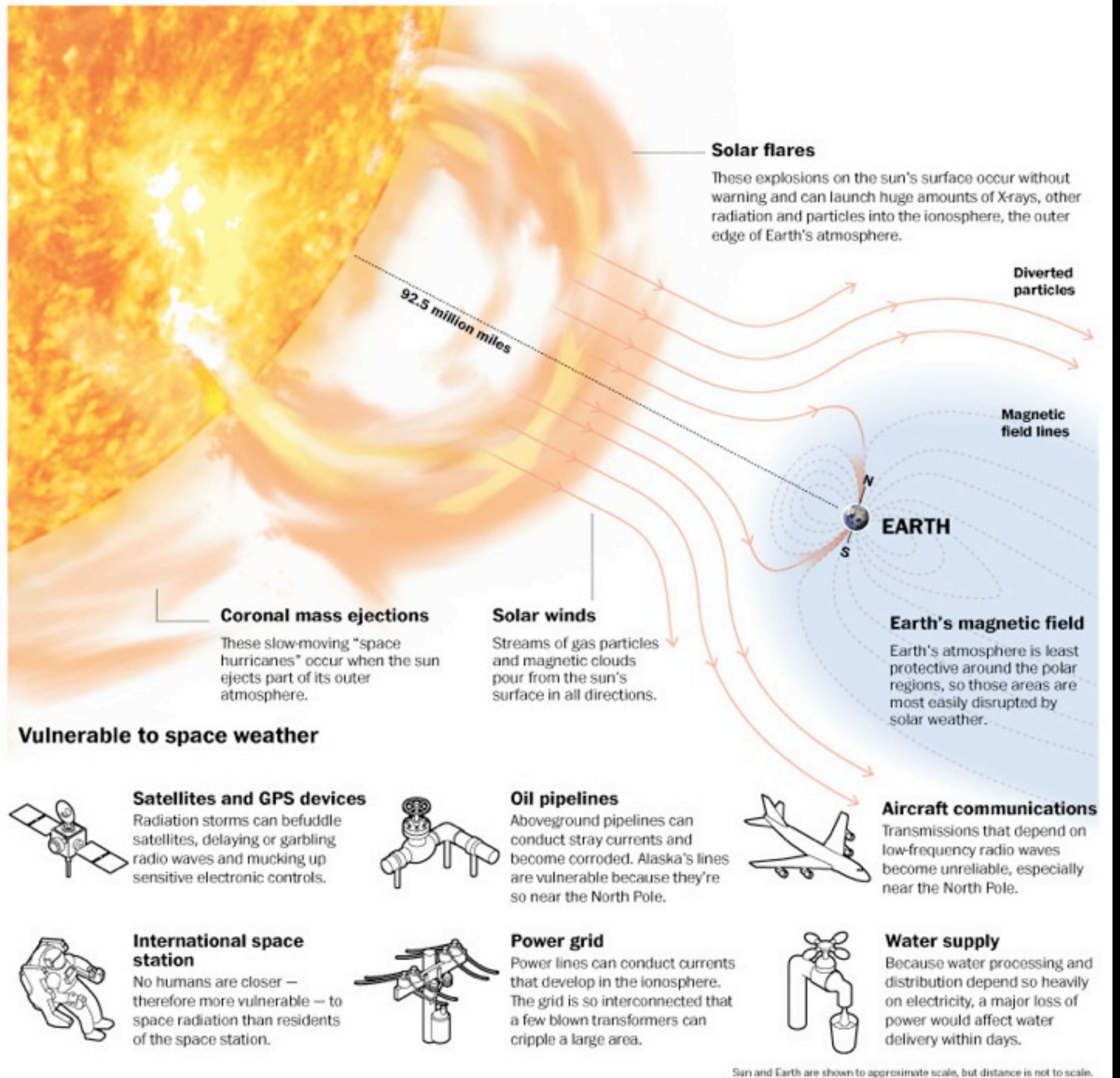
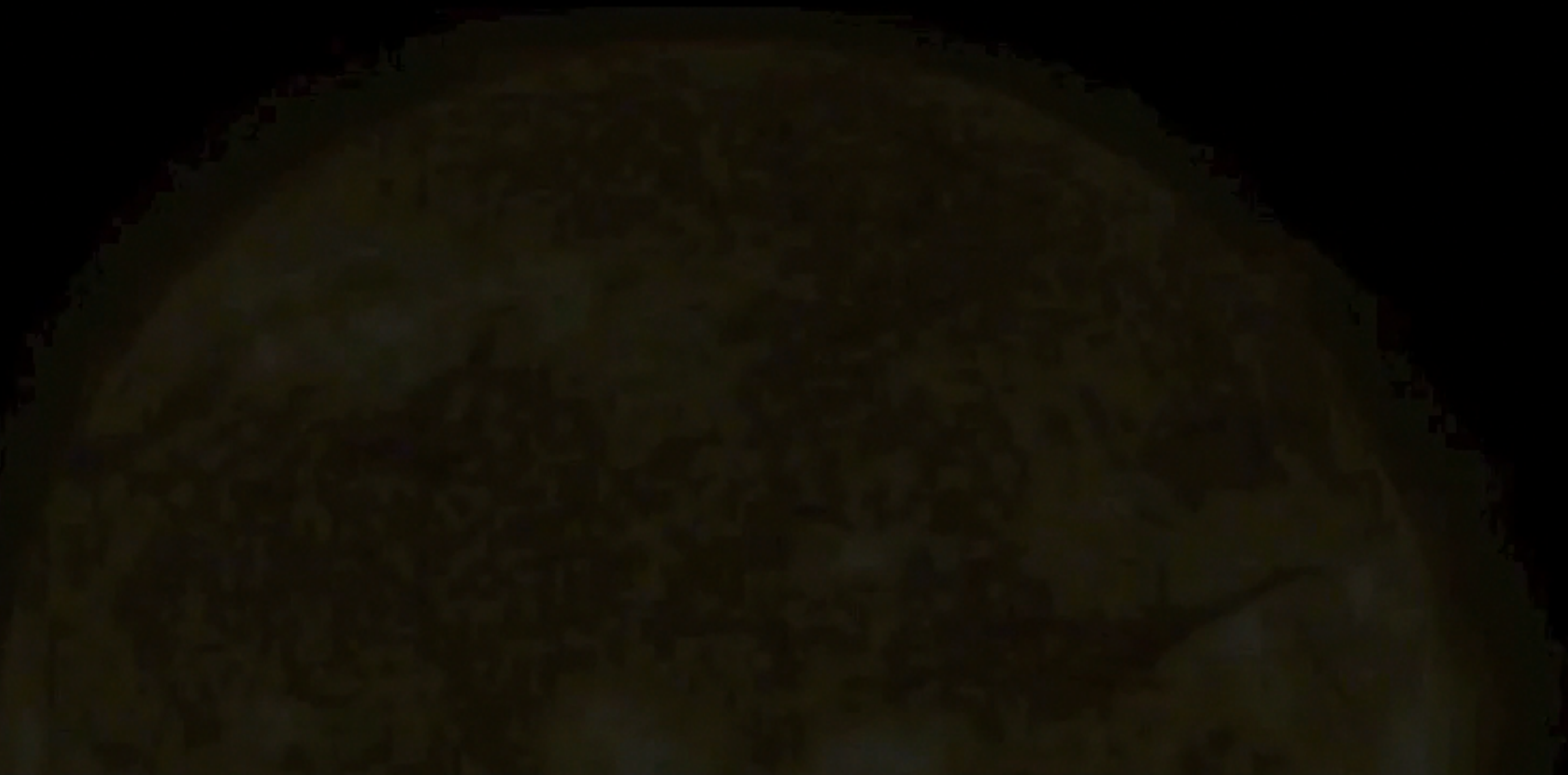
Space Weather in Ionosphere and Thermosphere

Yihua Zheng

For SW REDI 2015

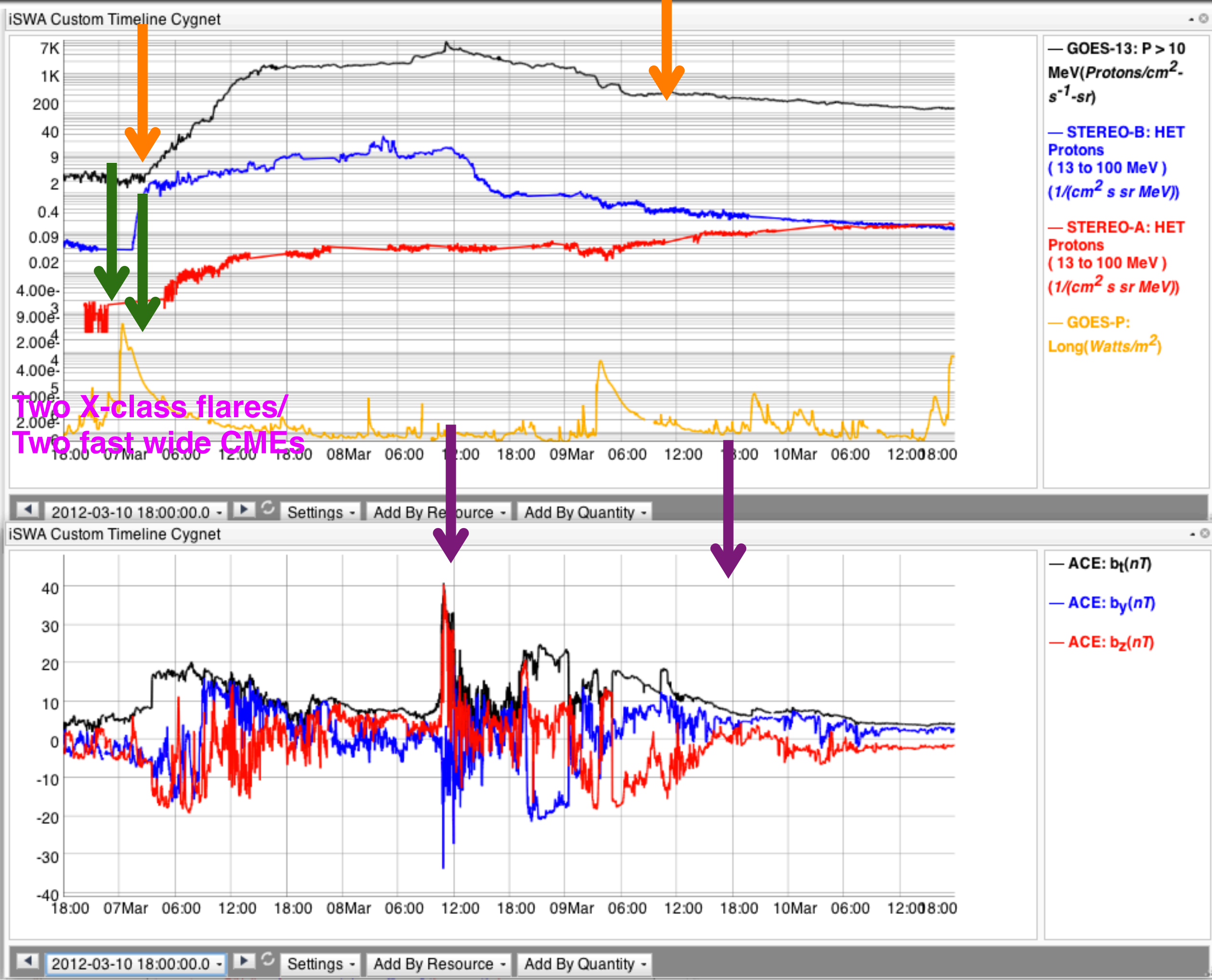
Space Weather Illustrated





Space Weather Effects and Timeline

(Flare and CME)



Flare effects at Earth:
~ 8 minutes (radio blackout storms)
Duration: minutes to hours

SEP radiation effects reaching Earth: 20 minutes – 1hour after the event onset
Duration: a few days

CME effects arrives @ Earth: 1-2 days (35 hours here)
Geomagnetic storms: a couple of days

