# Introduction to Space Weather

Antti Pulkkinen, NASA GSFC

# Preamble

- No single textbook that covers all of space weather.
- Recommended reads:
  - Koskinen, H., Physics of Space Storms: From the Solar Surface to the Earth, Springer, 419 p., 2011. (Available at Amazon and as an online textbook via SpringerLink.com, which can be accessed at NASA GSFC)
  - Daglis, I.A. (editor), Space Storms and Space Weather Hazards, Nato Science Series II, Vol. 38, 2001.
  - Song, P., H. J. Singer, and G. L. Siscoe (eds.), Space Weather, AGU Geophysical Monograph Series, Vol. 125, 2001.

# Preamble

- Recommended reads cont'd:
  - Kivelson, M. G., and Russell (eds.), C. T., Introduction to Space Physics, Cambridge University Press, 1995.
  - Parks, G. K., Physics of Space Plasmas. An Introduction, Westview Press, 2004.
  - Bothmer, V. and I. Daglis, Space Weather: Physics and Effects, Springer, 438 p., 2007. (Available as an online textbook via SpringerLink.com, which can be accessed at NASA GSFC).
  - Knipp, D., Understanding Space Weather and the Physics Behind It, McGraw-Hill, 744 p., 2011. (undergraduate level)

# Preamble

- Recommended reads cont'd:
  - Carlowicz, M.J., R.E. Lopez, Storms from the sun: the emerging science of space weather, Joseph Henry Press, 2002. (lighter read)
  - Clark, S., The Sun Kings: The Unexpected Tragedy of Richard Carrington and the Tale of How Modern Astronomy Began, Princeton University Press, 2007. (lighter read)

# Preamble

- Online resources:
  - CCMC REDI: http://ccmc.gsfc.nasa.gov/support/SWREDI/swredi.php.
  - NOAA SWPC: www.swpc.noaa.gov.
  - NASA Integrated Space Weather Analysis System (iSWA): iswa.gsfc.nasa.gov.
  - CUA Space Weather Academy: www.youtube.com/user/CUASpaceWeather.

# So let's get going!

# Introduction to Space Weather

- Basic physical concepts. Sun, solar wind, eruptive solar phenomena, magnetosphere, ionosphere, geomagnetic induction.
- Impacts. Technological systems in the space and on the ground, humans in space and high altitudes.

# Introduction to Space Weather

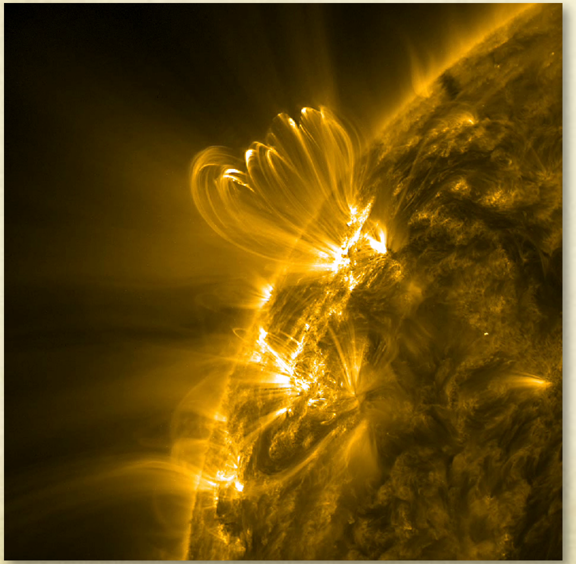
“Space weather refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human health. Adverse conditions in the space environment can cause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

US National Space Weather Program

# Introduction to 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)

# Introduction to Space Weather

- The range of space weather scales is extremely challenging.
  - Relevant time scales vary from $\approx 10^{-9}$ s (plasma fluctuations in the solar atmosphere) to $\approx 10^{8}$ s (solar cycle).
  - Relevant spatial scales vary from $\approx 1$ m (ionospheric plasma structures) to $\approx 10^{8}$ m (large-scale interplanetary plasma structures).
- Further, there is a strong coupling across the scales.

→ Forecasting space weather is a serious challenge…

# Introduction to Space Weather

- Although internal magnetospheric dynamics and galactic sources play an important role as well, the Sun is the ultimate source of (almost) all space weather.
- Consequently, lets start our run through space weather domains from the Sun.

# Introduction to Space Weather

Earth

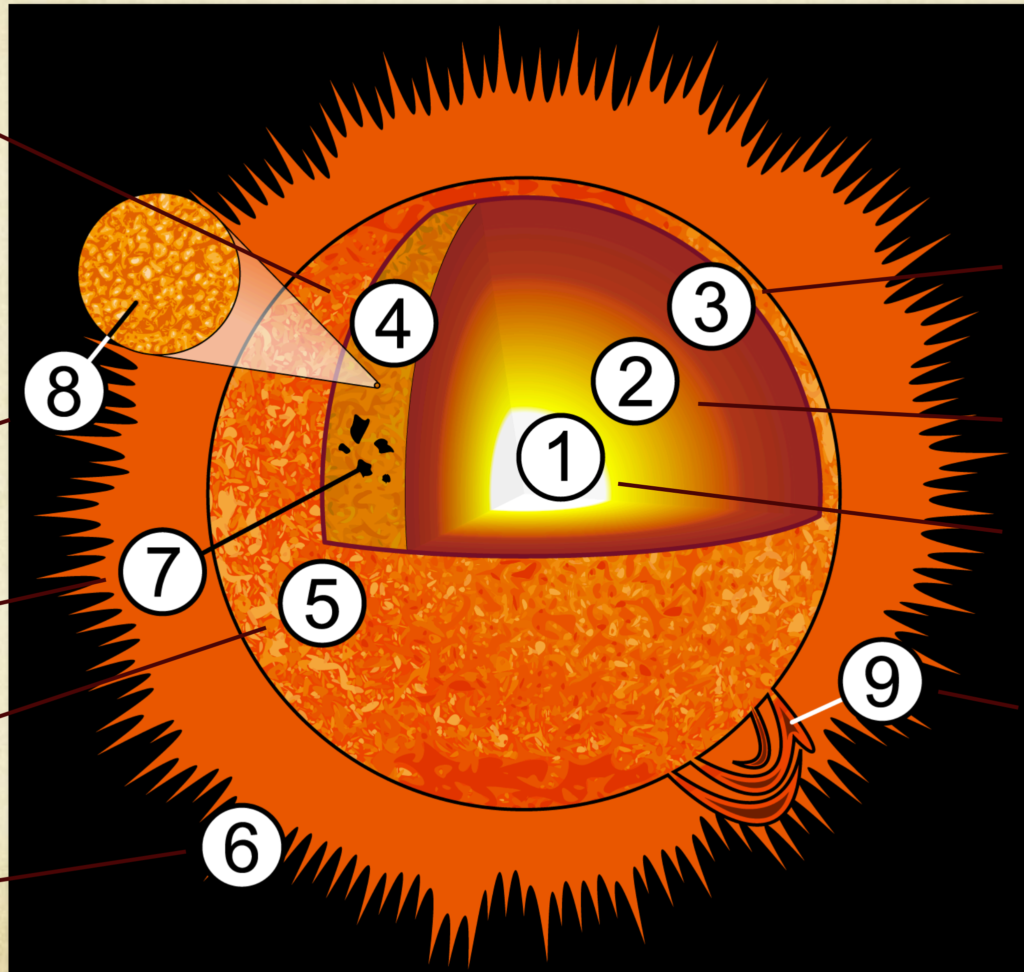
Photosphere at 4300 K (top)

Granulation

Sunspots

Chromosphere at 25000 K (top)

Corona at ≈$10^6$ K




Convection zone at 6600 K (top)

