Introduction to Space Weather

Adapted from slides by

Antti Pulkkinen

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

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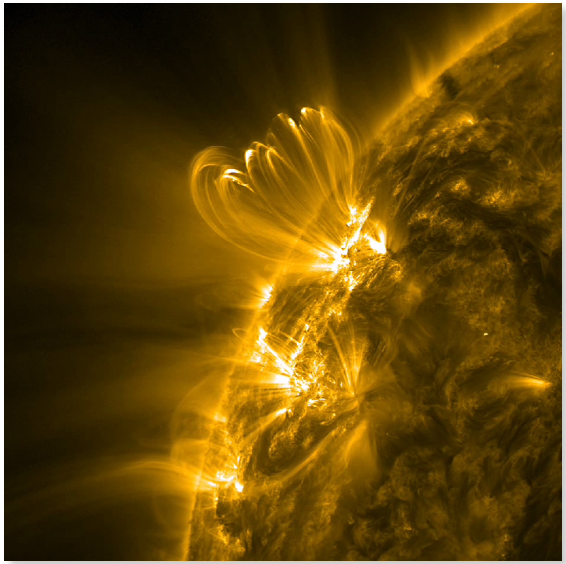
- The physics of space weather is *plasma physics*.

  "*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 ≈10^{-9} s (plasma fluctuations in the solar atmosphere) to ≈10^{8} s (solar cycle).
  - Relevant spatial scales vary from ≈1 m (ionospheric plasma structures) to ≈10^{8} m (large-scale interplanetary plasma structures).
- Further, there is a strong coupling across the scales.

→ Forecasting space weather is a serious challenge…

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Earth

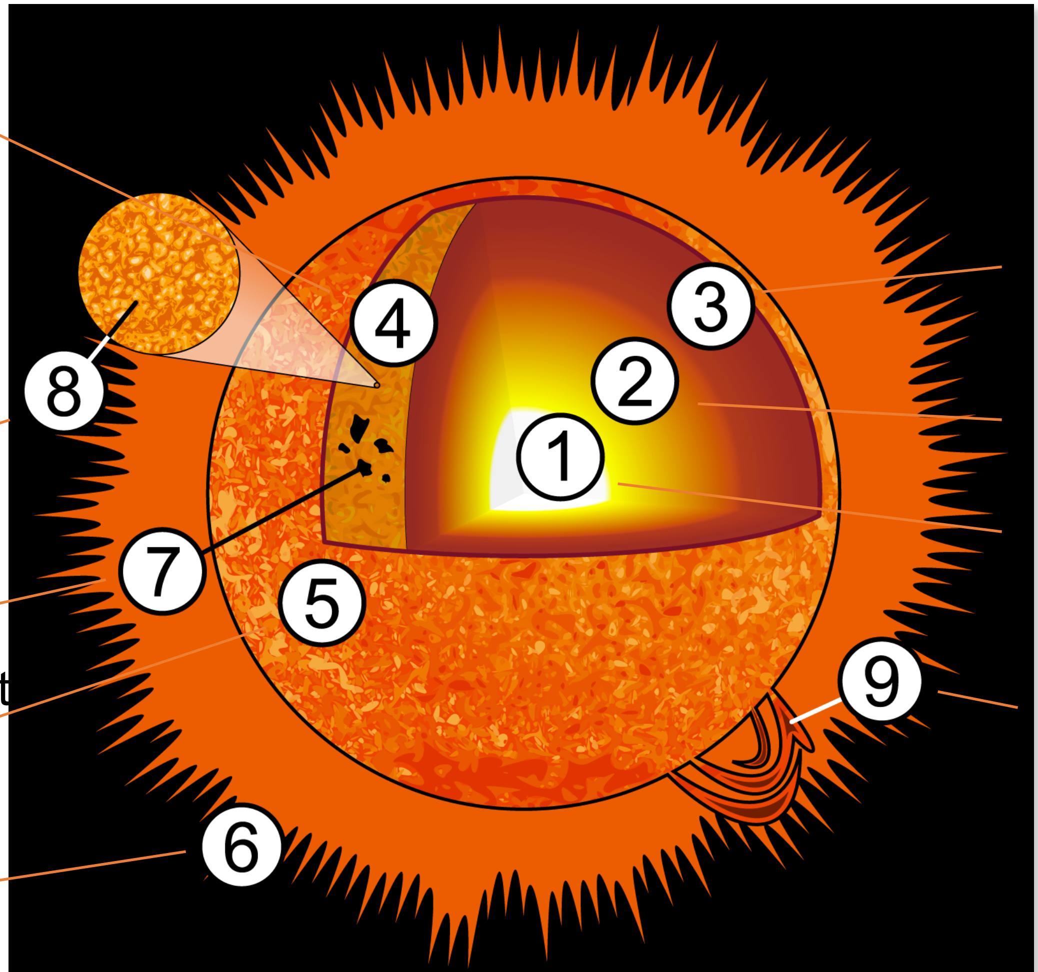
Photosphere at 4300 K (top)

Granulation

Sunspots

Chromosphere at 25000 K (top)

Corona at ≈10^6 K



Convection zone at 6600 K (top)

