



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.



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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)



Preamble

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



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 socioeconomic losses.”

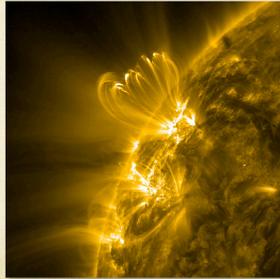
US National Space Weather Program



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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”



EUV image of solar corona
(credit: NASA SDO)



Image of auroras at visible wavelengths
(credit: spaceweather.com)

-SDO image of ~million degree plasma in solar corona.

-Green auroras generated by emission from oxygen atoms.



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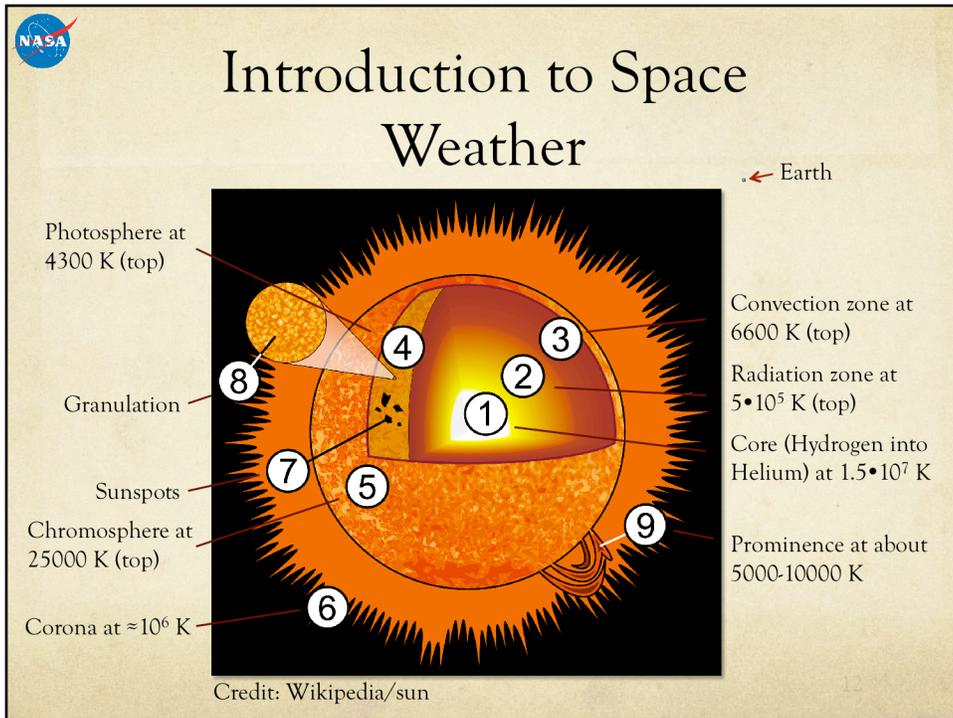
- The range of space weather scales is extremely challenging.
 - Relevant time scales vary from $\approx 10^9$ s (plasma fluctuations in the solar atmosphere) to $\approx 10^8$ s (solar cycle).
 - Relevant spatial scales vary from ≈ 1 m (ionospheric plasma structures) to $\approx 10^8$ m (large-scale interplanetary plasma structures).
- Further there is a strong coupling across the scales.
 - Pretty crazy stuff! No wonder forecasting space weather is a serious challenge...

- Ionospheric structures at 1 m scales important for example for scintillation.



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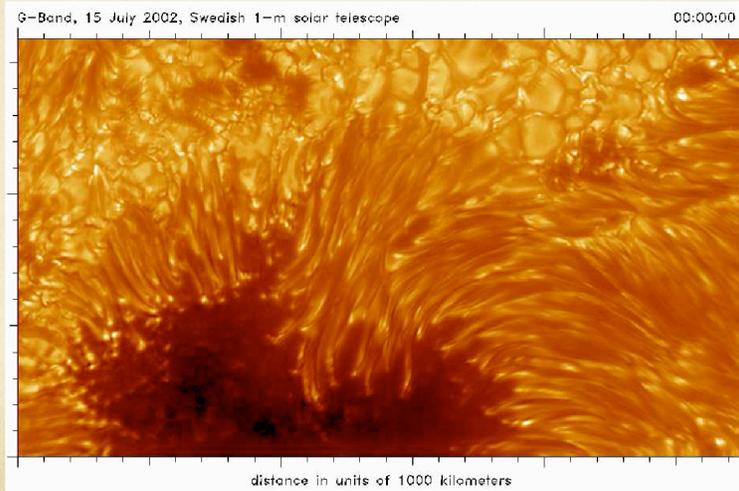
- Although internal magnetospheric dynamics and galactic sources play an important role as well, the Sun is the ultimate source of (almost) all space weather.
- Consequently, let's start our run through space weather domains from the Sun.