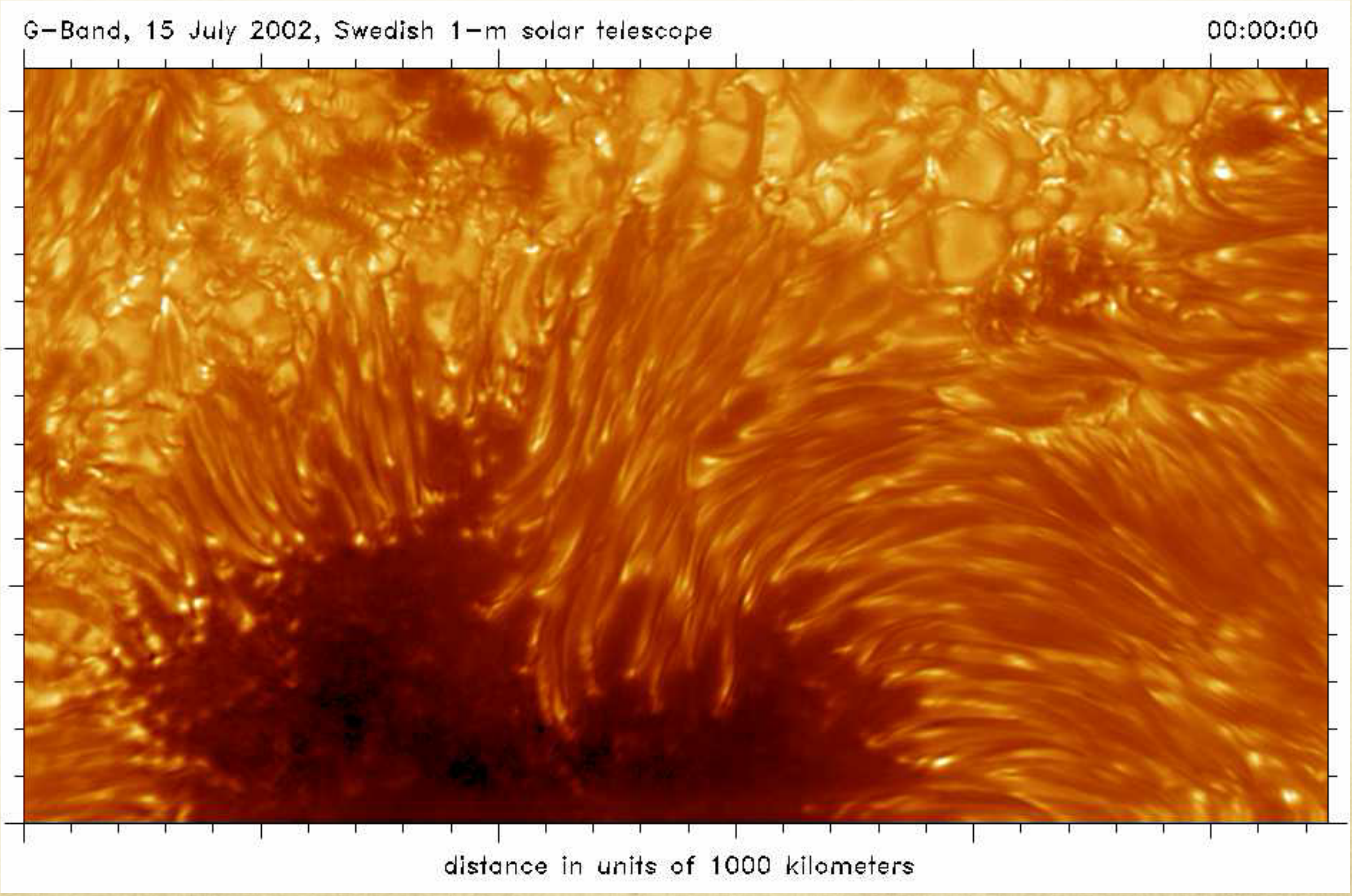
Radiation zone at $5 \cdot 10^5$ K (top)

Core (Hydrogen into Helium) at $1.5 \cdot 10^7$ K

Prominence at about 5000-10000 K

Credit: Wikipedia/sun

# Introduction to Space Weather



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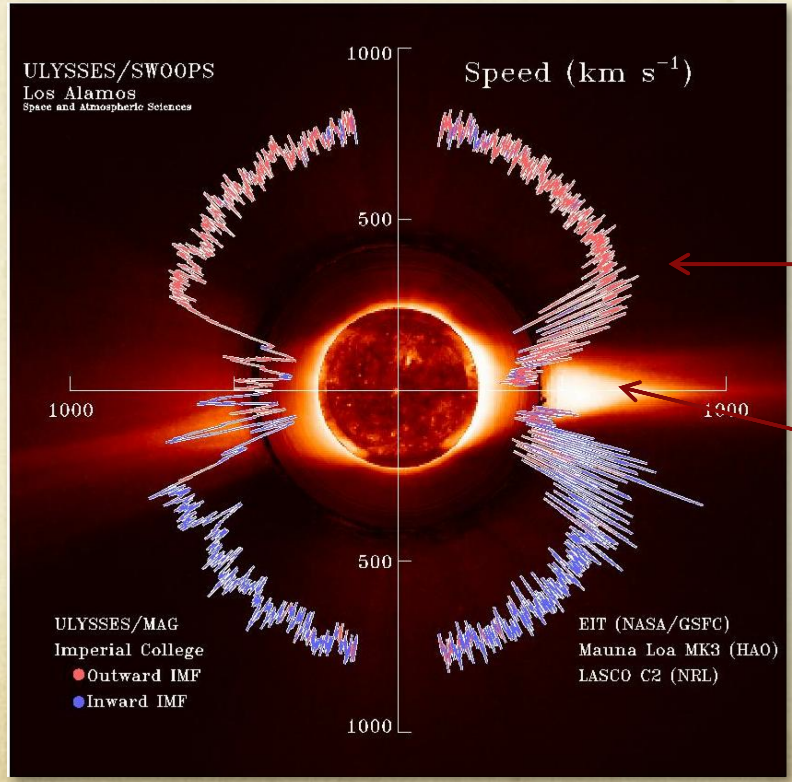
- Solar atmospheric mass, momentum and energy are being carried away by *solar wind.*



