Summary of space weather and its impacts

Main Drivers of Space weather: **Flares**/**CMEs**/**high speed solar wind streams**

Solar Flares

radiation across the electromagnetic spectrum

most pronounced in EUV (extreme ultraviolet) and soft X-ray

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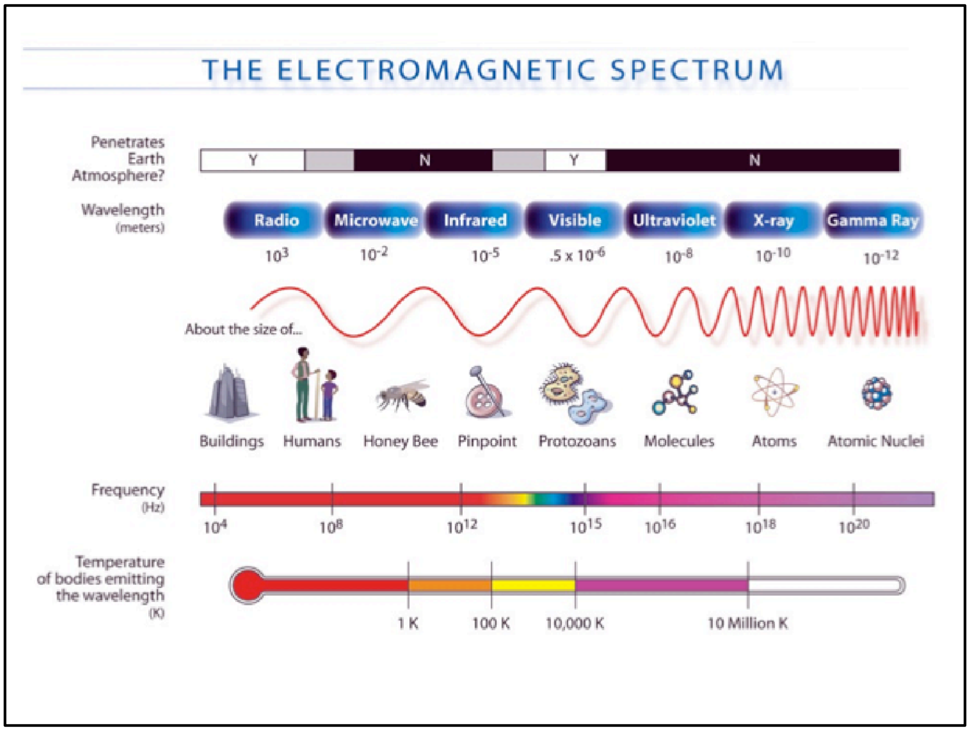
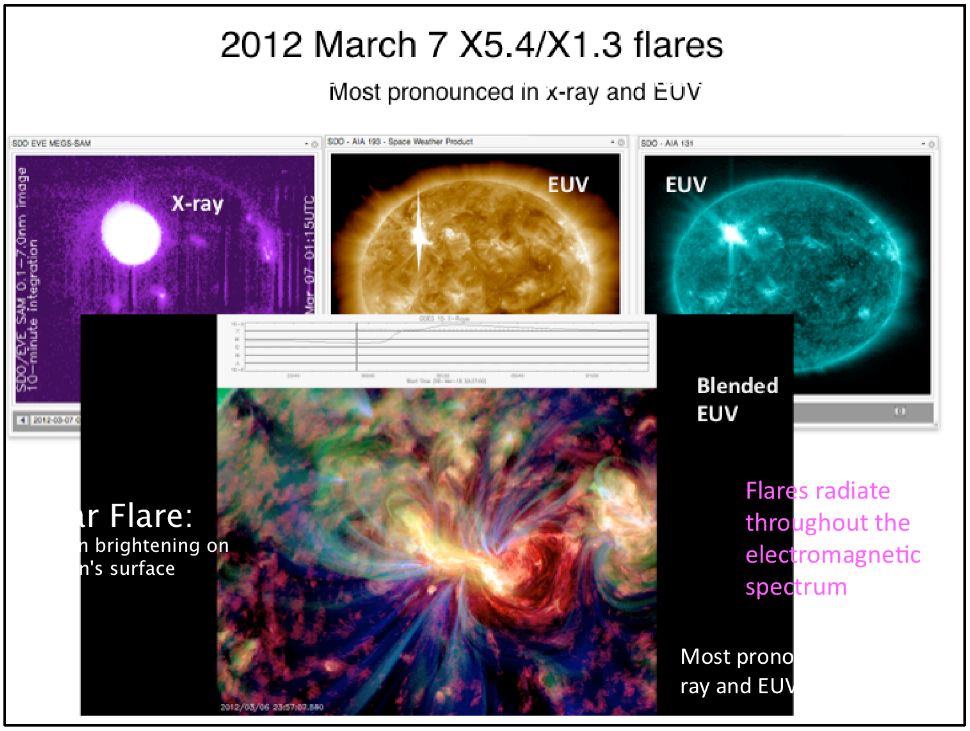

THE ELECTROMAGNETIC SPECTRUM
Penetrates Earth Atmosphere?
Y
N
Y
N
Wavelength (meters)
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
10^3
10^-2
10^-5
.5 x 10^-6
10^-8
10^-10
10^-12
About the size of...
Buildings
Humans
Honey Bee
Pinpoint
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^4
10^8
10^12
10^15
10^16
10^18
10^20
Temperature of bodies emitting the wavelength (K)
1 K
100 K
10,000 K
10 Million K



Solar flares represent one type of solar eruptive event, appearing as a sudden brightening on the sun's surface. You can see them in the beautiful high spatial and temporal AIA (Atmospheric Imaging Assembly) images obtained from the NASA SDO (Solar Dynamics Observatory) mission. For a powerful solar flare event, such as the two X class ones here, the radiation energy is on the order of 10^25 Joule. Such flares radiate throughout the electromagnetic spectrum, from gamma rays to x-rays, through visible light to kilometer-long radio waves.