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

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

Prominence at about 5000-10000 K

Credit: Wikipedia/sun

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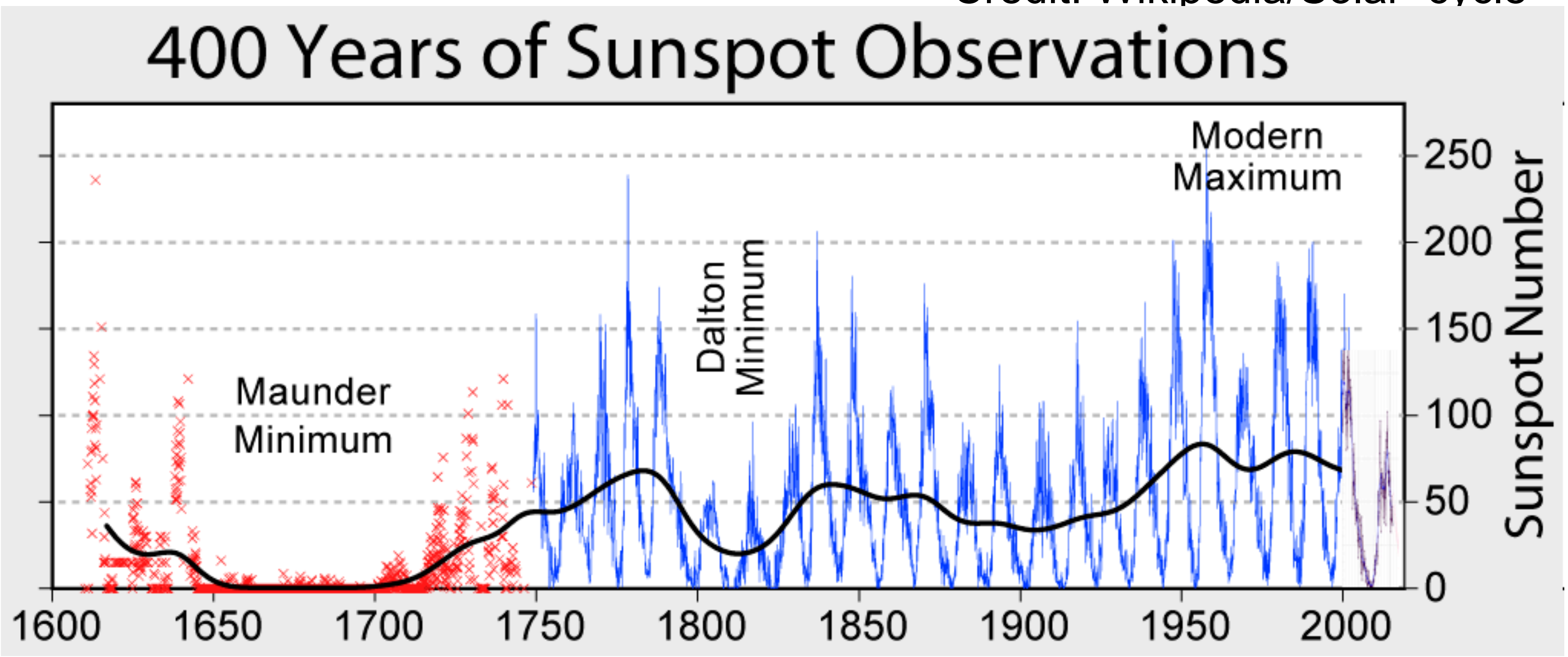
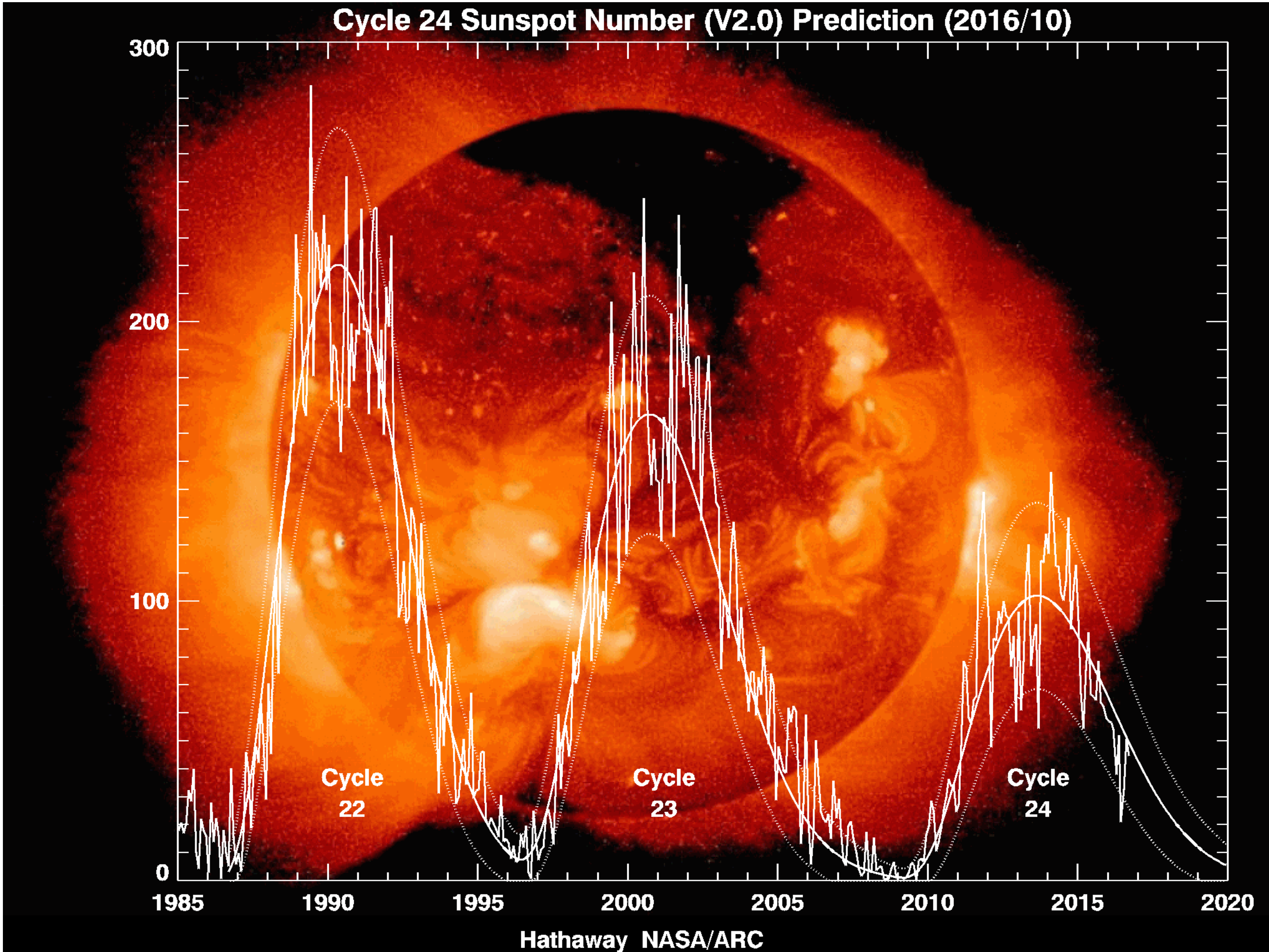
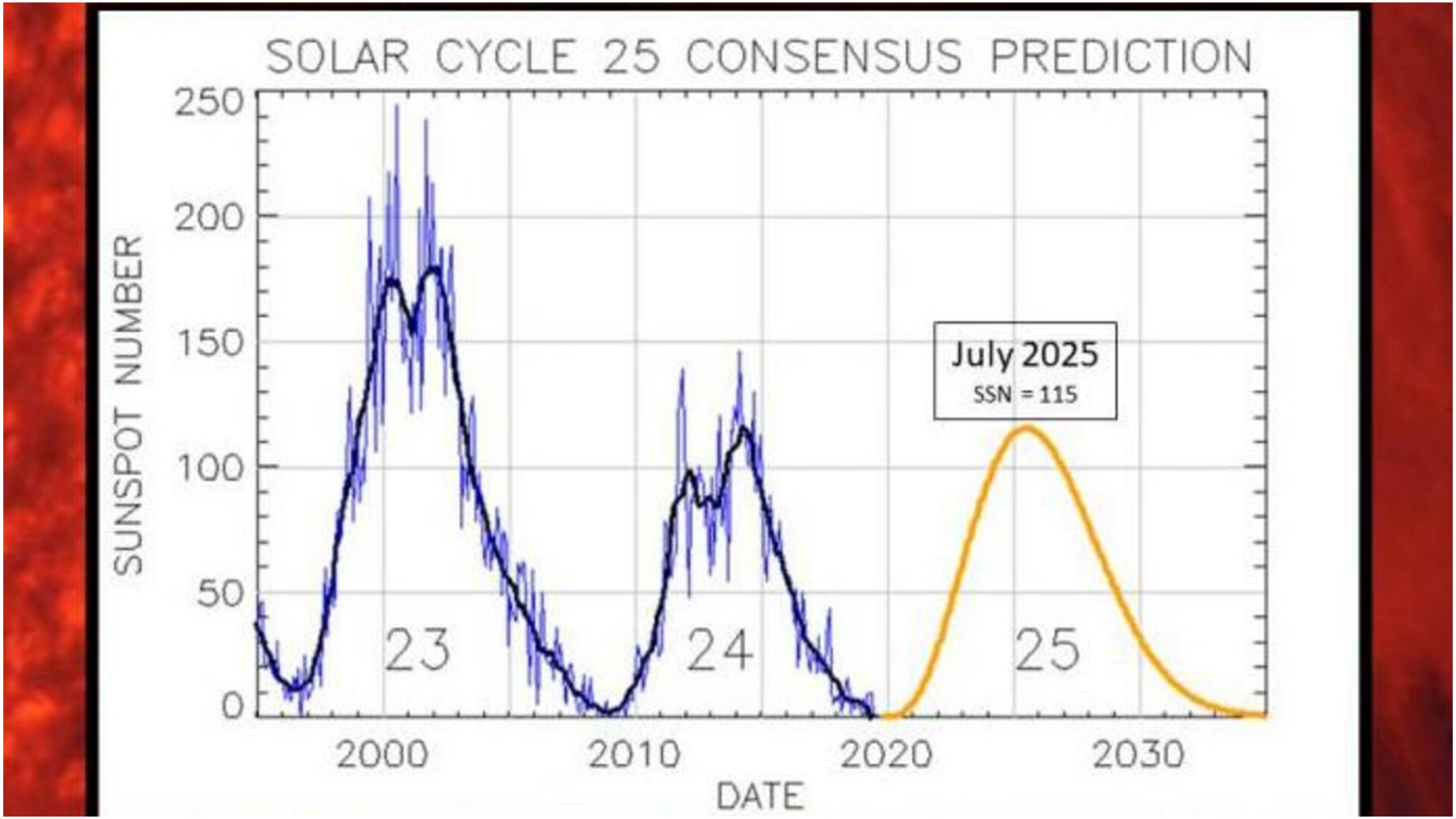
Credit: Wikipedia/Solar cycle



