Tractebel

Space Weather Training Course

Jan Janssens
Solar-Terrestrial Centre of Excellence

21 October 2019

Hullie
MichelvGiersbergen - hoogspanningsforum.net

Overview

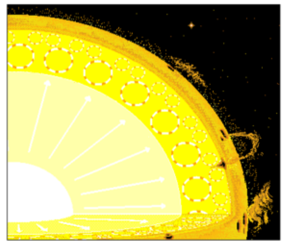
- Introduction
- Drivers of SWx
- SWx effects
- Extreme events
- URSIgram

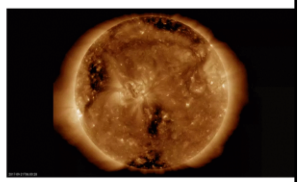
Introduction

Jan Janssens

The Sun is a star

- Large & heavy
- Closest star to Earth
  - +/- 150 million km
    - *1 Astronomical Unit*
- Hot
  - Interior: 15 million degrees
  - Surface: +/- 6000 degrees
  - Corona: 2-3 million degrees
    - ***Plasma (charged particles)***
    - ***Coronal holes***
- Radiating
  - Total Solar Irradiance
    - *1362 W/m^2*





Source of:	Earth protected by:
Radiation: over the entire EM spectrum	Its atmosphere
Particles: ***Solar Wind***	Its magnetic field

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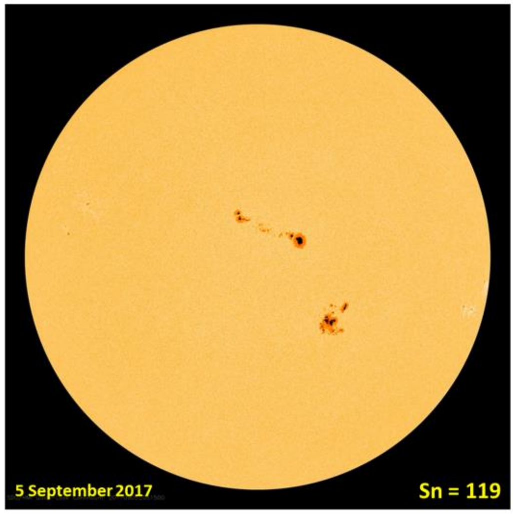
The Sun is a star
Radiating
3,84 * 10^{26} Watt
= 1362 W/m^2 at Earth
Big
1.392.000 km (109 * D_E)
Heavy
1,99 * 10^{30} kg (332.980 * M_E)
Closest star
149.597.870 km
= 1 Astronomical Unit
The solar interior:
Core (R = +/- 175.000 km)
Energy production (proton-proton cycle)
Radiation zone (325.000 km)
Energy transport thru radiation
Convection zone (200.000 km)
Energy transport thru convection
The solar atmosphere
Photosphere
The “solar surface” ; The Sun in visible light
Chromosphere (very thin)
Prominences
The Corona
The Sun’s outer atmosphere, as visible during a solar eclipse
Very hot!

The Sun is a variable star

- Sunspots
  - Magnetic disturbances on the Sun
  - Sources of solar eruptions
- Sunspot number (Sn)
  - Sn = 10.g + s,
    - with g the number of groups, and s the number of spots
  - Determined by the SIDC/SILSO (Uccle)!
    - http://www.sidc.be/silso
    - Network of about 80 stations



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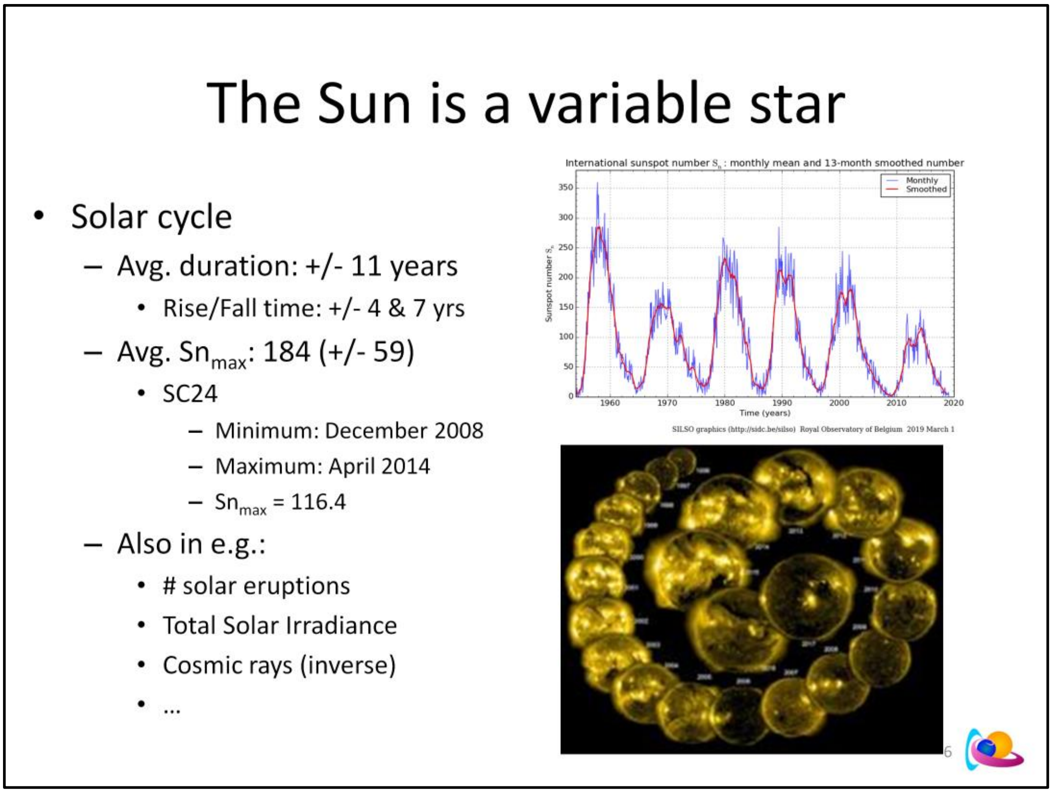
Links
SILSO: http://sidc.oma.be/silso/ (Sunspot Index and Long-term Solar Observations)
USET: http://www.sidc.be/uset/ (Uccle Solar Equatorial Table)
Catania: http://web.ct.astro.it/sun/draw.jpg

The International sunspot number is a quantity that measures the number of sunspots and groups of sunspots present on the surface of the sun.
It is computed from a number of international observers using the formula:

$$R = k\,(10\,g + s)$$

where

s is the number of individual spots,
g is the number of sunspot groups, and
k is a factor that varies with location and instrumentation (also known as the observatory factor or the personal reduction coefficient). It is not to be computed or applied by the observer.



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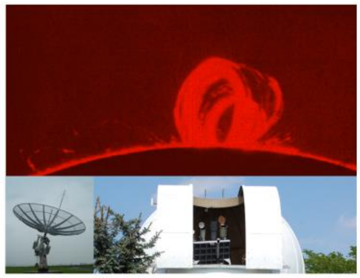
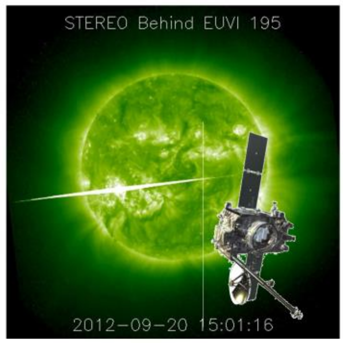
Observations

- From ground:
  - White light
  - Radio window
  - Magnetometer, GNSS,…
- From space:
  - EUV and X-ray
    - solar atmosphere
    - solar eruptions
    - At various « temperatures »
  - Coronagraphs
  - Radio
    - Low frequencies
  - White light (24hrs)
  - Solar wind (in-situ)
  - …





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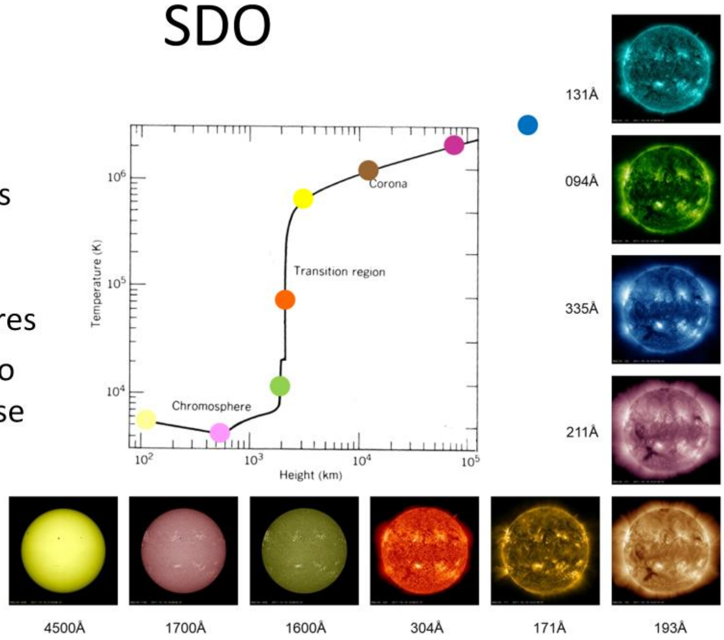
More on the 20 September 2012 flare at http://www.stce.be/news/263/welcome.html

SDO

- AIA
  - Some filters peak at multiple temperatures
  - AIA 4500 no longer in use



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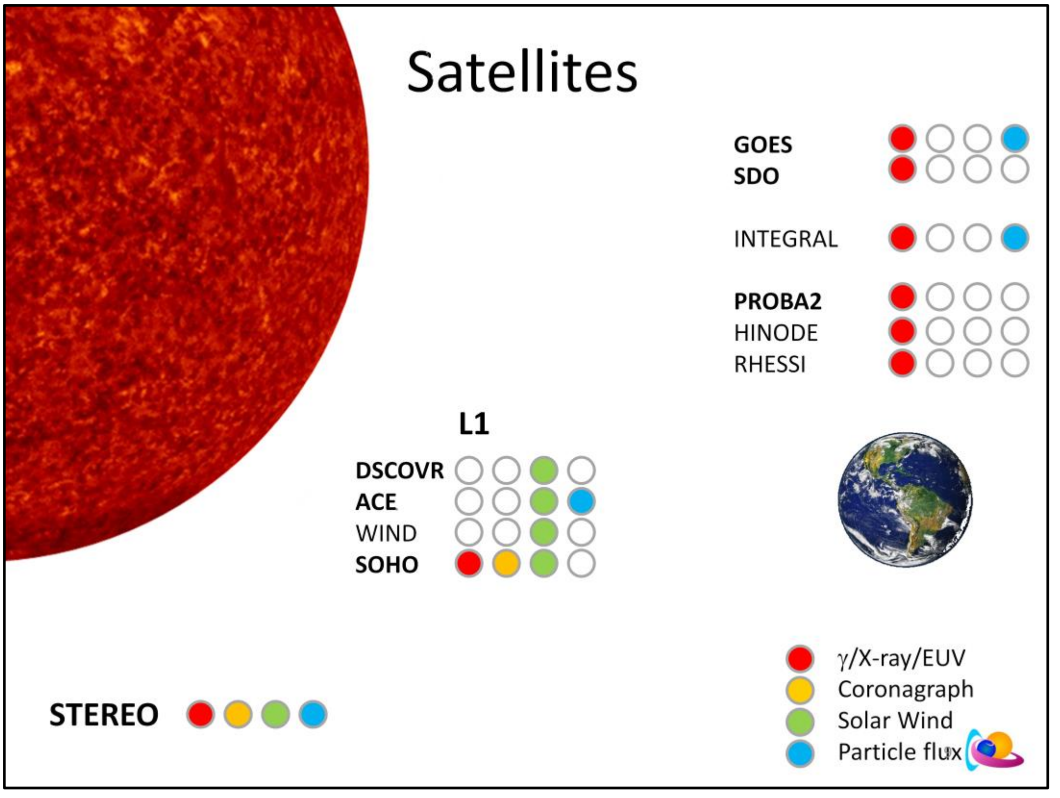
More info at http://aia.lmsal.com/public/instrument.htm
And at https://www.nasa.gov/content/goddard/how-sdo-sees-the-sun



Lagrangian points: https://en.wikipedia.org/wiki/Lagrangian_point

Earth orbits: https://en.wikipedia.org/wiki/List_of_orbits#Altitude_classifications_for_geocentric_orbits

* GEO: GOES, SDO (inclined)
Advantages and disadvantages of SDO in GEO at https://sdo.gsfc.nasa.gov/mission/project.php
Orbit
The rapid cadence and continuous coverage required for SDO observations led to placing the satellite into an inclined geosynchronous orbit. This allows for a nearly-continuous, high-data-rate, contact with a single, dedicated, ground station.
Nearly continuous observations of the Sun can be obtained from other orbits, such as low Earth orbit (LEO). If SDO were placed into an LEO it would be necessary to store large volumes of scientific data onboard until a downlink opportunity. The large data rate of SDO, along with the difficulties in managing a large on-board storage system, resulted in a requirement of continuous contact.
The disadvantages of this orbit include higher launch and orbit acquisition costs (relative to LEO) and eclipse (Earth shadow) seasons twice annually, During these 2-3 week eclipse periods, SDO will experience a daily interruption of solar observations. There will also be three lunar shadow events each year from this orbit.
This orbit is located on the outer reaches of the Earth's radiation belt where the radiation dose can be quite high. Additional shielding was added to the instruments and electronics to reduce the problems caused by exposure to radiation. Because this is a Space Weather effect, SDO is affected by the very processes it is designed to study!

:Issued: 2014 Apr 17 1325 UTC
:Product: documentation at http://www.sidc.be/products/tot
#--#
DAILY BULLETIN ON SOLAR AND GEOMAGNETIC ACTIVITY from the SIDC
#--#
SIDC URSIGRAM 40417
SIDC SOLAR BULLETIN 17 Apr 2014, 1304UT

SIDC FORECAST (valid from 1230UT, 17 Apr 2014 until 19 Apr 2014)
SOLAR FLARES : Active (M-class flares expected, probability >=50%)
GEOMAGNETISM : Quiet (A<20 and K<4)
SOLAR PROTONS : Quiet

PREDICTIONS FOR 17 Apr 2014 10CM FLUX: 180 / AP: 013
PREDICTIONS FOR 18 Apr 2014 10CM FLUX: 184 / AP: 007
PREDICTIONS FOR 19 Apr 2014 10CM FLUX: 188 / AP: 005

COMMENT: Eleven sunspot groups were reported by NOAA today. NOAA ARs 2035,2036, and 2037 (Catania numbers 24, 25, and 26 respectively) maintain the beta-gamma configuration of the photospheric magnetic field. The strongest flare of the past 24 hours was the M1.0 flare peaking at 19:59 UT yesterday in the NOAA AR 2035 (Catania number 24). The flare was associated with an EIT wave and a weak coronal dimming, but the associated CME was narrow and is not expected to arrive at the Earth.
We expect further flaring activity on the C-level, especially in the NOAA ARs 2035 and 2037 (Catania numbers 24 and 26 respectively) as well as in the NOAA AR 2042 (no Catania number yet) that yesterday appeared from behind the east solar limb, with a good chance for an M-class event.

Since yesterday evening the Earth is situated inside a solar wind structure with an elevated interplanetary magnetic field magnitude (occasionally up to 10 nT). It may be a weak ICME or the compression region on the flank of an ICME that missed the Earth. The solar origin of this structure is not clear. The north-south magnetic field component Bz was not strong, so no significant geomagnetic disturbance resulted (K index stayed below 4). Currently the solar wind speed is around 380 km/s and the IMF magnitude is around 8 nT.
We expect quiet to unsettled (K index up to 3) geomagnetic conditions, with active geomagnetic conditions (K = 4) possible, but unlikely.

TODAY'S ESTIMATED ISN : 145, BASED ON 17 STATIONS.
99999

SOLAR INDICES FOR 16 Apr 2014
WOLF NUMBER CATANIA : ///
10CM SOLAR FLUX : 184
AK CHAMBON LA FORET : 012
AK WINGST : 004
ESTIMATED AP : 004
ESTIMATED ISN : 139, BASED ON 29 STATIONS.

NOTICEABLE EVENTS SUMMARY
DAY BEGIN MAX END LOC XRAY OP 10CM Catania/NOAA RADIO_BURST_TYPES
16 1954 1959 2004 S14E09 M1.0 1N 24/2035 II/2
END

:Issued: 2014 Apr 17 1325 UTC
:Product: documentation at http://www.sidc.be/products/tot
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DAILY BULLETIN ON SOLAR AND GEOMAGNETIC ACTIVITY from the SIDC
#--#
SIDC URSIGRAM 40417
SIDC SOLAR BULLETIN 17 Apr 2014, 1304UT

Finding your way in the URSIgram

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Satellites & Instruments

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Sunspot numbers

NOTICEABLE EVENTS SUMMARY

DAY	BEGIN	MAX	END	LOC	XRAY	OP	10CM	Catania/NOAA	RADIO_BURST_TYPES
16	1954	1959	2004	S14E09	M1.0	1N		24/2035	II/2

END

Drivers of space weather

Jan Janssens

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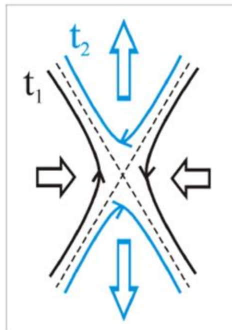
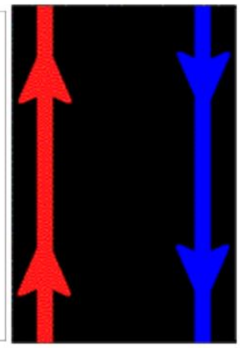
- SWx effects
- Extreme events
- URSIgram

Magnetic reconnection

- What
  - Antiparallel magnetic field lines
  - Break (disconnect) at X point
  - Reconnect with new partners
- Conversion
  - Magnetic energy => Kinetic energy
  - Magnetic restructuring
- Where
  - Solar eruptions
  - Geomagnetic storms





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Text from the CISM Summer School (Boulder, August 2013) – SW101_4_Flares
https://www.bu.edu/cism/SummerSchool/summerlist.html

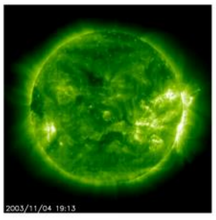
Right animation from ESA: http://sci.esa.int/cluster/36447-direct-observation-of-3d-magnetic-reconnection/

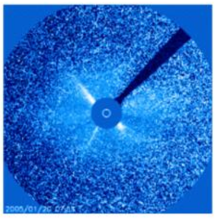
Solar eruptions

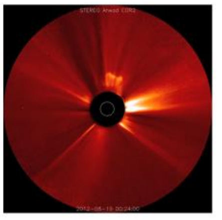
Magnetic Reconnection

Radiation | **Particles**

Solar flares | Proton events | Coronal Mass Ejections







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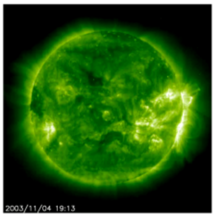
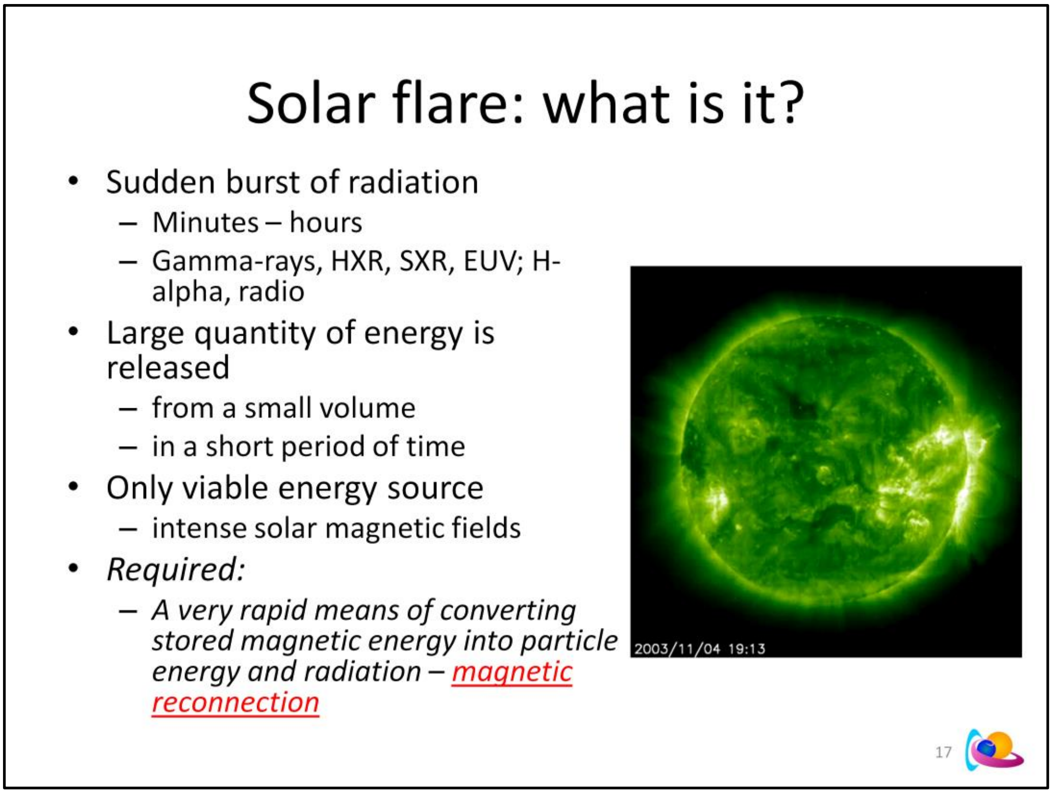
Solar eruptions

Magnetic Reconnection

Radiation

Solar flares





From the CISM Summer School (Boulder, August 2013) – SW101_4_Flares
https://www.bu.edu/cism/SummerSchool/summerlist.html

Solar flares are **sudden bursts of radiation** lasting minutes – hours at wavelengths that can include:

Gamma-rays, HXR, SXR, EUV; H-alpha, radio

A **large quantity of energy is released** from a small volume **in a short period of time**. This requires:

Either a large amount of energy stored in that small volume that can be quickly transformed and released as energetic electrons and photons.

Or very efficient transport of energy into that volume where it is then converted into the observed forms.

The only viable energy source is **intense solar magnetic fields**.

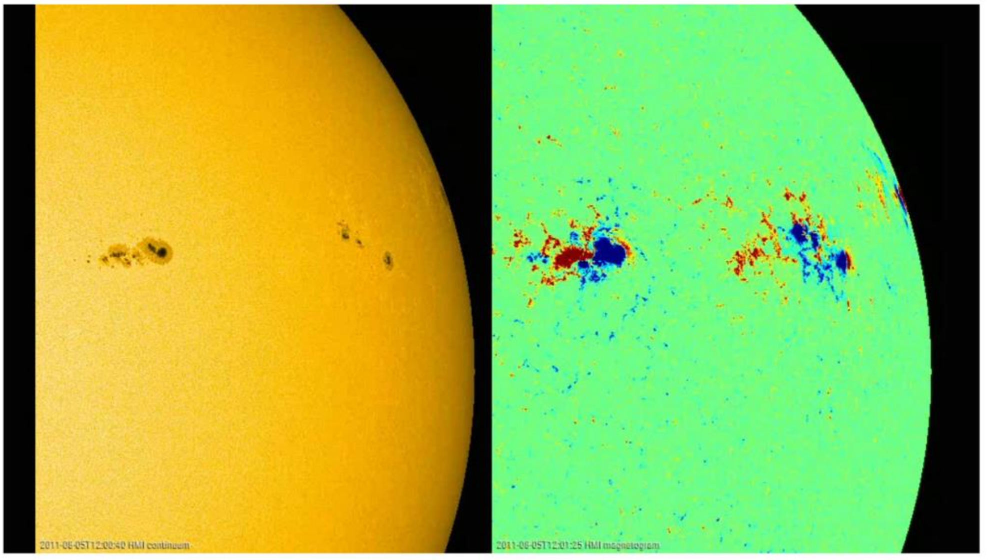
Thus we need a very rapid means of converting stored magnetic energy into particle energy and heat – ***magnetic reconnection***.

Magnetic energy is converted to thermal/radiative energy (flare, radio bursts) and kinetic energy (mass movement from CMEs and SEPs).

http://solarphysics.livingreviews.org/Articles/lrsp-2011-6/
Solar Flares: Magnetohydrodynamic Processes
Kazunari Shibata and Tetsuya Magara

Solar flares are explosive phenomena observed in the solar atmosphere filled with magnetized plasma.
Flares are observed in a wide range of electromagnetic waves such as radio, visible light, X-rays, and gamma rays.
Also, a flare usually produces high-energy particles which travel through the interplanetary space.
The discovery of coronal radio and X-ray emissions from a flaring site has revealed that flares are actually coronal phenomena.