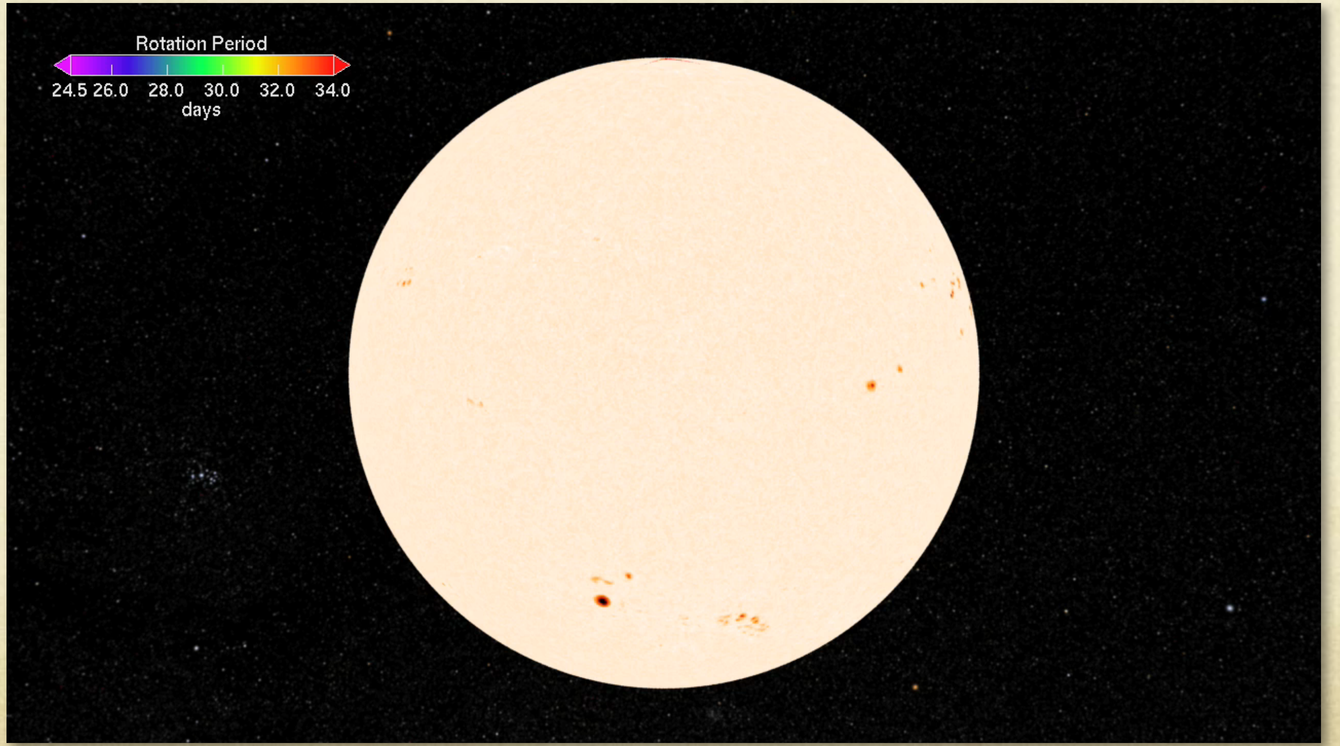

NASA/ESA Ulysses spacecraft data from 1.3-5.3 AU (credit: NASA/ESA)

Fast wind from coronal hole(s)

Denser low speed wind from lower latitudes

# Introduction to Space Weather

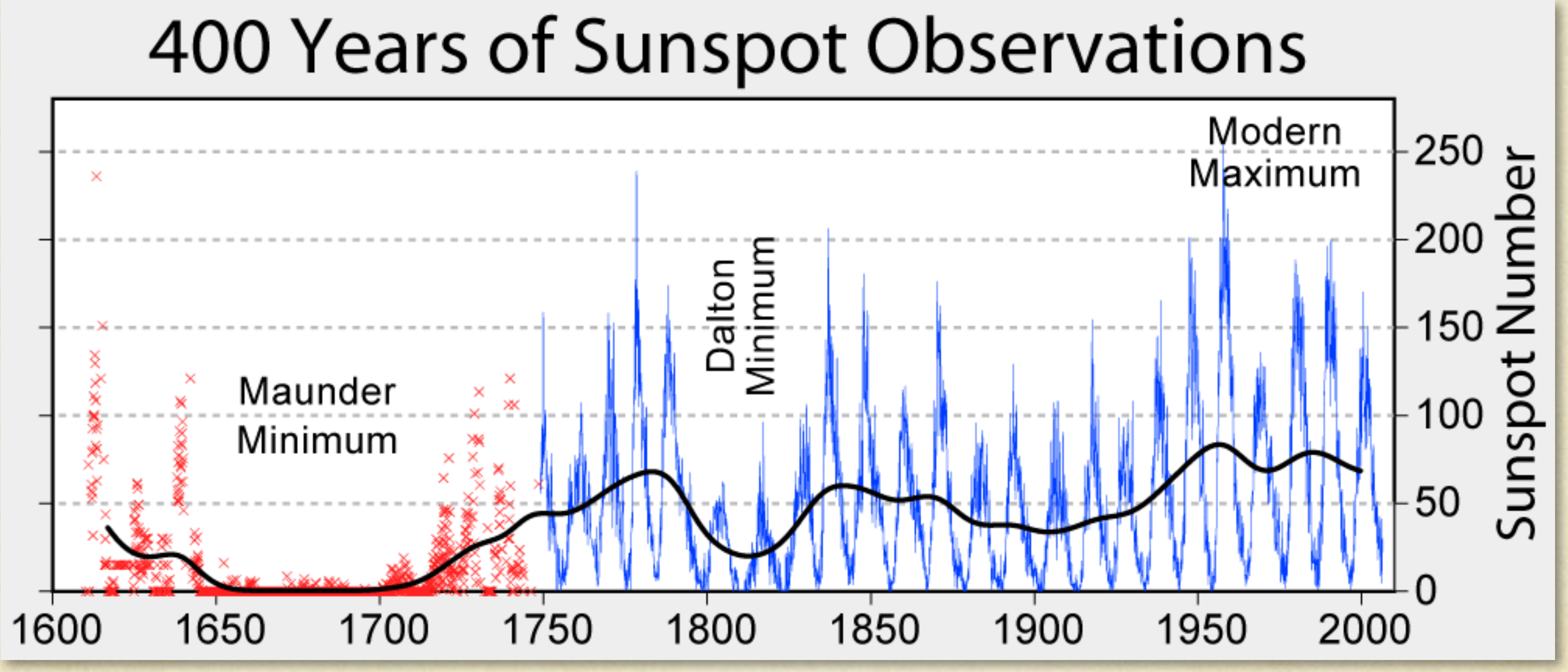
- The Sun is a magnetic beast. The magnetic field generated through *dynamo process*. both convection zone *turbulence* and solar *differential rotation* play important roles.




Credit: NASA GSFC SVS

# Introduction to Space Weather

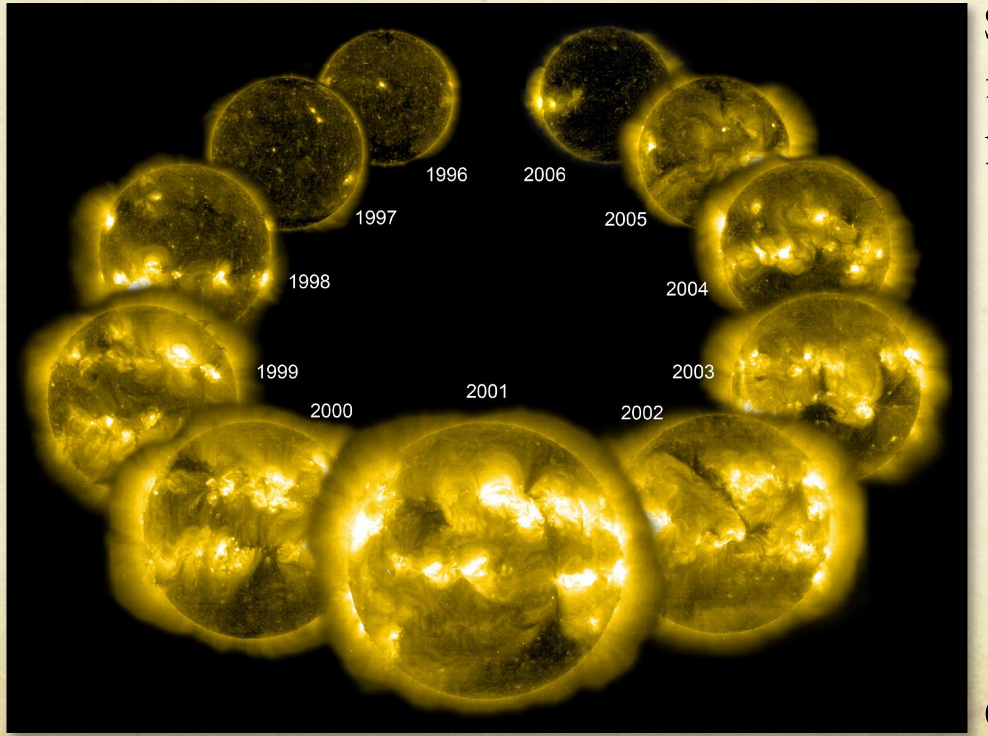
Credit: Wikipedia/Solar_cycle




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

# Introduction to Space Weather

- 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

# Quick quiz

- How do you think Space Age has changed our capacity to observe space weather?