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


Cycle 24 Sunspot Number (V2.0) Prediction (2016/10)
300
200
100
0
1985
1990
1995
2000
2005
2010
2015
2020
Cycle 22
Cycle 23
Cycle 24
Hathaway NASA/ARC



Credit: NOAA/NASA/ESA

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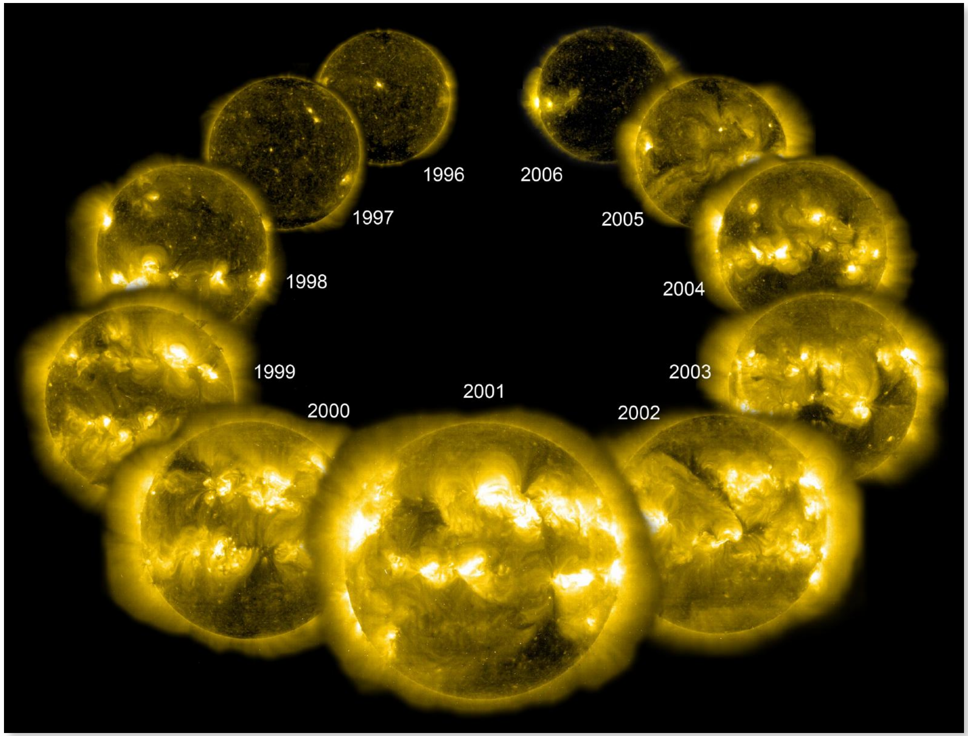
- As the global solar magnetic field structure gets more complicated also plasma configurations in the solar corona gain *complexity*.



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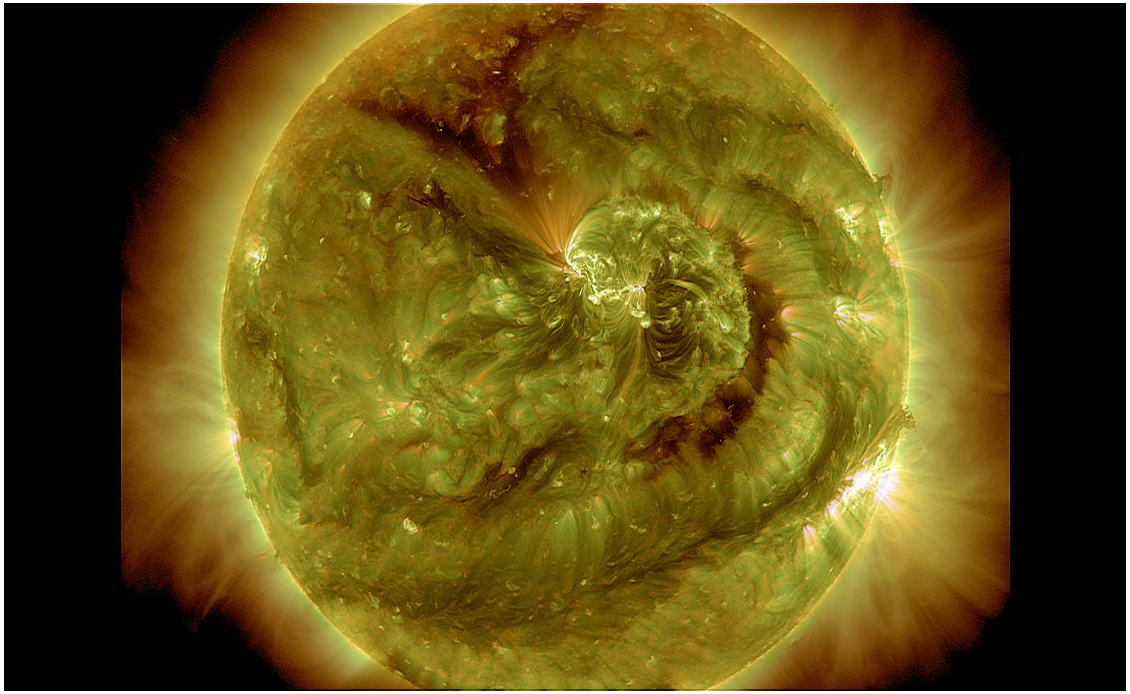
- *Solar flares* lasting, depending on the signature of interest, 1-60 min are the largest eruptions in the solar system. Energy of the order of 10^{25} J can be released by flares (annual world energy consumption ≈10^{20} J).



