Run Through Space Weather I

Antti Pulkkinen

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.

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- 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).

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- 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)

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

So let's get going!

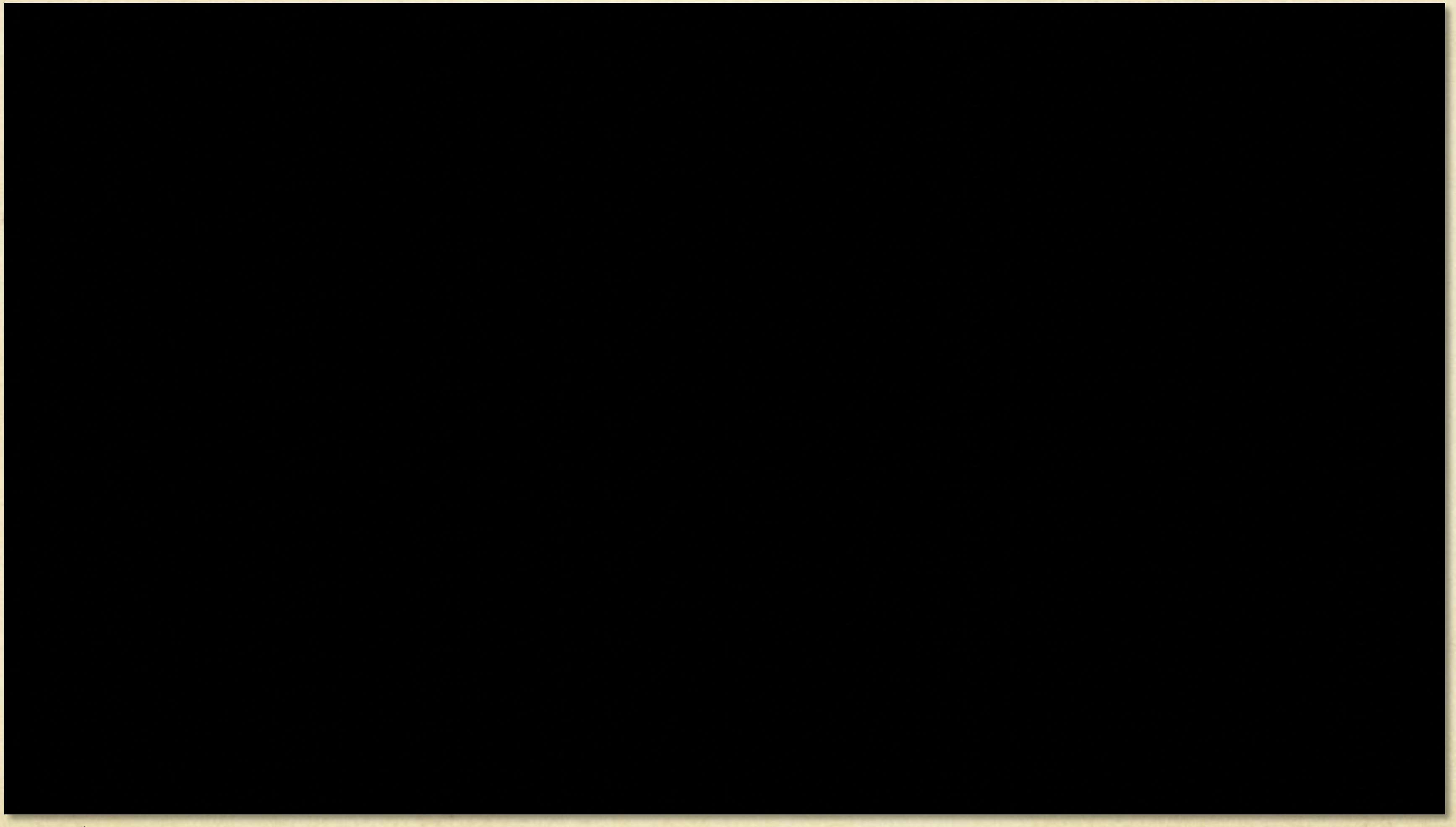
Run Through Space Weather I

- 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.

Run Through Space Weather I

“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



Credit: NASA GSFC SVS

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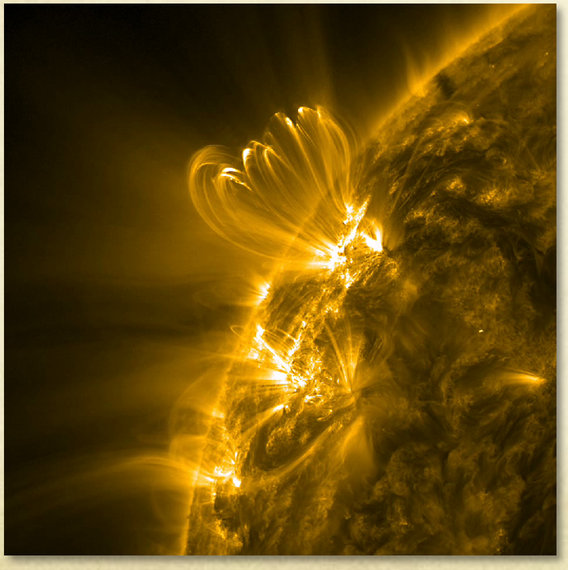
- The physics of space weather is *plasma physics.*

  "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)

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- 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 ≈ 1 m (ionospheric plasma structures) to $\approx 10^{8}$ m (large-scale interplanetary plasma structures).
- Further there is a strong coupling across the scales.

→ Pretty crazy stuff! No wonder forecasting space weather is a serious challenge…

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- 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.

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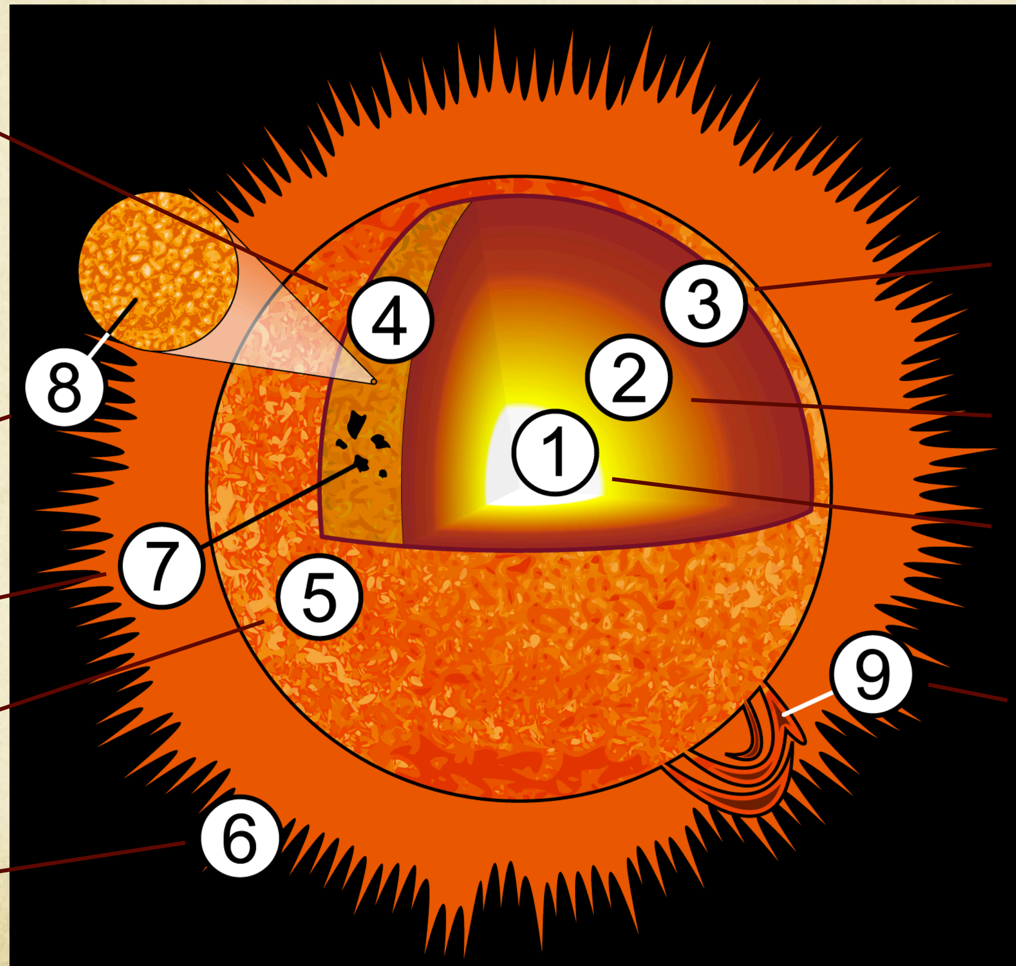