# Introduction to Space Weather

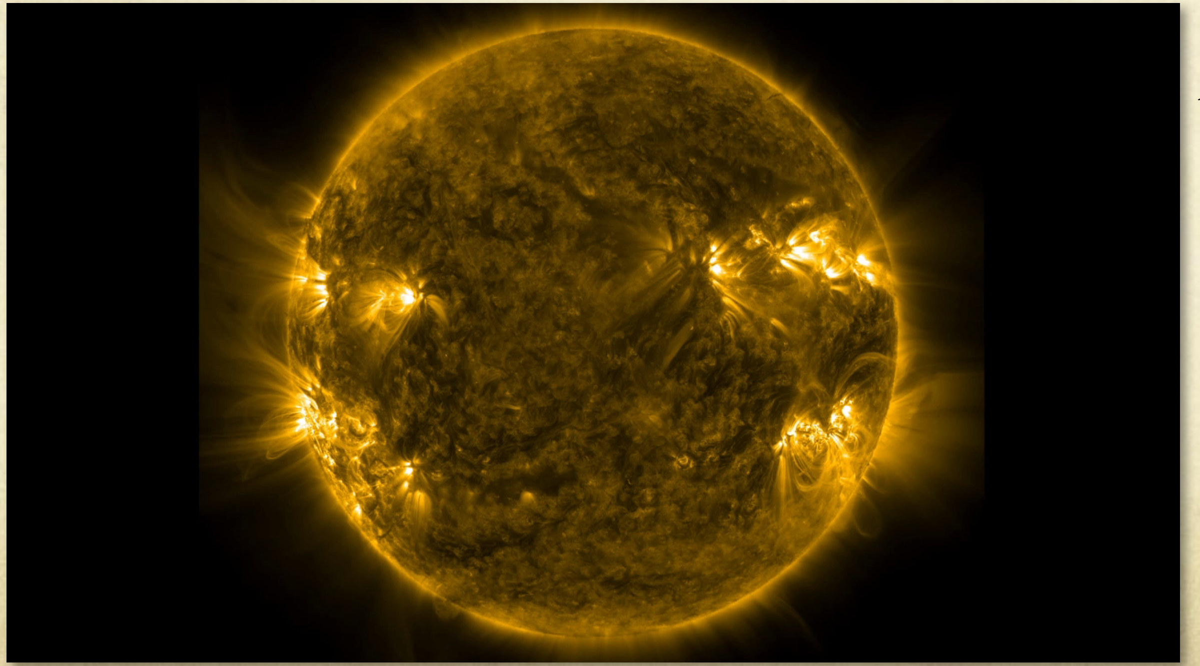
- The build up of complexity in the corona is associated with build up of *free energy* in plasma configurations.
- A variety of *plasma instabilities* such as flux tube instabilities are important for relaxation of plasma configurations in the solar corona.
- However, we believe that *magnetic reconnection* plays the key role in converting the (magnetic) free energy into thermal and kinetic energy (plus electromagnetic radiation) of the transients.

# Introduction to Space Weather

Credit: NASA

# Introduction to Space Weather

- *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

# Introduction to Space Weather

- 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.

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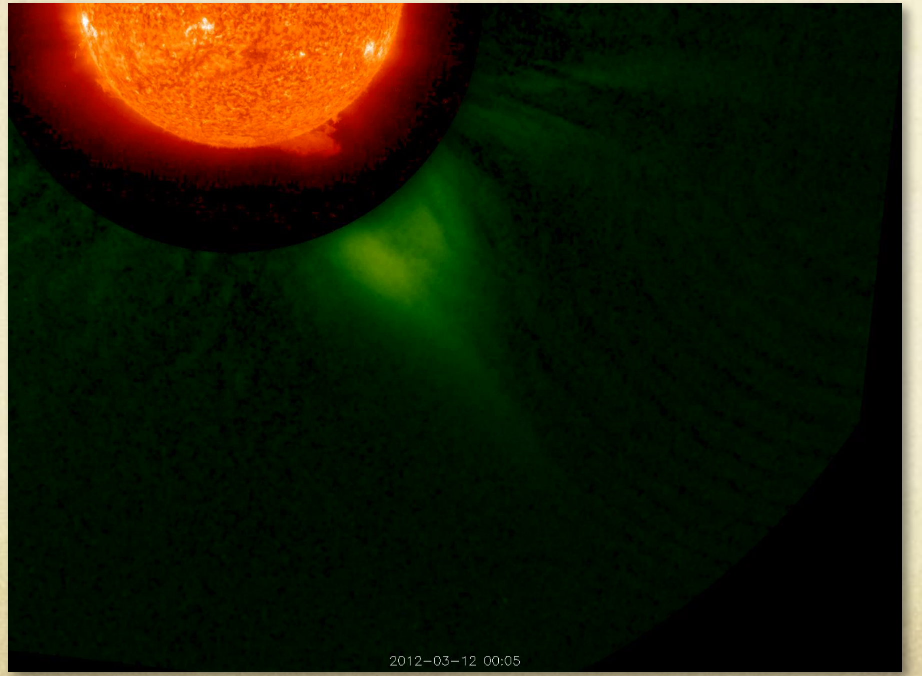
- Many large flares are associated with *coronal mass ejections* (CMEs) releasing billions of tons of solar corona material at speeds of 200-3000 km/s. Total kinetic energy of CMEs can be of the order of $10^{25}$ J.

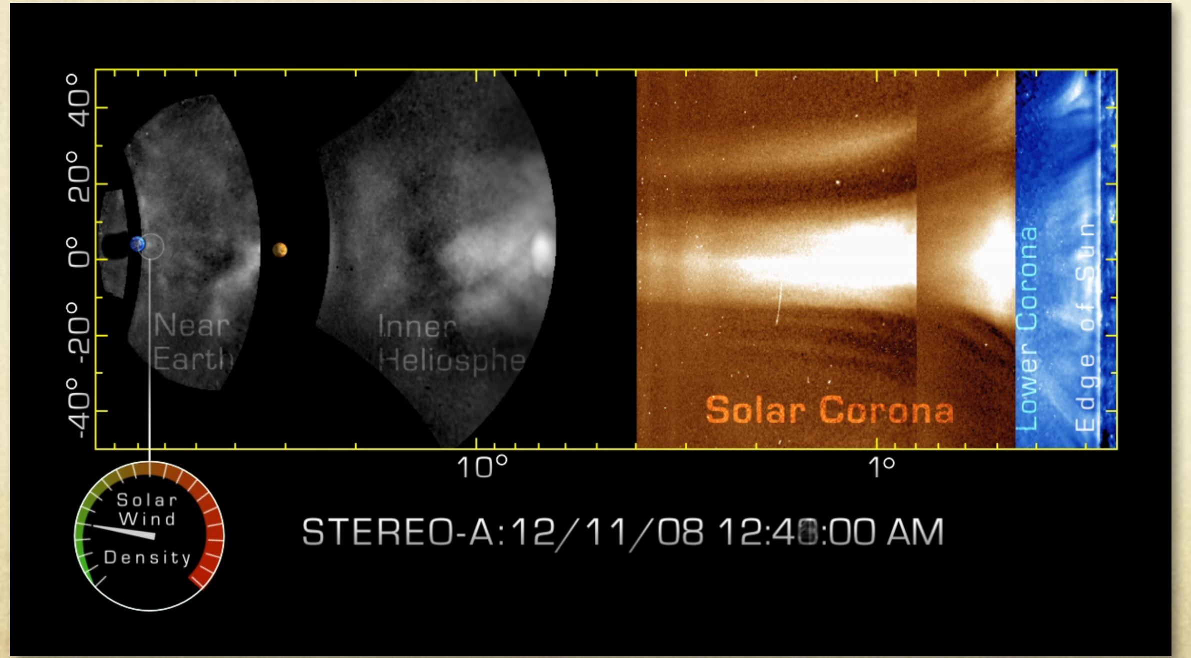



STEREO B 304 Angstrom EUV and white light coronagraph March 12, 2012

Credit: NASA

# Introduction to Space Weather

- 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.