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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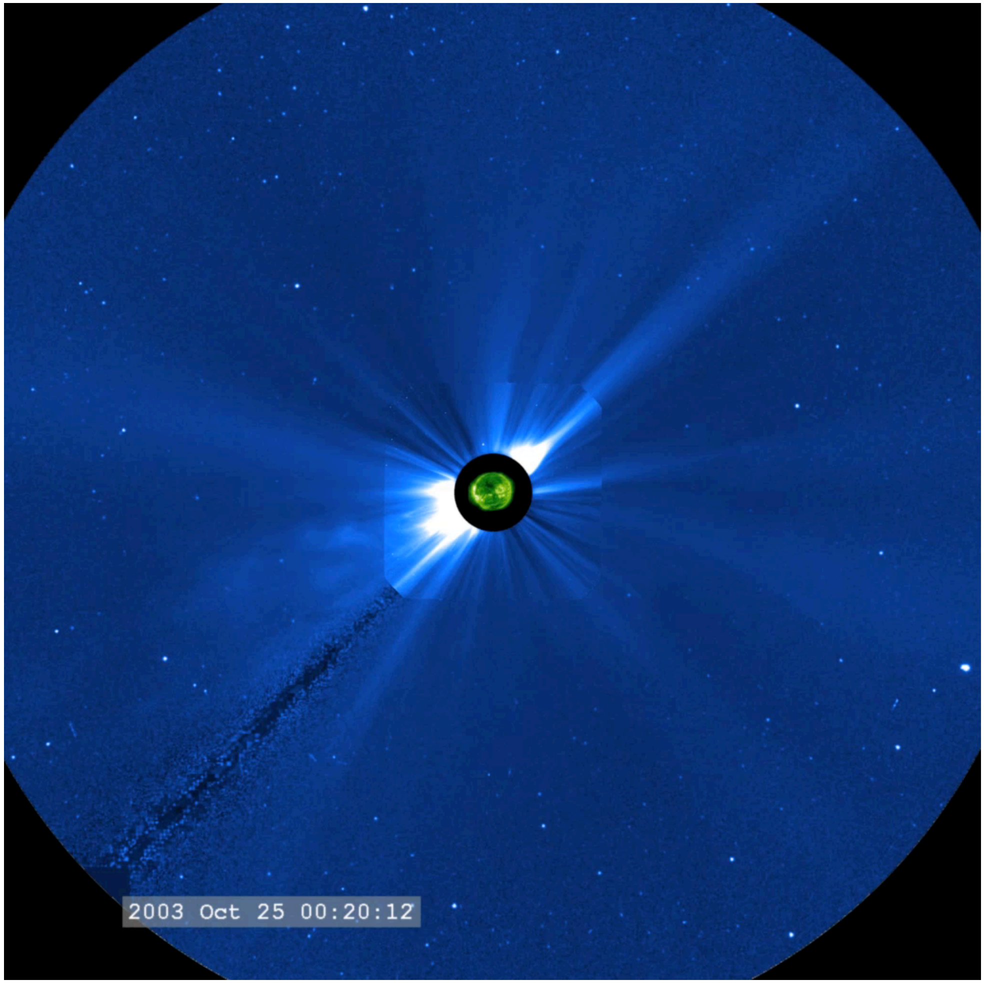

- Many large flares are associated with *coronal mass ejections* (CMEs) releasing billions of tons of solar corona material at speeds of 200-3000 km/s. Total kinetic energy of CMEs can be of the order of 10^{25} J.

Credit: ESA/NASA

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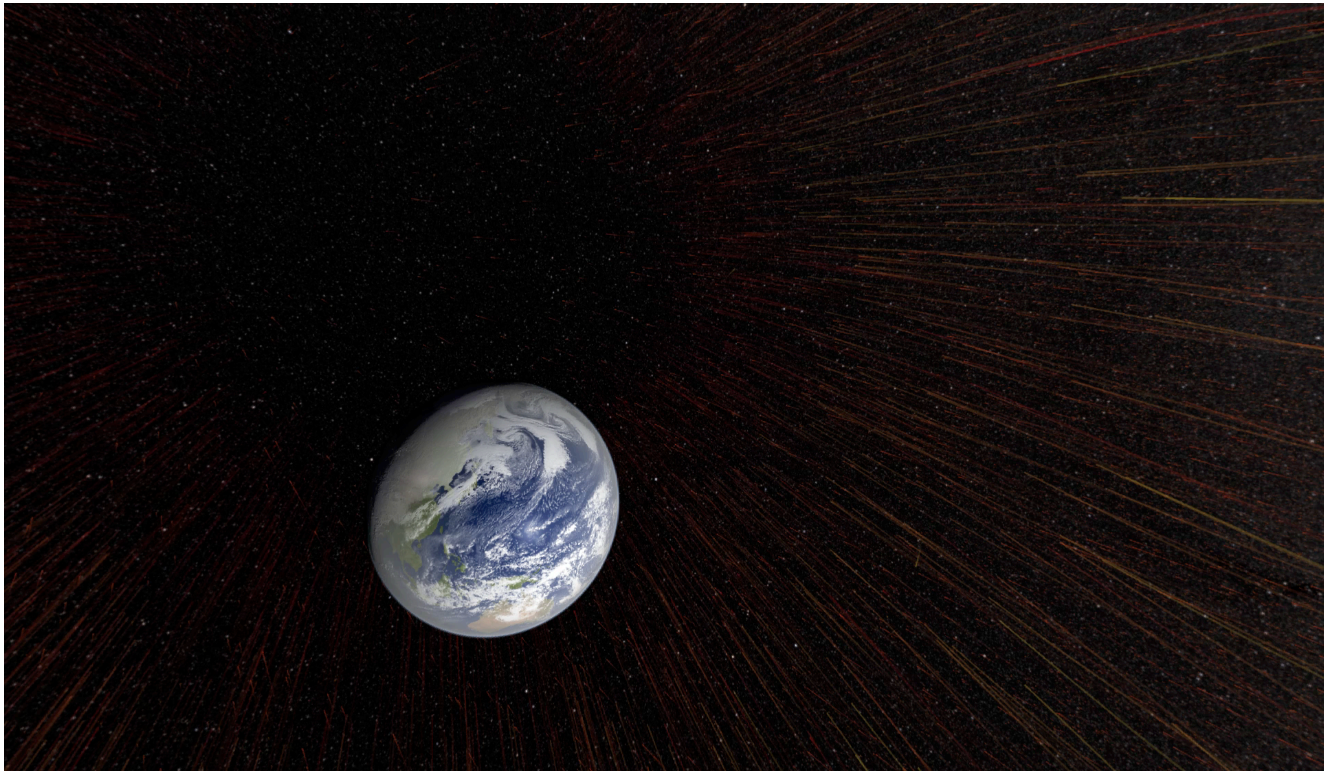
- Charged particles flowing from the Sun interact with the Earth's plasma environment called *magnetosphere*. Magnetic reconnection "opens up" magnetosphere to allow entry of mass, momentum and energy.



