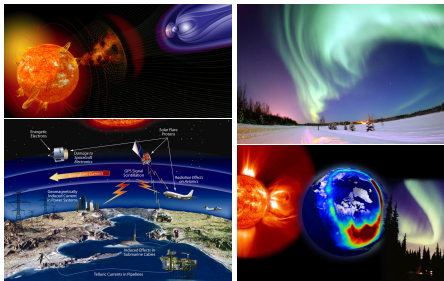


Space Weather

Lecture 1: Introduction



Elena Kronberg (room 442)
elena.kronberg@lmu.de

I. Introduction

- Weather is the state of the atmosphere, to the degree that it is hot or cold, wet or dry, calm or stormy, clear or cloudy.
- Human activities and technologies have always been prey to the extremes of weather



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... around the middle
of the 19th century

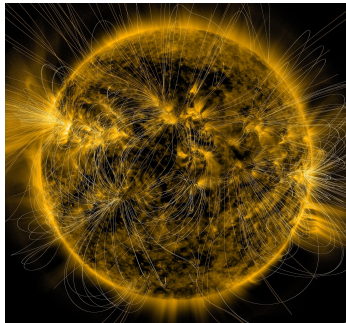
I. Introduction

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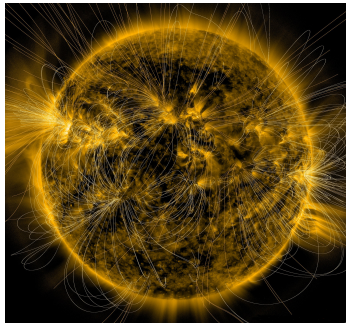
I. Introduction: Space Weather definition

- Space Weather are disturbances of the upper atmosphere and near-Earth space environment driven by the magnetic activity of the Sun.



I. Introduction: Space Weather definition

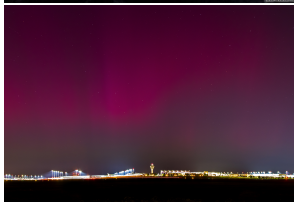
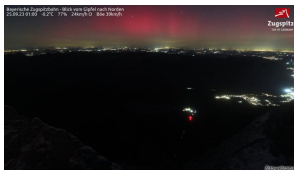
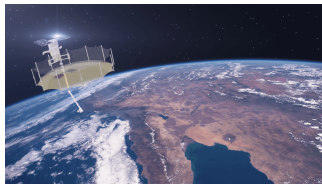
- Space Weather are disturbances of the upper atmosphere and near-Earth space environment driven by the magnetic activity of the Sun.



A planet habitability depends on space weather!

I. Introduction: some of the most recent events

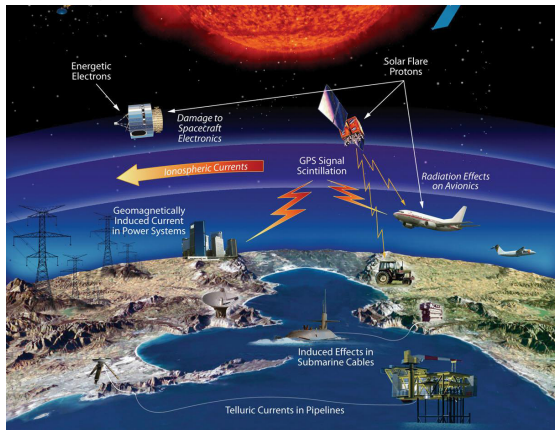
- Capella's Earth-imaging satellites deorbiting faster than anticipated (August 4, 2023)
- 40 from 49 Starlink satellites were burned in the atmosphere (February 4, 2022)
- Northern lights above Zugspitze (September 25, 2023)
- Super storm on May 10, 2024



Credit: Ralf Plechinger

I. Introduction

- Since middle of the 19th century growth of the electric power industry, the development of telephone, radio, space-based communications and navigation systems has dramatically increased the vulnerability of modern society to space weather.



submarine = "under water"

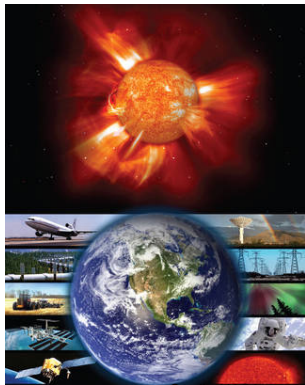
Credit: NASA

I. Introduction

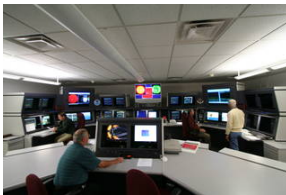


I. Motivation: to learn about

- the potential societal and economic impacts
- the technologies used for forecasting Space Weather events
- the infrastructure behind Space Weather services
- the physics behind Space Weather phenomena
- ~ 9 lectures and 2 tutorials



Credit: NASA



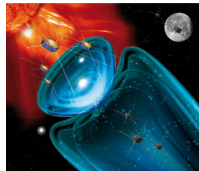
Credit: NOAA SWPC



Credit: W. Redal

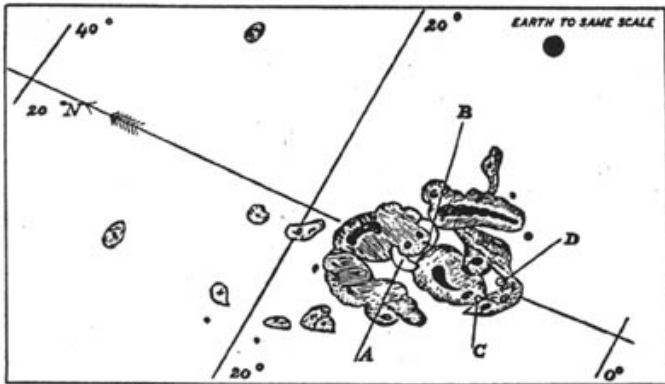
Lecture's programm

- 1 Introduction (What is space weather? The potential societal and economic impacts, the technologies used for forecasting Space Weather events, the infrastructure behind Space Weather services)
- 2 The Sun and the Solar Wind
- 3 Bow Shock
- 4 Kelvin-Helmholtz Instability and Field Line Resonances
- 5 Earth's Magnetic Field
- 6 Interaction with Interplanetary Magnetic Field and Reconnection
- 7 Magnetospheric Substorms and Storms
- 8 Radiation belts
- 9 Ionosphere