Solar flares: Example 1/3



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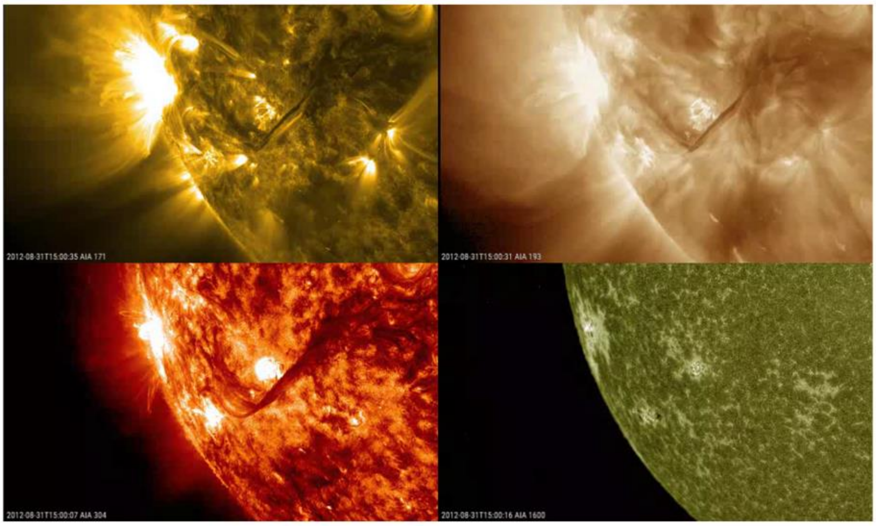
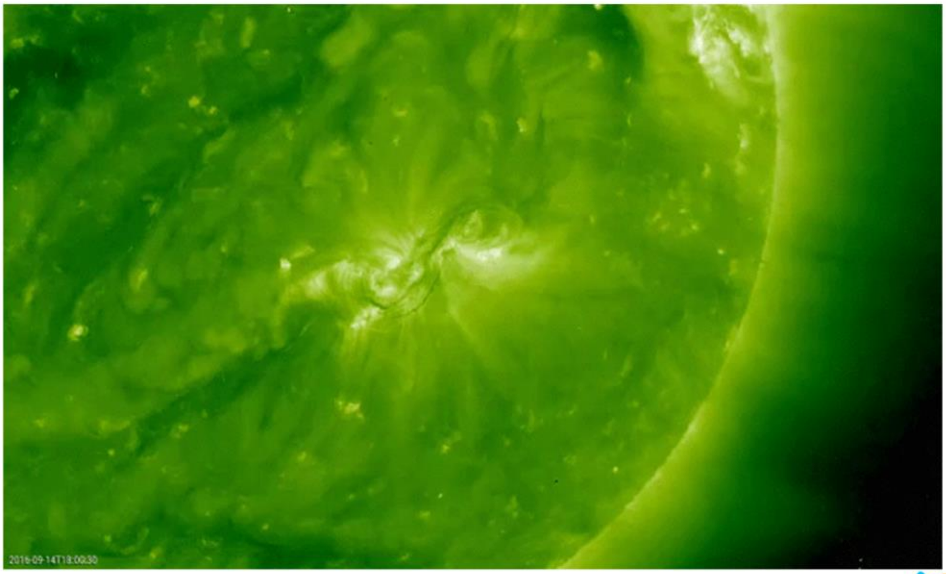
Magnetic flux emergence: X6.9 flare on 9 August 2011: http://www.stce.be/news/353/welcome.html
Blue/black is negative (inward) magnetic polarity, red/white is positive (outward) polarity

Solar flares: Example 2/3



http://www.stce.be/news/157/welcome.html
http://www.stce.be/news/218/welcome.html

Solar flares: Example 3/3



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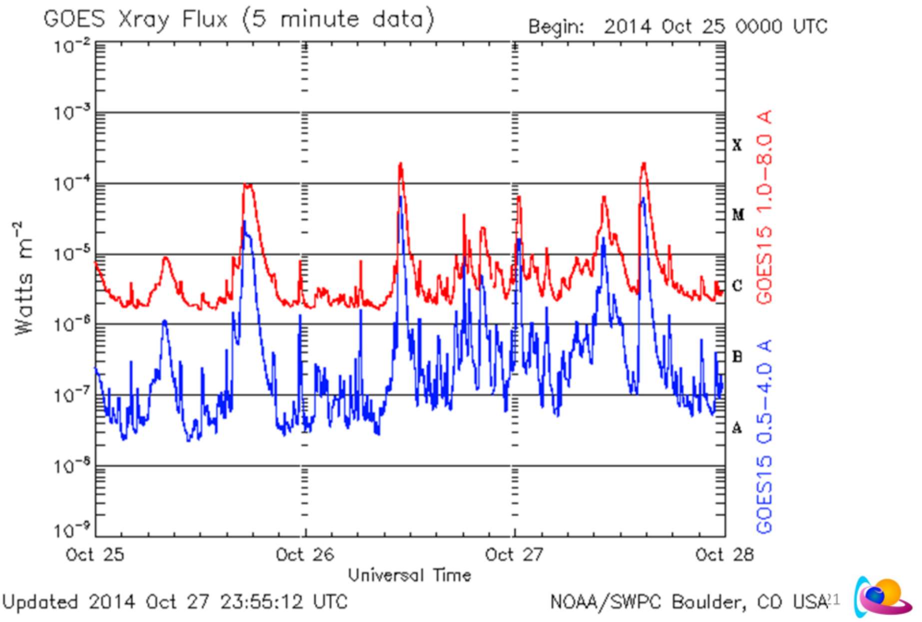
http://www.stce.be/news/362/welcome.html

Mason et al. (2016): Relationship of EUV Irradiance Coronal Dimming Slope and Depth to Coronal Mass Ejection Speed and Mass
http://adsabs.harvard.edu/abs/2016ApJ...830...20M
Large regions of temporary dimming or darkening of preexisting solar coronal emission often accompany coronal mass ejections (CMEs) and may trace field lines opened during the CME. The plasma of the solar corona responds in a number of ways to an eruptive event. Mason et al. (2014) provide details about the physics behind coronal dimming and the observational effects to be considered during analysis. Therein, the case is made for two hypotheses: that the slope of de-convolved, extreme-ultraviolet (EUV) dimming irradiance light curves should be directly proportional to CME speed, and similarly, that dimming depth should scale with CME mass. Dimming regions can be extensive, representing at least part of the “base” of a CME and the mass and magnetic flux transported outward by it.
Extensive surveys of EUV images containing coronal dimming events and their relation to CMEs have been performed by Reinard & Biesecker (2008, 2009). For their sample of 100 dimming events, Reinard & Biesecker (2008) found mean lifetimes of 8 hr, with most disappearing within a day. Reinard & Biesecker (2009) studied CMEs with and without associated dimmings, finding that those with dimmings tended to be faster and more energetic. Bewsher et al. (2008) found a 55% association rate of dimming events with CMEs and conversely that 84% of CME events exhibited dimming.
The timescale for dimming development is typically several minutes to an hour. This is much faster than the radiative cooling time, which implies that the cause of the decreased emission is more dependent on density decrease than temperature change (Hudson et al. 1996). Studies have demonstrated that dimming regions can be a good indicator of the apparent base of the white light CME (Thompson et al. 2000; Harrison et al. 2003; Zhukov & Auchère 2004). Thus, dimmings are usually interpreted as mass depletions due to the loss or rapid expansion of the overlying corona (Hudson et al. 1998; Harrison & Lyons 2000; Zhukov & Auchère 2004).

Solar flare classification: X-ray



Source: http://iopscience.iop.org/article/10.1086/304521/fulltext/36016.text.html

From SWPC ’s « The Weekly » User guide
(https://www.swpc.noaa.gov/sites/default/files/images/u2/Usr_guide.pdf ; page 2)
The letter classification of solar flares used in these definitions (Table 1) was initiated on 01 January 1969. This classification ranks solar activity by its peak x-ray intensity in the 0.1-0.8 nm band as measured by the Geostationary Operational Environmental Satellites (GOES). This x-ray classification offers at least two distinct advantages compared with the standard optical classifications: it gives a better measure of the geophysical significance of a solar event, and it provides an objective means of classifying geophysically significant activity regardless of its location on the solar disk.

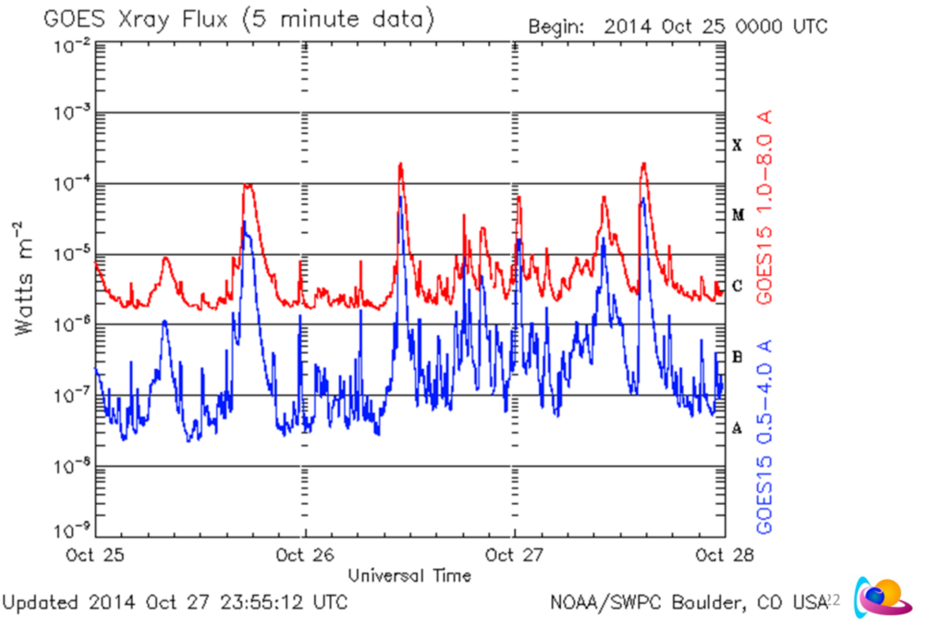
Table 1. The SWPC x-ray flare classification
Peak Flux Range (0.1-0.8 nm)

Classification	mks system (W m-2)		cgs system (erg cm-2s-1)
A	Φ <10-7		Φ <10-4
B	10-7 ≤ Φ <10-6	10-4 ≤ Φ <10-3	
C	10-6 ≤ Φ <10-5	10-3 ≤ Φ <10-2	
M	10-5 ≤ Φ <10-4	10-2 ≤ Φ <10-1	
X	10-4 ≤ Φ		10-1 ≤ Φ

The letter designates the order of magnitude of the peak value and the number following the letter is the multiplicative factor. A C3.2 event for example, indicates an x-ray burst with 3.2x10-6Wm-2 peak flux. Solar flare forecasts are usually issued only in terms of the broad C, M, and X categories. Since x-ray bursts are observed as a **full-Sun value**, bursts below the x-ray background level are not discernible. The background drops to class A level during solar minimum; only bursts that exceed B1.0 are classified as x-ray events. During solar maximum the background is often at the class M level, therefore class A, B, or C x-ray bursts cannot be discerned. Data are measured by the NOAA GOES satellites, monitored in real time in Boulder (Grubb 1975).

The C is often referred to as « Common » , M as « Medium (or moderate) », and X as « eXtreme

Solar flare classification: X-ray



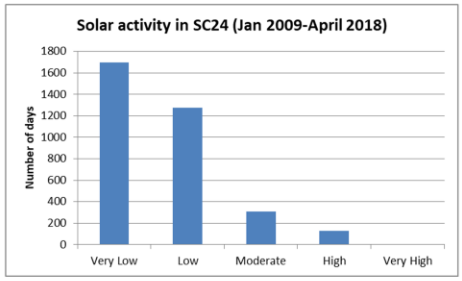
Source: http://iopscience.iop.org/article/10.1086/304521/fulltext/36016.text.html

X-ray Background: The daily average background x-ray flux as measured by the GOES satellite. To better reflect mid day values, the average is the lower of (a) the average of 1-minute data between 0800UT to 1600UT, or (b) the average of the 0000UT to 0800UT and the 1600UT to 2400UT data. The value is given in terms of x-ray class (Donnelly 1982); (Bouwer, et al.1982). X-ray flux values below the B1 level can be erroneous because of energetic electron contamination of the x-ray sensors. At times of high electron flux at geosynchronous altitude, the x-ray measurements in the low A-class range can be in error by 20-30 percent. Measurements taken during periods of low energetic electron fluxes are much more accurate.

Barbara Poppe – Sentinels of the Sun (2006) – pp. 120
First, ¡n the mid-1960s Don Baker classified solar flares using x-ray data. The Naval Research Laboratory used German-made Vela V2 rockets, captured by the Americans after the war, to measure x-rays from the Sun. Baker, then working at the Space Disturbances Laboratory (SDL), used these data to identify the wavelengths, 1 to 8 angstroms, that best characterized a flare's intensity. He created NOAA's flare classification, labeled "CMX": C, M, and X stand for small, medium, and large flares, with a range within each category from 1 to 9 (e.g., an M1 flare is one step higher than a C9 flare). Having C represent the smallest flare left A and B open should there be observations smaller than those currently known. Similarly, Y and Z could follow X ¡f scientists discovered extremely large flares. A and B flares can now in fact be seen with improved instrumentation and are categorized as such. Y and Z have never been used, despite the orderly progression that should have followed as scientists classified bigger and bigger Hares (an X1 to X9 would be followed by Y1 to Y9, then Z1 to Z9). Instead we have now seen an X28 flare. This classification system replaced an older one that reported flux numbers; that is, the flare is an M5 rather than flux Φ = 5 x 10^(-5) watts/m2. The improvement was obvious.

Solar flare classification: X-ray

- Frequency terminology
  - Solar (flaring) activity
  - For a 24 hour period



Terms Used to Describe Solar Activity

Very Low: x-ray events less than C-class.

Low: C-class x-ray events.

Moderate: isolated (one to four) M-class x-ray events.

High: several (5 or more) M-class x-ray events, or isolated (one to four) M5 or greater x-ray events.

Very High: several (5 or more) M5 or greater x-ray events.

PRF User Guide – August 2012

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Source: https://www.swpc.noaa.gov/sites/default/files/images/u2/Usr_guide.pdf

Solar Activity in SC24 (Jan 2009 - Dec 2016)
Very Low 1291 Low 1214 Moderate 299 High 118 Very High 0

Solar flare classification: X-ray

- NOAA-scales: R-scale

SC23 / SC24 (#)

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
R 5	Extreme		X20 (2×10^{-3})	Less than 1 per cycle **2 / 0**
R 4	Severe		X10 (10^{-3})	8 per cycle (8 days per cycle) **4 / 0**
R 3	Strong		X1 (10^{-4})	175 per cycle (140 days per cycle) **120 / 49**
R 2	Moderate		M5 (5×10^{-5})	350 per cycle (300 days per cycle) **150 / 81**
R 1	Minor		M1 (10^{-5})	2000 per cycle (950 days per cycle) **1292 / 646**

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From the SWPC webpage:

NOAA Space Weather Scales

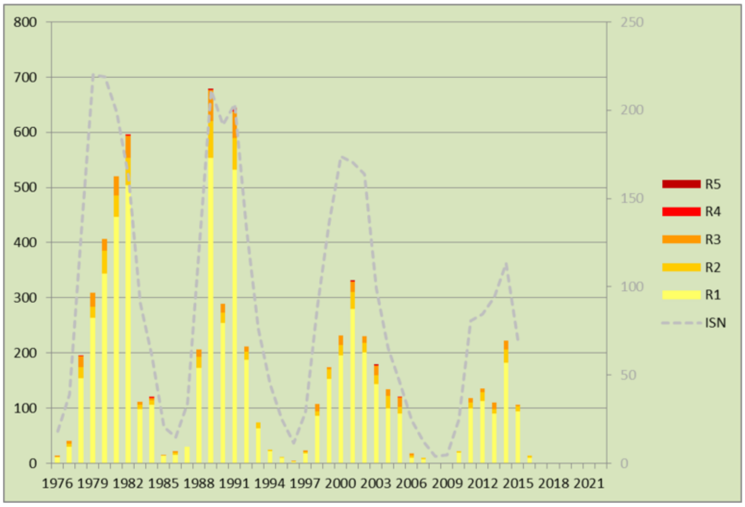
The NOAA Space Weather Scales were introduced as a way to communicate to the general public the current and future space weather conditions and their possible effects on people and systems. Many of the SWPC products describe the space environment, but few have described the effects that can be experienced as the result of environmental disturbances. These scales are useful to users of our products and those who are interested in space weather effects. The scales describe the environmental disturbances for three event types: geomagnetic storms, solar radiation storms, and radio blackouts. The scales have numbered levels, analogous to hurricanes, tornadoes, and earthquakes that convey severity. They list possible effects at each level. They also show how often such events happen, and give a measure of the intensity of the physical causes.

The « R » stands for Radio Blackout. Note it starts only from M1 class flares and higher.

More at http://www.stce.be/news/366/welcome.html

Solar flare classification: X-ray

- NOAA-scales: R-scale



25

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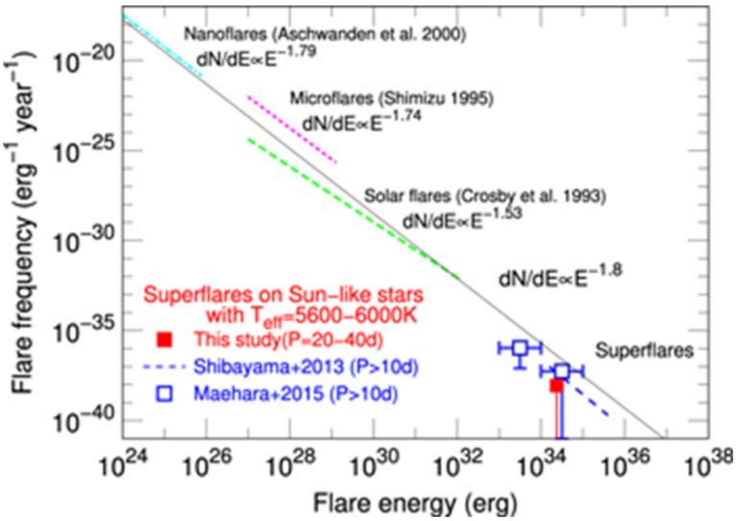
The « R » stands for Radio Blackout. Note it starts only from M1 class flares and higher.

More at http://www.stce.be/news/366/welcome.html
Systematic satellite observations of the Sun started in 1976 with GOES. For each year and for each disturbance type, one can count for every level the number of events. E.g. so far for 2016, we've had only 10 R1 events (flares with intensity between M1 and M5) and 4 R2 events (intensity between M5 and X1). Data can be retrieved at resp. NGDC/NOAA, NASA/NOAA and WDC Kyoto, and run through mid-October 2016.
Each graph shows the yearly accumulation of the events, with the yearly International Sunspot Number (SILSO) superposed on it as the gray dashed line. E.g. in the chart above, for 2014 -the year of SC24 maximum-, the number of radio blackouts amounted to 222, consisting of 183 minor (R1), 23 moderate (R2), and 16 strong (R3) events. This is clearly less than during previous solar cycles such as e.g. in 1989 when there were no less than 679 radio blackouts including 59 strong or more intense events! Also, SC24 has not produced any severe or extreme event so far, i.e. X10 or stronger flare.

Solar flare frequency



Notsu et al., 2019: https://doi.org/10.3847/1538-4357/ab14e6

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From Notsu et al. (2019): « Do Kepler Superflare Stars Really Include Slowly Rotating Sun-like Stars? – Results Using APO 3.5m Telescope Spectroscopic Observations and Gaia-DR2 Data » , https://iopscience.iop.org/article/10.3847/1538-4357/ab14e6 ; https://doi.org/10.3847/1538-4357/ab14e6

Figure 17. Comparison between the frequency distribution of superflares and solar flares. The red square, blue dashed line, and blue open squares indicate the occurrence frequency distributions of superflares on Sun-like stars (slowly rotating solar-type stars with Teff = 5600–6000 K). The red square corresponds to the updated frequency value of superflares on the stars with Prot = 20–40 days, which are calculated in this study and presented in Figure 16. Horizontal and vertical error bars are the same as those in Figure 16. For reference, the blue dashed line and blue open squares are the values of superflares on the stars with Prot > 10 days, which we presented in Figure 4 of Maehara et al. (2015) on the basis of original superflare data using Kepler 30-minute cadence data (Shibayama et al. 2013) and 1-minute cadence data (Maehara et al. 2015), respectively. Definitions of error bars of the blue open squares are the same as those in Figure 4 of Maehara et al. (2015). Three dashed lines on the upper left side of this figure indicate the power-law frequency distribution of solar flares observed in hard X-ray (Crosby et al. 1993), soft X-ray (Shimizu 1995), and EUV (Aschwanden et al. 2000). Occurrence frequency distributions of superflares on Sun-like stars and solar flares are roughly on the same power-law line with an index of −1.8 (black solid line) for the wide energy range between 1024 and 1035 erg.

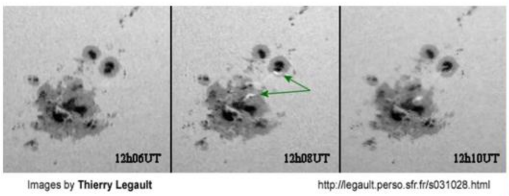
It might be better to use only the data of stars rotating as slowly as the Sun (Prot ~ 25 days and t ~ 4.6 Gyr). Then, in Figure 17 we newly plot the frequency value of superflares on Sun-like stars with Prot = 20–40 days (t > 3.2 Gyr) taken from Figure 16, in addition to the data of solar flares and superflares shown in Figure 4 of Maehara et al. (2015). As a result, the newly added data point of superflares on Sun-like stars is roughly on the same power-law line, though the exact value of superflare frequency of stars with Prot = 20–40 days (t > 3.2 Gyr) is a bit smaller than those of stars with Prot > 10 days (t > 1 Gyr). **From this figure, we can roughly remark that superflares with energy >1034 erg would be approximately once every 2000–3000 yr on old Sun-like stars with Prot ~ 25 days and t ~ 4.6 Gyr**, though the error value is relatively large because of the small amount of data of slowly rotating stars.

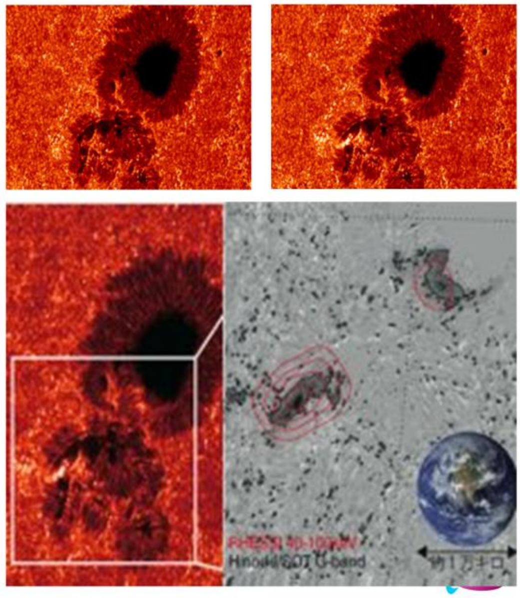
Wikipedia (https://en.wikipedia.org/wiki/Superflare) summarizes it as follows: An estimate based on the original Kepler photometric studies suggested a frequency on solar-type stars (early G-type and rotation period more than 10 days) of once every 800 years for an energy of 1034 erg and every 5000 years at 1035 erg. One-minute sampling provided statistics for less energetic flares and gave a frequency of one flare of energy 1033 erg every 5–600 years for a star rotating as slowly as the Sun; this would be rated as X100 on the solar flare scale. … There is no evidence for any flare greater than the Carrington event (about 1032 erg, or 1/10,000 of the largest superflares) in the last 200 years. … The more energetic superflares seem to be ruled out by energetic considerations for our sun, which suggest it is not capable of a flare of more than 1034 ergs. A calculation of the free energy in magnetic fields in active regions that could be released as flares gives a lower upper bound of around 3×1032 erg suggesting the most energetic a super flare can be is three times that of the Carrington event.

Different types of solar flares

White-light flare

- WLF
  - Flare visible in white light
  - Carrington, 01 September 1859
- Acceleration of huge amounts of particles to the solar "surface"
  - Hinode (2010)
    - Match of HXR location and WL location





NASA: Hinode Discovers the Origin of White Light Flare (2010)
https://www.nasa.gov/centers/marshall/news/news/releases/2010/10-052.html
White light emissions were observed by the Solar Optical Telescope during an X-class flare that occurred at 22:09 UT on Dec. 14, 2006 (see Fig. 1). The RHESSI satellite simultaneously recorded hard X-ray emissions, an indicator of non-thermal electrons accelerated by solar flares. The team found that the spatial location and temporal change of white light emissions are correlated with those of hard X-ray emissions (see Fig. 2). Moreover, the energy of white light emissions is equivalent to the energy supplied by all the electrons accelerated to above 40 keV (~40 percent of the light speed). This finding strongly suggests that highly accelerated electrons are responsible for producing white light emissions.
Hard X-rays are emitted when accelerated electrons impact the dense atmosphere near the solar surface. Normally, white light emissions primarily come from the solar surface, whereas 40 keV electrons can penetrate into the atmosphere about 1,000 km above the solar surface, i.e., the chromosphere.