Types of Storms

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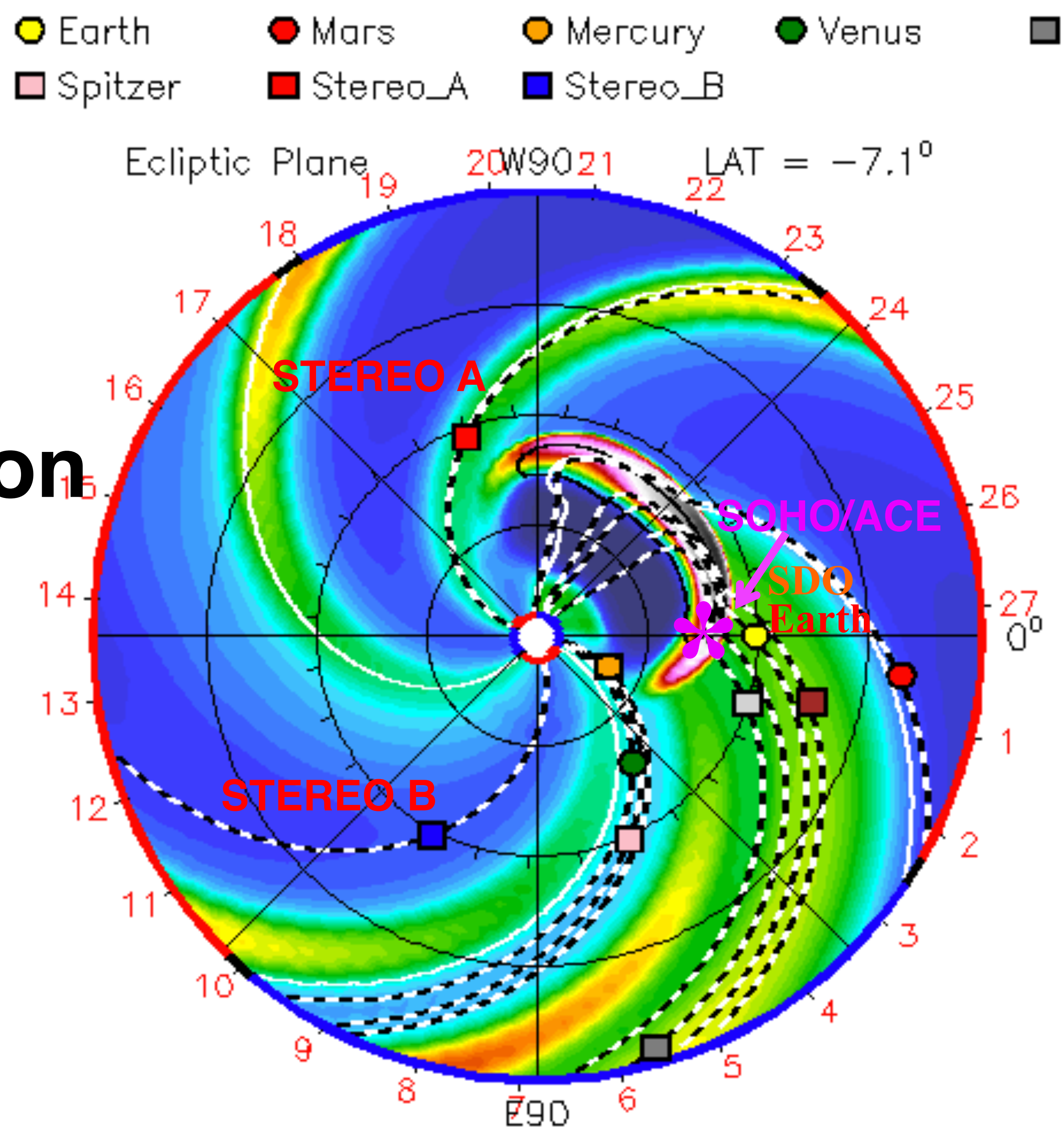
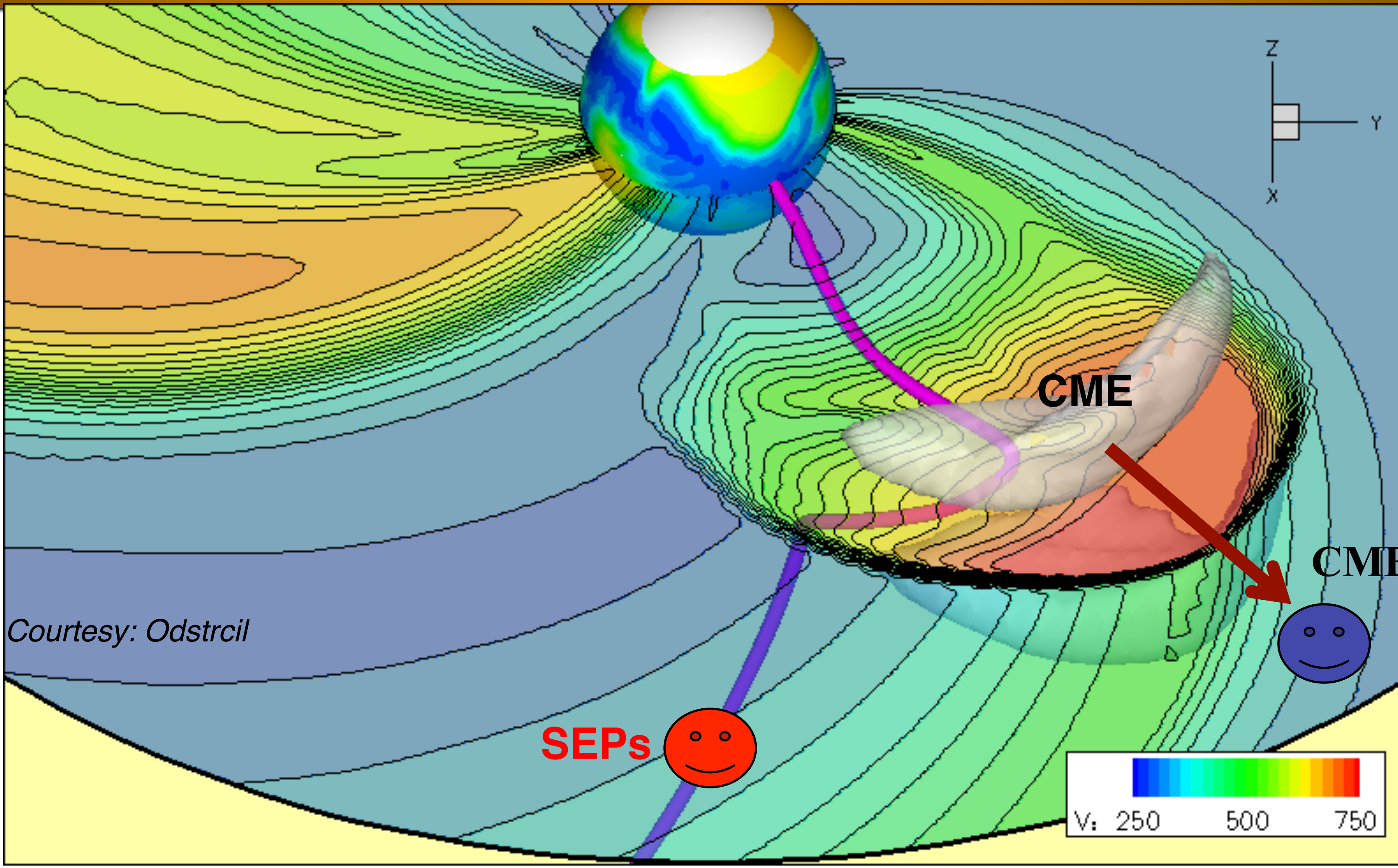
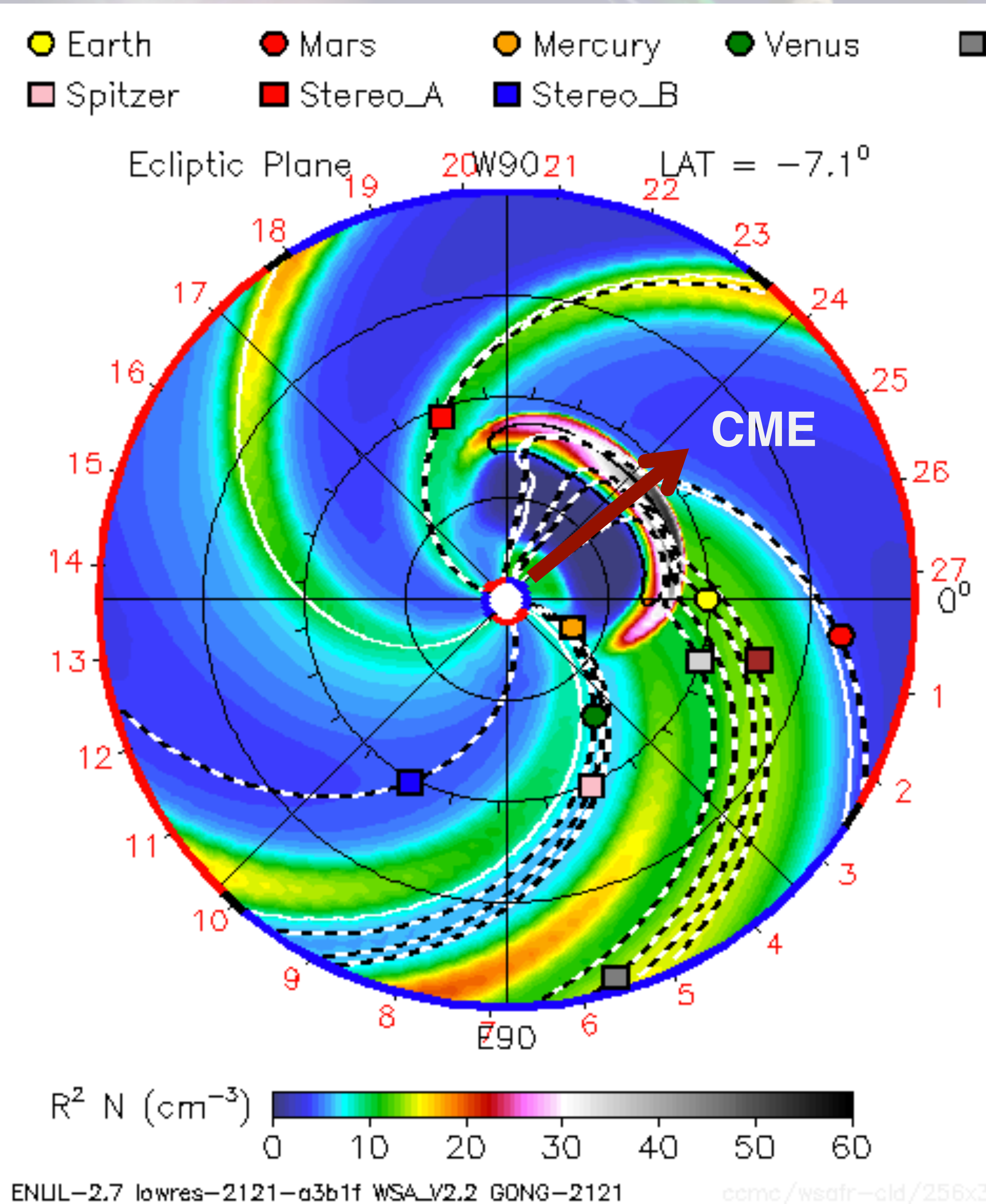


Earth
Mars
Mercury
Venus
Spitzer
Stereo_A
Stereo_B
Ecliptic Plane
W90
LAT = −7.1°
E90
STEREO A
STEREO B
SOHO/ACE
SDO
Earth