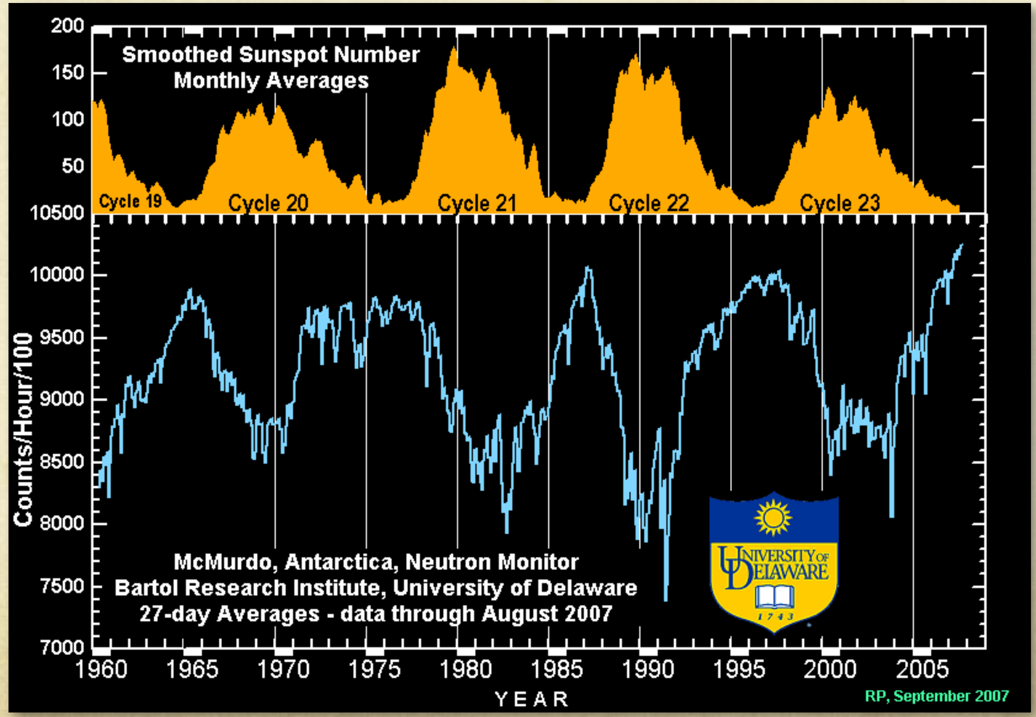



STEREO A white light coronagraphs and heliospheric imagers December 2008

Credit: NASA GSFC

# Introduction to Space Weather

- 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

# Introduction to Space Weather

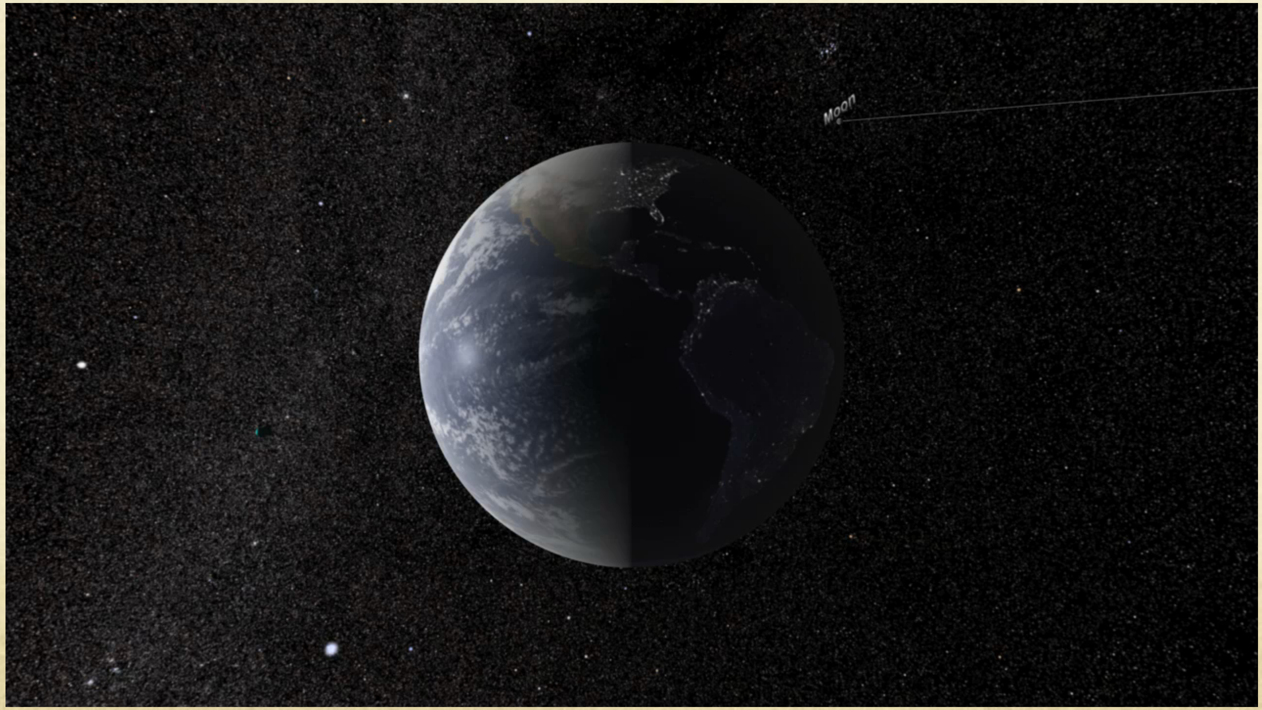
- Charged particles flowing from the Sun interact with the Earth's plasma environment called *magnetosphere*. Magnetic reconnection "opens up" magnetosphere to allow entry of mass, momentum and energy.

Solar wind and CME plasma flow interacting with the Earth's magnetosphere.

Credit: NASA GSFC SVS

# Introduction to Space Weather

- The entry of mass, momentum and energy powers very complex dynamic phenomena in the magnetosphere. Radiation belts are one central part of these phenomena.




Energetic (100 keV-10 MeV) electrons in the radiation belts

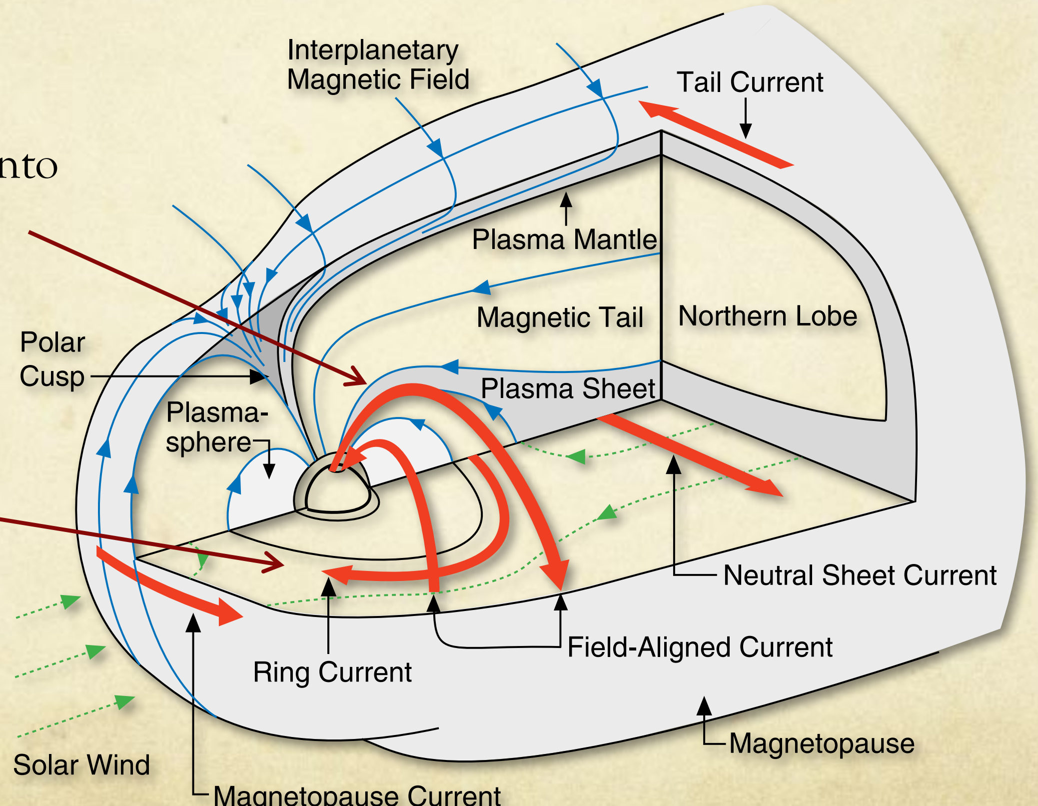
Credit: NASA GSFC SVS

# Introduction to Space Weather

- Also various magnetospheric electric current systems get powered.