II. Historical Background: The Carrington Event August-September 1859

- Richard Carrington (England) noted an outburst of “two patches of intensely bright and white light” from a large group of sunspots near the center of the Sun’s disk – *solar flare*



Richard Carrington's 1859
drawing

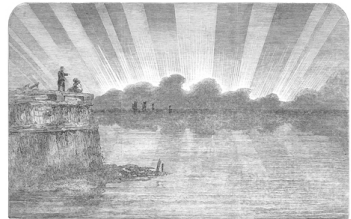
FIG. 36. Solar sketch, September 1, 1859, by R. C. Carrington

II. Historical Background: The Carrington Event August-September 1859

- It was followed the next day by *auroras* seen e.g. in Sub-Saharan Africa, Mexico, Cuba, Hawaii, and even in Colombia.



Church's 1865 painting
"Aurora Borealis"



"The Aurora Borealis, seen
from the pier, Boulogne, 1853"

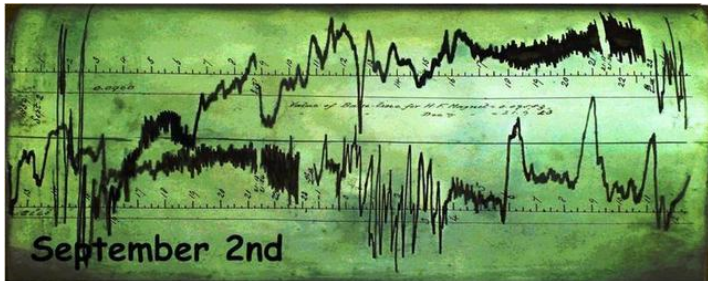
www.mrjacklowe.com

II. Historical Background: The Carrington Event August-September 1859

- Shortly after midnight on September 2, 1859, campers in the Rocky Mountains were awakened by an “auroral light, so bright that one could easily read common print. Some of them partly insisted that it was daylight and began preparation of breakfast.”
(*The Rocky Mountain News*)

II. Historical Background: The Carrington Event August-September 1859

- A *magnetic storm* was also observed. The storm strength range (*Dst*) from -800 nT to -1750 nT. (March 14, 1989, -589 nT; November 20, 2003, -422 nT; May 10, 2024, -412 nT)
- “The *solar spots*, the mean daily range of the magnetic needle and the frequency of *auroras* – are somehow dependent the one upon the other”. (*Elias Loomis, US, 1860*)



A magnetogram Greenwich Observatory, Declination, or compass direction, (D) is the lower trace and the horizontal force (H) is the upper trace.

II. Historical Background: The Carrington Event

Socioeconomic impacts

- Disruptions of telegraph service “at the busy season when the telegraph is more than usually required”(Walker, 1861),
- the telegraph companies associated loss of income.



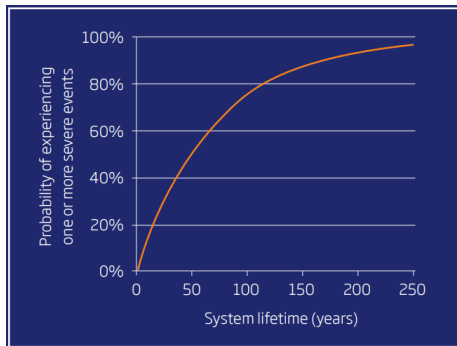
A STORM OF ELECTRICITY

TELEGRAPH WIRES USELESS FOR SEVERAL HOURS.

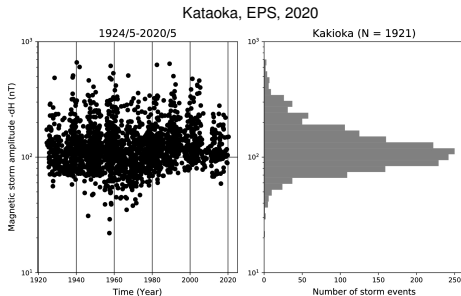
ONE OF THE MOST SEVERE DISTURBANCES
FOR MANY YEARS, EXTENDING EVEN TO
EUROPE—TELEPHONE WIRES ALSO OB-
STRUCTED—BUSINESS DELAYED A GOOD
PART OF THE DAY.

Yesterday's storm was accompanied by a more serious electrical disturbance than has been known for years. It very seriously affected the workings of the telegraph lines both on the land and in the sea, and for three hours—from 9 A. M. until noon—telegraph business east of the Mississippi and north of Washington was at a stand-still.

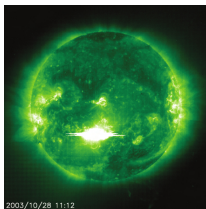
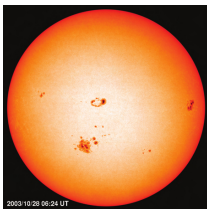
II. Historical Background: Probability of the Carrington Event



Estimated economic impact is US\$9.1 trillion, 1.4 percent reduction in global Gross Domestic Product (GDP)
(*Lloyd's & Cambridge Centre for Risk studies*)



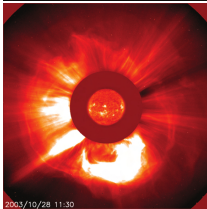
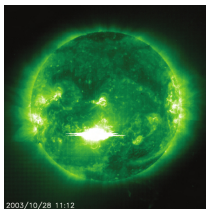
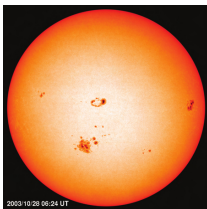
II. Recent event: Magnetic Storm October, 2003



- A large sunspot (SOHO/MDI image, upper-left) erupted with a strong *X-ray flare* (SOHO/EIT image, upper-right).