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

Credit: NASA GSFC SVS

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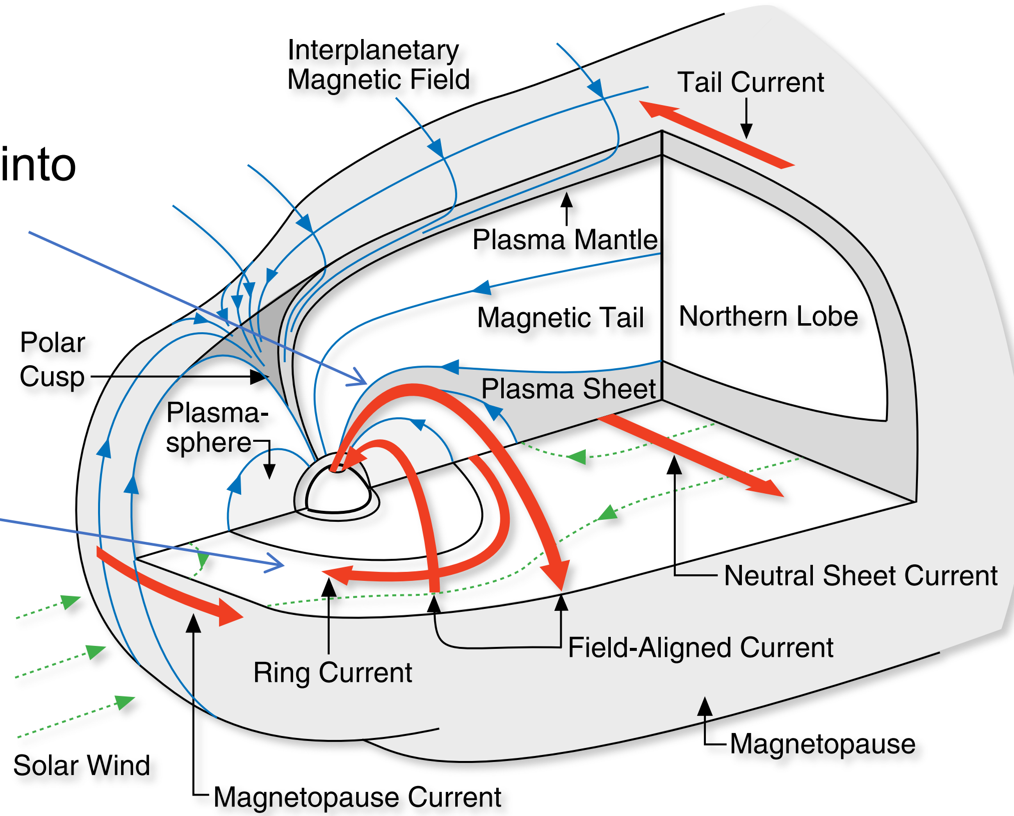
- Also various magnetospheric electric current systems get powered.

≈ 1 MA current into the ionosphere

Charged particles carrying the ring current



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

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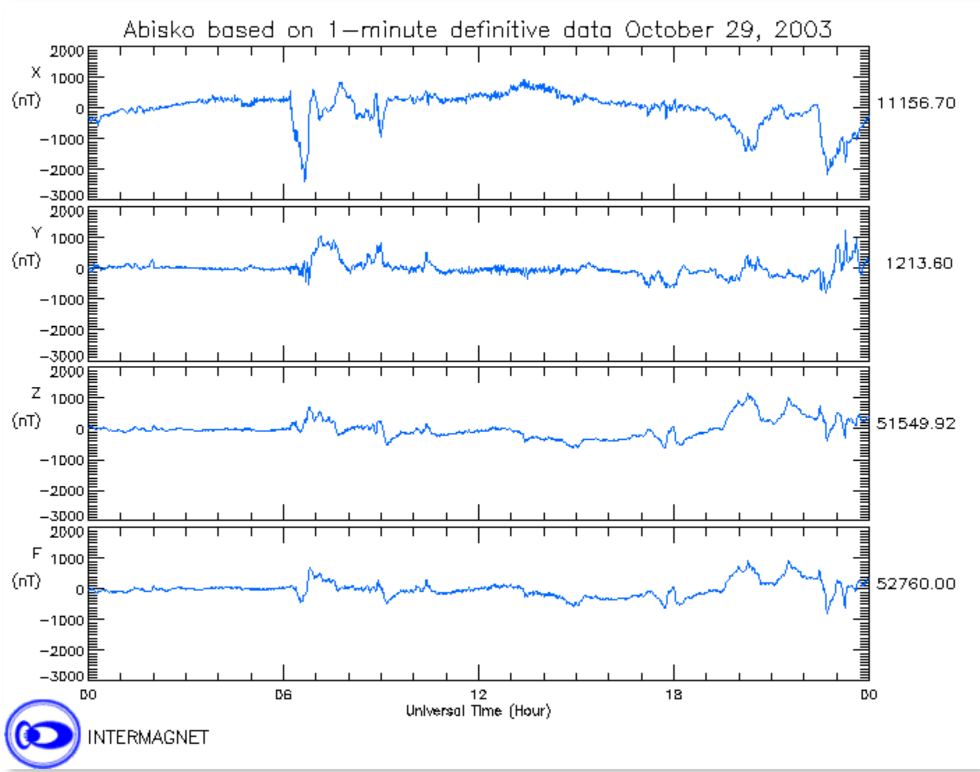
- Electric currents flowing in the near-space generate magnetic field perturbations on the surface of the Earth. These fluctuations are called *geomagnetic storms*.



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.

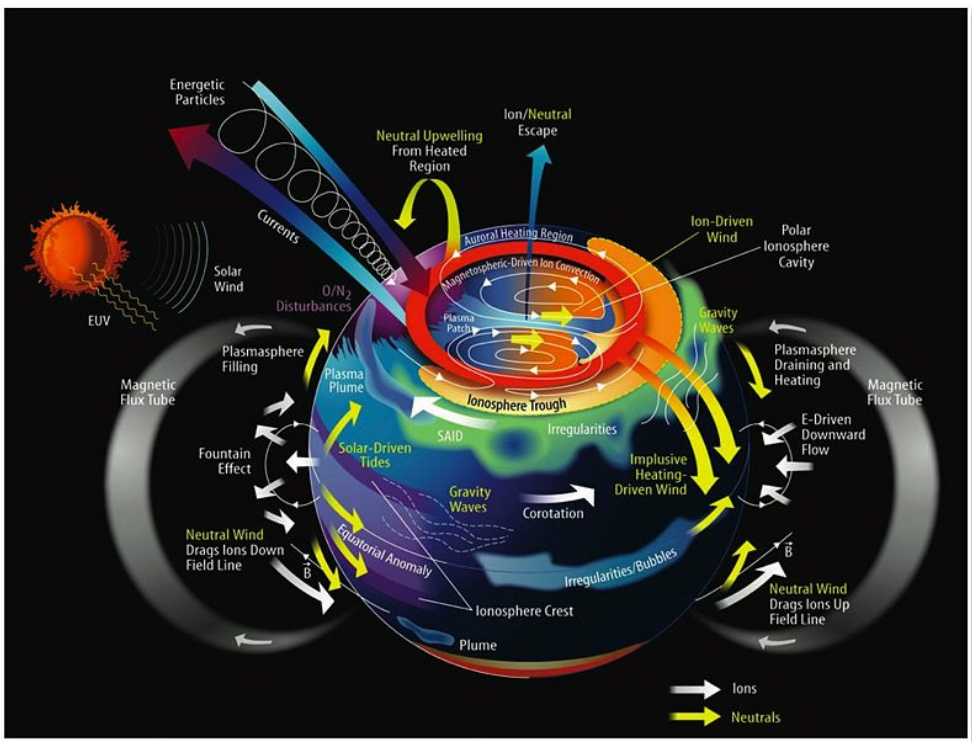

Illustration of upper atmospheric dynamics.