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 (solar energetic particles) – proton/ion radiation (lasting a couple of days)

Coronal Mass Ejections (CMEs)

7

CME

- Massive burst of solar materials/charged particles and magnetic field/flux into the interplanetary space: 10^15 g
- Kinetic energy 10^32 erg (1 erg = 10^-7 joules)
- Yashiro et al. (2006) find that virtually all X-class flares have accompanying CMEs

http://1.usa.gov/1e5ZBDW
March 7 2012 event

CME viewed by coronagraph imagers

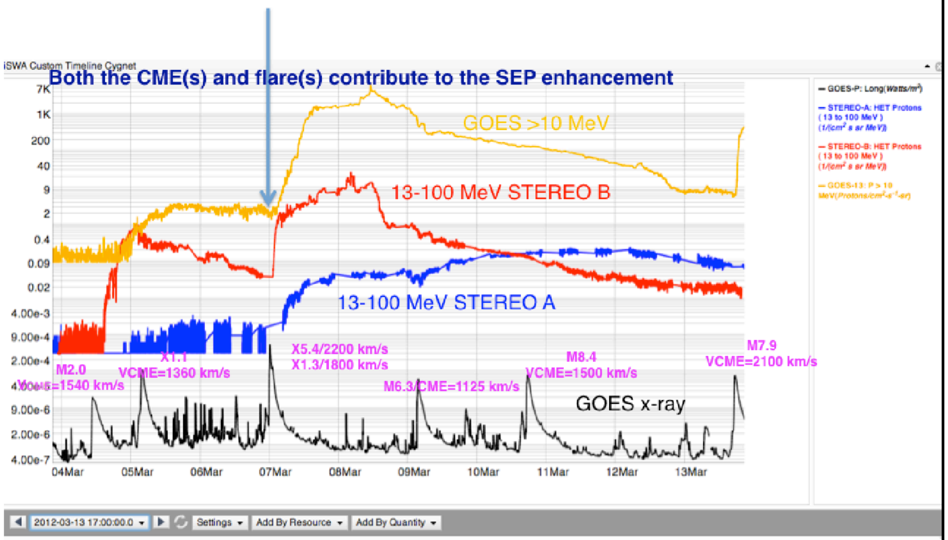
- **Eclipses allow corona to be better viewed**
  - **Does not happen often**
- **Modern coronagraph imager is inspired by that: occulting disk blocks the bright sun so we can observe corona features better**

SWx Impacts of a CME

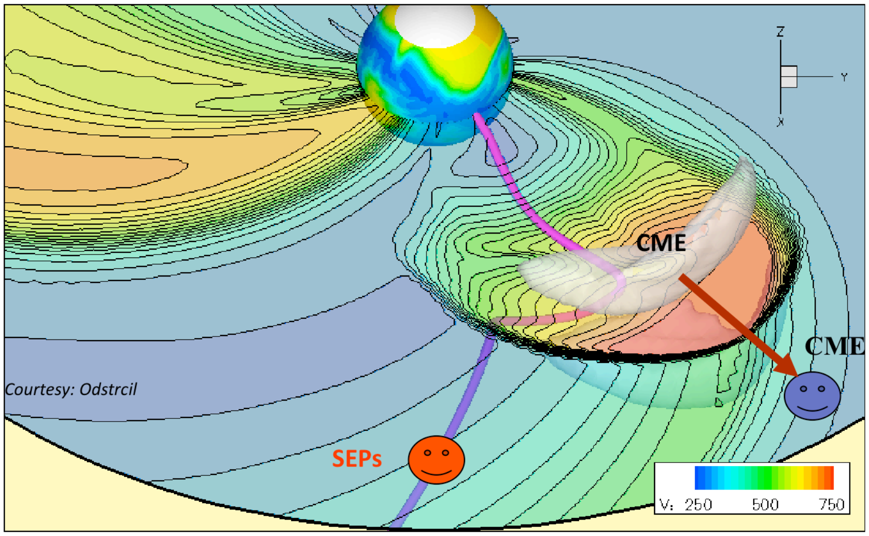
- Contribute to SEP (proton/ion radiation): 20-30 minutes from the occurrence of the CME/flare
- Result in a geomagnetic storm: takes 1-4 days arriving at Earth
- Result in electron radiation enhancement in the near-Earth space (multiple CMEs): takes 1-3 days
- Affecting spacecraft electronics – surfacing charging/internal charging, single event upsets (via SEPs)
- Radio communication, navigation
- Power grid, pipelines, and so on

http://1.usa.gov/1e5ZBDW
March 7 2012 event

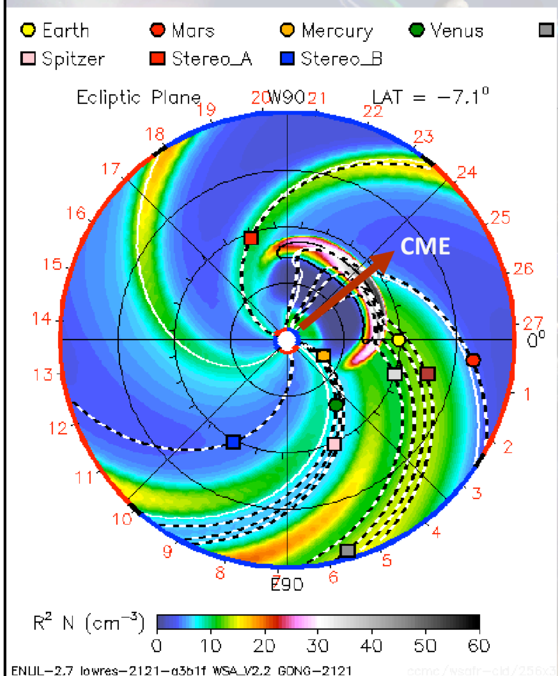
SEP (solar energetic particle) radiation