- Solar radius 109 times that of the Earth.
- Density of the core about 150 g/cc. The density of water 1 g/cc.
- Photosphere irradiates a thermal blackbody radiation at 5778 K.
- Chromosphere got its name from colorful flash seen from this region at the beginning and end of total solar eclipse.
- Prominences located in corona much cooler and denser structures.



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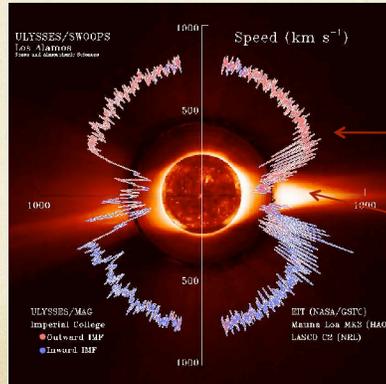


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- Solar atmospheric mass, momentum and energy are being carried away by *solar wind*.



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

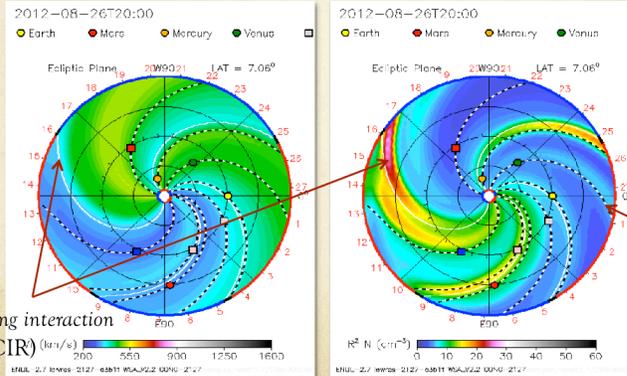
Fast wind from coronal hole(s)

Denser low speed wind from lower latitudes



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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.



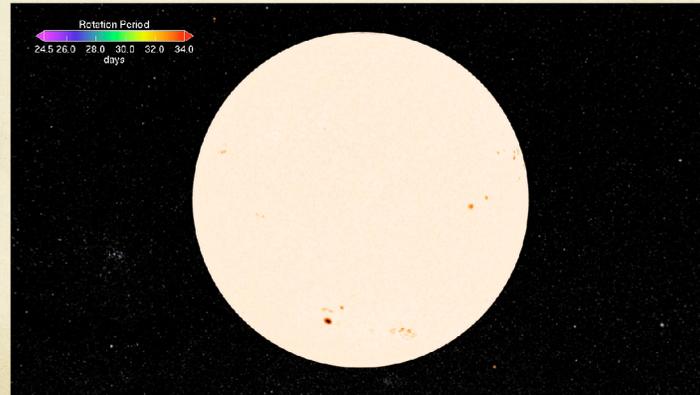
WSA-Enlil prediction of the solar wind conditions (credit: iSWA)

Spiral (IMF field-line)