Fig. 1, above, White light images of solar surface observed by the Hinode Solar Optical Telescope at 22:07 UT, before the flare, and below, at 22:09 UT, during the flare on Dec. 14, 2006. Image Credit: NASA/JAXA
Fig.2: White light emission, left, taken by Hinode/SOT, and the difference image of white light emission and RHESSI hard X-ray contours at 22:09 UT. The background image is the differential white light image (the average of the images taken at 22:07 UT and 22:17 UT is subtracted). Blue contours show 40-100 keV emission. Image credit: NASA/JAXA

An overview of WLFs is at http://users.telenet.be/j.janssens/WLF/Whitelightflare.html (last update: August 2012).

Radio bursts

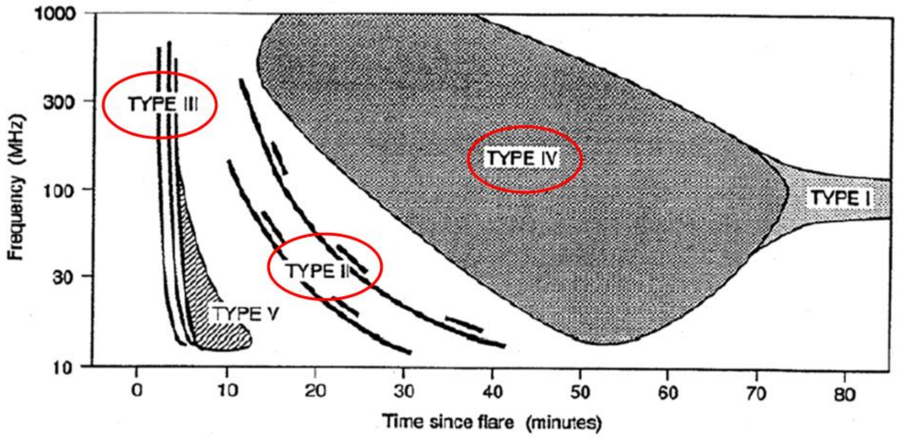


Figure 1. Schematic Radiospectrogram of Events Following a Large Solar Flare. This diagram illustrates each major type of solar radio burst in a typical configuration following a large flare. It should be noted that not all of these features are observed following every flare. (Source: *The New Culgoora Radiospectrograph Technical Report* IPS-TR-93-03, June 1993.)

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Source of Figure: SWPC 's « The Weekly » User guide
(https://www.swpc.noaa.gov/sites/default/files/images/u2/Usr_guide.pdf ; page 5)

Mind the orientation of the vertical axis! Other figures may have a reversed direction. As the frequency is proportional to the square root of the density, and the density decreases with increasing distance from the Sun, a decreasing frequency means locations higher up in the solar atmosphere.

The ionospheric cut-off frequency is around 15MHz (due to too low frequency and so reflected by ionosphere). In order to observe radio disturbances below this frequency, one has to use satellites (above the earth atmosphere) such as STEREO/SWAVES or WIND. Radio bursts at low frequencies (< 15 MHz) are of particular interest because they are associated with energetic CMEs that travel far into the interplanetary (IP) medium and affect Earth's space environment if Earth-directed. Low frequency radio emission needs to be observed from space because of the ionospheric cutoff.
Example: https://stereo-ssc.nascom.nasa.gov/browse/2017/01/16/insitu.shtml

Solar Radio Bursts and Space Weather, S.M. White
https://www.nrao.edu/astrores/gbsrbs/Pubs/AJP_07.pdf
White: Solar radio bursts at frequencies below a few hundred MHz were classified into 5 types in the 1960s (Wild et al., 1963).

Coronal Mass Ejections and solar radio emissions, N. Gopalswamy
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.708.626&rep=rep1&type=pdf
Gopalswamy: The three most relevant to space weather radio burst types are type II, III, and IV. Three types of low-frequency non-thermal radio bursts are associated with coronal mass ejections (CMEs): Type III bursts due to accelerated electrons propagating along open magnetic field lines, type II bursts due to electrons accelerated in shocks, and type IV bursts due to electrons trapped in post-eruption arcades behind CMEs.

[Radio burst type II, III, and IV are also the only ones that ever get mentioned in the Ursigrams.]

:Issued: 2014 Apr 17 1325 UTC
:Product: documentation at http://www.sidc.be/products/tot
#--#
DAILY BULLETIN ON SOLAR AND GEOMAGNETIC ACTIVITY from the SIDC
#--#
SIDC URSIGRAM 40417
SIDC SOLAR BULLETIN 17 Apr 2014, 1304UT

SIDC FORECAST (valid from 1230UT, 17 Apr 2014 until 19 Apr 2014)
SOLAR FLARES : Active (M-class flares expected, probability >=50%)
GEOMAGNETISM : Quiet (A<20 and K<4)
SOLAR PROTONS : Quiet

PREDICTIONS FOR 17 Apr 2014 10CM FLUX: 180 / AP: 013
PREDICTIONS FOR 18 Apr 2014 10CM FLUX: 184 / AP: 007
PREDICTIONS FOR 19 Apr 2014 10CM FLUX: 188 / AP: 005

COMMENT: Eleven sunspot groups were reported by NOAA today. NOAA ARs 2035,2036, and 2037 (Catania numbers 24, 25, and 26 respectively) maintain the beta-gamma configuration of the photospheric magnetic field. The strongest flare of the past 24 hours was the M1.0 flare peaking at 19:59 UT yesterday in the NOAA AR 2035 (Catania number 24). The flare was associated with an EIT wave and a weak coronal dimming, but the associated CME was narrow and is not expected to arrive at the Earth.
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Since yesterday evening the Earth is situated inside a solar wind structure with an elevated interplanetary magnetic field magnitude (occasionally up to 10 nT). It may be a weak ICME or the compression region on the flank of an ICME that missed the Earth. The solar origin of this structure is not clear. The north-south magnetic field component Bz was not strong, so no significant geomagnetic disturbance resulted (K index stayed below 4). Currently the solar wind speed is around 380 km/s and the IMF magnitude is around 8 nT.
We expect quiet to unsettled (K index up to 3) geomagnetic conditions, with active geomagnetic conditions (K = 4) possible, but unlikely.

TODAY'S ESTIMATED ISN : 145, BASED ON 17 STATIONS.
99999

SOLAR INDICES FOR 16 Apr 2014
WOLF NUMBER CATANIA : ///
10CM SOLAR FLUX : 184
AK CHAMBON LA FORET : 012
AK WINGST : 004
ESTIMATED AP : 004
ESTIMATED ISN : 139, BASED ON 29 STATIONS.

Flares & Radio emission

NOTICEABLE EVENTS SUMMARY

DAY	BEGIN	MAX	END	LOC	XRAY	OP	10CM	Catania/NOAA	RADIO_BURST_TYPES
16	1954	1959	2004	S14E09	M1.0	1N		24/2035	II/2

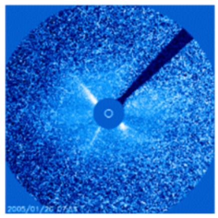
END

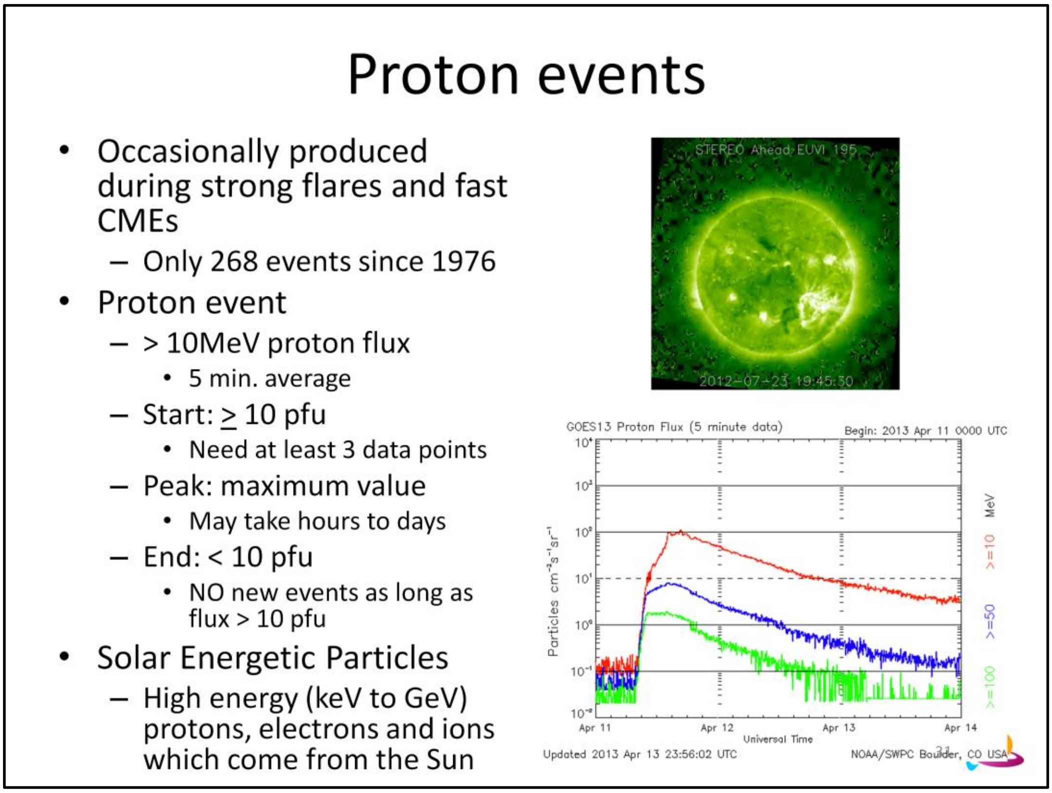
Solar eruptions

Magnetic Reconnection

Particles

Proton events





SWPC 's « The Weekly » User guide (https://www.swpc.noaa.gov/sites/default/files/images/u2/Usr_guide.pdf ; page 15)
Proton Events
A proton event starts when the integrated proton flux (5-minute average) rises above a specific threshold for at least three points.
The two alert thresholds are (1 pfu = particle / cm-2s-1sr-1):
- >10 MeV: ≥10 pfu
- >100 MeV: ≥ 1 pfu

The time of maximum is the time tag of the 5 minute averaged flux value that has the greatest value.

The term « **proton flare** » is also commonly used. According to the SWPC glossary at https://www.swpc.noaa.gov/content/space-weather-glossary , a proton flare is « Any flare producing significant counts of protons with energies exceeding 10 MeV in the vicinity of the Earth. »
Because proton events can originate from eruptions on the Sun's farside, i.e. without a flare recorded by GOES, proton flares are a subset of proton events.

From: http://www.stce.be/news/232/welcome.html
The issue here is that proton flares are not considered as separate events if the proton flux (particle energies larger than 10 MeV) at the time of the event is still above the threshold of 10 protons per flux unit (pfu). Example: 6 January 2014 X1 proton flare.

From: SESC: https://umbra.nascom.nasa.gov/SEP/ (contains list of all proton events since 1976)
Please Note: Proton fluxes are integral 5-minute averages for energies >10 MeV, given in Particle Flux Units (pfu), measured by GOES spacecraft at Geosynchronous orbit: 1 pfu = 1 p / cm^{-2} sr^{-1} s^{-1}. SESC defines the start of a proton event to be the first of 3 consecutive data points with fluxes greater than or equal to 10 pfu. The end of an event is the last time the flux was greater than or equal to 10 pfu. This definition, motivated by SESC customer needs, allows multiple proton flares and/or interplanetary shock proton increases to occur within one SESC proton event. Additional data may be necessary to more completely resolve any individual proton event.

SEP definition: from SWPC's glossary
https://www.swpc.noaa.gov/content/space-weather-glossary#Solar%20Energetic%20Particles
Solar Energetic Particles are high energy (keV to GeV) protons, electrons and ions which come from the Sun.

Proton event classification

- NOAA-scales: S-scale

SC23 / SC24 (#)

Scale	Description	Effect	Physical measure (Flux level of >= 10 MeV particles)	Average Frequency (1 cycle = 11 years)
S 5	Extreme		10^5	Fewer than 1 per cycle 0 / 0
S 4	Severe		10^4	3 per cycle 6 / 0
S 3	Strong		10^3	10 per cycle 11 / 6
S 2	Moderate		10^2	25 per cycle 26 / 9
S 1	Minor		10	50 per cycle 51 / 27

From the SWPC webpage (https://www.swpc.noaa.gov/noaa-scales-explanation)

NOAA Space Weather Scales

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The « S » stands for Solar radiation Storm. Since observations started in 1976, no S5 event has been recorded.

More at http://www.stce.be/news/366/welcome.html

Proton event classification

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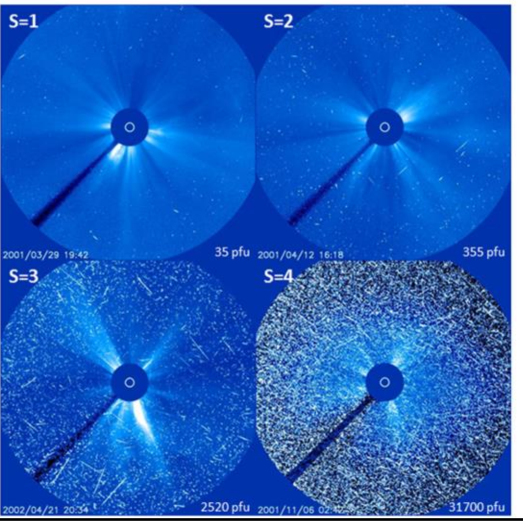

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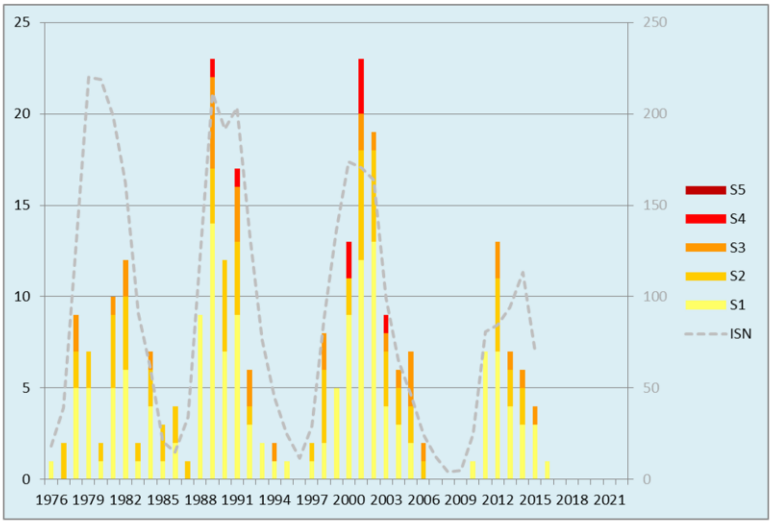
More on NOAA scales at http://www.stce.be/news/366/welcome.html
More on proton intensity at http://www.stce.be/news/233/welcome.html

Proton event classification

- NOAA-scales: S-scale



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Proton flux / events

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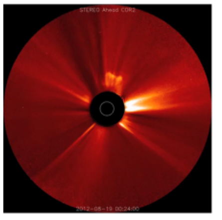
Magnetic Reconnection

Particles

Coronal Mass Ejections



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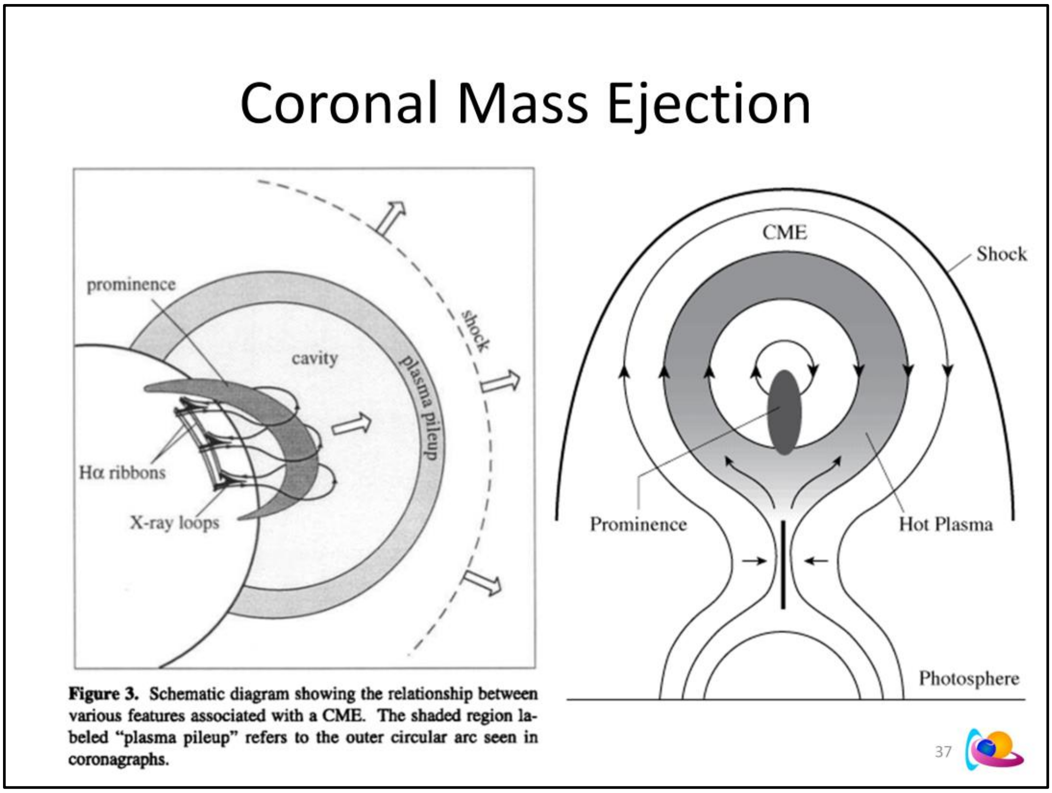


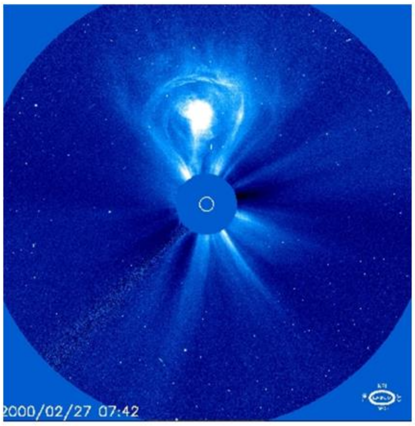
Figure 3. Schematic diagram showing the relationship between various features associated with a CME. The shaded region labeled "plasma pileup" refers to the outer circular arc seen in coronagraphs.

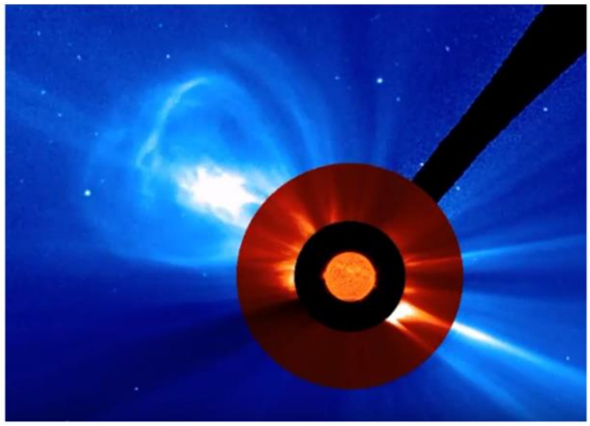
Figure to the right taken from https://ase.tufts.edu/cosmos/print_images.asp?id=27
A magnetic reconnection takes place at a current sheet (*dark vertical line*) beneath a prominence and above closed magnetic field lines. The coronal mass ejection, abbreviated CME, traps hot plasma below it (*hatched region*). The solid curve at the top is the bow shock driven by the CME. The closed field region above the prominence (*center*) is supposed to become a flux rope in the interplanetary medium. [Adapted from Petrus C. Martens and N. Paul Kuin (1989).]
In this model of a three-part coronal mass ejection, portrayed by Terry Forbes (2000), swept-up, compressed mass and a bow shock have been added to the eruptive-flare portrayal of Tadashi Hirayama (1974). The combined representation includes compressed material at the leading edge of a low-density, magnetic bubble or cavity, and dense prominence gas. The prominence and its surrounding cavity rise through the lower corona, followed by sequential magnetic reconnection and the formation of flare ribbons at the footpoints of a loop arcade. [Adapted from Hugh S. Hudson, Jean-Louis Bougeret and Joan Burkepile (2006).]

Figure to the left taken from Forbes (2000): A review on the genesis of coronal mass ejection
http://adsabs.harvard.edu/abs/2000JGR...10523153F
http://onlinelibrary.wiley.com/doi/10.1029/2000JA000005/epdf

When CMEs were first clearly identified by Skylab in 1973, many researchers assumed that they were caused by the outward expansion of hot plasma produced by a large flare. We now know that this is not the case, for several reasons. First, less than 20% of all CMEs are associated with large flares [Gosling, 1993]. Second, CMEs that are associated with flares often appear to start before the onset of the flare [Wagner et al., 1981; Simnett and Harrison, 1985]. Finally, the thermal pressure produced by a flare is too small to blow open the strong magnetic field of the corona.

Coronal Mass Ejection





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Expanding flux rope consisting of magnetic field lines and filament at bottom evolves into a CME with leading edge (pushed up by top of magnetic field lines from flux rope), cavity and core filament.

Left picture: SOHO Gallery: https://sohowww.nascom.nasa.gov/gallery/images/las02.html

Right picture: STCE: http://www.stce.be/news/342/welcome.html

Coronagraph: Wiki:a telescopic attachment designed to block out the direct light from the Sun so that nearby objects – which otherwise would be hidden in the star's bright glare – can be resolved.
In short: it is an instrument to create a permanent total solar eclipse.

Coronagraph Lasco: https://lasco-www.nrl.navy.mil/index.php?p=content/handbook/hndbk_5

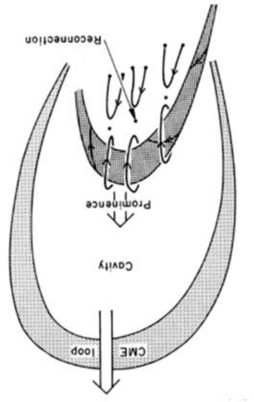
CMEs are mostly observed in white light by coronagraphs from space (SOHO, STEREO).
In order to make the faint CMEs better visible, difference images are used (one image subtracted from the other).

Ground-based observatories can observe CMEs very close to the Sun: MLSO (K-Cor):
http://download.hao.ucar.edu/d5/www/fullres/latest/latest.kcor.gif

Ground-based observatories can also observe CMEs by using interplanetary scintillation (IPS).

* Dorrian et al. (2008): Simultaneous interplanetary scintillation and Heliospheric Imager observations of a coronal mass ejection
https://core.ac.uk/download/pdf/16283575.pdf
Interplanetary scintillation (IPS) was first described by Hewish et al. [1964]. When the raypath from a compact radio source passes through the solar wind it encounters regions of varying plasma density, inducing phase variations. As the wave continues to the receiver these phase variations are converted into amplitude variations by interference [e.g., Coles, 1978].

Interplanetary CME



IN-SITU ICME SIGNATURES 35

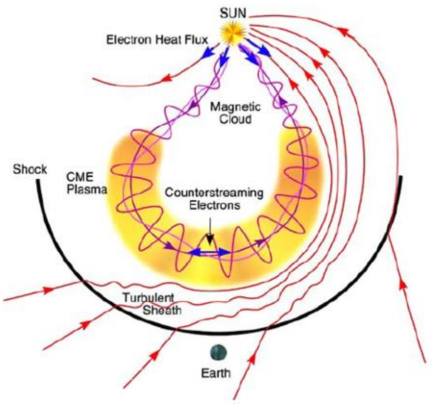


Figure 2. Schematic of the three-dimensional structure of an ICME and upstream shock, relating magnetic field, plasma, and BDE signatures.

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

An interplanetary CME (ICME) is a CME of which the solar wind features are measured in situ by spacecraft at Earth or in the solar system.

