SPACE WEATHER INTRODUCTORY COURSE

SWIC

Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

Space weather effects

Jan Janssens

Space Weather effects (SWx effects)

- ***Introduction***
- *SWx effects from*
  - *Solar flares*
  - *Proton events*
  - *ICMEs*
  - *Coronal holes*

Space Weather (SWx)

- Space weather refers to the environmental conditions in Earth’s magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind that can influence the functioning and reliability of spaceborne and ground-based systems and services or endanger property or human health.

NSWP

- Space Weather is the physical and phenomenological state of natural space environments. The associated discipline aims, through observation, monitoring, analysis and modelling, at understanding and predicting the state of the Sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them, and also at forecasting and nowcasting the potential impacts on biological and technological systems.

ESA, COST Action 724

NSWP: National Space Weather Program ; ESA: European Space Agency ; COST: (European) COoperation in Science & Technology 4

ESA: https://swe.ssa.esa.int/what-is-space-weather and Wall of Peace
Space Weather is the physical and phenomenological state of natural space environments. The associated discipline aims, through observation, monitoring, analysis and modelling, at understanding and predicting the state of the Sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them, and also at forecasting and nowcasting the potential impacts on biological and technological systems. -COST Action 724 , 2009

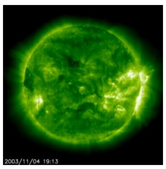
National Space Weather Program (USA)
http://www.spaceweathercenter.org/swop/NSWP/1.html

Drivers of disturbed space weather

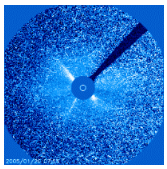
Solar eruptions — Solar corona

- Solar eruptions
  - **Magnetic Reconnection**
    - **Radiation**
      - Solar flares
    - **Particles**
      - Proton events
      - Coronal Mass Ejections
- Solar corona
  - **Solar wind**
    - **Particles**
      - Coronal Hole

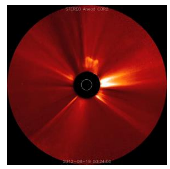
Solar flares



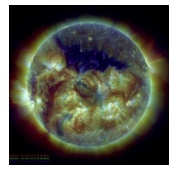
Proton events



Coronal Mass Ejections



Coronal Hole



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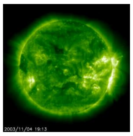
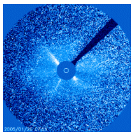
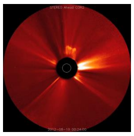
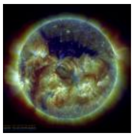
Disturbed Space weather

Causes

Solar flares	Proton events	Coronal Mass Ejections	Coronal Holes
			

	Solar flares	Proton events	Coronal Mass Ejections	Coronal Holes
Arrival	Immediately (8')	15 min to a few hours	20 to 72+ hours	2 to 4 days
NOAA scales	R1 (minor) => R5 (extreme)	S1 (minor) => S5 (extreme)	G1 (minor) => G5 (extreme)	
Parameter	M1 => $\geq$ X20	pfu (>10MeV): 10 => 10^5	Kp = 5 => Kp = 9	
Duration	Minutes to hours	Hours to days	Days	
Protection	Earth's atmosphere	Earth's magnetic field	Earth's magnetic field	

Effects

Radio communications	Satellites	Satellites	
Radar interference	Astronauts & Airplanes	Aurora	
	Communication/Navigation	Communication/Navigation	
	Ozone	Electrical Currents (GIC)	

1 pfu = 1 proton / cm^2 s sr)

Baker et al. (2016): Resource Letter SW1: Space Weather
https://ui.adsabs.harvard.edu/abs/2016AmJPh..84..166B/abstract
http://aapt.scitation.org/doi/pdf/10.1119/1.4938403

Valtonen (2004): Space Weather: Effects on Space Technology
http://slideplayer.com/slide/3603908/

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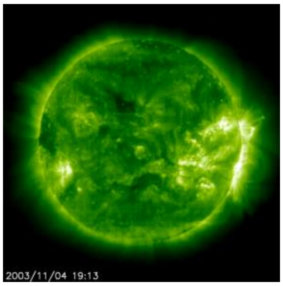
Solar flares



Effects from solar flares

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
R 5	Extreme	**HF Radio:** Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2×10^{-3})	Less than 1 per cycle
R 4	Severe	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5×10^{-5})	350 per cycle (300 days per cycle)
R 1	Minor	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

Info at:
https://www.swpc.noaa.gov/noaa-scales-explanation
SWPC: https://www.swpc.noaa.gov/phenomena/solar-flares-radio-blackouts
SWS: http://www.sws.bom.gov.au/Educational/1/3/5

Zhang et al. (2011): Impact factor for the ionospheric total electron content response to solar flare irradiation
http://onlinelibrary.wiley.com/doi/10.1029/2010JA016089/full
As one of the fastest and severest solar events, the solar flare, which is mainly classified according to the peak flux of soft X-rays in the 0.1–0.8 nm region measured on the GOES X-ray detector, has a great influence on the earth upper atmosphere and ionosphere. During a flare, the extreme ultraviolet (EUV) and X-rays emitted from the solar active region ionize the atmospheric neutral compositions in the altitudes of ionosphere to make the extra ionospheric ionization that causes many kinds of sudden ionospheric disturbance phenomenon (SID), which are generally recorded as sudden phase anomaly (SPA), sudden cosmic noise absorption (SCNA), sudden frequency deviation (SFD), shortwave fadeout (SWF), solar flare effect (SFE) or geomagnetic crochet, and sudden increase of total electron content (SITEC) [*Donnelly*, 1969; *Mitra*, 1974].

Effects from solar flares

- From EUV & X-ray radiation
  - Solar flare effect (“magnetic crochet”)
    - => Effects from ICMEs
  - Shortwave fadeout (“Radio Blackout”)
    - => PECASUS
- From radio emission
  - GNSS disturbances
  - Radar disturbances

EUV: Extreme Ultraviolet ; GNSS: Global Navigation Satellite Systems ; VLF: Very Low frequency ; MF/HF: Medium/High Frequency 9
PECASUS: Partnership for Excellence in Civil Aviation Space weather User Services

A very comprehensive discussion on the immediate effects from solar flares is at
NGDC: Sudden Ionospheric Disturbance
https://www.ngdc.noaa.gov/stp/space-weather/ionospheric-data/sids/documentation/readme_sudden-ionospheric-disturbances.pdf
https://www.ngdc.noaa.gov/stp/space-weather/ionospheric-data/sids/documentation/

Sudden Ionospheric Disturbance (after Wikipedia, 2014) – A sudden ionospheric disturbance (SID) is an abnormally high ionization/plasma density in the D region of the ionosphere caused by a solar flare. The SID results in a sudden increase in radio-wave absorption that is most severe in the upper medium frequency (MF) and lower high frequency (HF) ranges, and as a result often interrupts or interferes with telecommunications systems. The Dellinger effect, or Mögel–Dellinger effect, is another name for a sudden ionospheric disturbance. The effect was discovered by John Howard Dellinger around 1935 and also described by the German physicist Hans Mögel in 1930. The fadeouts are characterized by sudden onset and a recovery that takes minutes or hours. When a solar flare occurs on the Sun a blast of intense ultraviolet and x-ray radiation hits the dayside of the Earth after a propagation time of about 8 minutes. This high energy radiation is absorbed by atmospheric particles, raising them to excited states and knocking electrons free in the process of photoionization. The low-altitude ionospheric layers (D region and E region) immediately increase in density over the entire dayside. The ionospheric disturbance enhances VLF radio propagation. Scientists on the ground can use this enhancement to detect solar flares; by monitoring the signal strength of a distant VLF transmitter, sudden ionospheric disturbances (SIDs) are recorded and indicate when solar flares have taken place.
Short wave radio waves (in the HF range) are absorbed by the increased particles in the low altitude ionosphere causing a complete blackout of radio communications. This is called a short-wave fading. These fadeouts last for a few minutes to a few hours and are most severe in the equatorial regions where the Sun is most directly overhead. The ionospheric disturbance enhances long wave (VLF) radio propagation. SIDs are observed and recorded by monitoring the signal strength of a distant VLF transmitter. SIDs are classified in a number of ways including; ShortWave Fadeouts (SWF), Sudden Cosmic Noise Absorption (SCNA), Sudden Enhancement of Atmospherics (SEA/SDA), Sudden Phase Anomalies (SFA), Sudden Enhancements of Signal (SES), Sudden Field Anomalies (SFA) and Sudden Frequency Deviations (SFD).

Effects from solar flares

- GNSS disturbance

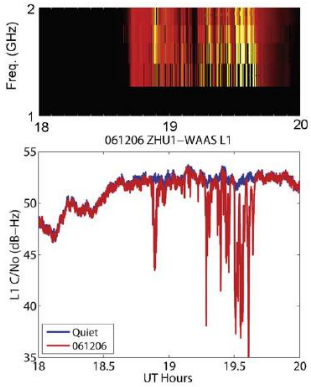


Figure 2. Response of a GPS receiver to the solar radio burst on 6 December 2006. The red line corresponds to C/N_0 on 6 December 2006, and the blue line corresponds to the previous sidereal day.

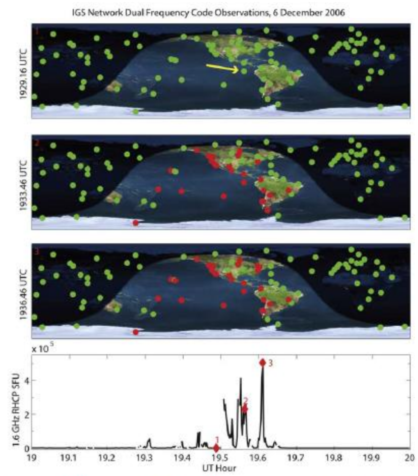
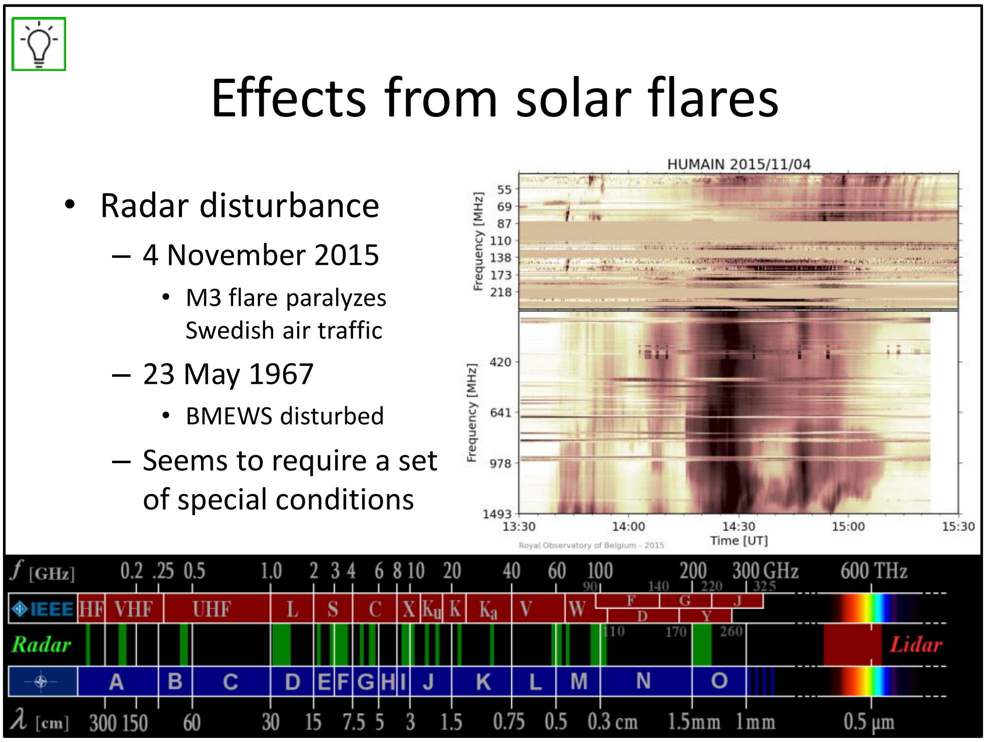


Figure 6. Receivers in the Global GPS Network that were analyzed during the solar radio burst. Green indicates the normal number of satellites being tracked. (fourth panel) During the burst (power at 1.6 GHz), several sunlit receivers tracked fewer than the four satellites needed for a full positioning solution (marked in red). (Image of Earth from the The Living Earth, 1996 and is used here by permission of the publisher. Day/night overlay created using Earth Viewer by J. Walker.)

Cerruti at al. (2008): Effect of intense December 2006 solar radio bursts on GPS receivers
https://ui.adsabs.harvard.edu/abs/2008SpWea...610D07C/abstract
Solar radio bursts during December 2006 were sufficiently intense to be measurable with GPS receivers. The strongest event occurred on 6 December 2006 and affected the operation of many GPS receivers. This event exceeded 1,000,000 solar flux unit and was about 10 times larger than any previously reported event. Prior to the events of December 2006, the record solar burst near the GPS frequencies, according to reports collected by the National Oceanic and Atmospheric Administration (NOAA), was 165,000 SFU at 1415 MHz for a SRB in April 1973. Second place was 88,000 SFU at 1415 MHz in February 1979.
The strength of the event was especially surprising since the solar radio bursts occurred near sola r minimum. The strongest periods of solar radio burst activity lasted a few minutes to a few tens of minutes and, in some cases, exhibited large intensity differences between L1 (1575.42 MHz) and L2 (1227.60 MHz). Civilian dual frequency GPS receivers were the most severely affected, and these events suggest that continuous, precise positioning services should account for solar radio bursts in their operational plans. This investigation raises the possibility of even more intense solar radio bursts during the next solar maximum that will significantly impact the operation of GPS receivers.

Figures taken from the Cerruti paper



On 4 November, NOAA 2443 produced an M3.7 flare peaking at 13:39UT. This at first sight very normal flare was associated with strong radio and ionospheric disturbances that also affected radar and GPS frequencies. As a result, Swedish air traffic was halted for about an hour during the afternoon. The air traffic problems started at the most intense phase of the radio storm, and followed right on the heels of a minor geomagnetic storm caused by the high speed stream of a coronal hole. The CME associated with the M3 flare would cause a moderate (Kp = 6) geomagnetic storm during the first half of 7 November. During the ESWW12, it was communicated that signals from some GPS satellites were affected (degradation), but that there was always a sufficient number of satellites available to assure a properly operating GPS service.

See also STCE news item at https://www.stce.be/news/326/welcome.html
and http://www.cbc.ca/news/technology/solar-storm-sweden-1.3304271
and https://phys.org/news/2015-11-sweden-solar-flare-flight.html

A full discussion of this event:
Opgenoorth et al. (2016): Solar activity during the space weather incident of Nov 4., 2015 - Complex data and lessons learned
https://ui.adsabs.harvard.edu/abs/2016EGUGA..1812017O/abstract
During the afternoon of November 4, 2015 most southern Swedish aviation radar systems experienced heavy disturbances, which eventually forced an outing of the majority of the radars. In consequence the entire southern Swedish aerospace had to be closed for incoming and leaving air traffic for about 2 hours. Immediately after the incident space weather anomalies were made responsible for the radar disturbances, but it took a very thorough investigation to differentiate disturbances from an ongoing magnetic storm caused by earlier solar activity, which had no disturbing effects on the flight radars, from a new and, indeed, extreme radio-burst on the Sun, which caused the Swedish radar anomalies.
Other systems in various European countries also experienced major radio-disturbances during this extreme event, but they were not of the gravity as experienced in Sweden, or at least not causing a similar damage. One of the problems in reaching the right conclusions about the incident was that the extreme radio-burst around 1400 UT on Nov 4 (more than 50000 SFU at GHz frequencies), emerged from a medium size M3.7 Flare on the Sun, which did not trigger any immediate warnings. We will report about the analysis leading to the improved understanding of this extreme space weather event, evaluate the importance of solar radio observations, and discuss possible mitigation strategies for future events of similar nature.

Radar figure taken from http://www.radartutorial.eu/07.waves/Waves%20and%20Frequency%20Ranges.en.html

Knipp et al. (2016) - **The May 1967 great storm and radio disruption event: Extreme space weather and extraordinary responses** -https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016SW001423
The solar radio bursts significantly disturbed the United States' Ballistic Missile Early Warning System, BMEWS for short.