SOHO spacecraft observations in a halo orbit around the Sun–Earth L1 point.
Credit: NASA

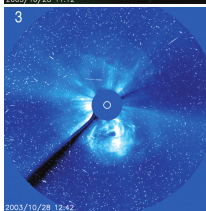
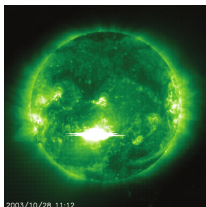
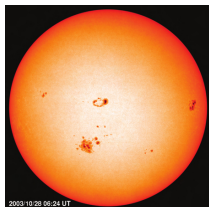
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SOHO spacecraft observations in a halo orbit around the Sun–Earth L1 point.
Credit: NASA

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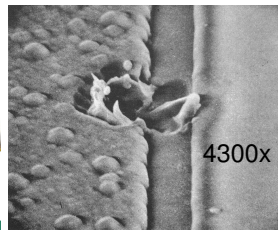
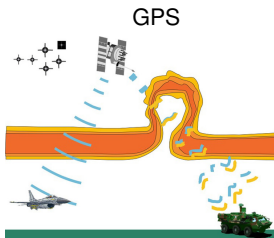
SOHO spacecraft observations in a halo orbit around the Sun–Earth L1 point.
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- Within minutes, SOHO/LASCO detected a halo *coronal mass ejection (CME)* emerging from the Sun (lower-left).
- 1.5 hour after the flare, a shower of *energetic protons* reached the SOHO spacecraft, creating the “snow” in the lower-right image.
- This CME triggered powerful *magnetic storm* (~ 400 nT).

III. Effects of extreme space weather on modern technology

can be divided in several categories:

- (a) Power grid outages
- (b) Interference with Global Navigation Satellite System (GNSS) signals
- (c) High Frequency (HF) radio communication blackouts
- (d) Spacecraft hardware damages
- (e) Radiation exposure for high-altitude flights and space missions

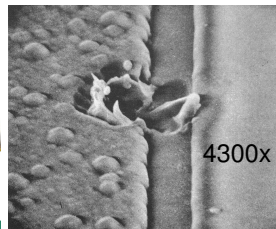
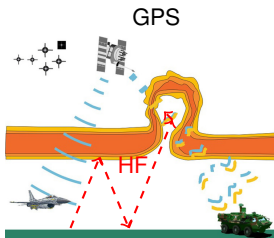


Credit: US Air Force Research
Laboratory (AFRL)

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Credit: US Air Force Research
Laboratory (AFRL)

III.a Effects: Power Grids – Examples

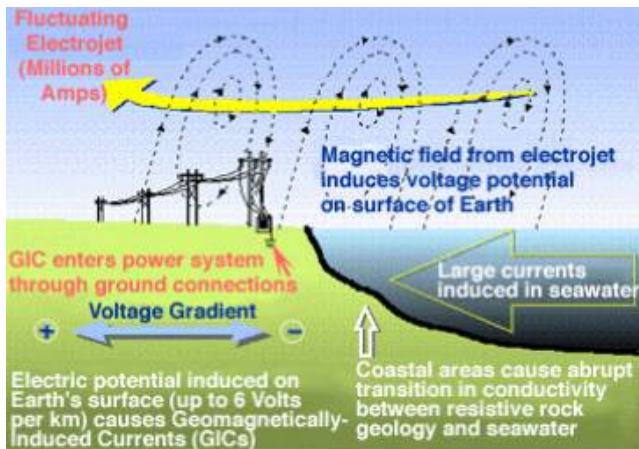
- The March 13, 1989 magnetic superstorm: a voltage depression on the Hydro-Quebec power system in Canada. The system collapsed within seconds. The province Quebec was blacked out for approximately 9 hours.



Hydro Quebec,
Electric Power
Transformer

III.a Effects: Power Grids – Reason

- Power transmission systems are vulnerable to Direct Currents (DC) driven by magnetic induction
- Induced electric potential: $\mathcal{E} = -\partial_t \iint_S \mathbf{B} \cdot d\mathbf{S}$ ($d\mathbf{S}$ is element of enclosed surface)



III.a Effects: Power Grids – Reason

- Too much DC causes hot spots, wires melt and oil baths catch fire



III.a Effects: Power Grids – Solutions?

- Operators of the North American power grid constantly analyze potential risks associated with space weather events
 - * monitoring voltages and ground currents in real time
 - * in case of significant currents invoke conservative and mitigating operation practices.
- Forecasts are produced by National Oceanic and Atmospheric Administration's (NOAA) Space Weather Prediction Center (SWPC): see <http://www.swpc.noaa.gov>

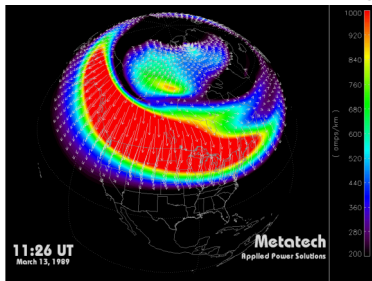
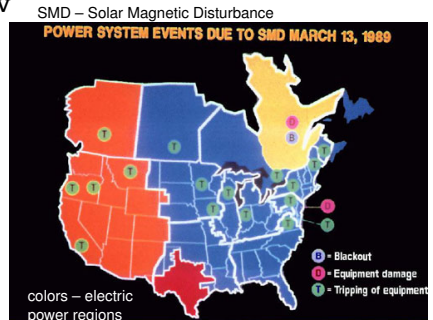


Figure 2-14. Simulation of geomagnetic conditions at 11:26 UT, on March 13, 1989.



III.b Effects: GNSS

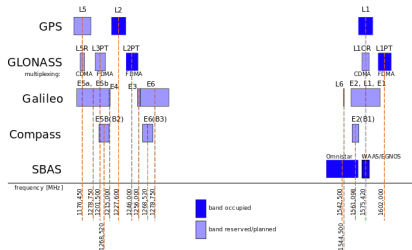
GNSS Services

- The GNSS is a constellation of satellites which provides global coverage.
- Sub-daily ultra-rapid product (IGS) had better than 10 cm accuracy during the October 2003 magnetic storm.
- However, high-rate and real-time GNSS analysis can be critical, e.g. *in aviation*, autonomous driving, in detecting seismic surface waves, tsunami warning system, etc.