Pending the mutual positions of the Earth and the CME, Earth may experience the following impacts from this (I)CMEs:

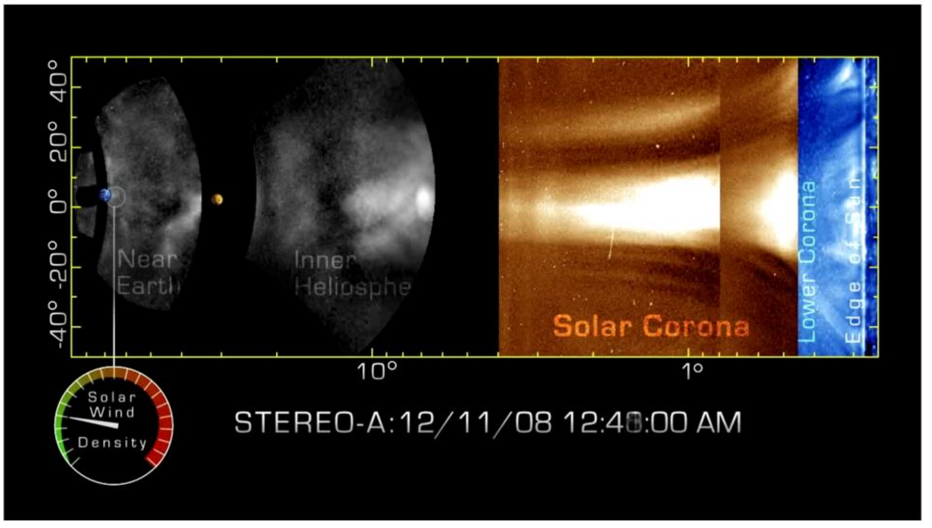
1. Nothing
2. Shock + Sheath
3. Shock + Sheath + Magnetic Cloud leg (long)
4. Shock + Sheath + Magnetic Cloud (head-on) + rarefied region
5. No shock, still magnetic cloud

These all give different signatures in the various solar wind parameters.

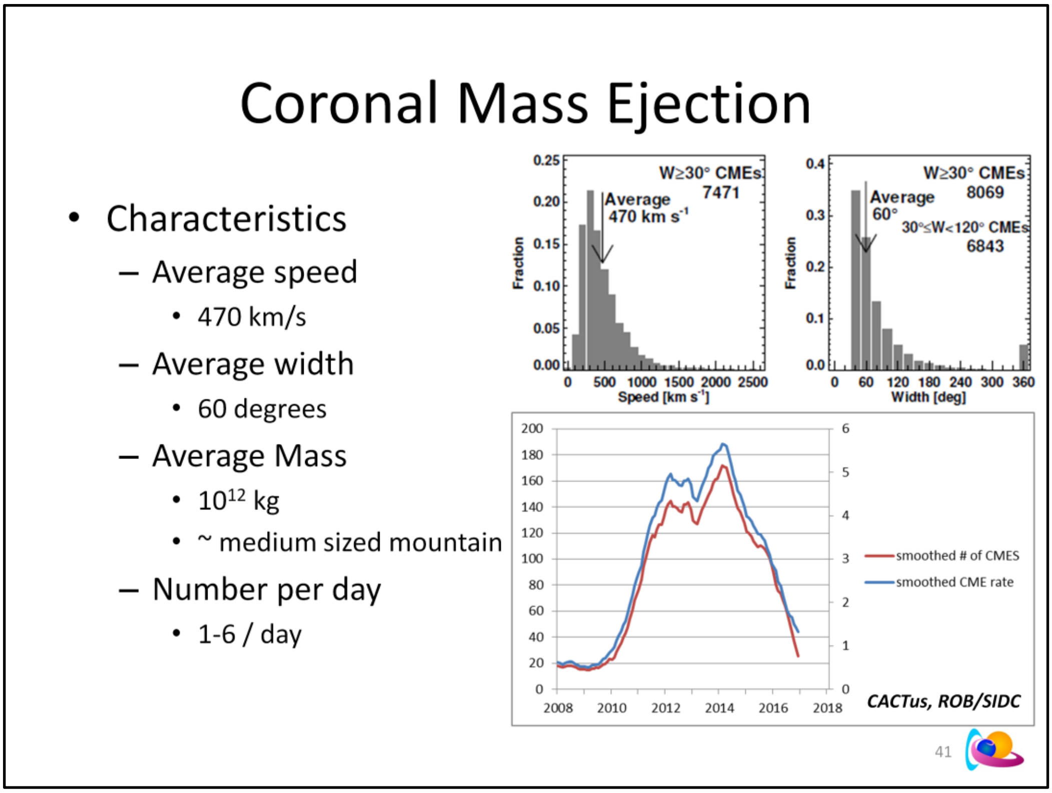
The figure on the left was taken from:
Priest (1988): The initiation of solar coronal mass ejections by magnetic nonequilibrium
http://adsabs.harvard.edu/abs/1988ApJ...328..848P (Fig. 1c, upside down)

Rodriguez et al. (2016): Typical Profiles and Distributions of Plasma and Magnetic Field Parameters in Magnetic Clouds at 1 AU
http://adsabs.harvard.edu/abs/2016SoPh..291.2145R

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

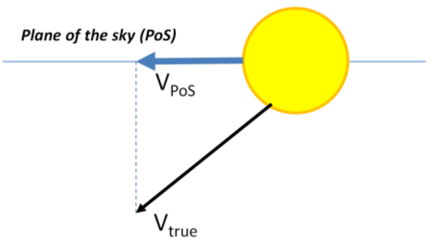


Source file: Webb et al. (2012): Coronal Mass Ejections: Observations
http://link.springer.com/article/10.12942/lrsp-2012-3

* Webb et al. (2012): Coronal Mass Ejections: Observations
http://link.springer.com/article/10.12942/lrsp-2012-3
5.2 Interplanetary scintillation (IPS) observations
The IPS technique relies on measurements of the fluctuating intensity level of a large number of point-like distant meter-wavelength radio sources. They are observed with one or more ground arrays operating in the MHz–GHz range. IPS arrays detect changes to density in the (local) interplanetary medium moving across the line of sight to the source. Disturbances are detected by either an enhancement of the scintillation level and/or an increase in velocity. When built up over a large number of radio sources a map of the density enhancement across the sky can be produced. The technique suffers from relatively poor temporal (24-hour) resolution and has a spatial resolution limited to the field of view of the radio telescope. For example, high-latitude arrays such as the long-deactivated 3.5 ha array near Cambridge in the UK could not observe sources in the mid-high latitude southern hemisphere. Scattering efficiency also poses a limitation on IPS measurements as increasing the frequency at which to measure the sources allows an observer to detect disturbances closer to the Sun. Higher frequencies means fewer sources, however, so the spatial resolution is effectively decreased. Finally, ionospheric noise limits viewing near the Sun and near the horizon, and a model-dependence for interpreting the signal as density or mass. Workers have, however,
been working with these difficulties for 50 years and a number of techniques have evolved to extract reliable CME measurements using IPS. Recent papers involving such measurements include Jones et al. (2007), Bisi et al. (2008), Jackson et al. (2010b), Tappin and Howard (2010), and Manoharan (2010).

Coronal Mass Ejection

- Speed
  - We see the projected speed
    - Plane of the sky (PoS)
  - Typical
    - Value: 470 km/s
    - Range: 300 - 1500 km/s



- Bz
  - North-South component of magnetic field (nT) perpendicular to the ecliptic
  - Intensity varies much more than speed
  - *Negative (« south »), strong and long-lasting Bz is necessary to get a strong geomagnetic storm*
  - *Typical Bz-values for strong ICMEs: -15 to -45 nT*
  - Need to predict both orientation and intensity
    - Not easy + potentially changing during Sun-Earth transit!

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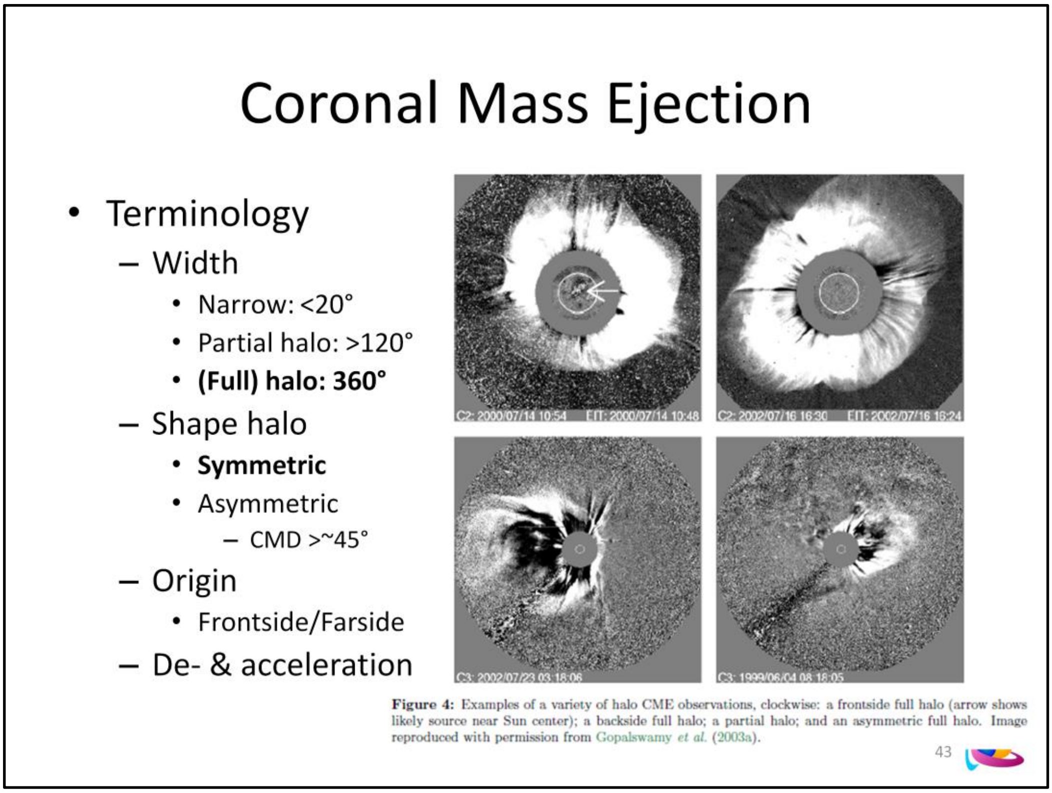
Ecliptic: The ecliptic is the apparent path of the Sun on the celestial sphere, and is the basis for the ecliptic coordinate system. It also refers to the plane of this path, which is coplanar with the orbit of Earth around the Sun (and hence the apparent orbit of the Sun around Earth).
From Wikipedia: https://en.wikipedia.org/wiki/Ecliptic

Zhukov (2017): Predicting Geomagnetic Storms on the Base of Solar Observations
https://events.oma.be/indico/event/21/
The solar wind-magnetosphere coupling is governed by the duskward electric field Ey ~ vBz. However, v varies only by a factor of 2 (maybe 5 in extreme events). Bz varies by a factor of 10 and is thus a parameter more important for predictions. To be geoeffective, the CME-associated disturbance should have a suitable magnetic field configuration: the interplanetary magnetic field (IMF) Bz component should be negative (southward), strong enough and long-lasting.

Li et al. (2018): Magnetic Clouds: Solar Cycle Dependence, Sources, and Geomagnetic Impacts
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6190751/ (DOI: 10.1007/s11207-018-1356-8)
In Solar Cycle 23 (24), the MC speeds range from 300 to 1000 (700) km s−1, the magnetic magnitudes within MCs range from 8 to 62 (40) nT, the south magnetic fields within MCs range from 0 to 45 (22) nT, and the south magnetic fields in the MC sheaths range from 0 to 42 (17) nT. The ICMEs are slower and the field strengths are much weaker in Cycle 24. In Cycle 23, the highest values of all parameters appear in the declining phase of the solar cycle between the solar maximum and the next solar minimum. Cycle 24 seems to have the same tendency, but it is less obvious, perhaps for two reasons: first, that the values are all less significant, and second, that the cycle is still not complete.



Source file: Webb et al. (2012): Coronal Mass Ejections: Observations
http://link.springer.com/article/10.12942/lrsp-2012-3

CACTus automatically identified many more events than in the CDAW (manual) catalog but half of them were narrow (< 20° of apparent angular width).

Some CMEs appear as narrow jets, some arise from pre-existing coronal streamers (the so-called streamer blowouts), while others appear as wide almost global eruptions. CMEs spanning very large angular ranges are probably not really global, but rather have a large component along the Sun-observer line and so appear large by perspective. These include the so-called halo CMEs (Howard et al., 1982) – see Section 2.3. The CDAW CME catalog (Yashiro et al., 2004) defines a “partial halo” as a CME with an apparent position angle range > 120°. Hence, again, the definition of a CME is restricted by its viewing perspective.

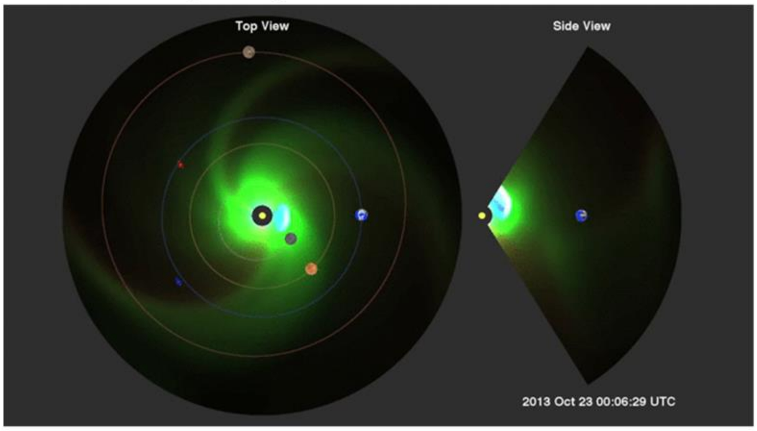
Partial and full halo CMEs occur at a rate of about 10% that of all CMEs, but 360° halo CMEs are only detected at a rate of ∼ 4% of all CMEs.

CMEs that are aligned near the relative disk center tend to be more geoeffective while those nearer the relative solar limb are less so. The vast majority of the most intense geomagnetic storms of Cycle 23, for example, were caused by halo CMEs (Gopalswamy, 2010a).

Because of their increased sensitivity, field of view and dynamic range, the SOHO/LASCO and STEREO/COR coronagraphs now frequently observe halo CMEs, which appear as expanding, circular brightenings that completely surround the coronagraphs’ occulting disks (Figure 4). Observations of associated activity on the solar disk are necessary to help distinguish whether a halo CME was launched from the front or backside of the Sun relative to the observer. This has had limited success, as frontsided CMEs that do not have a solar surface association can be mistaken for backsided events. In recent years several CMEs have been observed by the “three eyes” of STEREO-B, LASCO and STEREO-A by a variety of viewing points, thus reducing this latter problem.

Coronal Mass Ejection

- Terminology (cont'd)
  - CME cannibalism
    - 2nd faster CME overtakes 1st slower CME
    - Enhanced geomagnetic storms



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Animation from NASA/GSFC at https://svs.gsfc.nasa.gov/4099

In this research model run, the Sun has launched three coronal mass ejections (CMEs) which may merge into a single front as it expands into the solar system. These events are sometimes called 'cannibal' CMEs.

This model run is based on estimated parameters from solar events of October 23-24, 2013

Also at https://science.nasa.gov/science-news/science-at-nasa/2001/ast27mar_1

Coronal Mass Ejection

- Terminology (cont'd)
  - Fast Transit Events (FTE)
    - Sun-Earth transit < 24 hrs
    - 23 July 2012!

BAKER ET AL.: DEFINING EXTREME SPACE WEATHER SCENARIOS

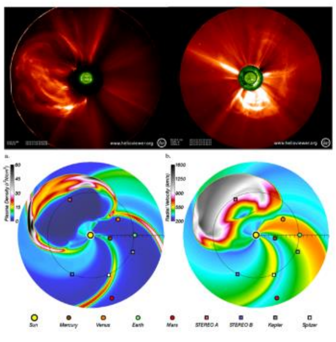

TABLE III
"Fast-transit" events, 1859–2003.

Flare date	Transit time (h)	References
04 Aug. 1972	14.6	1, 2, 3
01 Sep. 1859	17.6	4, 5, 6, 7, 8
06 Feb. 1946	17.8	3, 9
28 Feb. 1941	18.4	10
16 Jul. 1959	19.4	11
28 Feb. 1942	19.5	8, 12
17 Sep. 1941	19.8	8, 13
29 Oct. 2003	∼20[a]	14
28 Oct. 2003	20.3[a]	14
15 Apr. 1938	21.2	8, 15
12 Nov. 1960	21.2	11
16 Jan. 1938	21.8	15, 16

References: (1) Dryer *et al.*, 1975; (2) Vaisberg and Zastenker, 1976; (3) Cliver *et al.*, 1990b; (4) Carrington, 1860; (5) Hodgson, 1860; (6) Hale, 1931; (7) Bartels, 1937; (8) Newton, 1943; (9) Nicholson and Hickox, 1946; (10) Newton, 1941a; (11) Ellison, McKenna, and Reid, 1961; (12) Newton, 1942; (13) Newton, 1941b; (14) Skoug *et al.*, 2004; (15) Bartels, 1940; (16) Bartels, Heck, and Johnston, 1939.
[a]Preliminary.

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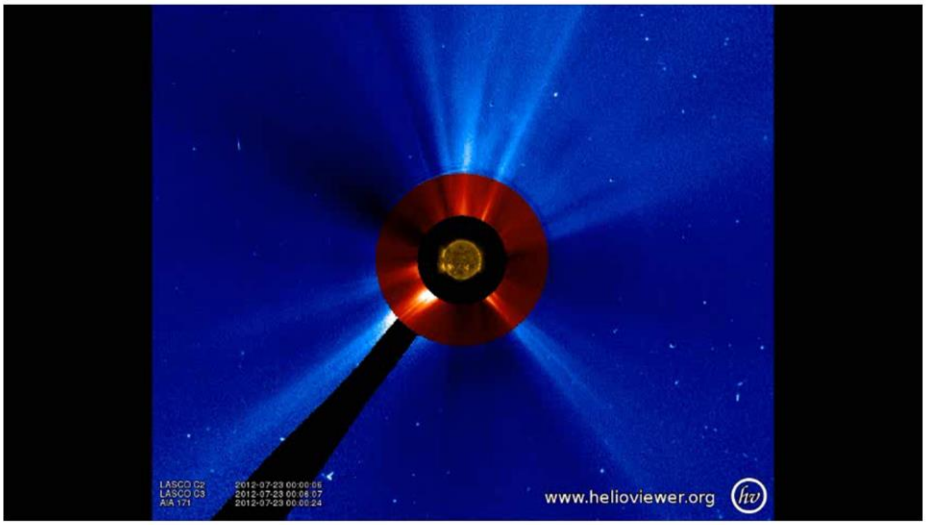
Fast transit event
Cliver et al. (2004): The 1859 Solar-Terrestrial Disturbance And the Current Limits of Extreme Space Weather Activity
adsabs.harvard.edu/abs/2004SoPh..224..407C
2.3. SUN–EARTH TRANSIT TIME
Cliver, Feynman, and Garrett (1990a,b) compiled a list of 10 "fast transit" events occurring from 1859–1989 in which a solar flare was followed within ∼20 h by the sudden commencement of a geomagnetic storm. Table III is an update of their list through 2003. The shortest transit time (measured from inferred/observed flare onset to geomagnetic storm sudden commencement) for the listed events is 14.6 h for the 4 August 1972 flare-storm pair. The 1859 event had the second shortest delay, 17.6 h. On average, fast transit events appear to occur 1–2 times per solar cycle, but the temporal distribution is very uneven, with 6 such events occurring from 1938–1946 and a 31-year gap between the 4 August 1972 and 28 October 2003 events followed by a one day gap between the two October 2003 events. Solar wind measurements for the three modern events on the list (4 August 1972 (Vaisberg and Zastenker, 1976; d'Uston *et al.*, 1977) and 28 and 29 October 2003 (Skoug *et al.*, 2004)) indicate peak speeds ∼ 2000 km/s.

A nice example of the most recent FTE can be found in the STCE News item: A CME with an Olympic Speed
http://www.stce.be/news/152/welcome.html
This CME had a transit time of about 19 hours, but was directed towards ST-A, not Earth.
It is believed that, if the CME had been earth-directed, the space weather consequences would have been similar to the Carrington event.

Baker et al. (2013): A major solar eruptive event in July 2012: Defining extreme space weather scenarios
http://adsabs.harvard.edu/abs/2013SpWea..11..585B

Farside solar eruption

23 July 2012 - Carrington-like event in NOAA 1520



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Description of the events at
STCE news item « A CME with an Olympic speed » at http://www.stce.be/news/152/welcome.html

:Issued: 2014 Apr 17 1325 UTC
:Product: documentation at http://www.sidc.be/products/tot


```
#--------------------------------------------------------------------------------------------------#
# DAILY BULLETIN ON SOLAR AND GEOMAGNETIC ACTIVITY from the SIDC     #
#--------------------------------------------------------------------------------------------------#
SIDC URSIGRAM 40417
SIDC SOLAR BULLETIN 17 Apr 2014, 1304UT

SIDC FORECAST (valid from 1230UT, 17 Apr 2014 until 19 Apr 2014)
SOLAR FLARES  : Active (M-class flares expected, probability >=50%)
GEOMAGNETISM  : Quiet (A<20 and K<4)
SOLAR PROTONS : Quiet

PREDICTIONS FOR 17 Apr 2014  10CM FLUX: 180 / AP: 013
PREDICTIONS FOR 18 Apr 2014  10CM FLUX: 184 / AP: 007
PREDICTIONS FOR 19 Apr 2014  10CM FLUX: 188 / AP: 005
```

COMMENT: Eleven sunspot groups were reported by NOAA today. NOAA ARs 2035,2036, and 2037 (Catania numbers 24, 25, and 26 respectively) maintain the beta-gamma configuration of the photospheric magnetic field. The strongest flare of the past 24 hours was the M1.0 flare peaking at 19:59 UT yesterday in the NOAA AR 2035 (Catania number 24). The flare was associated with an EIT wave and a weak coronal dimming, but the associated CME was narrow and is not expected to arrive at the Earth.

We expect further flaring activity on the C-level, especially in the NOAA ARs 2035 and 2037 (Catania numbers 24 and 26 respectively) as well as in the NOAA AR 2042 (no Catania number yet) that yesterday appeared from behind the east solar limb, with a good chance for an M-class event.

Since yesterday evening the Earth is situated inside a solar wind structure with an elevated interplanetary magnetic field magnitude (occasionally up to 10 nT). It may be a weak ICME or the compression region on the flank of an ICME that missed the Earth. The solar origin of this structure is not clear. The north-south magnetic field component Bz was not strong, so no significant geomagnetic disturbance resulted (K index stayed below 4). Currently the solar wind speed is around 380 km/s and the IMF magnitude is around 8 nT.

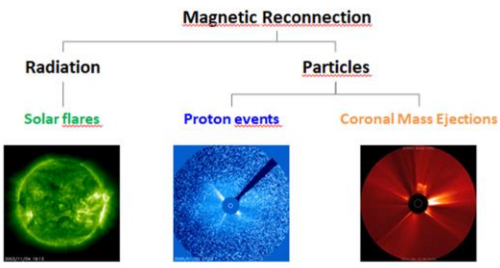
We expect quiet to unsettled (K index up to 3) geomagnetic conditions, with active geomagnetic conditions (K = 4) possible, but unlikely.

```
TODAY'S ESTIMATED ISN          : 145, BASED ON 17 STATIONS.
99999

SOLAR INDICES FOR 16 Apr 2014
WOLF NUMBER CATANIA            : ///
10CM SOLAR FLUX                : 184
AK CHAMBON LA FORET            : 012
AK WINGST                      : 004
ESTIMATED AP                   : 004
ESTIMATED ISN                  : 139, BASED ON 29 STATIONS.

NOTICEABLE EVENTS SUMMARY
DAY BEGIN MAX  END   LOC     XRAY  OP  10CM Catania/NOAA RADIO_BURST_TYPES
16  1954   1959 2004  S14E09  M1.0  1N             24/2035       II/2
END
```

CME & ICME

Summary

- Solar Eruptions



- **Magnetic reconnection**
- **Solar flares**
  - Mechanism & examples
  - Classification
    - X-ray, NOAA scale (R)
    - Frequency
  - Radio bursts
- **Proton events**
  - Definition
  - NOAA scale (S)
- **Coronal Mass Ejections**
  - Morphology
  - Terminology
    - Halo CME
    - CME cannibalism
    - Fast Transit Event
  - ICME

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Space weather effects

Jan Janssens

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Overview

- Introduction
- Drivers of SWx
- SWx effects
- Extreme events
- URSIgram

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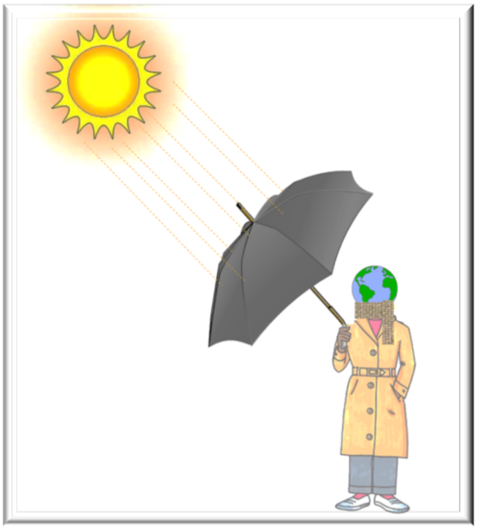
Space Weather (SWx)

- 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, ESA

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ESA: 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.
http://www.esa.int/Our_Activities/Operations/Space_Situational_Awareness/Space_Weather_-_SWE_Segment

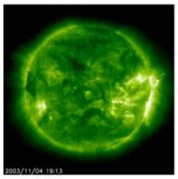
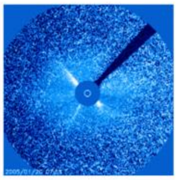
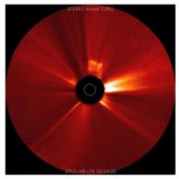
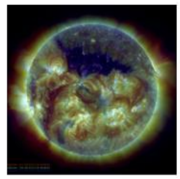
National Space Weather Program (USA)
http://www.spaceweathercenter.org/swop/NSWP/1.html

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 possible impacts on biological and technological systems.

