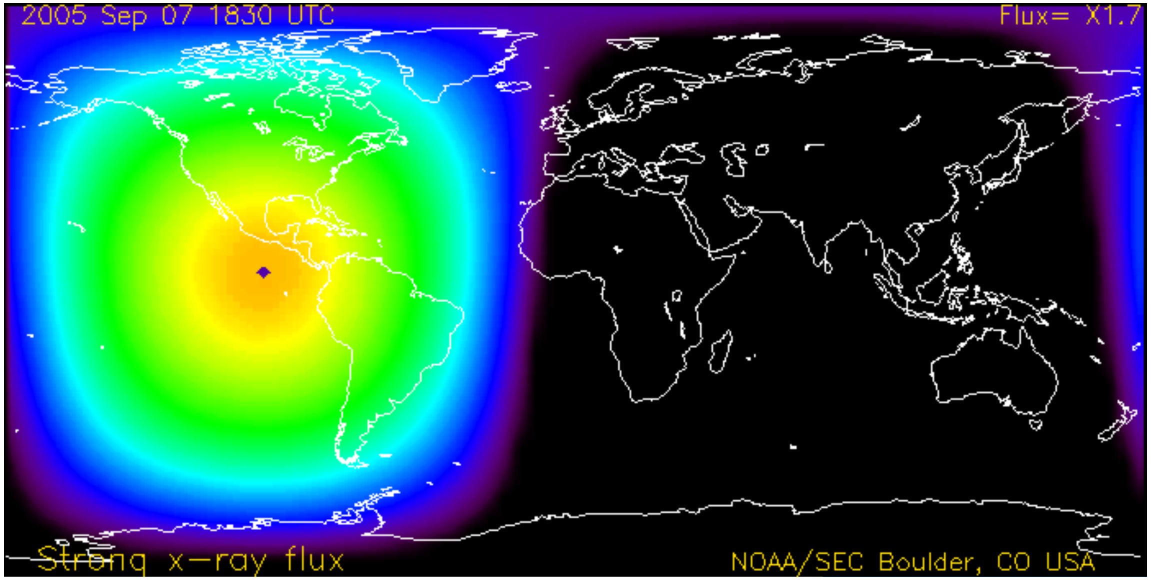
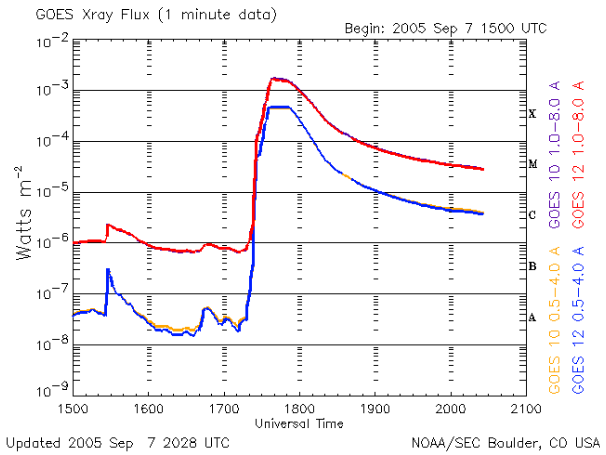
Ionospheric Storms

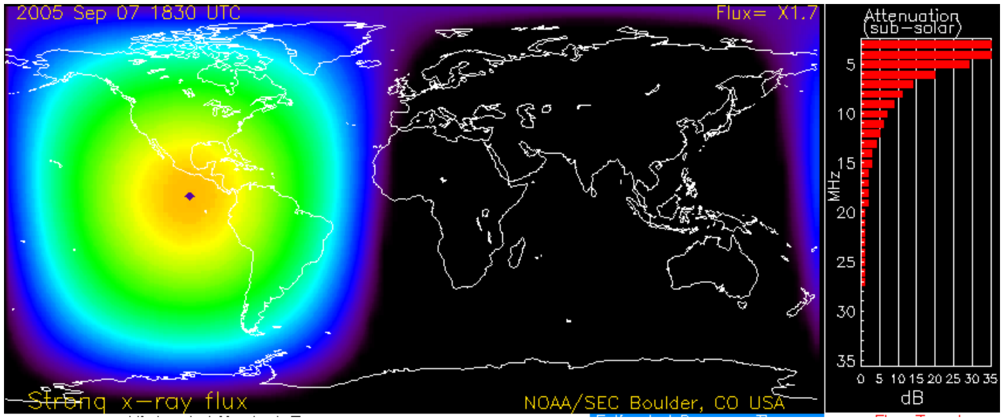


Ken Larson KJ6RZ
March 2024

www.skywave-radio.org

Ionospheric Storms

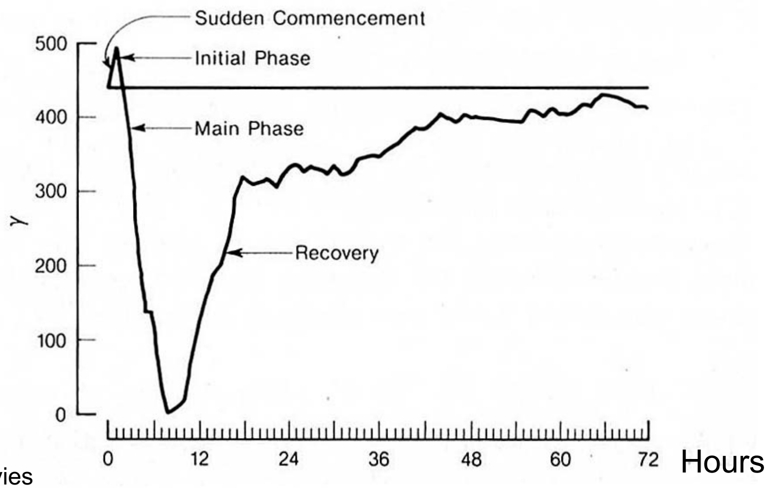




- **An ionospheric storm is characterized by**
  - A **sudden** change in ionospheric conditions
  - Which is **triggered** by events occurring on the Sun
- One of two things, or both, occur during an ionospheric storm
  - Absorption of 160 thru 20 meter radio signals dramatically increases
  - Critical frequencies suddenly drop adversely affecting 20 through 10 meters
- An ionospheric storm can last minutes to days

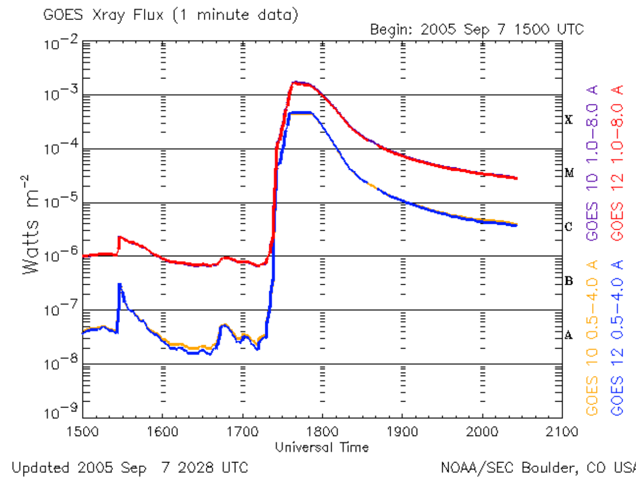
Geomagnetic vs Ionospheric Storms

Magnetic Field Strength



Davies

Solar X-ray Flux

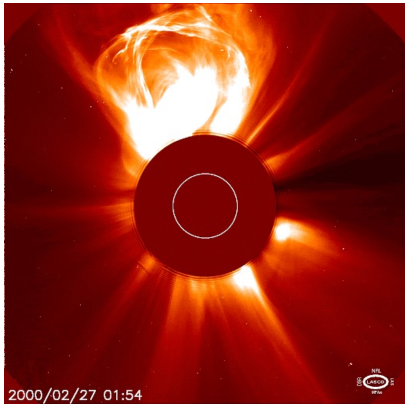


Geomagnetic Storm

Ionospheric Storm

- Ionospheric storms are much different than geomagnetic storms
- Geomagnetic storms cause fluctuations in Earth's magnetic field potentially causing serious trillion dollar damage to our technological infrastructure
- Ionospheric storms cause perturbations in Earth's ionosphere disrupting HF communications

Ionospheric & Geomagnetic Storms Caused by the Same Solar Events



astronet.ru

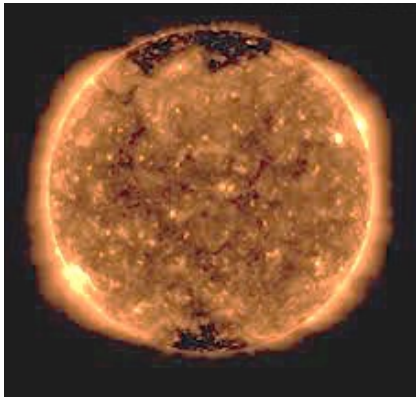
Coronal Mass Ejection (CME)

NASA

Coronal Loop

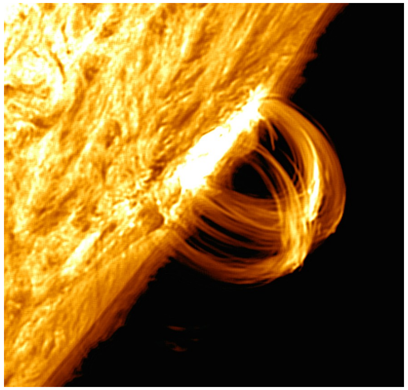
wral.com

Solar Flare



NOAA

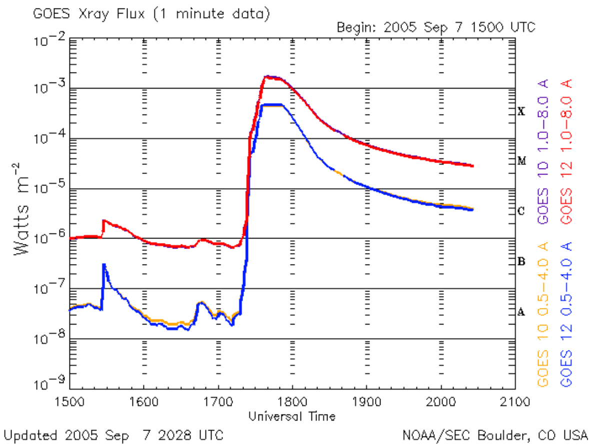
Coronal Holes

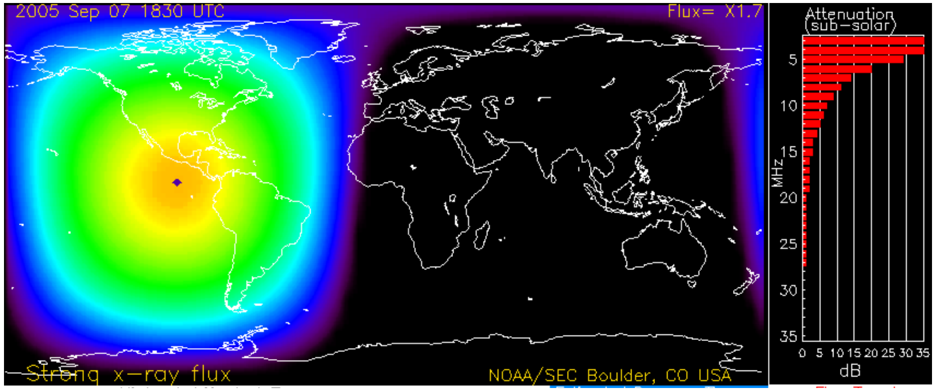


Astronomy Magazine

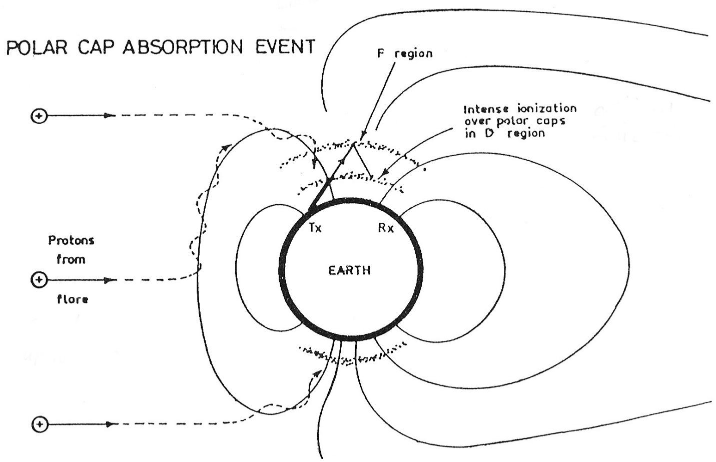
Prominence

Three Types of Ionospheric Storms



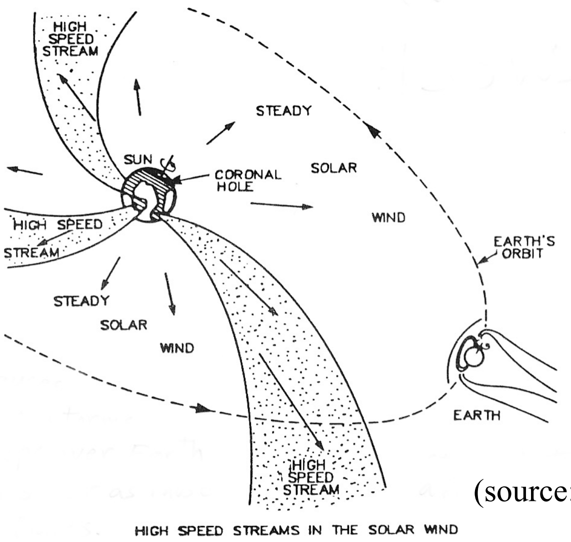


X-ray Radiation Storms



(source: McNamara)

