Space Weather

AN INTRODUCTION

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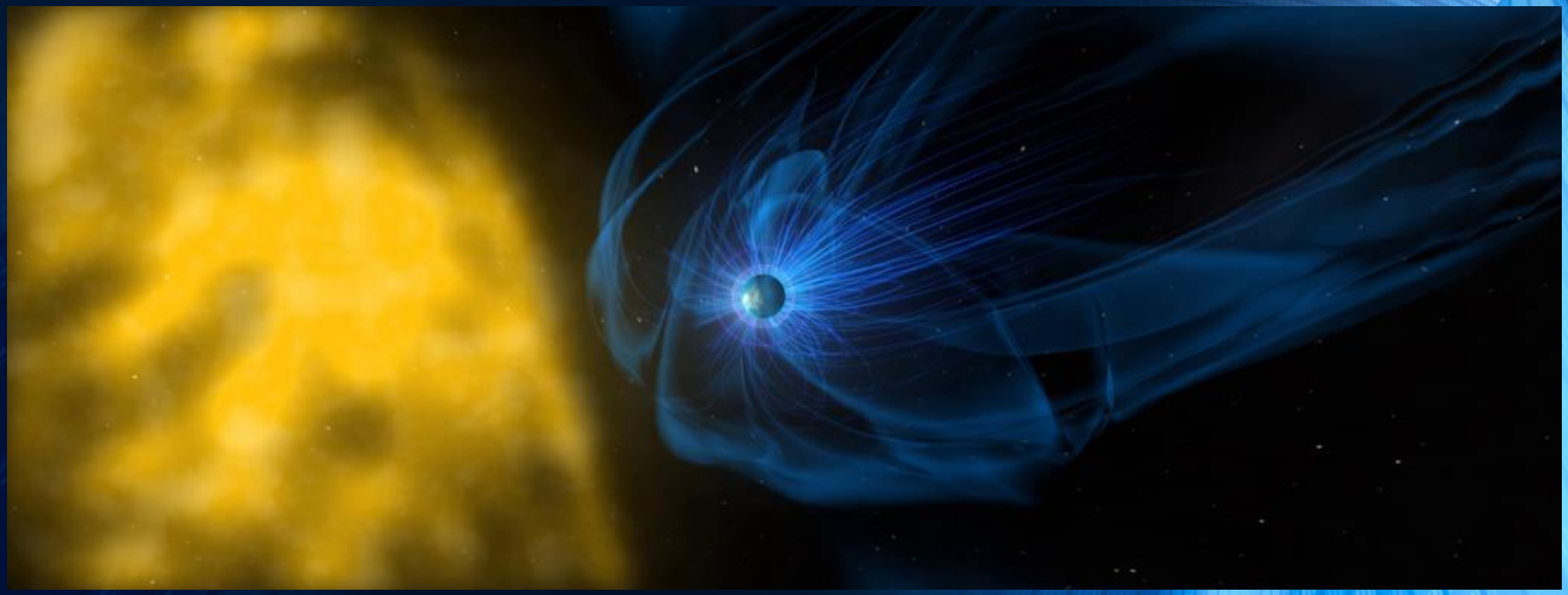
(with material from SWREDI 2017 bootcamp (A. Pulkkinen, NASA GSFC), MIT Haystack Observatory (A. Coster), and NASA GSFC Visualization Studio)



What is Space Weather?

- Space weather refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human health. Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electric power distribution grids, leading to a variety of socioeconomic losses.

Heliophysics

helio-, pref., on the Sun and environs, from the Greek helios.
physics, n., the science of matter and energy and their interactions.

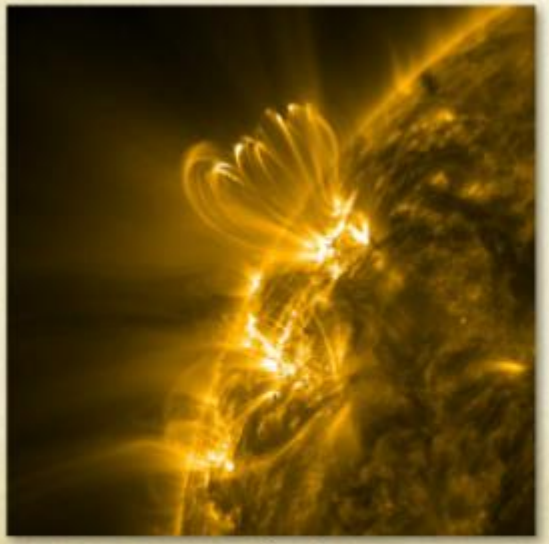
Heliophysics is the

- *comprehensive new term for the science of the Sun - Solar System Connection.*
- *exploration, discovery, and understanding of our space environment.*
- *system science that unites all of the linked phenomena in the region of the cosmos influenced by a star like our Sun.*

Heliophysics concentrates on the Sun and its effects on Earth, the other planets of the solar system, and the changing conditions in space. Heliophysics studies the magnetosphere, ionosphere, thermosphere, mesosphere, and upper atmosphere of the Earth and other planets. Heliophysics combines the science of the Sun, corona, heliosphere and geospace. Heliophysics encompasses cosmic rays and particle acceleration, space weather and radiation, dust and magnetic reconnection, solar activity and stellar cycles, aeronomy and space plasmas, magnetic fields and global change, and the interactions of the solar system with our galaxy.