Credit: Wikipedia/sun

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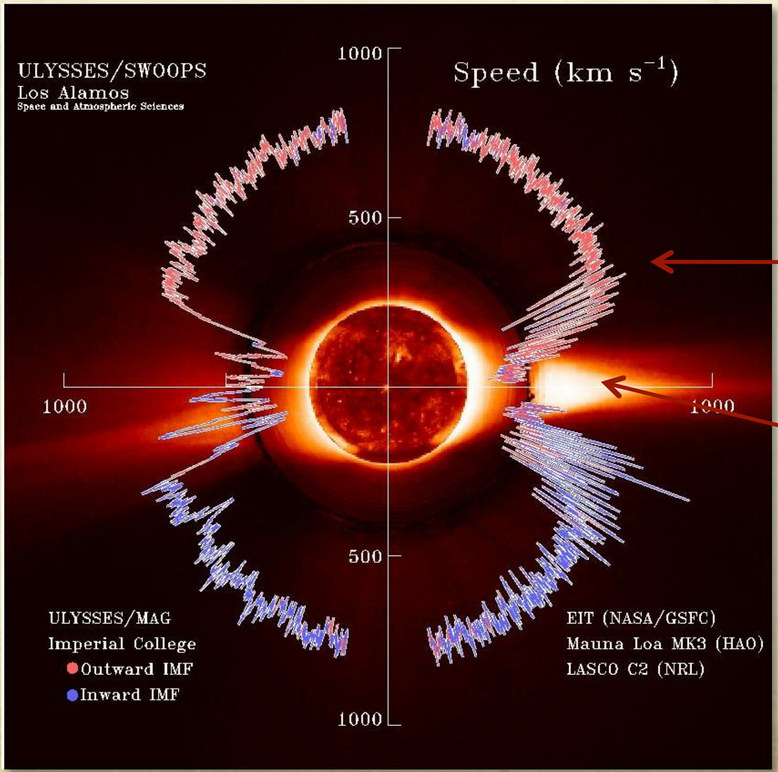
- Solar atmospheric mass, momentum and energy are being carried away by *solar wind*.



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

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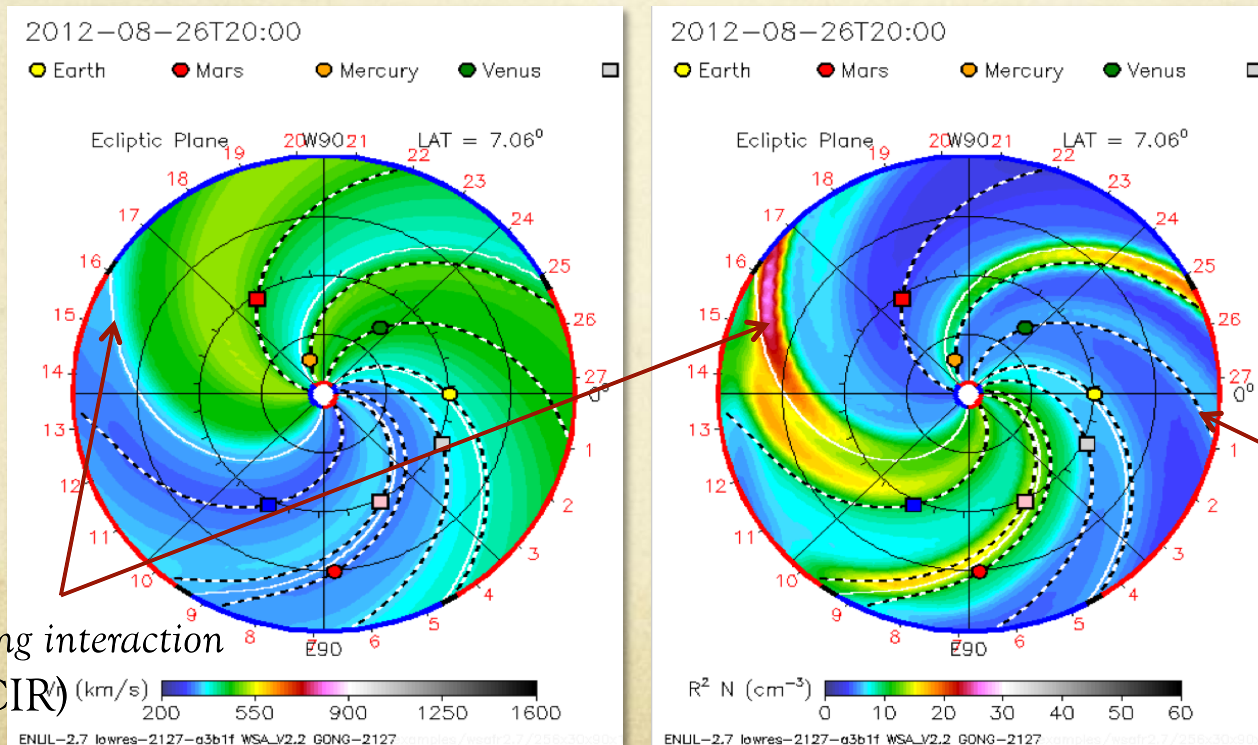
- Solar wind is *magnetized – interplanetary magnetic field* (IMF). Flow generates *Parker spiral*. Also, interaction between slow and fast wind very important.



WSA-Enlil prediction of the solar wind conditions (credit: iSWA)

Spiral (IMF field-line)

Corotating interaction region (CIR)

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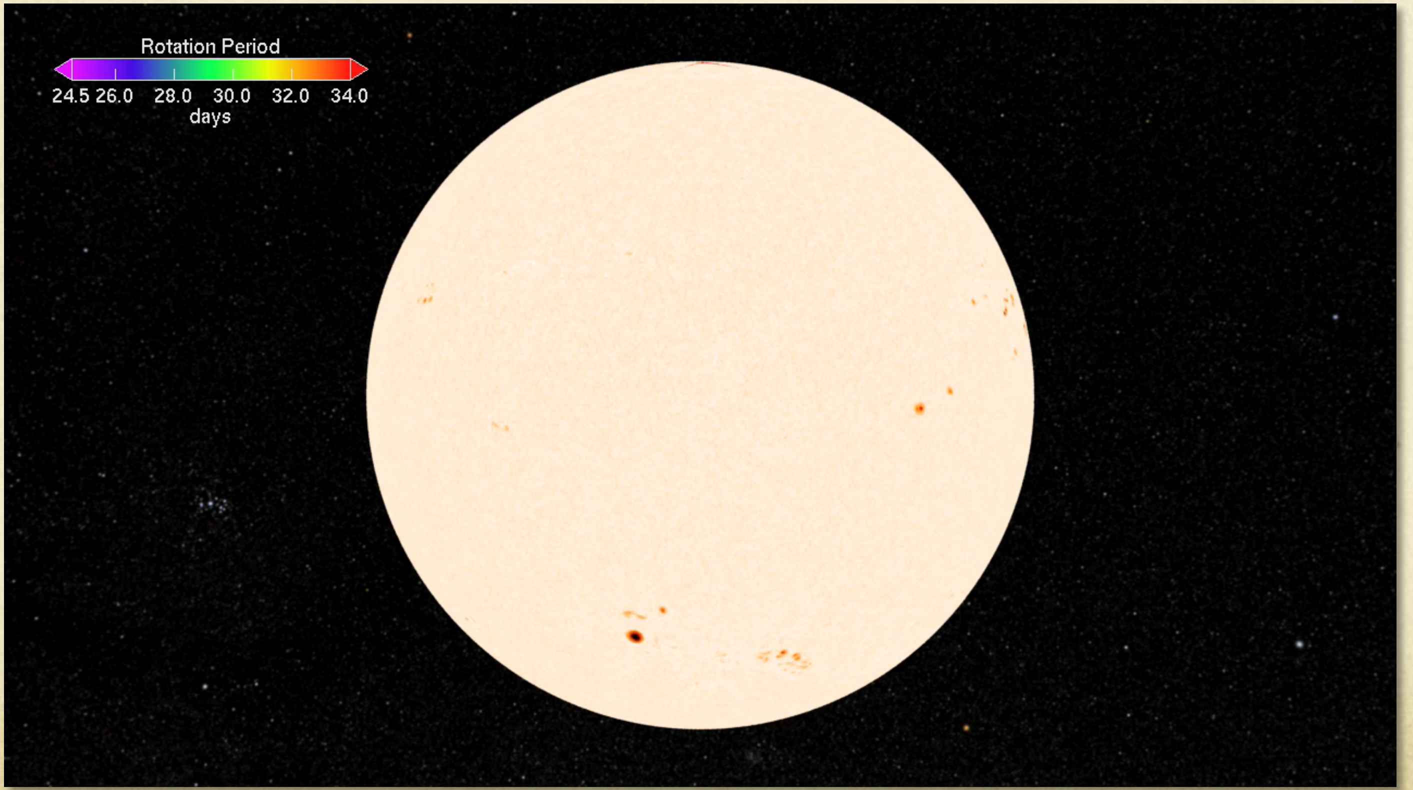
- The Sun is a magnetic beast. The magnetic field generated through *dynamo process*.