High Energy Particle Storms

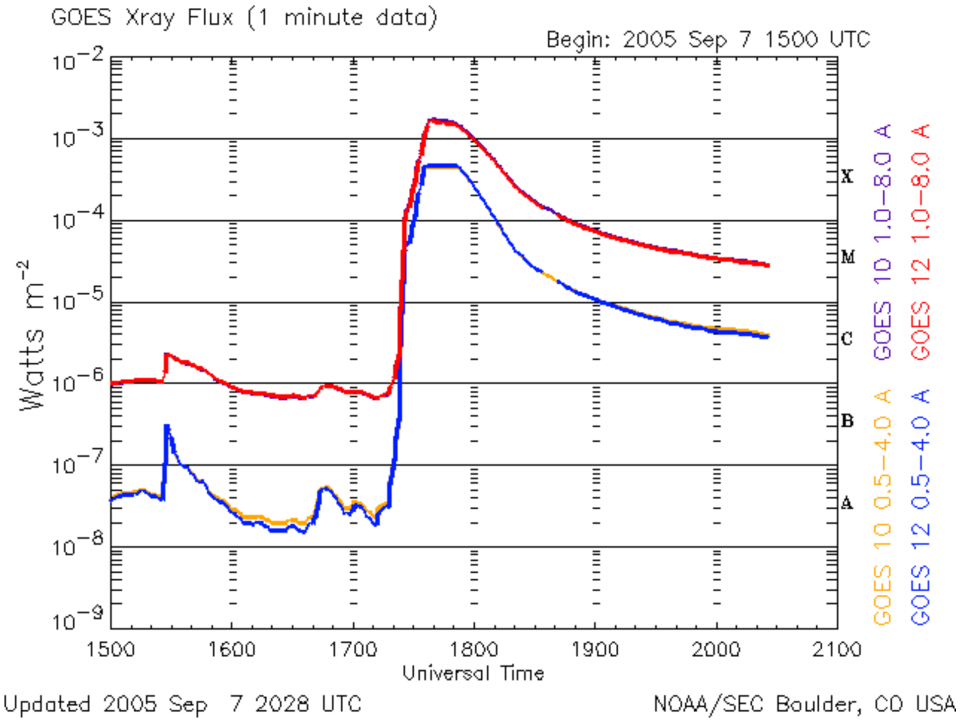


(source: McNamara)

Solar Wind Storms

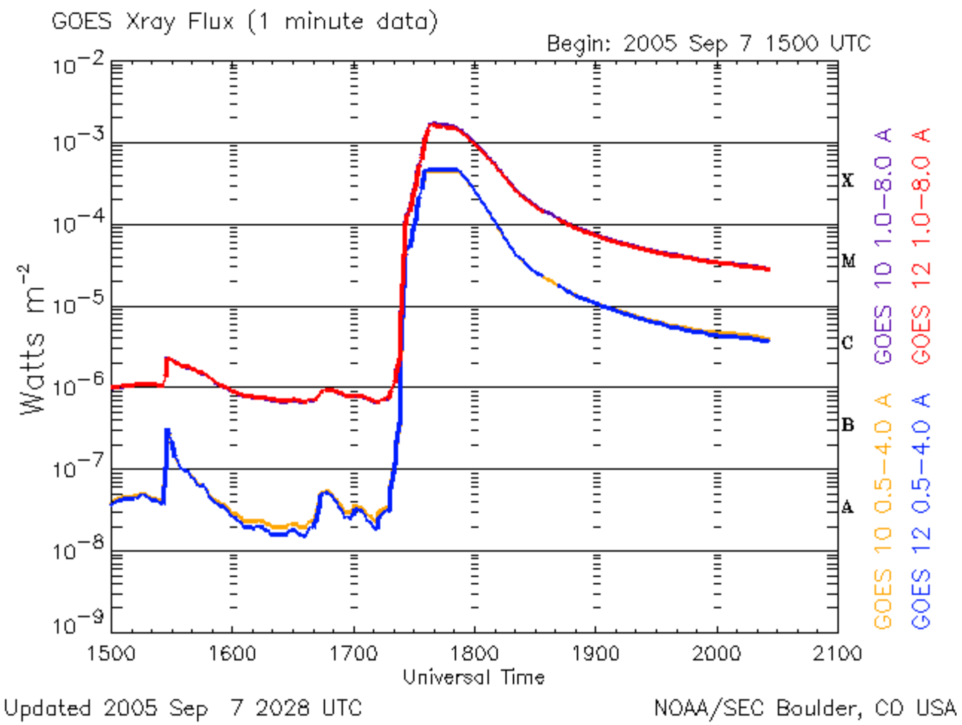
X-ray Radiation Storms

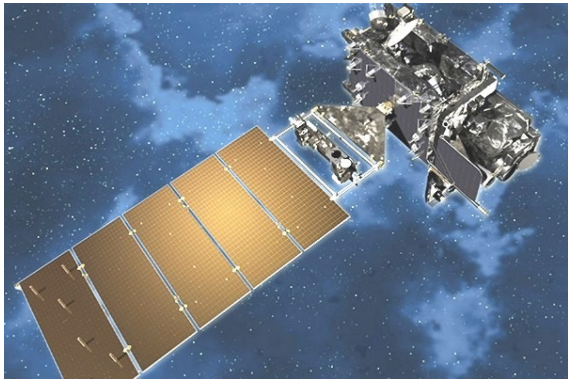
Solar Flare



- An x-ray radiation storm is caused by a sudden dramatic increases in x-ray radiation from the Sun
- An x-ray radiation storm is produced by a solar flare
- X-ray radiation from a solar flare reaches Earth in little over **8 minutes**

Measuring X-ray Radiation

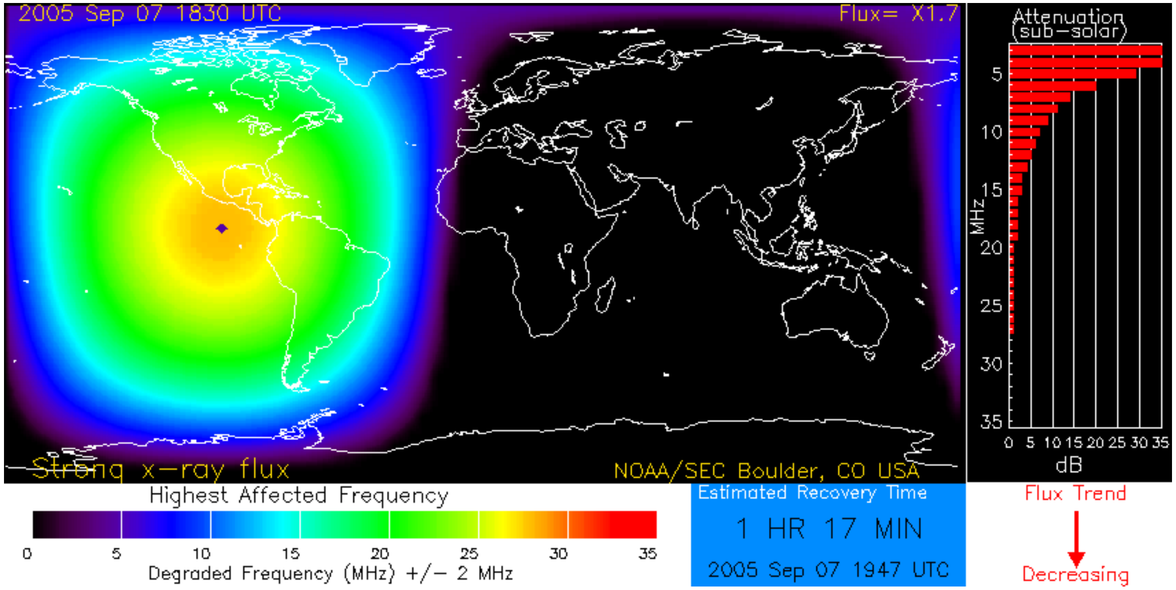




GOES satellite
NOAA

- X-ray radiation is measured by GOES satellites in synchronous Earth orbit
- X-ray radiation is absorbed in Earth's atmosphere so can not be measured by ground based sensors
- Vertical axis indicates the strength of the x-ray radiation
- The vertical axis is similar to the earthquake Richter scale.
- Each band (A, B, C, etc) represents a times 10 increase in x-ray radiation strength.
- This flare produced a 1,000 times increase in x-ray radiation levels

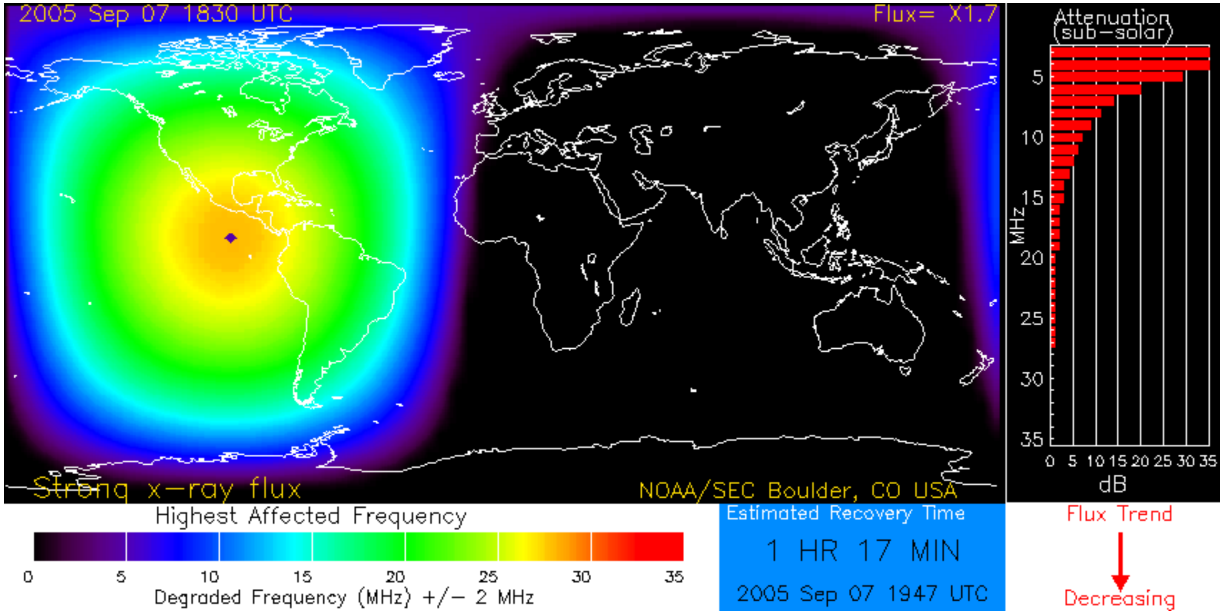
X-ray Radiation Storms Heavily Ionizes D Layer



NOAA/SWPC

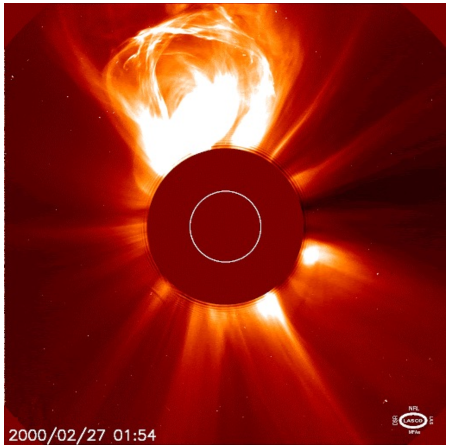
- An x-ray radiation storm heavily ionizes the ionosphere D – layer
- Causing extensive absorption of HF radio signals – **low frequencies hit hardest**
- Black diamond represents the Sun's location (local noon)
- Color bar represents the highest frequency bands affected
- Bar graph on right shows signal attenuation by frequency

