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 socioeconomic 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

- Photosphere at 4300 K (top)
- Convection zone at 6600 K (top)
- Radiation zone at $5 \times 10^5$ K (top)
- Core (Hydrogen into Helium) at $1.5 \times 10^7$ K
- Prominence at about 5000-10000 K
- Corona at $\approx 10^6$ K
- Chromosphere at 25000 K (top)
- Sunspots
- Granulation

Credit: Wikipedia/sun
Increasing sunspot number indicates more complex global solar magnetic field structure → eruptions more likely.
SOLAR CYCLE 25 CONSENSUS PREDICTION

July 2025
SSN = 115

Credit: NOAA/NASA/ESA
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
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

- 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).

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.
Introduction to Space Weather

- 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
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.

Credit: NASA GSFC SVS
Introduction to Space Weather

• Also various magnetospheric electric current systems get powered.

≈ 1 MA current into the ionosphere

Charged particles carrying the ring current

Introduction to Space Weather

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

Credit: INTERMAGNET

Storm-time magnetic field variations observed in a high-latitude station.
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
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
https://svs.gsfc.nasa.gov/11474
Introduction to Space Weather

Space weather impacts
Space Weather Training 2020

- **CME Arrival at Earth**
- **X-rays Observed On Earth**
- **Sun Flare**
- **Energetic Charged Particles**
- **Geomagnetic Storm**
- **Loss of Signal Near Poles**
- **Loss of Signal**
- **Microelectronic Upsets and Radiation Dose**
- **Loss of Signal Near Poles**
- **Microelectronic Upsets, Passenger Dose**
- **Geomagnetic Storm**
- **Transformer Heating, Voltage Instability**
- **Surface Charging, Reduced Accuracy**
- **Less Frequencies, More Interferences**

**ENVIRONMENTAL EFFECTS NEAR EARTH**

**TECHNOLOGICAL IMPACTS**
- Satellites
- Aviation
- High Frequency Communications
- GNSS
- Power Grid

**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**
Introduction to Space Weather

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

- 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)

Credit: NICT
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)
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.

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