GLONASS – Global Navigation Satellite System (Russia)

COMPASS – BeiDou Navigation Satellite System (China)

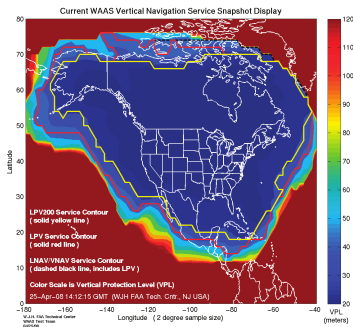
SBAS – satellite-based augmentation system (data from GNSS satellites is analysed on the ground and sent to users)



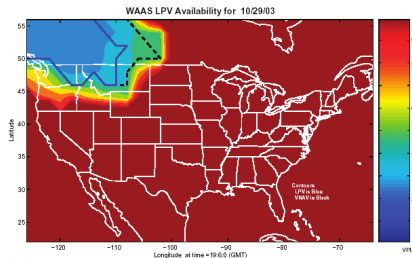
III.b Effects: GPS – Example

Aviation Navigation

- GPS was not available for 30 h in Oct 2003 leading to flight delays.



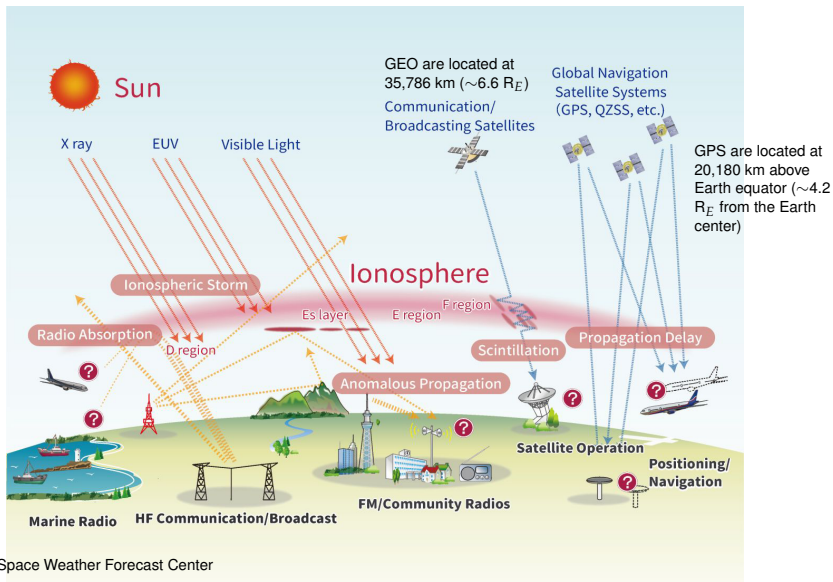
Vertical navigation service on a non-disturbed day.
Source: L. Eldredge, FAA



VPL – Vertical
Protection Level

Vertical navigation service on October 29, 2003.

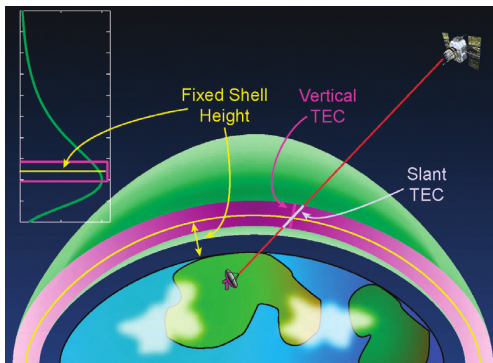
III.b Effects: GNSS – Reason



Source: Space Weather Forecast Center

III.b Effects: GNSS – Reason

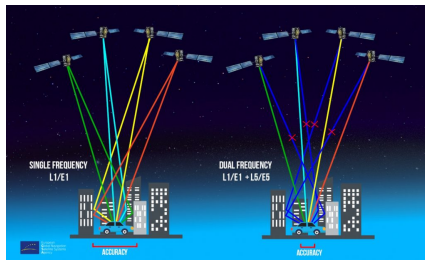
- The ionospheric corrections are done using a thin shell model.
- The accuracy depends on the Total Electron Content (TEC) in the ionosphere.
- During significant ionospheric disturbance the model can be used only for the horizontal navigation but not for the vertical.



Source: L. Eldredge, FAA

III.b Effects: GNSS – Solutions?

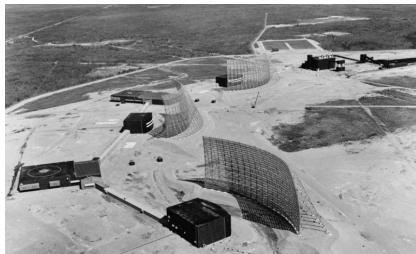
- To avoid such problems, switch to dual-frequency GNSS system has been started (accuracy increase from $\sim$ meters to $\sim$ centimeters).
- In May 2018, Xiaomi launched the first dual-frequency GNSS smartphone.
- However, during high ionospheric disturbances the signal is still inaccurate (can be $\sim$ 50m).
- Build better ionospheric models



III.c Radio blackout – Example

May 23, 1967

- Radar system designed to detect incoming Soviet missiles was disrupted, in what the military perceived to be an act of war.
- US Air Force authorized nuclear missile-carrying aircraft.
- Information from space-weather forecasters, who realized that it was a *solar flare* jamming the radar, managed to prevent military action.



Three radar stations at the Ballistic Missile Early Warning System in Anderson, Alaska, in 1962. Image: Wikimedia



The solar flare begins at exactly 18:40 UT on May 23, 1967. Image: National Solar Observatory

III.c Radio blackout – Example

USS Midway aircraft carrier: crewman's story

- The HF communication was occasionally interrupted by solar flares
- Could not do anything: needed to wait