CME and SEP path are different



CME: could get deflected, bended, but more or less in the radial direction



Important distinction

Ion Radiation storm vs Geomagnetic storm

CME impact and SEP (Solar Energetic Particle) impact are different

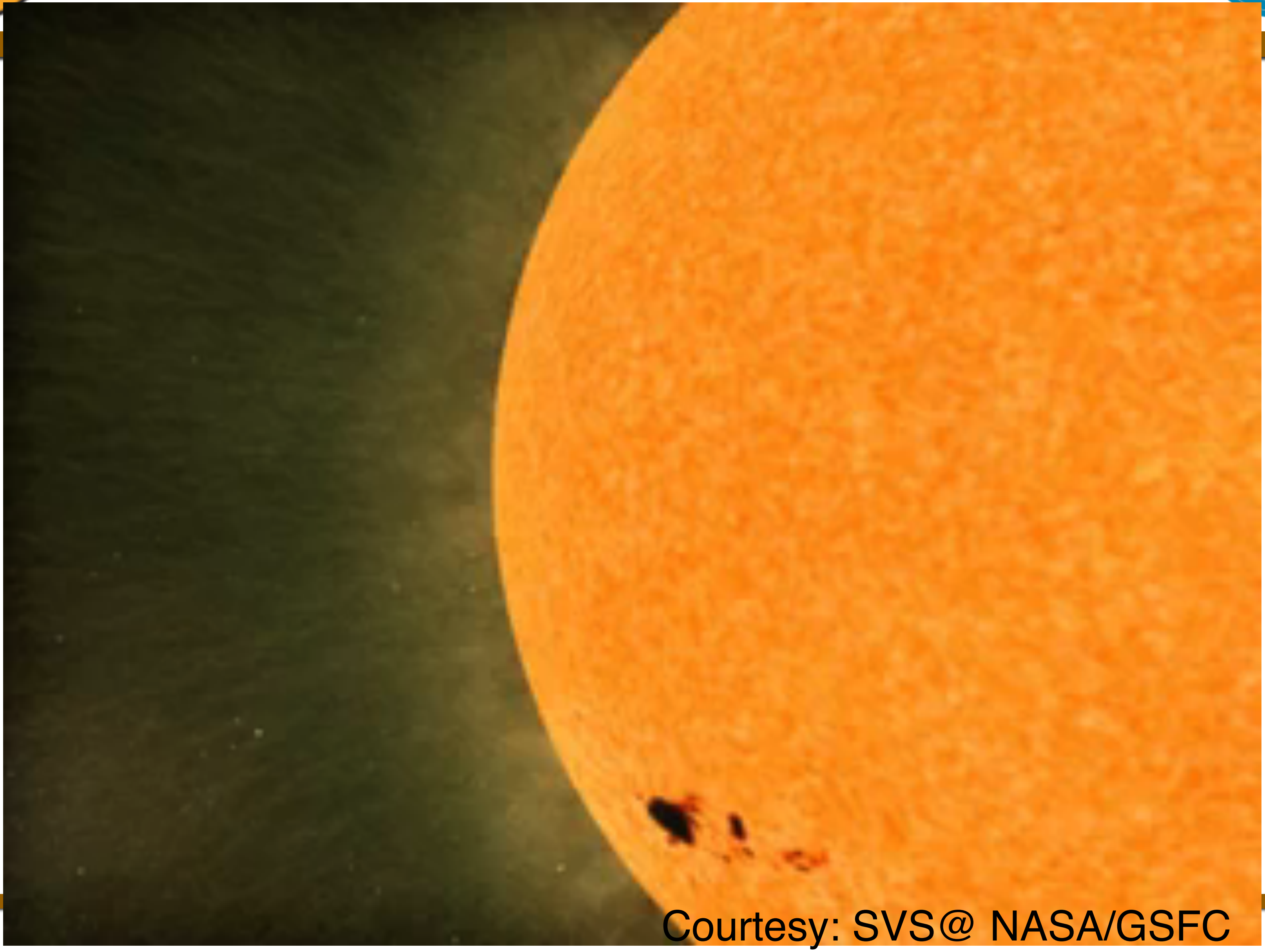
CME impact @ Earth: Geomagnetic Storm

Radiation storm @ Earth from SEPs

CME speed: 300 – 3500 km/s
SEPs: fraction of c
Light speed c: 3 x10^5 km/s

SEPs: ion radiation storms

Potentially affect everywhere in the solar system



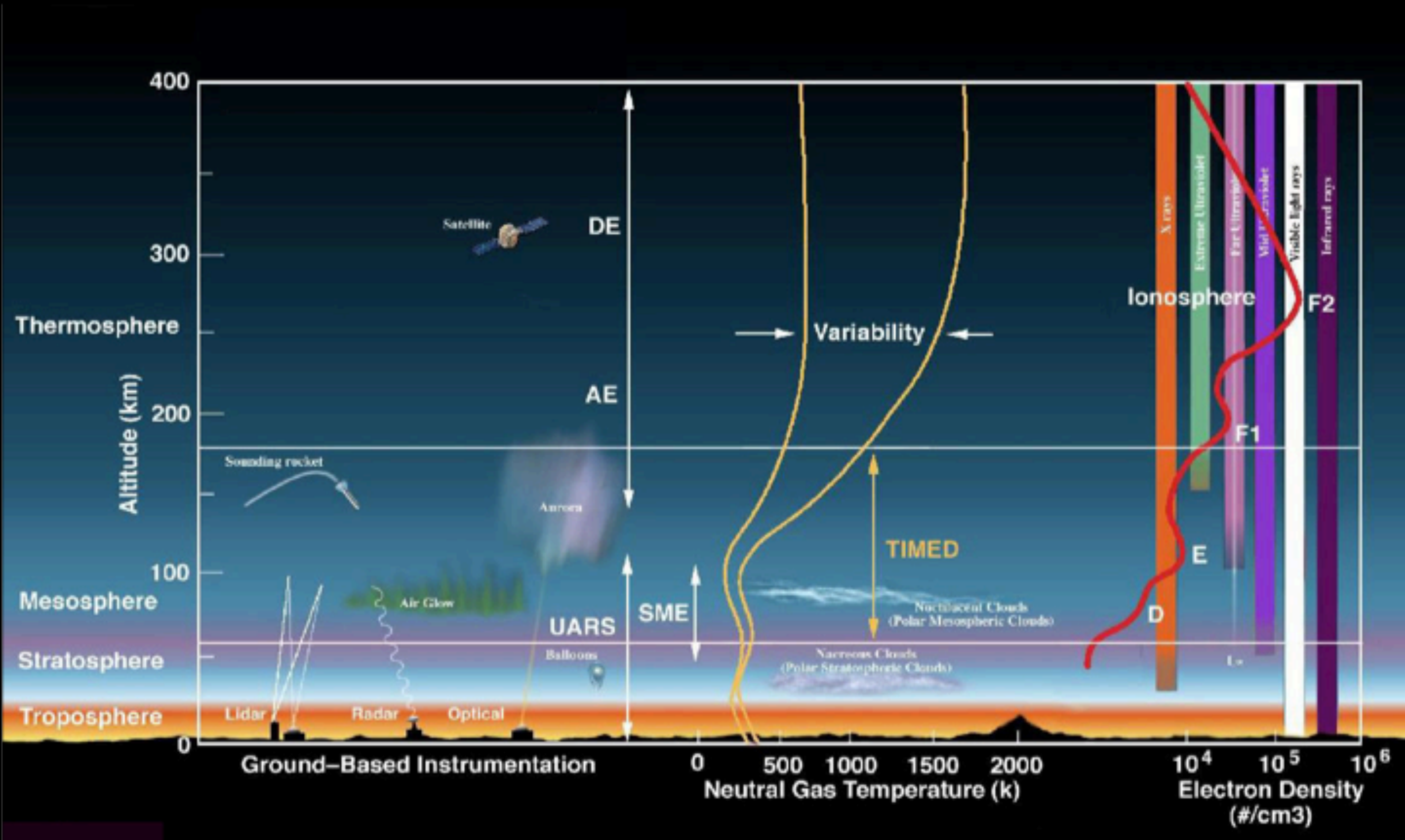
Geomagnetic Storms:

CME interaction with Earth (magnetic field)

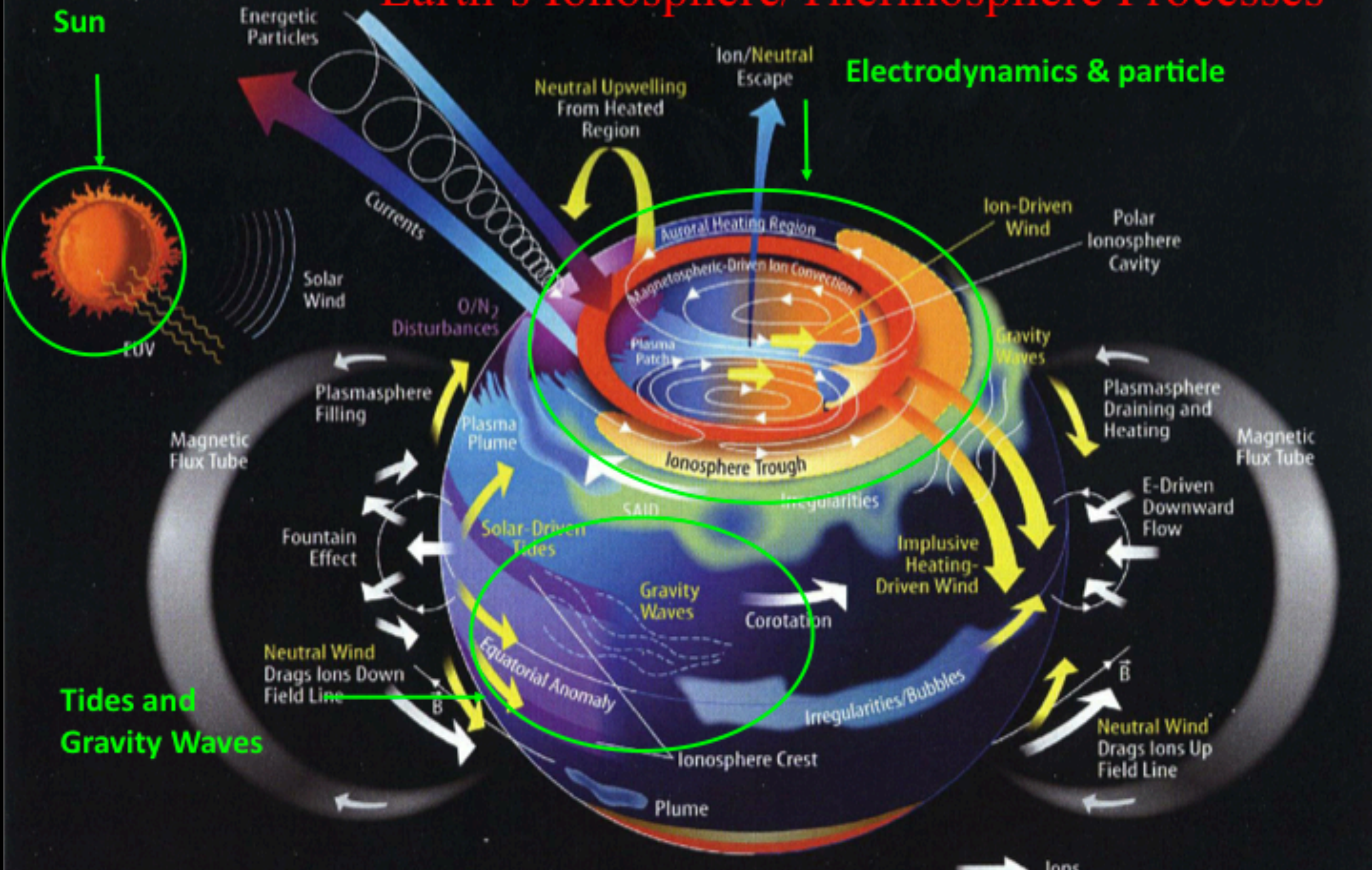
Geomagnetic storms due to CIRs are at most moderate

Ionospheric Dynamics/Storms

Ionosphere - Thermosphere Overview



Earth's Ionosphere/Thermosphere Processes



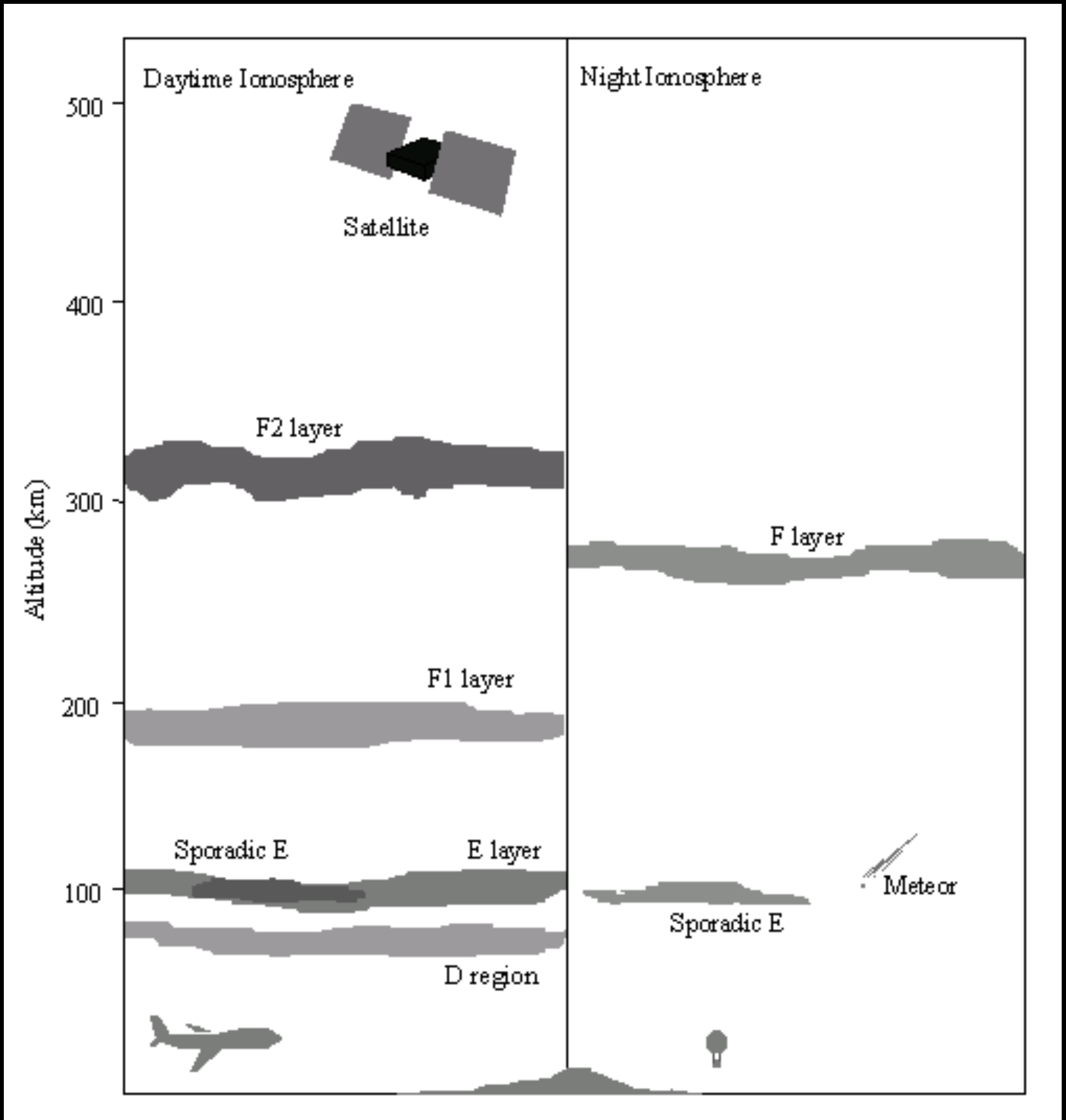
NASA/GSFC, internal use only :-)