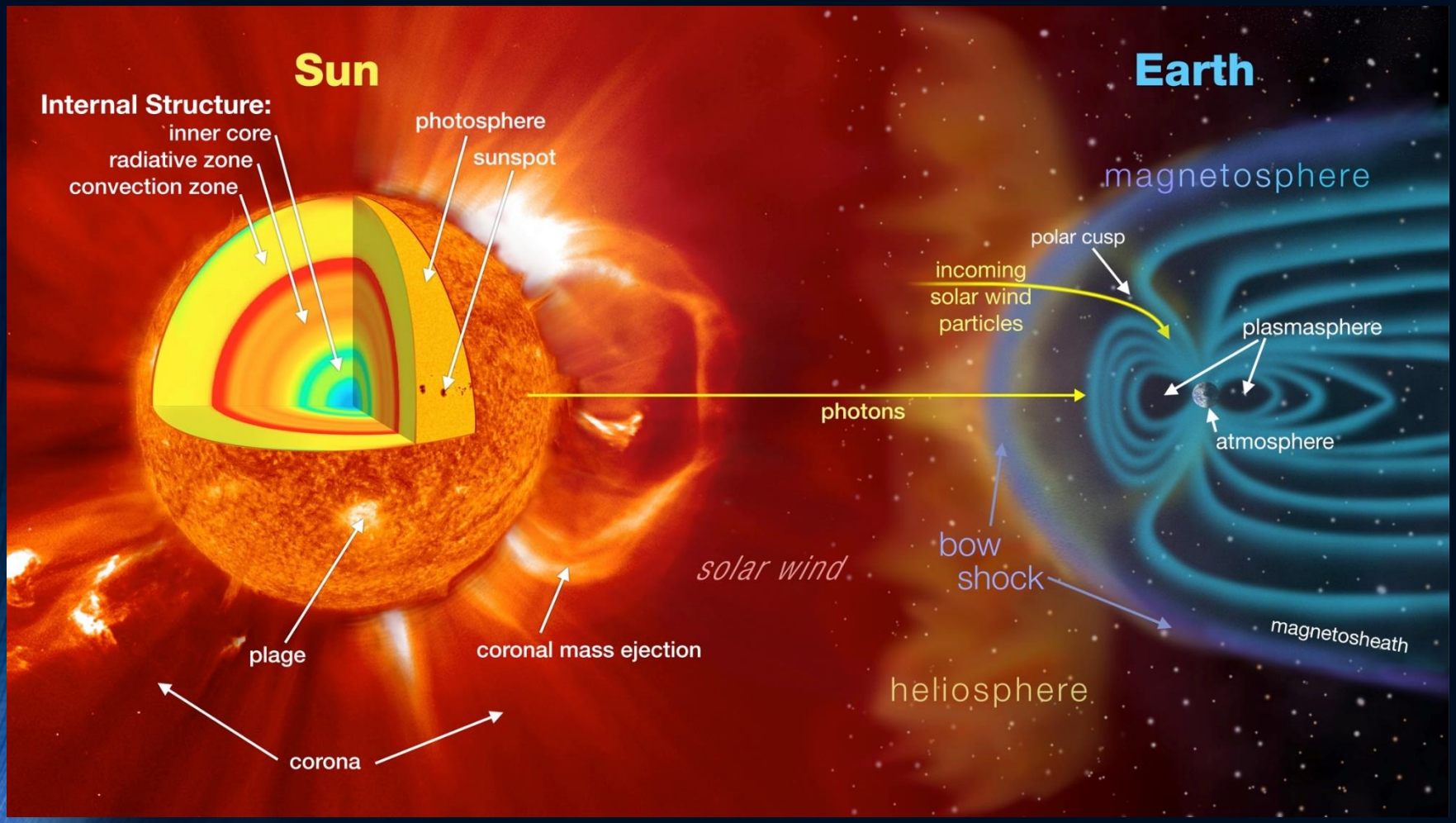
Physics of Space Weather

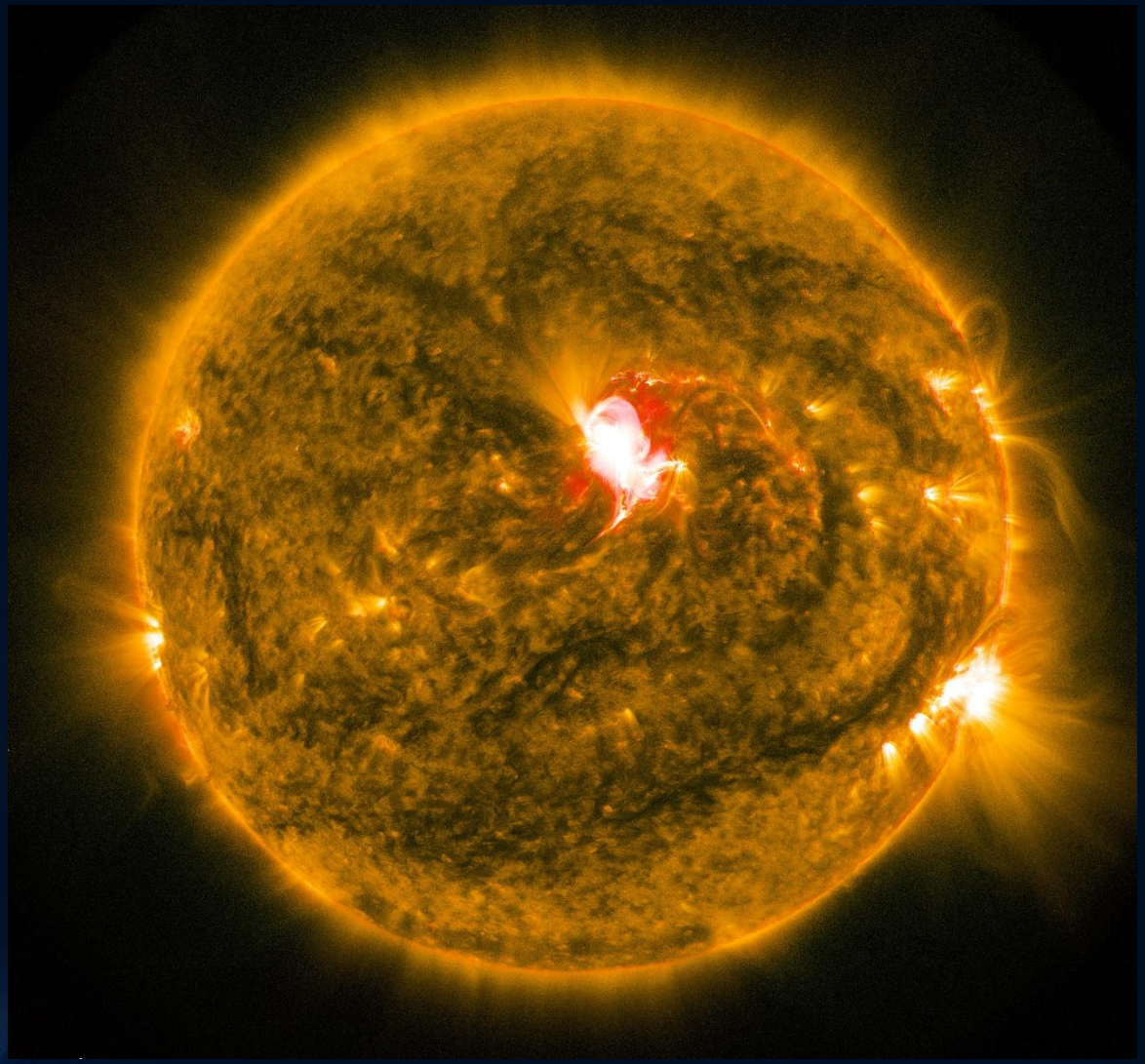
- The physics of space weather is plasma physics.
- "Plasma is quasi-neutral ionized gas containing enough free charges to make collective electromagnetic effects important for its physical behavior"



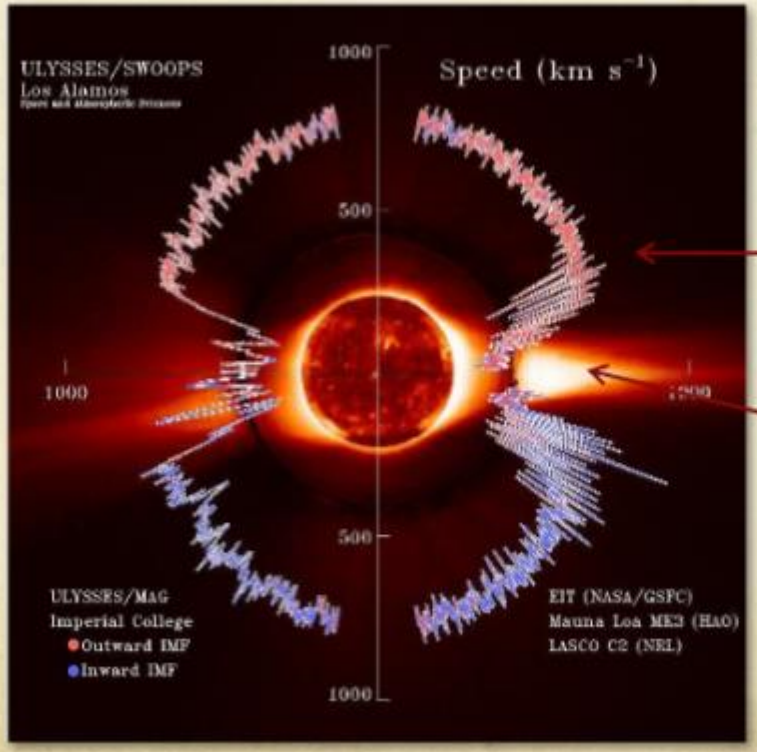
EUV image of solar corona
(credit: NASA SDO)

Image of auroras at visible wavelengths
(credit: spaceweather.com)


Sun
Earth
Internal Structure:
inner core
radiative zone
convection zone
photosphere
sunspot
magnetosphere
polar cusp
incoming
solar wind
particles
plasmasphere
photons
atmosphere
bow
shock
solar wind
magnetosheath
plage
coronal mass ejection
heliosphere
corona



Solar atmospheric mass, momentum and energy are being carried away by *solar wind*.