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

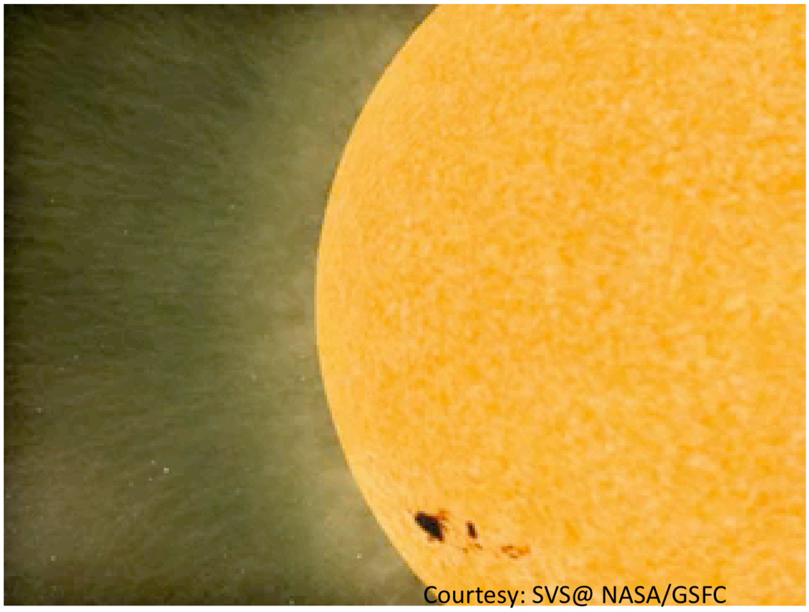
CME impact @ Earth: Geomagneti Storm

Radiation storm @ Earth from SEP

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

SEPs: ion radiation storms

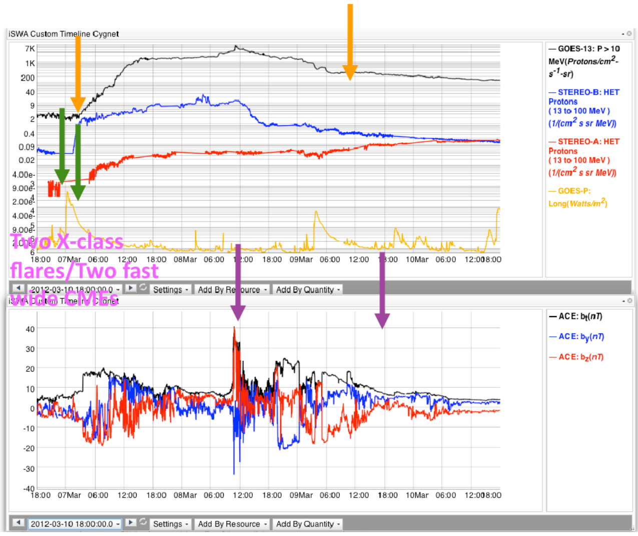
Potentially affect everywhere in the solar system



SEPs: applicable and potentially damaging everywhere that they have influence

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

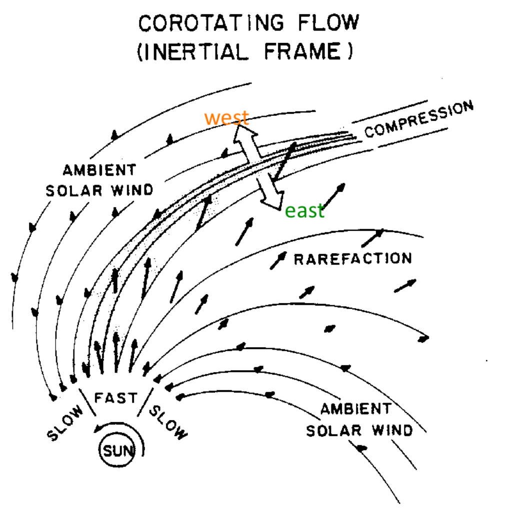


Figure 6. Schematic illustrating 2-D corotating stream structure in the solar equatorial plane in the inner heliosphere (from Pizzo, 1978).

SWx Consequences of CIR (corotating interaction region) HSS (high speed solar wind streams)

CIR HSS: usually long-duration (3-4 days)

- Radiation belt electron flux enhancement
- Surface charging
- Geomagnetic disturbances (moderate at most)
- heating of upper atmosphere: satellite drag

Energetic electron radiation: (the >0.8 MeV electron flux exceeding 10^5 pfu alert threshold): takes 2-3 days from the CIR interface

Although geomagnetic activity (due to CIR HSS) during the declining and minimum phases of the solar cycle appears to be relatively benign (especially in comparison to the dramatic and very intense magnetic storms caused by interplanetary coronal mass ejections (ICMEs) that predominate during solar maximum), this is misleading. Research has shown that the time-averaged, accumulated energy input into the magnetosphere and ionosphere due to high speed streams can be greater during these solar phases than due to ICMEs during solar maximum!

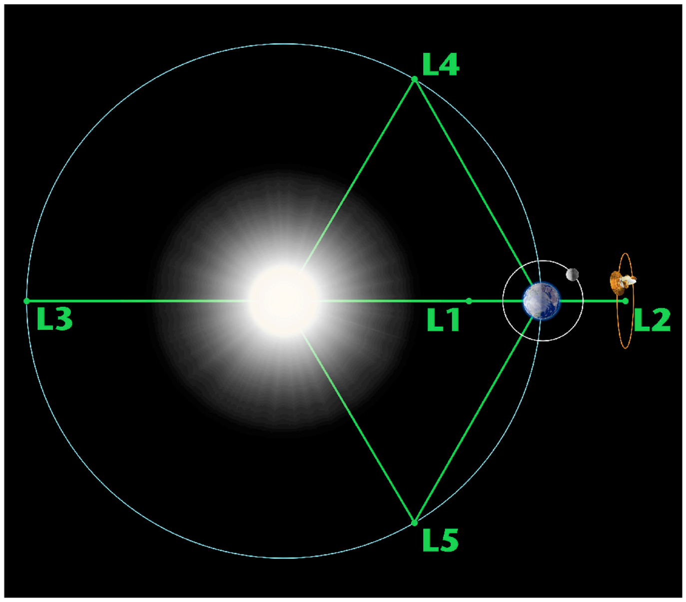
Tsurutani et al., 2006

High-Intensity, Long-Duration, Continuous AE Activity (HILDCAA) events are studied using long-term geomagnetic and solar wind/interplanetary databases. We use the strict definition of a HILDCAA event, that it occurs outside of the main phase of a magnetic storm, the peak AE is >1000 nT, and the duration is at least 2 days long. The overwhelmed majority (94%) of these latter cases were associated with high-speed solar wind stream (HSS) events. The remaining 6% of the cases occurred after the passage of interplanetary coronal mass ejections (ICMEs).

