SPACE WEATHER INTRODUCTORY COURSE

SWIC

Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

SPACE WEATHER

Drivers

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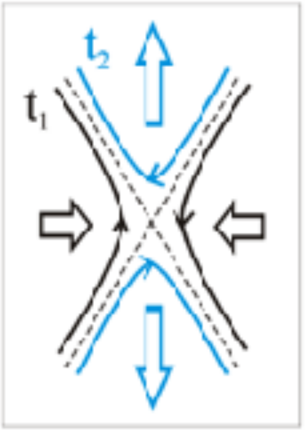
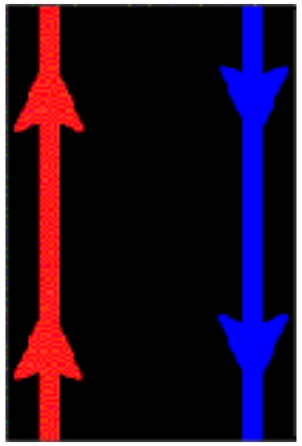
MAGNETIC RECONNECTION

- Conversion of magnetic energy into kinetic energy and radiation
- Where
  - Solar flares
  - CME release from the Sun
  - Geomagnetic storms at Earth



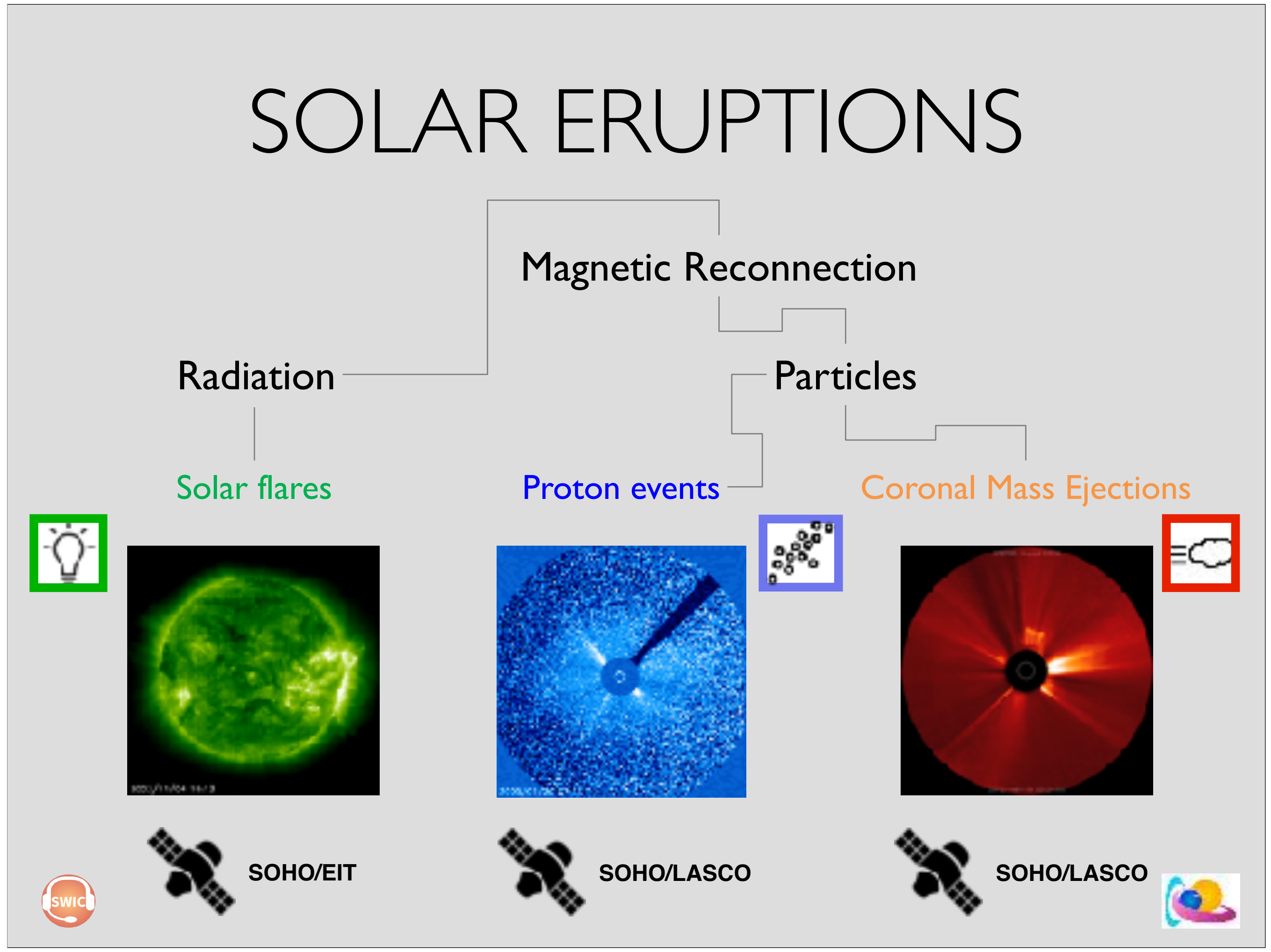


Magnetic reconnection occurs when antiparallel magnetic field lines are pushed towards each other and interact. The field lines disconnect at the X-point and form new connections, thus restructuring the magnetic field and creating new topological configurations.
During the process of magnetic reconnection (stored) magnetic energy is converted into kinetic energy and heat (radiation).

The first observational evidence for the reconnection process was found in solar flares.

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

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



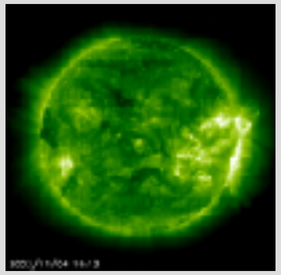
In this chapter we focus on eruptive solar events.
Magnetic reconnection is the physical principle at the base of the three types of space weather drivers: flares, proton events and coronal mass ejections.