Credit: NASA GSFC SVS

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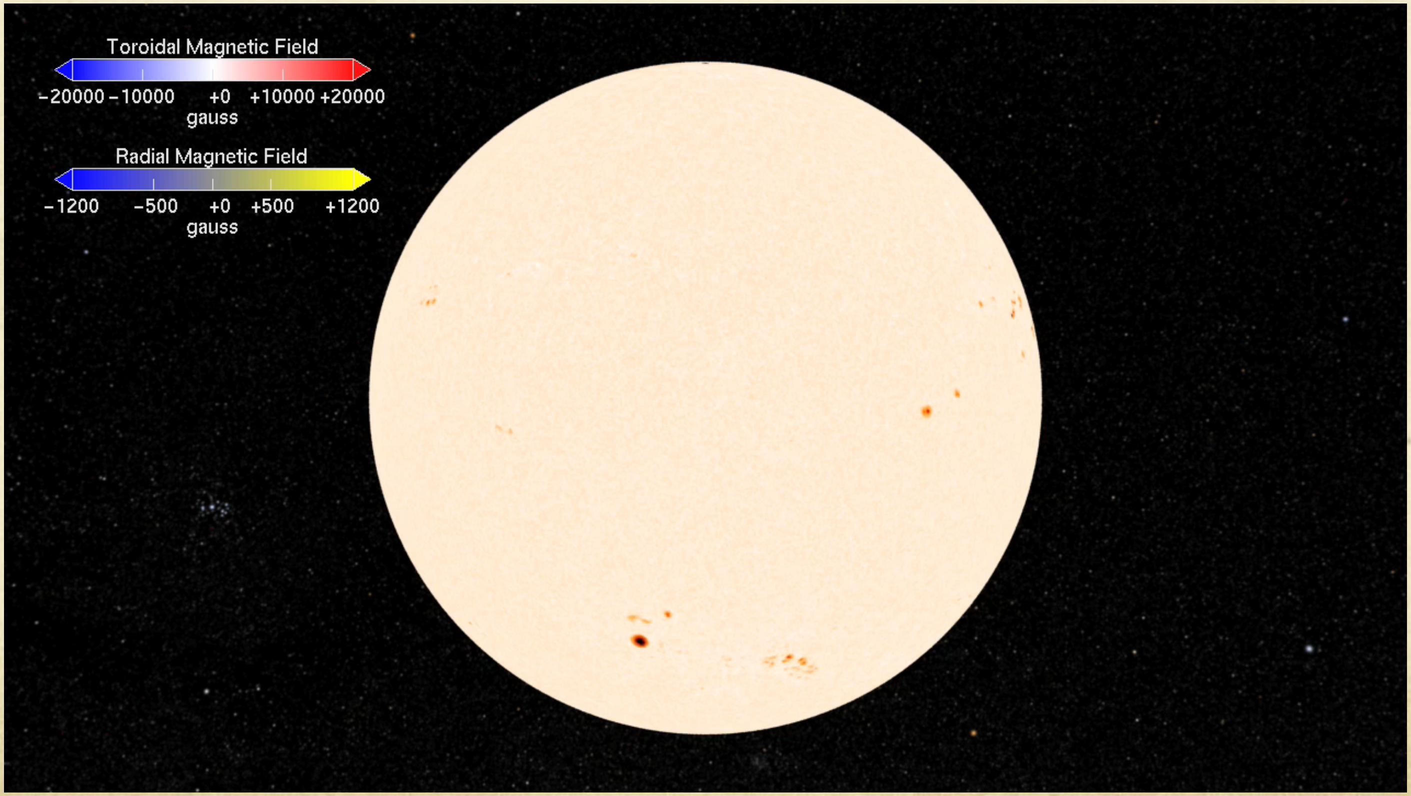
- In dynamo process both convection zone *turbulence* and solar *differential rotation* play a role.



Credit: NASA GSFC SVS

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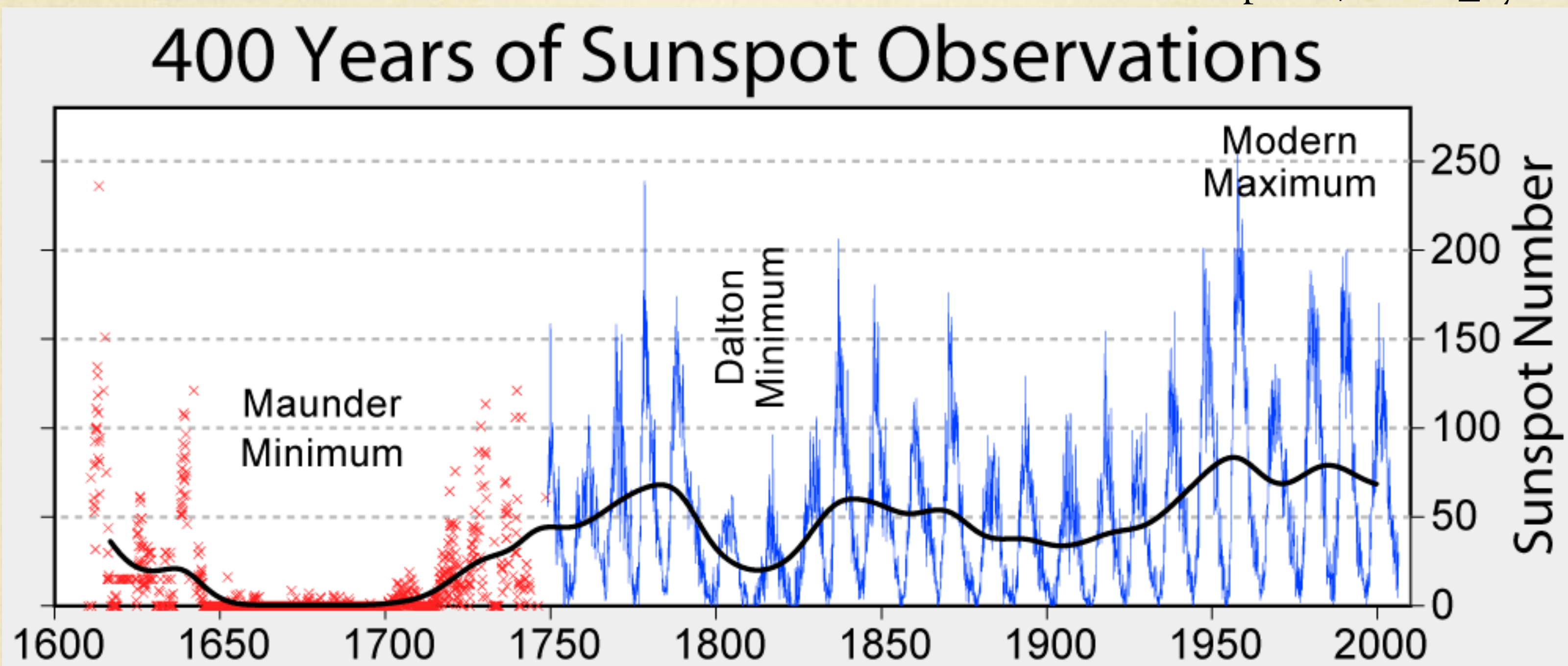
Credit: Wikipedia/Solar_cycle