Courtesy of Joseph Grebowsky, NASA GSFC

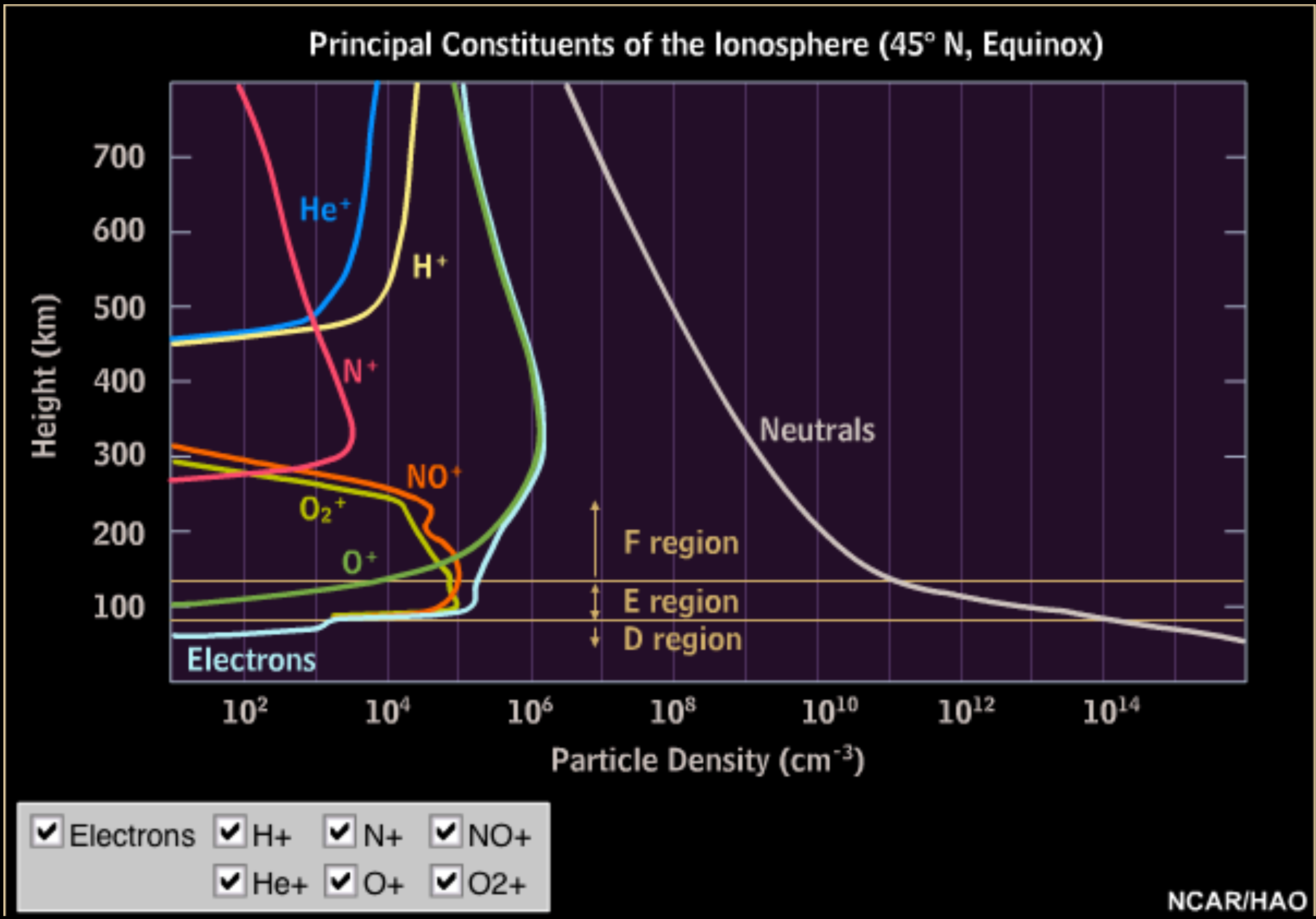
Day/night ionospheric structure

Day/night ionosphere is very different

D region 50 to 90 km;
E region 90 to 140 km;
F1 region 140 to 210 km;
F2 region over 210 km.

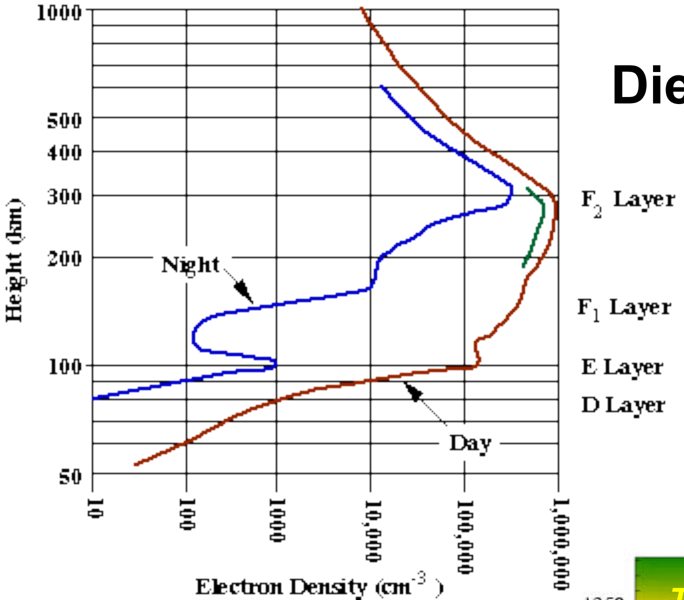


Composition of ionosphere



Ionosphere 101

Formed by solar EUV/UV radiation

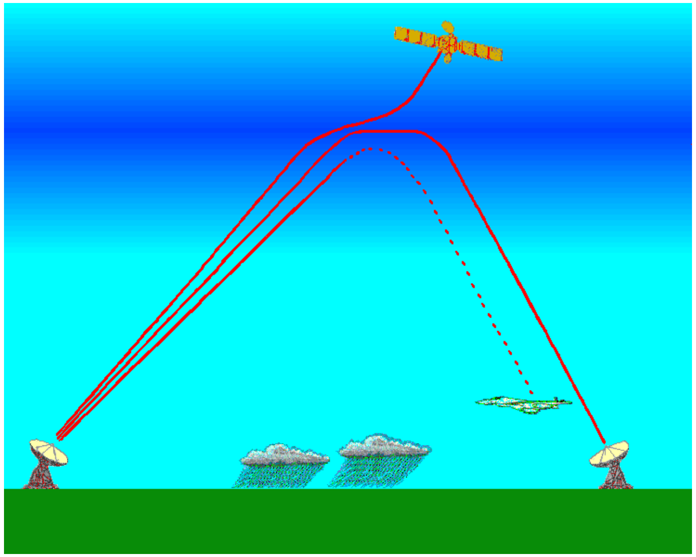


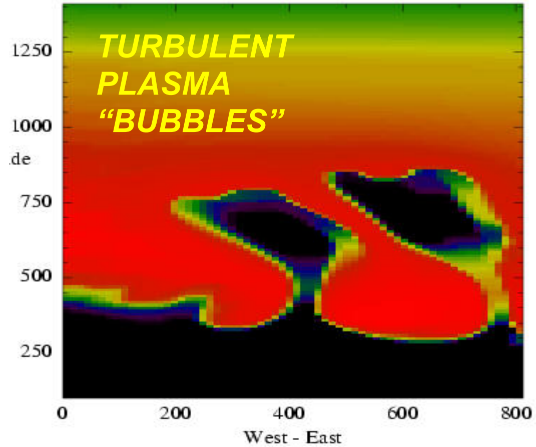
Dielectric Properties

$$\varepsilon = \left(1 - \frac{f_p^2}{f^2}\right)\varepsilon_o$$

$$f_p \approx 9 \cdot 10^3 \sqrt{n_e}$$

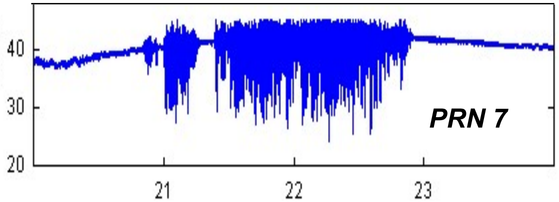
Reflects, refracts, diffracts & scatters radio waves, depending on frequency, density, and gradients





Subject to Raleigh-Taylor instability at night →formation of Equatorial Plasma Bubbles (EPBs)

Leads to highly variable reflection / refraction = "SCINTILLATION"



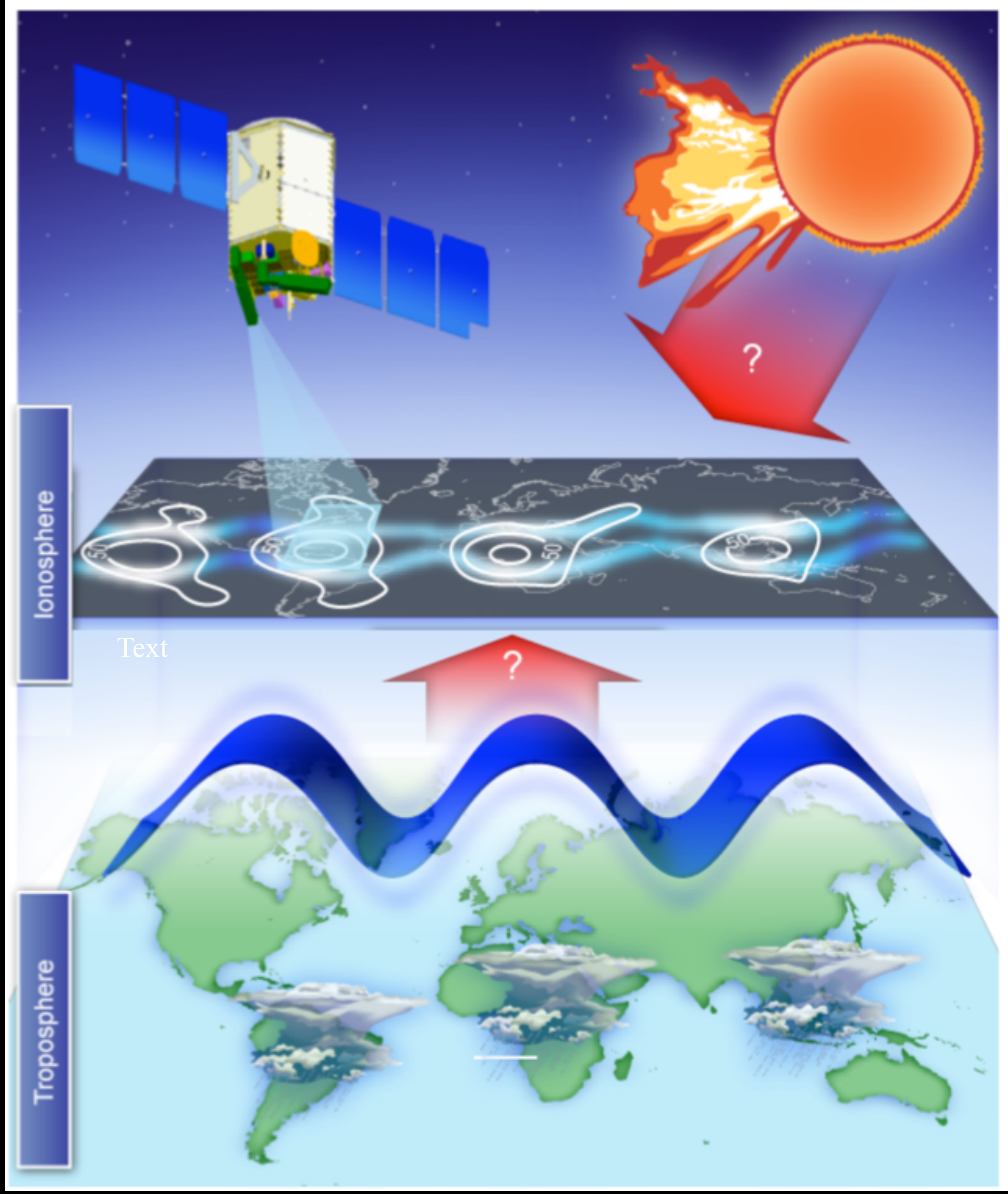
Scintillated GPS Signal

Courtesy: de la beaujardiere

The ionosphere is the densest plasma between the Earth and Sun, and is traditionally believed to be mainly influenced by forcing from **above** (solar radiation, solar wind/ magnetosphere)

Recent scientific results show that the ionosphere is strongly influenced by forces acting from **below**.

Research remains to be done:
How competing influences from above and below shape our space environment.