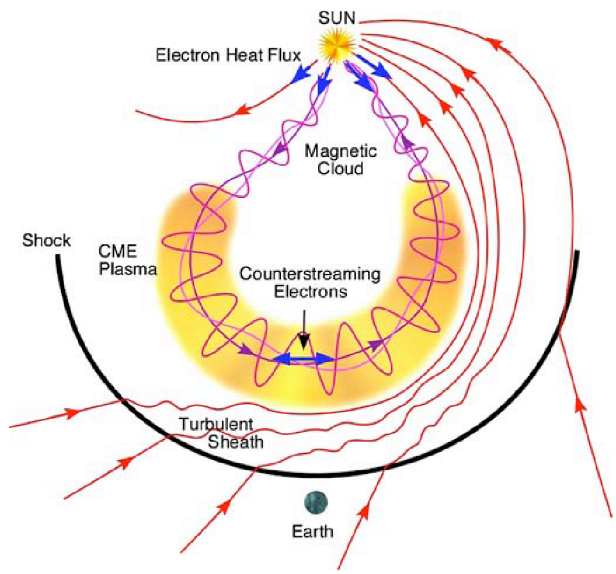
In-situ signatures of CME and CIR HSS at L1 (Lagrangian 1)

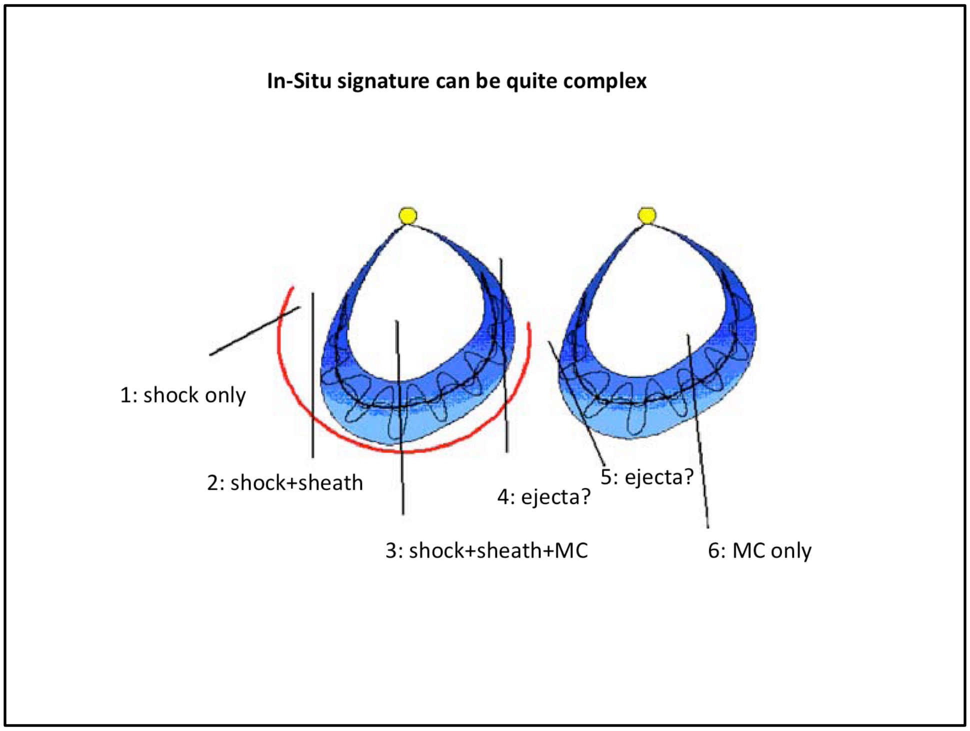
ACE and WIND spacecraft

Lagrangian points

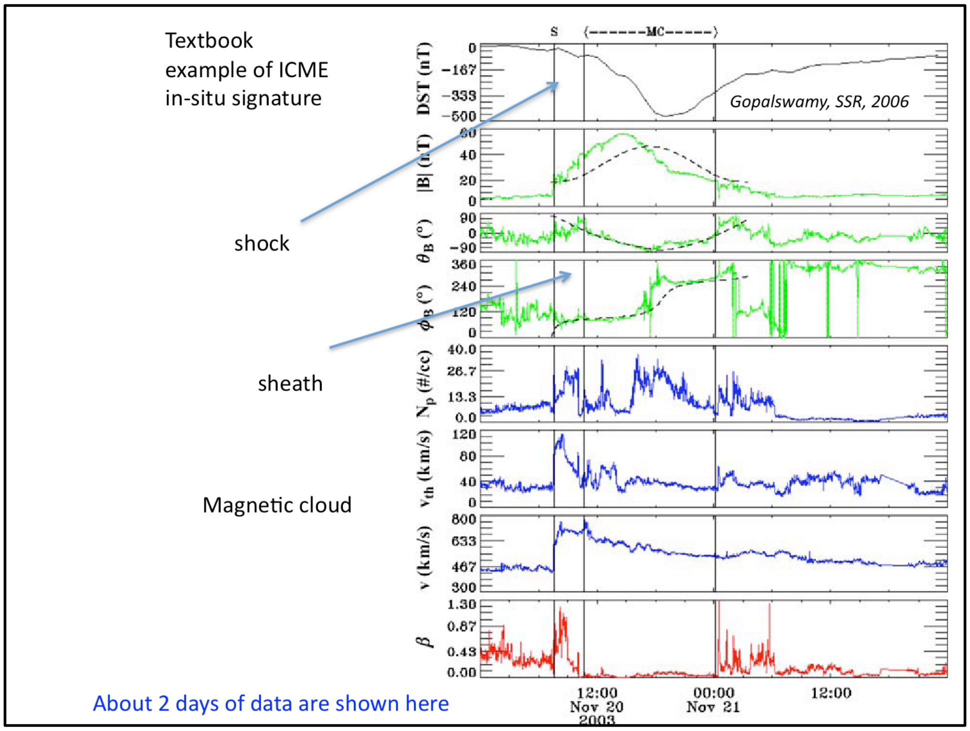


Schematic of the three-dimensional structure of an ICME and upstream shock



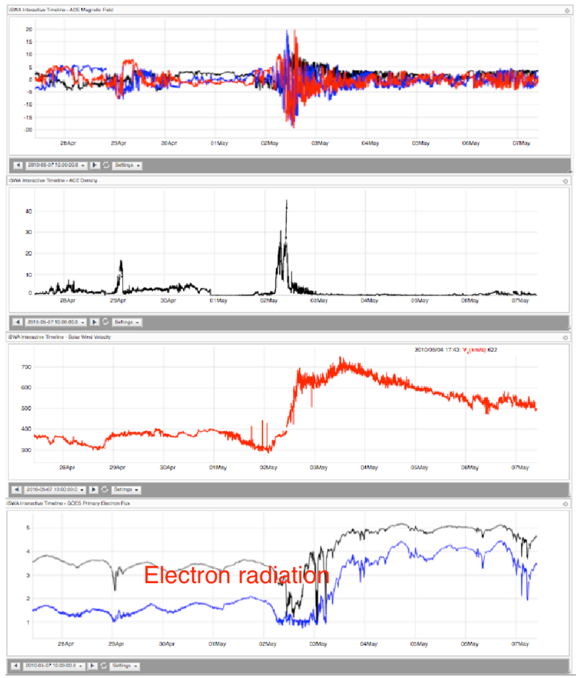


Six possible tracks of an observing spacecraft through an MC with a leading shock (left)
and another without (right). Tracks 1 and 2 never encounter the MC proper. They pass through the
shock and the compressed ambient medium in one of the flanks of the MC. Track 4 passes through
the nose of the MC. This situation arises when the observing spacecraft is along the Sun-Earth line
and a fast and wide CME erupts from close to the Sun center. Trajectory 4 passes through the shock,
sheath, and through the edge of the MC. Tracks 5 and 6 are similar to 4 and 3, respectively, except that
the MC is slow and hence it does not drive a shock. Trajectories 4 and 5 are not expected to observe
an MC structure.



Gopalswamy, N., PROPERTIES OF INTERPLANETARY CORONAL MASS EJECTIONS, Space Science Reviews (2006) 124: 145–168

A magnetic cloud is a transient ejection in the solar wind defined by relatively strong magnetic fields, a large and smooth rotation of the magnetic field direction over approximately 0.25AU at 1AU, and a low proton temperature [Burlaga et al., 1981]. Magnetic clouds are ideal objects for solar-terrestrial studies because of their simplicity and their extended intervals of southward and northward magnetic fields [Burlaga et al., 1990].



10 day data

Clean HSS (high speed solar wind stream)