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

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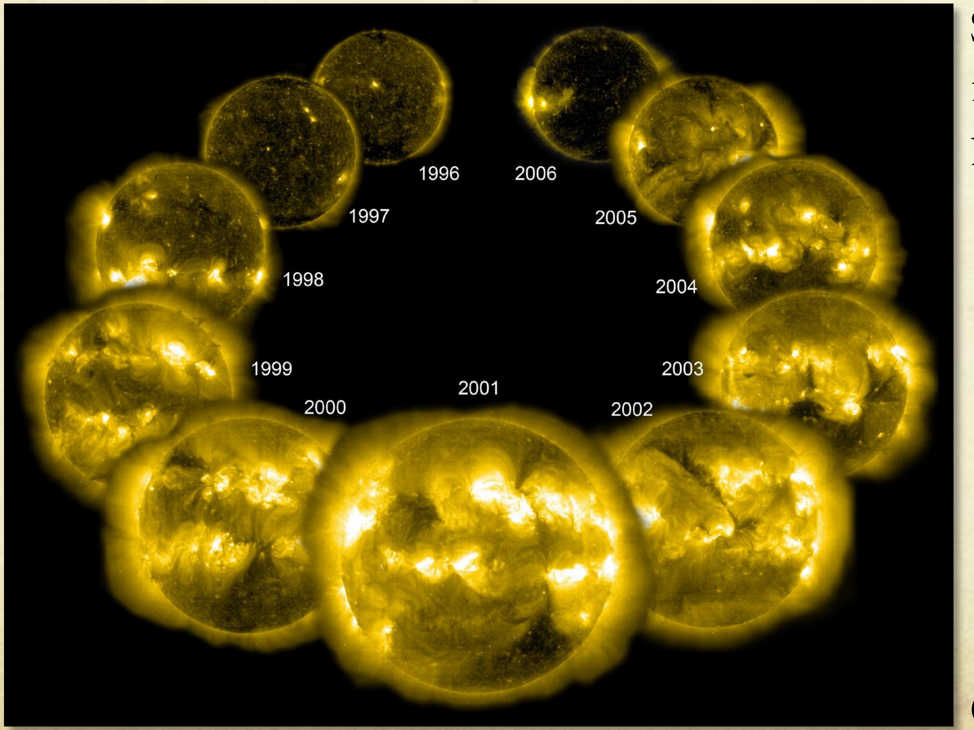
- As the global solar magnetic field structure gets more complicated also plasma configurations in the solar corona gain *complexity*.



SOHO EIT 284 Angstrom images (2 million degree plasma)

Credit: NASA/ESA

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- 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.

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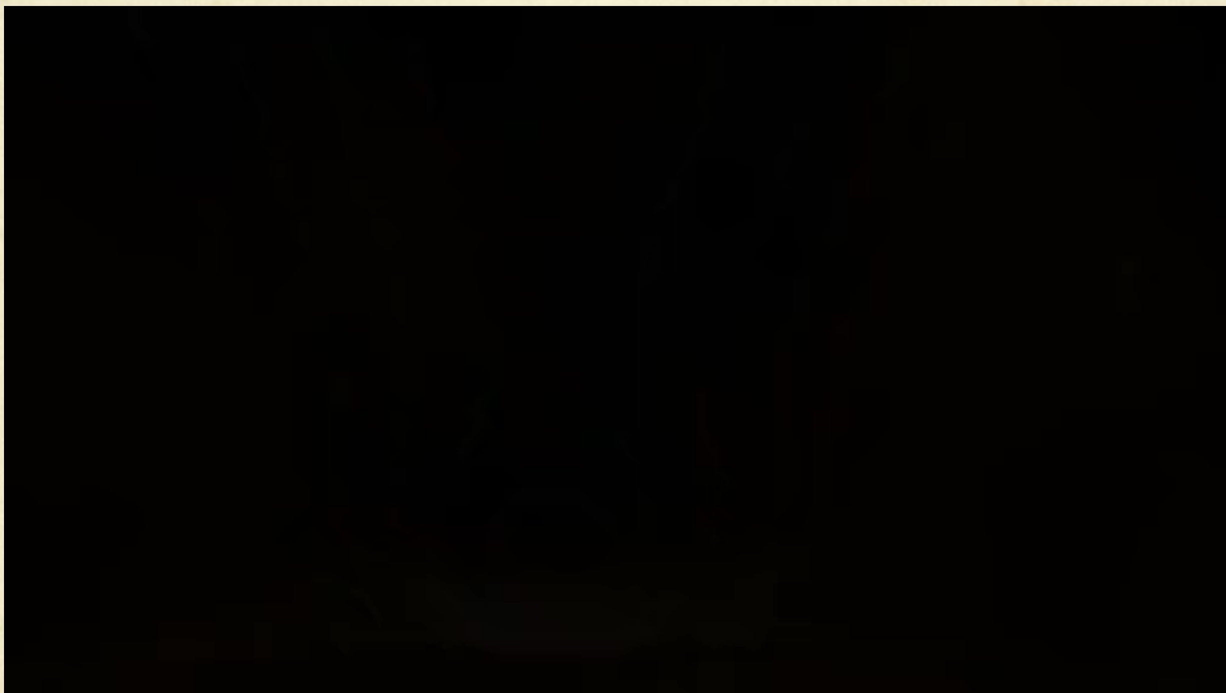

Credit: NASA

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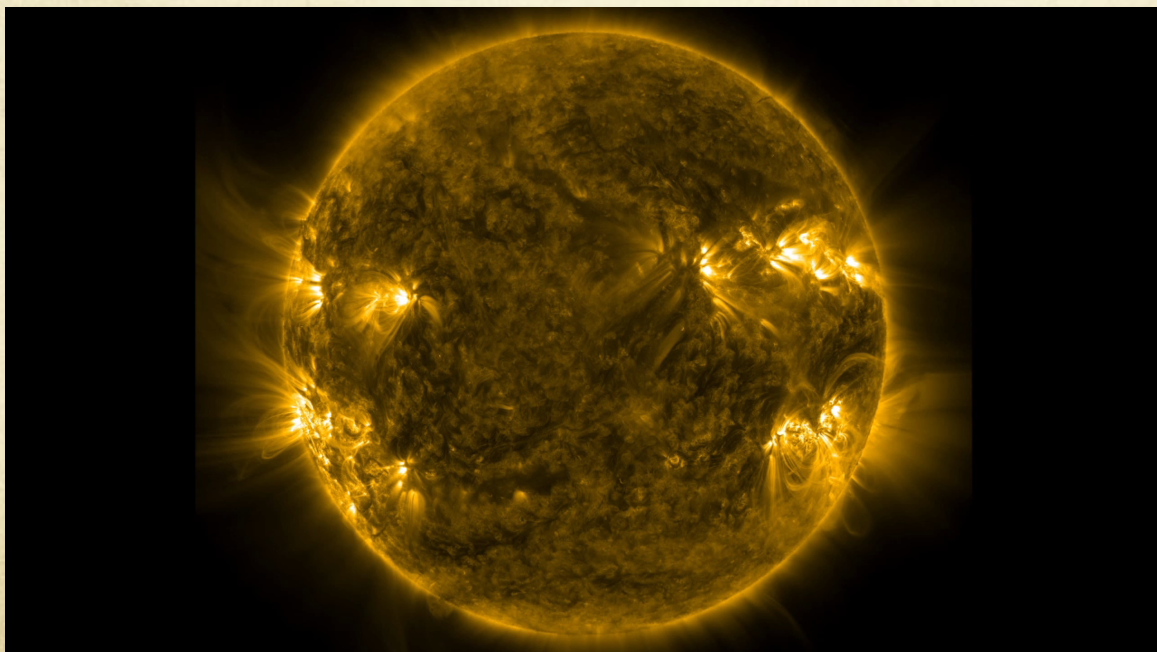
- *Solar flares* lasting, depending on the signature of interest, 1-60 min are the largest eruptions in the solar system. Energy of the order of 10^{25} J can be released by flares (annual world energy consumption ≈10^{20} J).