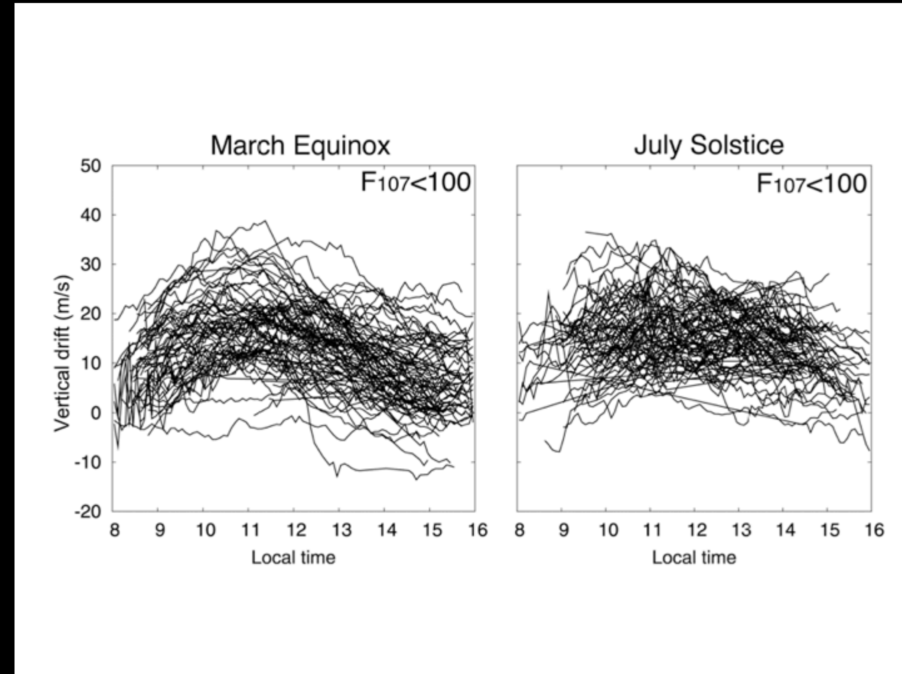
Courtesy: ICON

The daytime ionosphere exhibits significant variability in its motion and density.
the source of these changes: unknown

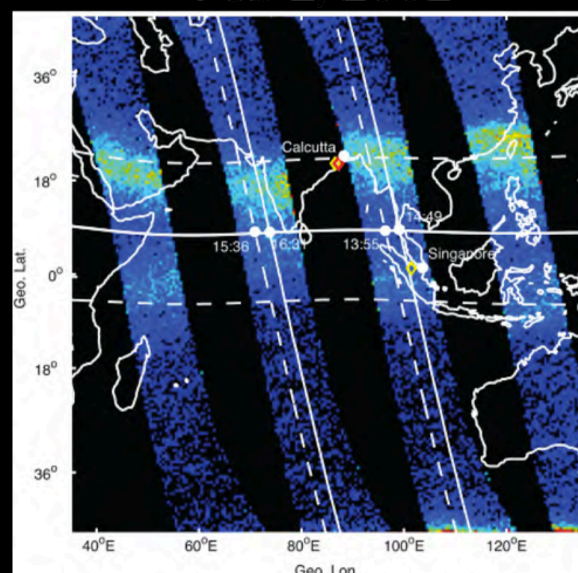
likely originates with modulation of
neutral and/or ionized state variables along the magnetic field - need to be determined

coupled ion-neutral dynamics

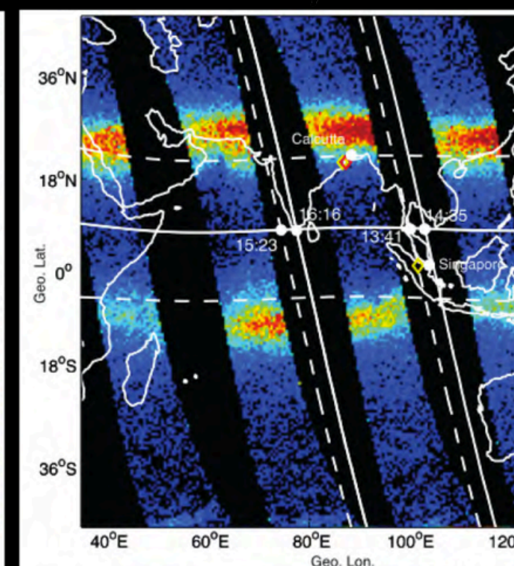
critical



Feb 2, 2002



Feb 3, 2002



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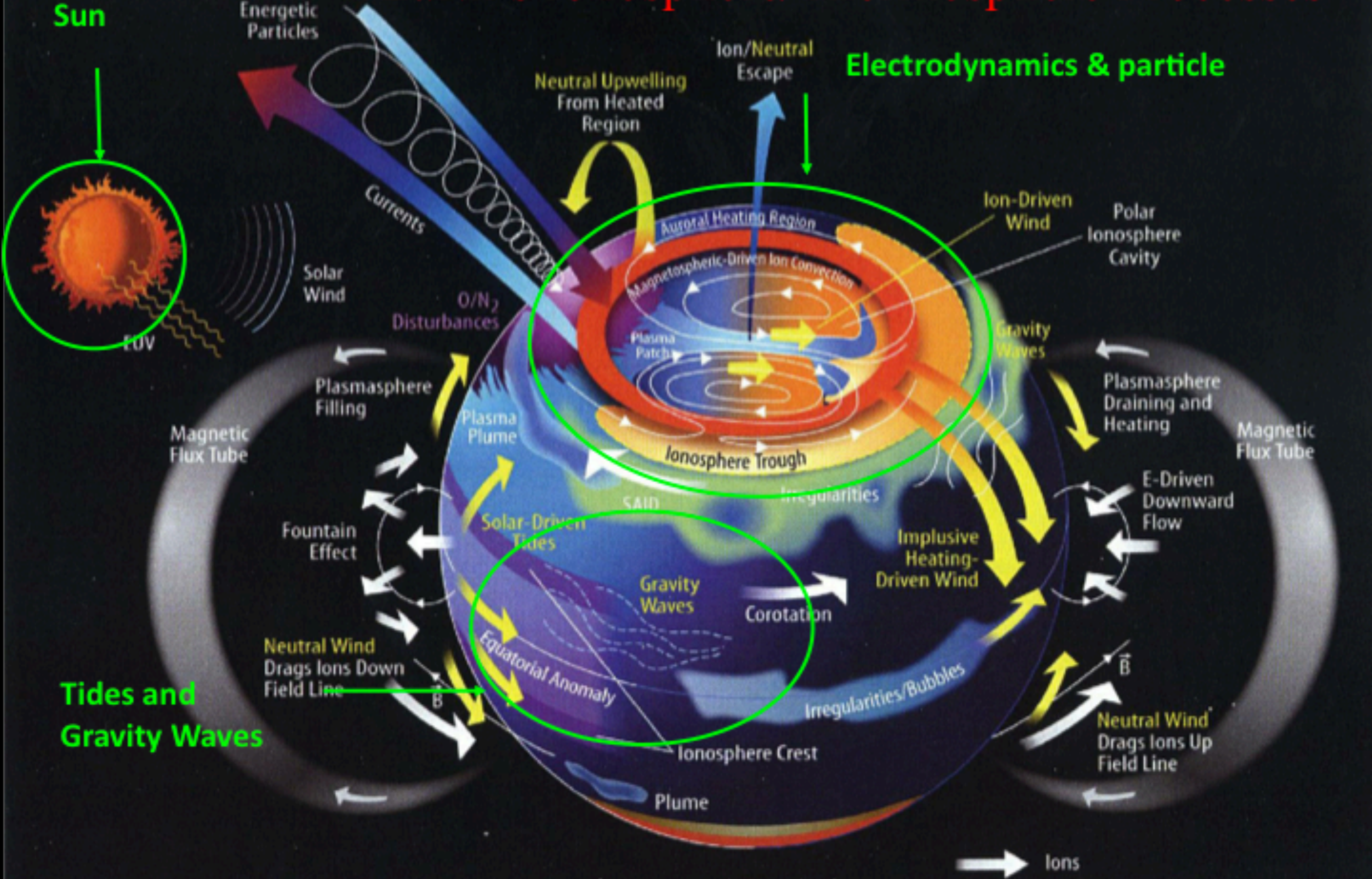


Courtesy of Joseph Grebowsky, NASA GSFC

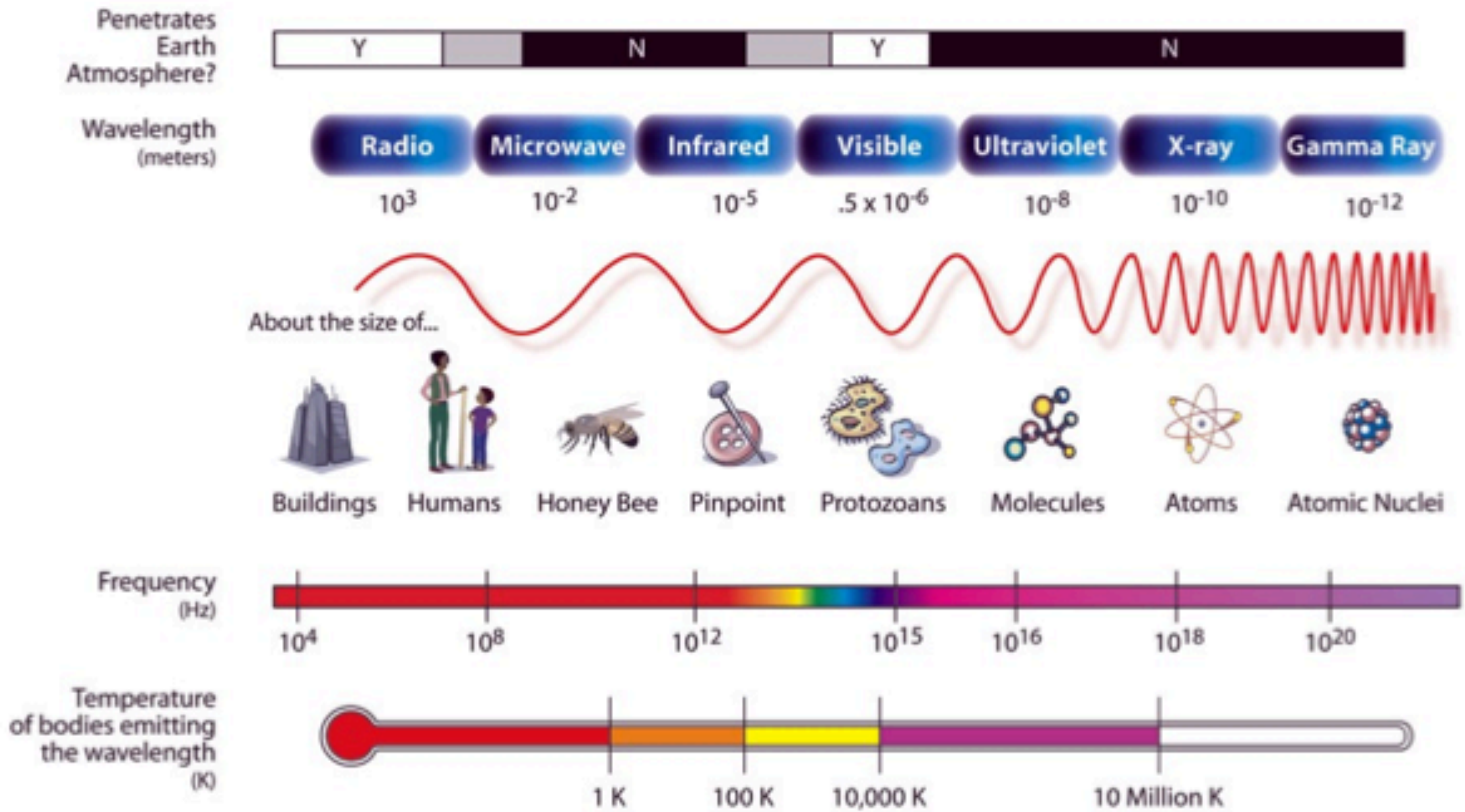
NASA/GSFC, internal use only :-)

Space Weather Phenomena and Effects in the Ionosphere

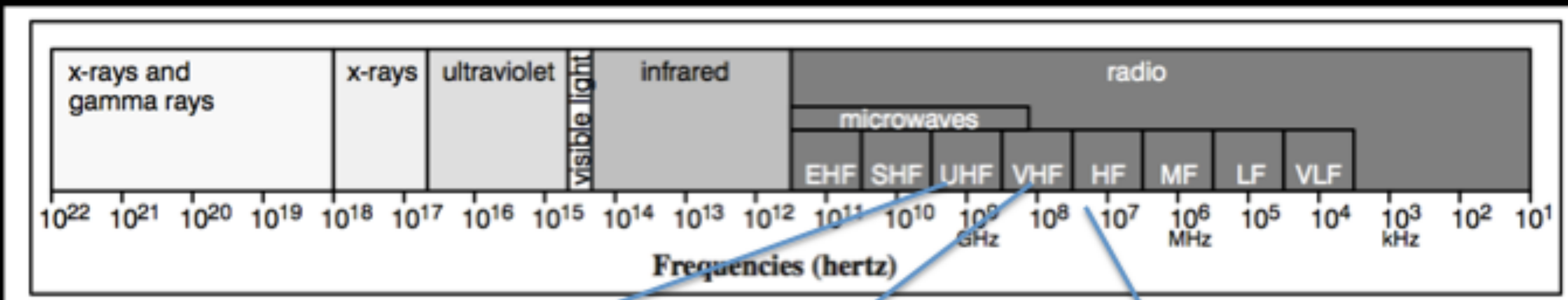
Aurora – hemispheric power (satellite charging, scintillation)
Satellite drag due to neutrals
Equatorial bubbles/irregularities –scintillation, communication problems
Radio blackout -- solar flare

Polar Cap Absorption - solar energetic particles

THE ELECTROMAGNETIC SPECTRUM



Types of space weather events affecting nav and commu



UHF – GPS

- Energetic protons/ particles – via SEEs - affecting GPS satellites components
- Geomagnetic storms/ ionospheric storm - cause scintillations

