanced Ring Current (Magnetic Storm)

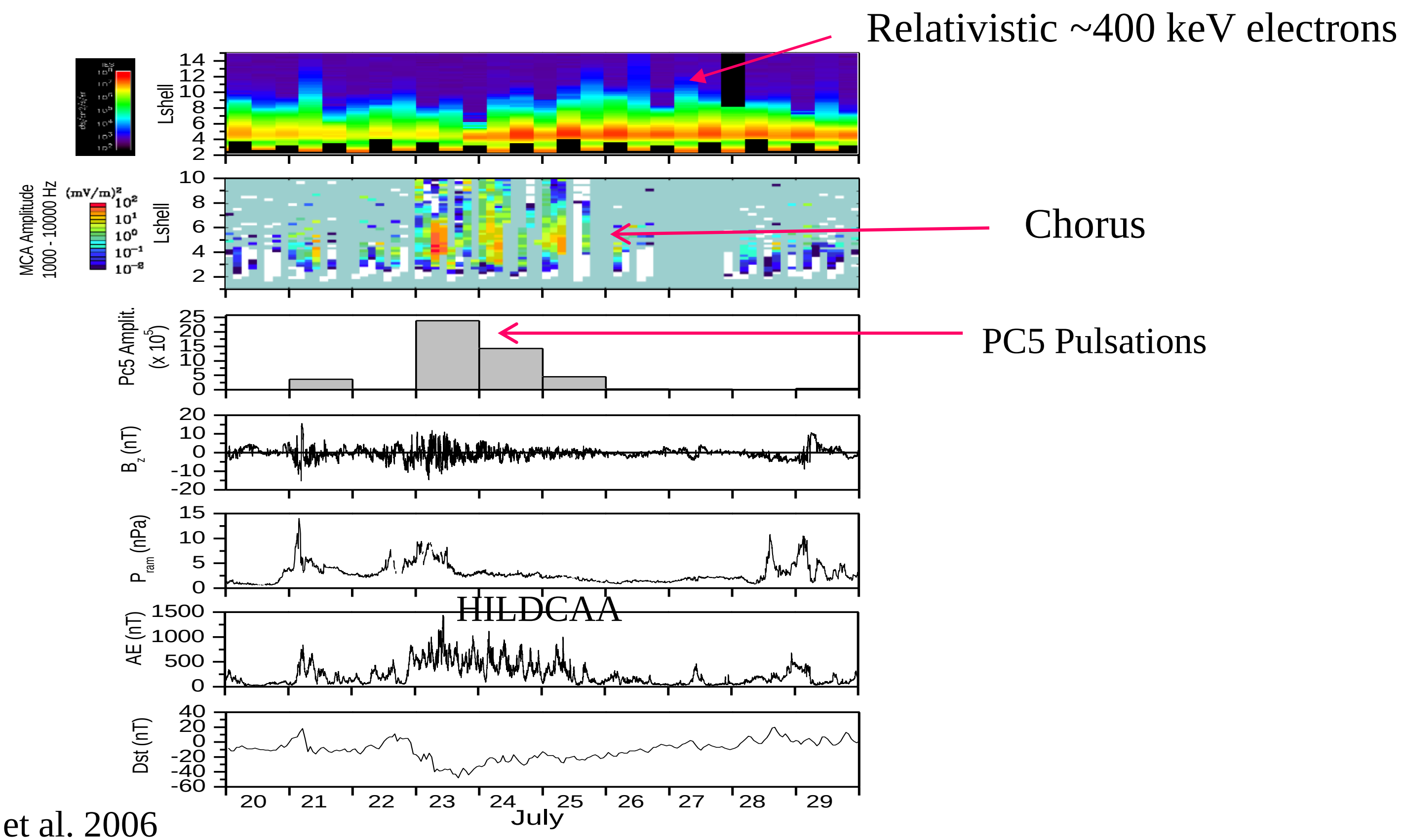


The decrease of the horizontal component of the Earth's surface field (Dst or SYM-H) is caused by the diamagnetic ring current of energetic particles, which is intensified during storms. Dessler and Parker (1959) and Sckopke (1966) showed that the total field decrease was linearly proportional to the total particle energy.