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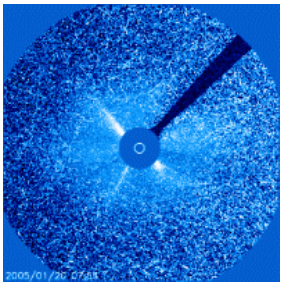
Proton events



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Effects from proton events

Scale	Description	Effect	Physical measure (Flux level of >= 10 MeV particles)	Average Frequency (1 cycle = 11 years)
S 5	Extreme	**Biological:** Unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Satellites may be rendered useless, memory impacts can cause loss of control, may cause 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 (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	**Biological:** Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	**Biological:** Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. **Satellite operations:** Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** Degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	**Biological:** Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk. **Satellite operations:** Infrequent single-event upsets possible. **Other systems:** Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	**Biological:** None. **Satellite operations:** None. **Other systems:** Minor impacts on HF radio in the polar regions.	10	50 per cycle

More info at
SWPC: https://www.swpc.noaa.gov/noaa-scales-explanation
SWPC: https://www.swpc.noaa.gov/phenomena/solar-radiation-storm

Listings of proton events:
- NOAA: https://umbra.nascom.nasa.gov/SEP/
- Shea, M. A.; Smart, D. F. (1990): A summary of major solar proton events
https://ui.adsabs.harvard.edu/abs/1990SoPh..127..297S/abstract

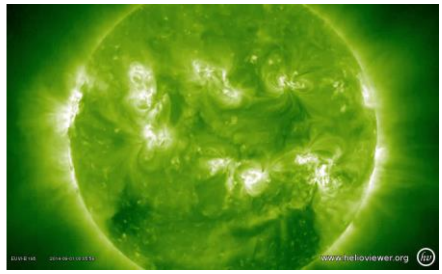
Effects from proton events

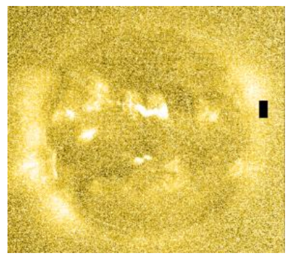
- Polar Cap Absorption (PCA)
  - => PECASUS
- Radiation
  - Astronauts, Polar flights
    - => PECASUS
- Satellites
  - Star trackers
  - Single Event Effects (SEE)
  - Solar arrays
- Ground Level Enhancement (GLE)

EVA: Extra-Vehicular Activity

Effects from proton events

- Satellites
  - Star trackers
    - Spacecraft orientation
    - Photonics noise
      - Proton « impacts »
        - » True stars?
      - Misorientation
        - » Solar panels
          - No energy
        - » Loss sun-lock
      - Data loss
        - » Gravity Probe-B





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Baker et al. (2016): Resource Letter SW1: Space Weather
https://ui.adsabs.harvard.edu/abs/2016AmJPh..84..166B/abstract
http://aapt.scitation.org/doi/pdf/10.1119/1.4938403
… Satellites can be oriented by the use of star sensors (and Sun sensors). For example, scientific satellites in orbit around Earth may need to know the Sun direction for use in interpreting data from on-board scientific instruments. Star sensors are used for scientific astronomical satellites, as well as for national security and other civil satellite purposes, such as communications. Charged particle radiation can produce false signals in the optical sensors, thus confusing the electronics—with resulting confusion of the orientation. In regions of intense radiation, such as during intervals of enhanced Van Allen belt radiation within Earth's magnetosphere, and during large solar particle events outside the magnetosphere, star and Sun sensors can be severely compromised. The design of attitude control systems usually includes automatic safing procedures as the principal mitigation action.

A good example of a proton storm induced orientation problem was on 1 September 2014 with ST-B.
See the news item at https://www.stce.be/news/266/welcome.html
https://sohowww.nascom.nasa.gov/pickoftheweek/old/05sep2014/
A far-side powerful flare erupted and triggered a huge and long-lasting proton storm that flew past the STEREO Behind spacecraft on Labor Day, Sept. 1, 2014. The storm was so strong that it temporarily confused the star trackers on both STEREO spacecraft. The "snowstorm effect" that you see was caused by high-energy particles hitting the spacecraft's detectors in the SECCHI instrument's extreme ultraviolet and inner coronagraph telescopes' (EUVI and COR1). The moment when the star tracker on Behind resets is evident when the spacecraft starts rolling. The spacecraft uses SECCHI's guide telescope to keep locked on the Sun, but depends on the star tracker to determine its roll angle. Once the star tracker came back online, the spacecraft almost immediately moved back to its correct orientation.

Gravity Probe B: https://en.wikipedia.org/wiki/Timeline_of_Gravity_Probe_B
January 2005 - A series of strong solar flares disrupted data taking for several days. On January 17 a very powerful radiation storm created multi-bit errors in the onboard computer memory, and saturated the telescope detectors so that *GP-B* lost track of the guide star. The science team, however, is confident that the temporary loss of science data will have no significant effect on the results. On January 20 the high level of proton flux was still generating "single bit errors" in *GP-B* memory, but the telescope is locked on the guide star again, and the gyroscope electronics seem to perform nominally.

Effects from proton events

- Satellites
  - Single Event Effect (SEE)
    - Direct hit of an electronic component by an energetic particle resulting in an anomaly
    - Several variations
      - SEU (bit flip), SEL, SEB,…
    - Sources
      - Galactic Cosmic Rays (GCR)
        - » DSCOVR
      - Solar proton storms
      - Radiation belts

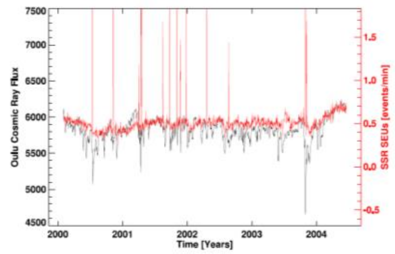
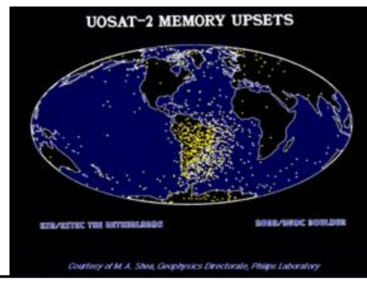


Figure 3: Subset of the data in Fig. 1 during solar maximum. The plot shows a dozen sharp spikes on top of the solar-cycle-modulated background of SSR SEUs triggered by cosmic ray hits. These spikes are caused by isolated strong SEP events. Most of them coincide with a CRF down spike.



SEU: Single Event Upset
SEL: Single Event Latchup
SEB: Single Event Burnout
DSCOVR: Deep Space Climate Observatory

Top Figure from Curdt et al. (2015): Solar and Galactic Cosmic Rays Observed by SOHO
https://ui.adsabs.harvard.edu/abs/2015CEAB...39..109C/abstract (Figure 3)

Galvan et al. (2014): Satellite Anomalies
http://www.rand.org/content/dam/rand/pubs/research_reports/RR500/RR560/RAND_RR560.pdf
Single Event Effects (SEEs) - SEEs are anomalies caused not by a gradual buildup of charge over time as with surface or internal charging, but by the impact of a single high-energy charged particle into sensitive electronic components of a satellite subsystem, this single event causing ionization and an anomaly. They typically occur because of high-energy (> 2 MeV) protons and electrons striking memory devices in the spacecraft's electronics systems, causing the spacecraft (or a subsystem) to halt operations, either temporarily or permanently (e.g., Speich and Poppe, 2000).
SEEs include "bit flips" or SEUs, where a high-energy particle imparts its charge to a solid-state memory device, causing errors in the system software, which may or may not damage hardware and can potentially be detected and repaired with error-detection-and-correction algorithms (EDACs) in the system software. One example of an EDAC is triple-modular redundancy (TMR), in which three processors perform the same calculations in parallel and then compare their answers. If one processor's answers differ from those of the other two, the "correct" two would outvote the incorrect one, and the third processor system could be rebooted or otherwise corrected, and the subsystem in general continues to operate.4 Other types of SEEs include single-event latchups (SELs), in which a subsystem hangs/crashes as a result of a high-energy particle impact. This causes the subsystem to draw excess current from the power supply, and the device must be turned off and then back on to be operable. Sometimes SEL can lead to destruction of the device if the excess drawn current is too high for the power supply. In this case, the SEE is referred to as single-event burnout (e.g., Wertz and Larson, 1999). Susceptibility to SEEs depends strongly on system design, and the risk is higher for satellites spending time in the Van Allen radiation belts or at GEO where there is a higher fluence of galactic cosmic rays and high-energy protons from Solar Proton Events (e.g., Mikaelian, 2001; Wertz and Larson, 1999;).

A good overview of the various SEE is in
Autran and Munteanu (2015) : Soft errors: from particles to circuits
https://www.researchgate.net/publication/274192779_Soft_Errors_From_Particles_to_Circuits (Fig. I.1)

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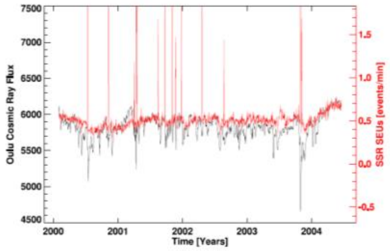
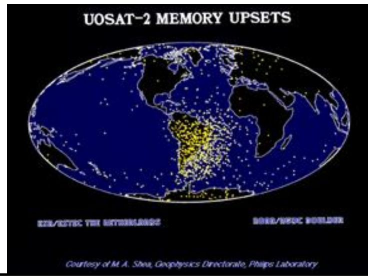


Figure 3: Subset of the data in Fig. 1 during solar maximum. The plot shows a dozen sharp spikes on top of the solar-cycle-modulated background of SSR SEUs triggered by cosmic ray hits. These spikes are caused by isolated strong SEP events. Most of them coincide with a CRF down spike.



SEU: Single Event Upset
SEL: Single Event Latchup
SEB: Single Event Burnout
DSCOVR: Deep Space Climate Observatory

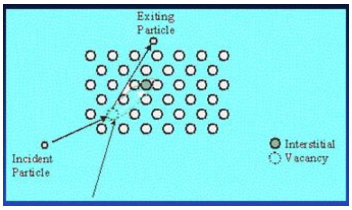
Top Figure from Curdt et al. (2015): Solar and Galactic Cosmic Rays Observed by SOHO
https://ui.adsabs.harvard.edu/abs/2015CEAB...39..109C/abstract (Figure 3)

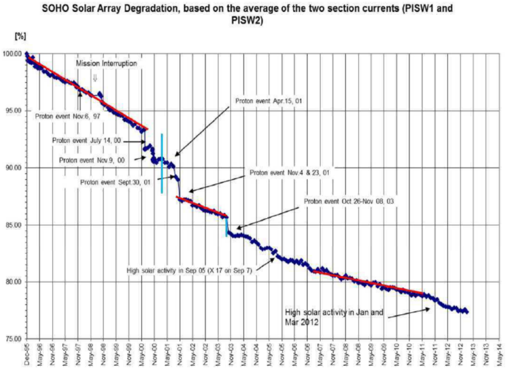
From: NOAA: Halloween Space Weather Storms of 2003
http://www.nuevatribuna.es/media/nuevatribuna/files/2016/10/28/2004_-noaa_halloweenstorms2003_assessment.pdf
CHIPS – The satellite computer went offline on 29 October and contact was lost with the spacecraft for 18 hours (loss of 3-axis control because its Single Board Computer (SBC) stopped executing). When contacted, the spacecraft was tumbling, but recovery was successful. It was offline for a total of 27 hrs.

Barbieri et al.: October--November 2003's space weather and operations lessons learned
http://onlinelibrary.wiley.com/doi/10.1029/2004SW000064/epdf
Sometimes, though the effect was undesirable and serious, it was accommodated in the mission's design: The effect was a consequence that may be considered acceptable in terms of the mission's risk tolerance. For example, the Cosmic Hot Interstellar Plasma Spectrometer (CHIPS) flies a single-board computer (SBC) that is not very radiation hardened and so is built to recover autonomously, which it occasionally has to do because of the South Atlantic Anomaly. (The South Atlantic Anomaly is the region where Earth's inner van Allen radiation belt makes its closest approach to the planet's surface. For a given altitude the radiation intensity is higher over this region than elsewhere. It is produced by a "dip" in the Earth's magnetic field at that location, caused by the fact that the center of Earth's magnetic field is offset from its geographic center by 450 km. The South Atlantic Anomaly is of great significance to satellites and other spacecraft that orbit at several hundred kilometers altitude and at orbital inclinations between 35 and 60; these orbits take satellites through the anomaly periodically, exposing them to several minutes of strong radiation each time. The International Space Station, orbiting with an inclination of 51.6, required extra shielding to deal with this problem). On 29 October the CHIPS SBC experienced a problem it could not recover from autonomously because it stopped executing. With the computer off-line the attitude control system was no longer able to maintain three-axis control, and CHIPS began tumbling. The flight operations team (FOT) responded to the anomaly by sending commands to reset the SBC, and the mission continued.

Effects from proton events

- Satellites
  - Solar Arrays
    - Displacement damage
    - Reduces efficiency in electricity production
    - Several % loss from one proton event is possible
      - 2% loss during Bastille Day event (14 July 00)
      - 5% loss during extreme 4 August 1972 event
  - Overall aging process of satellite and its instruments





Top figure taken from Valtonen (2004): Space Weather: Effects on Space Technology
http://slideplayer.com/slide/3603908/ (slide 33)

Bottom figure taken from Curdt et al. (2015): Solar and Galactic Cosmic Rays Observed by SOHO
https://ui.adsabs.harvard.edu/abs/2015CEAB...39..109C/abstract (Figure 5)
Fig. 5 shows the degradation of the solar array efficiency from Dec 1995 until Feb 2013. The total loss was ~22.5% during that time (and has reached 24% at the end of 2014). The degradation starts with a linear, continuous decrease of 0.00368% / d (1.344% per year) from launch to Jul 2000. We attribute this decrease to the CRF (Cosmic Ray Flux) during SOHO's first solar minimum. Then follows a phase of several stepwise decrements that can be associated to SEP events during the maximum of cycle 23 around 2001. Here, individual proton events start to dominate the scene. Later follow two more episodes with continuous — but less steep — decrease. Around 2002, the degradation rate is 0.00284% / d (from a starting point of 87.2%) and only 0.00168% / d (from a starting point of 82.1%) during the period from Feb 2007 to May 2011. There is no evidence for a significant solar cycle variation. It seems as if a continuous decrease of the degradation rate reduces the value by almost a factor of two. ... We speculate that in the solar arrays cells of different radiation hardness are found and that destruction of less-radiation hard cells is in progress all the time. Also, ageing effects of the cover-glass could be responsible for efficiency loss. We tried to quantify the effects of cosmic rays and the effects of SEPs during this period. In total, of the 22.5% power loss 8.5% can be attributed to proton events. Hereof, 5% occurred during a period of only 1.5 years. Altogether, 38% ± 2% of the degradation during 17 years can be attributed to proton events. In other words: the effect of a series of violent short-term events on the solar panels is comparable to the accumulated effect of the CRF over this period.

Another nice example of solar array degradation is in Hubner et al. (2012): INTEGRAL revisits Earth - Low perigee effects on spacecraft components
http://arc.aiaa.org/doi/abs/10.2514/6.2012-1291272

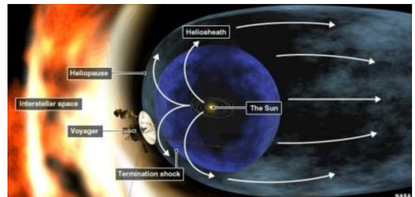
Some interesting statistics on solar array degradation provided by Intelsat:
http://www.intelsat.com/tools-resources/library/satellite-101/space-weather/

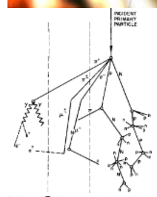
D. Knipp: On the Little-Known Consequences of the 4 August 1972 Ultra-Fast Coronal Mass Ejecta: Facts, Commentary, and Call
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018SW002024
Rauschenbach (1980) showed an ~5% drop in solar cell power generation capability for the INTELSAT IV F-2 solar panel arrays during the 4 August SEP event, roughly equivalent to 2 years of magnetospheric trapped-radiation exposure to the panels.

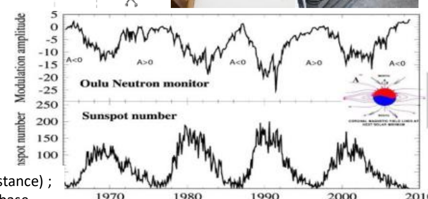
Effects from proton events

Intermezzo

- Heliosphere
  - Volume in interstellar space dominated by the solar wind
- Heliopause
  - Pressure balance between solar wind and interstellar space
  - +/- 120 AU (variable)
  - Acts as a magnetic shield against Galactic Cosmic Rays (GCR)
  - NOT particle proof
    - GCR can reach the Earth environment
      - Secondary particle shower
      - Detected on ground by neutron monitors
        - » E.g. Dourbes
    - The higher the solar activity, the less GCR can reach Earth
      - => Variation with SC







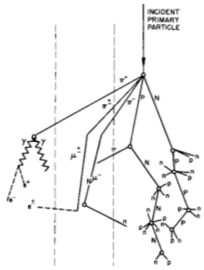
Potgieter et al. 2009

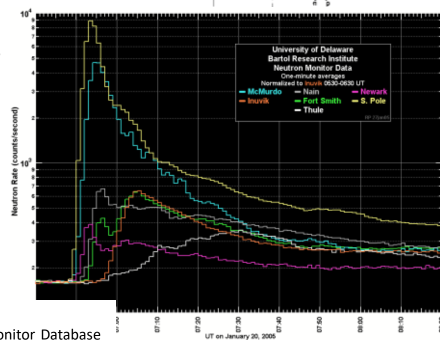
GCR: Galactic Cosmic Rays ; SC: solar cycle ; AU: Astronomical Unit (Sun-Earth distance) ; SEP: Solar Energetic Particles ; B/Gr: Background ; NMDB: Neutron Monitor Database

More info on GCR, neutron monitors,… at the following STCE Newsitems:
- Cosmic rays: https://www.stce.be/news/433/welcome.html
- GLEs and the solar cycle: https://www.stce.be/news/450/welcome.html
- Neutron counts are maxing! : https://www.stce.be/news/497/welcome.html

Effects from proton events

- Ground Level Enhancement (GLE)
  - Sharp increase of #neutrons at ground
  - Main source
    - Strong SEPs ~500 MeV/nucleon
      - X-class flares
      - Western hem.
      - Fast halo CMEs
      - => RARE!!
        - » Only 73 GLEs since the 1940s
        - » GLE#73: 28 Oct 2021
  - Thresholds GLE
    - SWPC: 10% above B/Gr GCR
      - Practice: 3% above B/Gr
    - At least 2 independent stations
  - Realtime monitoring
    - https://www.nmdb.eu/
    - List: https://gle.oulu.fi/#/





GCR: Galactic Cosmic Rays ; SC: solar cycle ; GeV: Giga electronvolt ;
SEP: Solar Energetic Particles ; B/Gr: Background ; NMDB: Neutron Monitor Database

Figure taken from Wikimedia Commons (NGDC/NOAA): https://www.ngdc.noaa.gov/stp/image/shower.gif

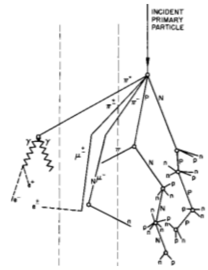
Perrone et al. (2004): **Polar cap absorption events of November 2001 at Terra Nova Bay, Antarctica**
https://ui.adsabs.harvard.edu/abs/2004AnGeo..22.1633P/abstract
The occurrence of SPE during minimum solar activity is very low, while in active Sun years, especially during the falling and rising phase of the solar cycle,
the SPEs may average one per month. It is well recognised that these solar particles have prompt and nearly complete access to the polar atmosphere via magnetic field lines interconnected between the interplanetary medium and the terrestrial field (van Allen et al., 1971). Consequently, they cause excess ionisation in the ionosphere, particularly concentrated in the polar cap, which, in turn, leads to an increase in the absorption of HF radio waves, termed polar cap absorption (PCA).
The ionisation occurs at various depths which depends on the incident particle energies, so that the ionisation in the D-region during PCA events is due mainly to protons with energy in the range of 1 to 100MeV that corresponds to an altitude between 30–80 km (Ranta et al., 1993; Sellers et al., 1977; Collis and Rietveld, 1990; Reid, 1974). Particles with even greater energies (>500 MeV) are recorded on the ground by a cosmic-ray detector; these events are called Ground Level Enhancement (GLE) (Davies, 1990).