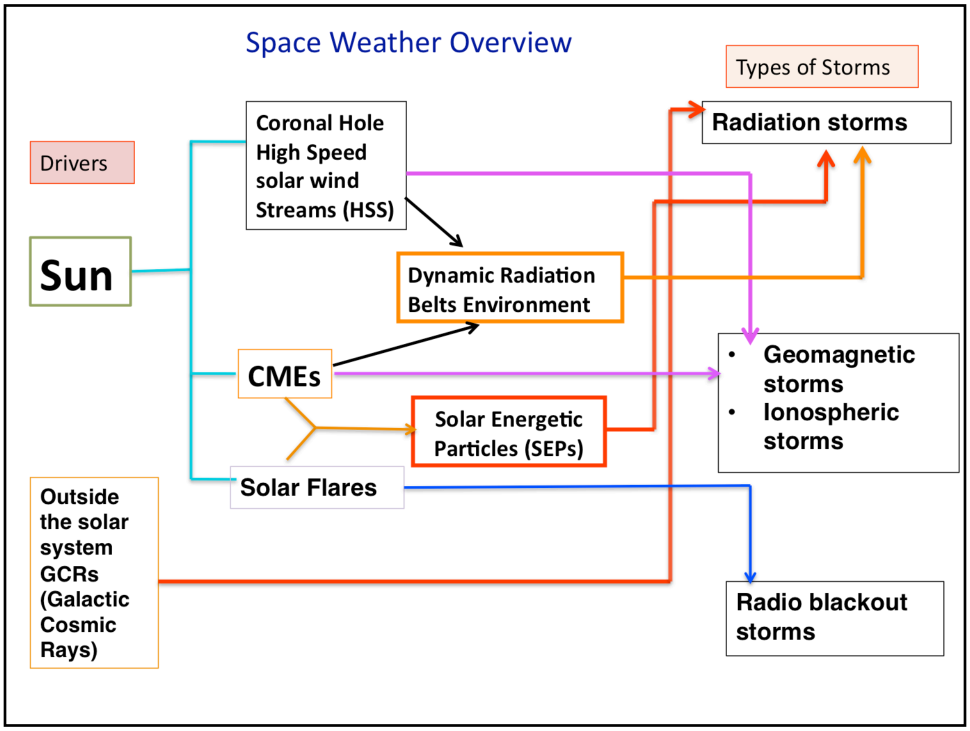
May 2, 2010

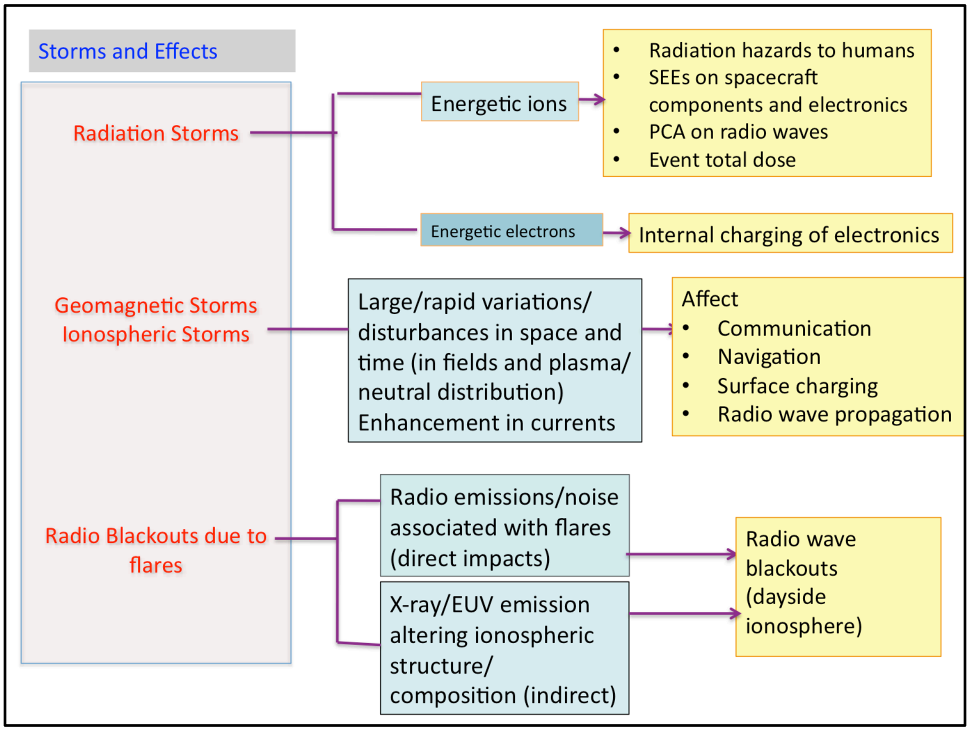
Dense (20-30 cc), HSS

IMFBz: -18 nT

may be more hazardous to Earth-orbiting satellites than ICME-related magnetic storm particles and solar energetic particles

Space Weather in a nutshell


Space Weather Overview
Types of Storms
Drivers
Coronal Hole High Speed solar wind Streams (HSS)
Radiation storms
Sun
Dynamic Radiation Belts Environment
CMEs
Geomagnetic storms
Ionospheric storms
Solar Energetic Particles (SEPs)
Solar Flares
Outside the solar system GCRs (Galactic Cosmic Rays)
Radio blackout storms


Storms and Effects
Radiation Storms
Energetic ions
Radiation hazards to humans
SEEs on spacecraft components and electronics
PCA on radio waves
Event total dose
Energetic electrons
Internal charging of electronics
Geomagnetic Storms
Ionospheric Storms
Large/rapid variations/ disturbances in space and time (in fields and plasma/ neutral distribution)
Enhancement in currents
Affect
Communication
Navigation
Surface charging
Radio wave propagation
Radio Blackouts due to flares
Radio emissions/noise associated with flares (direct impacts)
X-ray/EUV emission altering ionospheric structure/ composition (indirect)
Radio wave blackouts (dayside ionosphere)