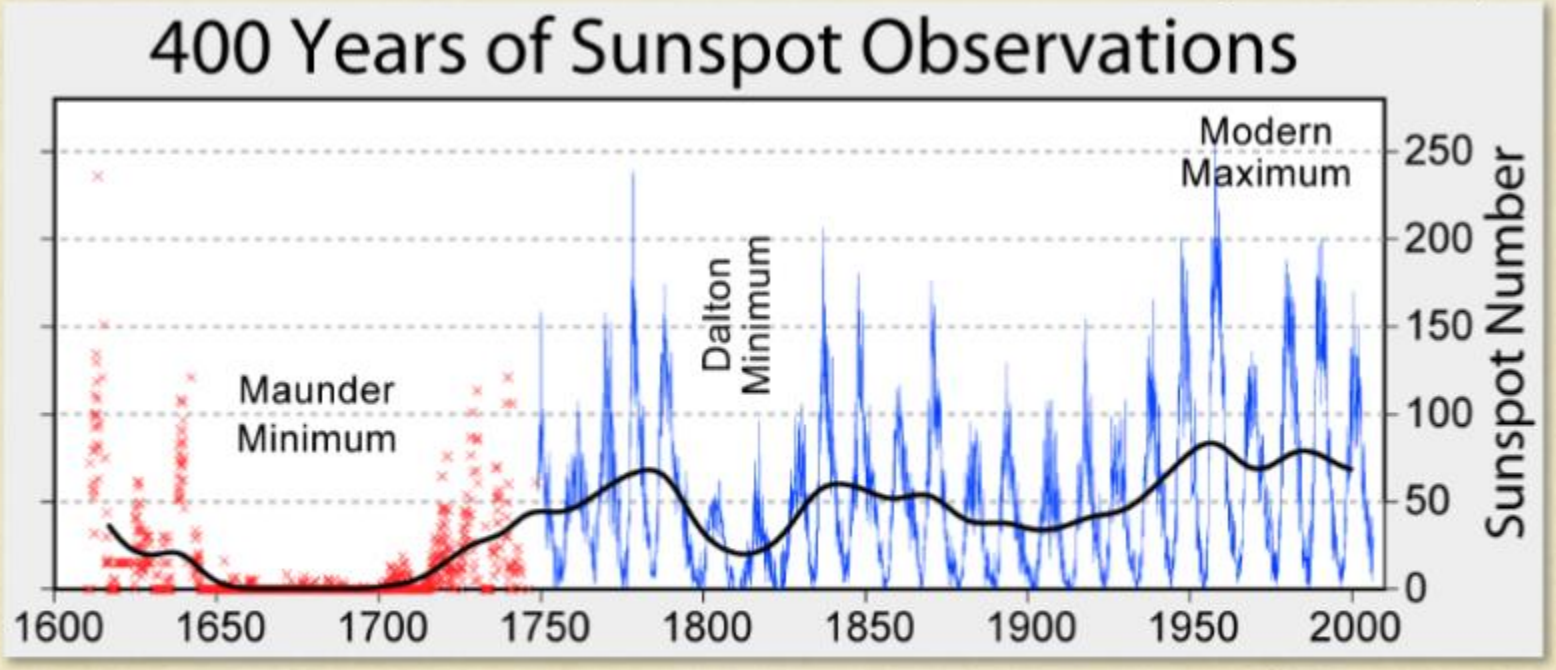


NASA/ESA Ulysses spacecraft data from 1.3-5.3 AU (credit: NASA/ESA)

Fast wind from coronal hole(s)

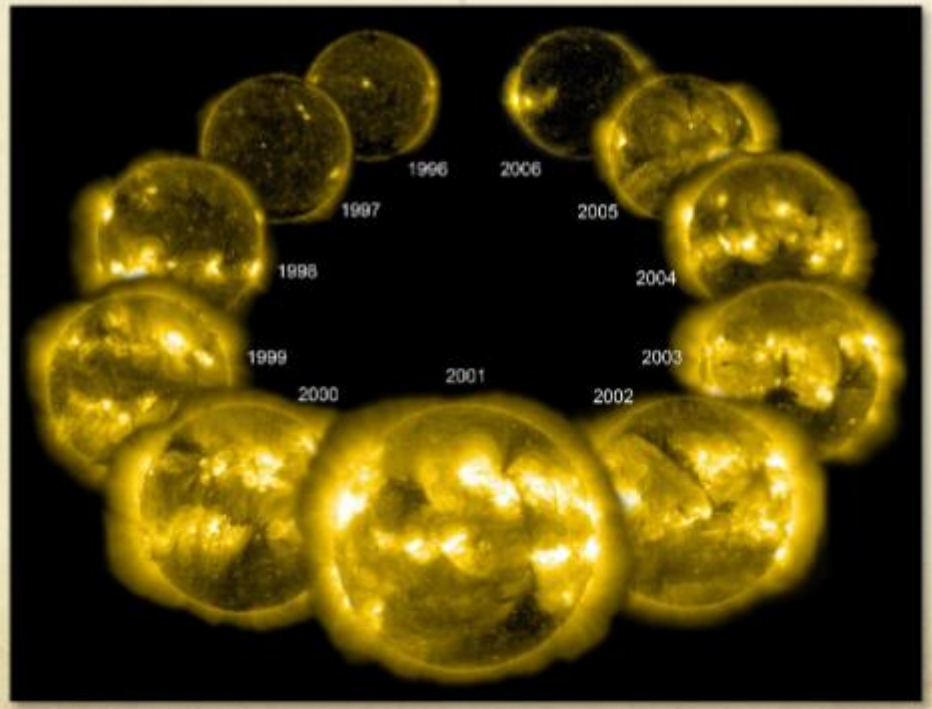
Denser low speed wind from lower latitudes

Credit: Wikipedia/Solar_cycle



Increasing sunspot number indicates more complex global solar magnetic field structure → eruptions more likely

As the global solar magnetic field structure gets more complicated also plasma configurations in the solar corona gain *complexity*.



SOHO EIT 284 Angstrom images (2 million degree plasma)

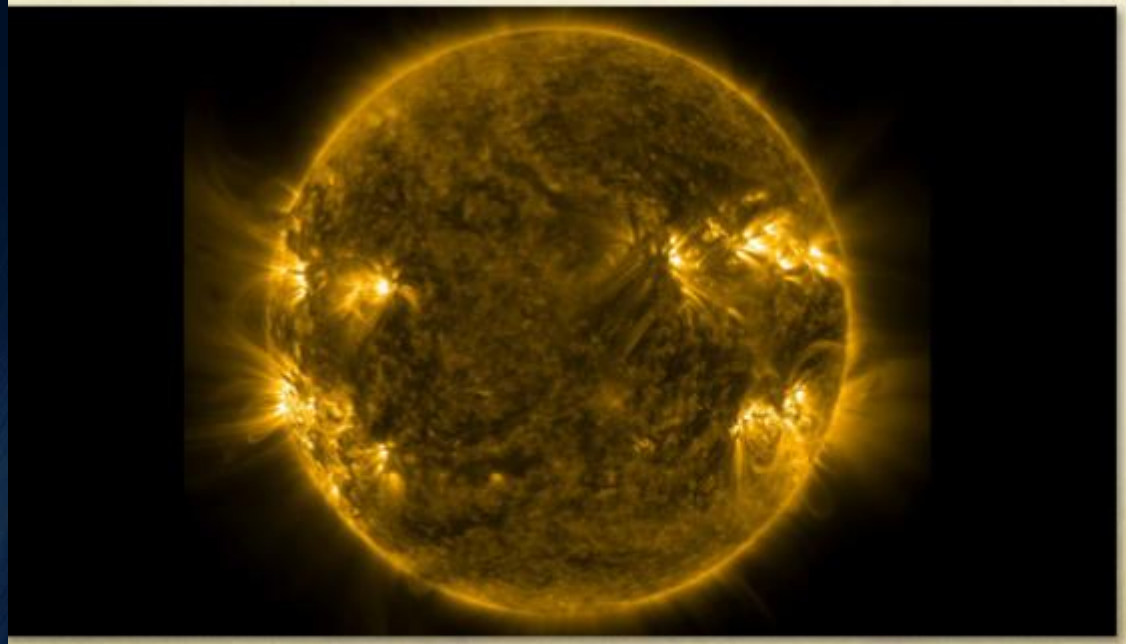
Credit: NASA/ESA

The build up of complexity in the corona is associated with build up of *free energy* in plasma configurations.