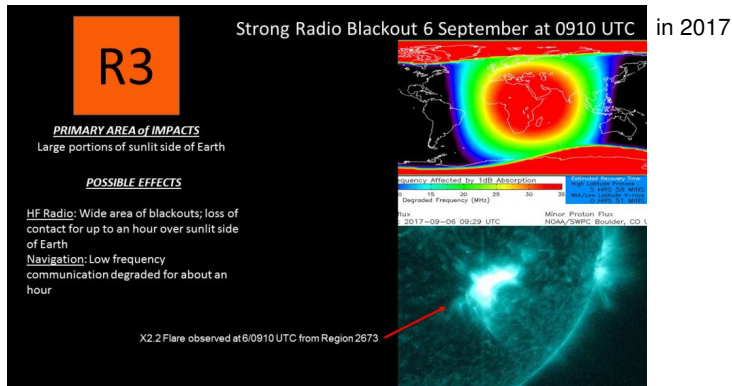


Source: Wikipedia



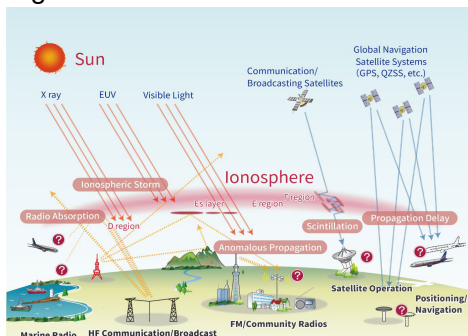
III.c Radio blackout – Reason

- Sudden outburst of electromagnetic energy – *solar flare* – travels at the speed of light and effects can be observed simultaneously.
- Increased level of X-ray and extreme ultraviolet radiation results in ionization in lower layers of the ionosphere on the sunlit side of Earth.



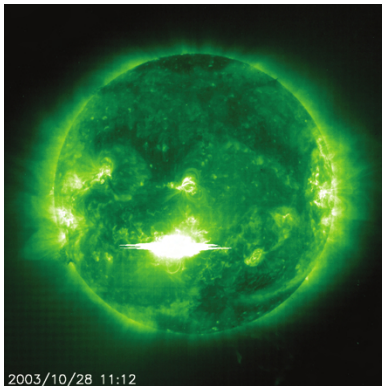
III.c Radio blackout – Reason

- A strong enough *solar flare* produces ionization in the lower, more dense *layers of the ionosphere*.
- Radio waves that interact with electrons in layers lose energy due to more frequent collisions in the higher density environment. This can cause HF radio signals to become degraded or completely absorbed.
- This results in a radio blackout – the absence of HF communication, primarily impacting the 3 to 30 MHz band.



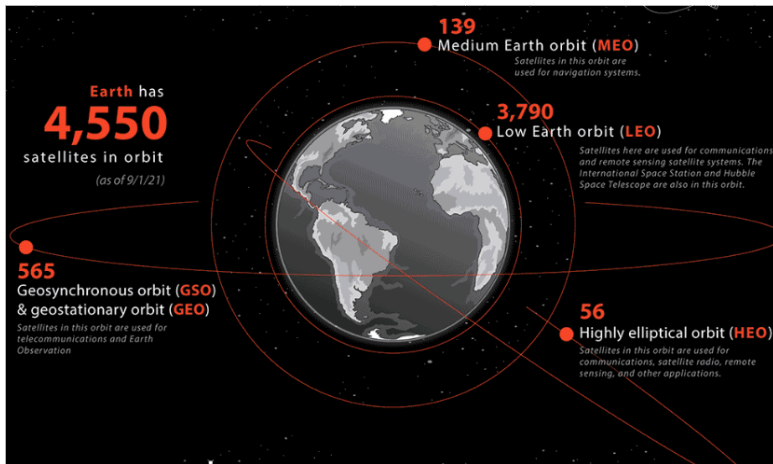
III.c Radio blackout – Solutions?

- Learn how to predict solar flares, e.g., using artificial intelligence



III.d Effects: Satellites

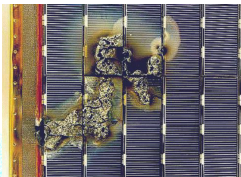
- As of May 2025, there are around 11,700 active satellites in orbit around Earth (Source: LiveScience)



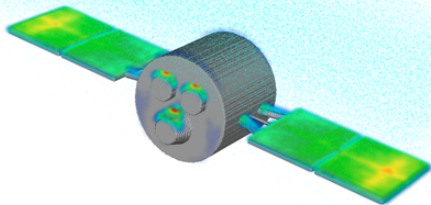
Source: DEWESoft, 2021

III.d Effects: Satellites – Examples

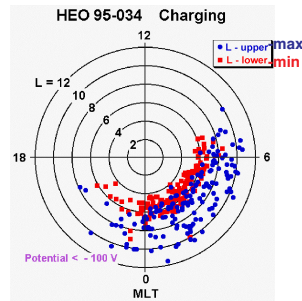
- On January 20, 1994, Telesat Antik E1 and E2 were disabled for $\simeq 7$ hours. Canadian press, TV and data services were lost.
- The electrostatic discharge is one of the major causes of spacecraft anomalies.



solar array of ESA's
EURECA retrievable carrier
in 1993, ESA



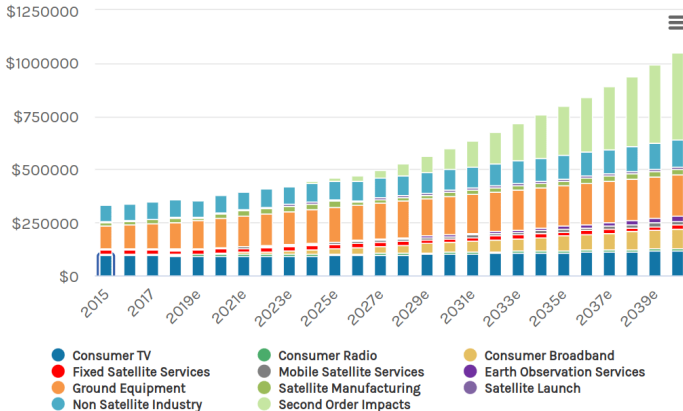
Credit: Tech-X Corporation



Fennell+08, several years of observations

III.d Effects: Satellites – Investing in Space

The Global Space Economy (\$t)

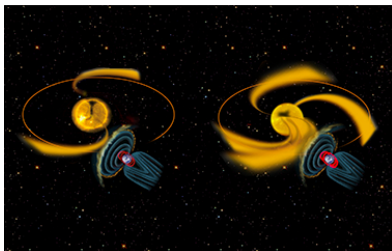


The revenue generated by the global space industry may increase to more than \$1 trillion by 2040.