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**

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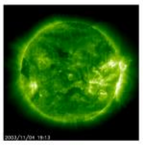
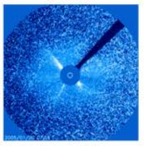
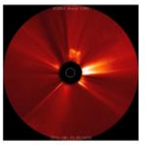
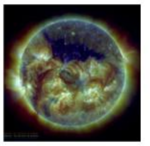
Disturbed Space weather

Causes

Solar flares	Proton events	Coronal Mass Ejections	Coronal Holes
			

	Solar flares	Proton events	Coronal Mass Ejections	Coronal Holes
Arrival	Immediately	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

Solar flares	Proton events	Coronal Mass Ejections	Coronal Holes
Radio communications	Satellites	Satellites	
Radar interference	Astronauts & Airplanes	Aurora	
	Communication/Navigation	Communication/Navigation	
	Ozone	Electrical Currents (GIC)	

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

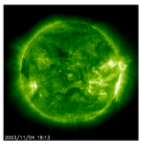
Brekke (2016): **AGF-216 lecture 2016: Space Weather**
http://www.slideshare.net/UniSvalbard/agf216-lecture-2016-space-weather

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

Disturbed Space weather

Causes

Solar flares



	Solar flares
Arrival	Immediately
NOAA scales	R1 (minor) => R5 (extreme)
Parameter	M1 => ≥ X20
Duration	Minutes to hours
Protection	Earth's atmosphere

Effects

Effects	Radio communications
	Radar interference

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

Brekke (2016): **AGF-216 lecture 2016: Space Weather**
http://www.slideshare.net/UniSvalbard/agf216-lecture-2016-space-weather

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

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)

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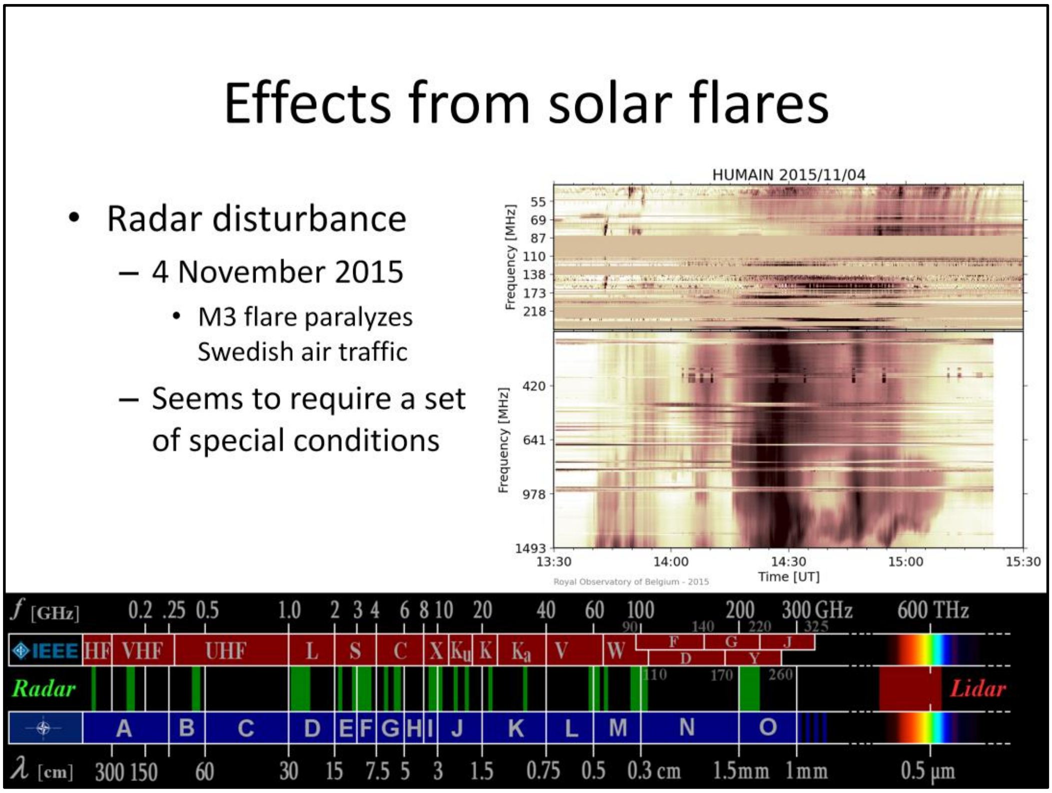
Info at:
https://www.swpc.noaa.gov/noaa-scales-explanation
SWPC: https://www.swpc.noaa.gov/phenomena/solar-flares-radio-blackouts
SWS: http://www.sws.bom.gov.au/Educational/1/3/5

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].



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.

See also STCE news item at http://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

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.

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
adsabs.harvard.edu/abs/2016EGUGA..1812017O
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.

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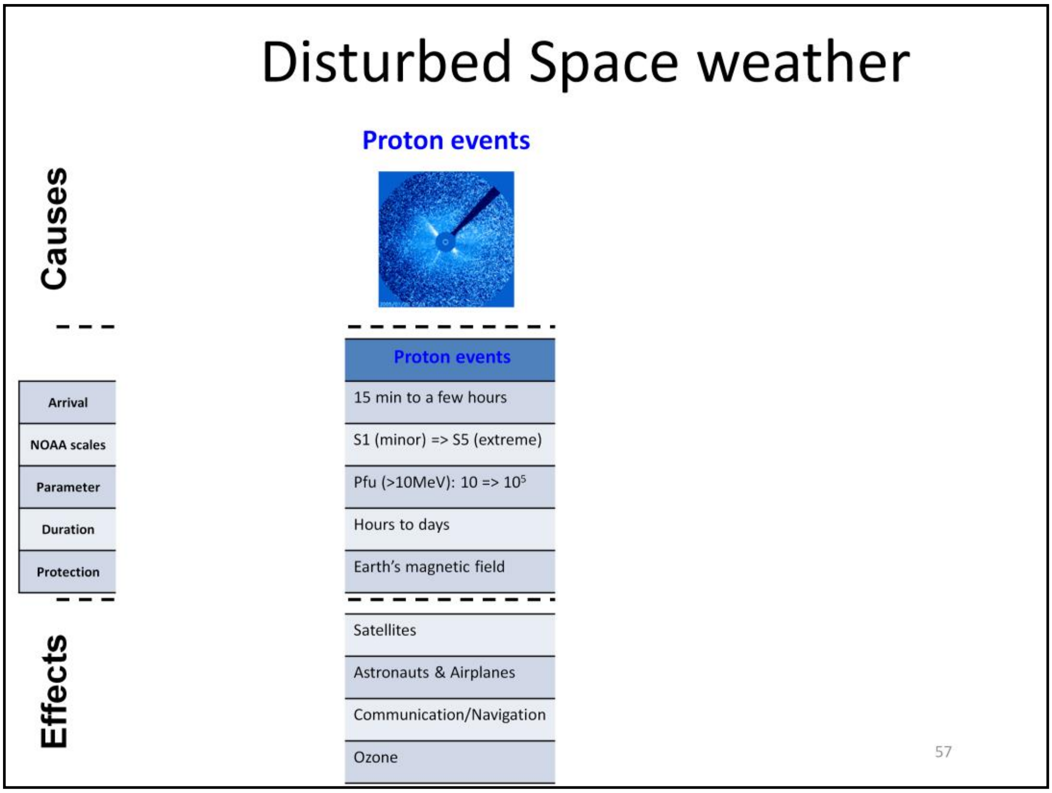


Baker et al. (2016): Resource Letter SW1: Space Weather
http://adsabs.harvard.edu/abs/2016AmJPh..84..166B
http://aapt.scitation.org/doi/pdf/10.1119/1.4938403

Brekke (2016): **AGF-216 lecture 2016: Space Weather**
http://www.slideshare.net/UniSvalbard/agf216-lecture-2016-space-weather

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

Effects from proton events

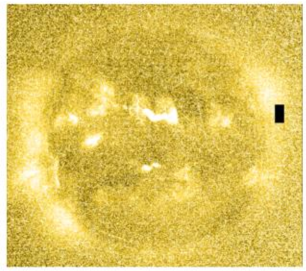
Scale	Description	Effect	Physical measure (Flux level of >= 10 MeV particles)	Average Frequency (1 cycle = 11 years)
S 5	Extreme	**Biological:** Unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed 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

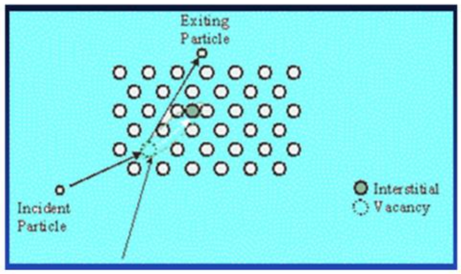
More info at
SWPC: https://www.swpc.noaa.gov/noaa-scales-explanation
SWPC: https://www.swpc.noaa.gov/phenomena/solar-radiation-storm

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
http://adsabs.harvard.edu/abs/1990SoPh..127..297S

Effects from proton events

- Satellites
  - Star trackers
    - Spacecraft orientation
  - Single event effects
    - Direct hit of an electronic component by an energetic particle resulting in an anomaly
  - Solar arrays
    - Displacement damage
      - Reduces efficiency in electricity production





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Baker et al. (2016): Resource Letter SW1: Space Weather
http://adsabs.harvard.edu/abs/2016AmJPh..84..166B
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.

A good example of a proton storm induced orientation problem was on 1 September 2014 with ST-B. See the news item at http://www.stce.be/news/266/welcome.html as well as https://sohowww.nascom.nasa.gov/pickoftheweek/old/05sep2014/

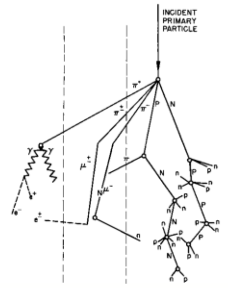
Galvan et al. (2014): Satellite Anomalies
http://www.rand.org/content/dam/rand/pubs/research_reports/RR500/RR560/RAND_RR560.pdf
Single Event Effects (SEEs) - SEEs are anomalies caused not by a gradual buildup of charge over time as with surface or internal charging, but by the impact of a single high-energy 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).
… 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;).

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

Curdt et al. (2015): Solar and Galactic Cosmic Rays Observed by SOHO
http://adsabs.harvard.edu/abs/2015CEAB...39..109C (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). … 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 ...

Effects from proton events

- Ground Level Enhancement
  - Sharp increase of #neutrons at ground
    - Secondary particle shower
    - Neutron monitors
    - Background: GCR
      - SC dependant
  - Main source
    - Strong SEPs ~1 GeV/nuc
      - X-class flares
      - Western hem.
      - Fast halo CMEs
      - => RARE!!
  - Thresholds GLE
    - SWPC: 10% above B/Gr
      - Practice: 3% above B/Gr
  - Realtime monitoring
    - http://www.nmdb.eu/



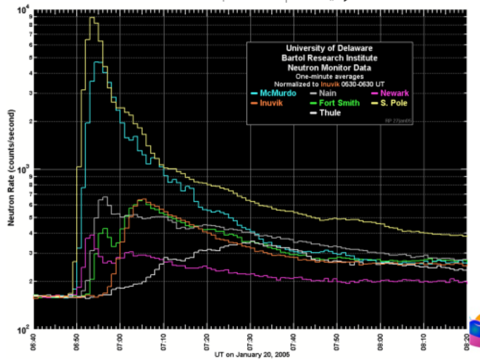


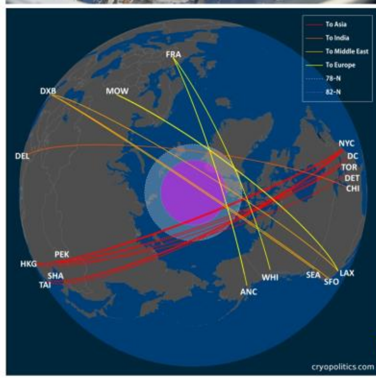
Figure taken from http://wwwgro.sr.unh.edu/neutron_monitors/shower.gif

Perrone et al. (2004): **Polar cap absorption events of November 2001 at Terra Nova Bay, Antarctica**
http://adsabs.harvard.edu/abs/2004AnGeo..22.1633P
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
http://adsabs.harvard.edu/abs/2014ApJ...790L..13T
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).

Effects from proton events

- Radiation dose
  - Astronauts
    - Burning eyes, light flashes
    - Protection
      - No EVA
      - Sheltering inside ISS
    - Outside earth environment
      - No protection
        - » GCR
  - A/C crew & passengers
    - Transpolar flights
      - Pregnant women
    - Protection
      - Lower altitudes
      - Rerouting via lower lat.
        - » Cost airlines up



Links
Radiation dose: http://www.radiologyinfo.org/en/info.cfm?pg=safety-xray (normal yearly background: 3 mSv; chest x-ray: 0.1 mSv)
ESA career limit: http://adsabs.harvard.edu/abs/2014JSWSC...4A..20J
Flight Safety: https://flightsafety.org/asw-article/flare-ups/
ESA SSA: http://swe.ssa.esa.int/nso_air
NASA: https://srag.jsc.nasa.gov/Publications/TM104782/techmemo.htm
EPCARD: http://www.helmholtz-muenchen.de/en/epcard-portal/information/determining-radiation-exposure-of-airline-staff/index.html
Space Weather index dor radiation at aviation altitudes: http://adsabs.harvard.edu/abs/2014JSWSC...4A..13M
Pregnancy foetus: http://publicsafety.tufts.edu/ehs/radiation-safety/more-information/pregnancy-and-radiation/ (5mSv over entire pregnancy, 0.5 mSv/month)

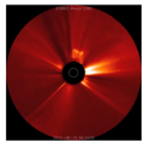
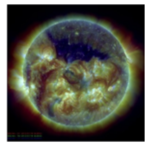
From https://www.translatorscafe.com/unit-converter/en/radiation-absorbed-dose/18-25/milligray-millisievert/
Radiation. Absorbed Dose
The absorbed dose characterized the amount of damage done to the matter (especially living tissues) by ionizing radiation. The absorbed dose is more closely related to the amount of energy deposited.
The SI unit of absorbed dose is the **gray** (Gy), which is equal to J/kg. 1 gray represents the amount of radiation required to deposit 1 joule of energy in 1 kilogram of any kind of matter. The **sievert (Sv)** is the International System of Units (SI) derived unit of equivalent radiation dose, effective dose, and committed dose. One sievert is the amount of radiation necessary to produce the same effect on living tissue as one gray of high-penetration x-rays. Quantities that are measured in sieverts are designed to represent the biological effects of ionizing radiation.

1 mSv = 1 mGy = 100 mRem = 100 mRad
https://www.translatorscafe.com/unit-converter/en/radiation-absorbed-dose/18-25/milligray-millisievert/

There’s also an excellent discussion of the topic at https://hps.org/publicinformation/ate/q10540.html

Disturbed Space weather

Causes

	Coronal Mass Ejections	Coronal Holes
		

	Coronal Mass Ejections	Coronal Holes
Arrival	20 to 72+ hours	2 to 4 days
NOAA scales	G1 (minor) => G5 (extreme)	
Parameter	Kp = 5 => Kp = 9	
Duration	Days	
Protection	Earth's magnetic field	

Effects

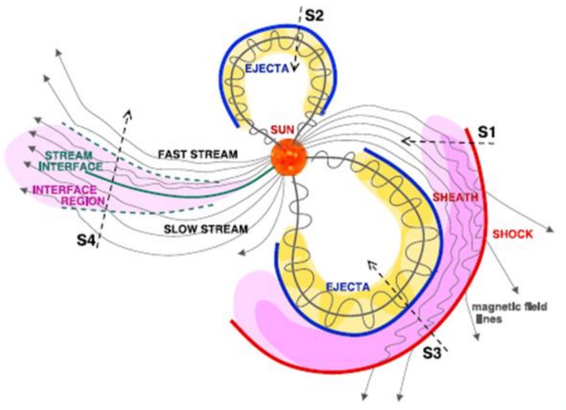
Satellites	
Aurora	
Communication/Navigation	
Electrical Currents (GIC)	

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

Brekke (2016): **AGF-216 lecture 2016: Space Weather**
http://www.slideshare.net/UniSvalbard/agf216-lecture-2016-space-weather

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

Effects from ICMEs and CHs



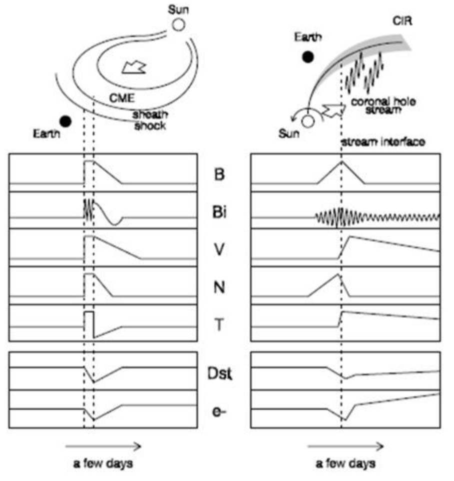


Figure 1. Schematic illustration of typical solar wind structures of coronal mass ejections (CMEs) and corotating interaction regions (CIRs): (top to bottom) magnetic field strength B, one of the Cartesian component B_i, solar wind speed V, density N, temperature T, expected response of the Dst index, 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
http://adsabs.harvard.edu/abs/2006SpWea...4.9004K

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

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

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?
http://www.stce.be/news/269/welcome.html

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

Effects from ICMEs

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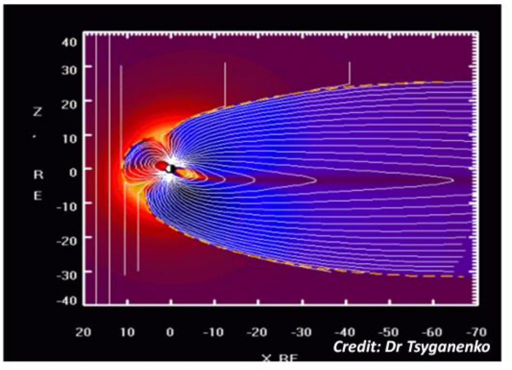
From the Sun to the Earth

The magnetosphere

- …that area of space, around a planet, that is controlled by the planet's magnetic field.
- Its … shape is the direct result of being blasted by solar wind.
- Field lines connect the magnetosphere with the ionosphere



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Definition from NASA:
https://www.nasa.gov/mission_pages/sunearth/science/magnetosphere2.html

Animation from https://commons.wikimedia.org/wiki/File:Animati3.gif

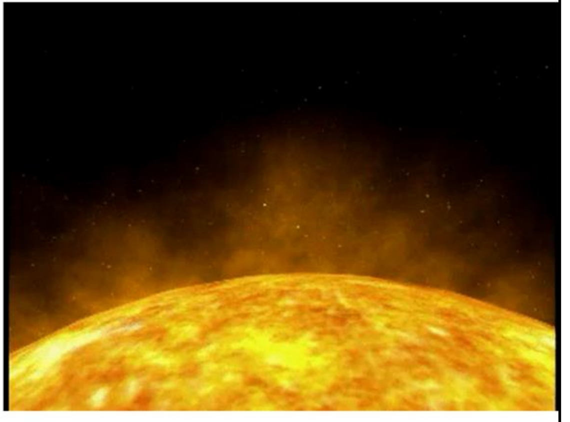
Created by Dr Tsyganenko (NASA)
More info and animations at http://geo.phys.spbu.ru/~tsyganenko/modeling.html

Note that planets without a (strong) intrinsic magnetic field have an “induced magnetosphere”, for which the above defintion obviously is not applicable. However, this is also not the focus of this lecture, which will consider the earth environment only.

“Induced magnetospheres” by Luhmann et al. (2004)
https://www.sciencedirect.com/science/article/pii/S0273117704000158
Induced magnetospheres occur around planetary bodies that are electrically conducting or have substantial ionospheres, and are exposed to a time-varying external magnetic field. They can also occur where a flowing plasma encounters a mass-loading region in which ions are added to the flow. In this introduction to the subject we examine induced magnetospheres of the former type. The solar wind interaction with Venus is used to illustrate the induced magnetosphere that results from the solar wind interaction with an ionosphere.

Geomagnetic (sub)storm

- Growth phase
  - Reconnection at magnetopause
    - Magnetic erosion
  - Open field lines are swept back into magnetotail
    - Some particles get access via cusps
    - Building of magnetic flux in magnetotail
- Expansion phase
  - Explosive release of built-up energy in magnetotail
    - Particles get accelerated to earth
      - Aurora, Ring current enhancement,…
    - A plasmoid gets ejected tailward back into solar wind
- Recovery phase



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See http://sci.esa.int/cluster/51744-magnetic-reconnection-in-earth-s-magnetosphere/ for another animation

A full description of the evolution of a geomagnetic (sub)storm can be found in the SIDC SWx Forecast Guide: http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf

Geomagnetic indices

- Measure for geomagnetic unrest
- Ground-based magnetometer networks
  - Intensity and changes in intensity of the geomagnetic field
  - Corrected for diurnal and seasonal variations (quiet Sun)

The K index is derived from the amplitude of the variations of the field's horizontal components (the H and D pair, or alternatively, the X and Y components) after subtracting the daily solar regular (S_R) variation for the particular component (cf. **Fig.2**).

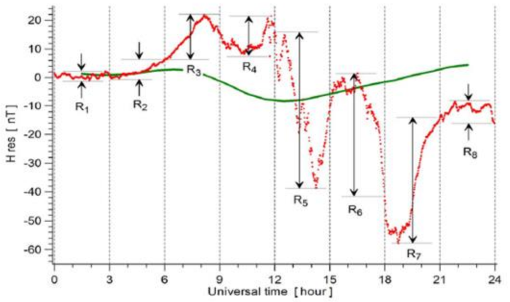

Fig.2. Calculation of the 3-hour K index over a 24 hour period. A daily record of 1-min measurements of the H component is presented here to illustrate the elimination of the solar regular variation, the S_R curve (the solid line), and the consequent determination of the 8 ranges (R_i, i=1,8). The difference between the upper (maximum) and lower (minimum) envelopes that are parallel to the S_R curve, determines the disturbance range within every 3-hour interval.

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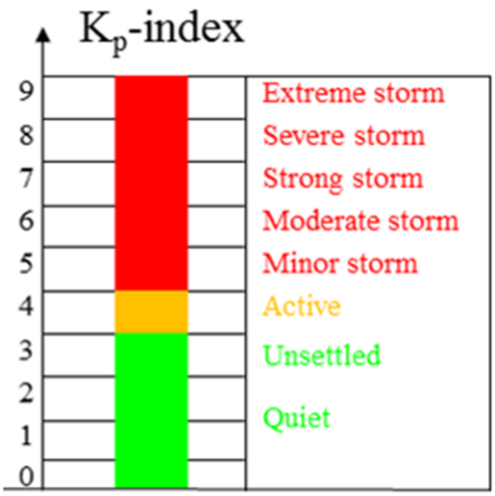
Figure from Stankov et al. (2010): Local Operational Geomagnetic Index K Calculation (K-LOGIC) from digital ground-based magnetic measurements
http://swans.meteo.be/sites/default/files/documentation/TN-RMI-2010-01_K-LOGIC.pdf

Geomagnetic indices

Kp index

- Planetarische Kennziffer
- From network (13 observatories)
- Quasi-logaritmic scale
- Expressed in 1/3
  - 0o, 0+, … => … , 9-, 9o
- 3hrs interval
  - 0-3UT, … , 21-24UT
- **Used in NOAA scales (G)**
  - Auroral visibility maps
- Estimated Kp
- Going back to 1932
- K index
  - Local (e.g. Dourbes)



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On the K and Kp index: SWPC: https://www.swpc.noaa.gov/sites/default/files/images/u2/TheK-index.pdf
Potsdam: https://www.gfz-potsdam.de/en/kp-index/

The reported values, be they updated every hour or every 3 hours, always cover the recordings of the last 3 hours.
E.g. the 10UT value reported by Dourbes covers the interval 07-10UT.