A variety of *plasma instabilities* such as flux tube instabilities are important for relaxation of plasma configurations in the solar corona.

However, we believe that *magnetic reconnection* plays the key role in converting the (magnetic) free energy into thermal and kinetic energy (plus electromagnetic radiation) of the transients.

Solar flares lasting, depending on the signature of interest, 1-60 min are the largest eruptions in the solar system. Energy of the order of 10^{25} J can be released by flares (annual world energy consumption $\approx 10^{20}$ J).



SDO AIA 171 Angstrom (1 million degree plasma)

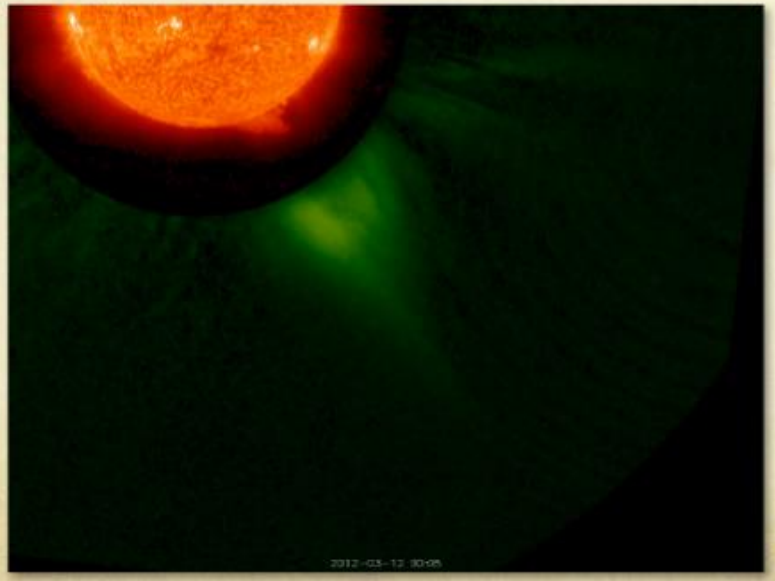
Credit: NASA GSFC SVS

Generally speaking in solar flares free magnetic energy converted into heat, non-thermal particle acceleration and electromagnetic radiation.

Solar flares generate, for example, X-ray, Extreme Ultraviolet (EUV) and radio emissions, and solar energetic particles (SEPs).

All of the above have significant space weather consequences.

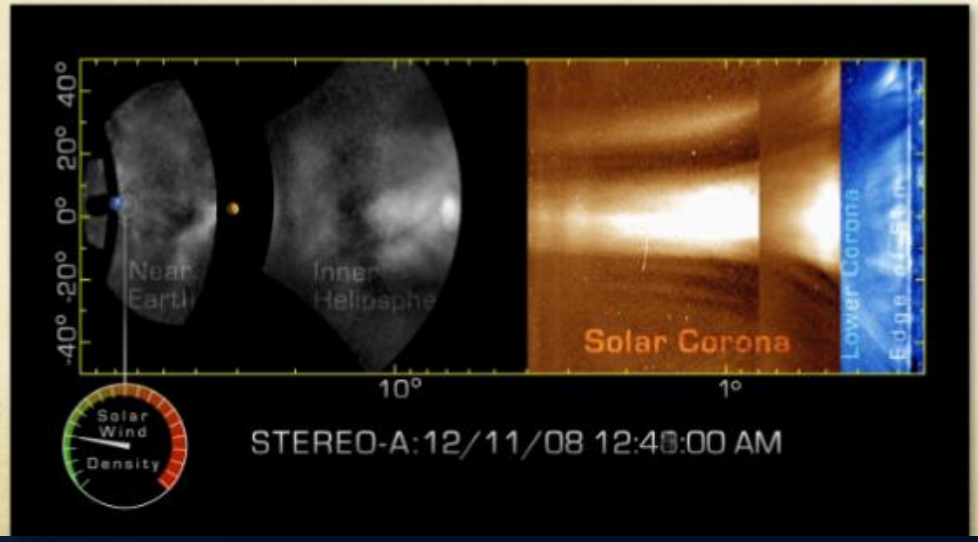
Many large flares are associated with *coronal mass ejections* (CMEs) releasing billions of tons of solar corona material at speeds of 200-3000 km/s. Total kinetic energy of CMEs can be of the order of 10^{25} J.



STEREO B 304 Angstrom EUV and white light coronagraph March 12, 2012

Credit: NASA

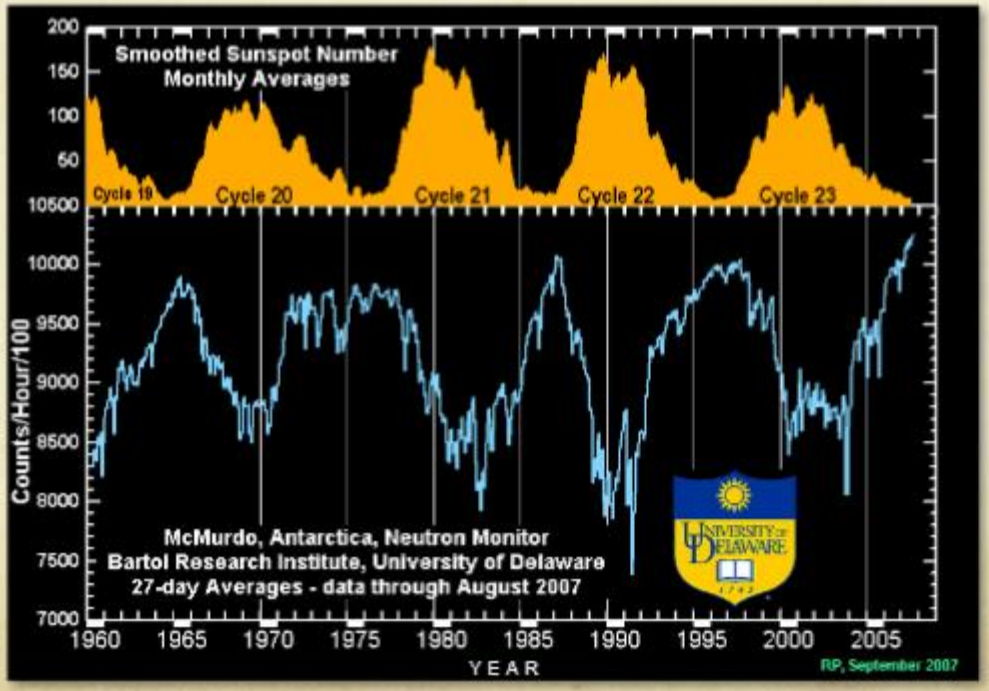
- CME eruptions drive shock waves that also accelerate charged particles. These particles generate the second (and often more significant) SEP component.
- CME propagation to the Earth takes typically 1-3 days.