≈ 1 MA current into the ionosphere

Charged (10-200 keV) particles carrying the ring current partly overlap with the radiation belts




Credit: Russell, C. (IEEE Trans. on Plasma Science, 2000)

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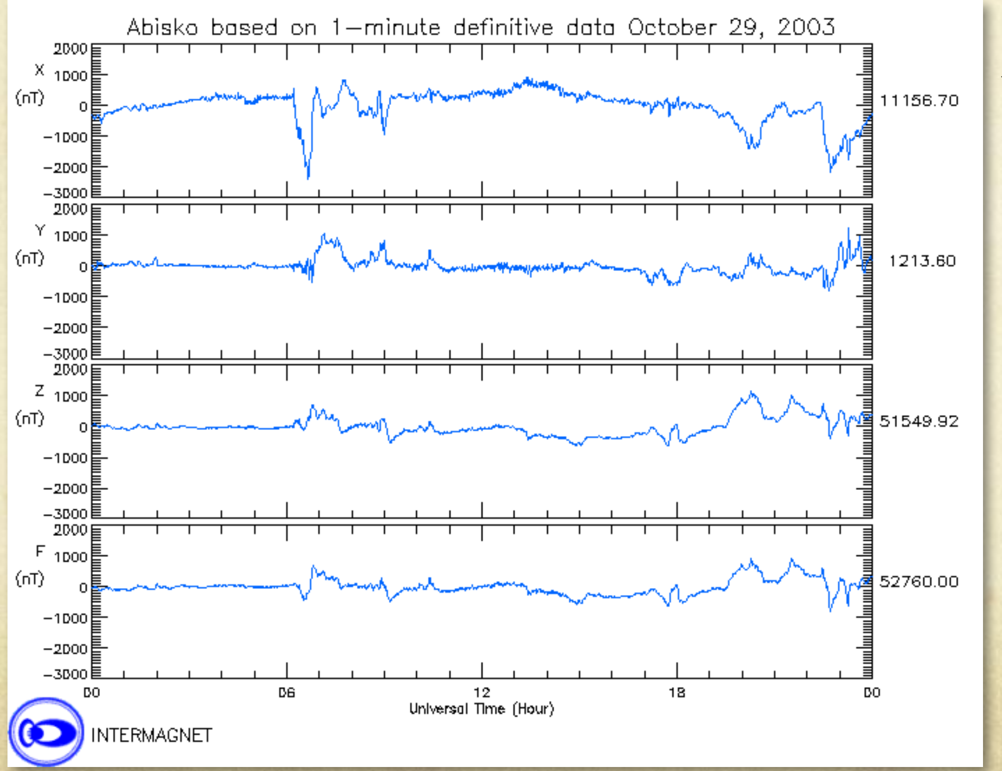
- Electric currents flowing in the near-space generate magnetic field perturbations on the surface of the Earth. These fluctuations are called *geomagnetic storms*.




Storm-time magnetic field variations observed in a high-latitude station.

Credit: INTERMAGNET

# Introduction to Space Weather

- Earth's ionized upper atmosphere (80-1000 km altitude) reacts for example to solar flare-related X-rays, EUV, SEP events and magnetospheric activity.

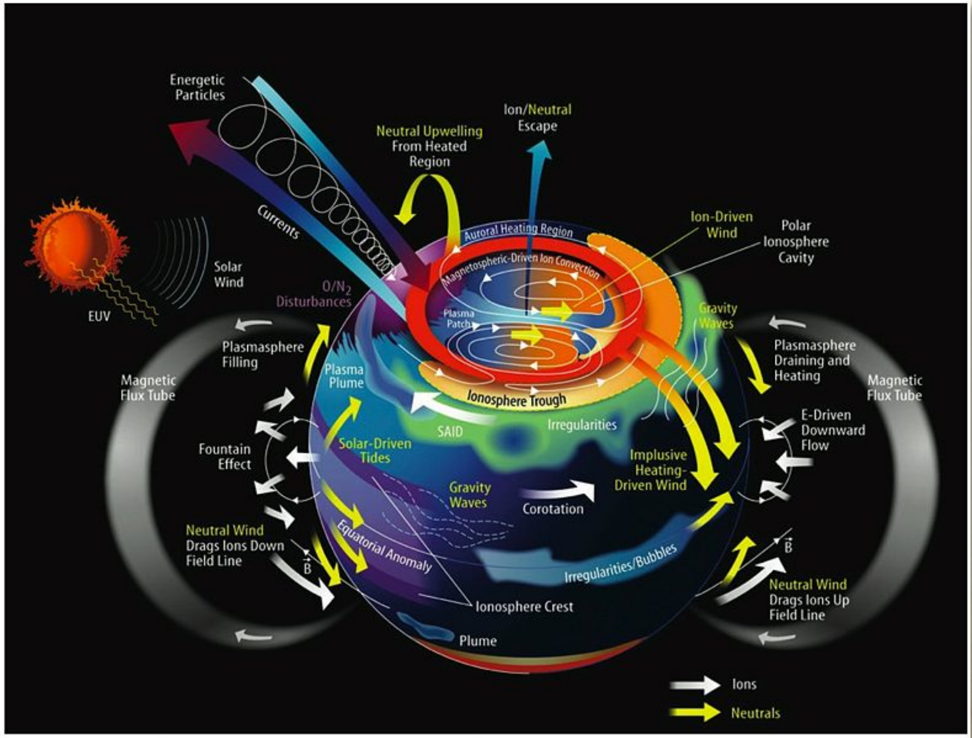
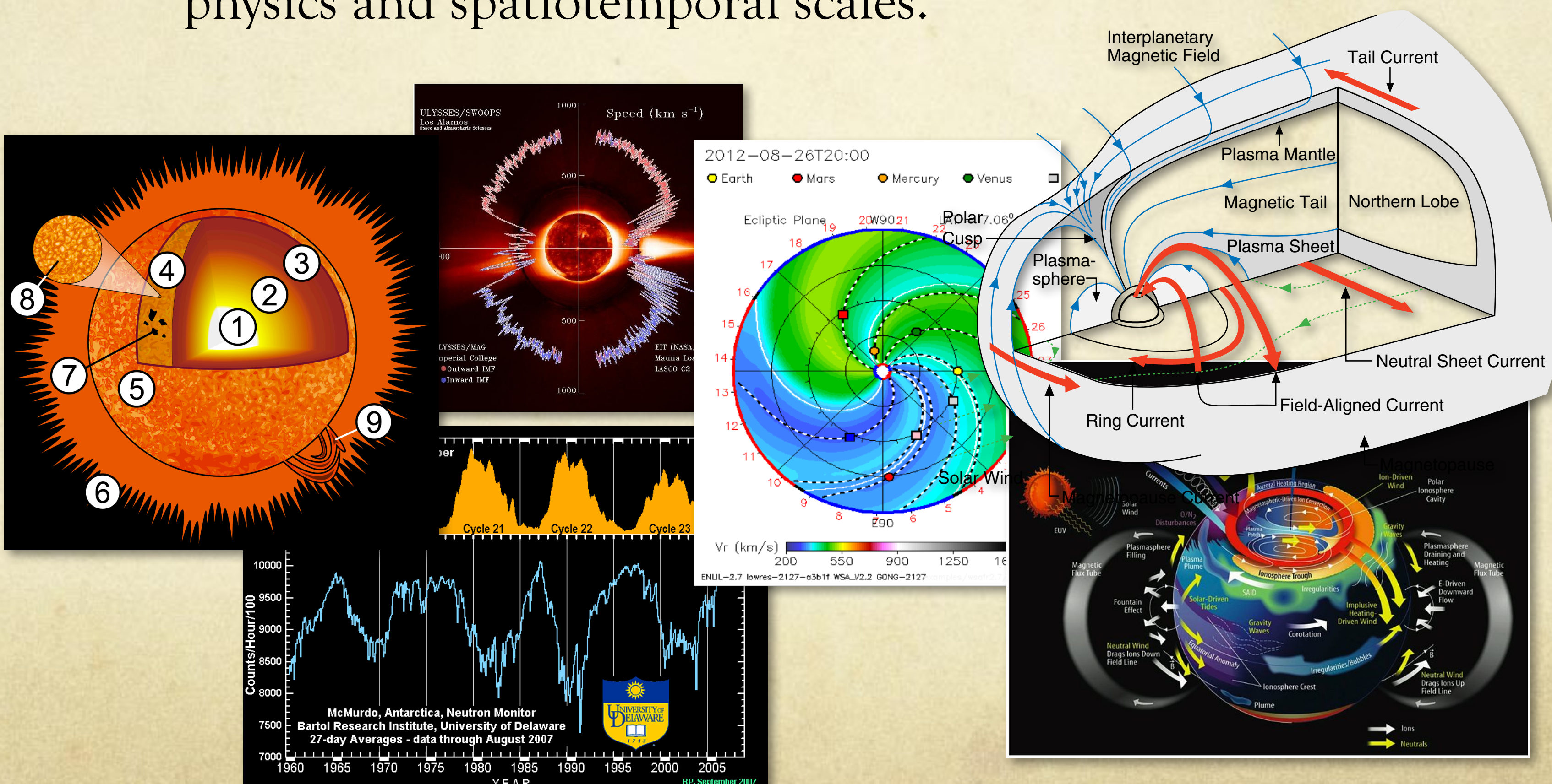