SWx Impacts on Satellites Electronics/ Components

hazards presented by the radiation and plasma environment in space

- Single Event Effects (affect all SC)
  - caused by protons and heavy ions with energies of 10s of MeV/amu
- Internal Charging (those in radiation belt)
  - caused by electrons with energies above about 100 keV that penetrate inside a vehicle
- Surface Charging (all in Earth's environment)
  - caused by electrons with energies of 10s of keV that interact with spacecraft surfaces
- Event Total Dose (all SC)
  - caused primarily by solar protons and possibly also by transient belts of trapped particles, typically protons with energies near 10 MeV

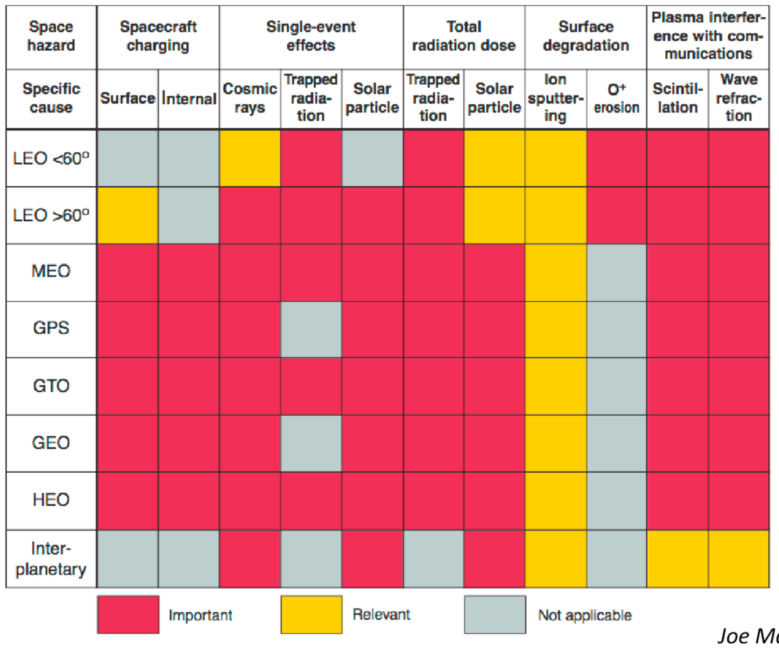
Effects on Satellite Orbit

- Satellite drag (LEO)
- Orientation effects (spacecraft that use Earth's magnetic field for orientation)

Effects on Satellite Communication

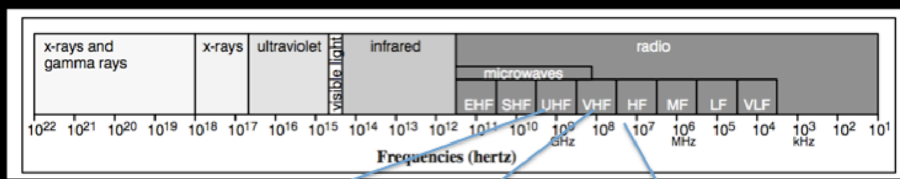
- During strong solar flares (strong radio noise)
  - Directly cause interference via solar radio noise
  - Through modification of the ionosphere
- Scintillation effects during geomagnetic storms

Environment Hazards for different orbits



Joe Mazur

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

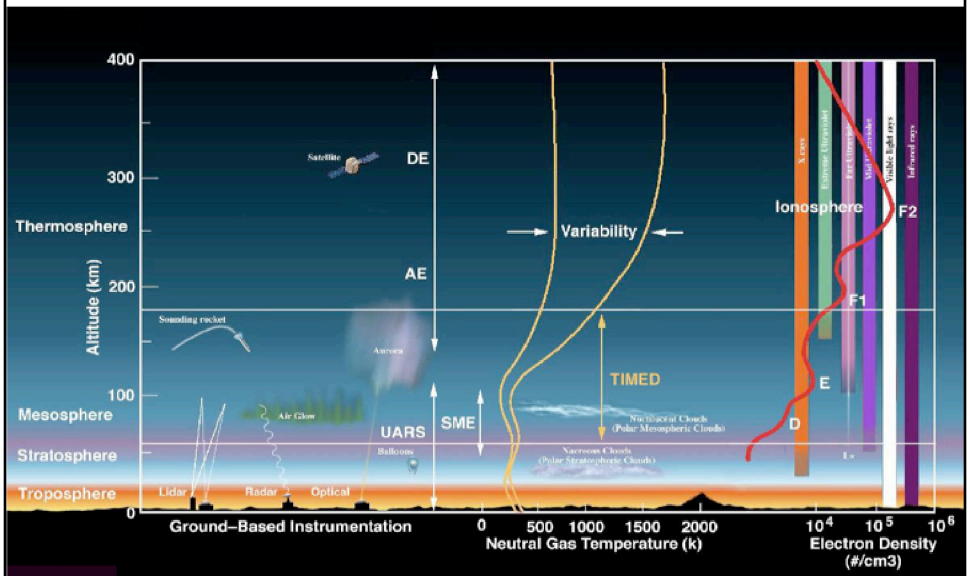
VHF:

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

HF:

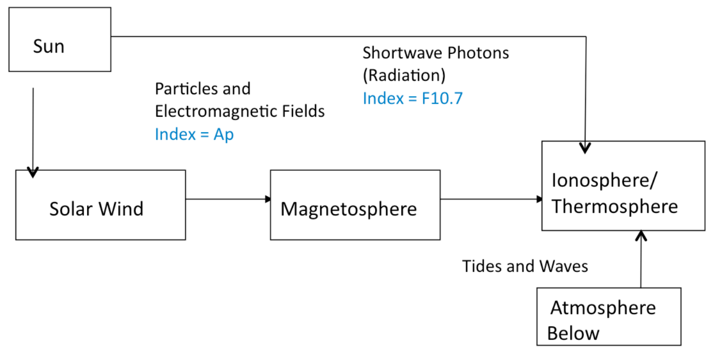
- Solar flares/x-ray
- Energetic protons - PCA
- Geomagnetic activities

Ionosphere - Thermosphere Overview



The ionosphere is a highly variable and complex physical system. It is produced by ionizing radiation from the sun and controlled by chemical interactions and transport by diffusion and neutral wind.

Energy Flow to the Thermosphere



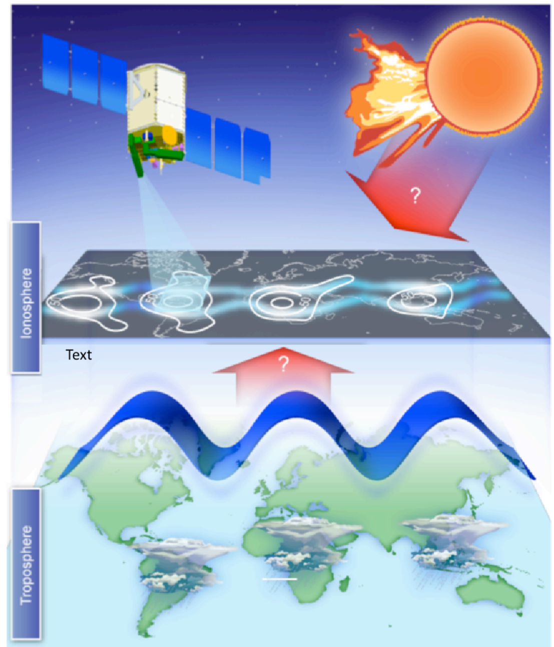
Knipp 2011 Understanding Space Weather and the Physics Behind It

Energy paths/sources for the thermosphere

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

A nice summary of our current understanding

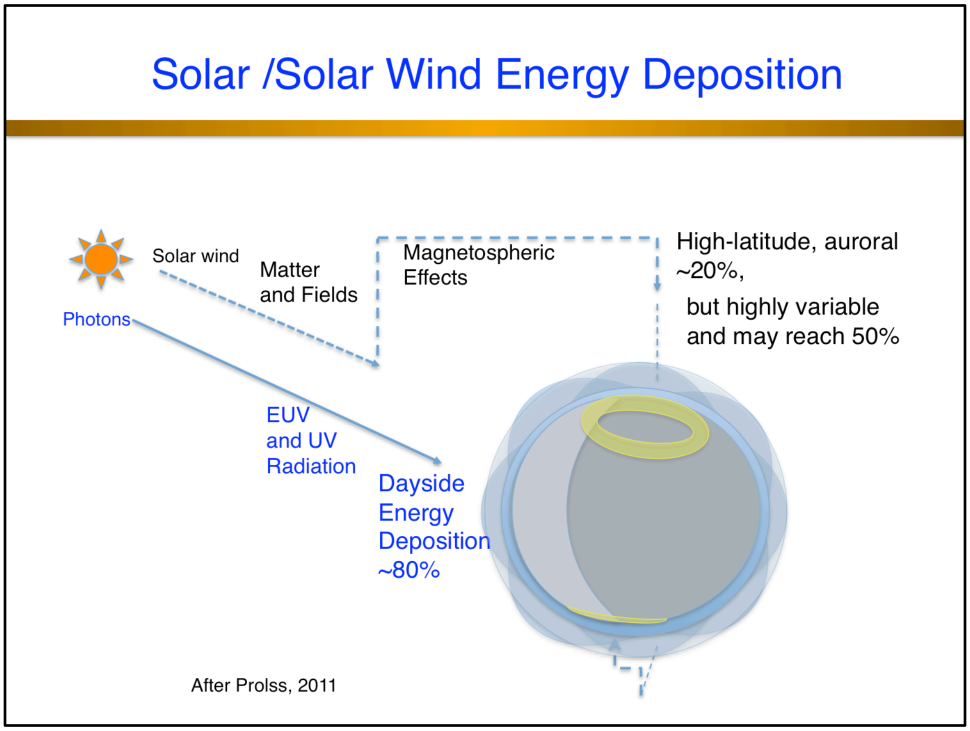
Tsunami's impact on the ionosphere-thermosphere

- the Tohoku-Oki tsunami of 11 March 2011 is modeled.
- It is shown that **gravity wave-induced variations in the neutral wind** lead to plasma velocity variations both perpendicular and parallel to the geomagnetic field. Moreover, the electric field induced by the neutral wind perturbations can map to the conjugate hemisphere. Thus, electron density variations can be generated in both hemispheres which impact the total electron content (TEC) and 6300 Å airglow emission. It is found that the TEC exhibits variations of total electron content unit (1 TECU = 10^{16} el m^{-2}) and the 6300 Å airglow emission variation is up to ~±2.5% relative to the unperturbed background airglow.