Working Around An X-ray Storm



- An x-ray radiation storm moves to the west as the Earth rotates eastward
- Look to the west for radio contacts if the solar flare occurs in the morning
- If it occurs in the afternoon, look to the east for radio contacts
- If the solar flare hits at noon, nothing you can do – go have a nice lunch
- BUT - look to the east for signals to recover as the storm moves westward

Ionospheric High Energy Particle Storms

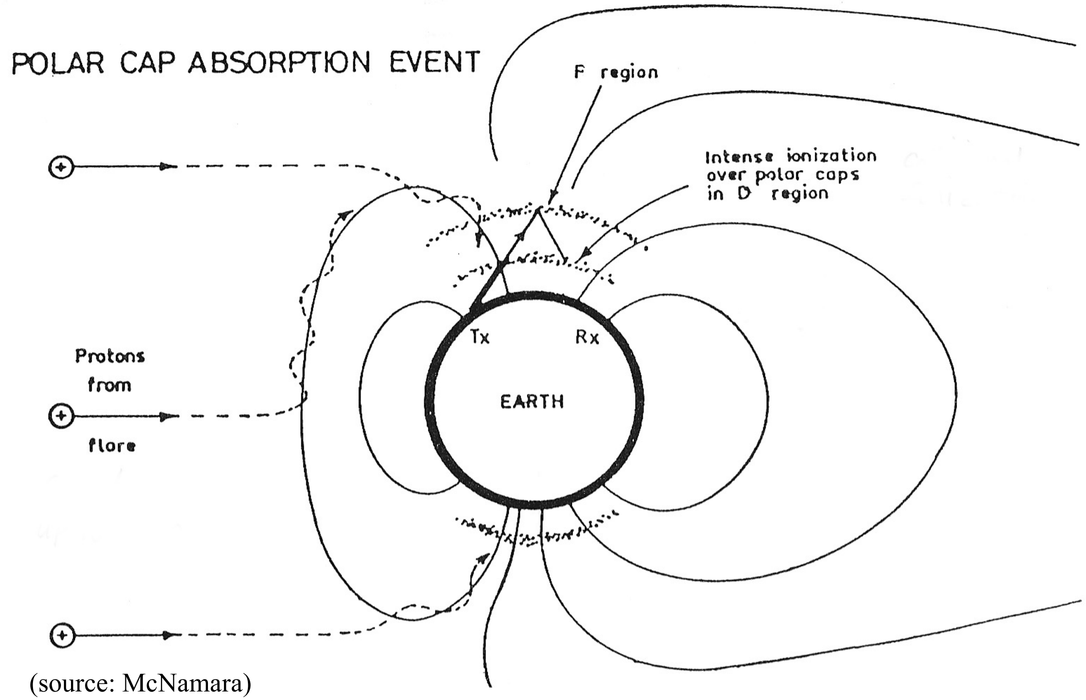


CME

Solar Flare

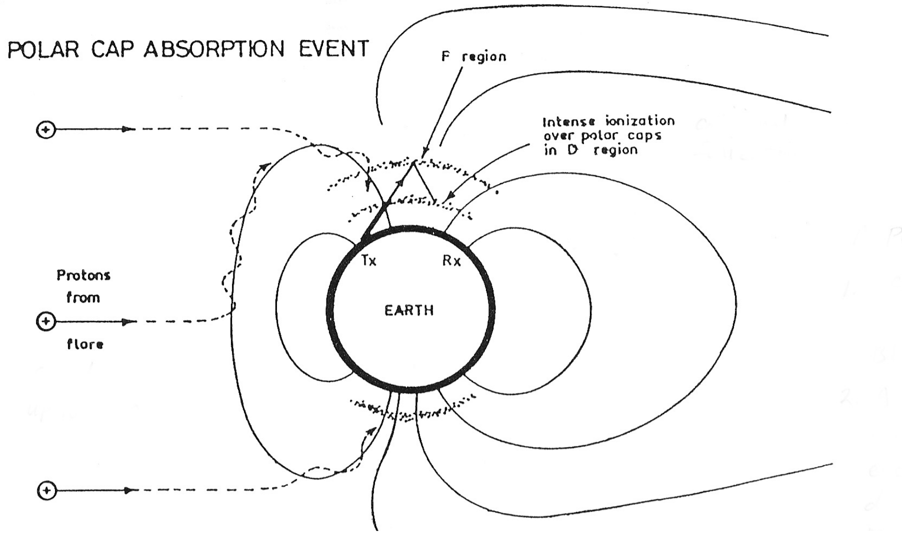
- Ionospheric high energy particle storms are produced by Solar Energetic Particles (SEPs) from CMEs and solar flares
- SEPs are primarily hydrogen protons stripped of their electrons and accelerated to nearly the speed of light
- Solar energetic particles reach Earth in **20 minutes to an hour or so**

SEPs Impacting Earth



(source: McNamara)

- Electrically charged particles can not cross Earth's magnetic field lines
- Upon reaching Earth, solar energetic particles are forced to travel along Earth's magnetic field lines, spiraling down into the polar cap regions as the magnetic field lines become vertical.
- SEPs highly ionize the D layer polar cap ionosphere causing HF radio signals passing through the area to be heavily absorbed, resulting in a Polar Cap Absorption event (PCA)

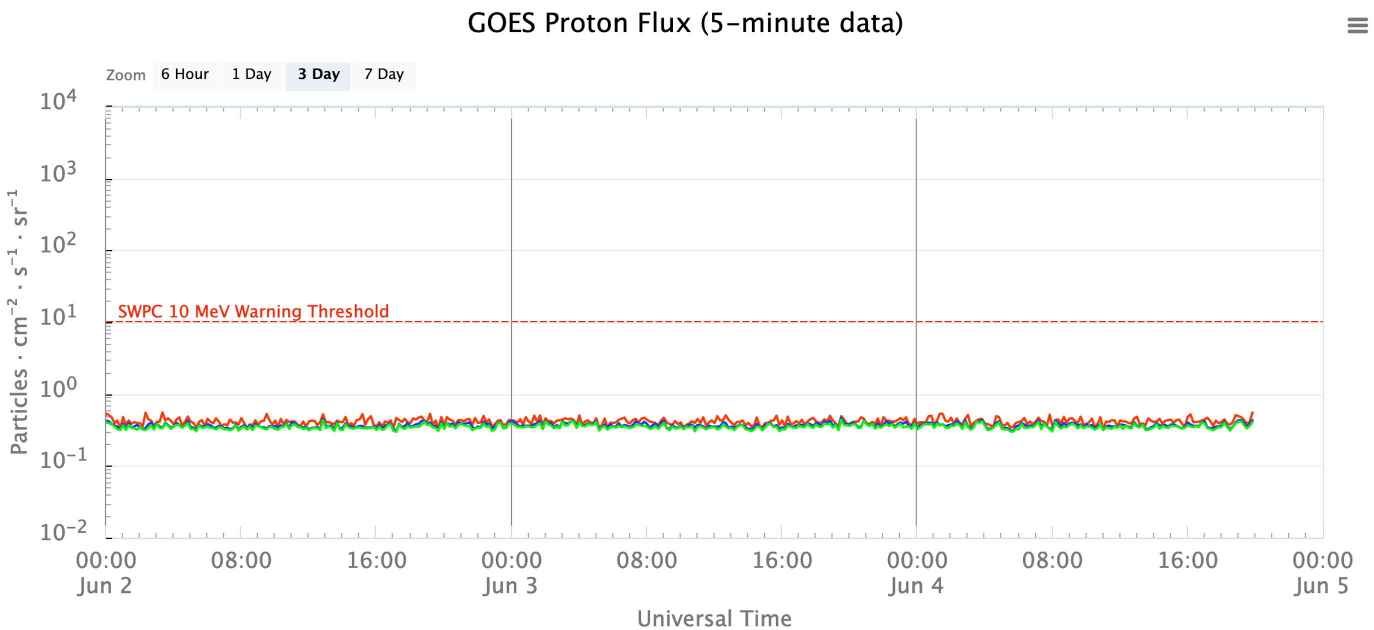


(source: McNamara)

Polar Cap Absorption Event (PCA)

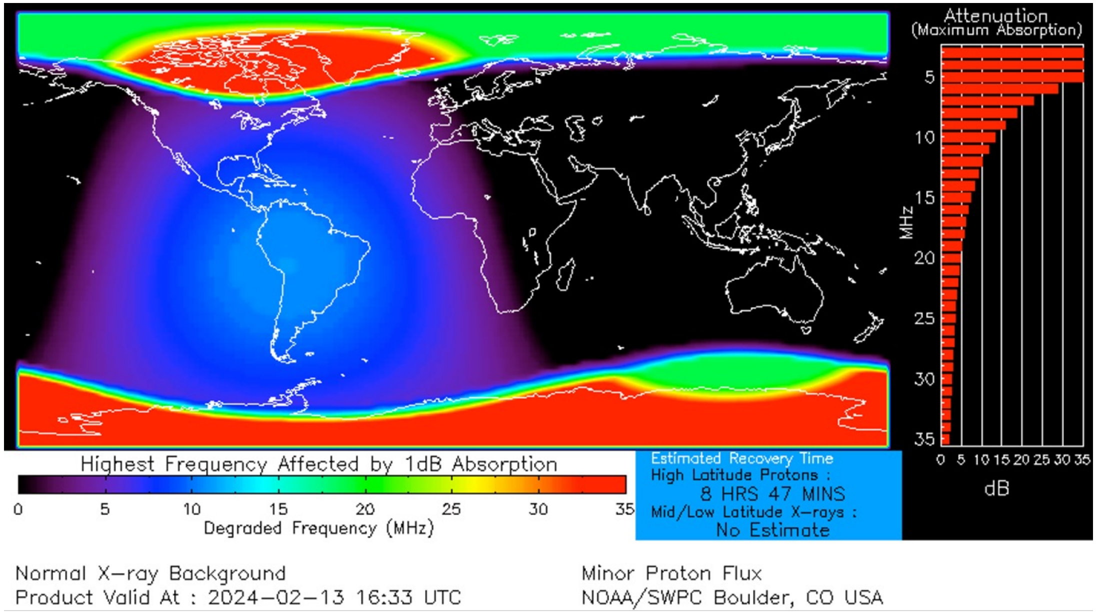
- PCAs occur more often during solar maximum when solar flares and CMEs are prevalent
- It is not unusual for PCAs to occur in groups with two or more occurring within a few days of each other
- PCAs tend to occur more during daylight hours than at night
- Only the largest solar flares and CMEs emit charged particles with high enough energy to create a PCA
- Consequently PCAs occur infrequently, around 10 per year during solar maximum and 1 – 2 per year during solar minimum

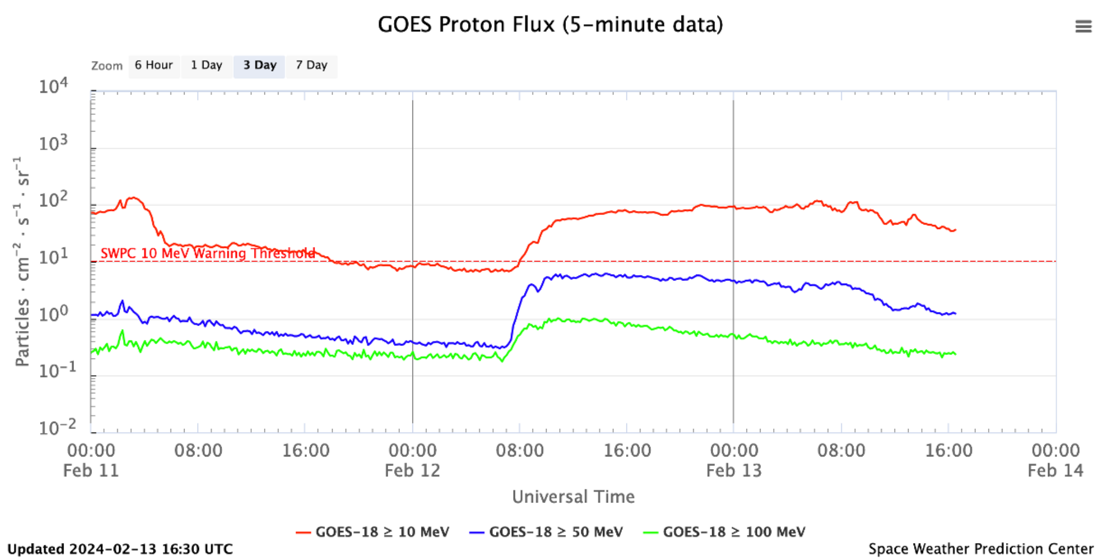
Proton Flux



- GOES satellites continuously monitor the proton flux arriving from the Sun
- NOAA Space Weather Prediction Center issues a warning if proton flux > 10 MeV
- To ionize the D layer charge particles must have enough energy to penetrate through the F and E regions and still have sufficient energy left to ionize D-layer molecules
- To do this, producing a PCA event, particles must have energy levels > 10 MeV