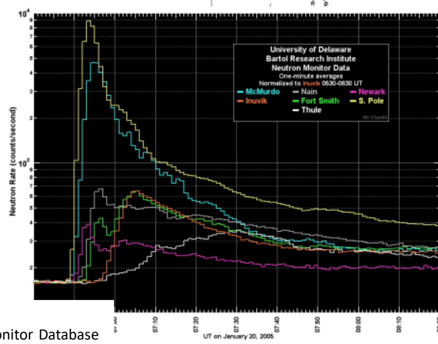
Thakur et al. (2014): Ground Level Enhancement in the 2014 January 6 Solar Energetic Particle Event
https://ui.adsabs.harvard.edu/abs/2014ApJ...790L..13T/abstract
Solar energetic particle (SEP) events, where particles accelerated to GeV energies are subsequently detected on the ground as a result of the air-shower process, are known as ground level enhancements (GLEs). With a typical detection rate of a dozen GLEs per cycle, an average of 16.3% SEP events were GLEs in cycles 19–23 (Cliver et al. 1982; Cliver 2006; Shea & Smart 2008; Mewaldt et al. 2012; Nitta et al. 2012; Gopalswamy et al. 2012a). In cycle 24, this fraction is much smaller (6.4%) with 2 GLEs out of 31 large SEP events (Gopalswamy et al. 2014). This is also much smaller than the ratio of 18% obtained when the first five years of cycle 23 are considered. GLEs are typically associated with intense flares (median soft X-ray intensity ∼X3.8) and fast coronal mass ejections (CMEs; average CME speed ∼2000 km s−1; see Gopalswamy et al. 2012a).

Usoskin et al. (2016): Database of Ground Level Enhancements (GLE) of High Energy Solar Proton Events
https://pos.sissa.it/236/054

Effects from proton events

- Ground Level Enhancement (GLE)
  - Sharp increase of #neutrons at ground
  - Main source
    - Strong SEPs ~500 MeV/nucleon
      - X-class flares
      - Western hem.
      - Fast halo CMEs
      - => RARE!!
        - » Only 73 GLEs since the 1940s
        - » GLE#73: 28 Oct 2021
  - Thresholds GLE
    - SWPC: 10% above B/Gr GCR
      - Practice: 3% above B/Gr
    - At least 2 independent stations
  - Realtime monitoring
    - https://www.nmdb.eu/
    - List: https://gle.oulu.fi/#/





GCR: Galactic Cosmic Rays ; SC: solar cycle ; GeV: Giga electronvolt ;
SEP: Solar Energetic Particles ; B/Gr: Background ; NMDB: Neutron Monitor Database

Event tresholds:

- SWPC glossary: https://www.swpc.noaa.gov/content/space-weather-glossary#groundlevelevent

ground-level event (GLE) A sharp increase in ground-level cosmic ray count to at least 10% above background, associated with solar protons of energies greater than 500 MeV. GLEs are relatively rare, occurring only a few times each solar cycle. When they occur, GLEs begin a few minutes after flare maximum and last for a few tens of minutes to hours. Intense particle fluxes at lower energies can be expected to follow this initial burst of relativistic particles. GLEs are detected by neutron monitors, e.g., the monitor at Thule, Greenland.

- Practice: List of GLE events from Gopalswamy et al. (2012): Properties of Ground Level Enhancement Events and the Associated Solar Eruptions During Solar Cycle 23 - https://ui.adsabs.harvard.edu/abs/2012SSRv..171...23G/abstract (Table 1: SC23 events)

NOTE: The 6 January 2014 event is currently not considered as a genuine GLE, despite its 2.5% increase, its increase in >700 MeV protons, and the fact that other events of similar intensity (such as e.g. 17 January 2005) barely reached 3%. Together with 4 other events in SC24, they are considered as « sub-GLEs ».
There were only 2 real GLEs during SC24 (out of 31 proton events: 6%):

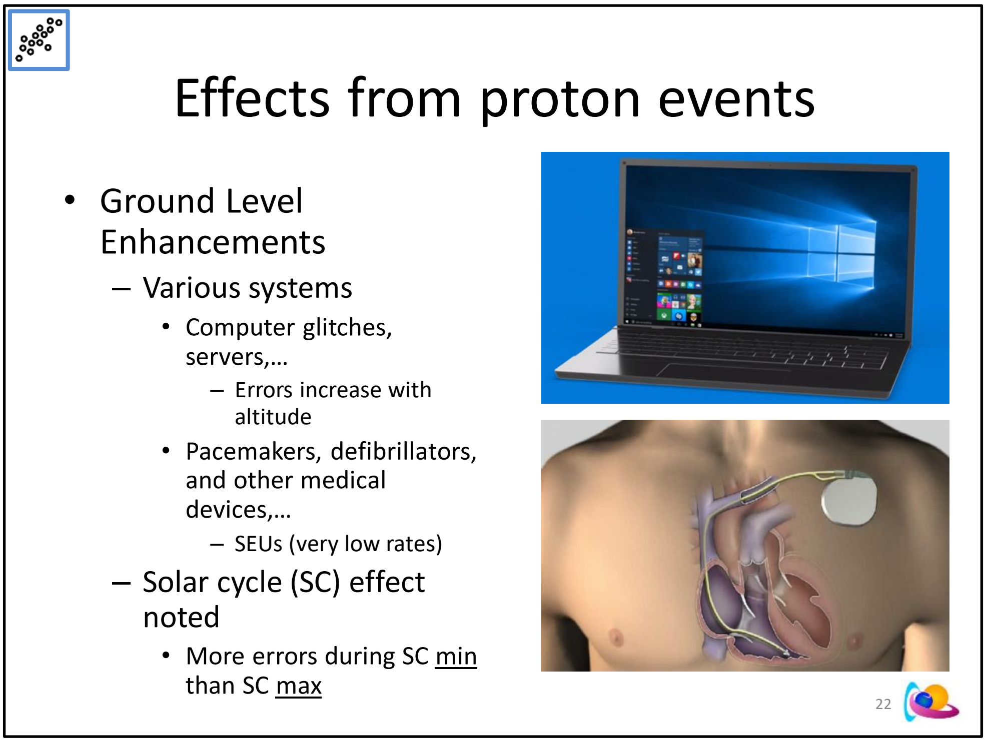
- GLE71 from 17 May 2012
- GLE72 from 10 September 2017

See the papers by Thakur (https://ui.adsabs.harvard.edu/abs/2014ApJ...790L..13T/abstract) and Gopalswamy (https://ui.adsabs.harvard.edu/abs/2013ApJ...765L..30G/abstract).
See https://gle.oulu.fi/#/ for an overview of the GLEs

There has already been 1 real GLE during SC25: GLE73 from 28 October 2021

Between January 1976 and December 2017: there have been 6333+ M-class flares and 495 X-class flares.
Only 268 proton events were recorded, and of those there were only 46 GLEs (17%)!
Since measurements started in 1942, only 72 GLEs have been recorded, the strongest in 1956.
See list at http://neutronm.bartol.udel.edu/~pyle/GLE_List.txt and at http://natural-sciences.nwu.ac.za/neutron-monitor-data

There are some good presentations on GLE and associated radiation risk from Bartols http://neutronm.bartol.udel.edu/



From the Royal Academy of Engineering (2013)
https://raeng.org.uk/media/lz2fs5ql/space_weather_full_report_final.pdf

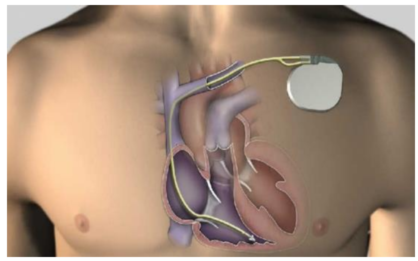
9.3 Engineering consequences of an extreme event on ground systems

The atmosphere provides considerable protection to ground level systems and for this reason this study focuses on airborne systems. Yet we know that SEEs are occasionally seen on ground systems [*normand*, 1996; *Ziegler et al.*, 1996] and are likely to be of increasing concern in the design of automotive electronics, miniaturised devices and safety-critical systems in general. Medical devices such as implantable cardiac defibrillators have been shown to give errors from cosmic rays [*bradley and normand*, 1994].

Upsets in major computing facilities correlate with altitude and, since a major server suffered significant outages and caused economic losses, certain server technologies have been tested in neutron radiation facilities [*lyons*, 2000]. In light of this evidence, safety-critical ground systems such as those in nuclear power stations should consider the impact of superstorm radiation at ground level within its electronic system reliability - and safety assessments. In the case of nuclear power a Carrington event may not be a sufficient case since relevant timescales for risk assessment may be as long as 10,000 years.

Effects from proton events

- Ground Level Enhancements
  - Various systems
    - Computer glitches, servers,…
      - Errors increase with altitude
    - Pacemakers, defibrillators, and other medical devices,…
      - SEUs (very low rates)
  - Solar cycle (SC) effect noted
    - More errors during SC min than SC max



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Pacemaker and other medical devices: http://www.solarstorms.org/SPacemakers.html

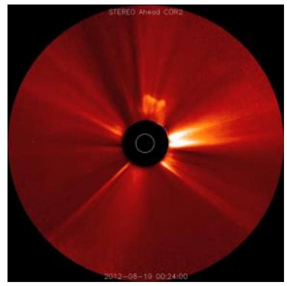
- Bradley et al. (1998): Single Event Upsets in Implantable Cardioverter Defibrillators
http://cardiacos.net/wp-content/uploads/ArticulosMedicos/20170707/1994---Single-Event-Upsets-in-Implantable-Cardioverter-Defibrillators.pdf
Also at http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/29/003/29003514.pdf
- Karnik et al. (2004): Characterization of Soft Errors Caused by Single Event Upsets in CMOS Processes
https://ieeexplore.ieee.org/document/1350778
- Santarini (2005): Cosmic radiation comes to ASIC and SOC design
http://www.edn.com/design/integrated-circuit-design/4324957/Cosmic-radiation-comes-to-ASIC-and-SOC-design
- DiCello (1989): An estimate of error rates in integrated circuits at aircraft altitudes and at sea level
https://ui.adsabs.harvard.edu/abs/1989NIMPB..40.1295D/abstract
- New Scientist (2008): Should every computer chip have a cosmic ray detector?
https://web.archive.org/web/20111202020146/https://www.newscientist.com/blog/technology/2008/03/do-we-need-cosmic-ray-alerts-for.html
- Normand (2013): Single Event Upset at Ground Level
https://web.archive.org/web/20131021190327/http://pdf.yuri.se/files/art/2.pdf
- Kobayashi (2001): Evaluation of LSI Soft Errors Induced by Terrestrial Cosmic rays and Alpha Particles
http://www.rcnp.osaka-u.ac.jp/~annurep/2001/genkou/sec3/kobayashi.pdf
- Wiki: https://en.wikipedia.org/wiki/Soft_error#cite_note-cosmicRayAlert-4
- Autran and Munteanu (2015) : Soft errors: from particles to circuits
https://www.researchgate.net/publication/274192779_Soft_Errors_From_Particles_to_Circuits (Table 1.4)

*** Stock market crash on 16 August 1989??
https://www.newscientist.com/article/mg12316812.400-solar-storms-halt-stock-market-as-computers-crash
http://www.edn.com/electronics-blogs/edn-moments/4394205/Solar-flare-impacts-microchips--August-16--1989
https://en.wikipedia.org/wiki/Solar_cycle_22#August_1989_geomagnetic_storm
http://www.solarstorms.org/SWChapter6.html
Coincided with a GLE.

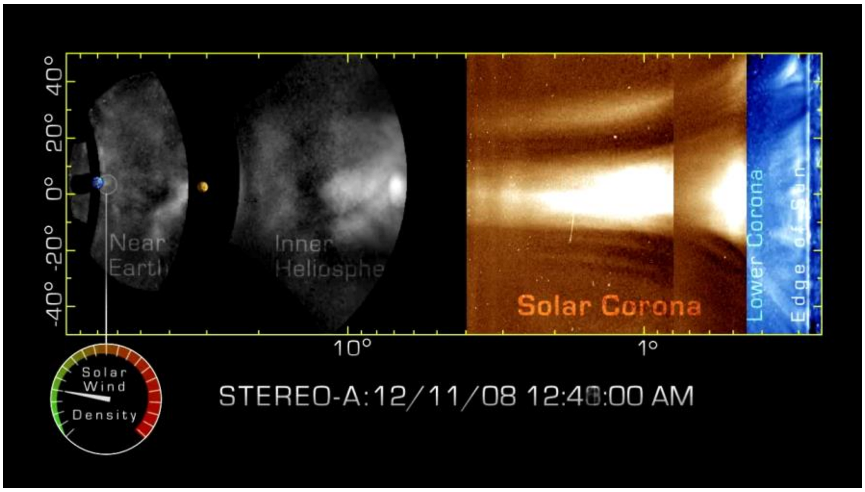
Space Weather effects (SWx effects)

- *Introduction*
- ***SWx effects from***
  - *Solar flares*
  - *Proton events*
  - ***ICMEs***
  - *Coronal holes*

Coronal Mass Ejections

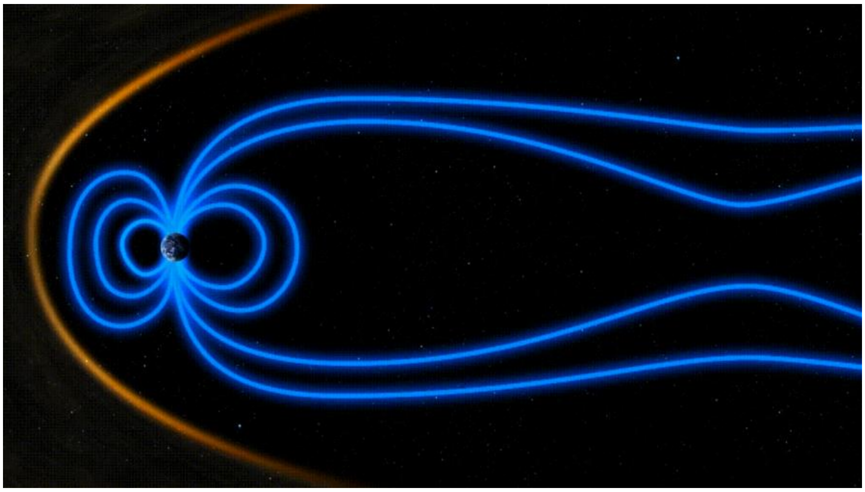


Effects from ICMEs



From the Sun to the Earth
https://www.nasa.gov/mission_pages/stereo/news/solarstorm-tracking.html
https://svs.gsfc.nasa.gov/10809

Effects from ICMEs



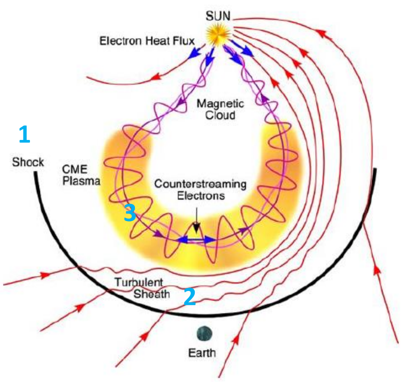
Credits: ESA

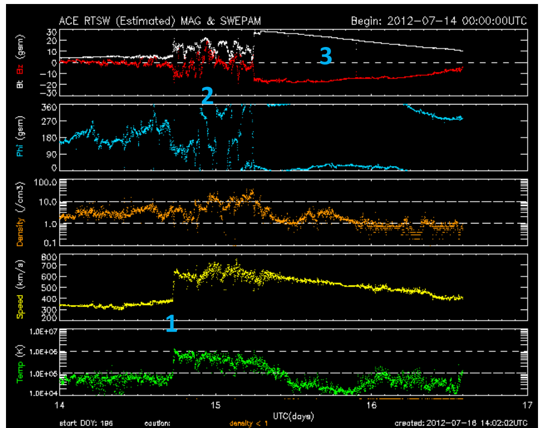
26

https://www.esa.int/ESA_Multimedia/Videos/2021/12/Magnetic_reconnection_in_Earth_s_magnetosphere