Huba, J. D., D. P. Drob, T.-W. Wu, and J. J. Makela (2015), Modeling the ionospheric impact of tsunami-driven gravity waves with SAMI3: Conjugate effects, Geophys. Res. Lett., 42, 5719–5726, doi:10.1002/2015GL064871.

Rolland, L. M., Occhipinti, G., Lognonné, P. & Loevenbruck, A. Geophys. Res. Lett. 37, L17101 (2010).
| Article | OpenURLPeltier, W. R. & Hines, C. O. J. Geophys. Res. 81, 1995-2000 (1976).

| Article | OpenURLLiu, J.-Y. *et al.* J. Geophys. Res. 111, A05303 (2006). | Article | OpenURL



Energy deposition variability
Most energy from solar photons, however during times with many strong CMEs, the energy from CME/magnetosphere interaction can equal that from photons (Knipp et al, 2004)

Summary

Significant Challenges are posed by satellite drag

- Track and identify active payloads and debris
- Collision avoidance and re-entry prediction
- Attitude Dynamics
- Constellation control
- “Drag Make-Up” maneuvers to keep satellite in control box
- Delayed acquisition of SATCOM links for commanding /data transmission
- Mission design and lifetime

Flare impact on neutral density (sat. drag)

Thermospheric Density: An Overview of Temporal and Spatial

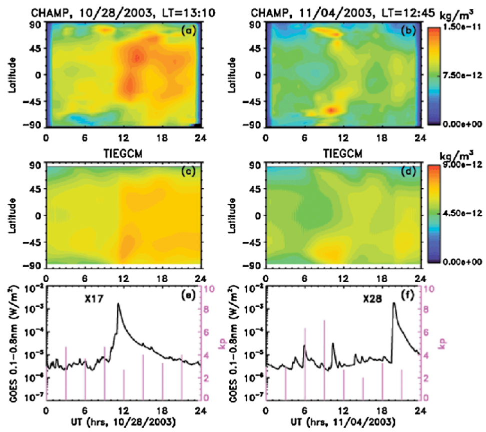


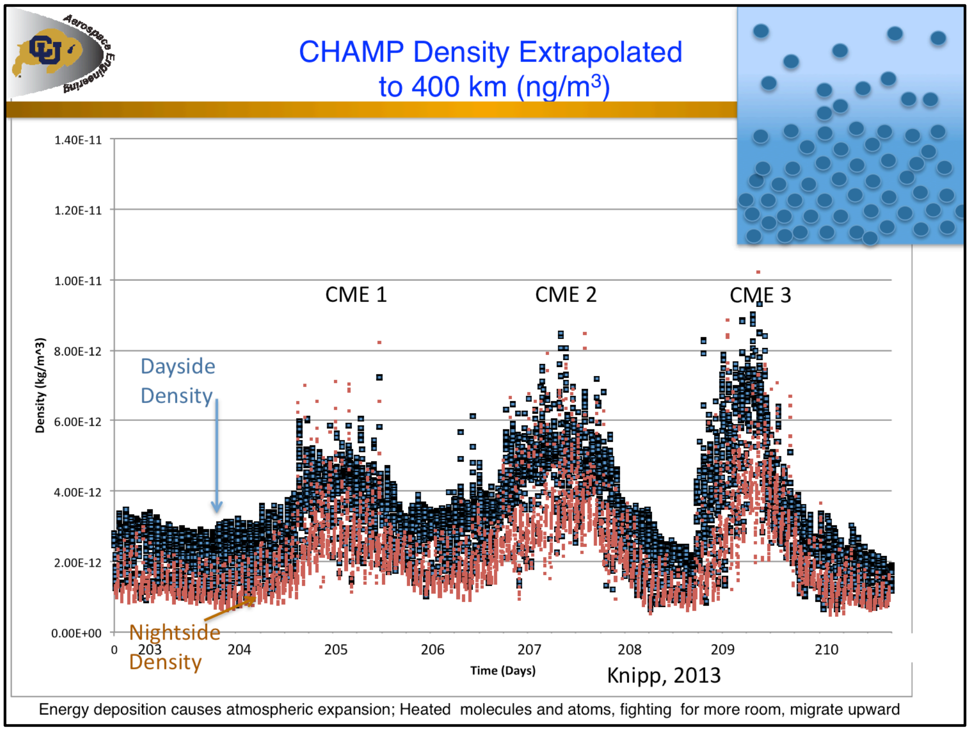
Fig. 1 Neutral density responses to an X17 flare occurred on October 28, 2003 and an X28 flare occurred on November 4, 2003. (**a**) Neutral density observed by CHAMP on October 28, 2003. The solar local time of CHAMP orbit was ~13:10. (**b**) Neutral density observed by CHAMP on November, 2003. The solar local time of CHAMP orbit was ~12:45. (**c**) Neutral density simulated by TIE-GCM for October 28, 2003, sampled along the CHAMP orbit. FISM flare spectra were used as solar input for the TIE-GCM. (**d**) Neutral density simulated by TIE-GCM for November, 2003, sampled along the CHAMP orbit. FISM flare spectra were used as solar input for the TIE-GCM; (**c**) GOES 0.1–0.8 nm solar irradiance and geomagnetic Kp index for October 28, 2003. (**d**) GOES 0.1–0.8 nm solar irradiance and geomagnetic Kp index for November 4, 2003

Solar flares can cause abrupt changes in dayside neutral density – as shown in the left panel with the X17 flare.

Neutral density response to a flare depends on the spectral characteristics of the emission enhancement – which is location dependent. Flare emission in the EUV range (~25 nm – 120 nm) is optically thick so a limb flare's influence on the neutral density is weaker – which explains why the X28 flare didn't make much enhancement in neutral density as it originated near the solar limb region.

Qian and Solomon (2011), Space Sci Rev
DOI 10.1007/s11214-011-9810-z

Title: Thermospheric density: An overview of temporal and spatial variations.



Density inferred from s/c acceleromter
Typical global response time is 6-8 hours
Energy arrives first in auroral zones….can begin disturbing mid latitudes within an hour