Source: Haver Analytics, Morgan Stanley Research forecasts

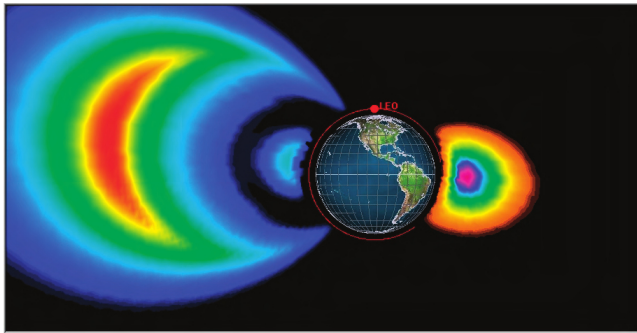
III.d Effects: Satellites – Reasons

- The satellites are damaged by enhancements of the *magnetospheric* electron intensity, which can cause electrical charge to build up on spacecraft surfaces. The electrostatic discharge occurs subsequently.
- Most of anomalies are related to major *magnetic storms* triggered by *CMEs* (like in 2003).
- They are also associated with *high-speed streams* emanating from the *coronal holes* during declining phase of the solar cycle.
- Also when CMEs and high-speed streams are absent, the damages can occur during *substorms*.



III.d Effects: Satellites – Solutions?

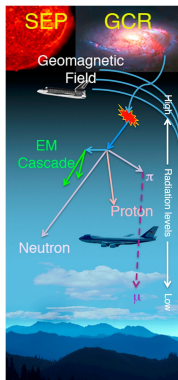
- To create more accurate long-term models of *the radiation belts and ring current*
- To better observe damages and then build better satellites



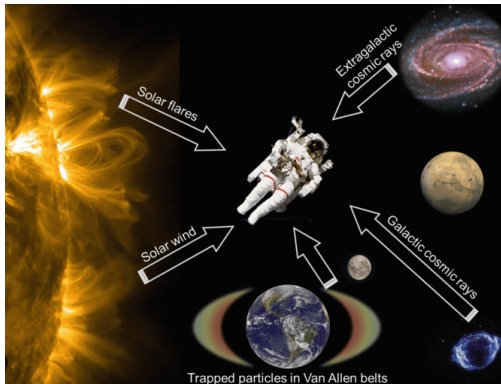
Credit: D. Chenette

III.e Effects: Radiation exposure – Examples & Reasons

- The exposure of a human body to ionizing radiation in high altitude flights and space has the same harmful effects as a medical X-ray.
- Two main sources: galactic cosmic radiation (GCR), which originates from outside our solar system, and *solar energetic particles (SEP)*.



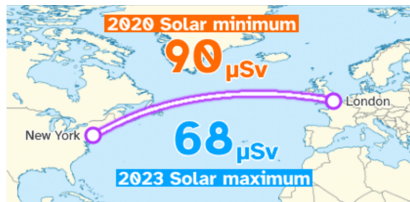
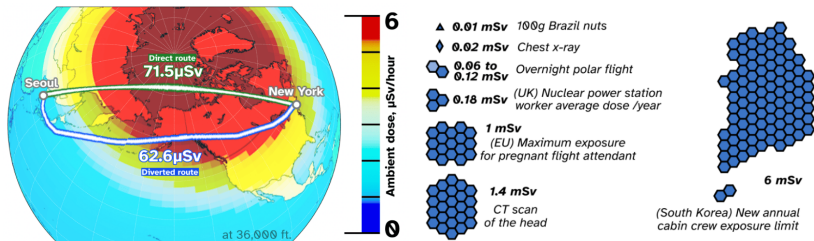
Tobiska et al., 2018



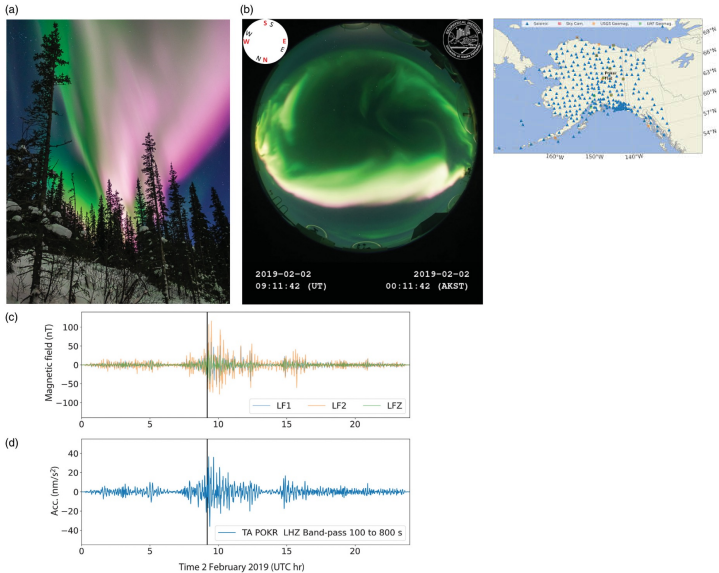
Radiation in Space: Relevance and Risk for Human Missions, 2020

III.e Effects: Radiation exposure – Solutions?

- Monitoring space weather
- Diverting flight routes, proper shielding of spacecraft



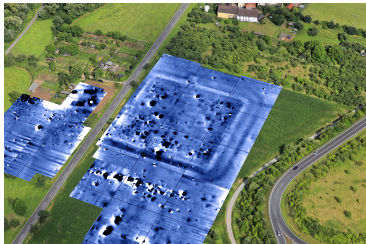
III. Effects: Related to Seismology



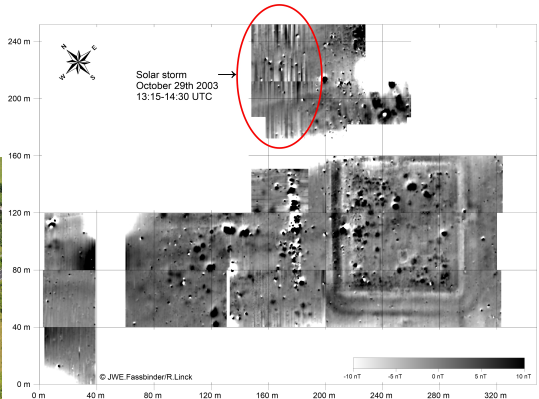
Credit: Tape+2020

III. Effects: Related to Archeology

- Archaeological site (the Roman fort Würth am Main) overlaid by a magnetogram.
- The magnetic storm has produced stripes in the magnetograms.