Credit: J. Grobowsky/NASA

Quick quiz

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

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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

https://svs.gsfc.nasa.gov/11474

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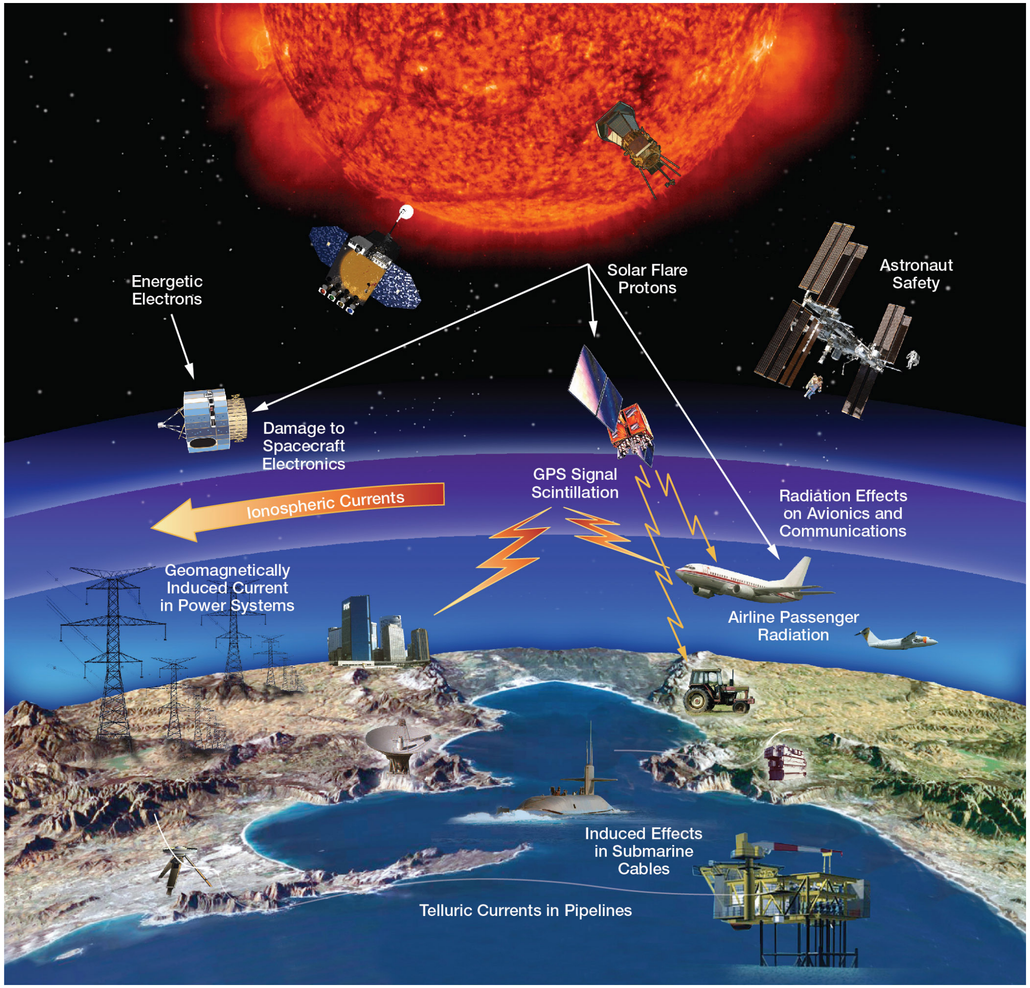
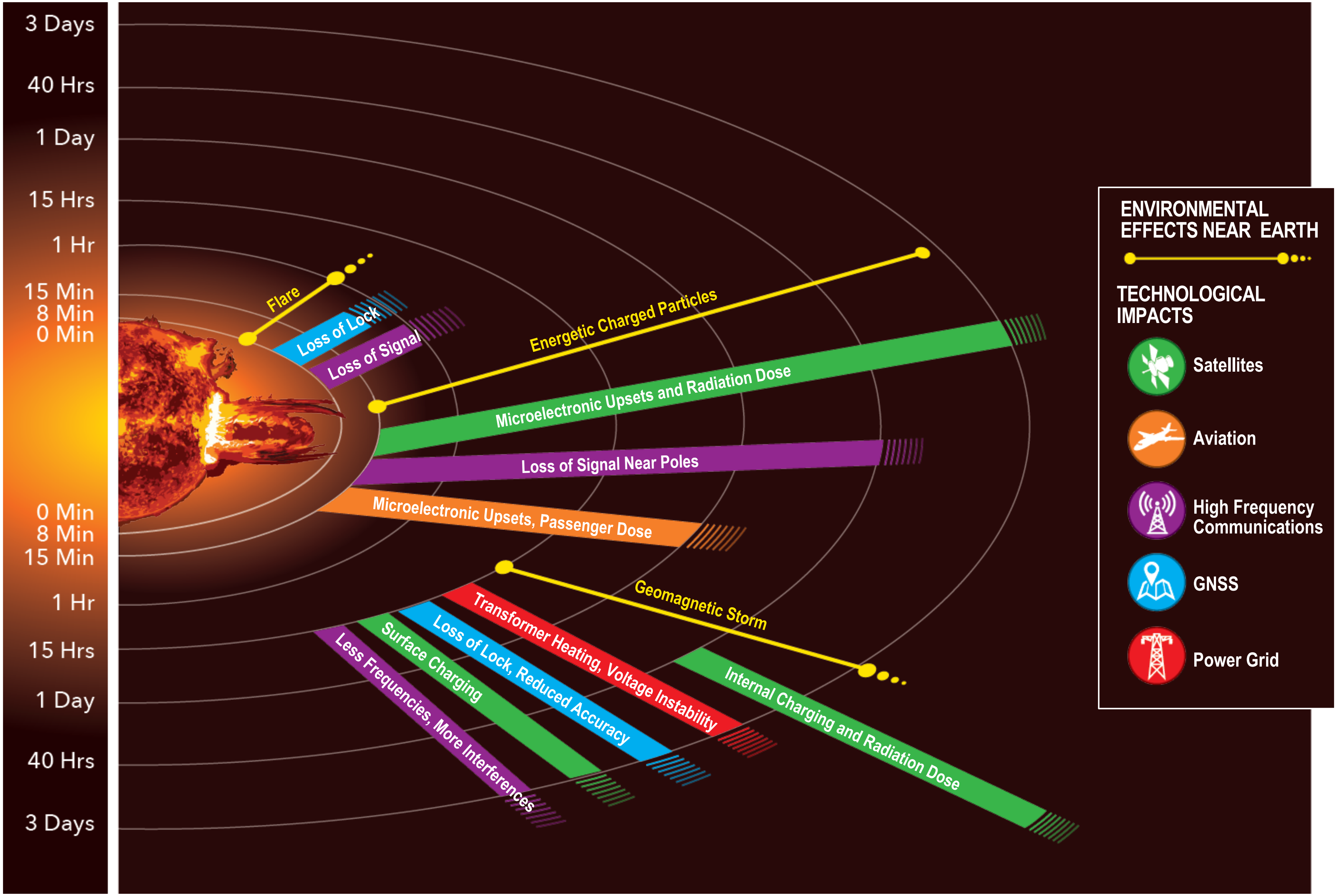