SDO AIA 171 Angstrom (1 million degree plasma)

Credit: NASA GSFC SVS

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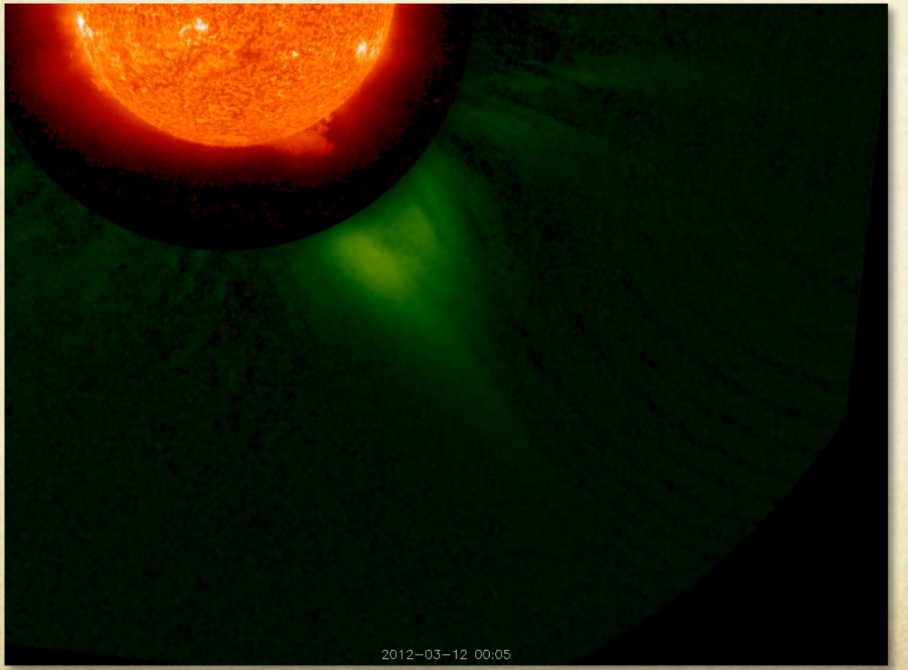
- Many large flares are associated with *coronal mass ejections* (CMEs) releasing billions of tons of solar corona material at speeds of 200-3000 km/s. Total kinetic energy of CMEs can be of the order of 10^{25} J.



STEREO B 304 Angstrom EUV and white light coronagraph March 12, 2102

Credit: NASA

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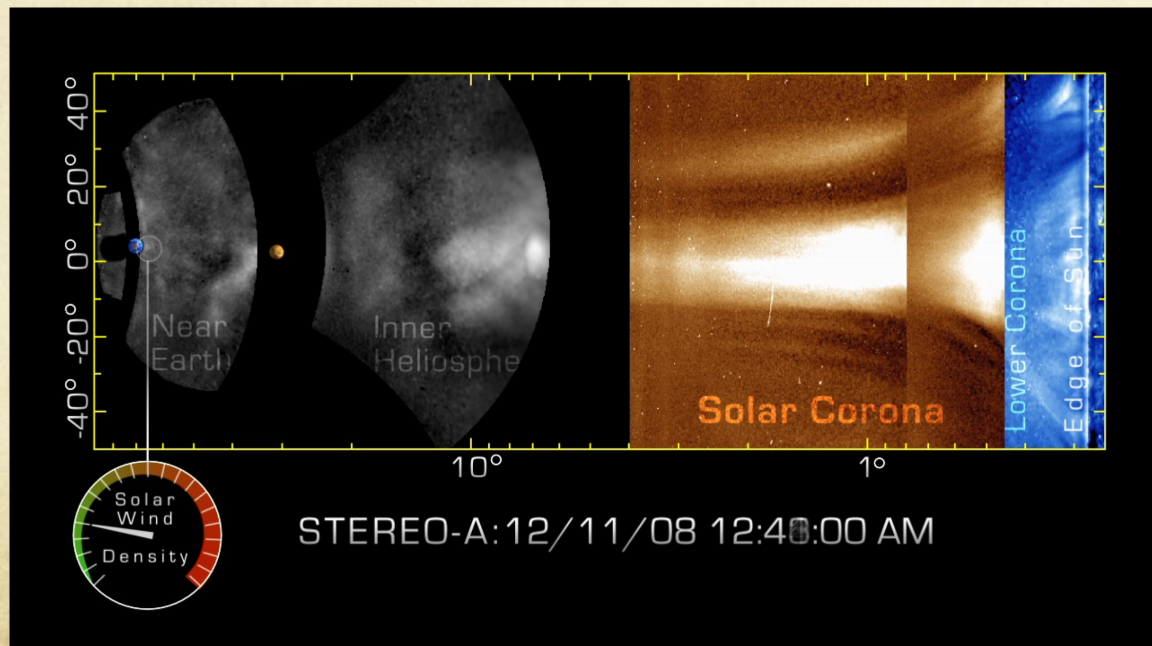
- CME eruptions drive shock waves that also accelerate charged particles. These particles generate the second (and often more significant) SEP component.
- CME propagation to the Earth takes typically 1-3 days.



STEREO A white light coronagraphs and heliospheric imagers December 2008

Credit: NASA GSFC

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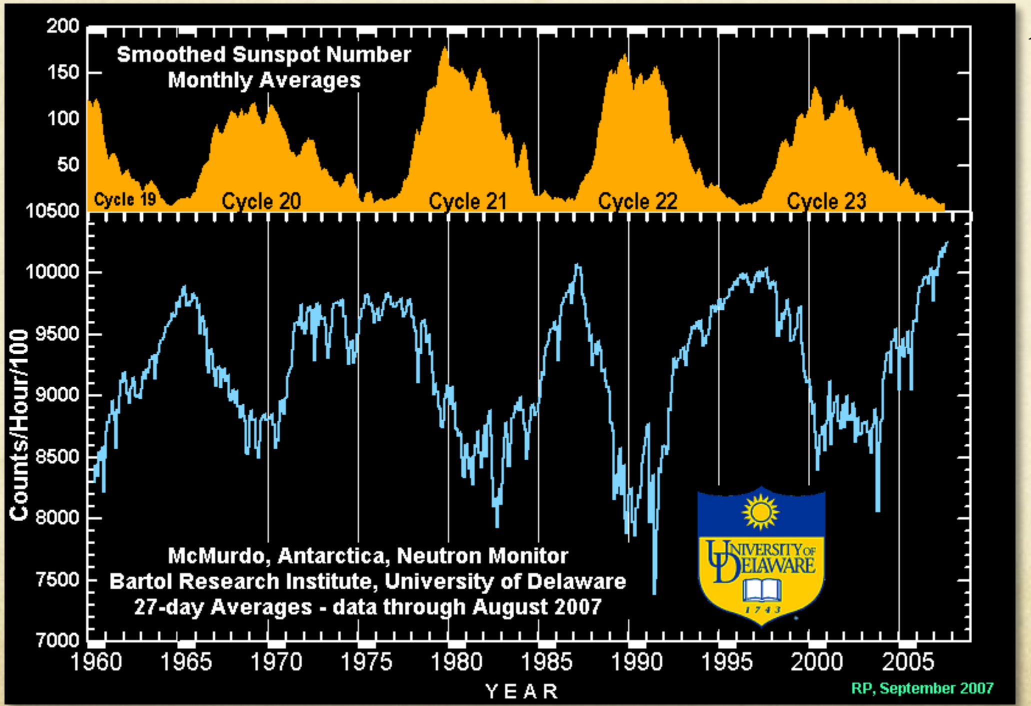
- Also low flux but very energetic *galactic cosmic rays* (GCRs) coming from galactic sources contribute to charged particle radiation in the solar system.



Anti-correlation between solar activity and GCRs

Credit: University of Delaware

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- 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

