Run Through Space
Weather I
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Overview

- 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)
Overview

Recommended reads cont’d:

Overview

- Recommended reads cont’ d:
Overview

Online resources:

- CUA Space Weather Academy: www.youtube.com/user/CUASpaceWeather.
So let’s get going!
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- 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.
“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 spaceborne 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
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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”
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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.

⇒ 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, let's start our run through space weather domains from the Sun.
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Photosphere at 4300 K (top)

Granulation

Sunspots

Chromosphere at 25000 K (top)

Corona at \( \approx 10^6 \) 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
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- Solar atmospheric mass, momentum and energy are being carried away by solar wind.

- Fast wind from coronal hole(s)

- Denser low speed wind from lower latitudes
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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)

Corotating interaction region (CIR)
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- The Sun is a magnetic beast. The magnetic field generated through *dynamo process*.
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Increasing sunspot number indicates more complex global solar magnetic field structure → eruptions more likely

Credit: Wikipedia/Solar_cycle
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As the global solar magnetic field structure gets more complicated also plasma configurations in the solar corona gain complexity.

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 $\approx 10^{20}$ 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.
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: 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.

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

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

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

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.

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

Transformer damage in South Africa

Illustration of mechanism for generating GIC

Credit: Gaunt and Coetzee (2007)