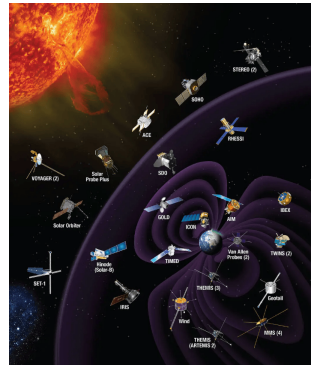


Credit: JWE Fassbinder



IV. Space Weather Services Infrastructure

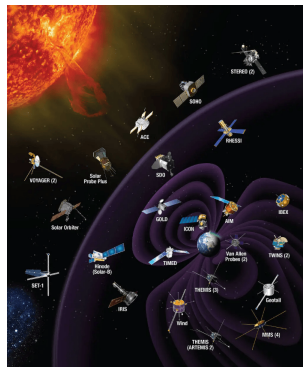
- Although heliospheric missions are all primarily for scientific research, they provide space weather data to both civilian and military customers.



Source: NASA-GSFC

IV. Space Weather Services Infrastructure

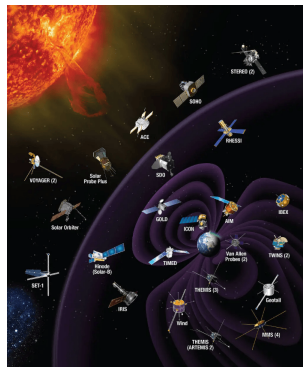
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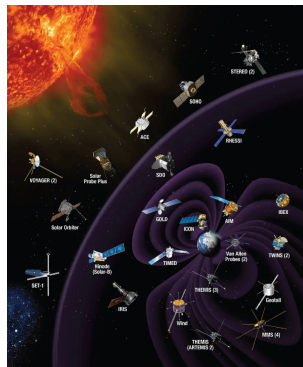


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- The Earth-orbiting spacecraft measure space weather effects in Earth's *magnetosphere and ionosphere* (e.g., GOES, THEMIS, MMS, SWARM).
- Ground-based observatories provide data for characterizing space weather conditions and effects (INTERMAGNET, SuperMag).

Source: NASA-GSFC



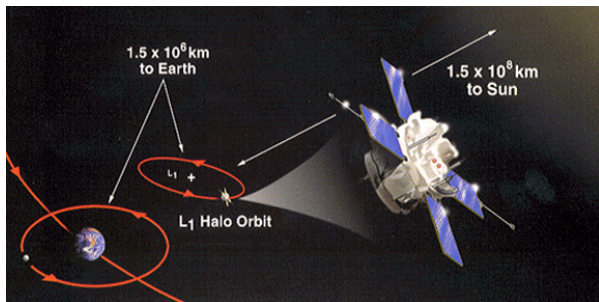
IV. Services Infrastructure: Sun observations

- SOHO measurements allow to predict arrival of MeV protons from solar events that can harm satellites and humans.

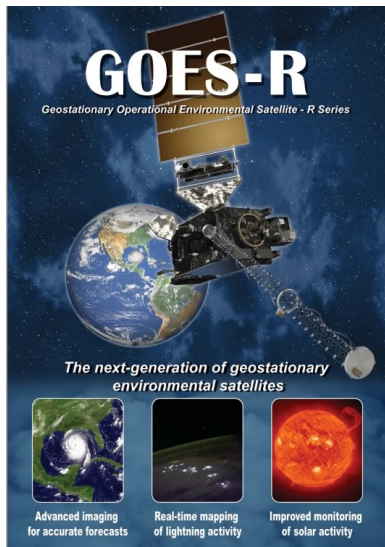


IV. Services Infrastructure: Sun observations

- ACE provides data from its position at Lagrangian point between the Sun and Earth (a point of Earth-Sun gravitational equilibrium about 1.5 million km from Earth and 148.5 million km from the Sun).
- It is a primary data source for measurements of solar particles and magnetic fields.
- ACE provides a ~ 45 minute advance warning before CME strikes Earth.



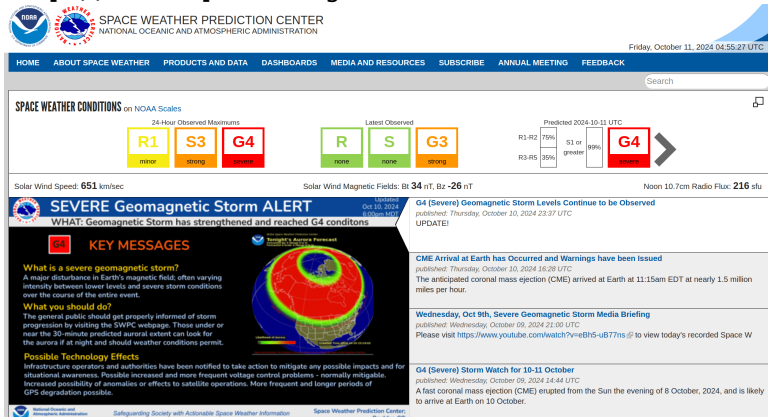
IV. Services Infrastructure: observations from geosynchronous orbit at $6.6 R_E$



- NOAA space weather prediction center products –
50% from GOES (magnetic field, particle fluxes, solar X-ray imager),
38% from ground-based magnetometers,
7% from ground-based solar telescopes,
1% from ACE.

IV. Services Infrastructure: Space Weather Scales

- NOAA uses different scales (G1–G5, S1–S5, R1–R5) to characterize the magnitude and impact of space weather events
- These scales are described in detail on NOAA website:
<http://www.swpc.noaa.gov>



IV. Services Infrastructure: Space Weather Scales

G-Scale → Geomagnetic Storms, Scale G5

- Power systems: widespread voltage control problems, some grid systems may experience complete collapse or blackouts, transformers may experience damage
- Spacecraft operations: extensive surface charging, problems with orientation
- Other systems: strong pipeline currents, HF radio propagation may be impossible for 1–2 days, degradation of satellite navigation, low-frequency radio navigation can be out for hours
- aurora can be seen as low as Florida and southern Texas ($\approx 40^\circ$ geo. lat)
- value $K_p=9$
- 4 days per solar cycle
- Examples: magnetic storms in 1989, 2003 (magnetic storm on Sept 8, 2017, $K_p=8$, Scale=G4)

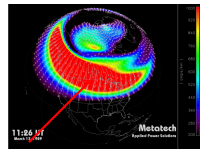
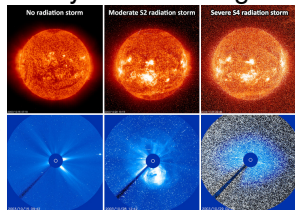


Figure 2-16. Simulation of geomagnetic conditions at 11:28 UT, on March 13, 1989.