VHF:

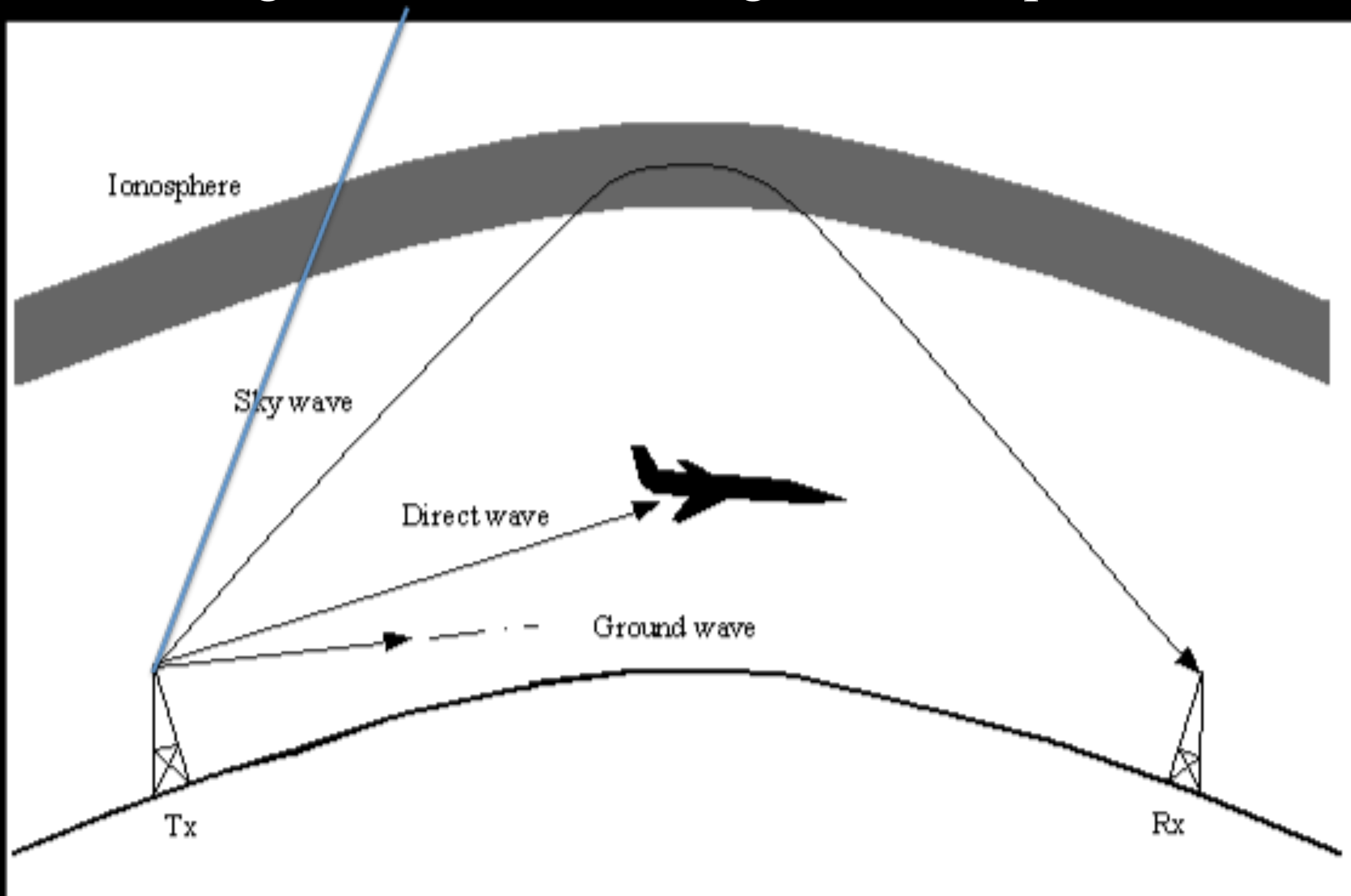
- Energetic protons - PCA
- Geomagnetic storms
- Solar radio emission associated with flare/CME

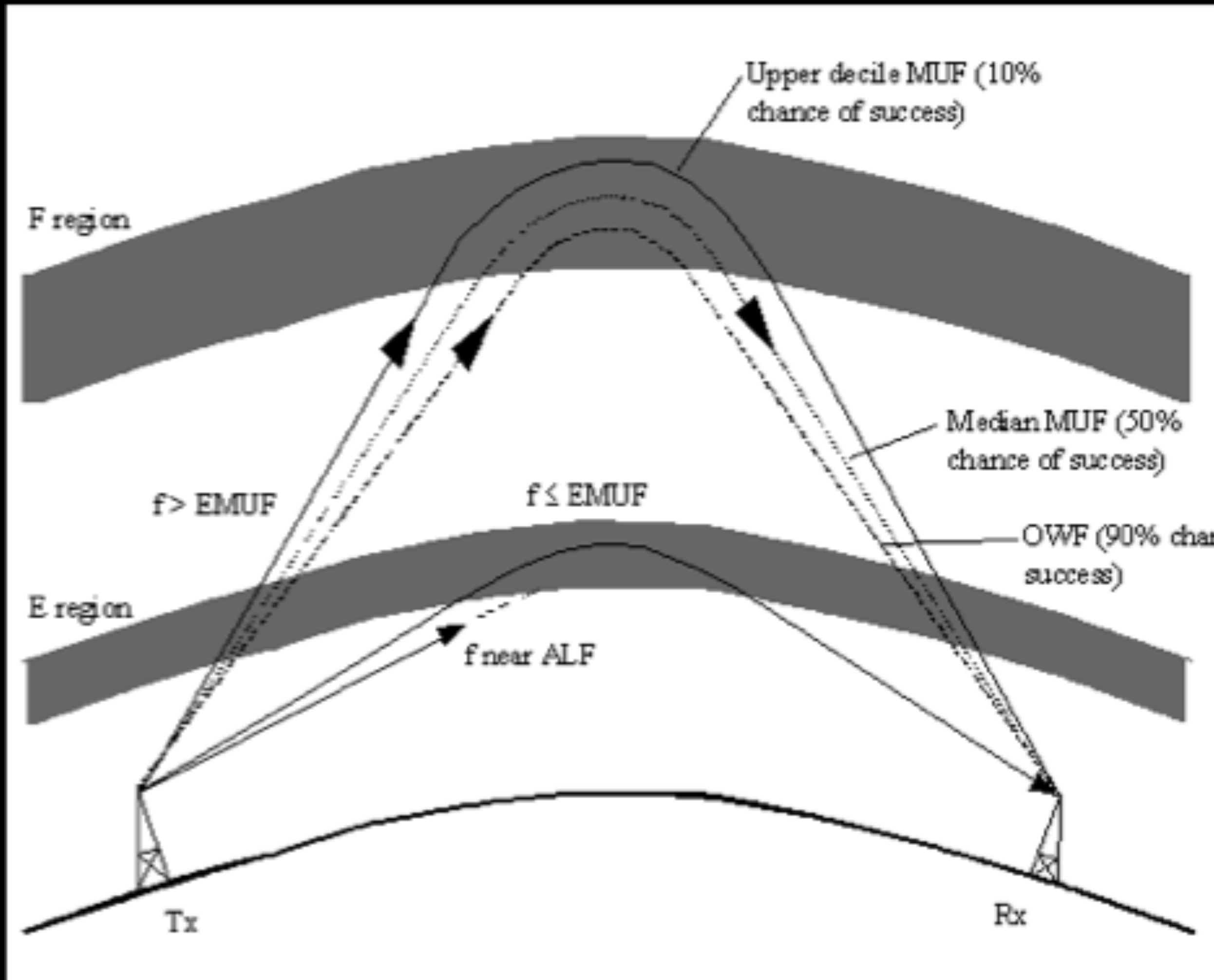
HF:

- Solar flares/x-ray
- Energetic protons - PCA
- Geomagnetic activities

Signals of different types with different purposes

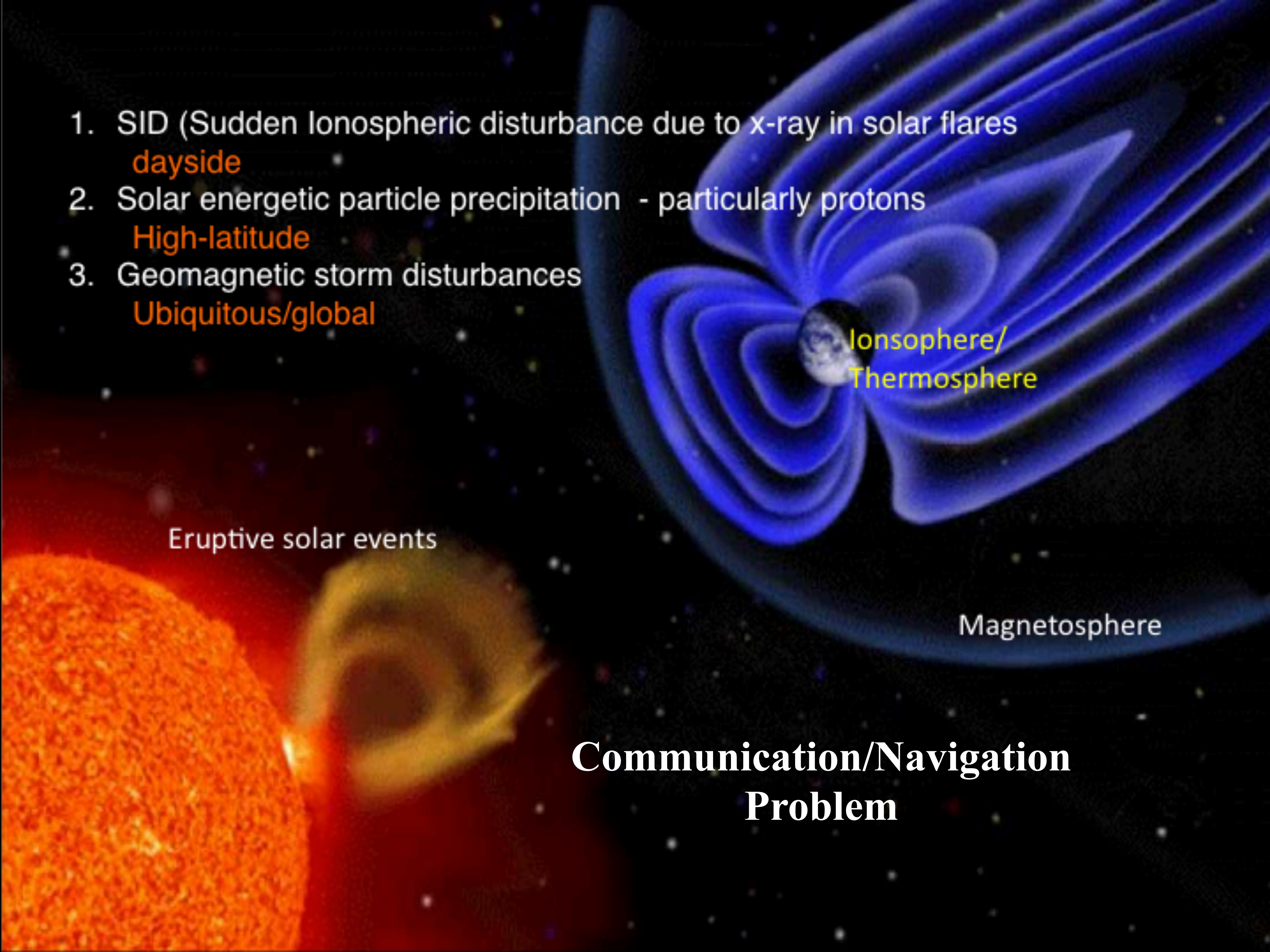
GPS signal: Penetrate through the ionosphere





ALF: Absorption Limiting Freq.