STEREO A white light coronagraphs and heliospheric imagers December 2008

Credit: NASA GSFC

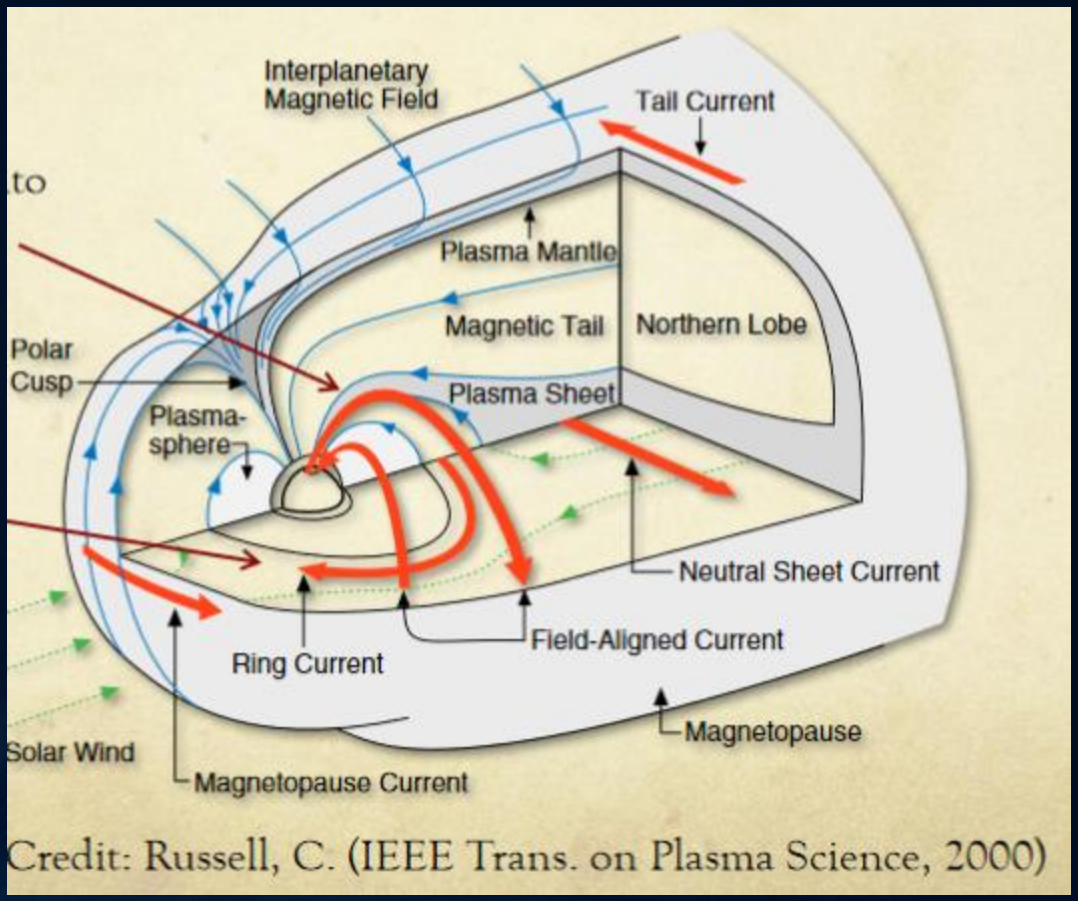
Also low flux but very energetic *galactic cosmic rays* (GCRs) coming from galactic sources contribute to charged particle radiation in the solar system.



Anti-correlation between solar activity and GCRs

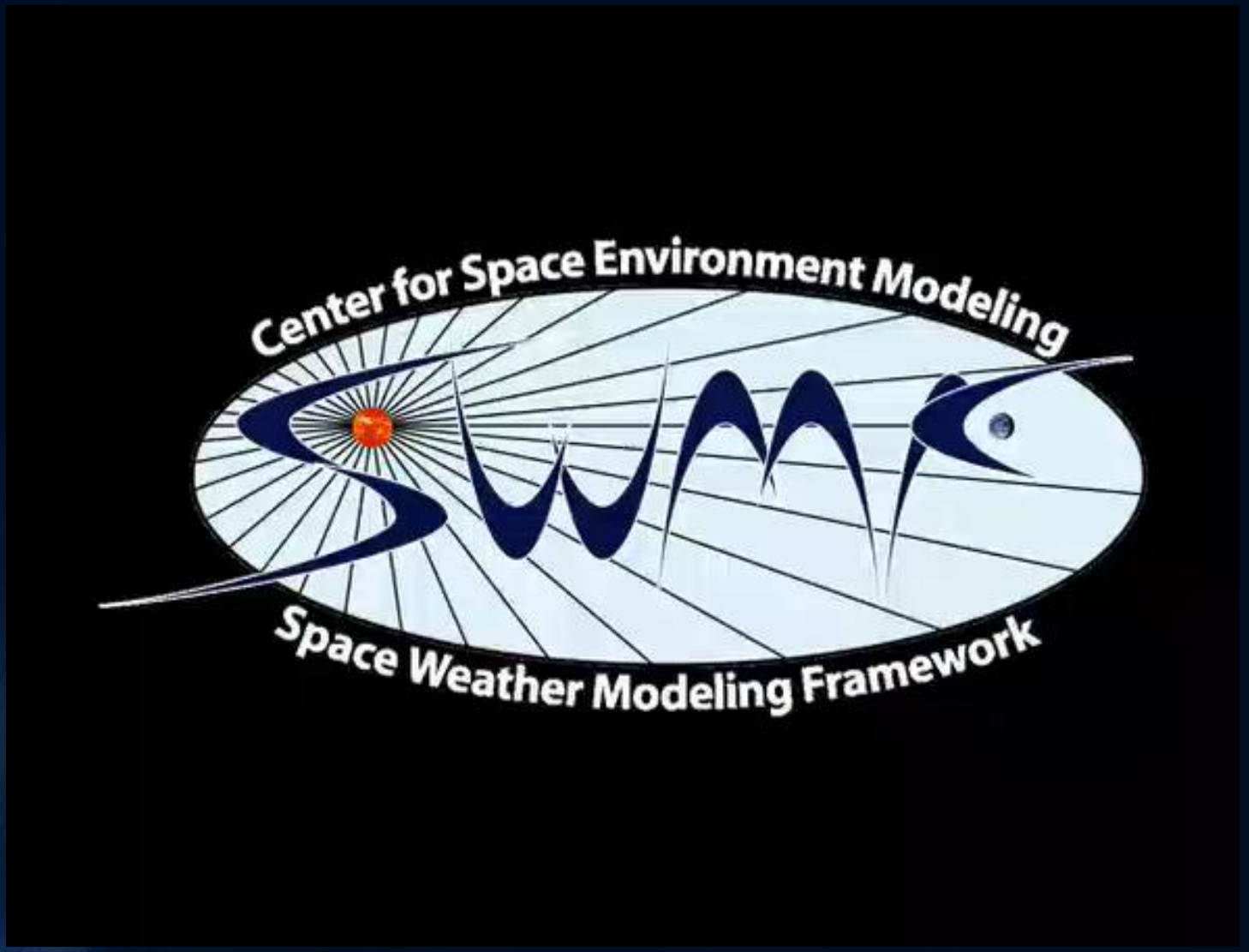
Credit: University of Delaware

- Charged particles flowing from the Sun interact with the Earth 's plasma environment called magnetosphere. Magnetic reconnection "opens up" magnetosphere to allow entry of mass, momentum and energy.