IV. Services Infrastructure: Space Weather Scales

S-Scale → *Solar Radiation Storms*, Scale S5

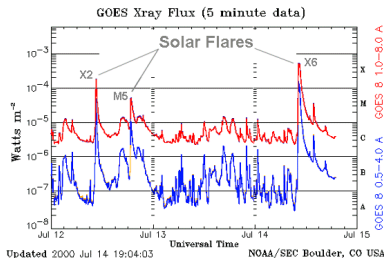
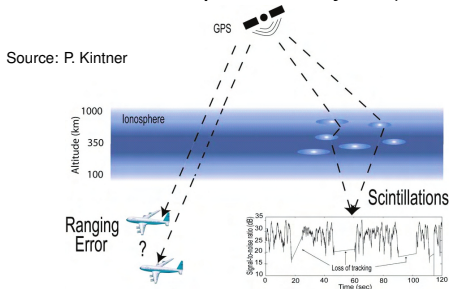
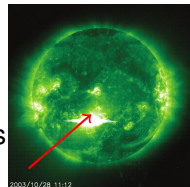
- Biological: unavoidable high radiation hazard to astronauts; passengers and crew in high-flying aircraft at high latitudes may expose radiation risks
- Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, serious noise in image data, star-trackers may be unable to locate sources, permanent damage to solar panels possible
- Other systems: complete blackout of HF communications possible through polar regions + position errors – extremely difficult navigation
- Flux level of ≥ 10 MeV ions
 - * Scale S5 $\geq 10^5$ protons/cm²/sec/ster
fewer than 1 per solar cycle
 - * Scale S2 still produces e.g. biological risks
 $\geq 10^2$ protons/cm²/sec/ster
25 per solar cycle



IV. Services Infrastructure: Space Weather Scales

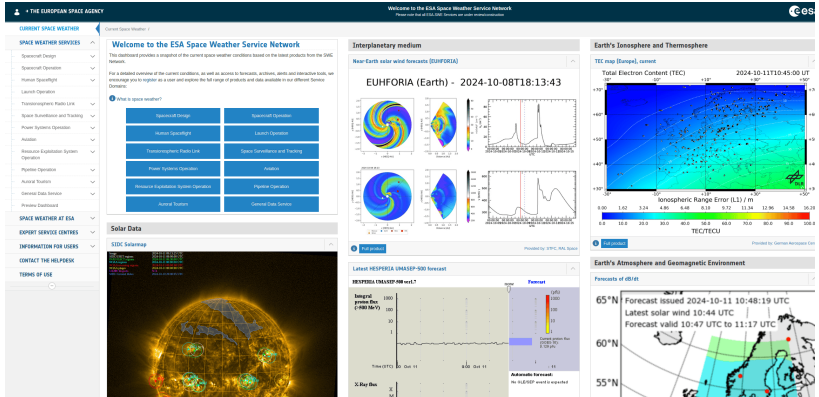
R-Scale → Radio Blackouts, Scale R5

- HF Radio: Complete HF radio blackout on the entire sunlit of the Earth lasting for a number of hours. No HF radio contact with mariners and en route aviators
- Navigation: the same but for low frequency signals
- GOES X-ray peak brightness by class X20 and by flux $2 \cdot 10^{-3} \text{ Watts/m}^2$
- fewer than 1 per solar cycle (strongest X28 on Nov 4, 2003)



IV. Services Infrastructure: Europe

- ESA Space Weather Service Network (<https://swe.ssa.esa.int>)
- The space weather landscape in Europe is “complicated” and “very fragmented”: operational activities from ~ 25 countries
- competition with other areas of astronomy $\rightarrow$ limited fundings

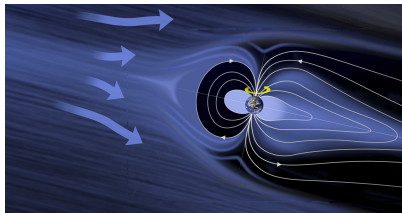
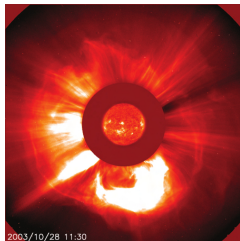


IV. Space Weather Services Infrastructure: Customers

Impact area	Customer	Action	Cost
Spacecraft	Lockheed Martin, Boeing, NASA	Postpone launch, in orbit reboot systems, turn off instruments/spacecraft	Loss of spacecraft ~\$500M
Electric Power	U.S. Nuclear Regulatory Commission, New York Power Authority	Adjust/reduce system load, disconnect components	\$3–6B loss in GDP (black-out)
Airlines	United Airlines, Lufthansa, Korean Airlines	Divert polar flights, change flight plans, change altitude	~\$100k per diverted flight
Navigation	FAA-WAAS, Dept. of Transportation	Postpone activities, use backup systems	\$50k–1M daily for single company

V. Summary and Outlook

- *“It is a challenging task, for both scientific and societal purposes, to develop technologies and mitigation strategies that will help to reliably forecast space weather and its impacts.” V. Bothmer*
- In the following lectures, we will discuss physical processes that are relevant for space weather: Sun spots, CME, solar flares, high-speed-streams, magnetic storms, substorms, polar lights, ionosphere. . . and their observations.



Credit: W.
Redal

E. Kronberg

VI. Literature

- Severe Space Weather Events – Understanding Societal and Economic Impacts, A Workshop Report, The National Academies Press, Washington, D.C., 2008. DOI: 10.17226/12507
- Walker, C. V. On Magnetic Storms and Earth-Currents. Philos. Trans. R. Soc. Lond. 151, 89–131, 1861.