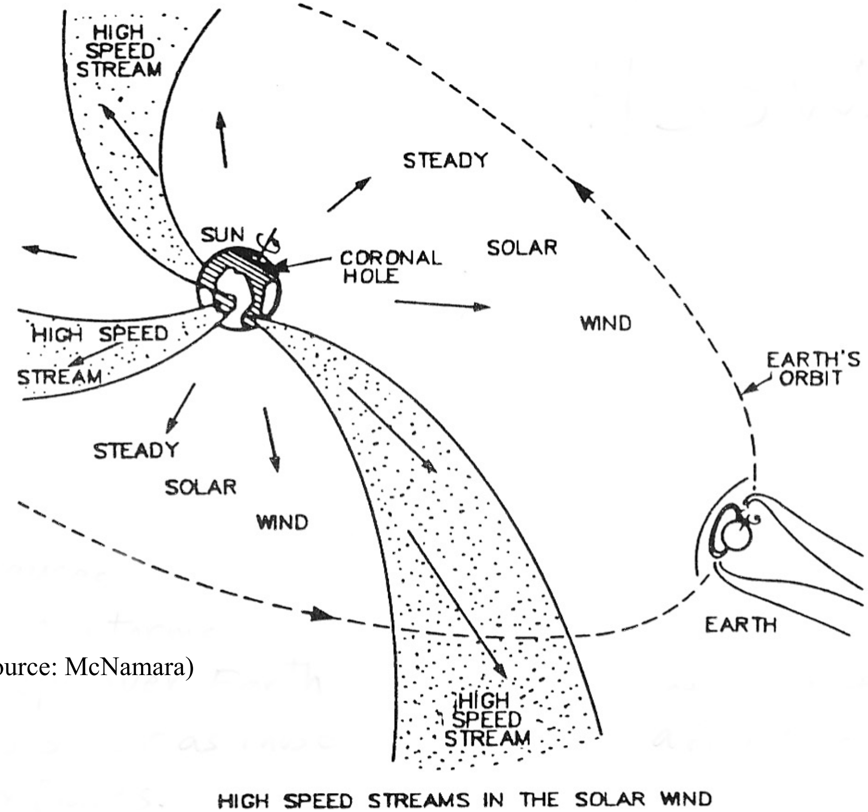
PCA Occurring on 2/13/2024





- Proton flux considerably over 10 MeV threshold
- Creating a PCA event throughout polar regions
- Which heavily absorbed transpolar HF signals
- Low frequency signals were absorbed the most
- This PCA was caused by a CME sweeping past Earth
- During a PCA avoid transpolar propagation paths

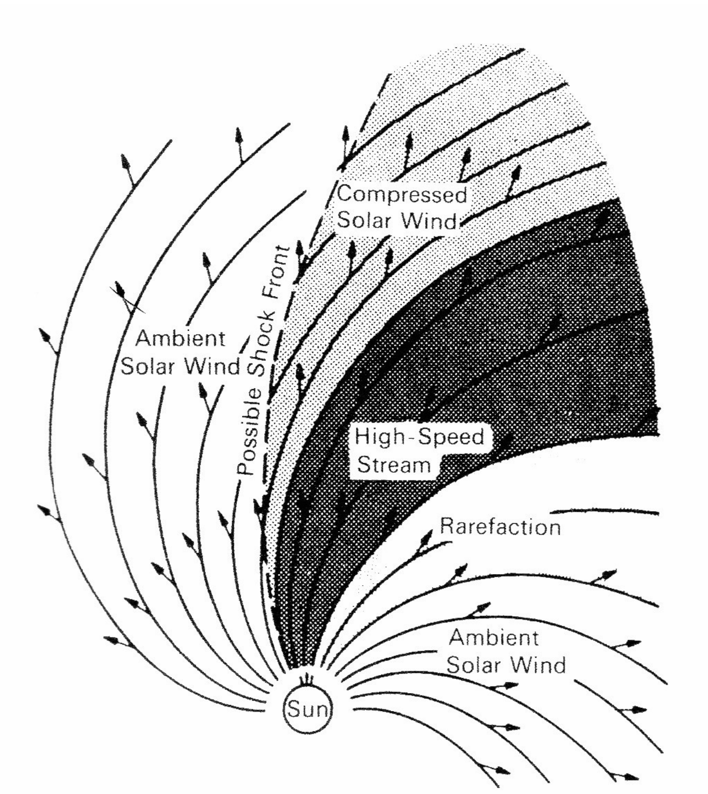
Ionospheric Solar Wind Storms



(source: McNamara)

- Ionospheric solar wind storms and geomagnetic storms are quite different
- However, they are both caused by high speed solar winds sweeping past Earth
- Geomagnetic storms cause significant dips and fluctuations in Earth's magnetic field
  - Inducing huge electrical currents in power & pipe lines
  - Potential damage > $1 trillion
- Ionospheric solar wind storms characterized by large drops in F2 critical frequency

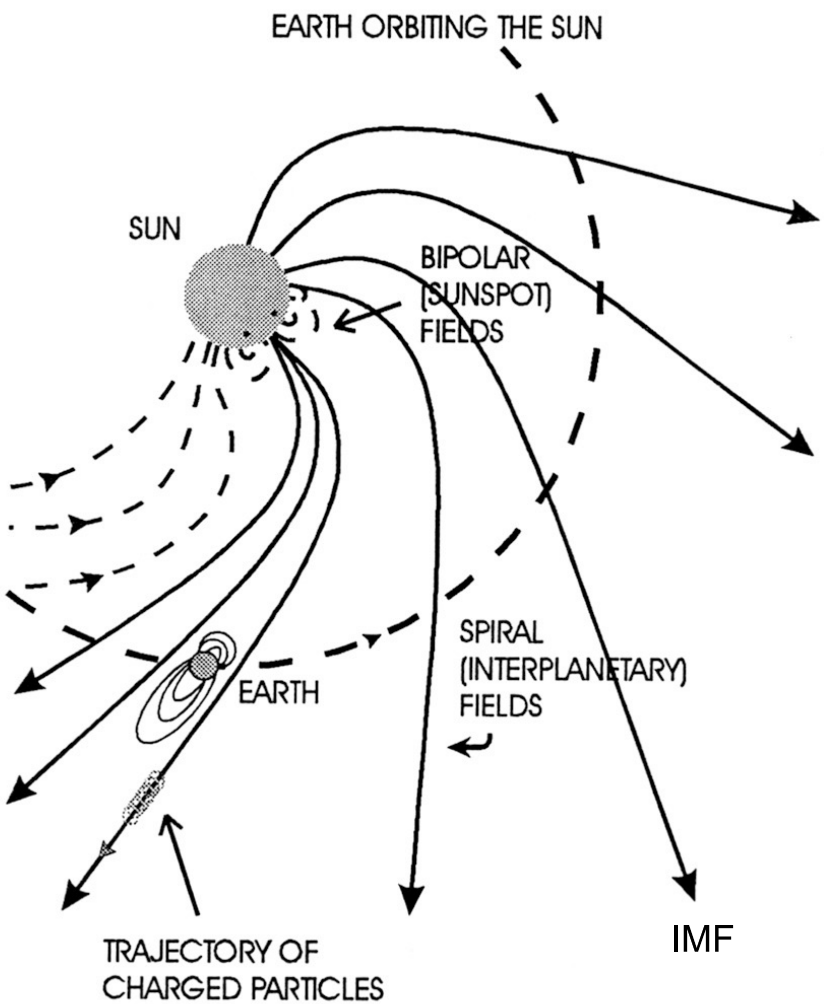
Solar Winds



(source: Hunsucker & Hargreaves)

- The solar wind is tenuous
- It originates from CMEs, solar flares, coronal holes and other disturbances on the Sun
- Its particle density is only around 5 particles per cubic cm
- Most of these are electrons, and protons (H^+) plus a few alpha particles (He^{+2})
- In contrast the ionosphere's peak electron density is ~ 10^6 electrons per cm^3
- Solar wind is hot, temp 100,000 - 150,000 ^oK
- Sun's Photosphere ~ 5,000 ^oK, Sun's Corona temperature is greater than a million degrees K
- The solar wind blows continuously, varying in speed, density, and temperature
- Solar wind has a weak embedded magnetic field

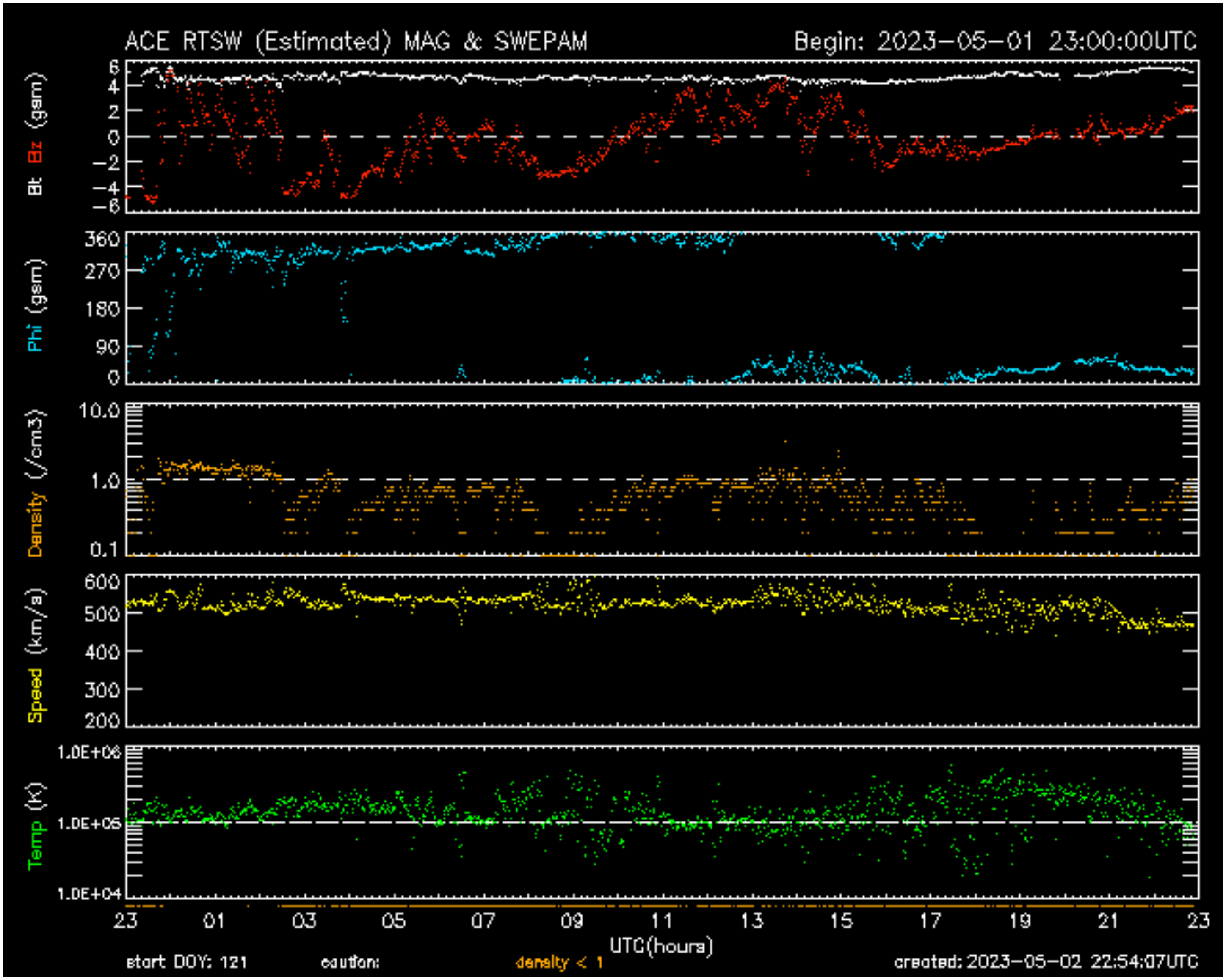
Interplanetary Magnetic Field (IMF)