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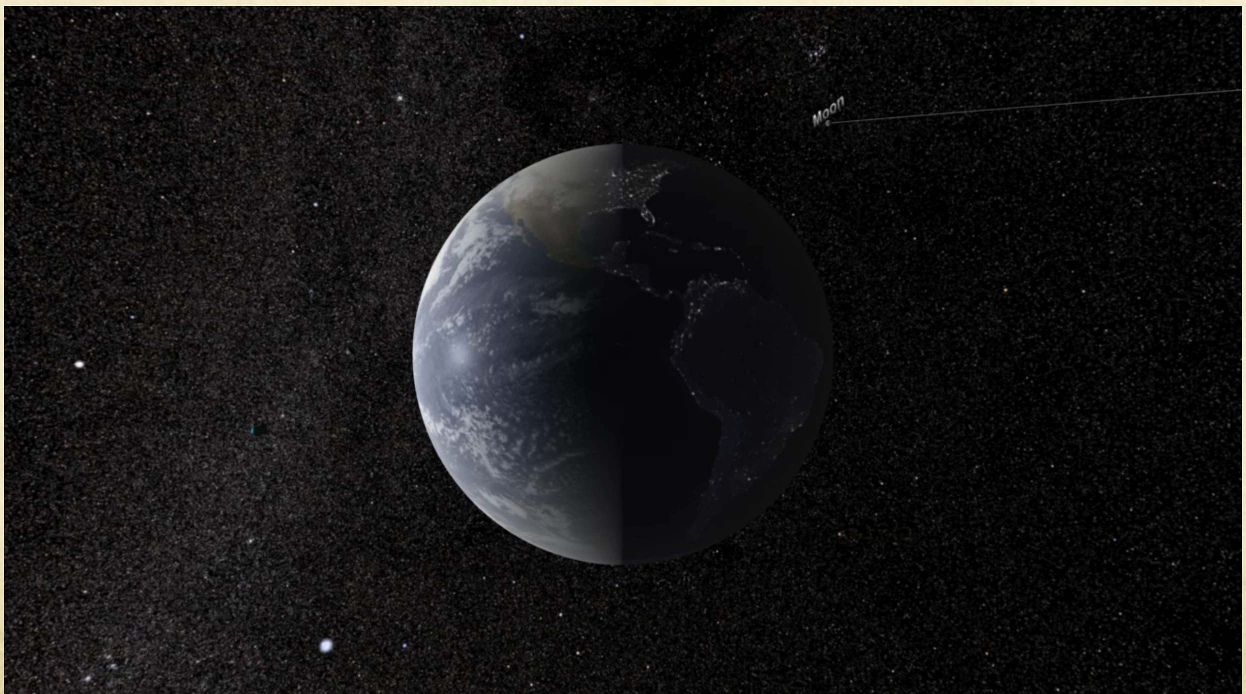
- The entry of mass, momentum and energy powers very complex dynamic phenomena in the magnetosphere. Radiation belts are one central part of these phenomena.



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

Credit: NASA GSFC SVS

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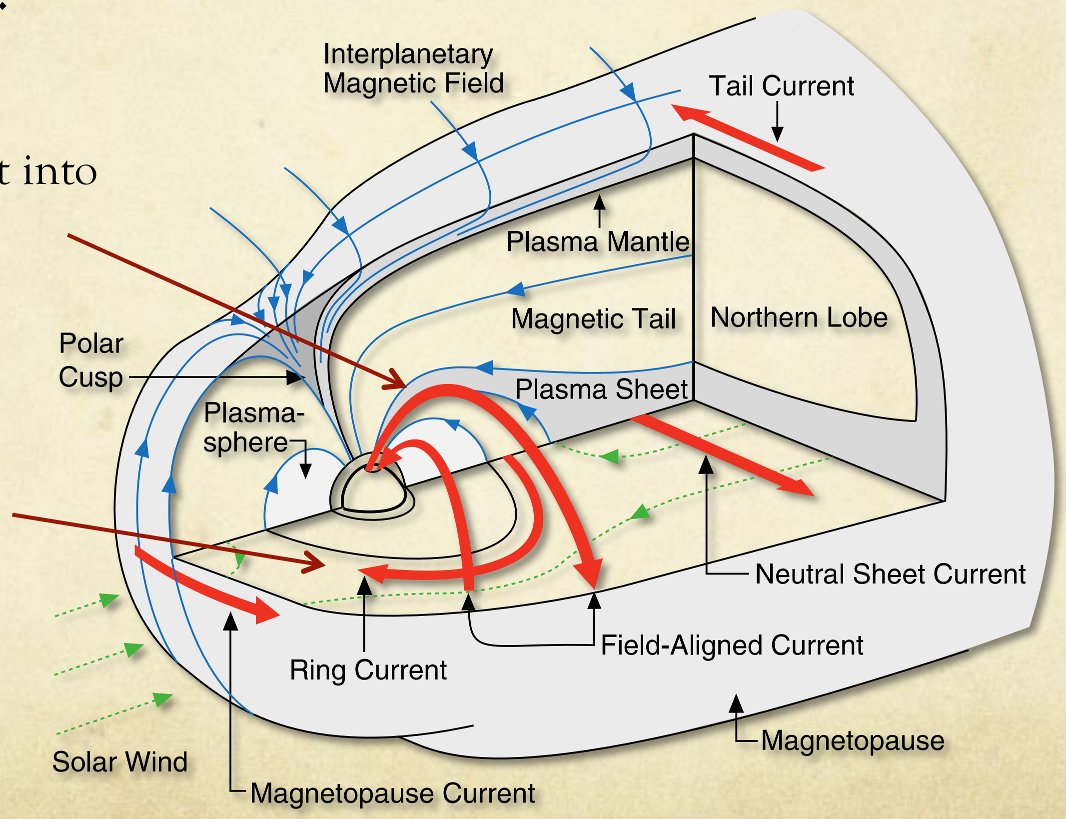
- Also various magnetospheric electric current systems get powered.

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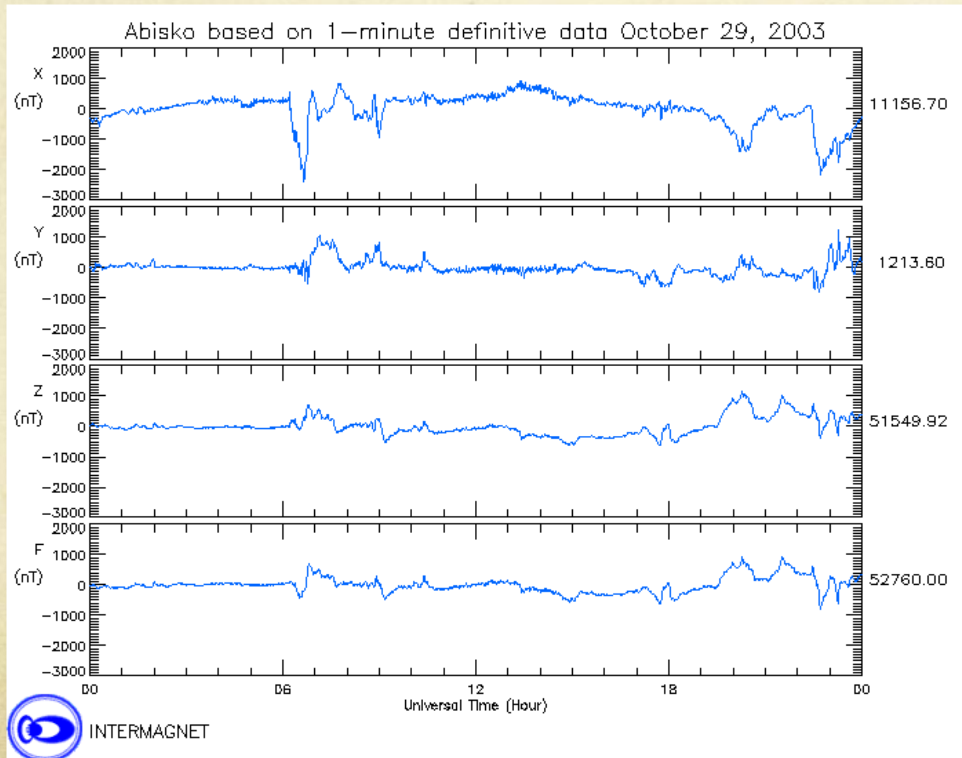
- Electric currents flowing in the near-space generate magnetic field perturbations on the surface of the Earth. These fluctuations are called *geomagnetic storms*.



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

Credit: INTERMAGNET

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

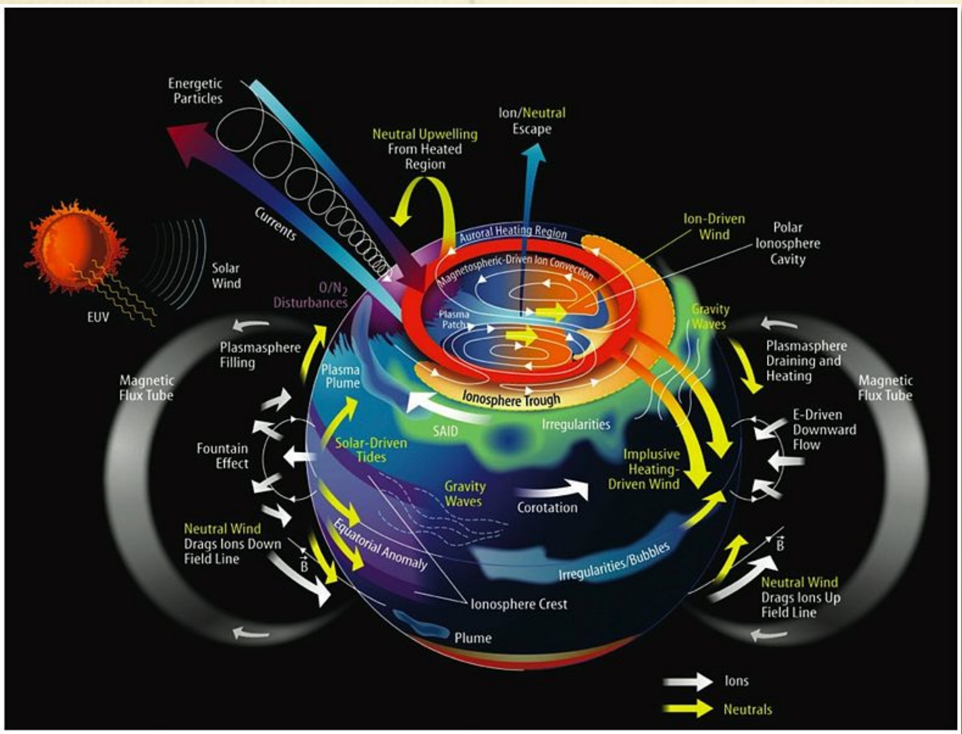

Illustration of upper atmospheric dynamics (quite simple, no?)