The estimated Kp values are the ones that can be found at NOAA/SWPC: https://www.swpc.noaa.gov/products/planetary-k-index

The final Kp values are determined by GFZ Potsdam and can be downloaded at Kyoto WDC: http://wdc.kugi.kyoto-u.ac.jp/kp/index.html

The maps for auroral visibility can be found at https://www.swpc.noaa.gov/content/tips-viewing-aurora

Left figure taken from HAO/UCAR SW103 Lecture 4: Geomagnetic indices and space weather models.
https://www2.hao.ucar.edu/sites/default/files/users/whawkins/SW102_4_Indices.pdf

The nomenclature is the one mentioned in NOAA/SWPC' User guide.
https://www.swpc.noaa.gov/sites/default/files/images/u2/Usr_guide.pdf

The 13 observatories for Kp are (currently operational: https://www.gfz-potsdam.de/en/kp-index/):
Sitka, Alaska, USA; Meanook, Canada; Ottawa, Canada; Fredericksburg, Virginia, USA; Hartland, UK; Wingst, Germany; Niemegk, Germany; Canberra, Australia; Brorfelde, Denmark; Eyerewell, New Zealand; Uppsala, Sweden; Eskdalemuir, UK; Lerwick, UK.

All these stations have geomagnetic latitudes between 35° and 60°. This zone is called the subauroral zone.

The main purpose of the standardized index Ks is to provide a basis for the global geomagnetic index Kp which is the average of a number of "Kp stations", originally 11. The Ks data for the two stations Brorfelde and Lovö/Uppsala, as well as for Eyerewell and Canberra, are combined so that their average enters into the final calculation, the divisor thus remaining 11.

The Estimated 3-hour Planetary Kp-index is derived at the NOAA Space Weather Prediction Center using data from the following ground-based magnetometers: Sitka, Alaska; Meanook, Canada; Ottawa, Canada; Fredericksburg, Virginia; Hartland, UK; Wingst, Germany; Niemegk, Germany; and Canberra, Australia.

Geomagnetic indices

- NOAA-scales: G-scale

SC23 / SC24 (days)

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme		Kp = 9	4 per cycle (4 days per cycle) 3 / 0
G 4	Severe		Kp = 8, including a 9-	100 per cycle (60 days per cycle) 40 / 9
G 3	Strong		Kp = 7	200 per cycle (130 days per cycle) 79 / 18
G 2	Moderate		Kp = 6	600 per cycle (360 days per cycle) 191 / 97
G 1	Minor		Kp = 5	1700 per cycle (900 days per cycle) 502 / 255

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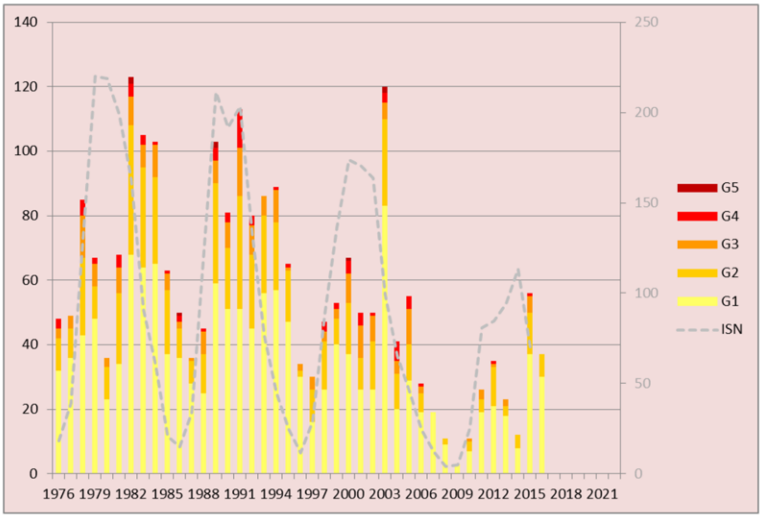
From the SWPC webpage:
NOAA Space Weather Scales
The NOAA Space Weather Scales were introduced as a way to communicate to the general public the current and future space weather conditions and their possible effects on people and systems. Many of the SWPC products describe the space environment, but few have described the effects that can be experienced as the result of environmental disturbances. These scales are useful to users of our products and those who are interested in space weather effects. The scales describe the environmental disturbances for three event types: geomagnetic storms, solar radiation storms, and radio blackouts. The scales have numbered levels, analogous to hurricanes, tornadoes, and earthquakes that convey severity. They list possible effects at each level. They also show how often such events happen, and give a measure of the intensity of the physical causes.

The « G » stands for Geomagnetic storms. Note it starts only from Kp =5 or higher.

More at http://www.stce.be/news/366/welcome.html

Geomagnetic indices

- NOAA-scales: G-scale



70

More on the NOAA-scales at at http://www.stce.be/news/366/welcome.html

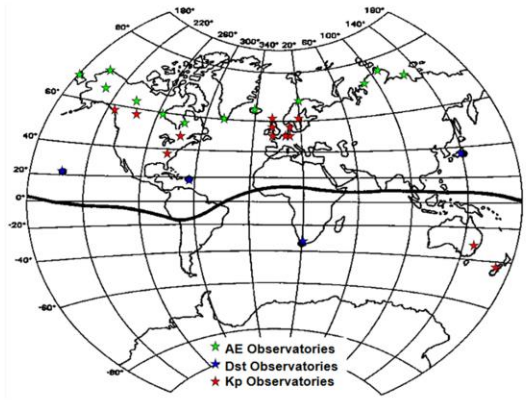
Each graph shows the yearly accumulation of the events, with the yearly International Sunspot Number (SILSO) superposed on it as the gray dashed line.
The plot of the geomagnetic storm days bears much less resemblance with the evolution of the sunspot number than in the previous two charts. This is because minor to strong geomagnetic disturbances can also be caused by the high speed solar wind streams (HSS) from coronal holes, hence distorting the familiar outlook of the sunspot cycle. Nonetheless, even then it is very clear that SC24 has been quite disappointing when it comes to the number and intensity of geomagnetic storms, with no extreme storms (G5) so far and precious few severe events (G4). Worse, the numbers even get depressingly low when one compares to other years such as e.g. the 120 storming days in 2003. Interestingly, the number of geomagnetic storm days is peaking in 2015-2016, so after the SC24 maximum in 2014. This is particularly due to the HSS from numerous coronal holes, and is a well-known aspect of this stage of a solar cycle.

More on SC24 geomagnetic performance at http://www.stce.be/news/243/welcome.html

A quick analysis of the final Kp indices as archived at the Kyoto World Data Centre (WDC) for geomagnetism reveals that the current solar cycle (SC24) is really underperforming so far. Not only has there not been any day with extreme geomagnetic storming, SC24 also has a lot more "quiet" days compared to the average of the previous 7 solar cycles (SC17-23). Of course, most of those cycles had already passed their maximum for 1-2 years, whereas SC24 is peaking only now and at a much lower solar activity level.

Geomagnetic indices (1/3)

- Ap, ap
  - Derived from Kp
    - Unit: nT
- aa
  - 2 antipodal , subauroral stations
    - Canberra, Hartland
  - Going back to 1868
- AE index
  - Auroral Electrojet
- Dst index
  - Disturbance storm time index
  - Extreme storms
    - 30 Oct 2003: -383 nT
    - 14 Mar 1989: -589 nT



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From GFZ/Potsdam: https://www.gfz-potsdam.de/en/kp-index/
The three-hour index ap and the daily indices *Ap*, … are directly related to the *Kp* index. In order to obtain a linear scale from *Kp*, J. Bartels gave the [above] table to derive a three-hour equivalent range, named ap index. This table is made in such a way that at a station at about dipole latitude 50 degrees, *ap* may be regarded as the range of the most disturbed of the two horizontal field components, expressed in the unit of 2nT.

On the aa-index: F. De Meyer (2006): The geomagnetic aa index as precursor of solar activity www.meteo.be/meteo/download/de/520427/pdf/
The availability of magnetic records from two old observatories, Greenwich (51.5° N,0.0° E) and Melbourne (37.8° S,145.0° E), which are almost antipodal, gave the possibility of obtaining a reliable long series if K scalings were made on their records (Mayaud, 1972). The two stations are nearly at the same geomagnetic latitude (one in the northern hemisphere, Greenwich: 50.1°, and one in the southern hemisphere, Melbourne: {48.9°) and about 10 h apart in longitude. The K indices from these two observatories at sub-auroral latitudes were first standardized for the corrected geomagnetic latitude of 50° in order to obtain a value identical with the one that would be obtained at a distance of 19° from the auroral zone. The converted equivalent amplitudes ak of the two stations were then averaged to provide the three-hourly index aa (expressed in units of nanotesla), which aims at monitoring the average intensity of the transient magnetic variations at sub-auroral latitudes.

More information on the aa-index also at BGS:
http://www.geomag.bgs.ac.uk/data_service/data/magnetic_indices/aaindex.html

Geomagnetic indices (2/3)

- Ap, ap
  - Derived from Kp
    - Unit: nT
- aa
  - Derived (weighted average) from K indices from 2 antipodal , subauroral stations
    - Canberra, Hartland
  - Unit: nT
  - Going back to 1868

- AE index
  - Auroral Electrojet
    - Ionospheric closure current
  - 12 auroral stations
    - Northern hem.
    - +60° to +71°
    - Quite evenly spaced
  - Unit: nT
  - Best to determine aurora visibility

Kp	0o	0+	1-	1o	1+	2-	2o	2+	3-	3o	3+	4-	4o	4+
ap	0	2	3	4	5	6	7	9	12	15	18	22	27	32
Kp	5-	5o	5+	6-	6o	6+	7-	7o	7+	8-	8o	8+	9-	9o
ap	39	48	56	67	80	94	111	132	154	179	207	236	300	400

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From GFZ/Potsdam: https://www.gfz-potsdam.de/en/kp-index/
The three-hour index ap and the daily indices *Ap*, … are directly related to the *Kp* index. In order to obtain a linear scale from *Kp*, J. Bartels gave the [above] table to derive a three-hour equivalent range, named ap index. This table is made in such a way that at a station at about dipole latitude 50 degrees, *ap* may be regarded as the range of the most disturbed of the two horizontal field components, expressed in the unit of 2nT.

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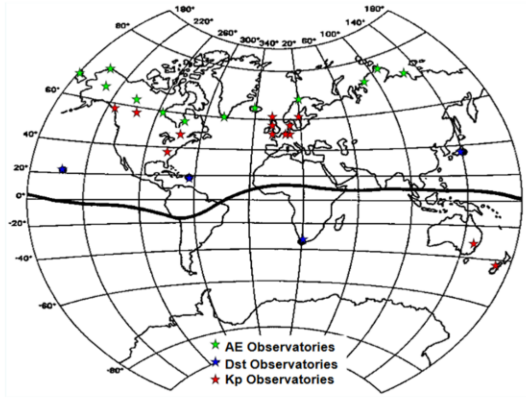
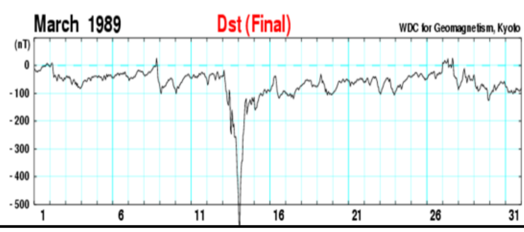
More information on the aa-index also at BGS:
http://www.geomag.bgs.ac.uk/data_service/data/magnetic_indices/aaindex.html

Geomagnetic indices (3/3)

- Dst
  - Hourly measurements
    - 4 stations close to magnetic equat.
  - Unit: nT
    - NOT a range index
  - Nomenclature
    - > -30 nT: Quiet
    - -30 - -50 nT: Weak storm
    - -50 - -100 nT: Moderate storm
    - -100 - -250 nT: Intense storm
    - < -250 nT: Extreme storm
  - Real-time monitoring Kyoto, WDC
  - Most intense storms of SC24
    - 17 March 2015 (-223 nT)
    - 23 Jun 2015 (-204 nT)
  - Extreme storms
    - 30 Oct 2003: -383 nT
    - 14 Mar 1989: -589 nT





Real time monitoring at http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/presentmonth/index.html

Top right figure taken from HAO/UCAR SW103 Lecture 4: Geomagnetic indices and space weather models. https://www2.hao.ucar.edu/sites/default/files/users/whawkins/SW102_4_Indices.pdf

Source: Love J.J., Remick K.J. (2007) Magnetic Indices. In: Gubbins D., Herrero-Bervera E. (eds) Encyclopedia of Geomagnetism and Paleomagnetism. Springer, Dordrecht - https://doi.org/10.1007/978-1-4020-4423-6_178 ; https://geomag.usgs.gov/downloads/publications/Magnetic_Indices.pdf

One of the most systematic effects seen in ground-based magnetometer data is a general depression of the horizontal magnetic field as recorded at near-equatorial observatories (Moos, 1910). This is often interpreted as an enhancement of a westward magnetospheric equatorial ring current, whose magnetic field at the Earth's surface partially cancels the predominantly northerly component of the main field. The storm-time disturbance index Dst (Sugiura, 1964) is designed to measure this phenomenon. Dst is one of the most widely used indices in academic research on the magnetosphere, in part because it is well
motivated by a specific physical theory. The calculation of Dst is generally similar to that of AE, but it is more refined, since the magnetic signal of interest is quite a bit smaller. One-min resolution horizontal intensity data from low-latitude observatories are used, and diurnal and secular variation baselines are subtracted. A geometric adjustment is made to the resulting data from each observatory so that they are all normalized to the magnetic equator.
The average, then, is the Dst index. It is worth noting that, unlike the other indices summarized here, Dst is not a range index.

The 4 stations are Kakioka (Japan), Hermanus (South Africa), Honolulu (Hawaii, USA), San Juan (USA).

From the SIDC SWx Forecast Guide: http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf
The Dst or disturbance storm time index is a measure of geomagnetic activity used to assess the severity of magnetic storms. It is often considered to reflect variations in the intensity of the symmetric part of the ring current that circles Earth at altitudes ranging from about 3 to 8 Earth radii (RE), and is proportional to the total energy in the drifting particles that form the ring current (Wanliss et al. 2006, and references therein). It is calculated as an hourly index from the horizontal magnetic field component (H) at four observatories located close enough to the magnetic equator that they are not strongly influenced by auroral current systems. At the same time, these stations are far enough away from the magnetic equator so that they are not significantly influenced by the equatorial electrojet current that flows in the ionosphere. They are also relatively evenly spaced in longitude … . The convolution of their magnetic variations forms the Dst index, measured in nT, which is thought to provide a reasonable global estimate of the variation of the horizontal field near the equator. So: Dst represents an induced magnetic field caused by the ring current particles, which are plasmasheet particles that are accelerated towards Earth during (sub)storms, where electrons rotate around Earth in one sense, and the ions in the other sense (as in the radiation belts) thus creating a current.

:Issued: 2014 Apr 17 1325 UTC
:Product: documentation at http://www.sidc.be/products/tot
#--#
DAILY BULLETIN ON SOLAR AND GEOMAGNETIC ACTIVITY from the SIDC
#--#
SIDC URSIGRAM 40417
SIDC SOLAR BULLETIN 17 Apr 2014, 1304UT

Finding your way in the URSIgram

SIDC FORECAST (valid from 1230UT, 17 Apr 2014 until 19 Apr 2014)
SOLAR FLARES : Active (M-class flares expected, probability >=50%)
GEOMAGNETISM : Quiet (A<20 and K<4)
SOLAR PROTONS : Quiet

PREDICTIONS FOR 17 Apr 2014 10CM FLUX: 180 / AP: 013
PREDICTIONS FOR 18 Apr 2014 10CM FLUX: 184 / AP: 007
PREDICTIONS FOR 19 Apr 2014 10CM FLUX: 188 / AP: 005

COMMENT: Eleven sunspot groups were reported by NOAA today. NOAA ARs 2035,2036, and 2037 (Catania numbers 24, 25, and 26 respectively) maintain the beta-gamma configuration of the photospheric magnetic field. The strongest flare of the past 24 hours was the M1.0 flare peaking at 19:59 UT yesterday in the NOAA AR 2035 (Catania number 24). The flare was associated with an EIT wave and a weak coronal dimming, but the associated CME was narrow and is not expected to arrive at the Earth.
We expect further flaring activity on the C-level, especially in the NOAA ARs 2035 and 2037 (Catania numbers 24 and 26 respectively) as well as in the NOAA AR 2042 (no Catania number yet) that yesterday appeared from behind the east solar limb, with a good chance for an M-class event.

Since yesterday evening the Earth is situated inside a solar wind structure with an elevated interplanetary magnetic field magnitude (occasionally up to 10 nT). It may be a weak ICME or the compression region on the flank of an ICME that missed the Earth. The solar origin of this structure is not clear. The north-south magnetic field component Bz was not strong, so no significant geomagnetic disturbance resulted (K index stayed below 4). Currently the solar wind speed is around 380 km/s and the IMF magnitude is around 8 nT.
We expect quiet to unsettled (K index up to 3) geomagnetic conditions, with active geomagnetic conditions (K = 4) possible, but unlikely.

TODAY'S ESTIMATED ISN : 145, BASED ON 17 STATIONS.
99999

SOLAR INDICES FOR 16 Apr 2014
WOLF NUMBER CATANIA : ///
10CM SOLAR FLUX : 184
AK CHAMBON LA FORET : 012
AK WINGST : 004
ESTIMATED AP : 004
ESTIMATED ISN : 139, BASED ON 29 STATIONS.

Geomagnetic activity

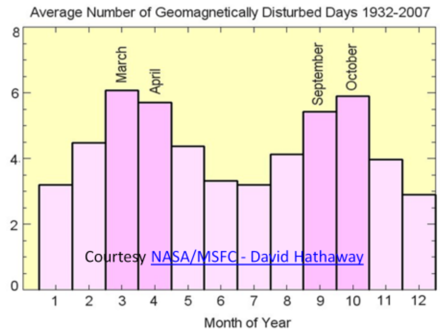
NOTICEABLE EVENTS SUMMARY

DAY	BEGIN	MAX	END	LOC	XRAY	OP	10CM	Catania/NOAA	RADIO_BURST_TYPES
16	1954	1959	2004	S14E09	M1.0	1N		24/2035	II/2

END

Miscellaneous

- Seasonal variation
  - More geomagnetic storms during equinoxes than during solstices
  - Probable explanation by Russell & McPherron (1973)



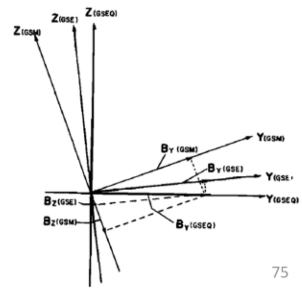


Fig. 4. One of the possible orientations of the *Y-Z* planes of the solar equatorial (GSEQ), solar ecliptic (GSE), and solar magnetospheric (GSM) coordinates, showing how a vector in the solar equatorial plane can have a southward (along the −*Z* axis) GSE and GSM component.

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From the SIDC SWx Forecast Guide:
http://www.sidc.be/PRODEX_SIDEx/docs/Space_Weather_Forecasting_Guide_latest.pdf
Another element is the seasonal variation of the geomagnetic disturbances (Figure 52). Already in 1856, Edward Sabine showed from magnetic recordings that "… January and June are the months of minimum disturbance, September and April the months of maximum disturbance. The aggregate value of the disturbances in the equinoctial months is about three times as great as in the solstitial months." (Sabine 1856). This finding has been assessed and confirmed on numerous occasions and for various geomagnetic indices (e.g. Cliver et al. 2001, Svalgaard et al. 2002, Balan et al. 2017). The semiannual variation has been interpreted in terms of the (1) axial hypothesis based on the variation of the heliospheric latitude of the Earth with time of year (e.g., Cortie 1912), (2) equinoctial hypothesis based on the variation of the angle between the Earth–Sun line and Earth's dipole axis (e.g., Bartels 1932) and (3) Russell–McPherron (RM) effect based on the varying angle between the GSM (geocentric solar magnetospheric) Z-axis and GSE (geocentric solar ecliptic) Y-axis (Russell and McPherron 1973). From a review of subsequent papers, Bothmer et al. 2007 concluded that hypothesis (1) does not seem to play a key role in the origin of the semiannual variation.

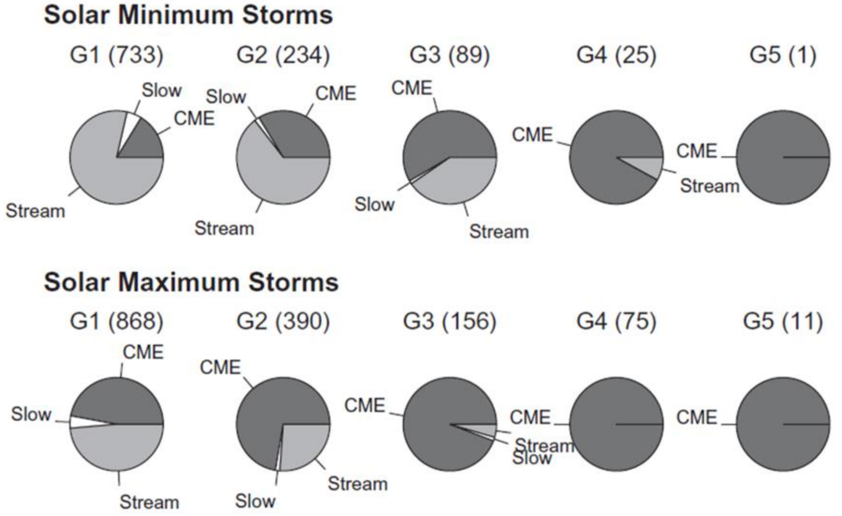
Russell, C. T., McPherron, R. L. (1973): Semiannual variation of geomagnetic activity
http://adsabs.harvard.edu/abs/1973JGR....78...92R
*** … geomagnetic activity is caused by substorms, and, whereas the magnitude of the southward component has been shown to control substorm activity, the solar wind velocity, which controls the Kelvin-Helmholtz instability, has not. … The semiannual variation of geomagnetic activity is a manifestation of the varying probability of a southward component occurring in solar magnetospheric coordinates due to the changing orientation of the solar magnetospheric coordinate system relative to the solar equatorial system. This theory is both an axial theory, because the solar equatorial system depends on the heliographic latitude of the earth, and an equinoctial hypothesis, because the orientation of the solar magnetospheric coordinate system depends on the orientation of the earth's rotation axis relative to the solar wind. … We can further test the models, though, by examining auxiliary predictions of the models.
In particular, the southward component model predicts that the spring maximum in activity is associated on the average with fields toward the sun and the fall maximum with fields away from the sun.***

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



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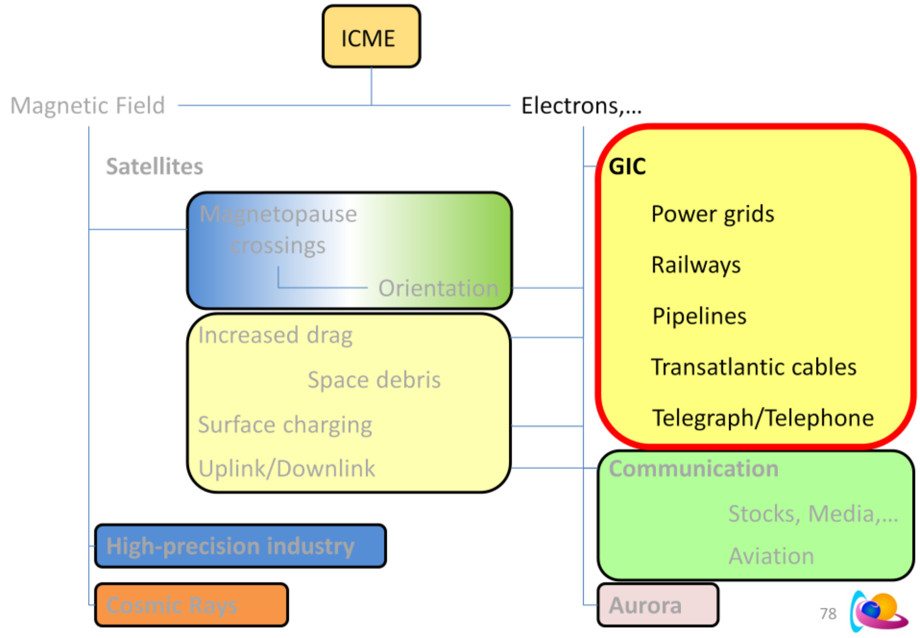
Richardson et al. (2012): Solar wind drivers of geomagnetic storms during more than four solar cycles
http://adsabs.harvard.edu/abs/2012JSWSC...2A..01R
Generally, the number of CME-associated storms (black curves in Fig. 1) follows solar activity levels, as would be expected since the ICME rate at 1 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



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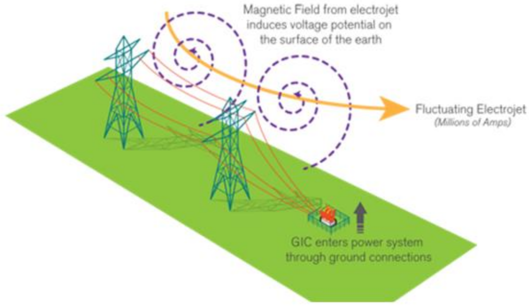
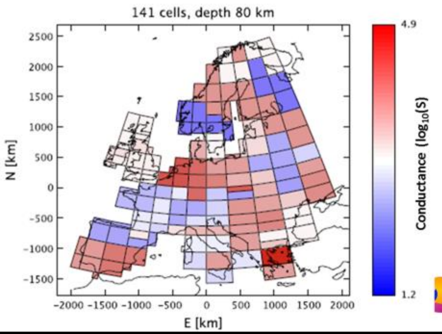
Effects from ICMEs

- 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 http://www.spxtransformersolutions.com/news/FERC_GIC_2.2014.html

Bottom figure:
Viljanen et al. (2014): Geomagnetically induced currents in Europe. Modelled occurrence in a continent-wide power grid
http://adsabs.harvard.edu/abs/2014JSWSC...4A..09V
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
http://adsabs.harvard.edu/abs/2015GeoRL..42.6554C
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!