1. SID (Sudden Ionospheric disturbance due to x-ray in solar flares
   dayside
2. Solar energetic particle precipitation - particularly protons
   High-latitude
3. Geomagnetic storm disturbances
   Ubiquitous/global



Communication/Navigation Problem

Flare: SWx impacts

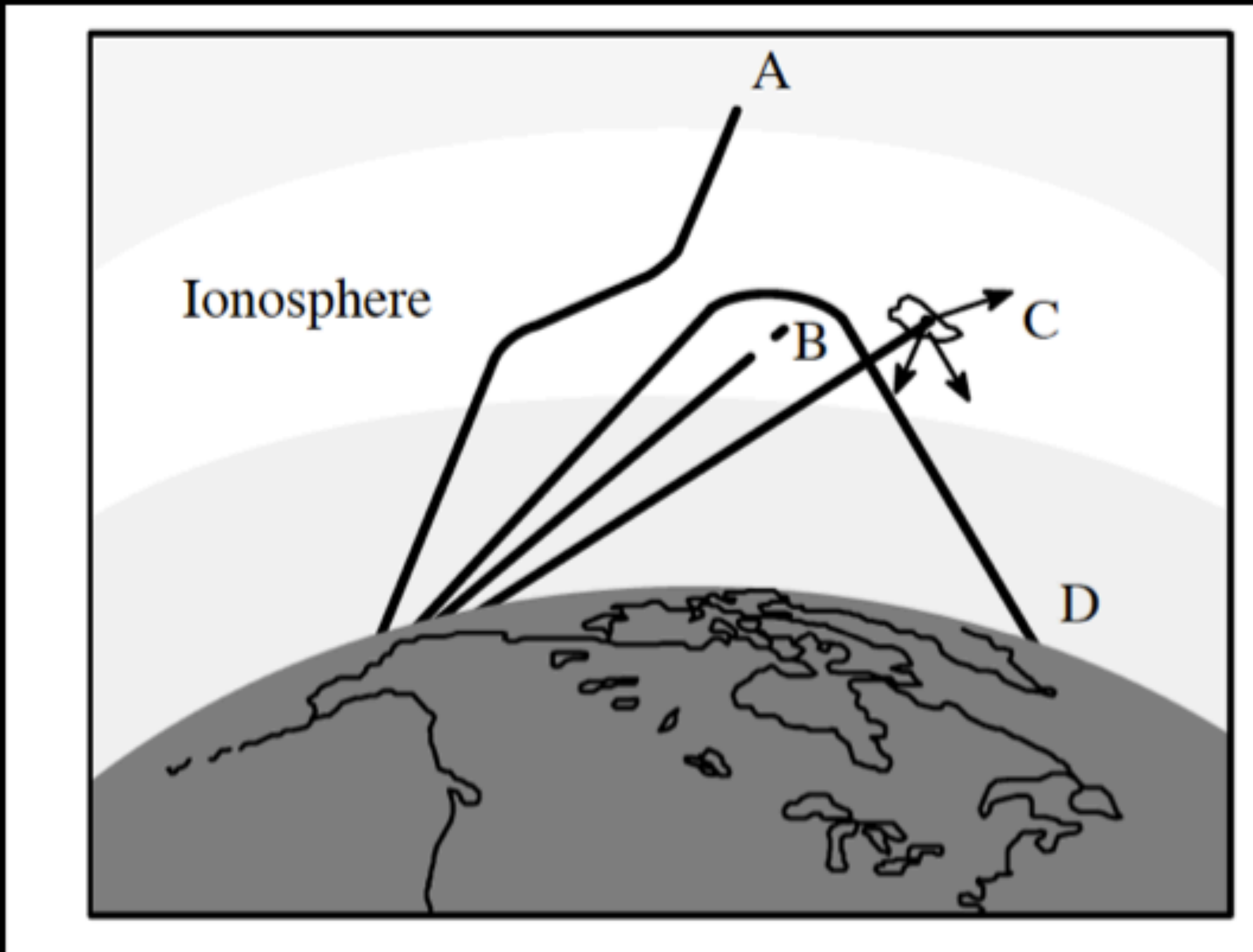
- Cause radio blackout through changing the structures/composition of the ionosphere (sudden ionospheric disturbances) – x ray and EUV emissions, lasting minutes to hours and dayside
- Affect radio comm., GPS, directly by its radio noises at different wavelengths
- Contribute to SEP – proton radiation, lasting a couple of days

Solar radio bursts can directly affect GPS operation

- Solar radio bursts during December 2006 were sufficiently intense to be measurable with GPS receivers. The strongest event occurred on 6 December 2006 and affected the operation of many GPS receivers. This event exceeded 1,000,000 solar flux unit and was about 10 times larger than any previously reported event. The strength of the event was especially *surprising* since the solar radio bursts occurred near solar minimum. The strongest periods of solar radio burst activity lasted a few minutes to a few tens of minutes and, in some cases, exhibited large intensity differences between L1 (1575.42 MHz) and L2 (1227.60 MHz). Civilian dual frequency GPS receivers were the most severely affected, and these events suggest that continuous, precise positioning services should account for solar radio bursts in their operational plans. This investigation raises the possibility of even more intense solar radio bursts during the next solar maximum that will significantly impact the operation of GPS receivers.

Cerruti et al., 2008, Space Weather

Ionospheric impact on signal path



Could cause potential problems

Sudden Ionospheric Disturbances – solar x-ray

- ✓ An SID can affect very low frequencies (e.g., OMEGA) as a sudden phase anomaly (SPA) or a sudden enhancement of signal (SES).At HF, and sometimes at VHF, an SID may appear as a short-wave fade (SWF).
- ✓ May last from minutes to hours, depending upon the magnitude and duration of the flare.
- ✓ Absorption is greatest at lower frequencies, which are the first to be affected and the last to recover. Higher frequencies are normally less affected and may still be usable.

Radio blackout events

Solar Radio Emission affecting VHF

- Type II radio emission
- Type IV radio emission
- Solar flares also create a wide spectrum of radio noise; at VHF (and under unusual conditions at HF) this noise may interfere directly with a wanted signal.

Solar energetic particles

Radiation Storms

- HF/VHF degradation in polar region (a.k.a. Polar Cap Absorption)
- Energetic particles have detrimental effects on the onboard systems of GPS satellites (SEE impacts on spacecraft component)
- Energetic particle events can persist for a few days at a time

Geomagnetic Storms

Global impacts

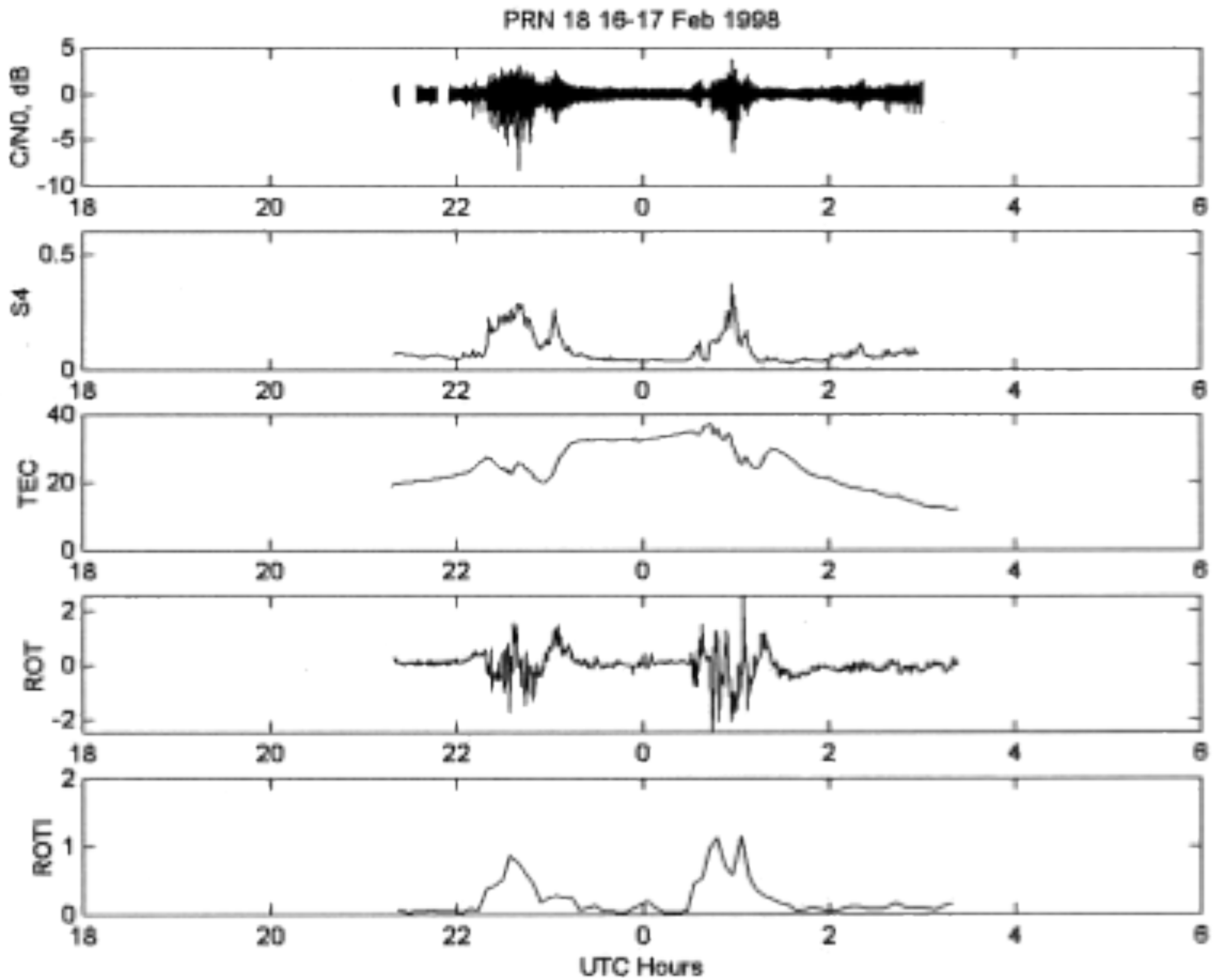
- CME storms
- CIR storms

Affect HF radio communication – especially when the signal passing through the auroral zone or ionospheric irregularities

GPS - scintillation

Geomagnetic storms may last several days, and ionospheric effects may last a day or two longer.

Scintillation



Basu et al., 1999

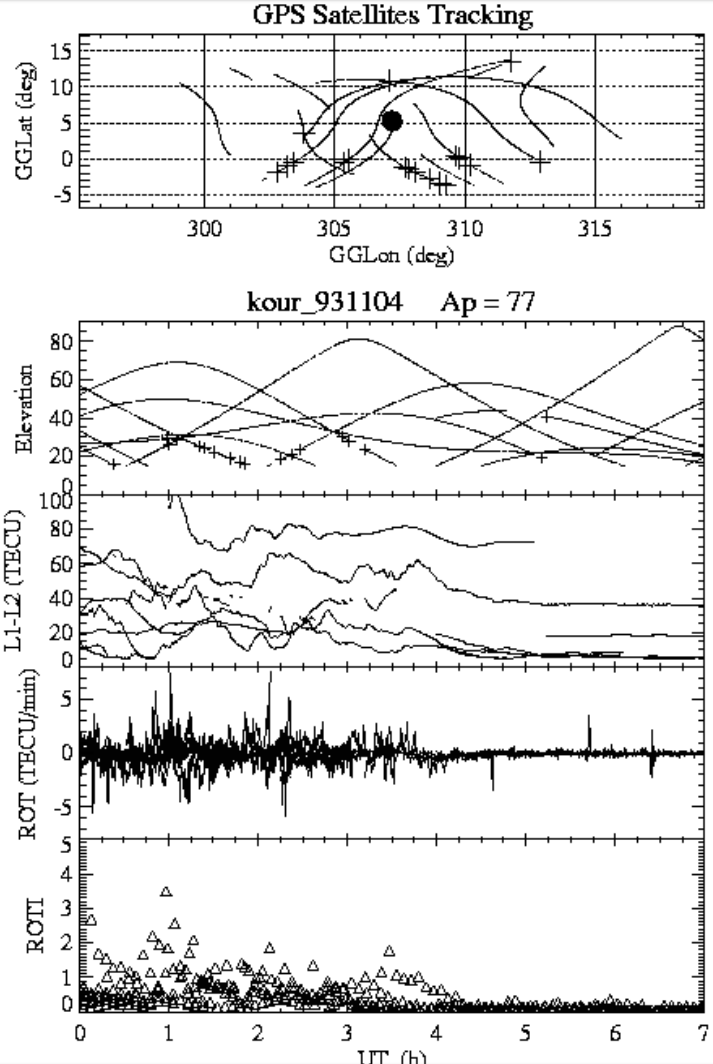
Scintillation

- Radio scintillation is the term used to represent the random fluctuations in signal phase and amplitude that develop when the radio waves propagate through ionospheric electron density irregularities. A measure of the degree of scintillation in the strength of a signal is the quantity S4 [Yeh and Liu, 1982], which describes the root-mean-square fluctuations in signal intensity, normalized by the average signal intensity:

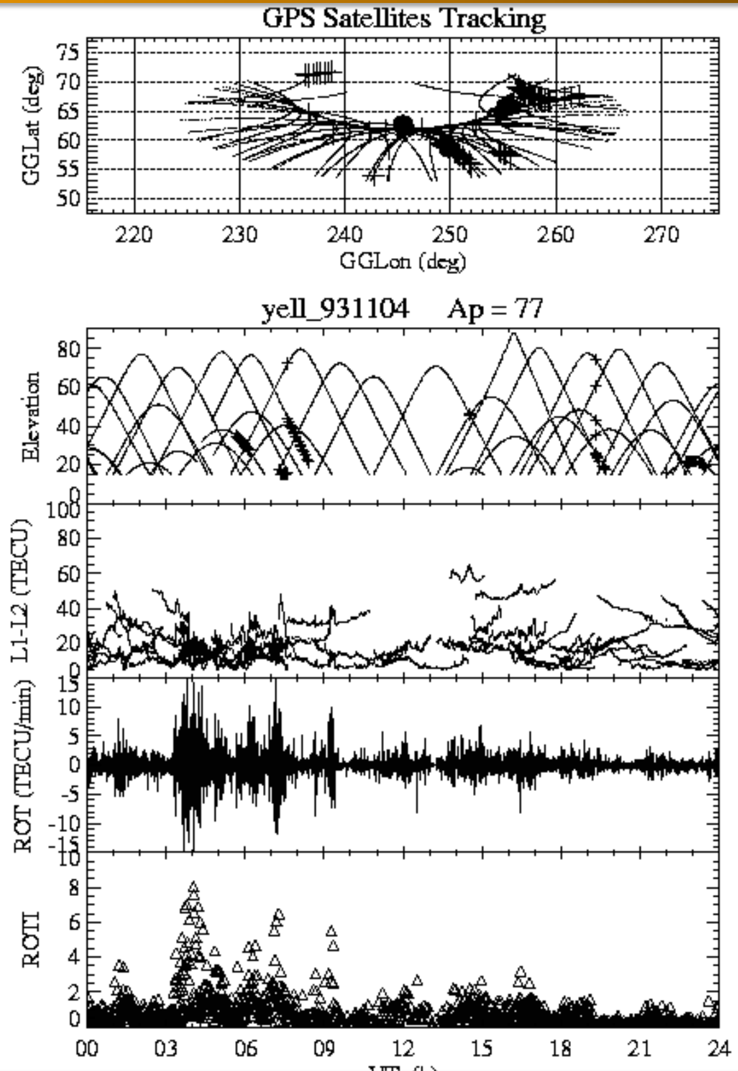
- Irregularly structured ionospheric regions can cause diffraction and scattering of trans-ionospheric radio signals. When received at an antenna, these signals present random temporal fluctuations in both amplitude and phase. This is known as ionospheric scintillation.