Space weather impacts


3 Days
40 Hrs
1 Day
15 Hrs
1 Hr
15 Min
8 Min
0 Min
0 Min
8 Min
15 Min
1 Hr
15 Hrs
1 Day
40 Hrs
3 Days
Flare
Loss of Lock
Loss of Signal
Energetic Charged Particles
Microelectronic Upsets and Radiation Dose
Loss of Signal Near Poles
Microelectronic Upsets, Passenger Dose
Geomagnetic Storm
Transformer Heating, Voltage Instability
Loss of Lock, Reduced Accuracy
Surface Charging
Less Frequencies, More Interferences
Internal Charging and Radiation Dose
ENVIRONMENTAL EFFECTS NEAR EARTH
TECHNOLOGICAL IMPACTS
Satellites
Aviation
High Frequency Communications
GNSS
Power Grid

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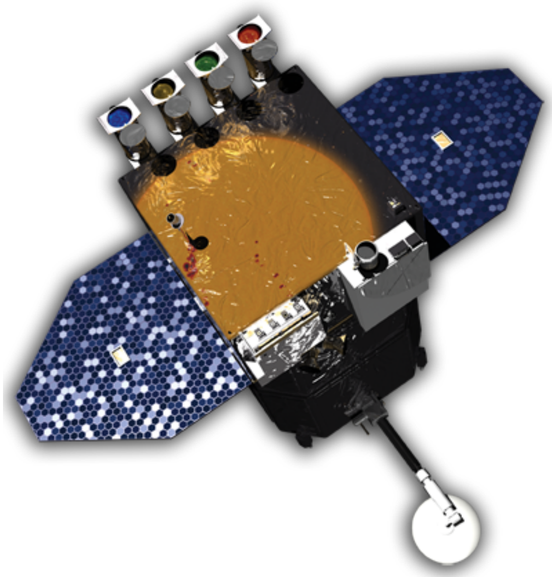
- Spacecraft can be impacted in a number of different ways depending on the orbit of the vehicle.



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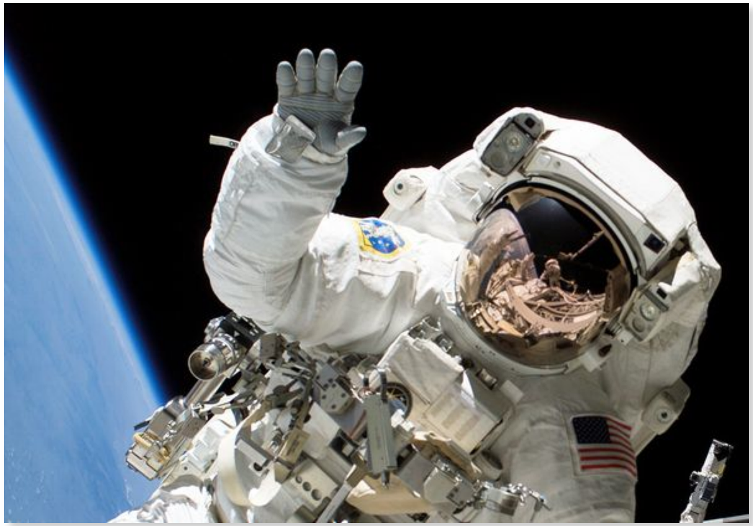
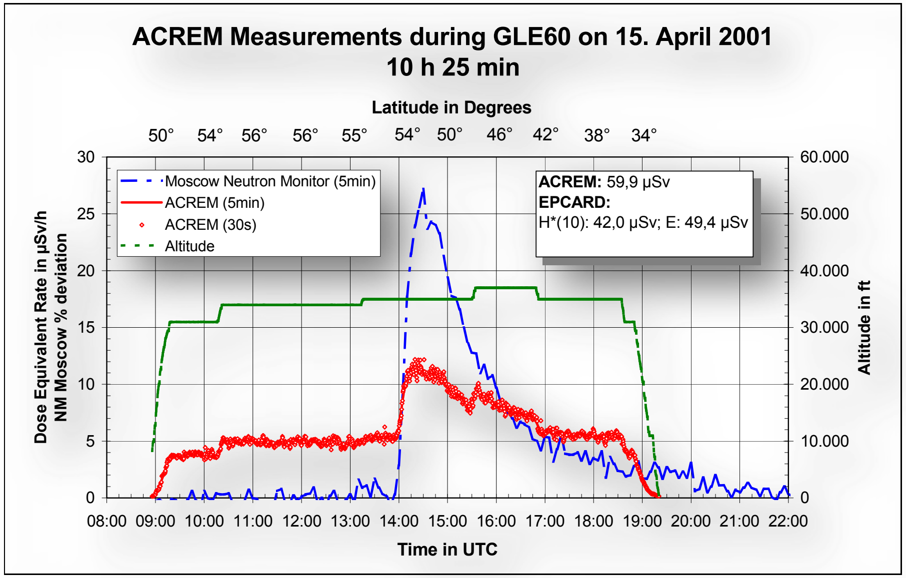
- Energetic charged particle radiation is a hazard for humans in space and at airline altitudes.
  Especially less predictable SEPs are a concern.