Illustration of upper atmospheric dynamics.

Credit: J. Grobowsky/NASA

# Introduction to Space Weather

- So we see that space weather really is a vast chain of complex interacting systems covering wide ranges of physics and spatiotemporal scales.



# Quick quiz

- What do you think are some of the major similarities and differences between space weather and “regular” weather?

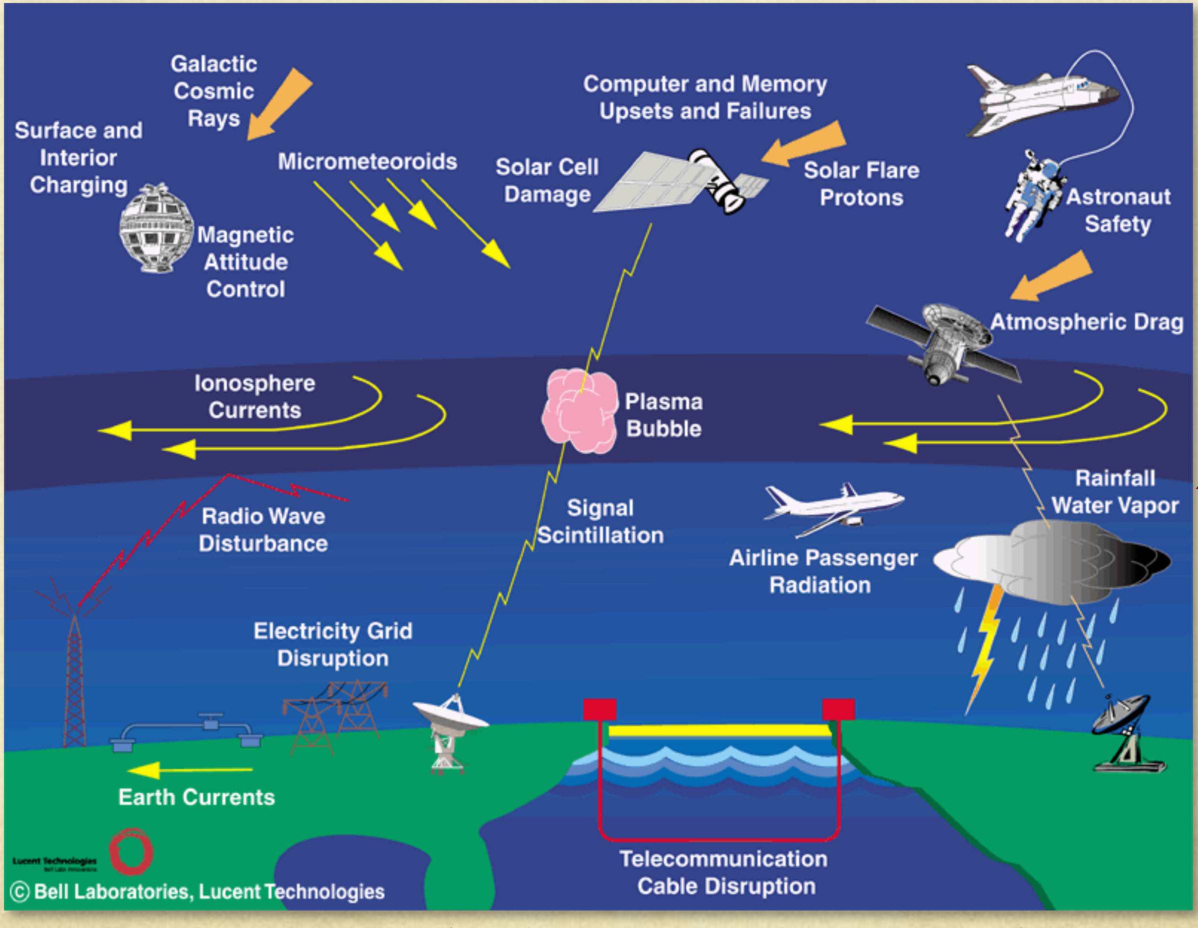
# Introduction to Space Weather

- Let us then very briefly review the *impacts* side of space weather. Perhaps the best known and positive "entertainment aspect" of space weather are the northern (and southern) lights.

Aurora Australis imaged from ISS Sep 11, 2011

Credit: NASA

# Introduction to Space Weather

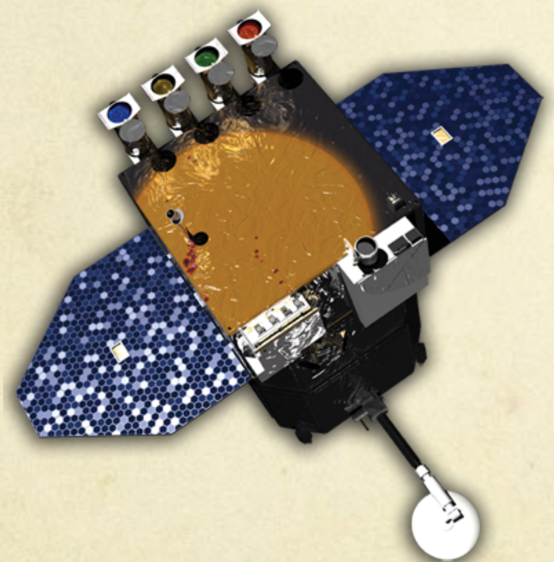



Space weather impacts (credit: L. Lanzerotti/Bell Labs)

We will not be discussing these

# Introduction to Space Weather

- Spacecraft can be impacted in a number of different ways depending on the orbit of the vehicle.