- Severe scintillation of the GPS satellite signals can result in loss of satellite tracking, which degrades GPS positioning accuracy. Even when satellite tracking is maintained, scintillation can cause errors decoding the GPS data messages, cycle slips, and ranging errors.

Phase Scintillation



Low Lat



High Lat

Ionospheric Scintillation Indices

$$S_4(f) = \sqrt{\frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2}} \propto f^{-1.5}$$

$$\sigma_\phi(f) = \sqrt{\langle \phi^2\rangle - \langle \phi\rangle^2} \propto f^{-1}$$

$$\mathrm{ROTI} = \sqrt{\langle \mathrm{ROT}^2\rangle - \langle \mathrm{ROT}\rangle^2}$$

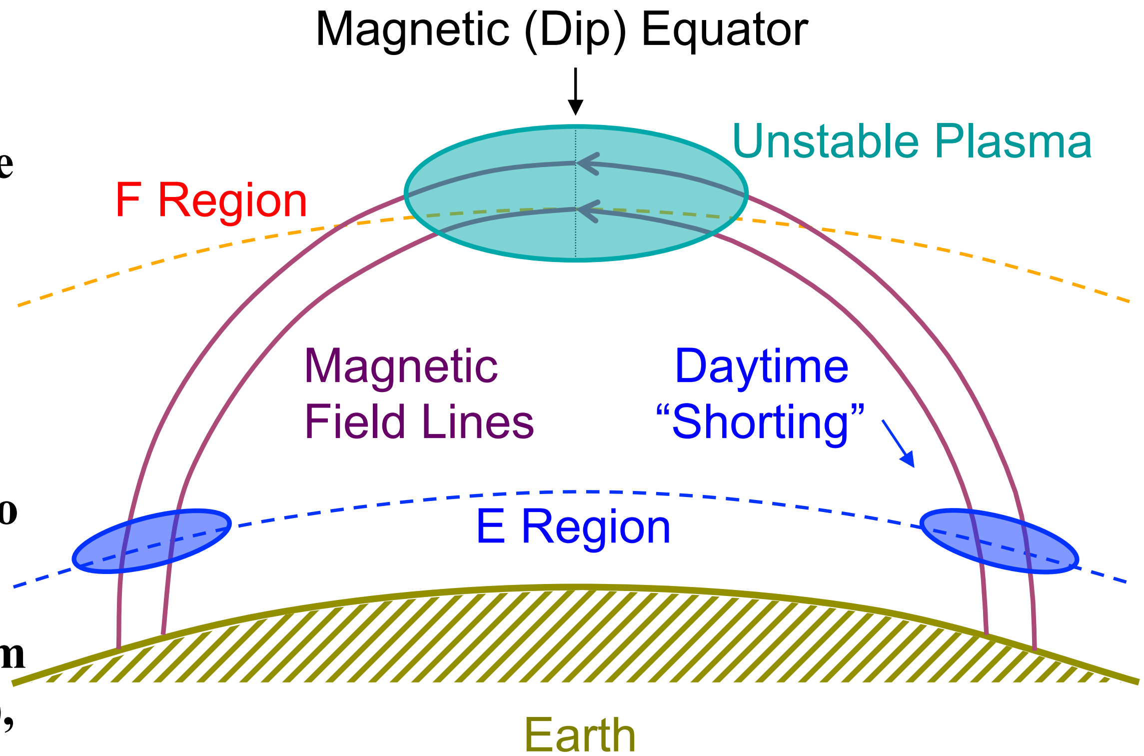
$$\mathrm{ROT} = C\,\frac{\Phi_I(t+\Delta t) - \Phi_I(t)}{\Delta t}$$

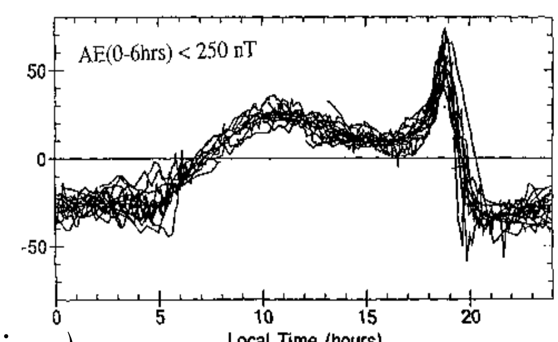
- **S_4 and σ_ϕ indices – amplitude and phase scintillation, respectively**
  - I – detrended signal intensity
  - ϕ – detrended signal phase
  - raw data is sampled at 20 or 10 ms (50 Hz or 100 Hz)
  - frequency dependent
  - Measurements of phase scintillation susceptible to local oscillator errors of transmitter and receiver
- **ROTI – Rate of TEC index**
  - ROT – detrended rate of TEC derived from dual-frequency phase data
  - ROT data sampled at 30 sec (or 1 s)
  - Not susceptible to local oscillator errors, in principle

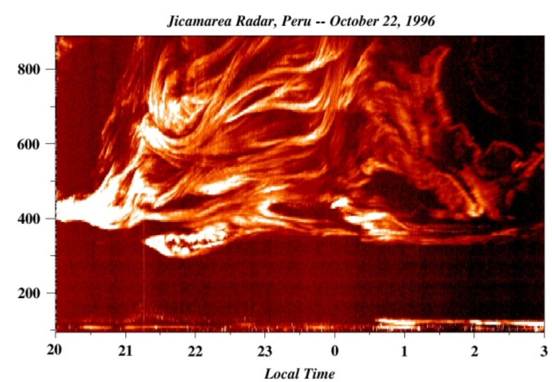
Courtesy: Pi at JPL

Equatorial Plasma Bubbles

- **Plasma moves easily along field lines**
- **Upward plasma drift supports plasma against gravity ⇒ unstable configuration**
- **E-region "shorts out" electrodynamic instability during day**
- **At night, E-region conductivity too small to short-out E field**
- **Instability in plasma grows to form equatorial plasma bubbles (EPBs), which contain irregularities seen by radars (right image) & which disrupt communications**
- **Irregularities mainly present during quiet times**







(Courtesy: de la beaujardiere)

Ionosphere Irregularities

- plasma bubbles: typical east–west dimensions of several hundred kilometers contain irregularities with scale-lengths ranging from tens of kilometers to tens of centimeters (Woodman and Tsunoda). Basu et al. (1978) showed that between sunset and midnight, 3-m scale irregularities that cause radar backscatter at 50 MHz, co-exist with sub-kilometer scale irregularities that cause VHF and L-band scintillations. After midnight, however, the radar backscatter and L-band scintillations decay but VHF scintillations caused by km-scale irregularities persist for several hours.

Journal of Atmospheric and Solar-Terrestrial Physics Volume 61, Issue 16, 1 November 1999, Pages 1219-1226

Spacecraft Drag

- Spacecraft in LEO experience periods of increased drag that causes them to slow, lose altitude and finally reenter the atmosphere. Short-term drag effects are generally felt by spacecraft <1,000 km altitude.

- Drag increase is well correlated with solar Ultraviolet (UV) output and additional atmospheric heating that occurs during geomagnetic storms.

- Most drag models use radio flux at 10.7 cm wavelength as a proxy for solar UV flux. Kp is the index commonly used as a surrogate for short-term atmospheric heating due to geomagnetic storms. In general, 10.7 cm flux >250 solar flux units and Kp>=6 result in detectably increased drag on LEO spacecraft.

- Very high UV/10.7 cm flux and Kp values can result in extreme short-term increases in drag. During the great geomagnetic storm of 13-14 March 1989, tracking of thousands of space objects was lost. One LEO satellite lost over 30 kilometers of altitude, and hence significant lifetime, during this storm.

Satellite Drag

- Atmospheric drag magnitude:

$$a_{drag} = \frac{1}{2}\beta\rho v^2$$

$\beta = \frac{c_D A}{m}$ **is ballistic coefficient**

ρ is atmospheric density

$$v \cong v_{sat}$$

Solar cycle and space weather have strong impact on neutral atmospheric density

Increasing atmospheric drag impacts:

Frequency of "Drag Make-Up" maneuvers for satellite to stay in control box

Covariance

Uncertainty in predicted atmospheric drag impacts:

Future satellite position predictions

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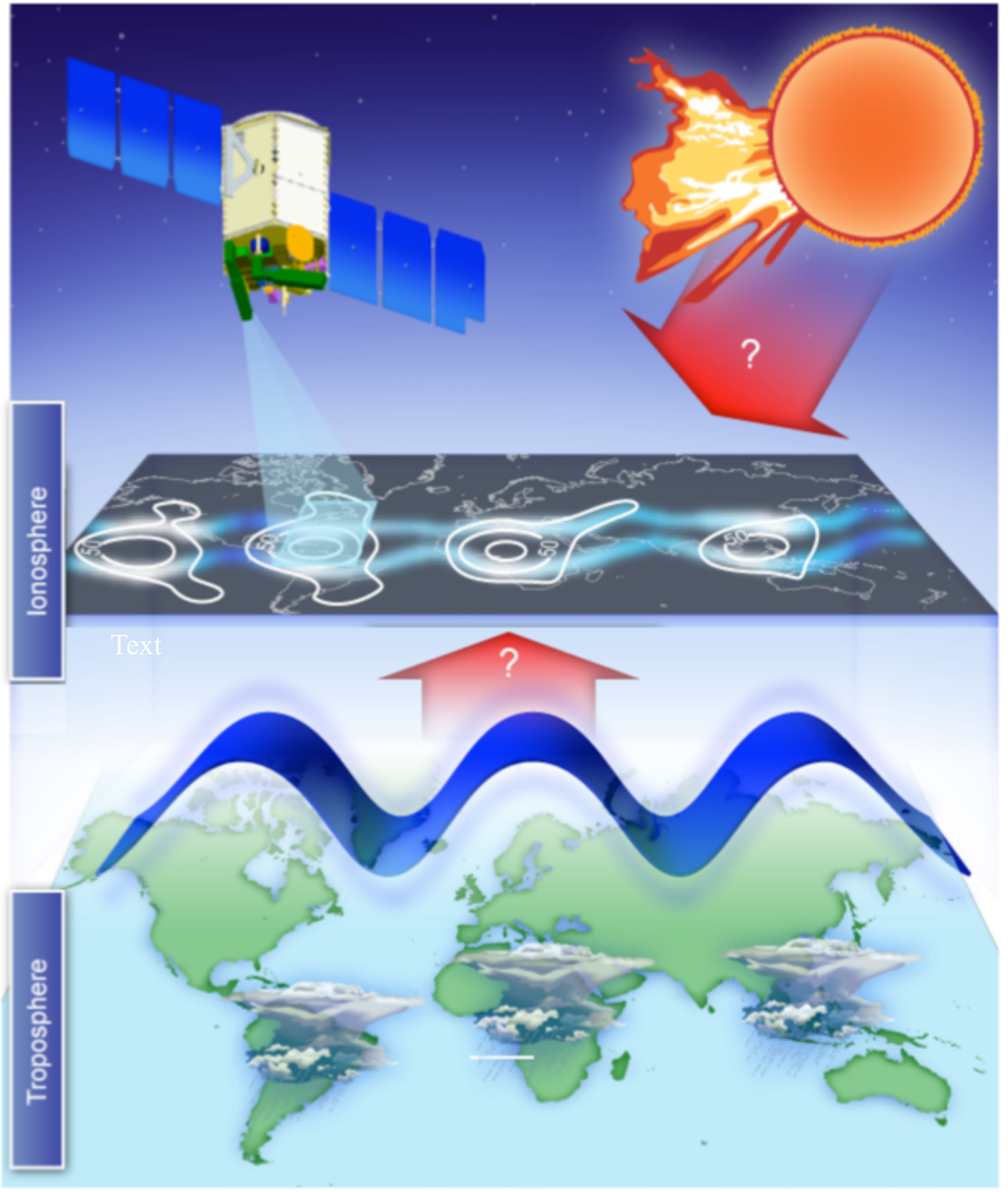

Courtesy: ICON

iSWA layout for ionosphere products

http://bit.ly/iono_layout