Credit: NASA



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

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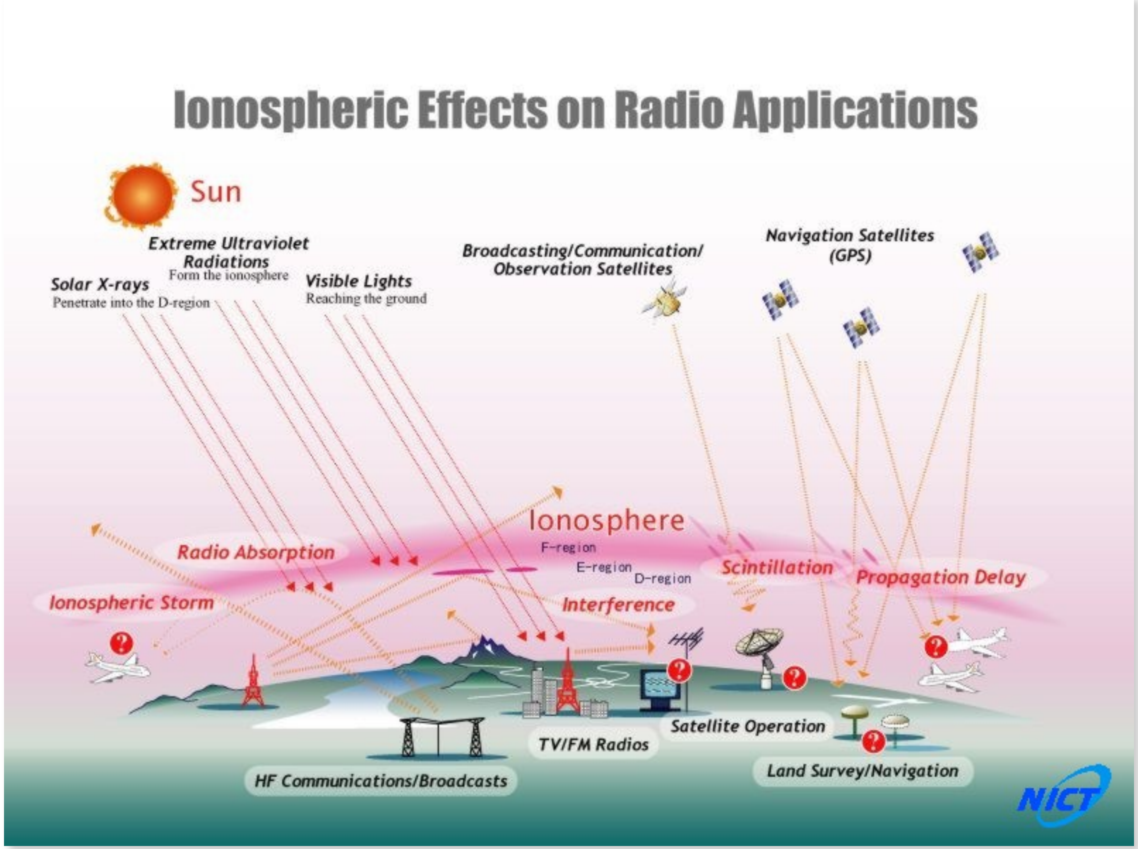
- Signals using ionosphere or “just” passing through ionosphere are affected by space weather.



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.

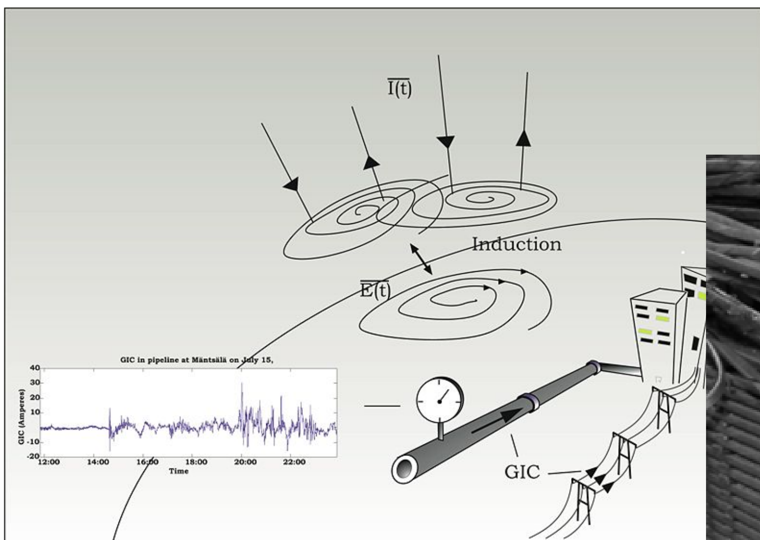

Illustration of mechanism for generating GIC

Transformer damage in South Africa

Credit: Gaunt and Coetzee (2007)

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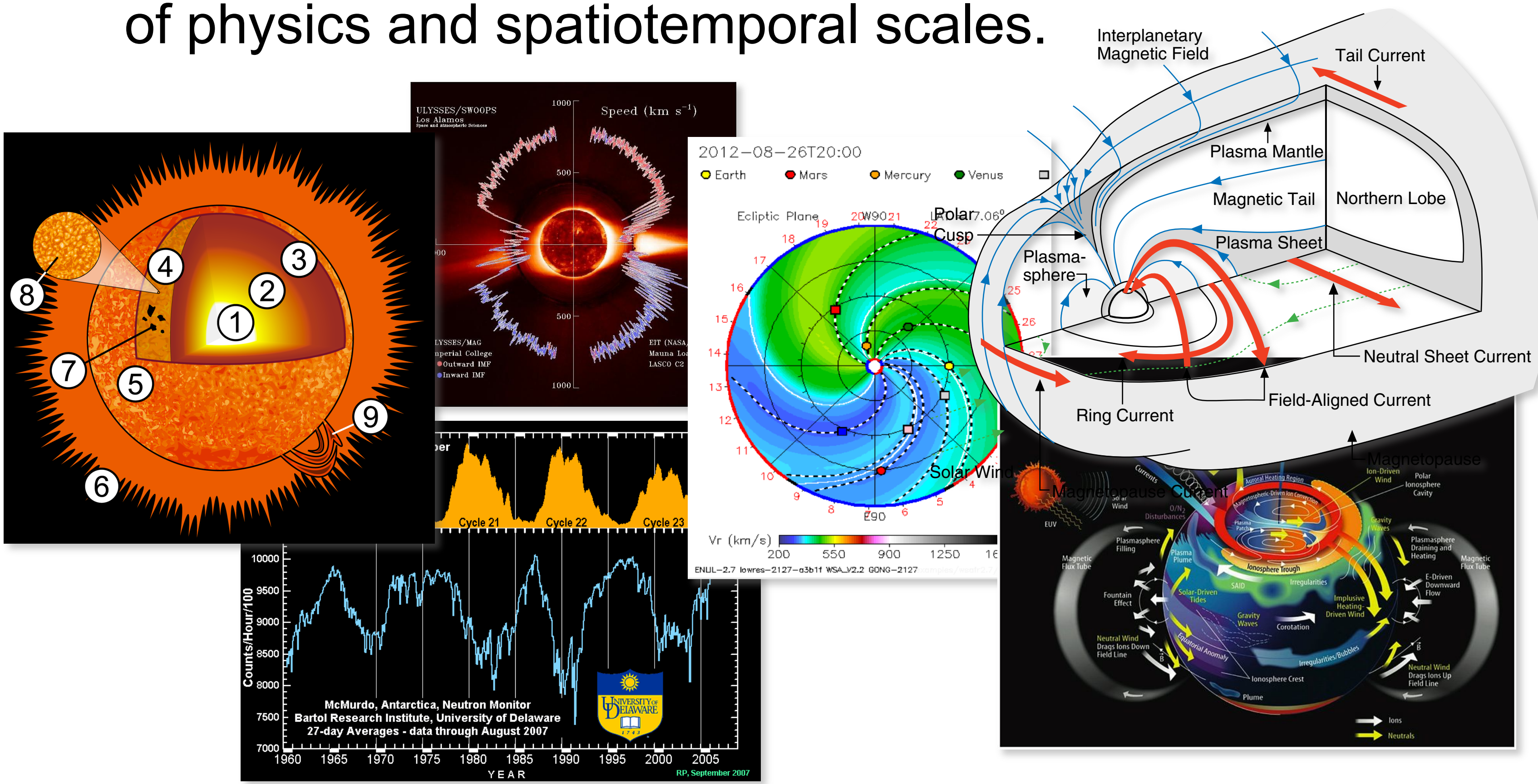
- So we see that space weather really is a vast chain of complex interacting systems covering wide ranges of physics and spatiotemporal scales.



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