Effects from ICMEs

- Solar wind features





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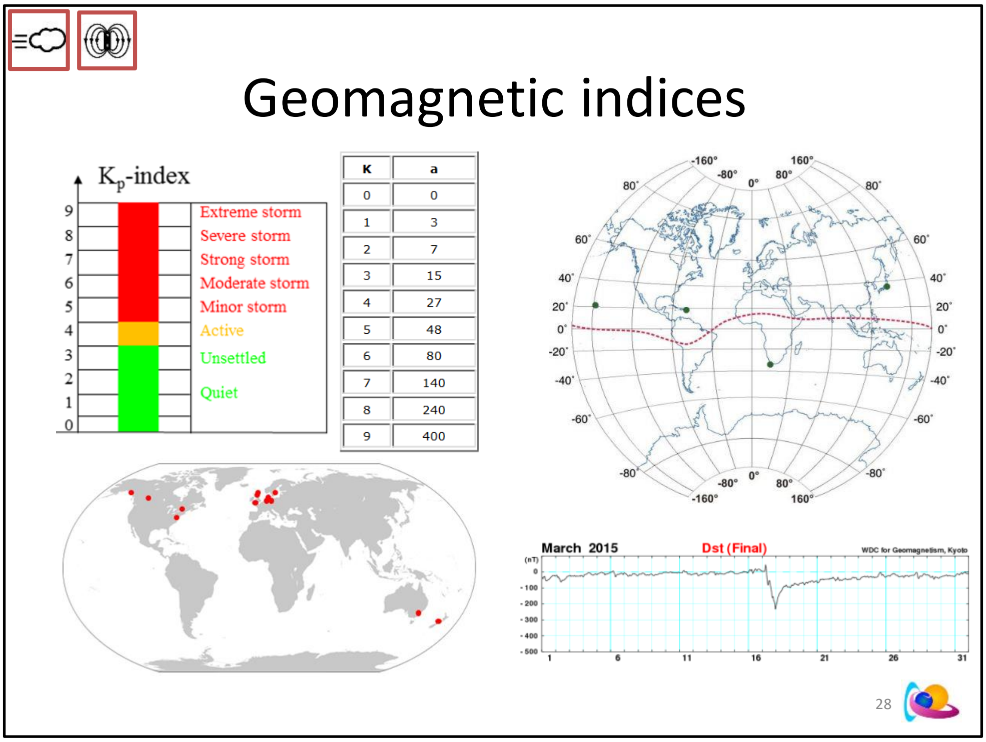
Zurbuchen et al. (2006): In-Situ Solar Wind and Magnetic Field Signatures of Interplanetary Coronal Mass Ejections
https://ui.adsabs.harvard.edu/abs/2006SSRv..123...31Z/abstract

The solar wind example is discussed at https://www.stce.be/news/150/welcome.html

On shock identification in solar wind - Scolini et al. (2018) - https://www.swsc-journal.org/articles/swsc/abs/2018/01/swsc170032/swsc170032.html
the following criteria have been applied:
Bdown/Bup ≥1.2; Np down / Np up ≥1.2; Vdown - Vup ≥ 20km·s-1;
where upstream and downstream values were calculated over a fixed time interval Dtup = Dtdown = 10 min before and after the shock.



https://www.swpc.noaa.gov/sites/default/files/images/u2/TheK-index.pdf

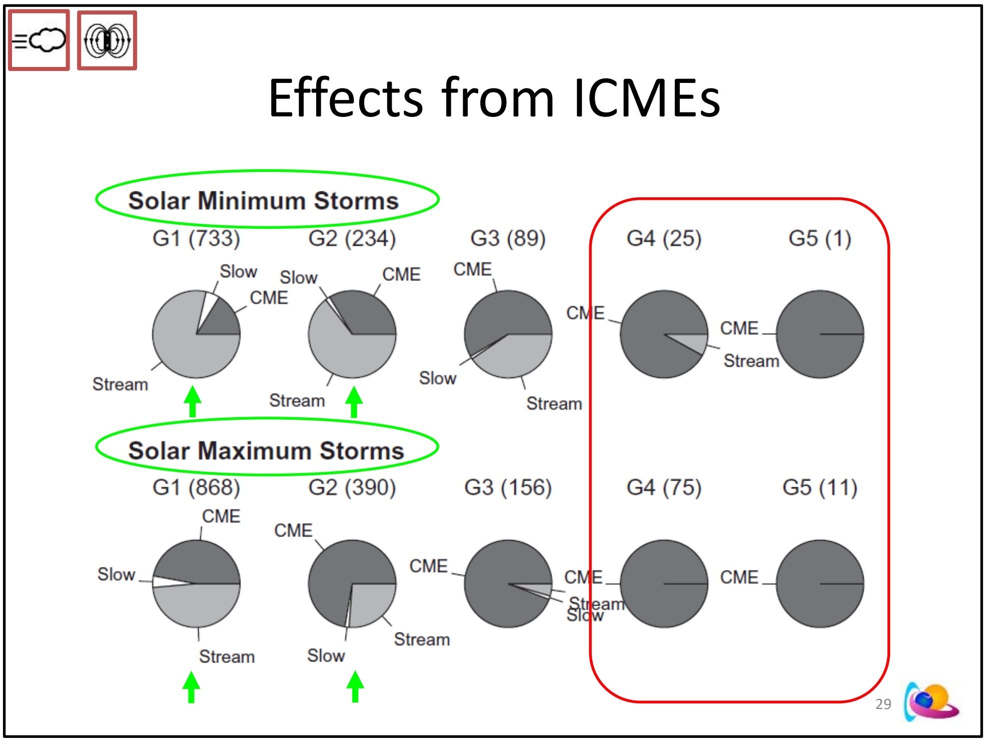
The A-index was invented because there was a need to derive some kind of daily average level for geomagnetic activity. Because of the non-linear relationship of the K-scale to magnetometer fluctuations, it is not meaningful to take averages of a set of K indices.

https://www.stce.be/news/243/welcome.html

https://www.stce.be/news/301/welcome.html

Cander et al. (1998): Forecasting ionospheric structure during the great geomagnetic storms
https://ui.adsabs.harvard.edu/abs/1998JGR...103..391C/abstract
The size of a geomagnetic storm is classified as moderate (−50 nT > minimum of Dst > −100 nT), intense (−100 nT > minimum Dst > −250 nT) or super-storm (minimum of Dst < −250 nT).

See also STCE’s SWx classification page: https://www.stce.be/educational/classification



Richardson et al. (2012): Solar wind drivers of geomagnetic storms during more than four solar cycles https://ui.adsabs.harvard.edu/abs/2012JSWSC...2A..01R/abstract

Generally, the number of CME-associated storms (black curves in Fig. 1) follows solar activity levels, as would be expected since the ICME rate at 1 AU (Richardson & Cane 2010) and the CME rate at the Sun (Robbrecht et al. 2009; Webb & Howard 1994; Yashiro et al. 2004) increase from solar minimum to solar maximum. Furthermore, Figure 1 indicates that the maximum rate of storms driven by CME associated flows approximately follows the size of the sunspot cycle, i.e. storm rates are higher in cycles 21 and 22 than in cycles 20 and 23.

Stream-associated storms … are typically most prominent for 3–4 years during the declining phase of the Cycle The solar minimum intervals are (arbitrarily) bounded by the years in which the smoothed sunspot number fell below or rose above 40 (cf. Fig. 1), i.e., 1962 (though the analysis commenced in 1964)–1966, 1973–1977, 1984–1987, 1993–1997, and 2004–2010. Thus, these results again show the different contribution of streams and CME-associated flows at solar minimum and maximum, though CME-associated flows tend to be responsible for the most severe storms throughout the solar cycle. This conclusion is consistent with other studies, such as that of Zhang et al. (2007) which found that only ~13% of intense (Dst < -100 nT) geomagnetic storms in 1996–2005 were driven by streams, while the remainder involved CME-associated flows (ICMEs and/or upstream sheaths) (see also Echer et al. 2008).

Effects from ICMEs

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

More info at
SWPC: https://www.swpc.noaa.gov/noaa-scales-explanation
https://www.swpc.noaa.gov/phenomena/geomagnetic-storms

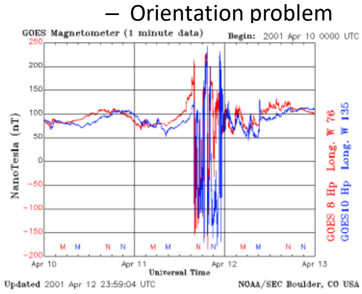
Effects from ICMEs

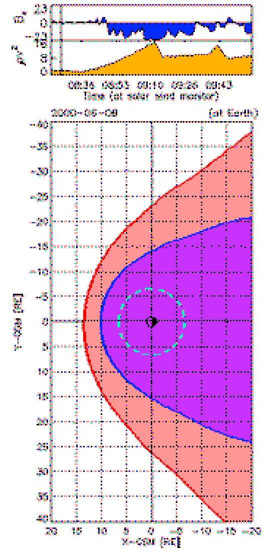
- From magnetic field
  - Satellites
    - Magnetopause crossings
  - High-Precision industry
  - GCR: Forbush decrease
- From particles
  - Satellites
    - Drag
    - Charging effects
    - Satellite-based Comms/Nav applications (GNSS)
      - => PECASUS
  - HF Communication (aviation)
    - => PECASUS
  - Geomagnetically Induced Currents (GIC)
  - Aurora

GCR: Galactic Cosmic Rays ; GNSS: Global Navigation Satellite Systems ; Comms/Nav: Communications/Navigation
PECASUS: Partnership for Excellence in Civil Aviation Space weather User Services ; HF: High Frequency

Effects from ICMEs

- Satellites
  - Magnetopause crossings
    - CME pushes magnetopause inside GEO
    - Satellites directly exposed to solar wind
      - Orientation problem





GEO: geostationary (equatorial) orbit

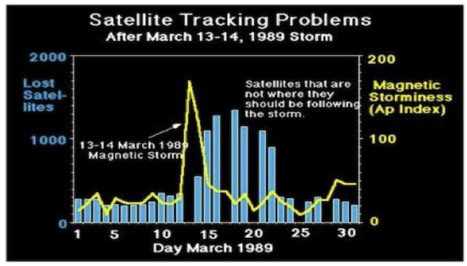
From: NOAA: Halloween Space Weather Storms of 2003
http://www.nuevatribuna.es/media/nuevatribuna/files/2016/10/28/2004_-noaa_halloweenstorms2003_assessment.pdf
Earth's magnetopause is the boundary that separates the solar wind from the region in space dominated by Earth's magnetic field. On the line between Earth and the sun, the magnetopause is typically located about 10 Earth radii from Earth's center. On the downstream side, in the midnight region, the magnetopause forms the boundary of the elongated geomagnetic tail that extends for hundreds of Earth radii. When the solar wind dynamic pressure is very large and the interplanetary field is directed southward, conditions are ripe for moving the upstream, dayside magnetopause, from its typical location to a location closer to Earth and sometimes within geosynchronous orbit (6.6 Earth radii). At these times, when geosynchronous spacecraft on the dayside become located outside of Earth's magnetic field, they encounter highly variable magnetic fields that can be directed opposite to what is normally expected. These conditions can have undesirable effects on spacecraft that use torquer currents as part of their attitude control and momentum management. Under these conditions, spacecraft operators will sometimes turn off the spacecraft torquer currents to avoid torquing against the abnormal magnetic fields. Furthermore, the plasma environment surrounding the spacecraft is altered since the plasma density is often greater when the spacecraft crosses the magnetopause.

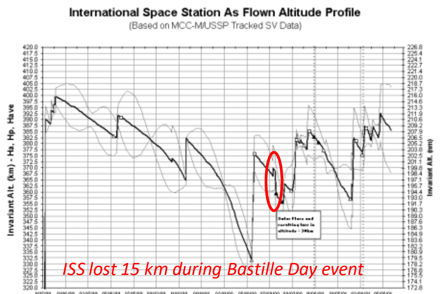
Animation from ESA/Cluster: http://sci.esa.int/cluster/36447-direct-observation-of-3d-magnetic-reconnection/
Top panel: z-component of the IMF (B_z), displayed in blue, and the dynamic pressure (ρv^2), displayed in orange, measured by the ACE spacecraft in the solar wind on 8 June 2000 (see text for details). Bottom panel: magnetopause position (blue line) and bow shock position (bright red line) estimated from the solar wind data as displayed in the top panel. Pink area between these two borders depicts the magnetosheath, while the purple area symbolises the magnetosphere. The dashed green circle, located at 6.6 R_E, depicts where many communication and weather satellites orbit the Earth.(Acknowledgments: S.M. Petrinec, Lockheed Martin)

The 8 June 2000 storm had a Kp = 7 and Dst = -90 nT.

Effects from ICMEs

- Satellites
  - Atmospheric drag
    - Low Earth Orbit (LEO)
    - Sources
      - Shortterm: ICME
        - » NOAA: Kp ≥ 6
      - Longterm: Solar EUV radiation (solar cycle)
        - » NOAA: $F_{10.7} \geq 250$ sfu
    - Slows down satellite
      - Burns up in atmosphere
    - Examples
      - March 1989
        - » 1000 satellites off-track
      - Premature mission end
        - » Solar Max, Skylab, Starlink
    - Space debris
      - Cleaned up by high solar activity





Top Image from UCAR (available at https://www.swpc.noaa.gov/impacts/satellite-drag)
ISS chart from Chad Hammons – Other charts with evolution ISS altitude: https://www.quora.com/Is-there-a-graph-showing-historical-altitudes-for-the-iss
It's easy to view the graphs and see that the ISS lost about 15 km altitude because of this one flare. [ed.: CME].

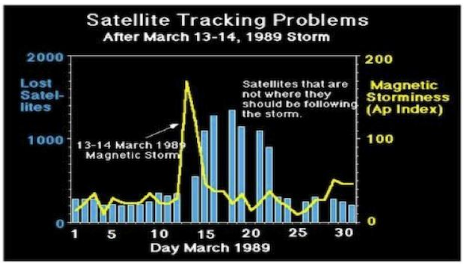
Drag: Bean (CCAR)
Usually fluctuations in the Earth's magnetic field only slightly affect the atmosphere. However, perturbations in atmospheric density under extreme conditions such as geomagnetic storms are important because it causes large orbital perturbations. Geomagnetic storms are major disturbances in the earth's magnetic field driven by strong energy input from the solar wind. Large perturbations in the solar wind velocity are supplied by sources such as coronal holes and solar flares.
[3] During a coronal mass ejection (CME), the sun spews out large amounts of solar mass consisting of charged particles including solar protons at speeds exceeding 700 km/s. A coronal mass ejection directed at the earth takes about 3-4 days to make the journey to the earth. When the charged particles reach the earth, the charged particles interact with the earth's magnetosphere. The charged particles have an electric charge so the magnetic field lines around the earth influence the charged particles. The interaction of the magnetic field with the solar wind deforms the earth's magnetic field. The effect of this interaction is the compression of magnetic field lines on the dayside and stretching of field lines on the night-side to form a comet-like tail known as the magnetotail. Some of the charged particles are trapped in the magnetic field lines and eventually enter the magnetosphere. In the magnetotail, particles can move along the magnetic field lines and precipitate into the atmosphere at the earth's poles.
[4] Atmospheric density is strongly influenced by atmospheric heating from solar extreme ultraviolet (EUV) radiation and Joule heating associated with enhancements in local ionospheric and geomagnetic field currents. Solar EUV radiation makes the strongest contribution to upper atmospheric heating. Thus, satellite drag variations are mainly driven by solar influences.

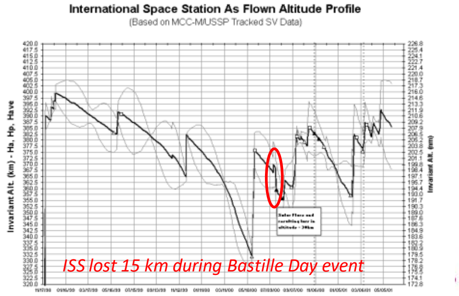
Minor storm, major impact (Starlink disaster): https://www.stce.be/news/573/welcome.html

Australian SWx forecasting center: https://www.sws.bom.gov.au/Educational/1/3

Effects from ICMEs

- Satellites
  - Atmospheric drag
    - Low Earth Orbit (LEO)
    - Sources
      - Shortterm: ICME
        - » NOAA: Kp $\geq$ 6
      - Longterm: Solar EUV radiation (solar cycle)
        - » NOAA: $F_{10.7} \geq 250$ sfu
    - Slows down satellite
      - Burns up in atmosphere
    - Examples
      - March 1989
        - » 1000 satellites off-track
      - Premature mission end
        - » Solar Max, Skylab, Starlink
  - Space debris
    - Cleaned up by high solar activity



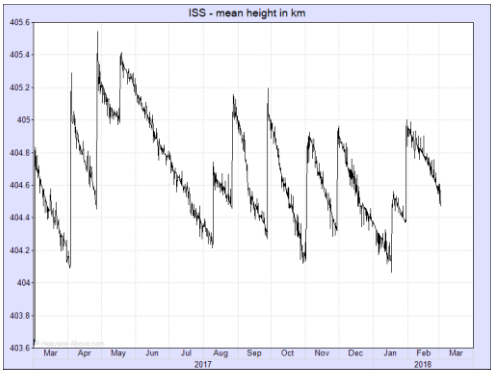


More info on space debris at SWPC: https://www.swpc.noaa.gov/impacts/satellite-drag
It is extremely important to keep track of spacecraft and objects flying in the space to avoid collisions with space junk and orbital debris that may be in their path. Collision avoidance has become of increasing concern due to the recent accidental hypervelocity collision of two intact spacecraft in February, 2009. The collision occurred at an altitude of 790 km, leaving pieces of debris that have been gradually separated into different orbital planes around the Earth, threatening other satellites for the next few decades. Since 1957, more than 25,000 artificial space debris have been cataloged (Figure 3), many of which have naturally decayed into the lower atmosphere. Currently, the U.S. Space Surveillance Network (SSN) tracks over 20,000 man-made objects larger than 10 cm in size, which are known as the “catalogued” population. Debris between 1 cm and 10 cm (approximately 500,000), referred to as the “lethal” population, are the most concerning as they cannot be tracked or cataloged and can cause catastrophic damage when colliding with a satellite. Objects smaller than 1 cm (approximately 135 million measuring from 1mm to 1cm, and many more smaller than 1 mm) that could disable a satellite upon impact are termed the “risk” population [3].