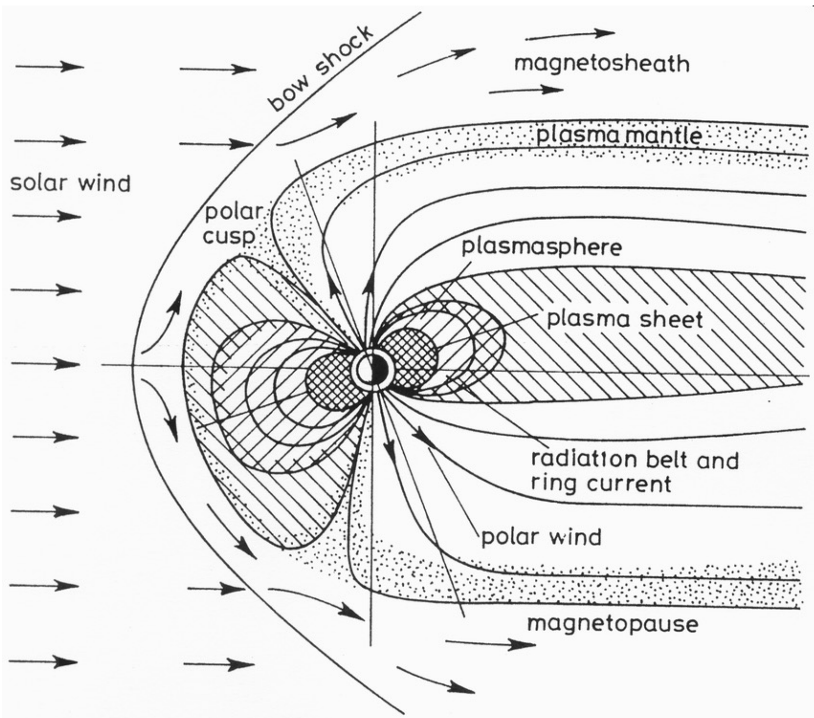
(source: J.P. Vallee)

- The solar wind's magnetic field is known as the Interplanetary Magnetic Field (IMF)
- The magnetic field originates internal to the Sun
- However, in the corona a small portion of the Sun's magnetic field becomes "frozen in" the solar wind plasma due to the plasma's very high electrical conductivity
- The IMF propagates throughout the solar system, carried along by the solar wind, hence its name "interplanetary magnetic field"
- The strength of the IMF field averages only about 5.6 nT, its very weak

Solar Wind Parameters – Available on www.skywave-radio.org



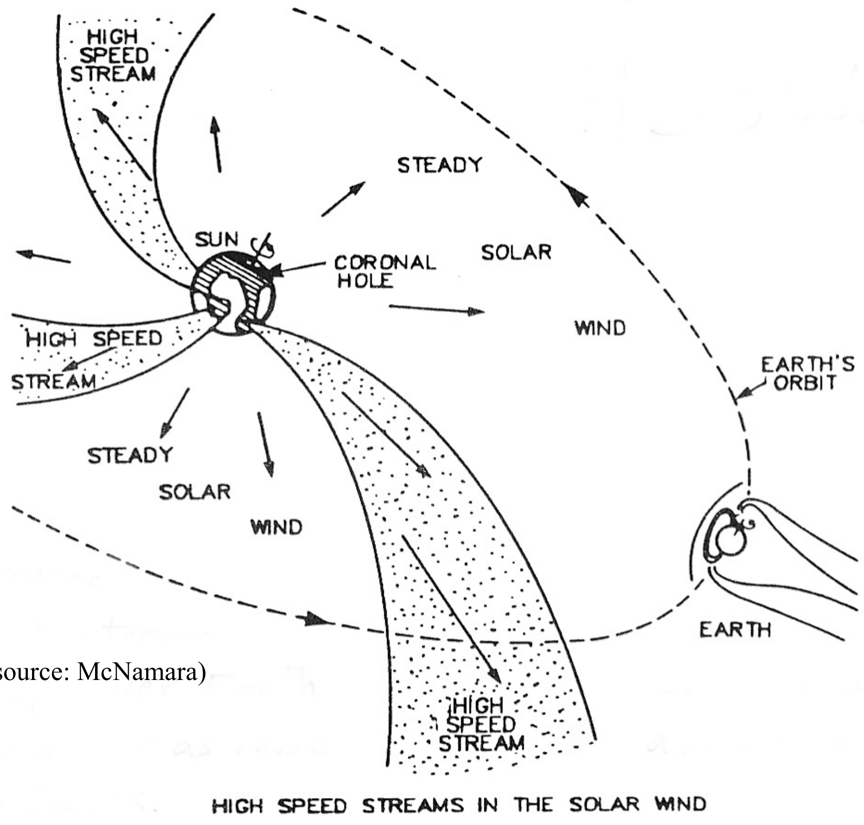
Earth's Magnetosphere



(source: Davies)

- While the solar wind is tenuous, it is supersonic as it approaches the Earth, typically traveling at 400 km/sec (nearly 1 million miles per hour)
- The solar wind deforms Earth's magnetic field into a comet shaped magnetosphere
- The bow shock always faces toward the Sun while the magnetosphere tail faces away from the Sun (same as a comet)
- The Earth rotates within the stationary magnetosphere
- The Earth's magnetic field shields the Earth from the ravages of the solar wind

High Speed Stream (HSS) Solar Wind

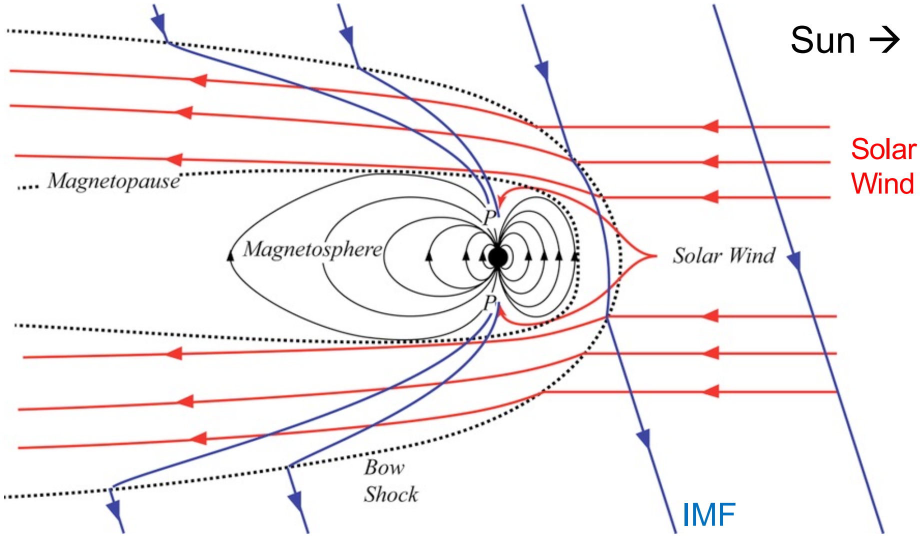


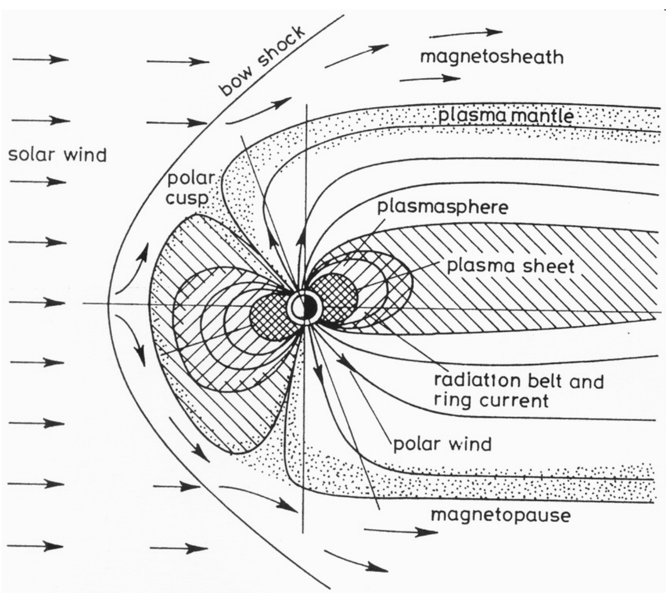
(source: McNamara)

- CMEs, coronal loops, solar flares, and coronal holes eject billions of tons of coronal material
- The ejected material produces a high speed stream (HSS) solar wind
- The HSS wind, with its embedded interplanetary magnetic field (IMF), spirals outward from the Sun
- The HSS solar wind reaches Earth in about **two to four days**

Solar Wind Storm – Southward IMF

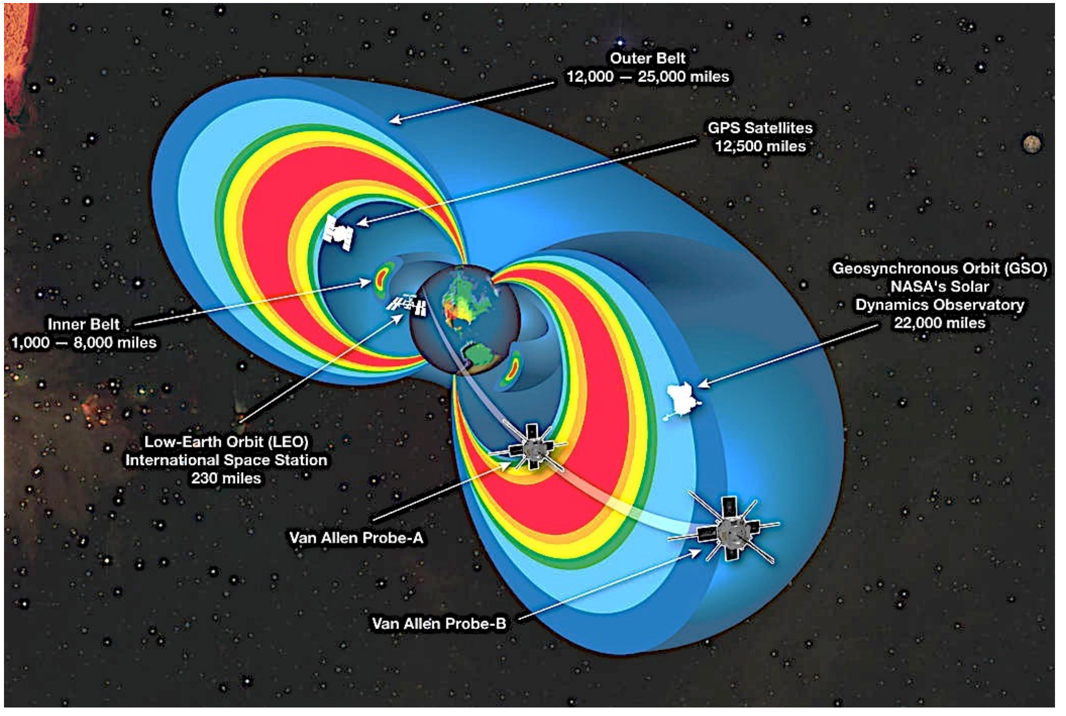
(source: ResearchGate)



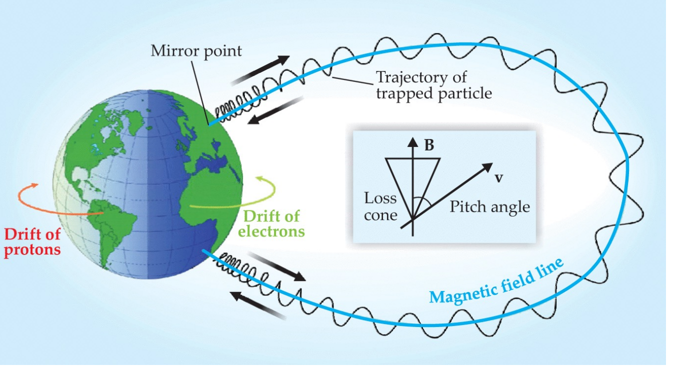


- When the HSS wind arrives at Earth one of two things can happen.
- If the IMF is northward, very little if anything happens.
- If the IMF is pointed southward it connects to Earth's northward magnetic field --- this is bad
- The interconnected magnetic fields are dragged across the polar region by the solar wind.
- In the process the polar magnetic field lines are pealed open in the vicinity of the polar cusp
- Allowing charged solar wind particles to stream down into the magnetosphere