What are the contributions of the magnetopause and tail currents to Dst? This is still being debated. This might vary from storm to storm, so there is not one "right" answer.

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

HILDCAAs, Chorus and Relativistic Electron Acceleration

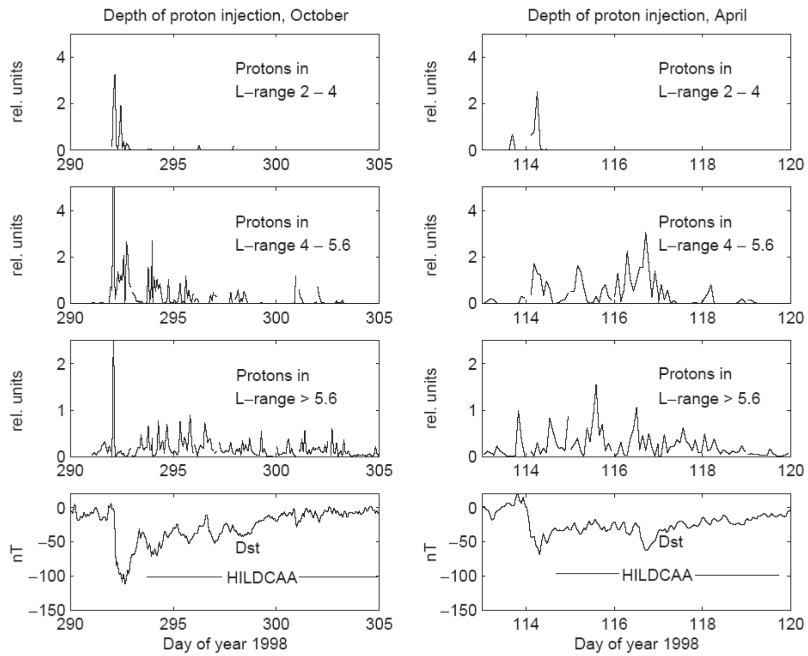


Tsurutani et al. 2006

Scenario: 1) ~10-100 keV electrons injected by B_s of interplanetary Alfvén waves, 2) chorus generated by anisotropic electrons, 3) ~400 keV relativistic electrons accelerated by chorus.

How high can the energy go by the bootstrap mechanism?

Alfvén Wave Bs in HSSs Cause Small Intensity and Shallow Injections of Plasma (L > 4)