Skylab: Wiki: https://en.wikipedia.org/wiki/Skylab#After_departure
British mathematician Desmond King-Hele of the Royal Aircraft Establishment predicted in 1973 that Skylab would de-orbit and crash to earth in 1979, sooner than NASA's forecast, because of increased solar activity.[162] Greater-than-expected solar activity[165] heated the outer layers of Earth's atmosphere and increased drag on Skylab. By late 1977, NORAD also forecast a reentry in mid-1979;[161] a National Oceanic and Atmospheric Administration (NOAA) scientist criticized NASA for using an inaccurate model for the second most-intense sunspot cycle in a century, and for ignoring NOAA predictions published in 1976. Re-entry on 11 July 1979.

Also from SWPC: https://ccmc.gsfc.nasa.gov/RoR_WWW/SWREDI/2015/SatDrag_YZheng_060415.pdf (Delores Knipp; Slide 4)
Spacecraft in LEO experience periods of increased drag that causes them to slow, lose altitude and finally reenter the atmosphere. Short-term drag effects are generally felt by spacecraft <1,000 km altitude. Drag increase is well correlated with solar Ultraviolet (UV) output and additional atmospheric heating that occurs during geomagnetic storms. Solar UV flux varies in concert with the 11-year solar cycle and to a lesser degree with the 27-day solar rotation period. Geomagnetic storms are sporadic, but most major storms occur during solar maximum years.
Most drag models use radio flux at 10.7 cm wavelength as a proxy for solar UV flux. (Before long, the GOES spacecraft will have continuous UV monitoring) Kp is the index commonly used as a surrogate for short-term atmospheric heating due to geomagnetic storms. In general, 10.7 cm flux >250 solar flux units and Kp>=6 result in detectably increased drag on LEO spacecraft. Very high UV/10.7 cm flux and Kp values can result in extreme short-term increases in drag. During the great geomagnetic storm of 13-14 March 1989, tracking of thousands of space objects was lost and it took North American Defense Command (NORAD) many days to reacquire them in their new, lower, faster orbits. One LEO satellite lost over 30 kilometers of altitude, and hence significant lifetime, during this storm.

Exercise on satellite drag



- This is the evolution of the altitude of the International Space Station (ISS) in 2017. Can you distinguish a SWx effect that prematurely decreased the station's orbit? What was its source?

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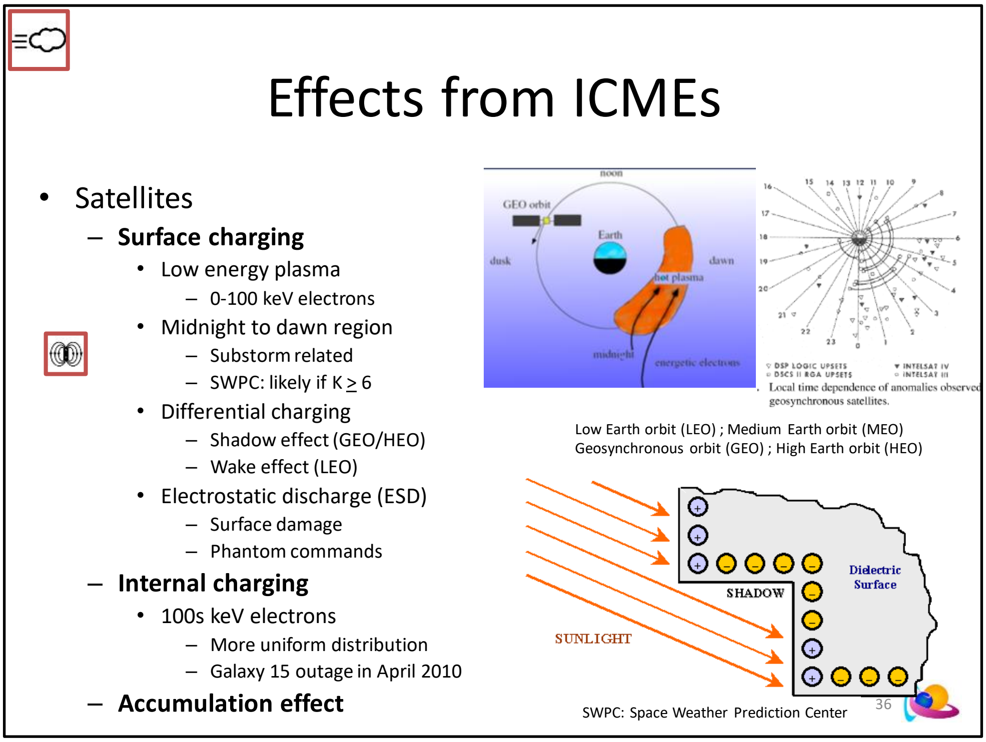
Graph: http://heavens-above.com/OrbitHeightPlot.aspx?Width=800&Height=600&satid=25544&cul=en

Calculations on drag and reboosts: https://physicsfromplanetearth.wordpress.com/2017/02/13/work-energy-and-the-satellite-drag-paradox/

Q (JJ) - Is there a reason for the 5 km drop-and-boost around 10 January 2017? There was no strong geomagnetic storm at that time. Maybe a maneuver? Thank you for the nice post.
A (Heavens above) - "It is very unlikely that there would be a sudden drop in altitude of the ISS. This would correspond to a de-boost and would be a waste of fuel under normal circumstances. In the days of the Shuttle, this was infrequently done to increase the payload capacity of the Shuttle when delivering new supplies, however, since then there have been no de-boosts as far as I know. So this was probably just a glitch in the published data, and if I look at the chart now, I can no longer see it. It has probably been corrected by Space-Track."



Topright image
Fennell et al. (2001): Spacecraft Charging: Observations and Relationship to Satellite Anomalies
https://ui.adsabs.harvard.edu/abs/2001ESASP.476..279F/abstract

2. Satellite Surface Charging

In the early 1970's, it became clear that many of the anomalies on geosynchronous satellites occurred in the near midnight to dawn region of the magnetosphere', as shown in Figure 1. This was reminiscent of the path that the hot substorm-injected electrons from the magnetotail take as they drift around the magnetosphere. Thus, it was thought that the anomalies might be substorm related and could be caused by satellite charging.

As we know, 10's of keV electrons do not penetrate the satellite surface materials but reside near the surface. The incident plasma and the solar UV also interact with materials to generate secondary electrons. The satellite's surface materials will take on a charge such that the net current between the surfaces and the plasma is zero under quiescent conditions. The result is that the surface voltages would not be zero. The sunlit areas are usually slightly positive and the shadowed areas are usually negative relative to the plasma at “infinity”. If the surface was a conductor, the potential of the surface would be uniform and either positive or negative relative to the plasma.

More info at
Dr Holbert - bottom image
Valtonen (2004): https://link.springer.com/chapter/10.1007/978-3-540-31534-6_8 (topleft image)
Gubby et al. (2002): Space environment effects and satellite design
https://ui.adsabs.harvard.edu/abs/2002JASTP..64.1723G/abstract

Also from SWPC/KSWC: https://www.spaceweather.go.kr/effect/english/07_03_01

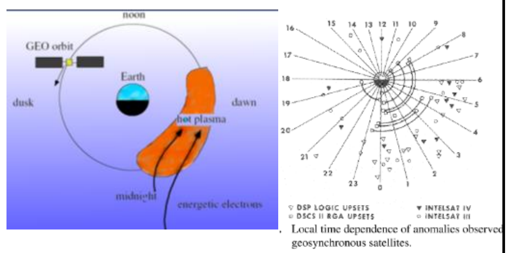
Surface Charging

Surface charging to a high voltage does not usually cause immediate problems for a spacecraft. However, electrical discharges resulting from differential charging can damage surface material and create electromagnetic interference that can result in damage to electronic devices. Variations in low energy plasma parameters around the spacecraft, along with the photoelectric effect from sunlight, cause most surface charging. Due to the low energy of the plasma, this type of charging does not penetrate directly into interior components. Surface charging can be largely mitigated through proper materials selection and grounding techniques.

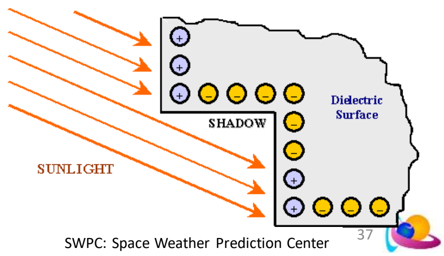
Surface charging occurs predominantly during geomagnetic storms. It is usually more severe in the spacecraft local times of midnight to dawn but can occur at any time. Night to day, and day to night transitions are especially problematic during storms since the photoelectric effect is abruptly present or absent, which can trip discharges. Additionally, thruster firings can change the local plasma environment and trigger discharges.

Effects from ICMEs

- Satellites
  - **Surface charging**
    - Low energy plasma
      - 0-100 keV electrons
    - Midnight to dawn region
      - Substorm related
      - SWPC: likely if K $\geq$ 6
    - Differential charging
      - Shadow effect (GEO/HEO)
      - Wake effect (LEO)
    - Electrostatic discharge (ESD)
      - Surface damage
      - Phantom commands
  - **Internal charging**
    - 100s keV electrons
      - More uniform distribution
      - Galaxy 15 outage in April 2010
  - **Accumulation effect**



Low Earth orbit (LEO) ; Medium Earth orbit (MEO)
Geosynchronous orbit (GEO) ; High Earth orbit (HEO)



SWPC: Space Weather Prediction Center

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The common measure for geomagnetic storms, and hence the occurrence of surface charging, is the K index. This index is a 3 hourly measure ranging from 0-9 (0=quiet, 9=severely disturbed.). It is derived from ground-based magnetometer data and is used as a surrogate for actual plasma measurements at satellite altitudes. In general, surface charging effects begin at the K=4 to K=5 level. Charging is probable at K>=6 (see Today's Space Weather). Geomagnetic substorms can be somewhat localized in space so the use of the planetary K index (Kp) may mask the severity of effect upon a specific spacecraft.

Also at STCE news item: Itchy satellites: https://www.stce.be/news/207/welcome.html

Denig et al. (2010): **Space Weather Conditions at the Time of the Galaxy 15 Spacecraft Anomaly**
https://www.ngdc.noaa.gov/stp/satellite/anomaly/2010_sctc/docs/1-2_WDenig.pdf
Solar activity was elevated but not remarkable. Global geomagnetic activity described by the AL auroral electrojet index and Kp were extreme. Other SWx indices were more moderate. Local measurements near Galaxy 15 show that a large geomagnetic substorm occurred 48 minutes prior to the anomaly. The substorm caused remarkable increases in the measured local flux of energetic particles known to cause surface or internal satellite charging.

Internal charging: Valtonen (2004): https://link.springer.com/chapter/10.1007/978-3-540-31534-6_8

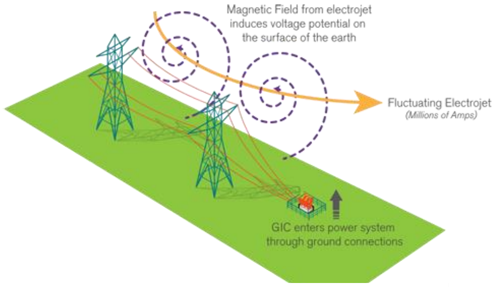
Another example of internal charging by CME is the Telstar-401 (11 January 1997):
Odenwald: http://www.solarstorms.org/SWChapter2.html
http://sdoisgo.blogspot.be/2016/06/telstar-401-ghost-of-space-weather-past.html

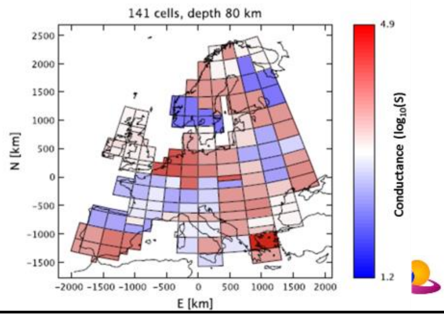
A less clear example (based more on circumstantial evidence) was the failure of the Galaxy-IV satellite, more than a week after the passage of several strong CMEs that even created a third radiation belt. The official report mentioned only technical causes, no link to the geomagnetic storms.
NASA: https://pwg.gsfc.nasa.gov/istp/outreach/events/98/
SPACECAST: http://fp7-spacecast.eu/help/bg_sa.pdf

Also at SWS: http://www.sws.bom.gov.au/Educational/1/3/2 : **Satellite Communications and Space Weather**

Effects from ICMEs

- Geomagnetically Induced Currents (GIC)
  - Electrons from magnetotail => ionospheric currents => Magnetic field => currents in crust surface
  - Affects all long conductors
    - Enters via ground connections
  - GIC depends on
    - Strength ICME
    - Geomagnetic latitude
      - Eq. Latitudes too!
    - Local conductance
    - Network details





Top figure from SPX Transformer Solutions (https://www.waukeshatransformers.com/)

Bottom figure:
Viljanen et al. (2014): Geomagnetically induced currents in Europe. Modelled occurrence in a continent-wide power grid
https://ui.adsabs.harvard.edu/abs/2014JSWSC...4A..09V/abstract
Figure 2 shows the blocks and the conductances calculated by integrating the conductivity from the surface down to 80 km. This map indicates qualitatively the expected magnitudes of the electric field. If the magnetic variation field is identical everywhere then the electric field is larger in blue areas with smaller conductivities in the top ground layers.

Carter et al. (2015): Interplanetary shocks and the resulting geomagnetically induced currents at the equator
https://ui.adsabs.harvard.edu/abs/2015GeoRL..42.6554C/abstract
Power grid infrastructure in the equatorial region is more susceptible to space weather than previously thought. The equatorial electrojet is the primary cause of this newly recognized threat, due to its ability to amplify magnetic perturbations from interplanetary shock arrivals by several fold. These d*B/*d*t* amplifications occur on the dayside for every interplanetary shock; including those that are precursors to geomagnetic storms and those that are not. While the focus of previous research on severe geomagnetic storms has been justified (given the many reports of equipment failures in the past), the present study clearly indicates that quiet geomagnetic periods must also be considered because of the influence of the electrojet at the magnetic equator.
For equatorial countries that are relying on infrastructure not designed to cope with space weather, this finding has profound implications. Given previous equipment failures reported at midlatitudes for d*B/*d*t* levels less than 100 nT/min [*Kappenman*, 2005; *Gaunt and Coetzee*, 2007], space weather impacts are likely to be a significant factor in power stability problems at the equator. As such, future studies investigating the direct impact of interplanetary shocks on equatorial power grids are strongly encouraged.

Effects from ICMEs

- GICs
  - Power grids
    - Distortions voltage pattern
    - Transformer damage
      - South-Africa, Oct 2003
    - Grid collapse
      - Québec, March 1989
    - Longterm effects of power loss!

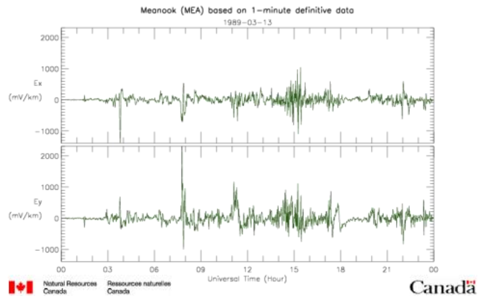


Table 3 Parameters for the GIC emergency alert model. The criterion for each alert level is shown in the second column, and the following columns show the expected extreme *dB/dt* values for RC-, AE-, and SC-type GICs

		dB/dt of GICs		
Alert level	Criterion	RC (nT/h)	AE (nT/min)	SC (nT/s)
Caution	Dst < −300 nT	100–150	2000	40–110
Warning	Dst < −600 nT	150–400	4000	40–110
Emergency	Dst < −900 nT	400–1250	6000	40–110
Transient alert	High SEP flux			40–110

Lower left figure from http://www.spaceweather.org/ISES/swxeff/5.pdf (South Africa transformers damaged)

GIC graphs available at
NR CAN: https://geomag.nrcan.gc.ca/plot-tracee/sdp-en.php
EURISGIC: http://eurisgic.org/

Kataoka et al. (2016): Extreme geomagnetically induced currents
https://ui.adsabs.harvard.edu/abs/2016PEPS....3...23K/abstract
Large-amplitude d B/d t values are the major cause of hazards associated with three different types of GICs: (1) slow d B/d t with ring current evolution (RC-type), (2) fast d B/d t associated with auroral electrojet activity (AE-type), and (3) transient d B/d t of sudden commencements (SC-type). We set "caution," "warning," and "emergency" alert levels during the main phase of superstorms with the peak Dst index of less than -300 nT (once per 10 years), -600 nT (once per 60 years), or -900 nT (once per 100 years), respectively. The extreme d B/d t values of the AE-type GICs are 2000, 4000, and 6000 nT/min at caution, warning, and emergency levels, respectively. For the SC-type GICs, a "transient alert" is also proposed for d B/d t values of 40 nT/s at low latitudes and 110 nT/s at high latitudes, especially when the solar energetic particle flux is unusually high.