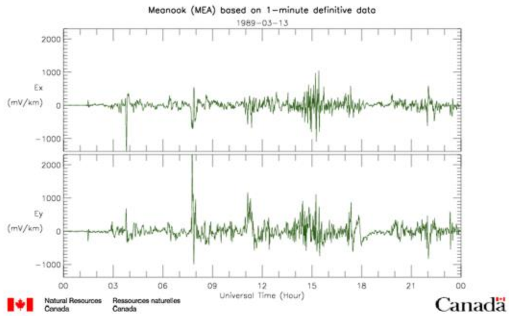


Table 3 Parameters for the GIC emergency alert model. The criterion for each alert level is shown in the second column, and the following columns show the expected extreme *dB/dt* values for RC-, AE-, and SC-type GICs

		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

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

GIC graphs available at
NR CAN: http://www.spaceweather.gc.ca/plot-tracee/geo-en.php
EURISGIC: http://eurisgic.org/

Table 3 from Kataoka et al. (2016): Extreme geomagnetically induced currents
http://adsabs.harvard.edu/abs/2016PEPS....3...23K

Longterm effect of power loss: In case of catastrophic failure: multiple transformers down would take a long time to replace/repair meaning that meanwhile, the population would cope with the effects of longterm no power available (traffic, fuel,…).

Effects from ICMEs

- GICs
  - Railways
    - Sweden, 13-14 July 1982
    - China, 17 March & 23 June 2015
  - Pipelines
    - Corrosion
      - Oil leaks
  - Telephone/Telegraph
    - Carrington event,…
    - Transcontinental cables
      - 4 August 1972
  - Transatlantic cables
    - Cupper to optical fibre
      - But « optical repeaters »!
      - March 1989 event

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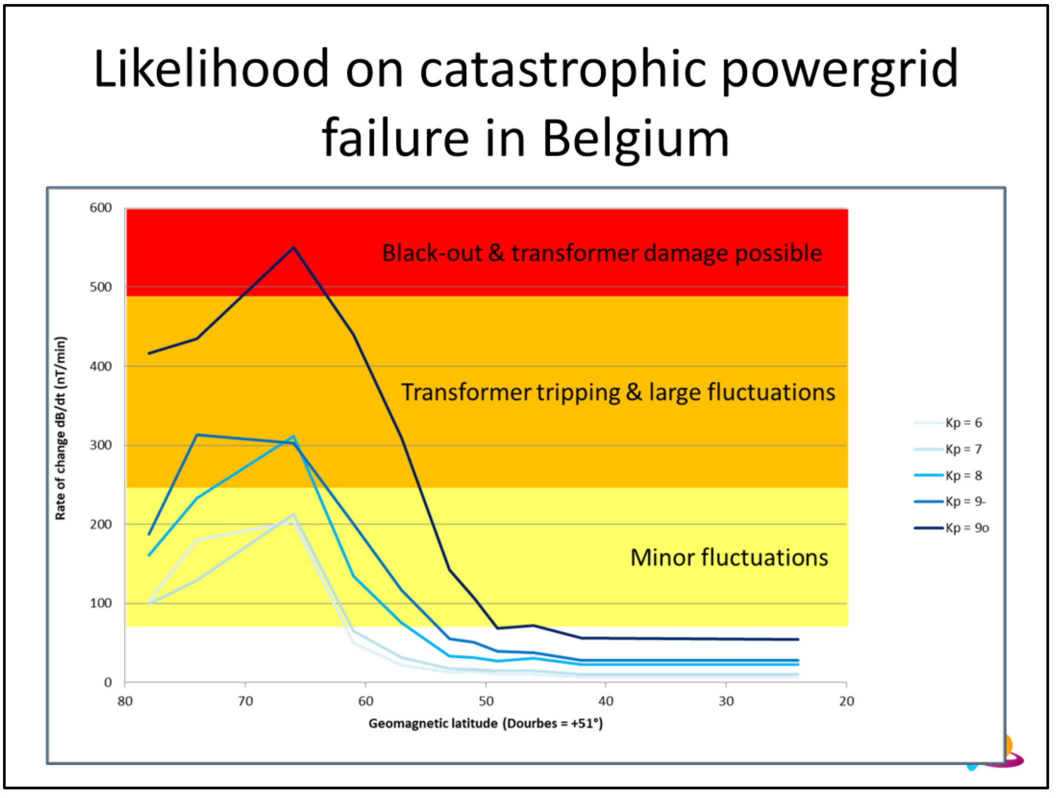
Top image from http://alyeska-pipeline.com/NewsCenter/Logos
Bottom image from http://www.submarinecablesystems.com/default.asp.pg-history

- Railways:
Liu et al. (2016): Analysis of the monitoring data of geomagnetic storm interference in the electrification system of a high-speed railway
http://adsabs.harvard.edu/abs/2016SpWea..14..754L
Wik et al. (2009): Space Weather events in July 1982 and October 2003…
http://adsabs.harvard.edu/abs/2009AnGeo..27.1775W
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
http://adsabs.harvard.edu/abs/2005AnGeo..23.3089H
- Also at http://www.windows2universe.org/space_weather/sw_in_depth/pipeline_effects.html
- Also at RNCan: http://www.spaceweather.gc.ca/tech/se-pip-en.php

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

RAE (2013): Extreme space weather: impacts on engineered systems and infrastructure
http://www.raeng.org.uk/publications/reports/space-weather-full-report
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.



This is from a poster accepted for the ESWW16 (18-22 Nov 2019) Session: 4 GICs: Ground system hazards from geomagnetically induced currents – research, developments, services, and operations.

Very low likelihood of a power grid black-out in Belgium during an extremely severe geomagnetic storm Jan Janssens (STCE)

Context. The STCE regularly gets questions from the broad public and space weather (SWx) end users on the probability of a power grid black-out in Belgium during a strong geomagnetic storm. In a recent report analysing black-outs and strong disturbances of the Belgian power grid, Elia, Belgium's main high-voltage transmission system operator, mentioned not a single SWx-related event during the period 1977-2017. At most, during the strongest geomagnetic storms, they noted some mild fluctuations on the grid which were easily handled.

Aims. This study compares the variations in the magnetic field in Belgium during strong geomagnetic storms with those from other magnetometer stations in the European sector, thereby putting them in perspective against a series of magnetic field fluctuations which are known to have caused failures and great disturbances in the power grid at more northern latitudes.

Methodology. First, for the period 1996-2017, a list of 179 days with strong geomagnetic storms was compiled (Kp >= 7). Then, a dozen of magnetometer stations in the European sector were selected from the Intermagnet database (http://www.intermagnet.org/). Belgium is represented by the geomagnetic observatory in Dourbes (geomagnetic latitude: + 51°).
For each station and each storm day, the maximum "rate of change" dB/dt was determined in both the x- and y-direction of the H-component of the Earth's magnetic field. "dB/dt" is considered to be proportional to the GIC, but the measured GIC-value depends also on the local conductivity of the Earth's surface, the lay-out of the power grid,... The maximum of the absolute values of dB/dt was determined per station and per storm day, and the average calculated for each Kp. A distinction has been made between Kp = 9- en 9o, as the differences in dB/dt were relatively large.
Finally, based on reports from 8 important GIC-events (2 in Canada, 5 in Sweden, 1 in China) during the 1972-2015 period, the dB/dt level was determined (1) for which black-outs/transformer damage happened (1972, 1989 and 2003), (2) when severe disturbances of the power grid happened, and (3) for what could be considered as "relatively" minor disturbances.

Result. The analysis clearly shows that Belgium has a near zero probability for a power grid failure similar to Québec in 1989. Maximum dB/dt values in Dourbes should be at least 4 to 5 times higher than those recorded during the Halloween storms in October 2003, i.e. 550 nT/min vs. the recorded 110 nT/min.

Likelihood on catastrophic powergrid failure

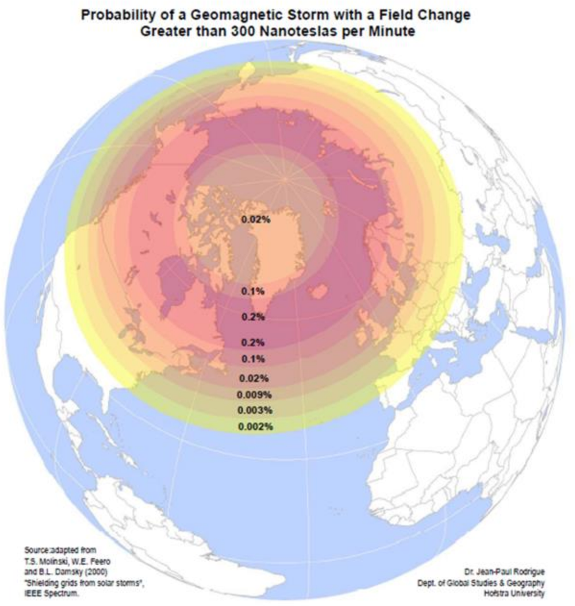


Table 1. Problems due to GIC in ground-based technological systems in Sweden.

Date	Effects
2 Sep 1859	Problems with the telegraph system in Gothenburg
13–15 May 1921	Fires in telegraph equipment
11 Feb 1958	Fires with severe damage in telegraph equipment
13 Nov 1960	30 line circuit breakers tripped in the high-voltage power network
13–14 Jul 1982	4 transformers and 15 lines tripped in the high-voltage power system. Railway traffic lights turned erroneously to red. Telecommunications were also affected.
8–9 Feb 1986	5 events in the high-voltage power system, 1–3 lines tripped per event
13–14 Mar 1989	5 130 kV lines tripped, 5-degree temperature increase in a generator
24 Mar 1991	9 220 kV lines and a transformer tripped
9 Nov 1991	One 220 kV line tripped. Large pipe-to-soil voltages in a pipeline
1999	Radio communication for protection lost in the power system
2000	Voltage drop in the 400 kV system
6 Apr 2000	Largest GIC ever measured in a transformer (about 300 A)
30 Oct 2003	Power blackout in Malmö, excess heating in a transformer
8 Nov 2004	GIC of over 100 A measured in a transformer in southern Sweden

M. Wik et al. (2009): Space weather events in Sweden

Original source: Shielding Grids From Solar Storms, Molinski et al. (2000)
https://spectrum.ieee.org/energy/the-smarter-grid/shielding-grids-from-solar-storms

Paper (2002) at https://ui.adsabs.harvard.edu/abs/2002JASTP..64.1765M/abstract
https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=3&cad=rja&uact=8&ved=2ahUKEwjA-6y8kZTlAhULiVwKHeuuAbYQFjACegQIAxAB&url=https%3A%2F%2Fwww.researchgate.net%2Fpublication%2F223649362_Why_utilities_respect_geomagnetically_induced_currents&usg=AOvVaw06Zcx_hRlIxPWBziEYiSU3

Figure found in https://core.ac.uk/download/pdf/38629068.pdf
The digital geomagnetic data can also be used to evaluate the rate of change of the magnetic field dB/dt. Figure 5 reproduces the percentage occurrences of dB/dt > 300nT/minute, derived from North American magnetic observatories. Since the probability variation with the geomagnetic latitude is smooth, the results were extrapolated along lines of constant geomagnetic latitude. The color grading extends from red, where the probability is higher, to yellow in those areas where the probability diminishes. A low probability for large GMD events is expected in most of North America and Central Europe (Molinski et al., 2000).

Also at https://transportgeography.org/?page_id=6416 and
https://transportgeography.org/?page_id=6295

The table to the right comes from Wik et al. (2009)
https://ui.adsabs.harvard.edu/abs/2009AnGeo..27.1775W/abstract

Summary SWx effects

- **Solar flares**
  - NOAA scale (R)
  - Communications
  - Navigation
- **Proton events**
  - NOAA scale (S)
  - Satellites
  - Communications (PCA)
  - Biological hazard
  - Ground Level Enhancement
- **ICMEs**
  - Geomagnetic storm
    - Mechanism
    - Indices
  - NOAA scale (G)
  - GIC
    - Mechanism
    - Powergrids
    - Other technologies
    - Belgium
- **Coronal Holes**
  - Impacts less severe than with (strong) CMEs

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Overview

- Introduction
- Drivers of SWx
- SWx effects
- Extreme events
- URSIgram

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Historic solar storms…

Date event	NOAA R	NOAA S	NOAA G	WLF?	Satellites / Instrum. down?	Strong GIC?	Transfo. loss?	Comms. loss?	Remarks
17 Jan 2005	3	3	3	Satellite	Some	No	No	Poles	United Airlines: 26 Polar flights detoured in 4 days!
28 Oct 2003	4	4	5	Yes	Loss of Midori-2	Yes	Malmö South-Africa	Day side	No contact with climbers Mt Everest and Trans-Atl. Sailing race Ozone layer affected Astronauts deep in ISS report « ocular shooting stars »
14 Jul 2000	3	4	5	Satellite	Loss of Astro-D	Yes	No	Poles	Ozone layer affected (1 %) ISS lost 15 km in just a few hours GPS errors double the usual
10 Mar 1989	4	3	5	Yes	Many	Yes	Québec	Poles	Tracking lost of 1300 objects! SMM burned up too soon
4 Aug 1972	3	5+	5-	Yes	-	Yes	British Columb. (CAN)	AT&T	Fastest Transit Event (FTE: 14.6 hrs!) Deadly dose for Apollo-astronauts if on the Moon
1 Sep 1859	5*	5+*	5+	Yes	-	Yes	-	Yes	First White Light Flare (WLF) Inoperable telegraph Aurora visible in Cuba & Hawaï G-storm 3* intenser than Mar 1989 Ozone layer affected (5%)

There's an excellent discussion of most of these events by S. Odenwald (NASA):
http://www.solarstorms.org/SRefStorms.html
As well as at http://www.solarstorms.org/S23rdCycle.html

Some general discussions of extreme solar activity:
- Cliver et al. (2004):The 1859 Solar-Terrestrial Disturbance And the Current Limits of Extreme Space Weather Activity
http://adsabs.harvard.edu/abs/2004SoPh..224..407C
- Cliver et al. (2013): The 1859 space weather event revisited: limits of extreme activity
http://adsabs.harvard.edu/abs/2013JSWSC...3A..31C
- Weaver et al. (2004): Halloween Space weather Storms of 2003
- Wikipedia: List of solar storms: https://en.wikipedia.org/wiki/List_of_solar_storms

*: Data from Cliver et al (2013): deduced from proxies resp. magnetic crochet en nitrogen in polar ice

Flares in X-ray (top to bottom): X3, X17, X5, X4 (X15?), X4, est. X45
Proton events: (top to bottom): 5040, 29500, 24000, 3500, 70000 (Knipp et al. 2018), 2000000 (?!)
Dst (top to bottom, in nT): -97, -383, -301, -589, -125, +/- 900 nT
1972: The transformer of British Columbia exploded!
The flare of 4 Aug 1972 occurred precisely halfway between the Apollo 16 and 17 missions

Ozone layer:
http://earthobservatory.nasa.gov/Features/ProtonOzone/
http://www.newscientist.com/article/dn11456-solar-superflare-shredded-earths-ozone.html#.UneVUxCMmSo
During intense proton storms, the particles also break down N2 (molecular nitrogen), and in stead of forming again O3 (ozone), NO2 is being formed.

WLF: White Light Flare; zie http://users.telenet.be/j.janssens/WLF/Whitelightflare.html Some WLFs are seen only by satellite (TRACE, SDO).

A polar cap absorption event results from the ionisation of the D-layer of the polar ionosphere by high energy protons. A PCA causes a HF radio blackout for trans polar circuits and can last several days. PCAs are almost always preceded by a major solar flare with the time between the flare event and the onset of the PCA ranging from few minutes to several hours.

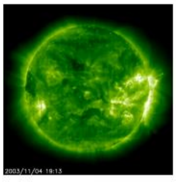
Drivers of disturbed space weather

Solar eruptions

Magnetic Reconnection

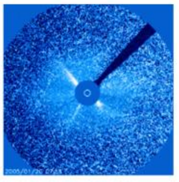
Radiation

Solar flares

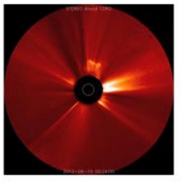


Particles

Proton events



Coronal Mass Ejections

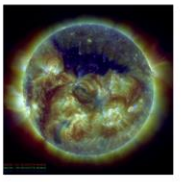


Solar corona

Solar wind

Particles

Coronal Holes



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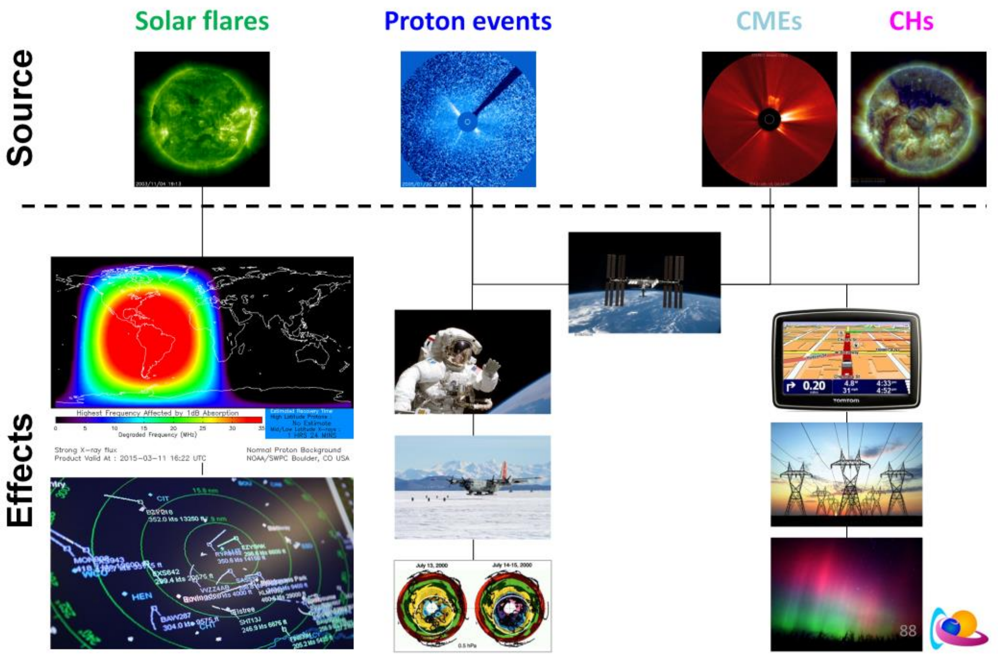
Effects from disturbed space weather



Topleft image from https://en.wikipedia.org/wiki/Solar_storm_of_1859
Topright magnetogram taken from http://www.geomag.bgs.ac.uk/education/carrington.html

Carrington (1859): Description of a Singular Appearance seen in the Sun on September 1, 1859
http://adsabs.harvard.edu/abs/1859MNRAS..20...13C

Cliver et al. The 1859 space weather event revisited: limits of extreme activity
http://www.swsc-journal.org/articles/swsc/pdf/2013/01/swsc130015.pdf

Wiki: https://en.wikipedia.org/wiki/Solar_storm_of_1859

May 15, 1921 - The entire signal and switching system of the New York Central Railroad below 125th street was put out of operation, followed by a fire in the control tower at 57th Street and Park Avenue. The cause of the outage was later ascribed to a ''ground current'' that had invaded the electrical system. Brewster New York, railroad officials formally assigned blame for a fire destroyed the Central New England Railroad station, to the aurora. [NYT,1921] ***This concerned the GIC effects from a CME***
https://spectregroup.wordpress.com/2010/05/12/a-carrington-event/

August 1972 - Topright movie downloaded from https://www.youtube.com/watch?v=kB8InKwVIg8
Also at https://solarscience.msfc.nasa.gov/flares.shtml

A discussion of this storm is at:
- NASA: https://www.nasa.gov/mission_pages/stereo/news/stereo_astronauts.html
- Odenwald: http://www.solarstorms.org/SRefStorms.html
- STCE: http://www.stce.be/news/233/welcome.html
- There were GLEs on both the 4th and 7th of August : http://natural-sciences.nwu.ac.za/neutron-monitor-data

AT&T: a huge solar flare on August 4, 1972, knocked out long-distance telephone communication across Illinois. That event, in fact, caused AT&T to redesign its power system for transatlantic cables. See http://science.nasa.gov/science-news/science-at-nasa/2008/06may_carringtonflare/
This event followed on 3 X-class flares from 2 August that kind if « cleaned the path », hence a Fast Transit Event (FTE). Other important FTE are those from 28-29 October 2003 (19h) & 1-2 September 1859 (17h) .
Also a transformer was destroyed: https://ics-cert.us-cert.gov/advisories/ICSA-11-084-01

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
http://www.stce.be/esww15/contributions/session1_Knipp_Little_Known_Consequences_posted.pdf
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*.

SWx storms and less-known GIC events

15 May 1921 – New York Railroad System

August 1972 – Transcont. cable, IL, USA

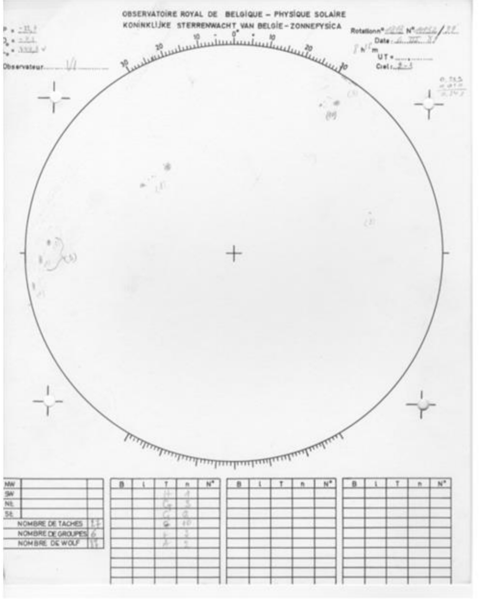
13-14 July 1982 – Railroad lights, Sweden

6-7 April 2000 – Pipeline corrosion, Canada

July 1982 - Wik et al. (2009): https://ui.adsabs.harvard.edu/abs/2009AnGeo..27.1775W/abstract
In the night between 13 and 14 July 1982, the traffic lights turned red without any obvious reason in a railway section of about 45 km in length in the southern part of Sweden … . After a while the lights turned green and back to red again later. The reason was that the geoelectric field affected the relays as follows. In normal conditions, in the absence of a train, a battery maintains a dc voltage of 3 to 5 V between the rails and over a relay, which is thus energised. A second circuit affected by the relay is connected to the traffic lights, which implies that the light is green when the relay is energised, whereas a de-energised relay produces a red light. When a train is present, the axles of the train short-circuit the rails making the voltage zero thus de-energising the relay leading to a red light. During this event, the voltage between the rails associated with the induced geoelectric field had magnitudes in the order of volts. Consequently, it was large enough to affect the above-mentioned voltage of 3–5 V. At times when the induced voltage was opposite to the battery voltage, the latter was cancelled (at least partly) resulting in a de-energisation of the relay, which thus reacted as if the rails were occupied and caused the traffic lights to turn red. When the induced voltage was reversed the lights became green again. Geoelectric field values of about 4–5 V/km were observed in Sweden during the July-1982 storm, which means that voltages of about 3–5 V are already obtained at length scales of one to two kilometres or even less, which can explain the railway traffic light malfunction.

April 2000: https://spaceweather.gc.ca/tech/se-pip-en.php?wbdisable=true
During magnetic storms, these variations can be large enough to keep a pipeline in the unprotected region for some time, which can reduce the lifetime of the pipeline. As an example, the geomagnetic storm on the 6-7 April 2000 is shown on the figure. The top panel shows geomagnetic field variations at Ottawa magnetic observatory; the bottom panel shows the pipe-to-soil potential difference on a pipeline in Canada, recorded at the same time. During the magnetic storm the pipe-to-soil potential difference went outside the safe region. That can increase the possibility of corrosion.