Soraas et al. 2003

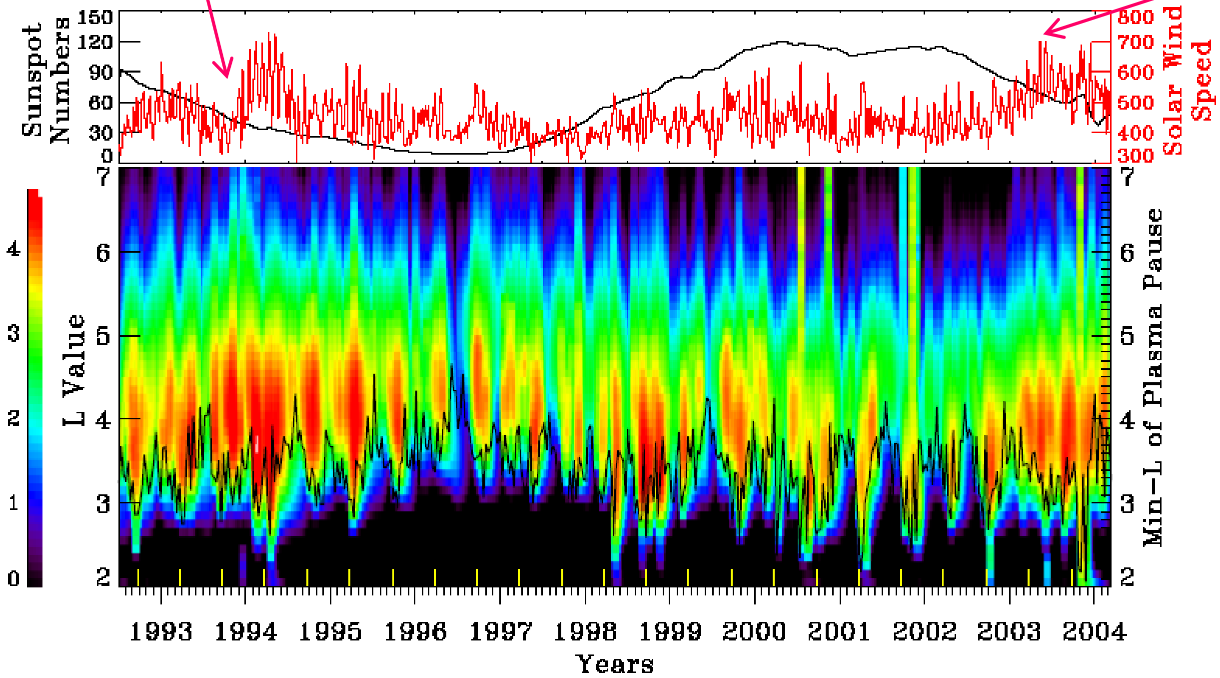
The inject plasmasheet particles are of relatively low ~10-100 keV energies and the energy deposition is mostly in the auroral zones.

There is also substantial energy deposition over the polar caps. Why?

Relativistic Electron Acceleration Occurs in the Solar Cycle Declining Phase When there are Coronal Holes and High Speed Streams

Declining phase

Declining phase



Li et al., 2006

SAMPEX 2-6 MeV Electrons

What is the electron spectra and spectral changes when these events occur?

SUMMARY: 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.

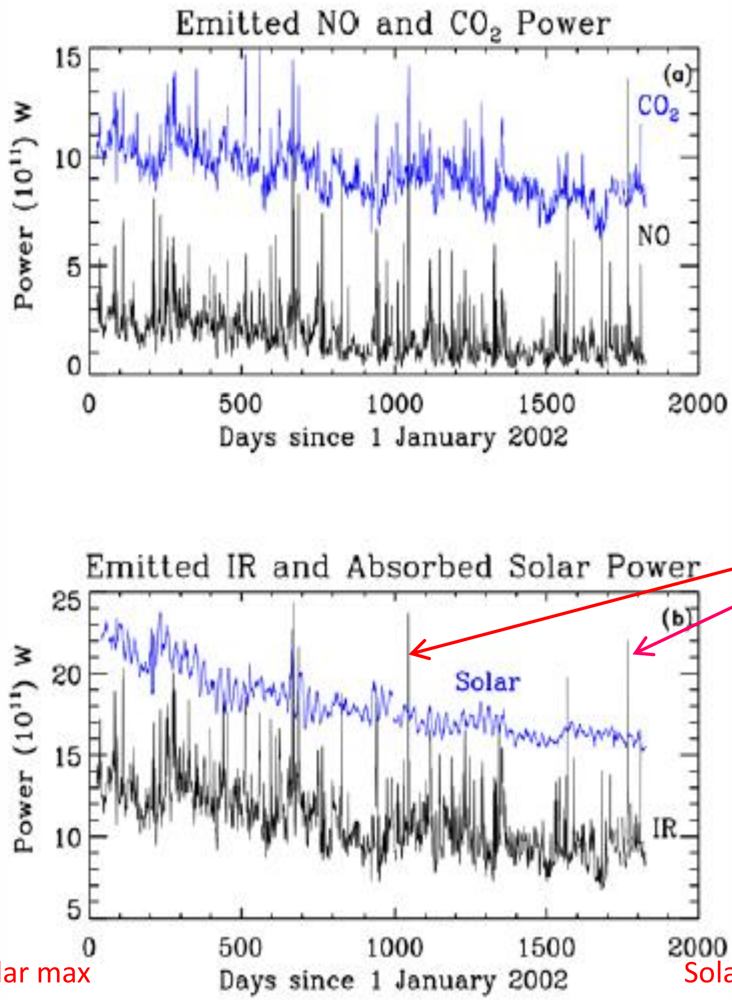
Summary: High Speed Streams

- 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.