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



Credit: NASA GSFC SVS

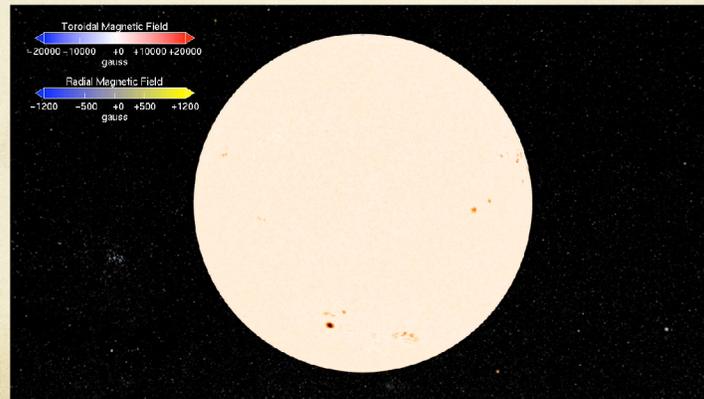
- Montana State University model of the solar dynamo. "The unusual minimum of sunspot cycle 23 a consequence of meridional plasma flow variations", Dibyendu Nandy, Andres Munoz-Jaramillo, and Petrus C. H. Martens, Nature, March 2011, in press.

- Differential rotation is caused by the interaction between solar convection and rotation. Convective motions in rotating fluid are disturbed by the Coriolis force. The back reaction disturbs rotation making it not uniform. (see <http://arxiv.org/pdf/1108.1604v2.pdf>)



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



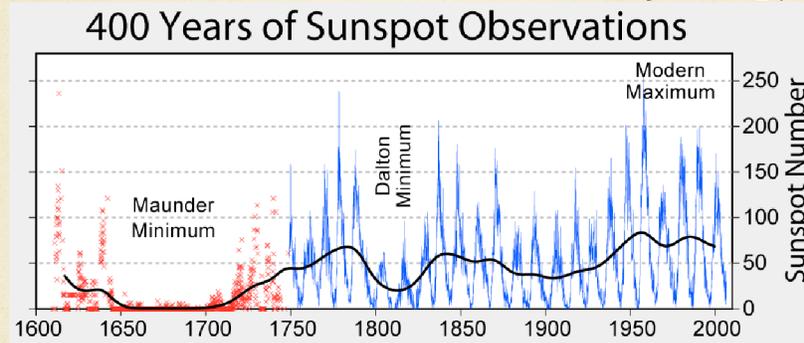
Credit: NASA GSFC SVS

-Montana State University model of the solar dynamo. "The unusual minimum of sunspot cycle 23 a consequence of meridional plasma flow variations", Dibyendu Nandy, Andres Munoz-Jaramillo, and Petrus C. H. Martens, Nature, March 2011, in press.



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Credit: Wikipedia/Solar_cycle

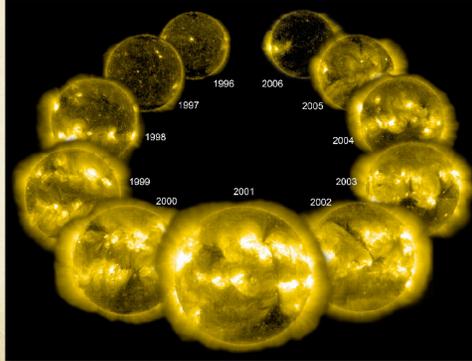


Increasing sunspot number indicates more complex global solar magnetic field structure → eruptions more likely



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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



Quick quiz

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



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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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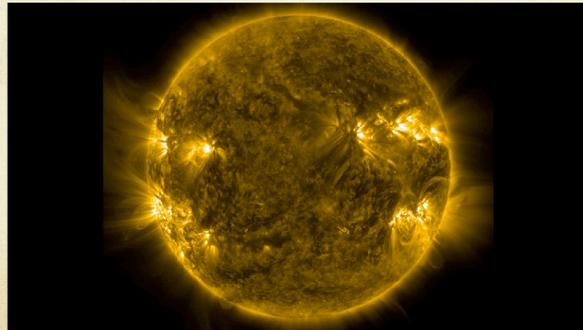


Credit: NASA



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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

- Duration: 21.2 seconds.



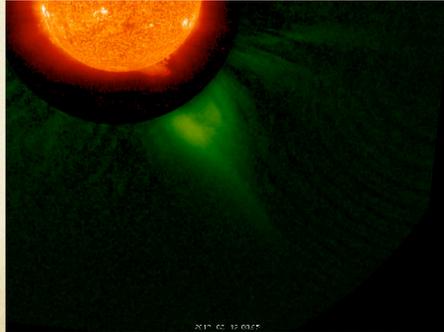
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- Generally speaking in solar flares free magnetic energy converted into heat, non-thermal particle acceleration and electromagnetic radiation.
- Solar flares generate, for example, X-ray, Extreme Ultraviolet (EUV) and radio emissions, and solar energetic 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.