Credit: J. Grobowsky/NASA

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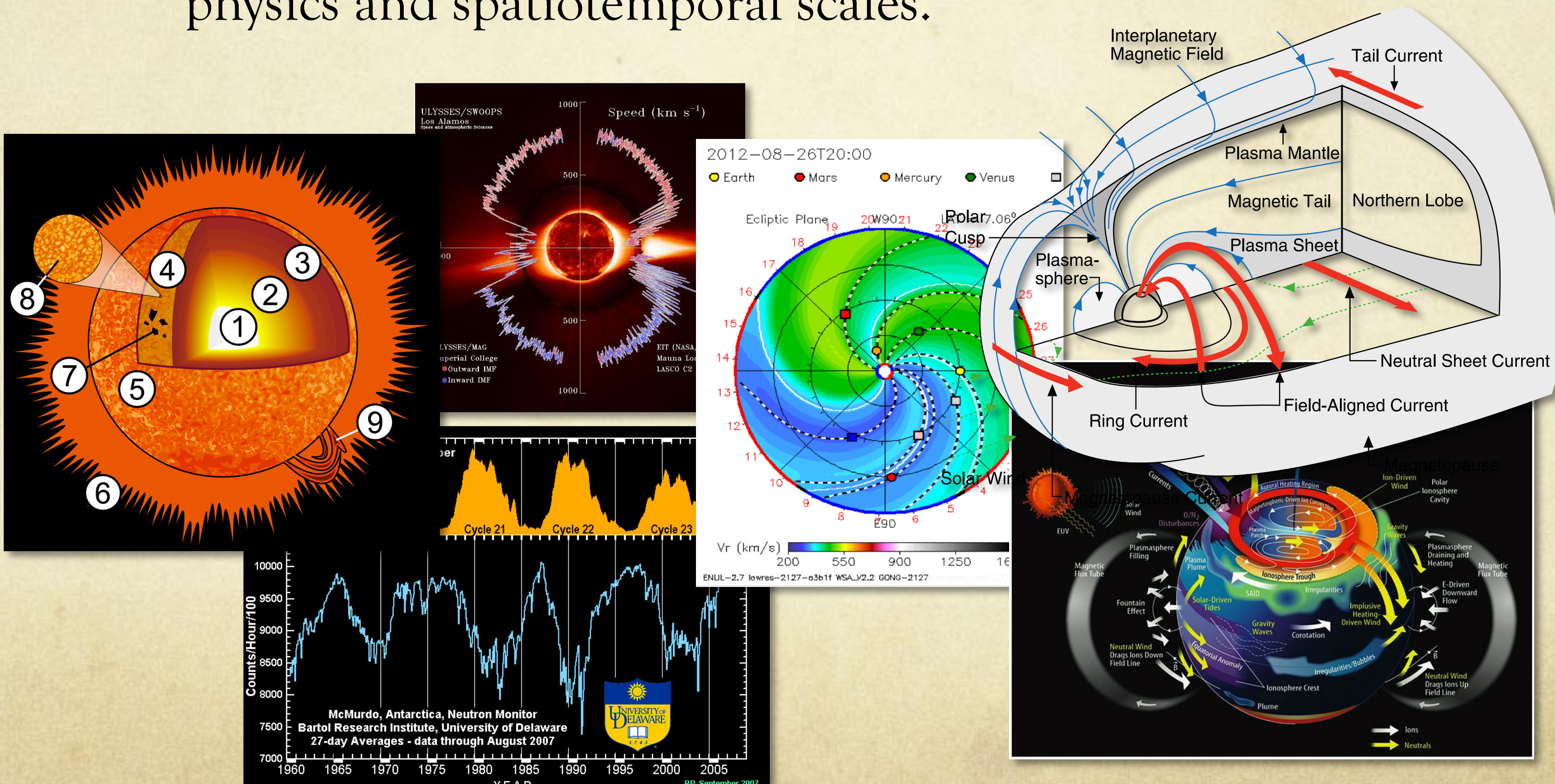
- So we see that space weather really is a vast chain of complex interacting systems covering wide ranges of physics and spatiotemporal scales.



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- 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

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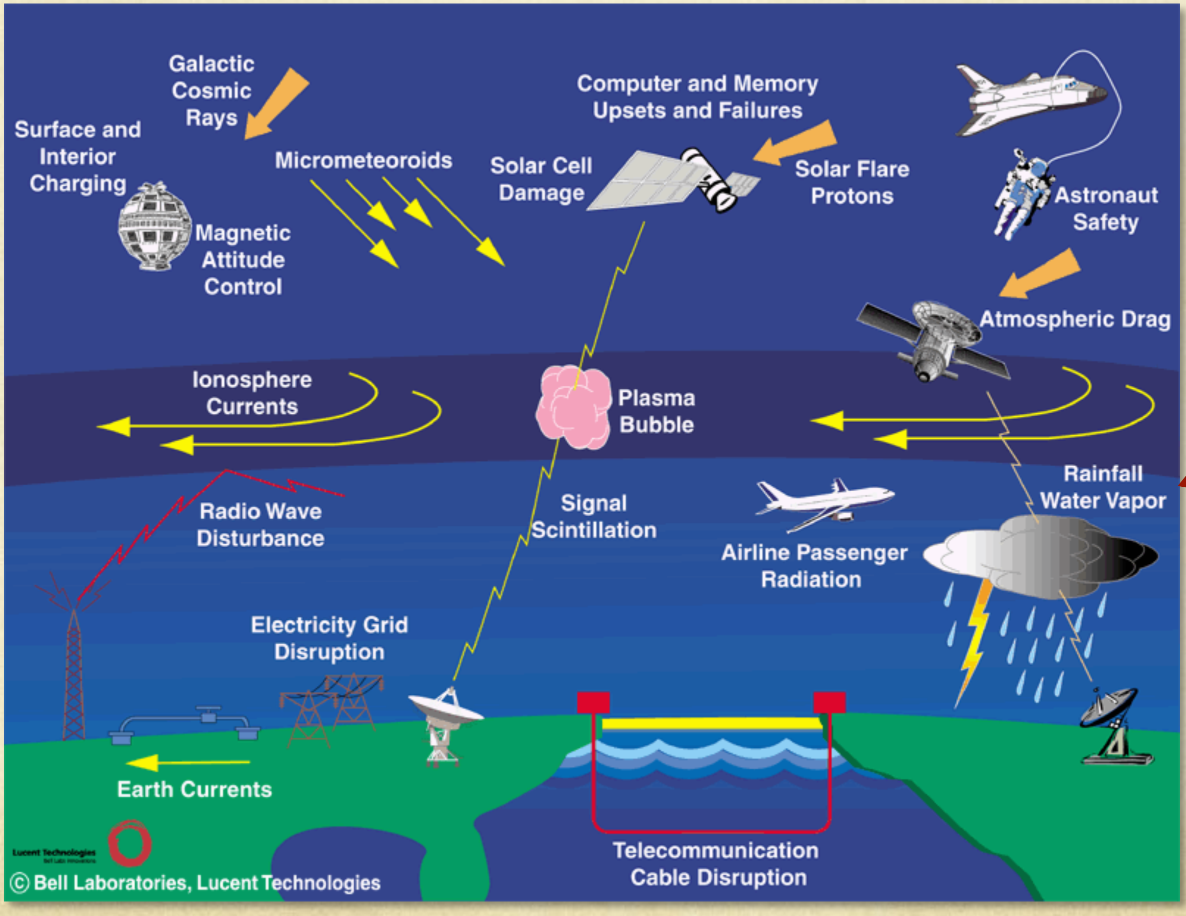