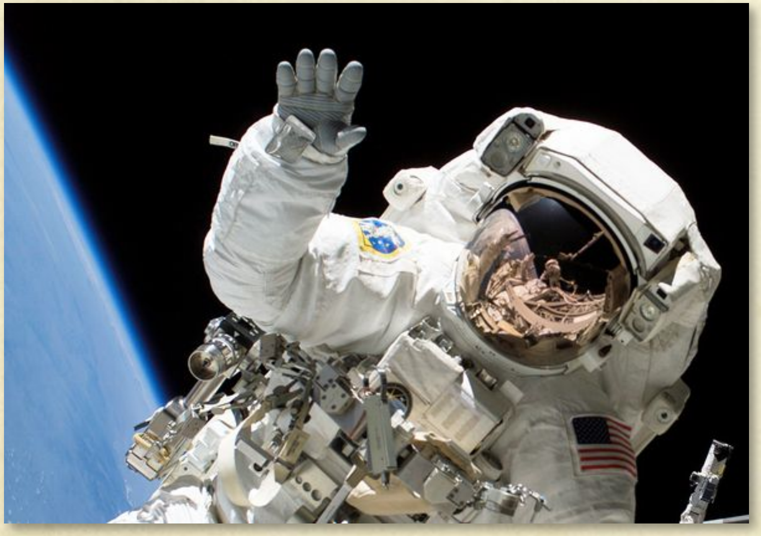


Solar Dynamics Observatory (credit: NASA)

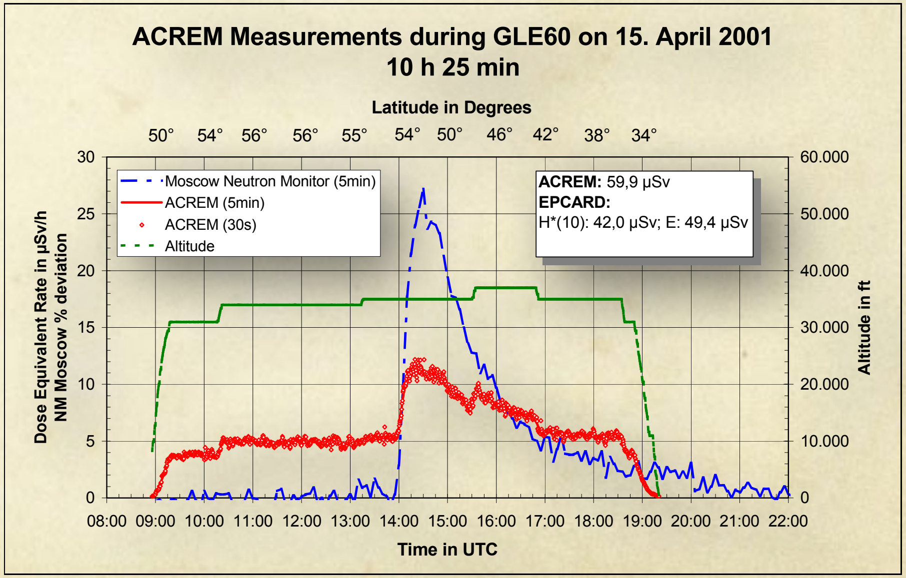
- Surface (auroral and ring current electrons) and deep internal charging (radiation belt electrons).
- Single event upsets (GCRs, SEPs, inner radiation belt protons).
- Drag effects (upper atmospheric expansion).
- Total dose effect (cumulative radiation in any environment).
- Effects on the attitude control systems (magnetic field fluctuations and SEPs).

# Introduction to Space Weather

- Energetic charged particle radiation is a hazard for humans in space and at airline altitudes. Especially less predictable SEPs are a concern.



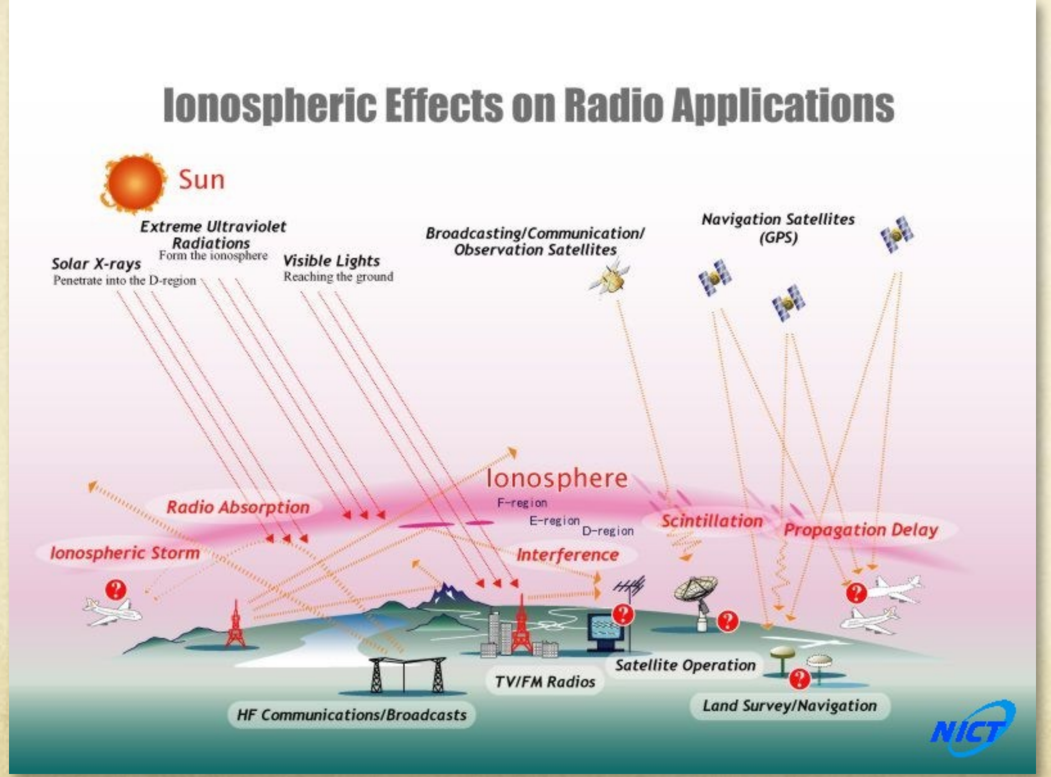
Credit: NASA




Dose observations from a commercial flight (Credit: Bartlett et al., 2002)

# Introduction to Space Weather

- Signals using ionosphere or "just" passing through ionosphere are affected by space weather.




Credit: NICT

- Global navigation satellite systems such as GPS (e.g., EUV, X-rays, SEPs, magnetospheric activity)
- High-frequency (HF) radio communications (e.g., EUV, X-rays, SEPs, magnetospheric activity)
- Other GHz range comms such as cell phones (solar radio noise)

# Introduction to Space Weather

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

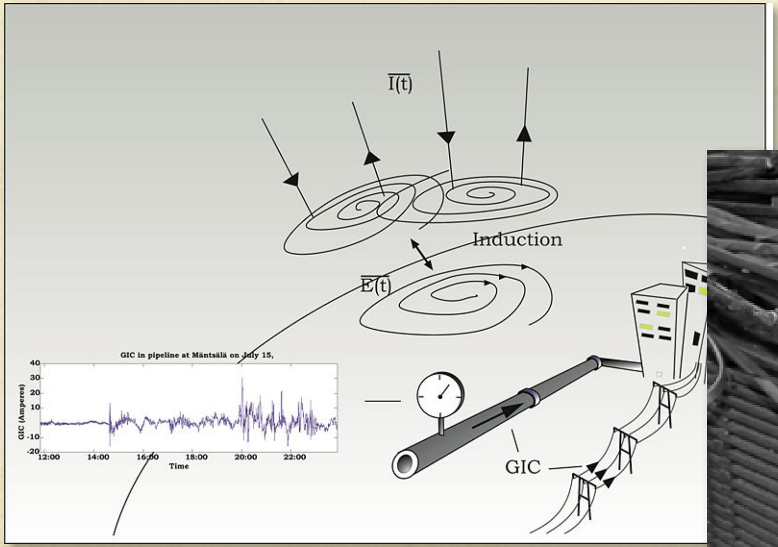



Illustration of mechanism for generating GIC

Transformer damage in South Africa

Credit: Gaunt and Coetzee (2007)

# Quick quiz

- How do you think space weather can impact your everyday life and should you be prepared?