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.



Solar max

Solar min

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.

Thermospheric irradiated power (SABER/TIMED)

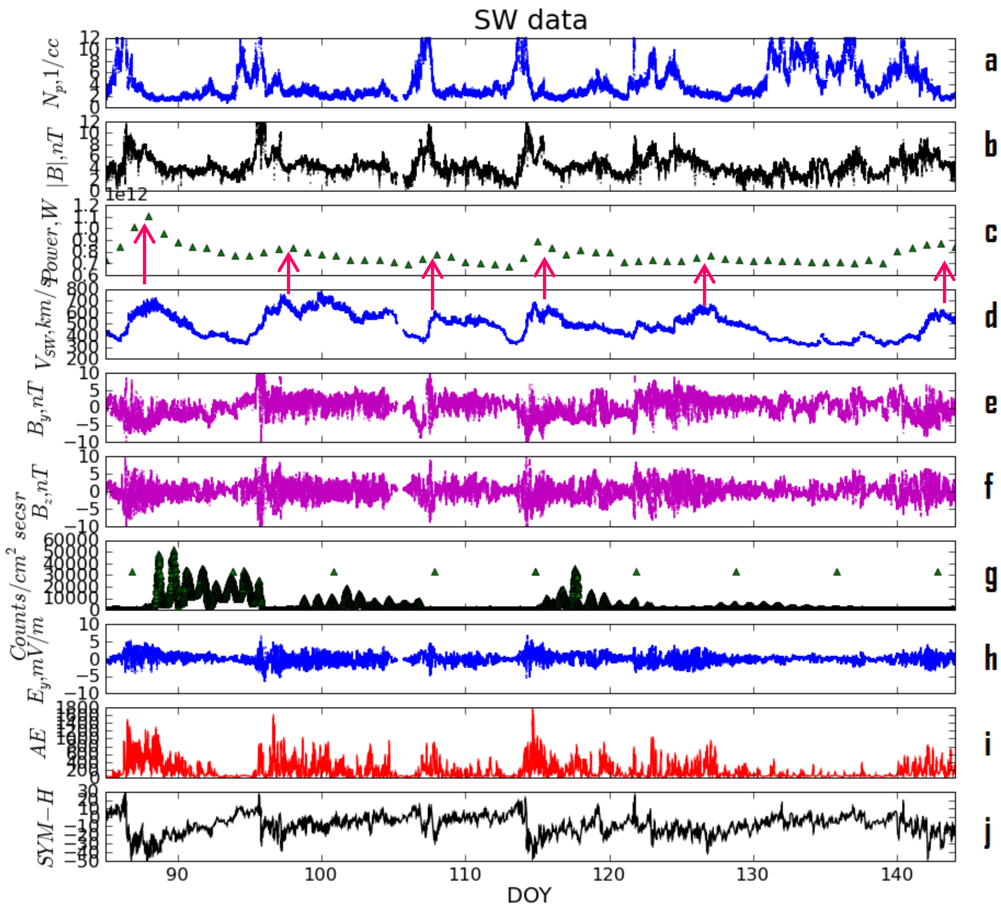
Anomalous spikes where radiated power is higher than solar input power

Solar irradiance decline since Jan 2002 plus thermospheric irradiance decline

Mlynczak et al., 2008

The Atmospheric Radiative Power Increases During High Speed Stream Intervals

WHI INTERVAL



Atmos. Rad. Power has a HSS dependence

HSS

Relativistic electrons

HILDCAAs

2008

Verkhoglyadova et al., 2011

These effects occur at auroral latitudes, as expected