13-14 March 1989: Québec event

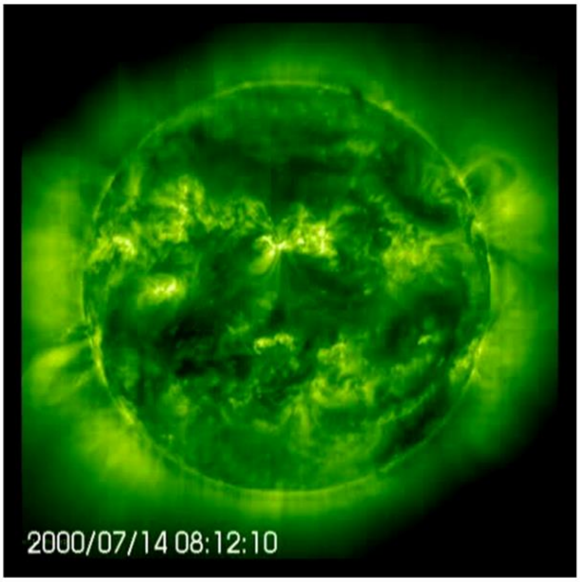


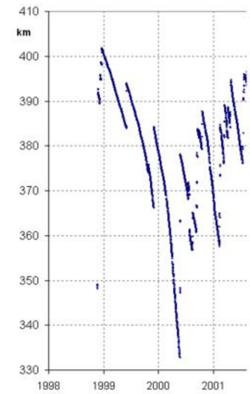
Topleft animation from images at USET: http://www.sidc.be/uset/

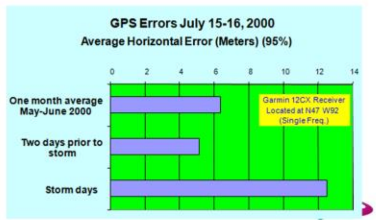
Topright movies obtained from http://sfd.njit.edu/ (NJIT Solar Film Digitization Project)
Bottom right image from
http://www.windows2universe.org/space_weather/sw_in_depth/sw_voltage_transformer_damage.html
Image courtesy of Public Service Electric and Gas and Peter Balma.

Wiki: https://en.wikipedia.org/wiki/March_1989_geomagnetic_storm
Odenwald: https://www.nasa.gov/topics/earth/features/sun_darkness.html
Odenwald: http://www.solarstorms.org/SWChapter1.html
Space.com: http://www.space.com/24983-auroras-1989-great-solar-storm.html

14 July 2000: Bastille Day Event



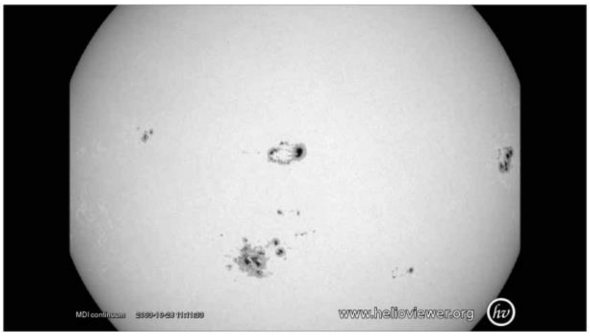




Left movie from https://sohowww.nascom.nasa.gov/gallery/Movies/flares.html
Topright image from http://www.heavens-above.com/IssHeight.aspx (old)
Bottomright image from
http://www.ofcm.gov/risk/presentations/day%201/1_intro_obj/fc_welcome_intro_obj_updated.ppt (old)

Wiki: https://en.wikipedia.org/wiki/Bastille_Day_event
Watari et al. (2001): The Bastille Day (14 July 2000) Event in Historical Large SUN EARTH Connection Events
http://adsabs.harvard.edu/abs/2001SoPh..204..425W
http://earthobservatory.nasa.gov/Features/ProtonOzone/

28 October 2003: Halloween event



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

Plunkett: https://www.nrl.navy.mil/content_images/05FA5.pdf
Weaver et al.: HALLOWEEN SPACE WEATHER STORMS OF 2003
http://www.nuevatribuna.es/media/nuevatribuna/files/2016/10/28/2004_-noaa_halloweenstorms2003_assessment.pdf

Big solar storms during SC24…

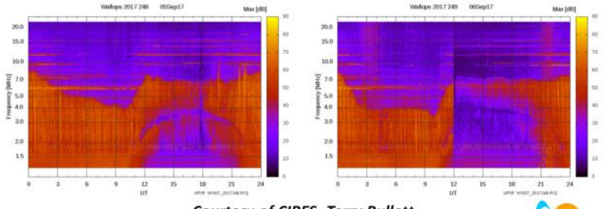
SWx effects!

Date event	NOAA R	NOAA S	NOAA G	Remarks
7 Jun 2011	1	1	-	Impressive eruption, NOAA 1226 (M2/72pfu)
3-4 Aug 2011	2	1	4	CME cannibalism; Aurora in NL, GE,… NOAA 1261 (M6/M9; 96pfu)
9 Aug 2011	3	1	-	Strongest flare of SC24 so far; NOAA 1263 (X6.9; 26pfu)
21-22 / 24-25 Oct 2011	1	-	3	GOES exposed; GIC; bloodred aurora in OK & AZ (USA), New-Z & Australia (M1/M1); WAAS/EGNOS!
23-24 Jan 2012	2	3	-	M8 LDE (6310 pfu) in NOAA 1402; several polar flights rerouted
7 Mar 2012	3	3	3+	Several SWx effects; NOAA 1429 (X5.4; 6530 pfu)
19 Jul 2012	2	-	-	Round post-flare coronal loops; NOAA 1520 (M7.7)
23 Jul 2012	Farside	1	Farside	FTE (19hrs): 3400 km/s; ; NOAA1520 (12 pfu); Carrington-like event
31 Aug 2012	-	1	1	Impressive filament eruption (C8; 59pfu)
29 Sep – 02 Oct 2013	-	2	4	Impressive filament eruption (C1; 182 pfu)
7 Jan 2014	3	3	-	NOAA 1944 (X1; 1033 pfu); Launch supply vessel ISS delayed
25 Feb 2014	3	2	2	NOAA 1990 (X4.9; 103 pfu)
1 Sep 2014	Farside	Enhanced	-	« NOAA2158 »; ST-A lost Sun-lock
10 Sep 2014	3	2	3	NOAA 2158 (X1; 126 pfu))
16-30 Oct 2014	3	-	-	NOAA 2192 (X1/X1/X3/X1/X2/X2); NO CMEs!
15 / 17 Mar 2015	-	-	4	Most intense G-storm of SC24 Dst -223nT ; NOAA 2297 (C9)
21-23 Jun 2015	2	3	4	NOAA 2371 (M7; 1070pfu); Dst: -204nT
4 Nov 2015	1	-	2	NOAA 2443 (M3.7); ATC Sweden out!
6-12 Sep 2017	3	3	4	NOAA 2673 (X9.3 and X8.2; 1490 pfu); HF & GPS: hurricane Irma

SWx effects!

SWx effects during SC24

- 24-25 October 2011
  - WAAS/EGNOS services interrupted; blood-red aurora
- 24 January 2012
  - Polar flight detours
- 7 March 2012
  - Polar flight detours
- 7 January 2014
  - Delay launch supply rocket ISS
- 1 September 2014
  - ST-B lost sun-lock
- 4 November 2015
  - Swedish Air Traffic down
- 6-12 September 2017
  - HF comms down during hurricane Irma



Courtesy of CIRES, Terry Bullett

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On 24-25 October 2011, another episode of major geomagnetic storming. … The Earth's magnetic field got so compressed that geosynchronous satellites were briefly exposed to the solar wind. Geomagnetically induced currents were recorded in Scandinavia, The storm will especially be remembered for its blood red aurora, some of which were seen as far south as Oklahoma and Arizona, as well as in New Zealand and in Australia.
http://onlinelibrary.wiley.com/doi/10.1002/2013SW000982/epdf : Federal Aviation Administration's Wide Area Augmentation System (WAAS) navigation service in the U.S.

24 January 2012
http://www.nydailynews.com/news/delta-air-lines-reroutes-flights-concerns-big-solar-flare-article-1.1011344
Jan 23/0530Jan 24/1530 6310 Halo /23 0400 Jan 23/0359M8/long durationN28W3611402

Event 3: 7 March 2012 – X5.4 flare in NOAA 1429
The second largest x-ray flare so far this solar cycle was accompanied by the strongest proton storm so far in SC24 ("S3" on the NOAA-scale for radiation storms), and caused airlines to detour their polar flights for lack of communication.

7-8 January 2014
From spaceweather.com:
ROCKET LAUNCH FOILED BY SOLAR ACTIVITY: Orbital Sciences Corp. scrubbed today's launch of their Antares supply rocket to the International Space Station in response to an ongoing solar radiation storm, described below. A launch at 1:10 p.m. EST Thursday is possible if the storm subsides.
http://www.space.com/24202-huge-solar-flare-delays-private-rocket-launch.html

1 September 2014 - Strong backside eruption
On 1 September, STEREO-B observed a strong flare in an active region on the backside of the Sun, estimated to be a low-level X-class flare. The flare is associated to a strong proton flux increase. Amazingly, so many particles were slamming into STEREO-B's camera pixels (creating the white dots in the images) that they saturated the star-trackers onboard the spacecraft, making them lose lock on the Sun for about 4 hours. This resulted in a not correct orientation of the solar images. The large number of particles would also enhance proton fluxes as observed on Earth, for more than a week!
Ref: STCE news item of 9 September 2014

On **4 November 2015**, 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.
See STCE news item « Strong radio event on 04 November » at http://www.stce.be/news/326/welcome.html

From **04-12 September 2017**, NOAA 2673 produced the two strongest flares of SC24 so far (X9.3 on 06 Sep and X8.2 on 10 Sep), as well as 27 (!) M and two other X-class flares. Two proton events were associated to all this flaring, the strongest reaching 1490 pfu on 11 September; GLE was 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). The flaring hampered rescue efforts in the wake of Hurricane Irma in the Carabean: HF comms was often not available due to the continued strong flaring, as well as GPS if GPS frequencies were affected (in part also because all GPS facilities onsite were destroyed).

Redmon et al. (2018): https://ui.adsabs.harvard.edu/abs/2018SpWea..16.1190R/abstract
Imagery from https://www.ncei.noaa.gov/news/large-solar-event-detected-during-irma

Summary Extreme events

- **Historical SWx storms**
  - Carrington event
  - Can cause significant damage
  - Not all effects are present during a strong SWx storm
  - 19th => 21st century
    - Better SWx predictions
    - Better technological protection
      - => less damage / impacts
      - New vulnerabilities

- **SWx storms during SC24**
  - Relatively weak SC
    - Limited number of strong flares and proton events
    - NO extreme geomagnetic storms so far
  - SWx effects
    - => have been limited, *but not zero*!
    - => Several events with small SWx effects
  - 23 July 2012: Carrington-like event missed Earth

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Overview

- Introduction
- Drivers of SWx
- SWx effects
- Extreme events
- URSIgram

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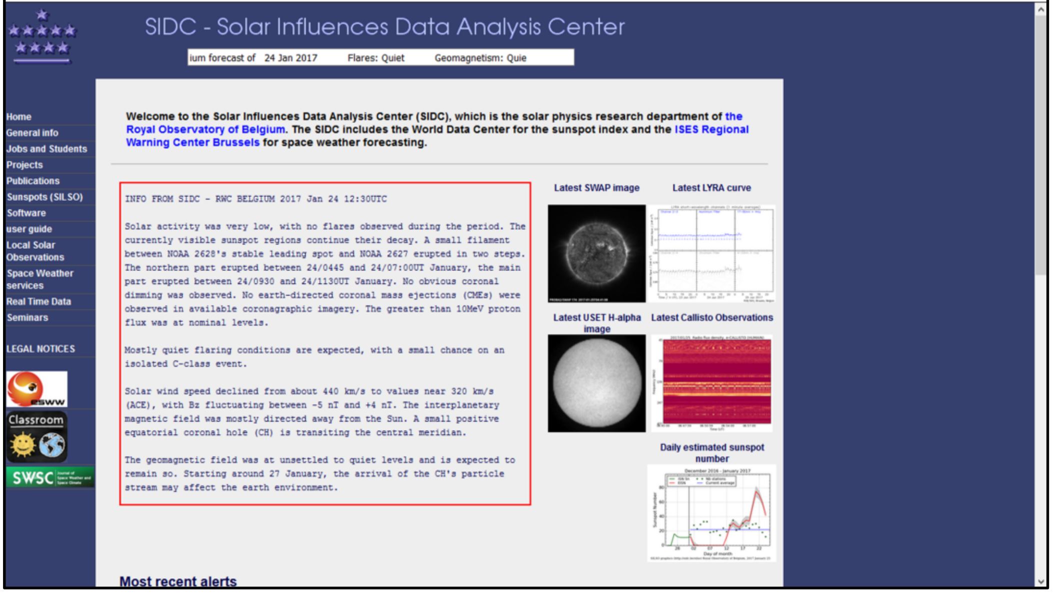
URSIgram

http://www.sidc.be/



:Issued: 2014 Apr 17 1325 UTC
:Product: documentation at http://www.sidc.be/products/tot
#--#
DAILY BULLETIN ON SOLAR AND GEOMAGNETIC ACTIVITY from the SIDC
#--#
SIDC URSIGRAM 40417
SIDC SOLAR BULLETIN 17 Apr 2014, 1304UT

SIDC FORECAST (valid from 1230UT, 17 Apr 2014 until 19 Apr 2014)
SOLAR FLARES : Active (M-class flares expected, probability >=50%)
GEOMAGNETISM : Quiet (A<20 and K<4)
SOLAR PROTONS : Quiet

PREDICTIONS FOR 17 Apr 2014 10CM FLUX: 180 / AP: 013
PREDICTIONS FOR 18 Apr 2014 10CM FLUX: 184 / AP: 007
PREDICTIONS FOR 19 Apr 2014 10CM FLUX: 188 / AP: 005

COMMENT: Eleven sunspot groups were reported by NOAA today. NOAA ARs 2035,2036, and 2037 (Catania numbers 24, 25, and 26 respectively) maintain the beta-gamma configuration of the photospheric magnetic field. The strongest flare of the past 24 hours was the M1.0 flare peaking at 19:59 UT yesterday in the NOAA AR 2035 (Catania number 24). The flare was associated with an EIT wave and a weak coronal dimming, but the associated CME was narrow and is not expected to arrive at the Earth.
We expect further flaring activity on the C-level, especially in the NOAA ARs 2035 and 2037 (Catania numbers 24 and 26 respectively) as well as in the NOAA AR 2042 (no Catania number yet) that yesterday appeared from behind the east solar limb, with a good chance for an M-class event.

Since yesterday evening the Earth is situated inside a solar wind structure with an elevated interplanetary magnetic field magnitude (occasionally up to 10 nT). It may be a weak ICME or the compression region on the flank of an ICME that missed the Earth. The solar origin of this structure is not clear. The north-south magnetic field component Bz was not strong, so no significant geomagnetic disturbance resulted (K index stayed below 4). Currently the solar wind speed is around 380 km/s and the IMF magnitude is around 8 nT.
We expect quiet to unsettled (K index up to 3) geomagnetic conditions, with active geomagnetic conditions (K = 4) possible, but unlikely.

TODAY'S ESTIMATED ISN : 145, BASED ON 17 STATIONS.
99999

SOLAR INDICES FOR 16 Apr 2014
WOLF NUMBER CATANIA : ///
10CM SOLAR FLUX : 184
AK CHAMBON LA FORET : 012
AK WINGST : 004
ESTIMATED AP : 004
ESTIMATED ISN : 139, BASED ON 29 STATIONS.

Geomagnetic activity

NOTICEABLE EVENTS SUMMARY
DAY BEGIN MAX END LOC XRAY OP 10CM Catania/NOAA RADIO_BURST_TYPES
16 1954 1959 2004 S14E09 M1.0 1N 24/2035 II/2
END

Fast alerts: automatic detection by SIDC software

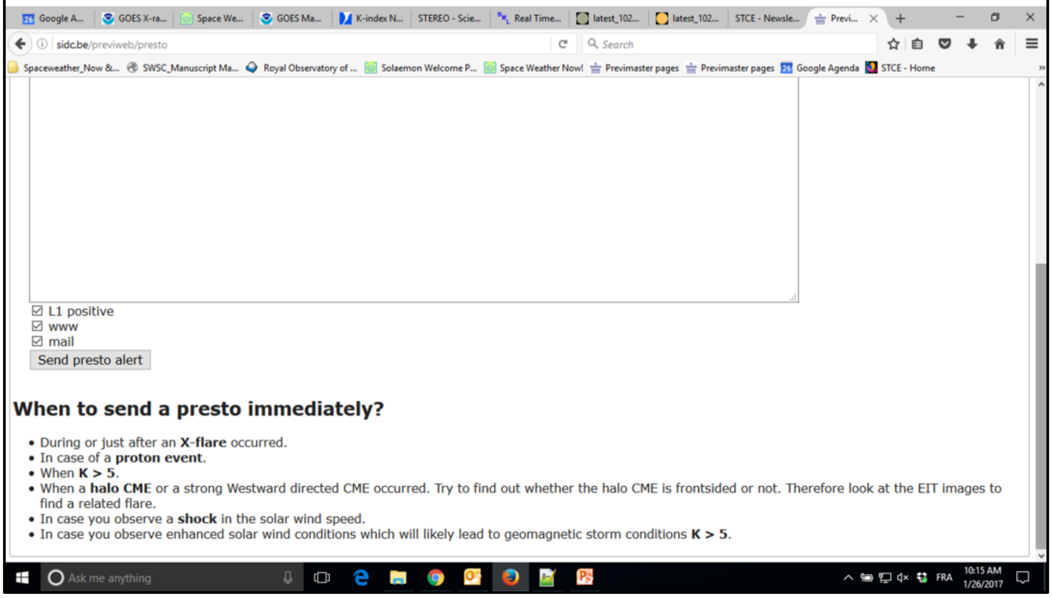
Flare > M5
SIDC in GOES X-ray

```
:Issued: 2016 Jul 24 0516 UTC
:Product: documentation at http://www.sidc.be/products/flaremail
#--------------------------------------------------------------------#
# Large flare alerts from the SIDC (RWC-Belgium), detected in GOES   #
# X-ray data                                                         #
#--------------------------------------------------------------------#
A class M5.5 solar X-ray flare occurred on 2016/07/23 with peak time 05:31UT
#--------------------------------------------------------------------#
# Solar Influences Data analysis Center - RWC Belgium                #
# Royal Observatory of Belgium                                       #
# Fax : 32 (0) 2 373 0 224                                           #
# Tel.: 32 (0) 2 373 0 491                                           #
#                                                                    #
# For more information, see http://www.sidc.be.  Please do not reply #
# directly to this message, but send comments and suggestions to     #
# 'sidctech@oma.be'. If you are unable to use that address, use      #
# 'rvdlinden@spd.aas.org' instead.                                   #
# To unsubscribe, visit http://sidc.be/registration/unsub.php        #
#                                                                    #
# Legal notices:                                                     #
# - Intellectual Property Rights:                                    #
#   http://www.astro.oma.be/common/internet/en/data-policy-en.pdf    #
# - Liability Disclaimer:                                            #
#   http://www.astro.oma.be/common/internet/en/disclaimer-en.pdf     #
# - Use and processing of your personal information:                 #
#   http://www.astro.oma.be/common/internet/en/privacy-policy-en.pdf #
#--------------------------------------------------------------------#
```

Halo CME (width > 150°)
CACTus in SOHO/LASCO

```
:Issued: 2016 Nov 05 1349 UTC
:Product: documentation at http://www.sidc.be/products/cactus
#--------------------------------------------------------------------#
# HALO CME ALERTS from the SIDC (RWC-Belgium), generated by CACTUS   #
#--------------------------------------------------------------------#
  A halo or partial-halo CME was detected with the following
characteristics:

            t0       | dt0| pa | da |  v  |  dv | minv| maxv|
005|2016/11/05 04:24| 03 | 338| 178| 0297| 0048| 0200| 0452

Details can be found here:
http://www.sidc.oma.be/cactus/out/latestCMEs.html

      t0: onset time, earliest indication of liftoff
     dt0: duration of liftoff (hours)
      pa: principal angle, counterclockwise from North (degrees)
      da: angular width of the CME (degrees),
       v: median velocity (km/s)
      dv: variation (1 sigma) of velocity over the width of the CME
   mindv: lowest velocity detected within the CME
   maxdv: highest velocity detected within the CME



  This message is sent whenever a CME wider than 150 degrees is detected by
cactus.
*--------------------------------------------------------------------*
```

PRESTO alert: Criteria



A shock is considered to have the following criteria, calculated using a 10 min average before and after the shock:

- A 20+ % increase in B, N (density), and T
- A 20+ km/s increase in V (speed)

From: Interplanetary shock database (S. Nikbakhsh, PhD thesis)
https://helda.helsinki.fi/bitstream/handle/10138/45227/Thesis.pdf

PRESTO alert: Example

PRESTO ALERT

Solar Influences Data analysis Center <sidc@oma.be>

Sent: Thu 1/26/2017 10:18 AM

To: jan.janssens@oma.be

:Issued: 2017 Jan 26 0917 UTC
:Product: documentation at http://www.sidc.be/products/presto

#--#
FAST WARNING 'PRESTO' MESSAGE from the SIDC (RWC-Belgium)
#--#

A weak shock was observed in the solar wind data (DSCOVR) on 26 January at 07:12UT. Solar wind speed suddenly increased from 335 km/s to values around 370 km/s. Density doubled from 8 to 16 particles per cm3, and magnetic field strength jumped from 6 to 10 nT. Bz briefly dipped to -8nT shortly after 08UT, but has returned to low near-zero values since. The effects on the geomagnetic field are expected to be of little consequence. The small shock may be a first sign of the expected arrival of the co-rotating interaction region (CIR) and associated high speed stream from the equatorial coronal hole later today or tomorrow.

#--#
Solar Influences Data analysis Center - RWC Belgium
Royal Observatory of Belgium
Fax : 32 (0) 2 373 0 224
Tel.: 32 (0) 2 373 0 491
# #
For more information, see http://www.sidc.be. Please do not reply
directly to this message, but send comments and suggestions to
'sidctech@oma.be'. If you are unable to use that address, use
'rvdlinden@spd.aas.org' instead.
To unsubscribe, visit http://sidc.be/registration/unsub.php

All quiet alert

Start/End of all quiet alert from the SIDC/RWC Belgium
Solar Influences Data analysis Center <sidc@oma.be>
Extra line breaks in this message were removed.
Sent: Mon 7/4/2016 1:33 PM
To: jan.janssens@oma.be

:Issued: 2016 Jul 04 1132 UTC
:Product: documentation at http://www.sidc.be/products/quieta
#--#
From the SIDC (RWC-Belgium): "ALL QUIET" ALERT
#--#
START OF ALL QUIET ALERT
....
The SIDC - RWC Belgium expects quiet Space Weather conditions for the next 48 hours or until further notice.
This implies that:
* the solar X-ray output is expected to remain below C-class level,
* the K_p index is expected to remain below 5,
* the high-energy proton fluxes are expected to remain below the event threshold.
#--#
Solar Influences Data analysis Center - RWC Belgium
Royal Observatory of Belgium
Fax : 32 (0) 2 373 0 224
Tel.: 32 (0) 2 373 0 491
# #
For more information, see http://www.sidc.be. Please do not reply

Start/End of all quiet alert from the SIDC/RWC Belgium
Solar Influences Data analysis Center <sidc@oma.be>
Sent: Wed 7/6/2016 12:11 AM
To: jan.janssens@oma.be

:Issued: 2016 Jul 05 2210 UTC
:Product: documentation at http://www.sidc.be/products/quieta
#--#
From the SIDC (RWC-Belgium): "ALL QUIET" ALERT
#--#
END OF ALL QUIET ALERT
....
The SIDC - RWC Belgium expects solar or geomagnetic activity to increase. This may end quiet Space Weather conditions.
#--#
Solar Influences Data analysis Center - RWC Belgium
Royal Observatory of Belgium
Fax : 32 (0) 2 373 0 224
Tel.: 32 (0) 2 373 0 491
# #
For more information, see http://www.sidc.be. Please do not reply
directly to this message, but send comments and suggestions to
'sidctech@oma.be'. If you are unable to use that address, use
'rvdlinden@spd.aas.org' instead.
To unsubscribe, visit http://sidc.be/registration/unsub.php
# #
Legal notices:

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This message is of the fast alert type. It is sent when quiet Space Weather conditions are expected for the next 48 hours or until further notice. This implies that:
- * the solar X-ray output is expected to remain below C-class level,
- * the K_p index is expected to remain below 5,
- * the high-energy proton fluxes are expected to remain below the event threshold.

All quiet alerts are send by the SWx forecaster, both to begin and to end the period.

The all quiet period is seldomly send during the solar cycle maximum, as new groups may quickly develop on disk or may round the east limb, or there may be filaments on disk that may result in flare/proton events.
The all quiet alert is also seldomly send during the ascending and declining phase as in view of the persistent high speed streams from coronal holes, as well as transients in the solar wind.

The criteria for the all quiet alerts are under debate.

Summary URSIgram

- URSIgram
  - Geomagnetic part is important for GIC
- Automatic notifications
- PRESTO alerts
- All quiet alerts

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Questions?