Effects from ICMEs

- GICs
  - Railways
    - New York (USA), 14-15 May 1921
    - Sweden, 13-14 July 1982
    - China, 17 March & 23 June 2015
  - Pipelines
    - Corrosion
      - Oil leaks
  - Telephone/Telegraph
    - Carrington event (1859),…
    - Transcontinental cables
      - 4 August 1972
  - Transatlantic cables
    - Copper to optical fibre
      - But « optical repeaters »!
      - March 1989 event

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Top image from https://www.alyeska-pipe.com/
Bottom image from https://www.submarinecablesystems.com/history

- Railways:
Liu et al. (2016): Analysis of the monitoring data of geomagnetic storm interference in the electrification system of a high-speed railway
https://ui.adsabs.harvard.edu/abs/2016SpWea..14..754L/abstract
Wik et al. (2009): Space Weather events in July 1982 and October 2003…
https://ui.adsabs.harvard.edu/abs/2009AnGeo..27.1775W/abstract
13–14 Jul 1982: 4 transformers and 15 lines tripped in the high-voltage power system. Railway traffic lights turned erroneously to red

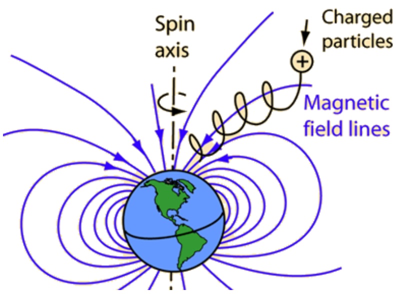
- Pipelines:
Hejda et al. (2005): Geomagnetically induced pipe-to-soil voltages in the Czech oil pipelines during October-November 2003
https://ui.adsabs.harvard.edu/abs/2005AnGeo..23.3089H/abstract
- Also at https://www.windows2universe.org/?page=/space_weather/sw_in_depth/pipeline_effects.html
- Also at NRCan: https://www.spaceweather.gc.ca/tech/index-en.php#pip

Systems affected by GIC
- GIC now! (FMI): https://space.fmi.fi/gic/
- Transatlantic cables
Medford et al. (1981): Geomagnetic induction on a transatlantic communications cable
https://ui.adsabs.harvard.edu/abs/1981Natur.290..392M/abstract
NRCan: https://www.spaceweather.gc.ca/tech/index-en.php#cab
- Transcontinental cables
Boteler et al. (1999): August 4, 1972 revisited: A new look at the geomagnetic disturbance that caused the L4 cable system outage -
https://ui.adsabs.harvard.edu/abs/1999GeoRL..26..577B/abstract

RAE (2013): Extreme space weather: impacts on engineered systems and infrastructure
https://raeng.org.uk/media/lz2fs5ql/space_weather_full_report_final.pdf
However, electric power is required to drive optical repeaters distributed along the transoceanic fibres and this is supplied by long conducting wires running alongside the fibre. These wires are vulnerable to GIC effects as was demonstrated during the geomagnetic storm of March 1989. The first transatlantic optical fibre cable, TAT-8, had started operations in the previous year and experienced potential changes as large as 700 volts [*Medford et al.*, 1989]. Fortunately the power system was robust enough to cope. Similar but smaller effects were also seen during the Bastille Day storm of July 2000 [*Lanzerotti et al.*, 2001]. We are not aware of any effects occurring during the Halloween event of 2003, but that event was relatively benign in terms of GIC effects.

Effects from ICMEs

- Aurora



© G. Gonzales, Iowa State University, Oct 2003

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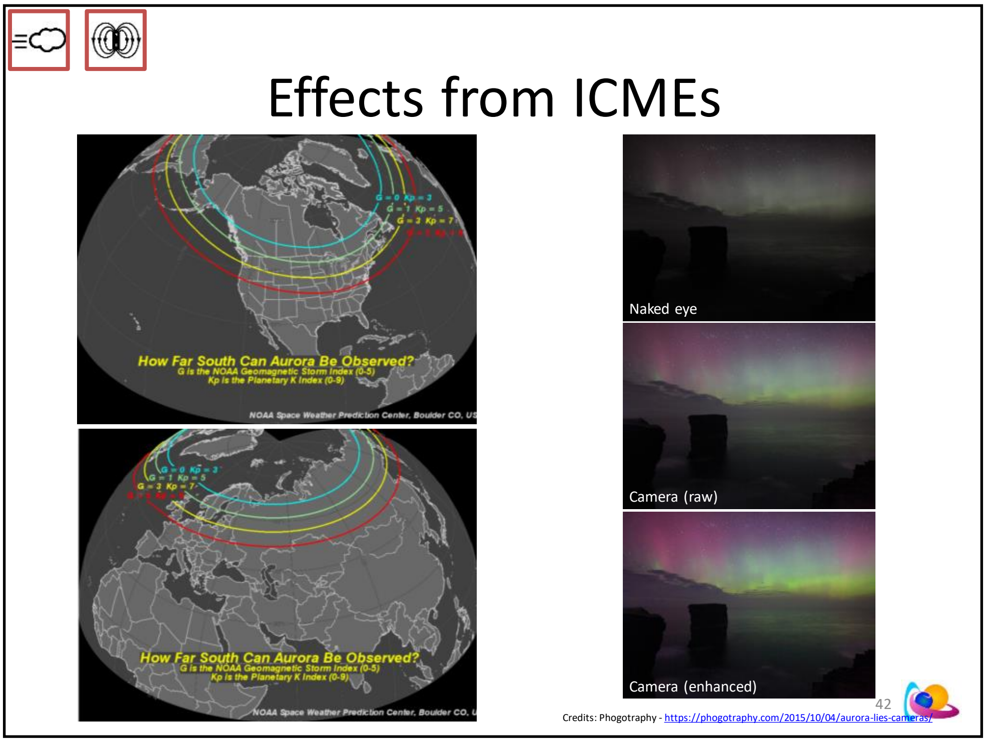
Abbott et al. (2016): New historical records and relationships among 14C production rates, abundance and color of low latitude auroras and sunspot abundance
https://ui.adsabs.harvard.edu/abs/2016AdSpR..58.2181A/abstract
Auroras are generated in the ionosphere by the excitation of specific atmospheric gas species by energetic charged particles. As the gas transitions to its normal, unexcited state, it emits energy, some in the form of visible light. Auroras have a characteristic suite of emission lines in the visible spectrum. Each emission line is associated with a transition in a specific gas species. The emission line's color reflects the energy of the transition (Fig. 1B) and its intensity depends on the flux of the exciting particles and on the excitation potential of the gas species (Fig. 1A). Many visible-light auroral emissions are due to trace gasses that require different excitation energies than major components of the atmosphere, so that some important auroral emissions do not originate with the gases N2 and O2 that compose 99% of the bulk atmosphere. Atmospheric composition varies both with elevation and time. Thus, the mix of emission lines changes, depending on the mixture of gases that are being excited, the relative intensities of excitation and the depth range of the excitation within the ionosphere. The perceived color of an aurora is determined by the response of the human visual system to the mix of emission lines.
Auroral emissions are dominated by monatomic nitrogen (N1), molecular nitrogen (N2) and molecular oxygen (O2) at altitudes of 90–150 km. From altitudes of 150 to 900 km, the most important gas is monatomic oxygen (O1). Above 900 km, the most important gases are helium (He) and monatomic hydrogen (H1) (Russell, 2005b).

Sketch from Hyperphysics: http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/aurora.html

Some comments on « red aurora »:
Spaceweather.com: http://spaceweather.com/archive.php?view=1&day=09&month=09&year=2015
Space.com: http://www.space.com/13383-spellbinding-northern-lights-display-skywatcher-photos.html



Tips on viewing the aurora:
SWPC: https://www.swpc.noaa.gov/content/tips-viewing-aurora

The average equatorward boundary of the midnight aurora is shown for levels of magnetic activity ranging from relatively low, Kp=3, to very high, Kp=9. These maps were created using satellite observations to determine the average equatorward boundary of the aurora as a function of the Kp index**. Using those data, the typical maximum extent of the aurora toward the equator for the hours around midnight for four levels of geomagnetic activity is displayed.

Another visibility chart for Western Europe: https://www.swpc.noaa.gov/products/aurora-30-minute-forecast

Visibility criteria (clear and moonless midnight, north direction without city light)

	Photographic	Visual
Belgium	Kp >= 6	Kp > 8 (9-)
Netherlands	Kp >= 5	Kp >= 7

Franky Dubois 27 February 2014 (Kp=6) : http://www.youtube.com/watch?v=_cw-tys0Ax8

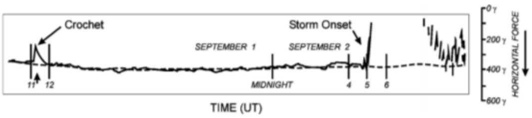
Examples (photographic from Friesland):
12 Sep 2014 (Kp=7): https://www.stce.be/news/268/welcome.html
04 Jan 2015 (Kp=5): https://www.stce.be/news/289/welcome.html

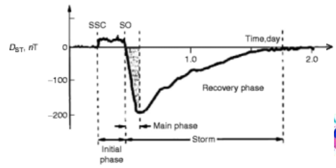
Effects from ICMEs

Rapid geomagnetic variations

- Solar flare effect (SFE)
  - Aka "magnetic crochet"
  - Source
    - Strong solar flare
      - H-α: 2B (30%)
      - X-ray: X1 (50%)
    - f(local time & latitude)
  - Examples
    - 4 Nov 2003: + 115nT
    - 1 Sep 1859: + 110nT

- Storm Sudden Commencement (SSC)
  - Sudden impulse (SI)
    - = no geomagnetic storm
  - Source
    - Dayside compression by strong ICME
    - Global, but f(local sit.)
  - Max. Amplitude: +/- 300 nT





Smith at el. (2019): **The Influence of Sudden Commencements on the Rate of Change of the Surface Horizontal Magnetic Field in the United Kingdom**
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019SW002281
Sudden commencements (SCs) are rapid increases in the northward component of the surface geomagnetic field, related to sharp increases in the dynamic pressure of the solar wind.
SCs can be further subdivided into two categories: storm sudden commencements (SSCs) and sudden impulses (SIs), which share the same physical origin (Curto et al., 2007). If the sharp increase in the *H* component is followed within a few hours by a geomagnetic storm, then it is termed an SSC, and if a storm is not initiated, then it is known as an SI.

Curto (2020): **Geomagnetic solar flare effects: a review**
https://www.swsc-journal.org/articles/swsc/full_html/2020/01/swsc190079/swsc190079.html
Solar flare effects (Sfe) are rapid variations in the Earth's magnetic field and are related to the enhancement of the amount of radiation produced during Solar flare events. They mainly appear in the Earth's sunlit hemisphere at the same time as the flare observation and have a crochet-like shape.

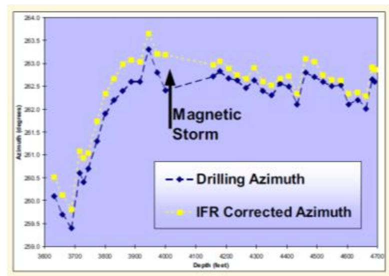
Lists of SSC and SFE can be found at the Ebre Observatory (http://www.obsebre.es/en/rapid) and at the International Service of Geomagnetic Indices (http://isgi.unistra.fr/events_sc.php)

Figures were taken from
- Cliver et al. (2005): The 1859 Solar–Terrestrial Disturbance And the Current Limits of Extreme Space Weather Activity
https://link.springer.com/article/10.1007/s11207-005-4980-z
- Lakhina et al. (2011): Supermagnetic Storms: Hazard to Society
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2011GM001073

Lakhina et al. (2016): Geomagnetic storms: historical perspective to modern view
https://geoscienceletters.springeropen.com/articles/10.1186/s40562-016-0037-4
From the deduced horizontal component magnetogram of September 1–2, 1859 from the Colaba Observatory recordings, the sudden commencement preceding the storm had an intensity of about +120 nT.

Effects from ICMEs

- High-precision industry
  - Industries depending on amplitude of magnetic field
    - magnetic anomaly surveys
    - directional wellbore drilling
  - Performance degradation
    - Mitigation possible
  - 4 August 1972
    - Vietnam: sea mine detonation



IIFR: Interpolated In-Field Referencing

Off-shore drilling: http://www.geomag.bgs.ac.uk/documents/estec_iifr.pdf

Precision drilling: ESA: http://swe.ssa.esa.int/nso_res

Watermann et al. (2007): The Magnetic Environment - GIC and Other Ground Effects
https://ui.adsabs.harvard.edu/abs/2007ASSL..344..269W/abstractThe two physically oriented categories of geomagnetic effects on technological systems concern
• systems and operations which are sensitive to the magnetic field amplitude, dB. They include magnetic anomaly surveys (e.g., aeromagnetic surveys) and
directional wellbore drilling.
• systems and operations which are sensitive to the magnetic field time derivative, dB/dt. They include electric power transmission grids, oil and gas pipelines and long-distance communication cables.
The two techno-economically oriented categories of geomagnetic effects on technological systems concern
• systems which are not directly damaged by large geomagnetic perturbations but whose operational performance degrades during geomagnetically active
times. They include magnetic anomaly surveys, directional wellbore drilling and communication via long-distance cables.
• systems which may suffer equipment damage as a result of enhanced geomagnetic activity. They include electric power transmission grids and gas and oil pipelines where the damage in the former case can be immediate and in the latter cumulative and long-term.

Also at http://swe.ssa.esa.int/TECEES/spweather/workshops/esww/proc/watermann.pdf

Also at FMI (top image)
Magnetic surveys are used for example in oil and gas exploration. The measurements concern changes of the magnetic field, so there is a problem of separating space weather-related variations from the desired spatial variations. Scheduling surveys for periods when disturbances are forecast to be small could be a solution.

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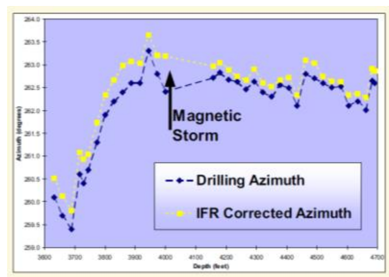
IIFR: Interpolated In-Field Referencing



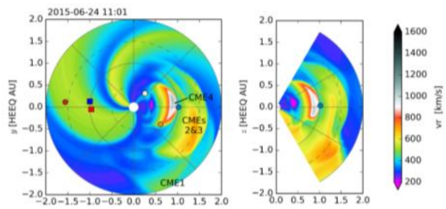
Mitigation possible:
Clark and Clarke (2001): Space weather services for the offshore drilling industry (bottom image)
https://nora.nerc.ac.uk/id/eprint/20528/
https://nora.nerc.ac.uk/id/eprint/20528/1/Clark_Clarke_ESTEC2001_SW_IIFR.pdf
The offshore oil industry use magnetic data in borehole surveying as a cheaper alternative to using gyroscopic survey tools. The technique known as
Interpolated In-Field Referencing (IIFR) has been jointly developed by BGS and Sperry-Sun Drilling Services to give accurate one-minute magnetic values at the oil well locations, enabling the technique of measurement-while-drilling (MWD) to be used.

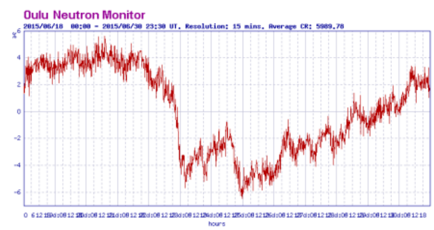
Buchanan et al. (2013): Geomagnetic referencing: The real-time compass for directional drillers
https://www.scribd.com/document/365274025/Geomagnetic-Referencing-The-Real-Time-Compass-for-Directional-Drillers
⇒ Accuracy of 0.1 to 0.01nT !!!

D. Knipp: On the Little-Known Consequences of the 4 August 1972 Ultra-Fast Coronal Mass Ejecta: Facts, Commentary, and Call
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018SW002024
Today the extreme space weather events of early August 1972 are discussed as benchmarks for Sun-Earth transit times of solar ejecta (14.6 hr) and for solar energetic particle fluxes (10 MeV ion flux >70,000 cm-2·s-1·sr-1). Although the magnetic storm index, Dst, dipped to only -125 nT, the magnetopause was observed within 5.2 RE and the plasmapause within 2 RE. Widespread electric- and communication-grid disturbances plagued North America late on 4 August. There was an additional effect, long buried in the Vietnam War archives that add credence to the severity of the storm impact: a nearly instantaneous, unintended detonation of dozens of sea mines south of Hai Phong, North Vietnam on 4 August 1972. The U.S. Navy attributed the dramatic event to *magnetic perturbations of solar storms*.