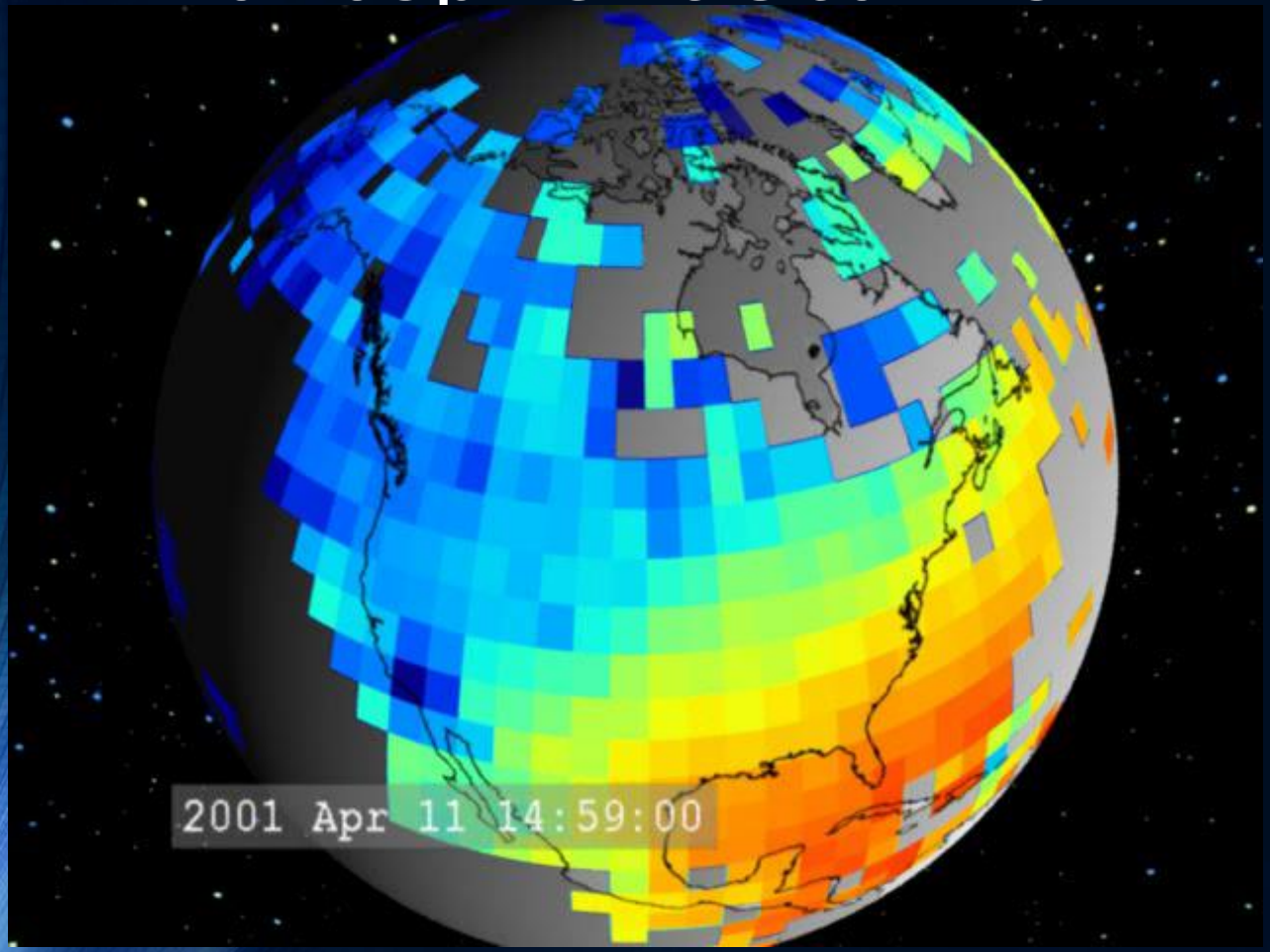


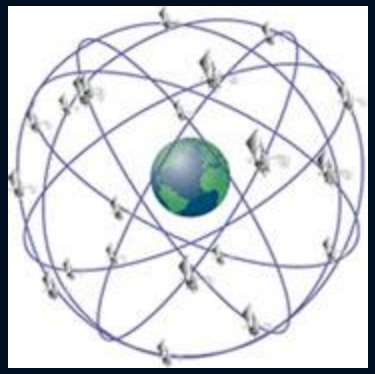
Solar Eruptions and Magnetic Storms

NASA/GSFC Scientific Visualization Studio.