Van Allen Radiation Belts

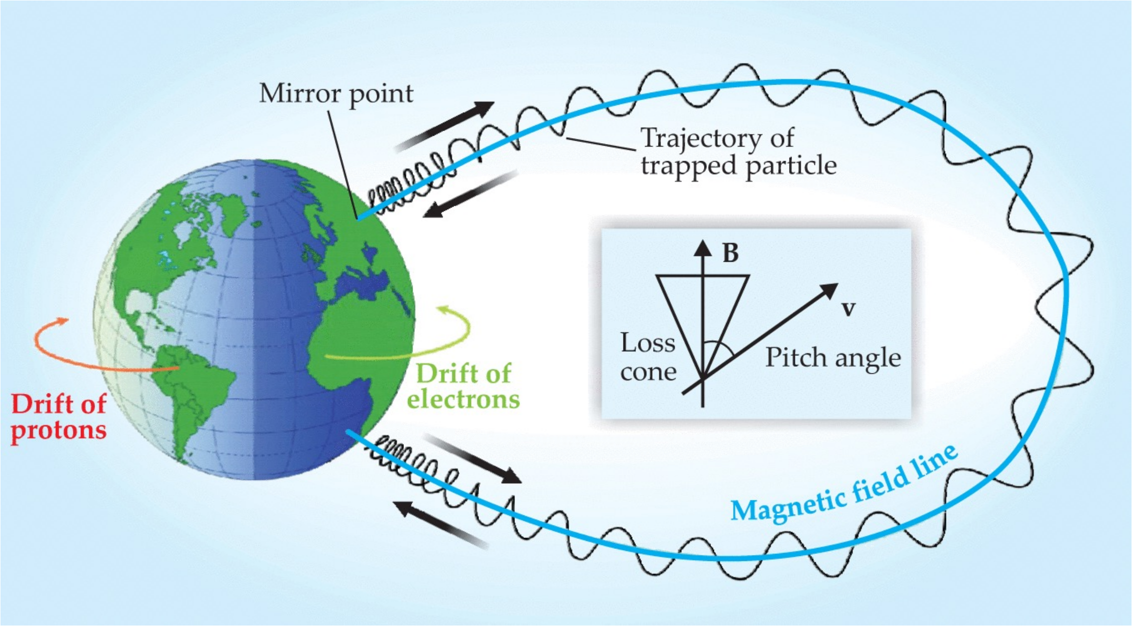


(source: NASA)



- Some of the particles entering the magnetosphere become trapped in Earth's Van Allen radiation belts
- The charged particles bonce back and forth along magnetic field lines between Earth's north and south polar regions

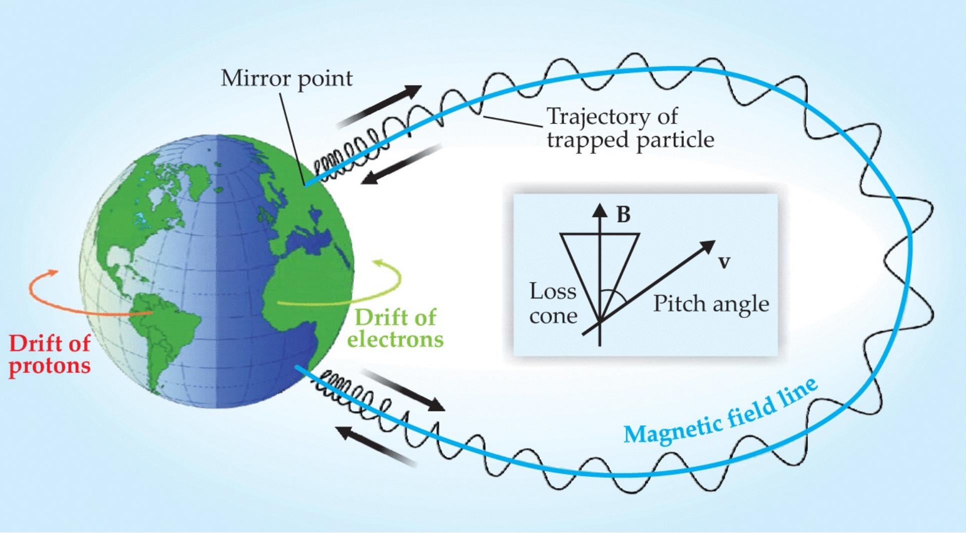
Equatorial Ring Current

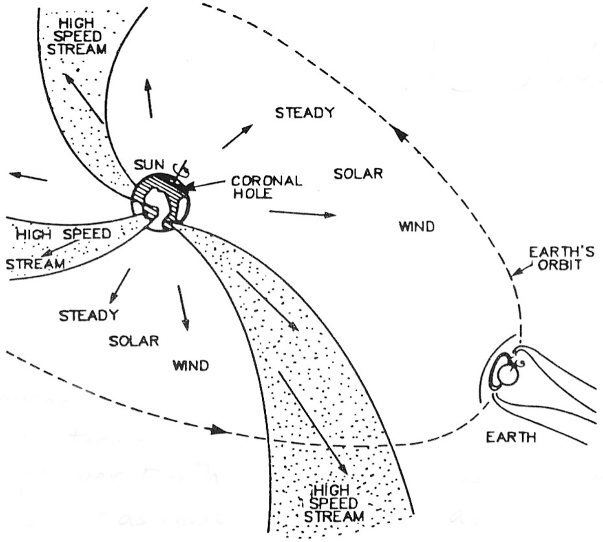


(source: Physics Today – Scitation)

- At an altitude of approximately 10,000 miles above the equator gradients in Earth's magnetic field cause the trapped positively charged particles to drift westward while the trapped electrons drift to the east, creating a westward equatorial electrical ring current

Geomagnetic Storm

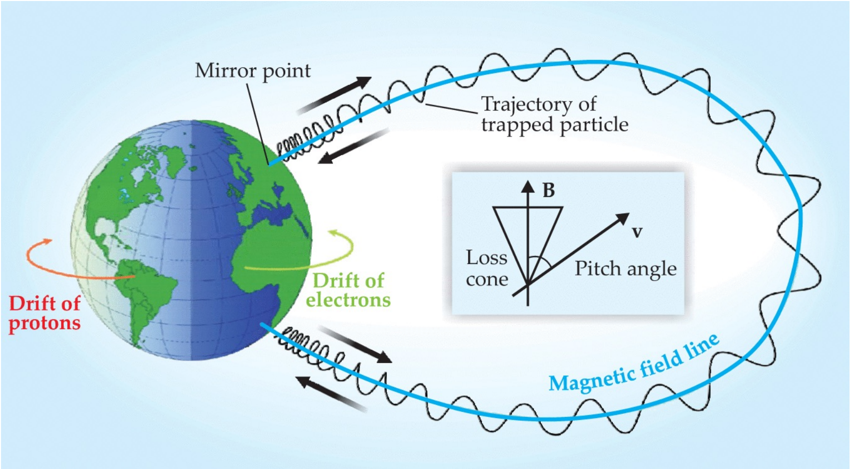


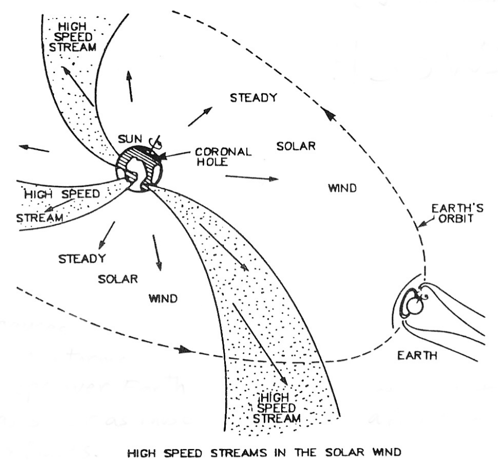


HIGH SPEED STREAMS IN THE SOLAR WIND

- The equatorial ring current is the primary cause of geomagnetic storms
- Normally the ring current is in a quiescent state
- The strength of the ring current dramatically increases when a HSS wind sweeps past Earth injecting huge quantities of solar wind particles into the radiation belts
- The fluctuating ring current produces its own magnetic field which opposes Earth's core magnetic field causing the core field itself to fluctuate
- This is a geomagnetic storm

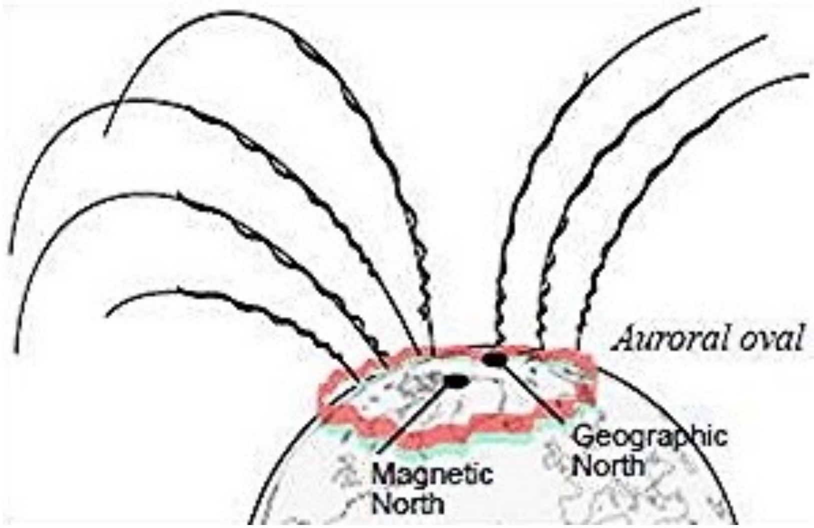
Impact of a Geomagnetic Storm





- A fluctuating magnetic field induces high electrical currents in electrical power distribution systems potentially causing devastating damage and long power outages
- Induced electrical currents also weaken long pipe lines and seriously damage other infrastructure perhaps causing hundreds of billions of dollars in damage
- This threat is the reason fleets of spacecraft are orbiting the Earth and Sun monitoring and studying solar events that could produce catastrophic geomagnetic storms

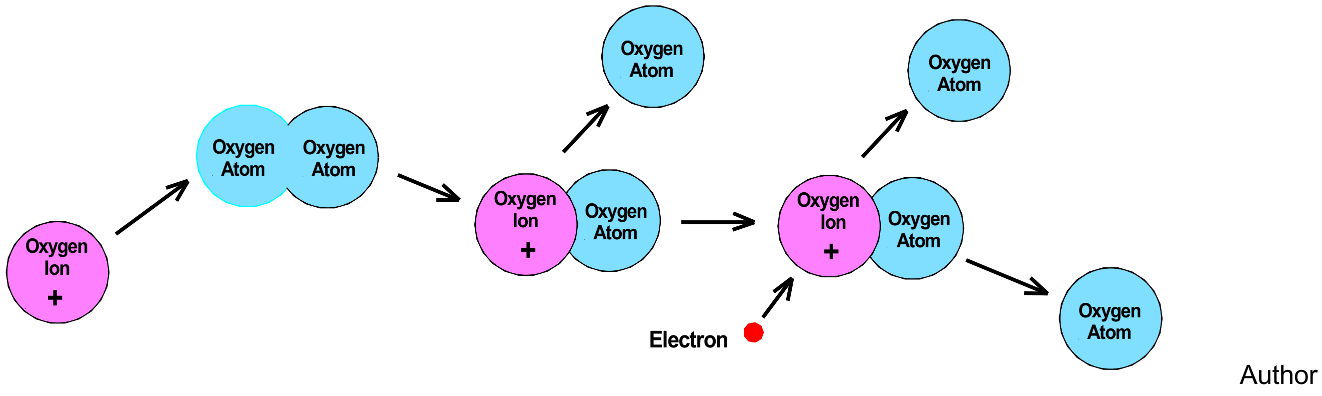
Ionospheric Solar Wind Storms



(source: NOAA Space Environment Center)

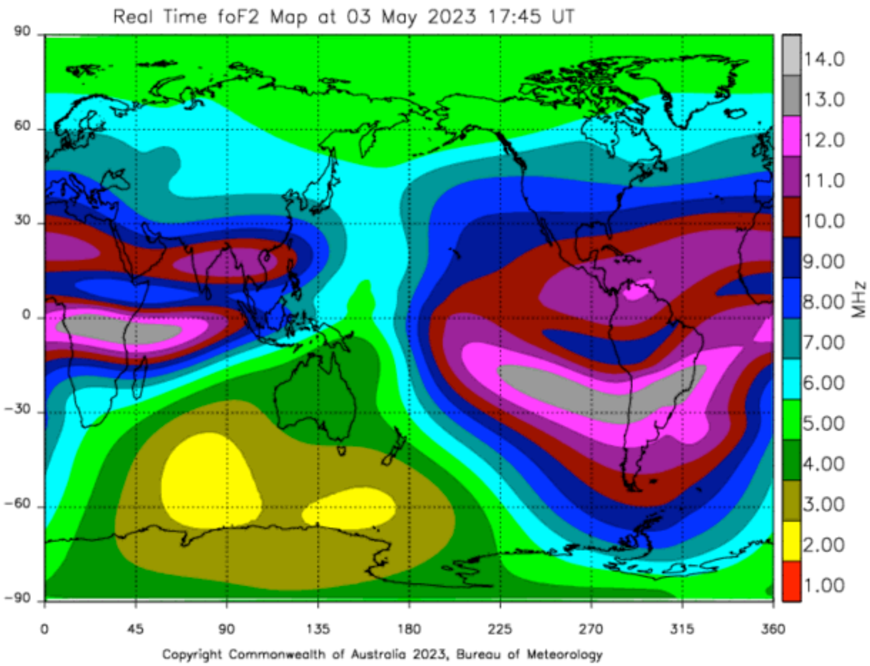
- Development of an ionospheric solar wind storm is much different
- Not all of the solar wind particles streaming into the magnetosphere are captured in the radiation belts
- Some continue down through the radiation belts and associated equatorial ring current into Earth's auroral zone atmosphere
- **Collisions of these particles with neutral atoms & molecules change**
  - The chemical composition of the auroral ionosphere,
  - Heat the atmosphere, and
  - Change the circulation patterns of the thermospheric winds.