Effects from ICMEs

- Cosmic rays
  - Forbush decrease
    - Decrease in neutron count over background levels
      - Due to the passage of strong ICME / multiple ICMEs
    - Threshold: > 3%
    - Amplitude:
      - Typical: 3-20%
      - Depends on
        - » Size and # CMEs
        - » B of CME
        - » Proximity CME to Earth
        - » cut-off rigidity (GCR)
    - Gradual recovery
      - 3-10 days





B: magnetic field strength ; GCR: Galactic Cosmic Rays

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A discussion of the June 2015 events that lead to the Solstice storm (2nd strongest geomagnetic storm of SC24) can be found in the STCE Newsletter at http://www.stce.be/newsletter/pdf/2015/STCEnews20150703.pdf

Topright figure: Pomoell et al. 2018: EUHFORIA: European heliospheric forecasting information asset https://www.swsc-journal.org/articles/swsc/full_html/2018/01/swsc170062/swsc170062.html

Other important Forbush decreases discussed in these STCE news items:
- https://www.stce.be/news/353/welcome.html
- https://www.stce.be/news/288/welcome.html
- https://www.stce.be/news/339/welcome.html
- https://www.stce.be/news/561/welcome.html

The strongest Forbush decreases in SC24 were those in March 2012 and June 2015.
https://cosmicrays.oulu.fi/

SWS: http://www.sws.bom.gov.au/Geophysical/1/4
The magnetic fields entrapped in and around coronal mass ejections exert a shielding effect on the galactic cosmic radiation (GCR) which is detected by the neutron monitors. This causes a reduction in the count rate from the monitor. The reduction is typically from about 3 to 20%. The reduction occurs typically over a timescale of several hours to a few days.
Forbush decrease events must be at least 3% for a Forbush decrease alert to be issued.
The reduction in the GCR due to a coronal mass ejection (CME) is dependent upon:
- the size of the CME
- the strength of the magnetic fields in the CME
- the proximity of the CME to the Earth
- the number of CMEs
- cut-off rigidity (GCR)

Effects from ICMEs

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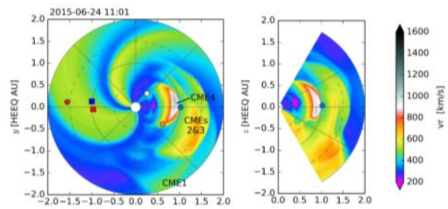

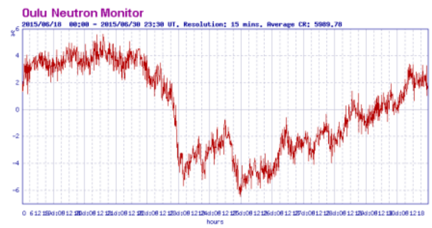

B: magnetic field strength ; GCR: Galactic Cosmic Rays

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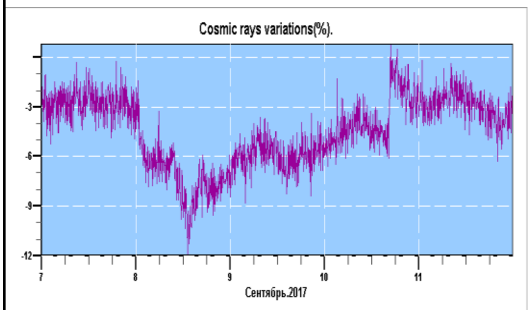
Because the reduction is dependent on three factors (rather than one), it is difficult to forecast the time from a Forbush Decrease to the arrival of a coronal mass ejection at the Earth. However, previous experience in SWS is that a Forbush Decrease is a reliable indicator of a geomagnetic storm, and that warning times of up to 24 hours or more may be made. The Forbush Decrease can be used in conjunction with other indications (e.g. coronagraph imagery) to further confirm the event. Detection of a Forbush Decrease is in use at the SWS ASFC for assistance in prediction of geomagnetic storms.

- Cane (2000): Coronal Mass Ejections and Forbush Decreases
https://ui.adsabs.harvard.edu/abs/2000SSRv...93...55C/abstract
- Lockwood (1971): Forbush Decreases in the Cosmic Radiation
https://ui.adsabs.harvard.edu/abs/1971SSRv...12..658L/abstract

Cut-off rigidity: https://spaceweather.surrey.ac.uk/
It is difficult for any electrically charged particles originating from outside of the Earth's magnetosphere to enter inside it, as they tend to be deflected away via the Lorentz force. However, the tendency to be deflected is opposed to some extent by the particles' momentum. Thus, the ability of a particle to penetrate into the geomagnetic field actually depends upon a quantity called the particle's magnetic rigidity, *P.* The rigidity parameter is extremely useful in describing the motion of particles in the geomagnetic field. This is because particles injected into the field with the same rigidity will follow identical trajectories, whereas particles with the same momentum or energy, but different charges, will not. For each point in the magnetosphere there will be a minimum rigidity (called the cut-off or threshold rigidity) required to reach that point. Particles with less rigidity than the cut-off will be deflected before they reach the point, whereas those with more than the cut-off will penetrate to it.
For a particle to penetrate the Earth's field successfully, the cut-off rigidity must be low. Thus, it is easier for particles to penetrate at high magnetic latitudes L (where cos4L is minimised) than near to the magnetic equator. The equation also shows the asymmetry in cut-off rigidity with respect to arrival direction. For example, for a positive ion, it is easiest to penetrate from the West (a = 0°). Cut-off rigidity is also inversely proportional to the square of geocentric radius. Therefore, at a given latitude, penetration to lower altitudes requires a greater rigidity. In other words, at a given latitude, the particles with the highest values of rigidity will be at the lowest altitude, and the particles of lowest rigidity will be at the highest altitude.

Exercise: Neutron counts



- These are 5-min neutron counts (%) by the OULU neutron monitor on Earth for the period 7-11 September 2017. Which of the following effects can be observed?
  - First a GLE, then a FD
  - First a FD, then a GLE
  - Only a FD
  - Only a GLE
  - No FD, no GLE

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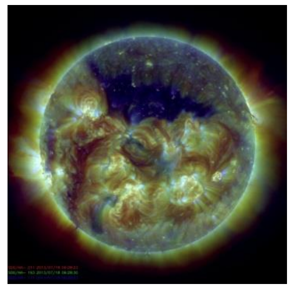
Source graph: http://cr0.izmiran.ru/oulu/main.htm
Alternative: http://www.nmdb.eu/

The FD is from a CME associated with the X9 flare from 06 September 2017, with the GLE being associated with the X8 flare (proton event – S3) on 10 September. The GLE is number 72 since measurements began in the 1940's, and only the 2nd so far this solar cycle (SC24; #71 was on 17 May 2012).

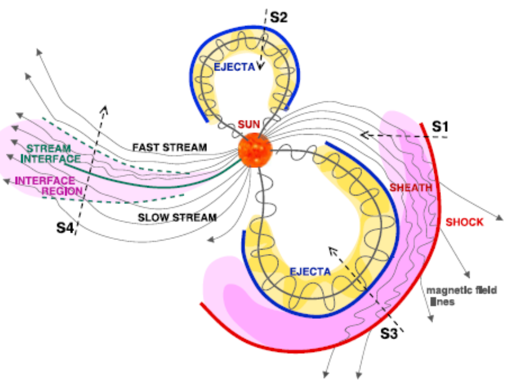
Space Weather effects (SWx effects)

- *Introduction*
- ***SWx effects from***
  - *Solar flares*
  - *Proton events*
  - *ICMEs*
  - ***Coronal holes***

Coronal Holes



Effects from CHs



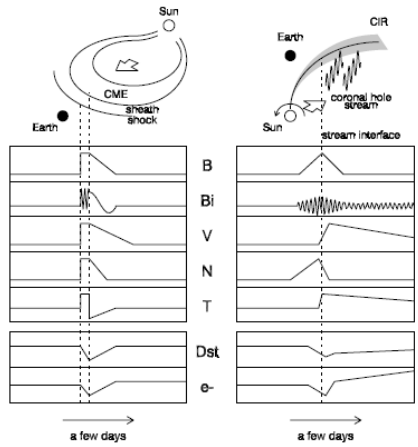


Figure 1. Schematic illustration of typical solar wind structures of coronal mass ejections (CMEs) and corotating interaction regions (CIRs): (top to bottom) magnetic field strength *B*, one of the Cartesian component B_i, solar wind speed *V*, density *N*, temperature *T*, expected response of the *Dst* index, and >2.0 MeV electron flux at geosynchronous orbit.

Topright picture
Kataoka et al. (2006): Flux enhancement of radiation belt electrons during geomagnetic storms driven by coronal mass ejections and co-rotating interaction regions
https://ui.adsabs.harvard.edu/abs/2006SpWea...4.9004K/abstract

Topleft picture
Kilpua et al. (2015).: Unraveling the drivers of the storm time radiation belt response
https://ui.adsabs.harvard.edu/abs/2015GeoRL..42.3076K/abstract

SIR/CIR
Jian et al. (2006): Properties of Stream Interactions at One AU During 1995 2004
https://ui.adsabs.harvard.edu/abs/2006SoPh..239..337J/abstract

Jian et al. (2010): http://www-ssg.sr.unh.edu/mag/JointMeet/Jian_SIRs.pdf

More info on (C)IR and SBC in this STCE News item: SBC or CIR?
https://www.stce.be/news/269/welcome.html

More info on associated shocks in this news item: Shocking news
https://www.stce.be/news/229/welcome.html

Effects from CHs

Co-rotating interaction regions (CIR)

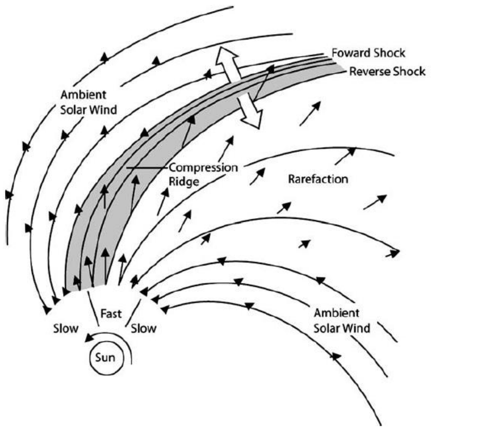
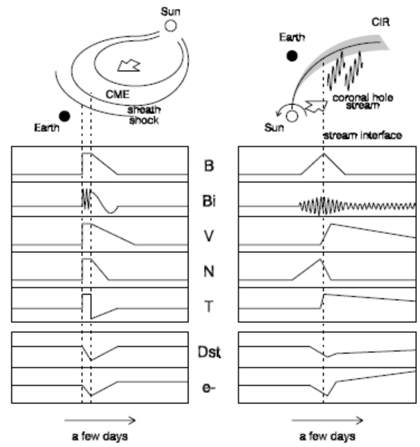


Figure 1. Schematic illustrating 2-D corotating stream structure in the solar equatorial plane in the inner heliosphere (after Pizzo, 1978).



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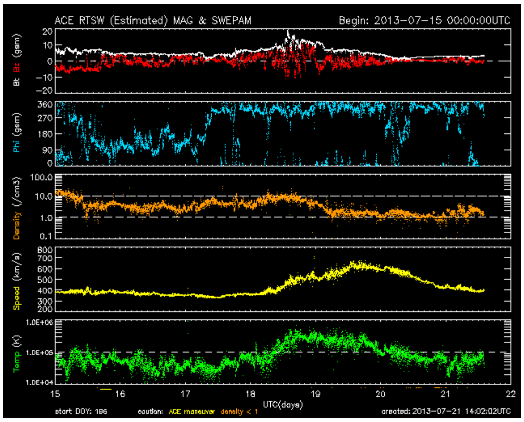

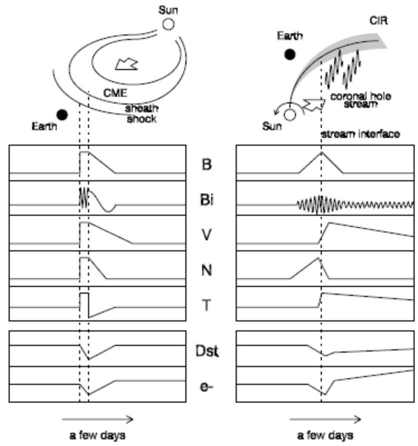

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Kataoka et al. (2006): Flux enhancement of radiation belt electrons during geomagnetic storms driven by coronal mass ejections and corotating interaction regions
https://ui.adsabs.harvard.edu/abs/2006SpWea...4.9004K/abstract

Topleft: 7 day solar wind parameter chart from ACE

SIR/CIR
Jian et al. (2006): Properties of Stream Interactions at One AU During 1995 2004
https://ui.adsabs.harvard.edu/abs/2006SoPh..239..337J/abstract

Jian et al. (2010): http://www-ssg.sr.unh.edu/mag/JointMeet/Jian_SIRs.pdf

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More info on associated shocks in this news item: Shocking news
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On shock identification in solar wind - Scolini et al. (2018) - https://www.swsc-journal.org/articles/swsc/abs/2018/01/swsc170032/swsc170032.html
the following criteria have been applied:
Bdown/Bup ≥1.2; Np down / Np up ≥1.2; Vdown - Vup ≥ 20km·s-1;
where upstream and downstream values were calculated over a fixed time interval Dtup = Dtdown = 10 min before and after the shock.

Effects from CHs

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

More info at
SWPC: https://www.swpc.noaa.gov/noaa-scales-explanation
https://www.swpc.noaa.gov/phenomena/geomagnetic-storms

Effects from CHs

- Similar to effects from ICMEs but less intense
- except…
- From particles
  - Satellites
    - **Deep di-electric charging**

GCR: Galactic Cosmic Rays ; GNSS: Global Navigation Satellite Systems ;
PECASUS: Partnership for Excellence in Civil Aviation Space weather User Services

Effects from CHs

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  - Satellite charging
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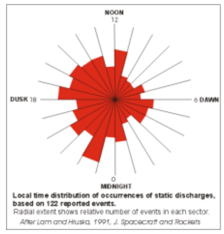
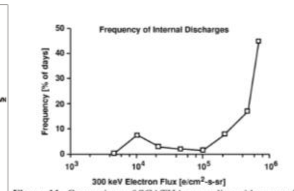
      - Also called « Internal charging »
        - » Several 100 keV to a few MeV (e^-)
        - » Penetrate S/C
        - » Accumulation effect within S/C (ESD)
        - » Dayside effect
        - » More during equinox
          - SNAP!
    - Fluxes > 2 MeV e^- (GEO)
  - CHs in declining phase SC
    - Also 1-2 days after strong ICME, e.g. 3-4 Nov 2021





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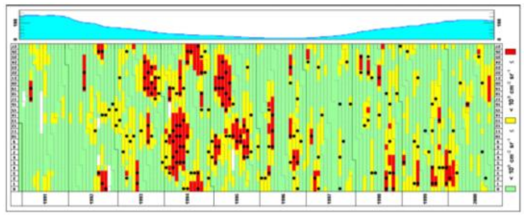

#ESDs on a GEO communications satellite

CH: Coronal hole ; e^- : electron ; S/C: spacecraft ; ESD: Electrostatic Discharge ; SNAP: Spring Negative Autumn Positive ; GEO: Geostationary orbit ; SC: Solar cycle

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Topright figure:
Fennell et al. (2001): Spacecraft Charging: Observations and Relationship to Satellite Anomalies
https://ui.adsabs.harvard.edu/abs/2001ESASP.476..279F/abstract

Bottomright figure:
Wrenn et al. (2002): A solar cycle of spacecraft anomalies due to internal charging
https://ui.adsabs.harvard.edu/abs/2002AnGeo..20..953W/abstract
The maximum of the smoothed sunspot number for cycle 22 was in July 1989; the minimum in May 1996, then heralded as the start of cycle 23, which peaked in April 2000. Each day of the years 1991 through 2000 is displayed in Fig. 1 as a traffic light presentation based on the 2-day fluences of >2MeV electrons measured at geostationary GOES satellites. The days are ordered by 27.4-day Carrington solar rotations, starting with 1837 and ending with 1971; therighthand panel plots the smoothed sunspot number on a scale from 0 to 180. Black spots mark those days on which the mode switching anomalies occurred.
The outer belt electron enhancements (OBEEs) tend to last for several days but often exhibit a 27-day recurrence that reflects the persistence of coronal holes on the Sun. Their occurrence peaks not at solar maximum, but during the declining phase when high-speed streams of solar wind are more stable and long-lived. Although there is no direct correlation, the long-lived high-speed streams do occur during 1994 and 1995, approaching solar minimum, but not near solar maximum. A few bursts and associated OBEEs are obviously non-recurrent and appear to be associated with solar proton events, or perhaps coronal mass ejections. This solar cycle pattern fits well with earlier measurements made during cycle 21 (Baker et al., 1993).
Figure 3 reinforces the main message by showing the distribution of anomalies with respect to fluence, but it also explores the significance of season by plotting the switches against displacement from equinox (the line is a simple linear fit). Since coupling between the solar wind and the magnetosphere
is easier near equinox, the electron fluences are generally higher and ESD occurrence frequency can be expected to increase.