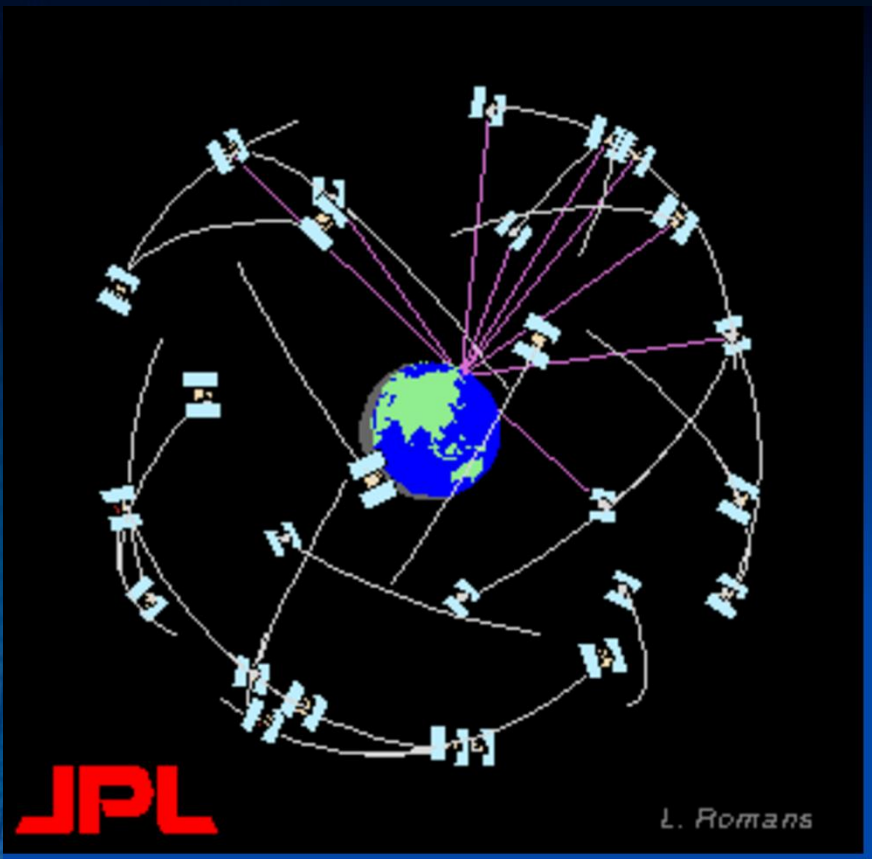

Center for Space Environment Modeling
SWMF
Space Weather Modeling Framework

Magnetic Storms: Ionospheric Storms





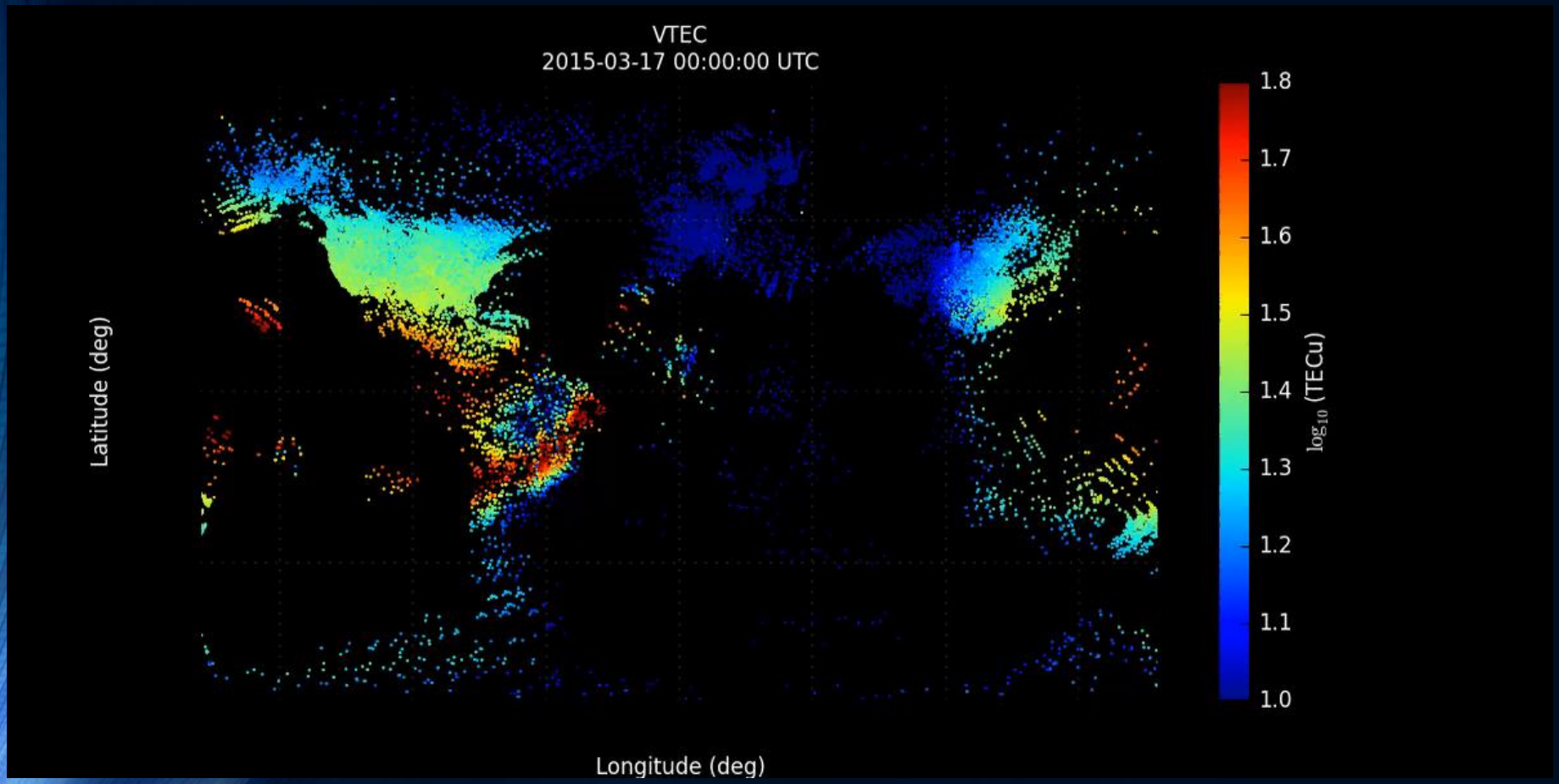
WAAS



GPS Background

- at most 32 satellites
- 6 orbital planes
- 4~6 satellites per plane
- 55° inclination angle
- near circular orbit
- ~ 20000 km altitude
- ~12 hours round trip

(11 hour 58 min 2.05 sec)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2015-03-17 00:00:00 UTC
Latitude (deg)
Longitude (deg)
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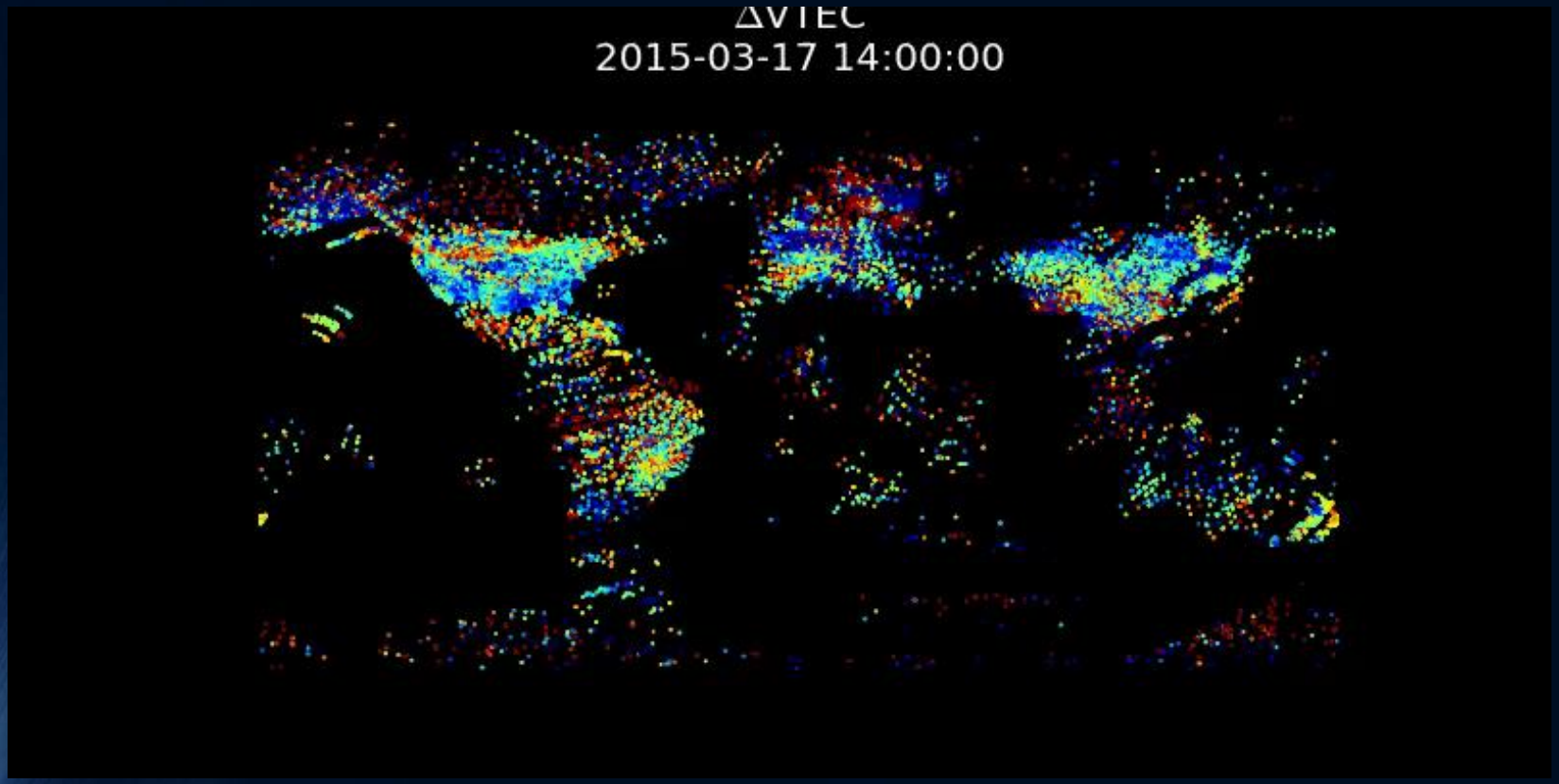
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
log10 (TECu)


ΔVTEC
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- Geomagnetic field fluctuations drive geomagnetically induced currents (GIC) that can be a hazard to long conductor systems on the ground.