Space weather impacts (credit: L. Lanzerotti/Bell Labs)

We will not be discussing these

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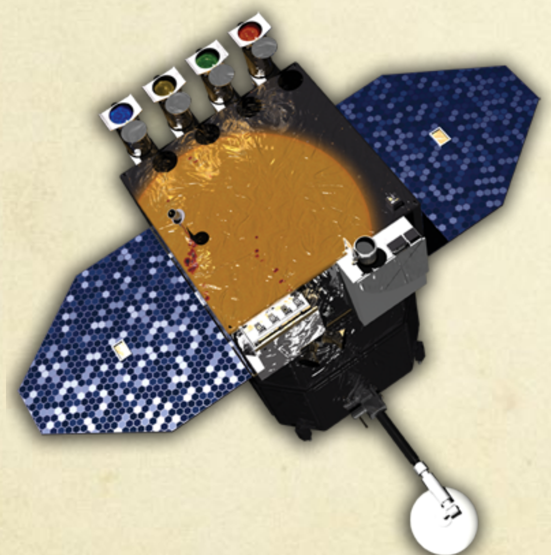
- Spacecraft can be impacted in a number of different ways depending on the orbit of the vehicle.



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).

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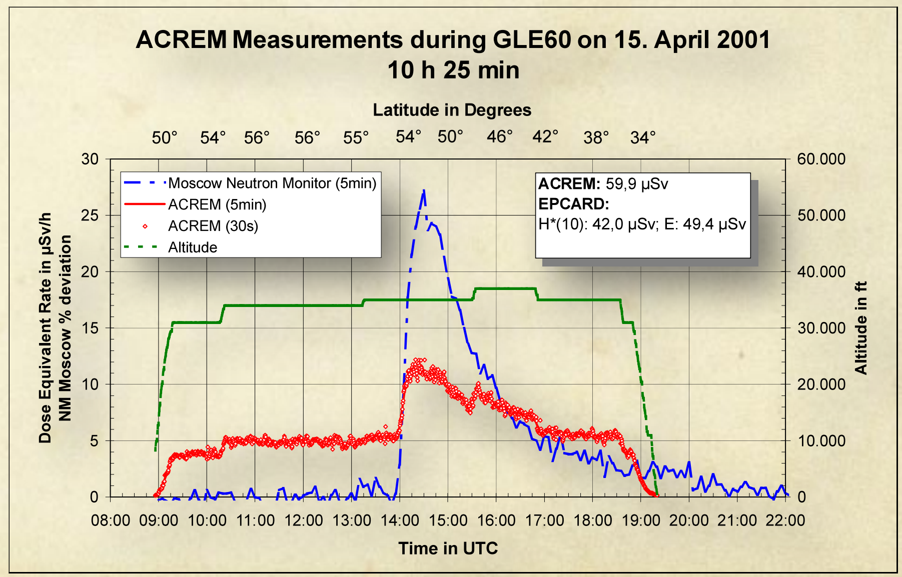
- Energetic charged particle radiation is a hazard for humans in space and at airline altitudes. Especially less predictable SEPs are a concern.

Credit: NASA



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

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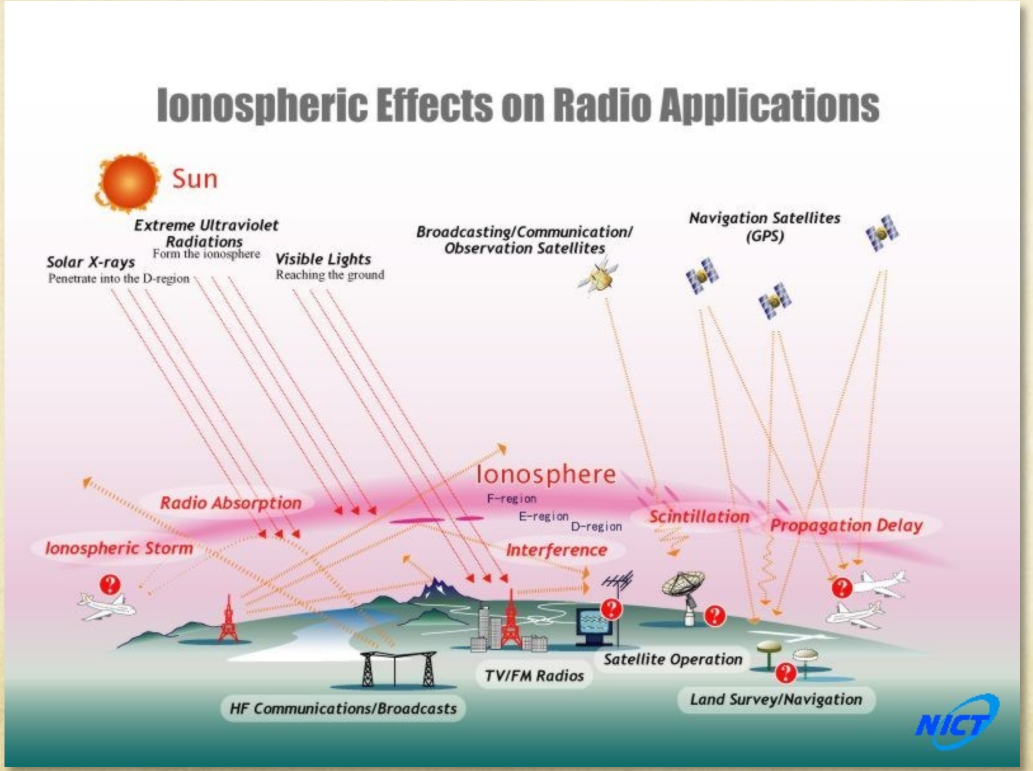
- Signals using ionosphere or "just" passing through ionosphere are affected by space weather.



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)

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

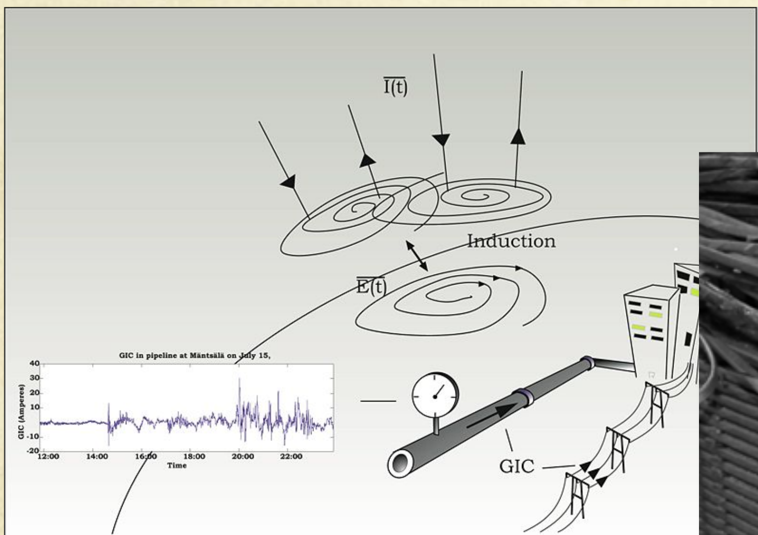
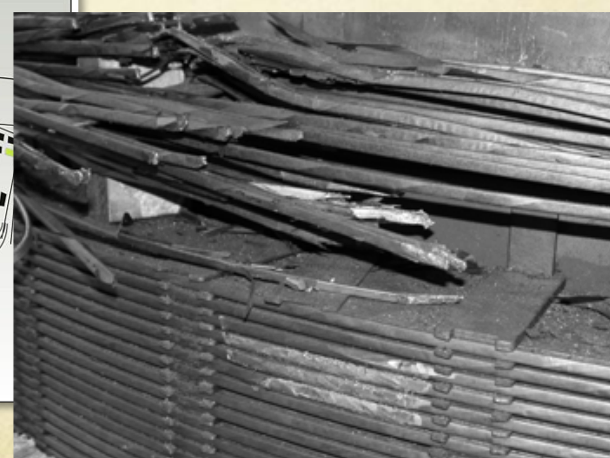


Illustration of mechanism for generating GIC

Transformer damage in South Africa



Credit: Gaunt and Coetzee (2007)