More info in these STCE Newsitems: https://sidc.be/news/207/welcome.html , https://www.stce.be/news/463/welcome.html , https://www.stce.be/news/513/welcome.html , https://www.stce.be/news/561/welcome.html
Also at the STCE's SWx Classification page https://www.stce.be/educational/classification#electrons and the STCE's SC25 Tracking page https://www.stce.be/content/sc25-tracking#electron

An excellent discussion on how the high-energy electrons are generated is in
High-speed solar-wind streams and geospace interactions
Kavanagh, Andrew; Denton, Michael in Astronomy & Geophysics, Volume 48, Issue 6, pp. 6.24-6.26, 2007
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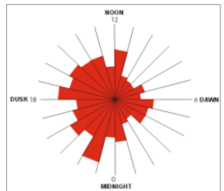
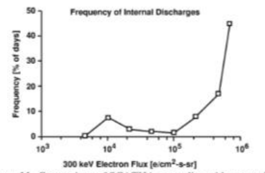


Local time distribution of occurrences of static discharges, based on 122 reported events.
Radial extent shows relative number of events in each sector.
After Lam and Hruska, 1991, J. Spacecraft and Rockets



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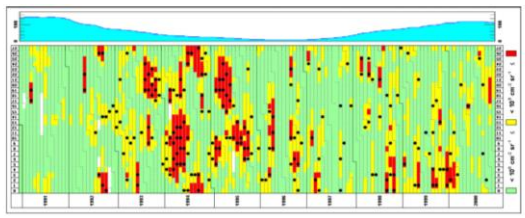

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As well as driving more obvious geomagnetic activity such as aurora, fast solar-wind streams also drive ultra-low-frequency (ULF) waves in the magnetosphere. These can transfer energy directly from the solar wind through the system to the ionosphere. These magnetic oscillations have periods ranging from 10s to 100s of seconds (known as Pc5 waves) and have been shown to depend strongly on solar-wind speed (e.g. Mathie and Mann 2000).
The production mechanism for these waves is not completely understood, but a leading candidate is the Kelvin–Helmholtz instability at the magnetopause, which can energize waveguide modes that carry pulsation power into the inner magneto-sphere and ionosphere. Recent estimates based on observations suggest that the energy can be significant in comparison with substorms (e.g. Rae et al . 2007). One important aspect of the Pc5 waves is their potential ability to accelerate electrons to relativistic energy within the outer radiation belts (e.g. Elkington et al. 1999).

Relativistic electrons
One area that is the subject of a concentrated research effort is the mechanism for generation and loss of relativistic electrons in the radiation belts. Large geomagnetic storms can have drastic effects on the population of relativistic electrons in the inner magnetosphere; this can include the creation of new radiation belts at low latitudes (e.g. Baker et al. 2004).The effect of CIRs and HSSs on the relativistic electron flux is almost as dramatic. During CIRs dramatic drop-outs occur in the electron fluxes in the outer radiation belt; this is followed by a gradual increase to above pre-CIR levels during the HSS and subsequent decay. The cause of the initial drop-out is unknown, though there is evidence to suggest enhanced precipitation (e.g. Green et al. 2004) through possible interaction with a number of different magnetospheric waves.The mechanisms for accelerating electrons to MeV energies are clearly efficient. Radial diffusion though interaction with Pc5 waves is one possible mechanism and energy diffusion by cyclotron resonance with electromagnetic whistler mode waves is another. The relative strengths of these mechanisms are currently unknown but it is clear that acceleration is enhanced during HSSs (e.g. Mathie and Mann 2000).

Also at Oulu: http://magbase.rssi.ru/REFMAN/SPPHTEXT/ulf.html
And Ham (2016): https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2016SW001492
And Spaceweather.com: https://www.spaceweather.com/archive.php?view=1&day=10&month=03&year=2020

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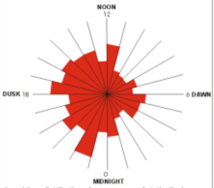

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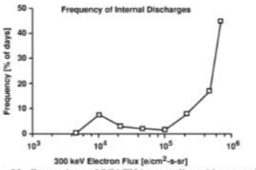

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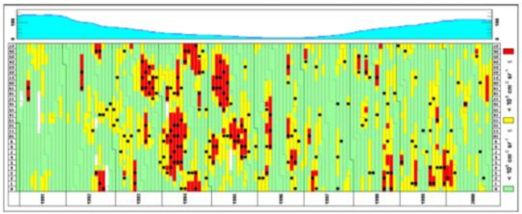

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List of effects on satellites from internal charging from:
Valtonen (2004): https://srl.utu.fi/AuxDOC/eikka/Effects_on_Tech/SpW_Effects_SpaceTech.ppt
Internal charging effects
- Discharge producing spurious signals
  - Electromagnetic transients coupling into electronics systems
    - control signals in coaxial cables
      - unintended logic changes
      - command errors
      - phantom commands
      - spurious signals
    - loss of synchronization
    - degraded sensor performance
    - damage to sensitive components connected to discharging cable
- Physical damage
  - Localised heating
  - Breakdown of thermal coatings
  - Ejection of surface material
- Difficult to distinguish from surface charging initiated discharges
  - Environmental parameters important (correlation with high-energy electron fluxes)

Failure of the ANIK-1 and -2 satellites occurred during a substorm following active to minor storming activity from a number of CHs (13-19 January). Both satellites were recovered, but at a cost of about $50-70 million, and plenty of problems for cable TV, telephone, newswire and data transfer services throughout Canada. http://www.solarstorms.org/SWChapter6.html
Leach and Alexander (1995): Failures and anomalies attributed to spacecraft charging https://ntrs.nasa.gov/search.jsp?R=19960001539

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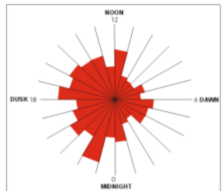

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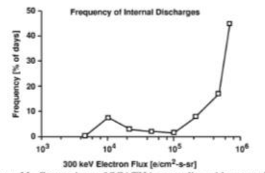

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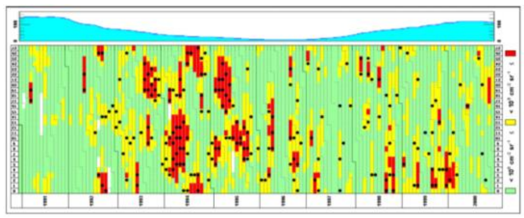

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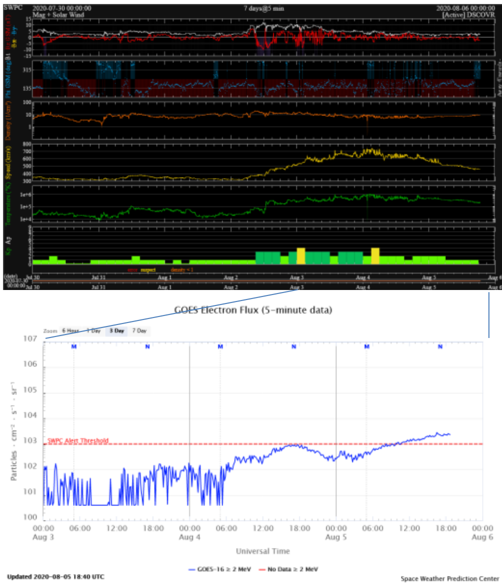
Alerts:
SWPC: https://www.swpc.noaa.gov/products/goes-electron-flux
The electron flux measured by the GOES satellites indicates the intensity of the outer electron radiation belt at geostationary orbit. Measurements are made in two integral flux channels, one channel measuring all electrons with energies greater than 0.8 million electron Volts (MeV) and one channel measuring all electrons with energies greater than 2 MeV.
Electron Event ALERTS are issued when the >2 MeV electron flux exceeds 1000 particles/(cm^2 s sr). High fluxes of energetic electrons are associated with a type of spacecraft charging referred to as deep-dielectric charging. Deep-dielectric charging occurs when energetic electrons penetrate into spacecraft components and result in a buildup of charge within the material. When the accumulated charge becomes sufficiently high, a discharge or arching can occur. This discharge can cause anomalous behavior in spacecraft systems and can result is temporary or permanent loss of functionality.

Forecast at https://www.swpc.noaa.gov/products/relativistic-electron-forecast-model
NRCan: https://www.spaceweather.gc.ca/forecast-prevision/space-spatiale/sffl-en.php
SWS: http://www.sws.bom.gov.au/Satellite/3/1
SIDC: https://www.sidc.be/

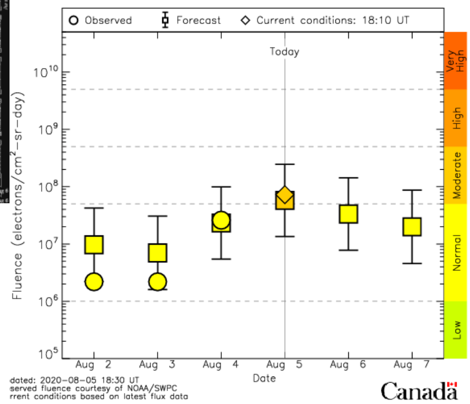
Also at Baker et al. (2004): Characterizing the Earth's outer Van Allen zone using a radiation belt content index - https://ui.adsabs.harvard.edu/abs/2004SpWea...2.2003B/abstract
Figure 7b shows the RBC index plotted as a 27-day running average from 1992 to 2001 (upper curve). Plotted below this is the 27-day running average of the solar wind speed, VSW. It is striking that the running-averaged values of VSW were significantly greater than 500 km/s only in 1994. That obviously was the time of the highest radiation belt electron content as well.

Another good website on deep di-electric charging is from the Australian Space Academy:
http://www.spaceacademy.net.au/spacelab/models/ddd.htm

Effects from CHs



HSS from 2-6 August 2020



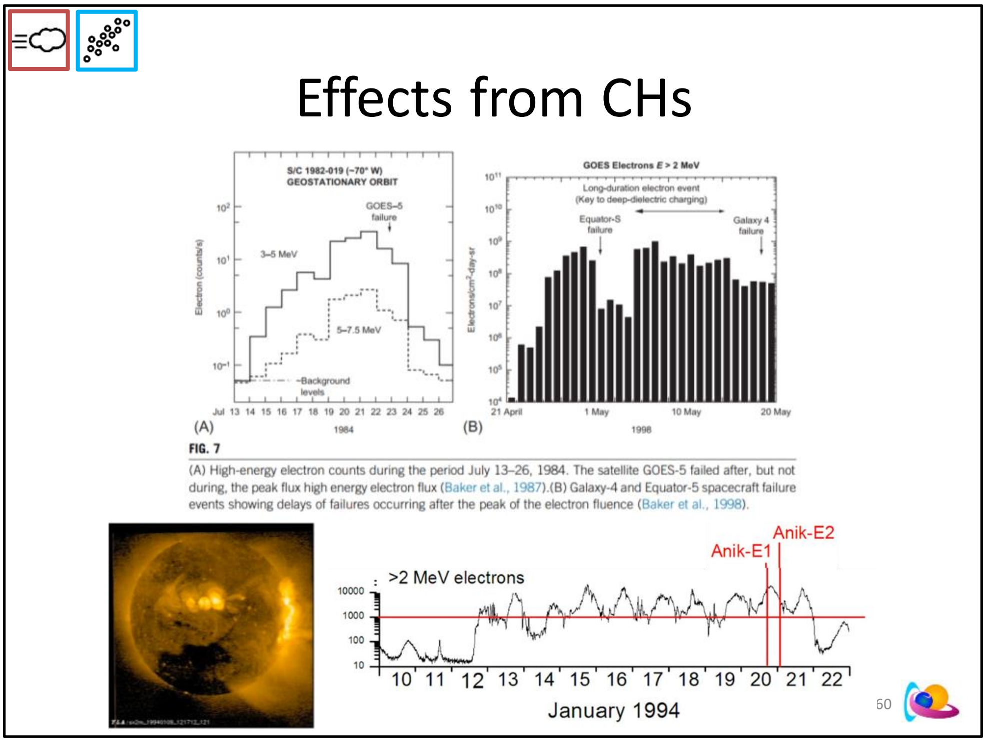


Fig. 7 from Lai et al. (2018): Deep Dielectric Charging and Spacecraft Anomalies
DOI: 10.1016/B978-0-12-812700-1.00016-9
https://www.researchgate.net/publication/323630151_Deep_Dielectric_Charging_and_Spacecraft_An
omalies

Two other figures from Lam et al. (2012): Anik-E1 and E2 satellite failures of January 1994 revisited
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2012SW000811

d 08 1231 UTC
u ntation at http://www.sidc.be/products/tot
---#
LY ON SOLAR AND GEOMAGNETIC ACTIVITY from the SIDC #
#---#
SIDC URSIGRAM 10208
SIDC SOLAR BULLETIN 08 Feb 2021, 1230UT
SIDC FORECAST (valid from 1230UT, 08 Feb 2021 until 10 Feb 2021)
SOLAR FLARES : Quiet conditions (<50% probability of C-class flares)
GEOMAGNETISM : Quiet (A<20 and K<4)
SOLAR PROTONS : Quiet
PREDICTIONS FOR 08 Feb 2021 10CM FLUX: 074 / AP: 005
PREDICTIONS FOR 09 Feb 2021 10CM FLUX: 074 / AP: 004
PREDICTIONS FOR 10 Feb 2021 10CM FLUX: 075 / AP: 004
COMMENT: Solar activity was at very low levels. No numbered sun spots were observed on the solar disc. No significant flares were detected in the last 24 hours and none are expected in the next 24 hours. No Earth-directed coronal mass ejections (CMEs) were detected in the available coronagraph imagery.

Finding your way in the URSIgram

The greater than 10 MeV proton flux was at nominal levels in the past 24 hours and is expected to remain so in the next 24 hours. The greater than 2MeV electron flux remained under the 1000 pfu threshold and is expected to remain so in the next 24 hours. The 24h electron fluence was at nominal levels and is expected to remain so, although slight increase is possible due to the influence of the HSS currently affecting the Earth.

Over the past 24 hours the solar wind conditions (ACE and DSCOVR) started to recover from the HSS which arrived to the Earth on Feb 6th. The total magnetic field varied between 0.8 nT an 6 nT and its Bz component weakly oscillated between -4 nT and 4 nT. The phi angle was predominantly positive reflecting the polarity of the coronal hole affecting the Earth. The solar wind speed showed a gradual decreased from 550 km/s to 410 km/s as the effect of the HSS starts to wane.

The geomagnetic conditions over the past 24 hours were predominantly quiet with several unsettled periods and two isolated locally active conditions with K Dourbes equal to 4. Mostly quiet conditions are expected in the next 24 hours as the influence of the HSS continues to wane. Isolated unsettled to active periods remain possible.

TODAY'S ESTIMATED ISN : 000, BASED ON 09 STATIONS.
99999

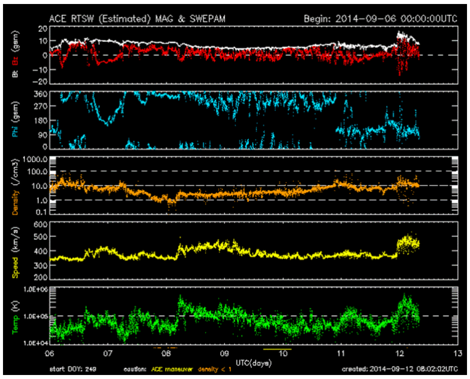
≥ 2MeV electron flux & fluence

SOLAR INDICES FOR 07 Feb 2021
WOLF NUMBER CATANIA : ///
10CM SOLAR FLUX : 073
AK CHAMBON LA FORET : 016
AK WINGST : ///
ESTIMATED AP : 022
ESTIMATED ISN : 000, BASED ON 08 STATIONS.

NOTICEABLE EVENTS SUMMARY
DAY BEGIN MAX END LOC XRAY OP 10CM Catania/NOAA RADIO_BURST_TYPES
NONE
END

Effects from SBC

- Sector Boundary Crossing (SBC)
  - Change IMF phi angle
    - Towards Sun <> Away Sun
    - Negative sector <> Positive sector
    - +/- 315° <> +/- 135°
  - Usually no (abrupt) change in SW speed
  - Little geomagnetic effect



IMF: Interplanetary Magnetic Field ; SW: solar wind

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SIR/CIR
Jian et al. (2006): Properties of Stream Interactions at One AU During 1995 2004
https://ui.adsabs.harvard.edu/abs/2006SoPh..239..337J/abstract

Jian et al. (2010): http://www-ssg.sr.unh.edu/mag/JointMeet/Jian_SIRs.pdf

More info on (C)IR and SBC in this STCE News item: SBC or CIR?
https://www.stce.be/news/269/welcome.html

More info on associated shocks in this news item: Shocking news
https://www.stce.be/news/229/welcome.html

Fennell et al. (2001): Spacecraft Charging: Observations and Relationship to Satellite Anomalies
https://ui.adsabs.harvard.edu/abs/2001ESASP.476..279F/abstract

Summary SWx effects (1/2)

- **Solar flares**
  - NOAA scale (R)
  - From EUV & X-ray radiation
    - Solar flare effect
      - "magnetic crochet"
      - => Effects from ICMEs
  - Shortwave fadeout
    - "Radio Blackout"
    - => PECASUS
  - From radio emission
    - GNSS disturbances
    - Radar disturbances

- **Proton events**
  - NOAA scale (S)
  - Polar Cap Absorption (PCA)
    - => PECASUS
  - Radiation
    - Astronauts, Polar flights
    - => PECASUS
  - Satellites
    - Star trackers
    - Single Event Effects (SEE)
    - Solar arrays
  - Ground Level Enhancement (GLE)

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Summary SWx effects (2/2)

- **ICMEs**
  - NOAA scale (G)
  - From magnetic field
    - Satellites
      - Magnetopause crossings
    - High-Precision industry
    - GCR: Forbush decrease
  - From particles
    - Satellites
      - Drag
      - Charging effects
        - » Electrostatic Discharges (ESD)
      - Satellite-based Comms/Nav applications (GNSS)
        - » => PECASUS
    - HF Communication (aviation)
      - => PECASUS
    - Geomagnetically Induced Currents (GIC)
    - Aurora

- **Coronal Holes**
  - NOAA scale (G)
    - Impacts similar but less severe than with (strong) ICMEs
    - Especially during the declining phase of Solar Cycle
    - SNAP (Spring - Autumn +)
  - Satellites
    - Deep di-electric charging