Ionospheric Solar Wind Storms continued

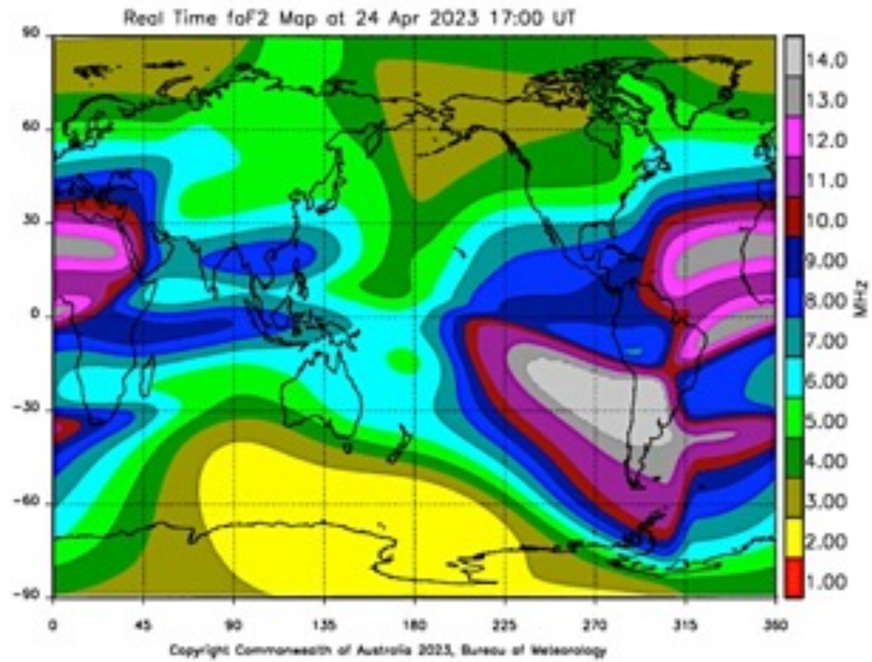


- Heating plus changes in chemical composition accelerate the recombination of electrons with ions
- This decreases electron densities in the auroral ionosphere, particularly in the F2 region
- Convection currents carry the electron depleted auroral plasma down into mid latitudes causing F2 layer critical frequencies to drop by a factor of 2 or more.
- The drop in critical frequency impacts the higher HF bands more than lower frequencies.
- Radio frequencies from 20 through 10 meters are affected most
- These bands often disappear for a week or more

Impact of an Ionospheric Solar Wind Storm



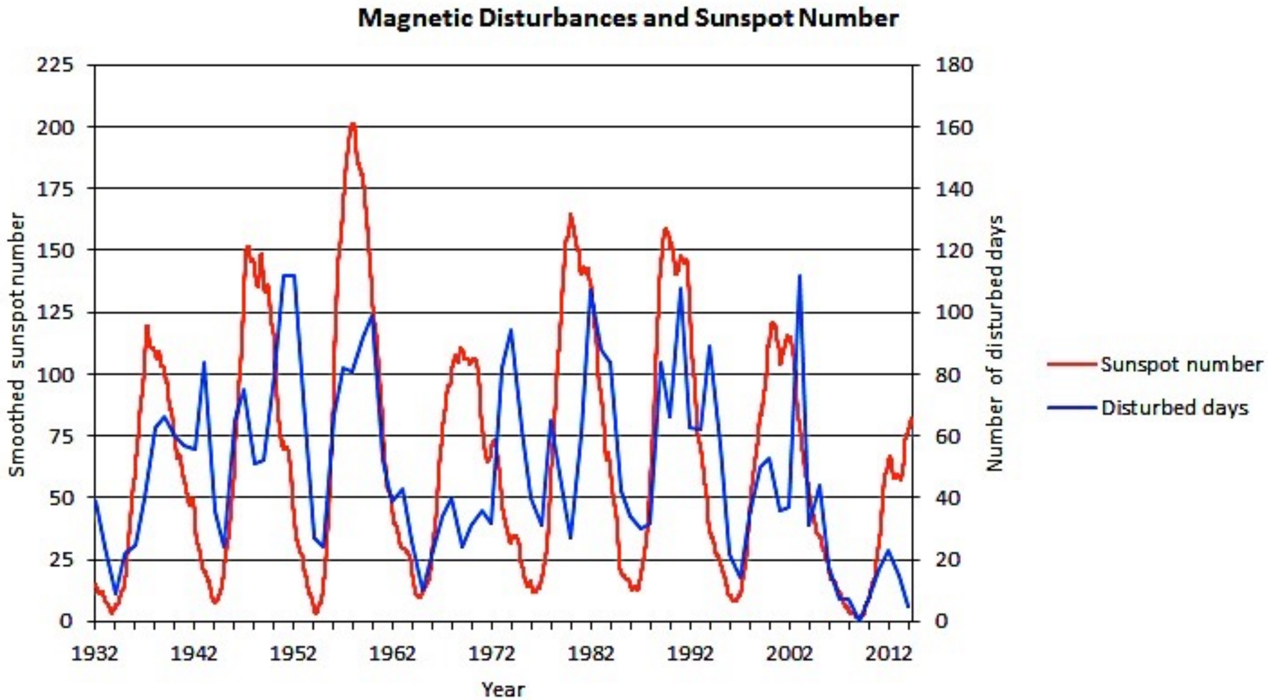
In The Absence of a Storm



Ionospheric Solar Wind Storm

- In these figures, critical frequencies are relative high in the absence of a storm, ~ 8 MHz in the central part of the United States
- During an ionospheric solar wind storm critical frequencies drop by a factor of 2
- For the above storm critical frequency dropped from 8 to around 5 MHz
- Forcing radio operations to lower frequencies (for example from 20 to 40 meters)

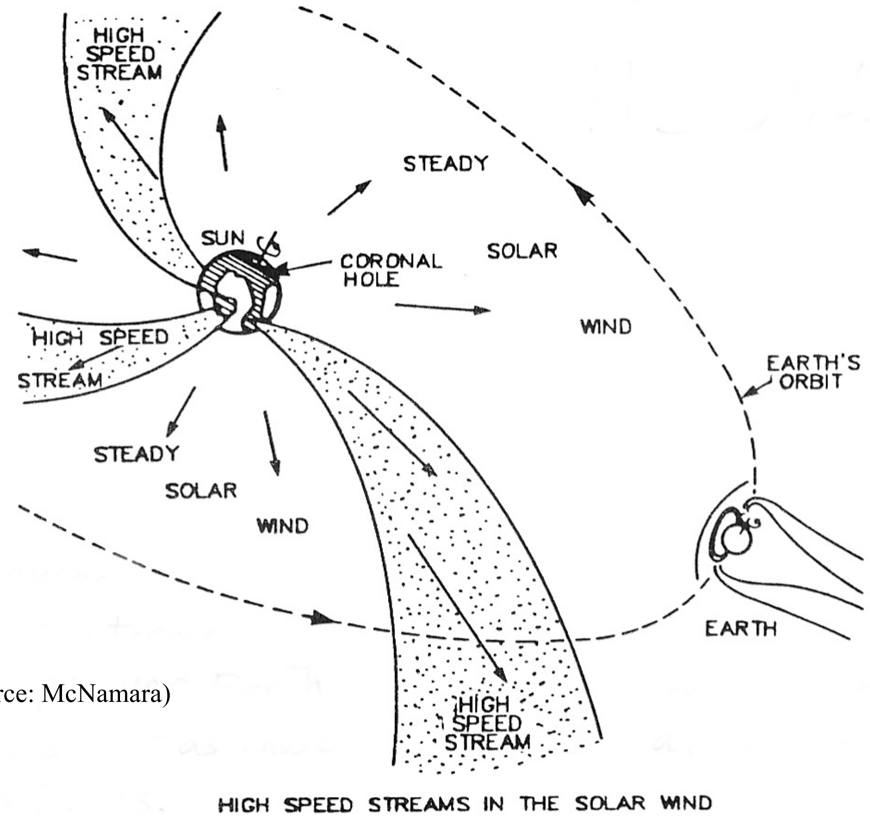
Highest Occurrence of Solar Wind Storms



(source: Space Weather Services)

- Surprisingly, the highest occurrence of solar wind storms occurs during the declining phase of the solar cycle, one to two years following solar maximum
- These storms are produced primarily by coronal holes.
- Unlike solar flares, coronal hole induced solar wind storms are **not** preceded by x-ray or high energy particle storms

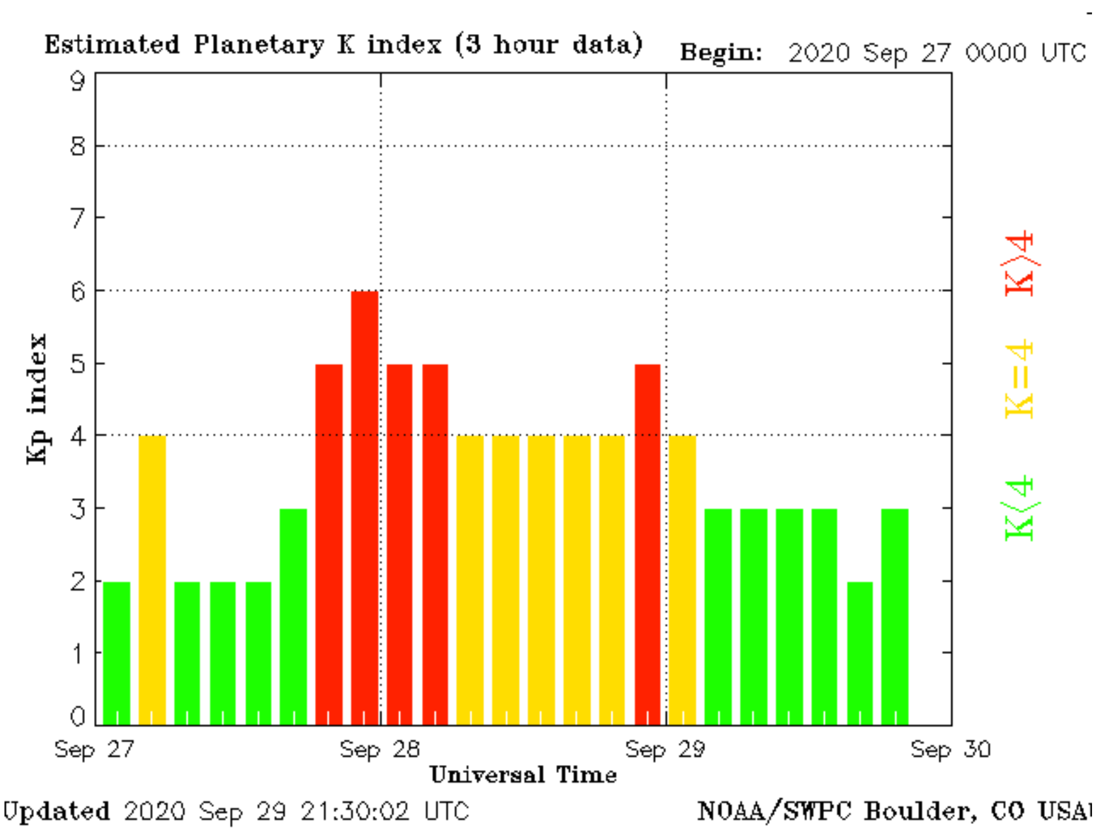
Reoccurring Coronal Hole Storms



(source: McNamara)