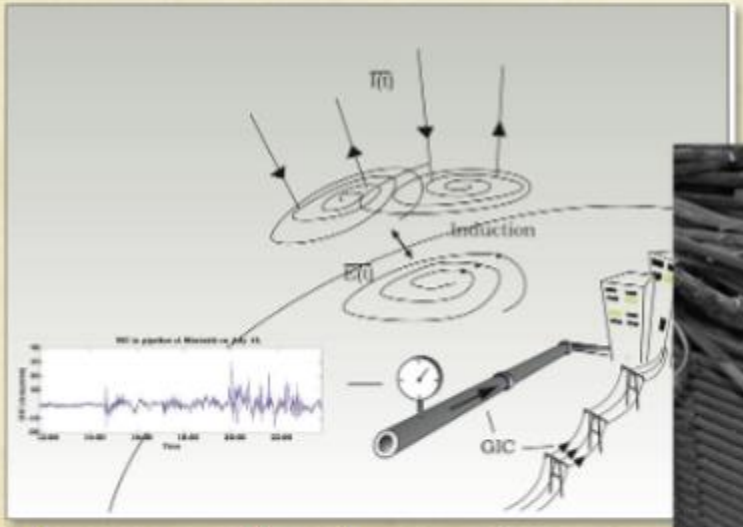


Illustration of mechanism for generating GIC

Transformer damage in South Africa

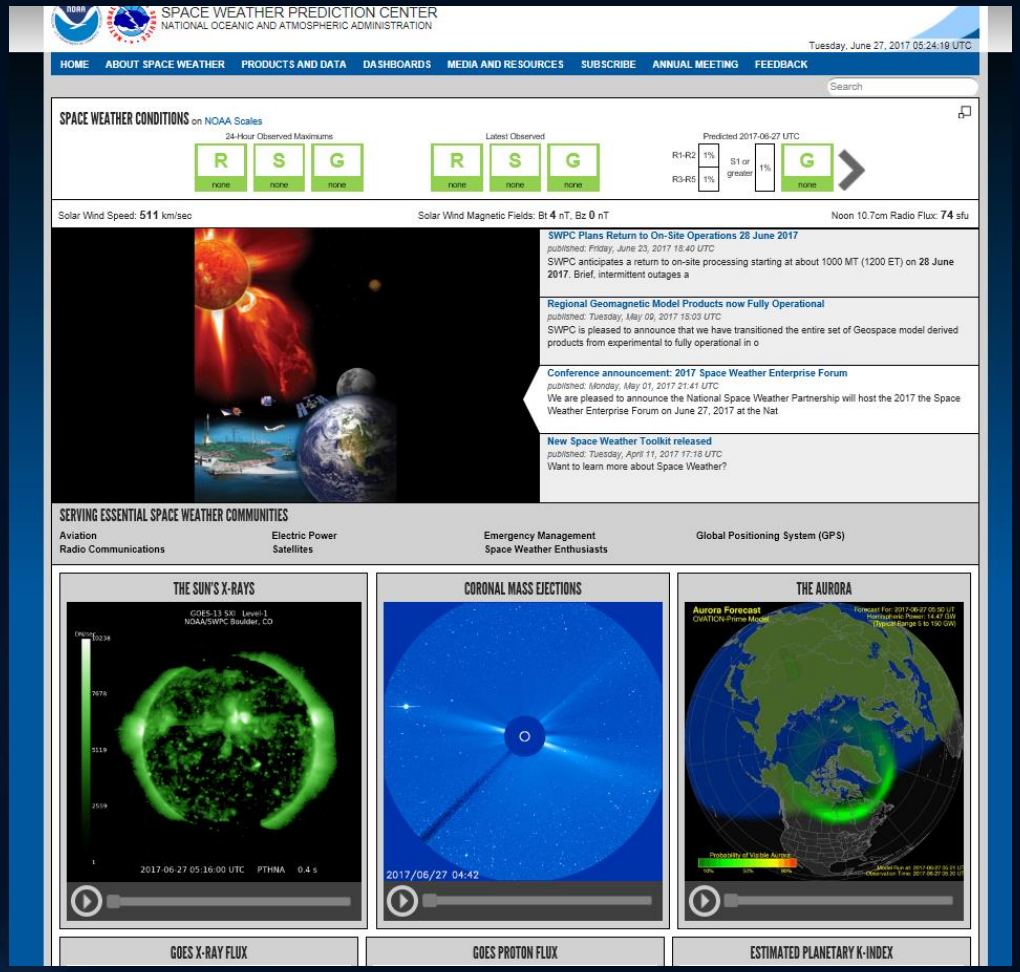
Credit: Gaunt and Coetzee (2007)


SPACE
WEATHER
IMPACTS
AURORA
(NORTHERN LIGHTS)
GPS
SATELLITES
COMMUNICATIONS
HUMAN SPACE
EXPLORATION
AVIATION
ELECTRIC POWER
WEATHER.GOV/SPACE

Resources

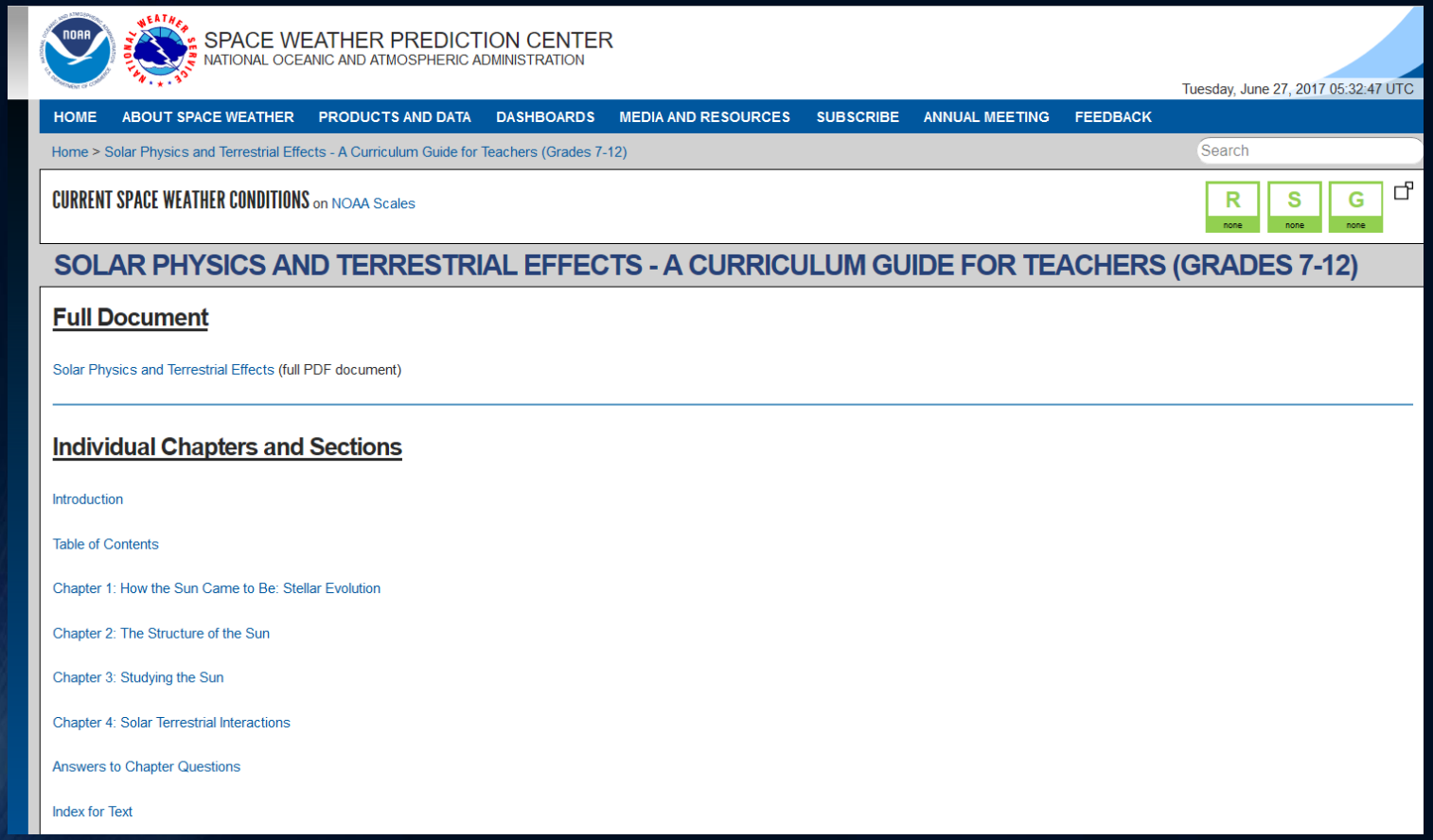
- NOAA Space Weather Prediction Center (http://spaceweather.gov)
  - Education and Outreach
- Spaceweather.com (http://spaceweather.com)
- Heliophysics @ UCAR (https://cpaess.ucar.edu/heliophysics/home)
- NASA Goddard CCMC (http://ccmc.gsfc.nasa.gov)
- NASA GSFC Visualization Studio (https://svs.gsfc.nasa.gov)
- Books

NOAA SWPC



- http://spaceweather.gov

NOAA SWPC Education and Outreach



- http://www.swpc.noaa.gov/content/solar-physics-and-terrestrial-effects-curriculum-guide-teachers-grades-7-12

Spaceweather.com

- http://spaceweather.com

UCAR

- https://cpaess.ucar.edu/heliophysics/home

Books:

- Carlowicz, M.J., R.E. Lopez, Storms from the sun: the emerging science of space weather, Joseph Henry Press, 2002.
- Clark, S., The Sun Kings: The Unexpected Tragedy of Richard Carrington and the Tale of How Modern Astronomy Began, Princeton University Press, 2007.
- Knipp, D., Understanding Space Weather and the Physics Behind It, McGraw -Hill, 744 p., 2011.
- Moldwin, M., An introduction to space weather, Cambridge UP, 146p., 2008.