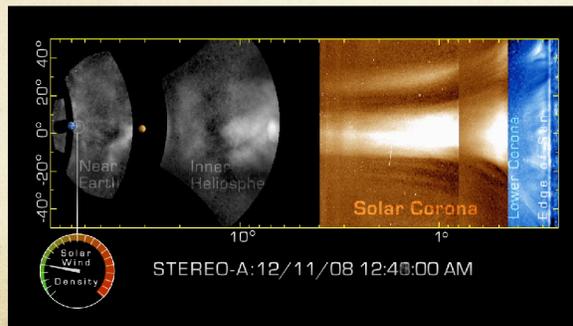
STEREO B 304 Angstrom
EUV and white light
coronagraph March 12, 2012

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.



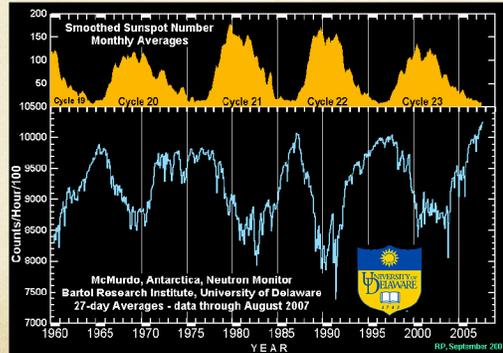
STEREO A white light coronagraphs and heliospheric imagers
December 2008

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

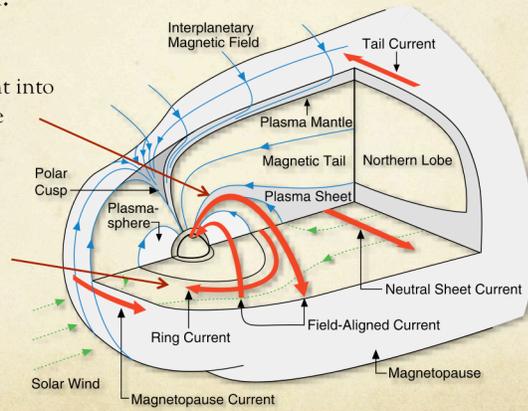


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- Also various magnetospheric electric current systems get powered.

≈ 1 MA current into the ionosphere

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

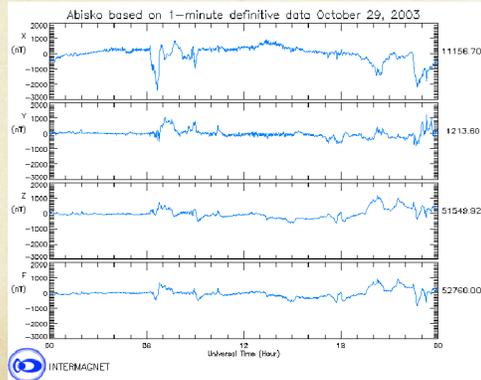


Credit: Russell, C. (IEEE Trans. on Plasma Science, 2000)



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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*.



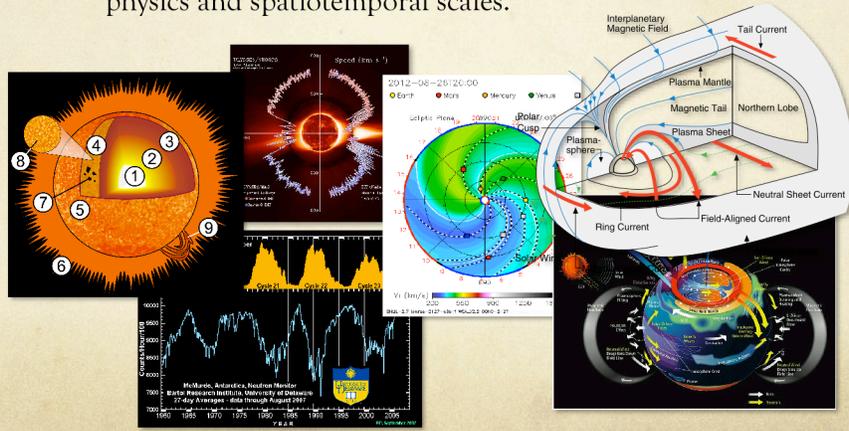
Storm-time magnetic field variations observed in a high-latitude station.