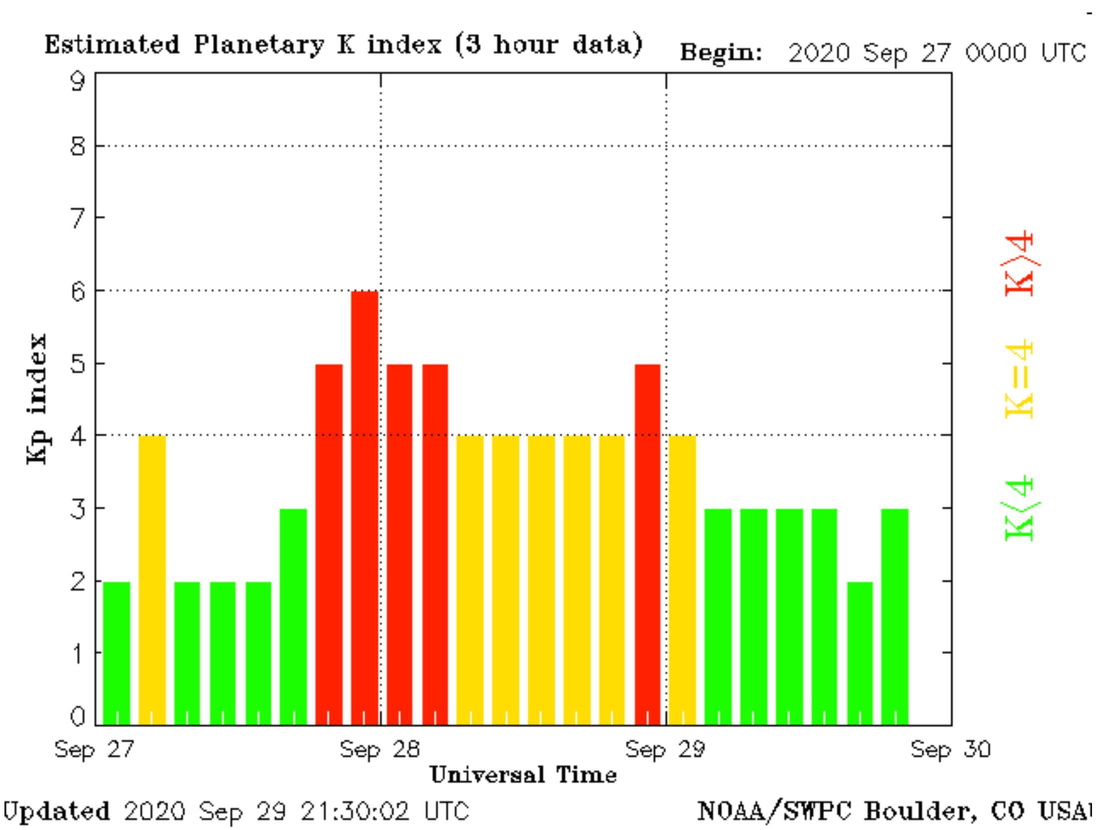
- Coronal holes can last for a long time
- Consequently, high speed solar wind flowing out of a particular coronal hole can sweep past Earth with each solar rotation
- As a result,
- Coronal hole induced solar wind storms can reoccur every 27 days

Kp Index is a Magnetic Field Indicator



- The planetary Kp index is a measure of geomagnetic activity
- A low K_p value ($K_p < 4$) indicates that Earth's magnetic field is quiet and solar winds are subdued
- **A K_p value around 4** indicates that the magnetic field is moderately active as the result of a modest solar wind
- A high K_p value ($K_p > 4$) signifies that a strong solar wind with a southward directed IMF is impacting Earth producing an intense geomagnetic storm.

Kp Also Indicator For Ionospheric Storms

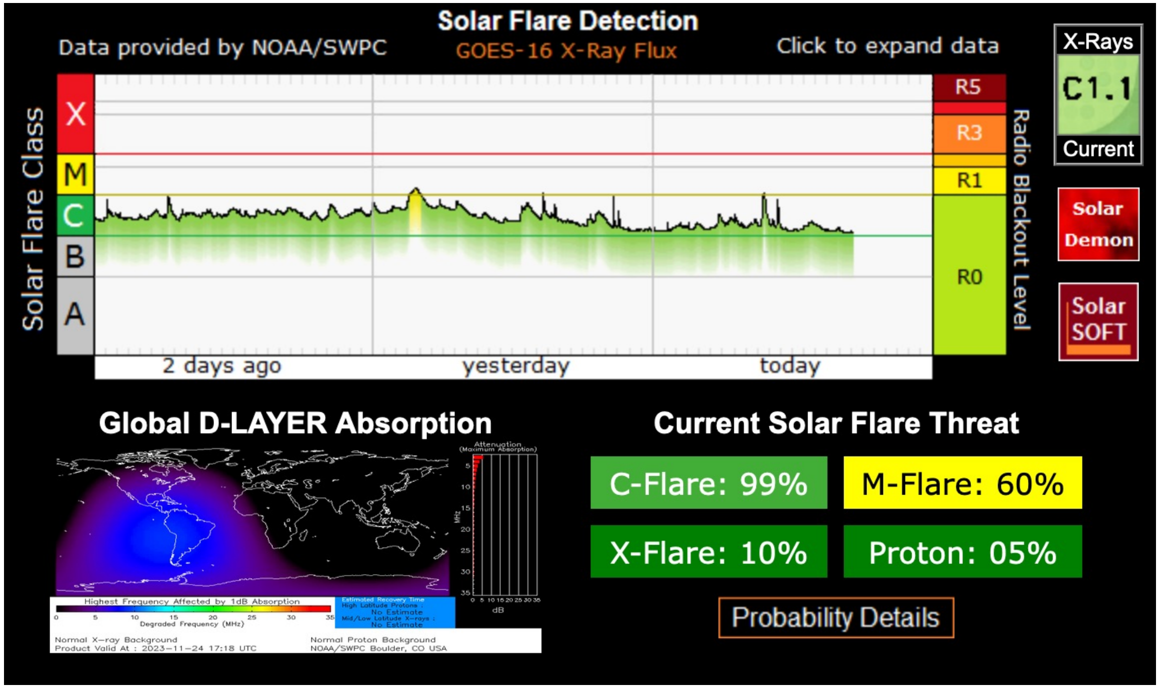


- The planetary Kp index is also a good measure of ionospheric solar wind storm severity
- Ionospheric solar wind and geomagnetic storms both result from strong solar winds with southward directed IMFs impacting Earth
- A high K_p value indicates that a strong ionospheric solar wind storm is occurring
- The storm suppresses F2 critical frequencies and adversely affects radio operations on 20 thru 10 meters

Conclusions

- Before turning on your radio
- Check ionospheric weather conditions by going to the “Current Conditions” tab at www.skywave-radio.org to determine if ionospheric storms are occurring
- Check for:
  - X-ray radiation storms,
  - High energy particle storms, and
  - Solar wind storms.

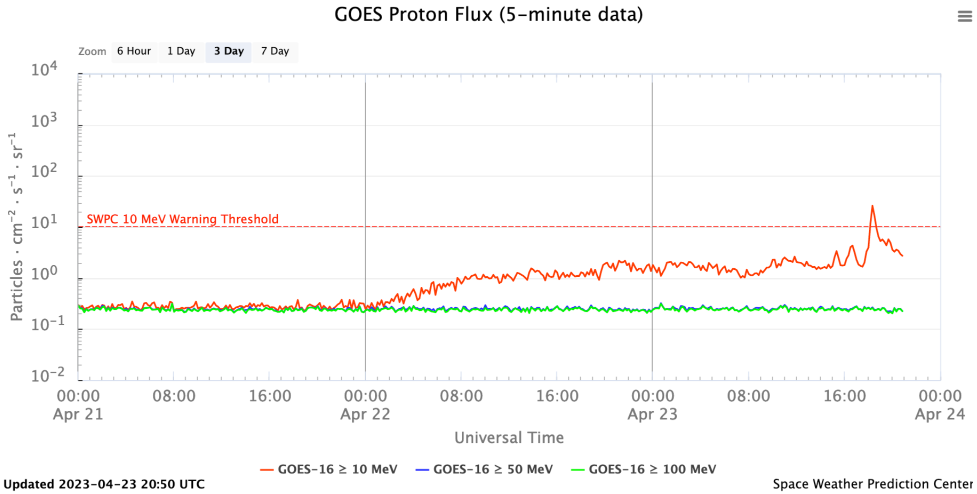
X-ray Radiation Storms

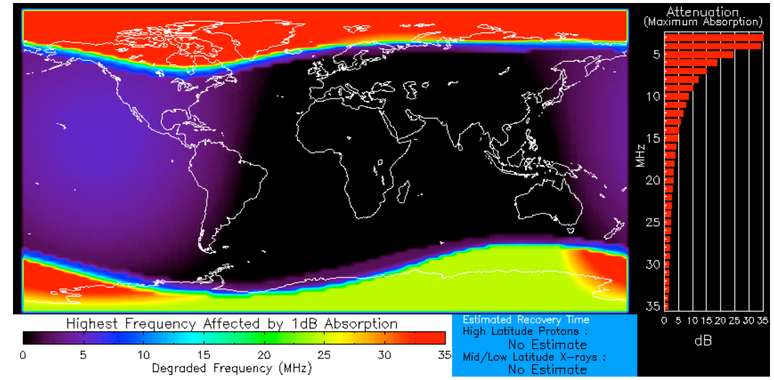


SolarHam VE3EN

- The presence of radiation storms is shown under the Space Weather Conditions tab
- On Nov. 24, 2023 (above figure) there were no radiation storms in progress since the X-ray flux was below M and X levels, however there was a:
- 99% chance of a C-Flare producing a minor radiation storm,
- 60% chance of a M-Flare producing a moderate radiation storm, and
- 10% chance of a X-Flare producing a strong radiation storm

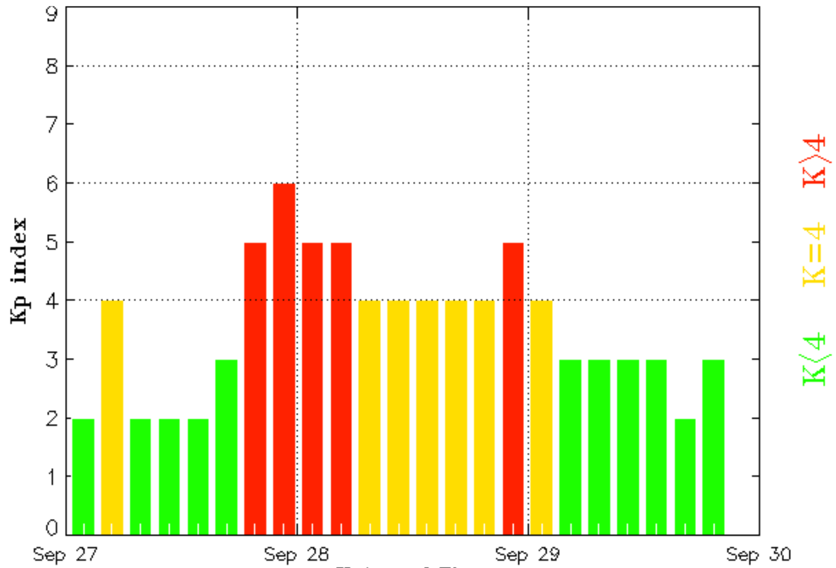
High Energy Particle Storms

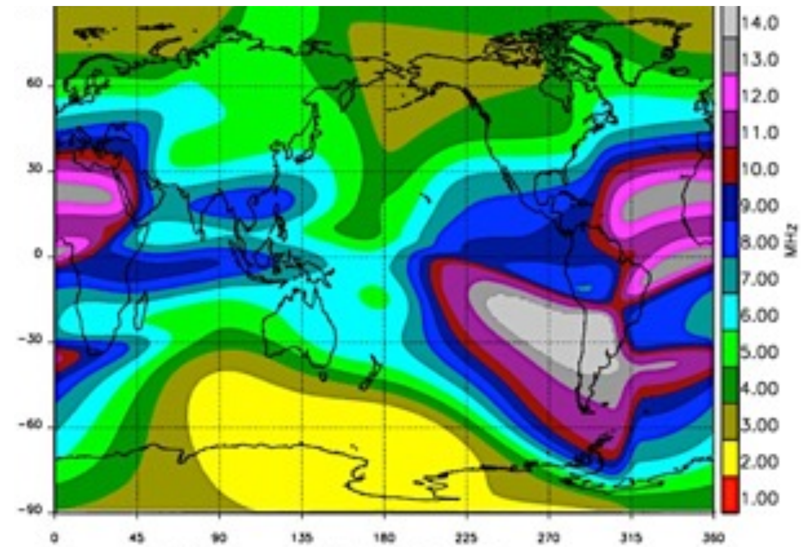




- Occurrence of high energy particle storms is shown under the Proton Flux tab
- On April 23, 2023 (above figure) proton flux levels crossed the 10 MeV warning threshold creating a short high energy particle storm and associated polar cap absorption PCA event
- Transpolar propagation should be avoided if a high energy particle storm is in progress with its accompanying PCA event. Under such conditions D-level absorption is very high over the poles (in the red)

Solar Wind Storms





- The K_p chart and critical freq levels indicates the presence of solar wind storms
- On Sept. 28 K_p values were somewhat high (in the red zone) but not as high as they could be, indicating perhaps a minor solar wind storm
- Critical frequencies over North America were lower than they had been indicating a solar wind storm
- During solar wind storms radio operations must move to lower frequencies, for example from 20 meters down to 40 meters, for perhaps a week or so