Credit: INTERMAGNET



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





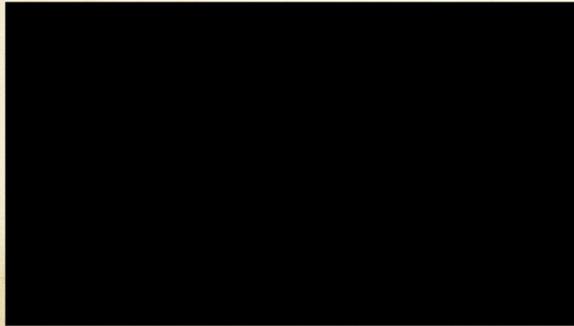
Quick quiz

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



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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.

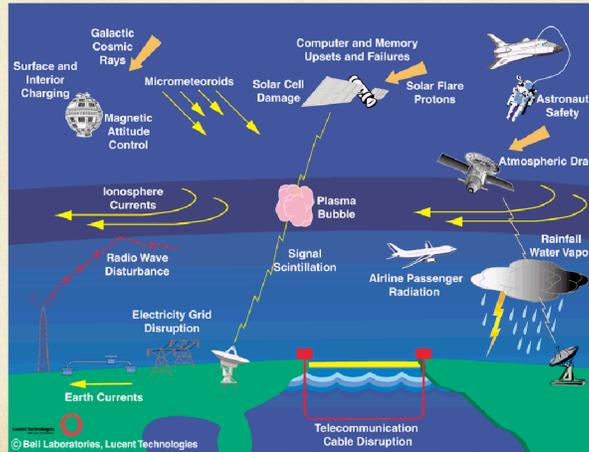


Aurora Australis
imaged from ISS Sep
11, 2011

Credit: NASA



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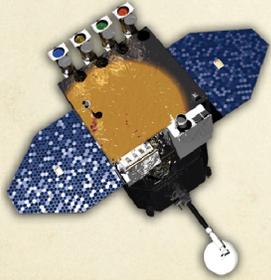
We will not be discussing these

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



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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).

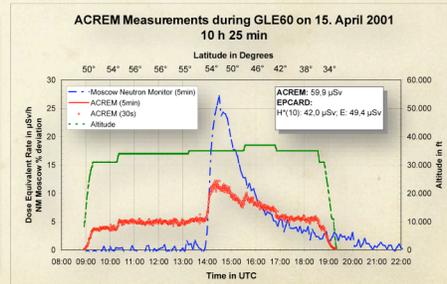


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- Energetic charged particle radiation is a hazard for humans in space and at airline altitudes. Especially less predictable SEPs are a concern.



Credit: NASA

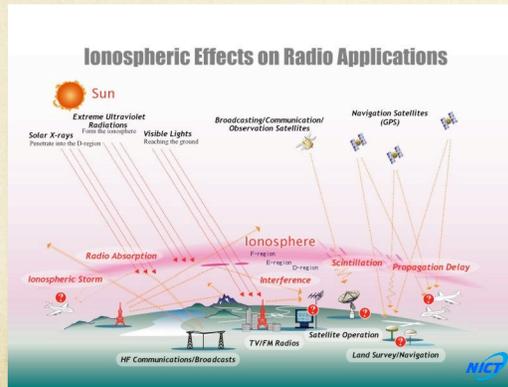


Dose observations from a commercial flight (Credit: Bartlett et al., 2002)



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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.

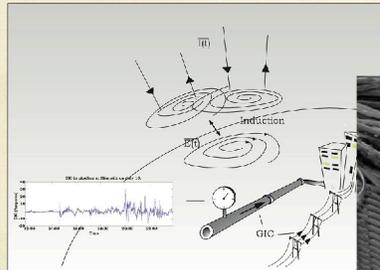


Illustration of mechanism for generating GIC

Transformer damage in South Africa



Credit: Gaunt and Coetzee (2007)



Quick quiz

- How do you think space weather can impact spacecraft launch operations?