SOLAR ERUPTIONS

Magnetic Reconnection

Radiation

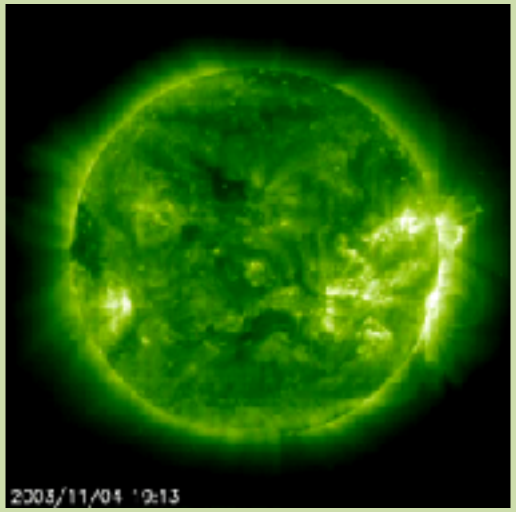
Solar flares



SOHO/EIT

SOLAR FLARES - OVERVIEW

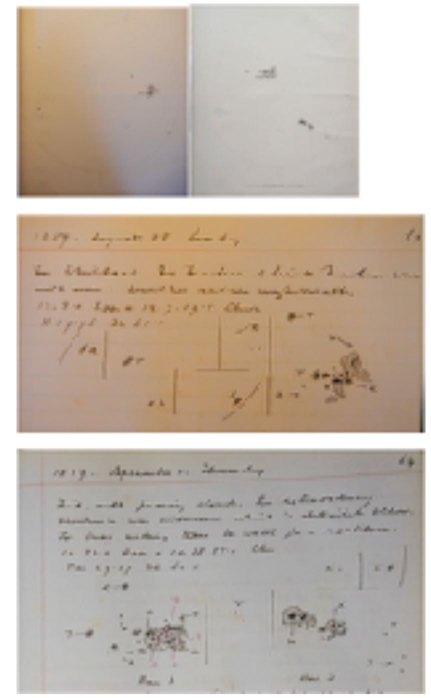
- **Characteristics**
  - **Definition**
  - **Standard model**
  - **Flare triggers**
  - **Flare features**
- Classification
- Flare predictions



SOHO/EIT

SOLAR FLARES - WHAT?

- Sudden burst of radiation
- First observation in 1859 (white light) by Carrington and Hodgson
- Large quantity of energy is released
  >10^20 Joule
- Required:
  A very rapid means of converting stored magnetic energy into particle energy and radiation – magnetic reconnection



Solar flares are sudden bursts of radiation lasting minutes to hours. Flares are observed in a wide range of electromagnetic waves such as radio, visible light, X-rays, and gamma rays.

Solar flares occur in a power-law spectrum of magnitudes; an energy release of typically 10^20 joules of energy suffices to produce a clearly observable event, while a major event can emit up to 10^25 joules. (For comparison: atomic bombs release energies of the order of 10^12 J to 10^15 J.)

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.

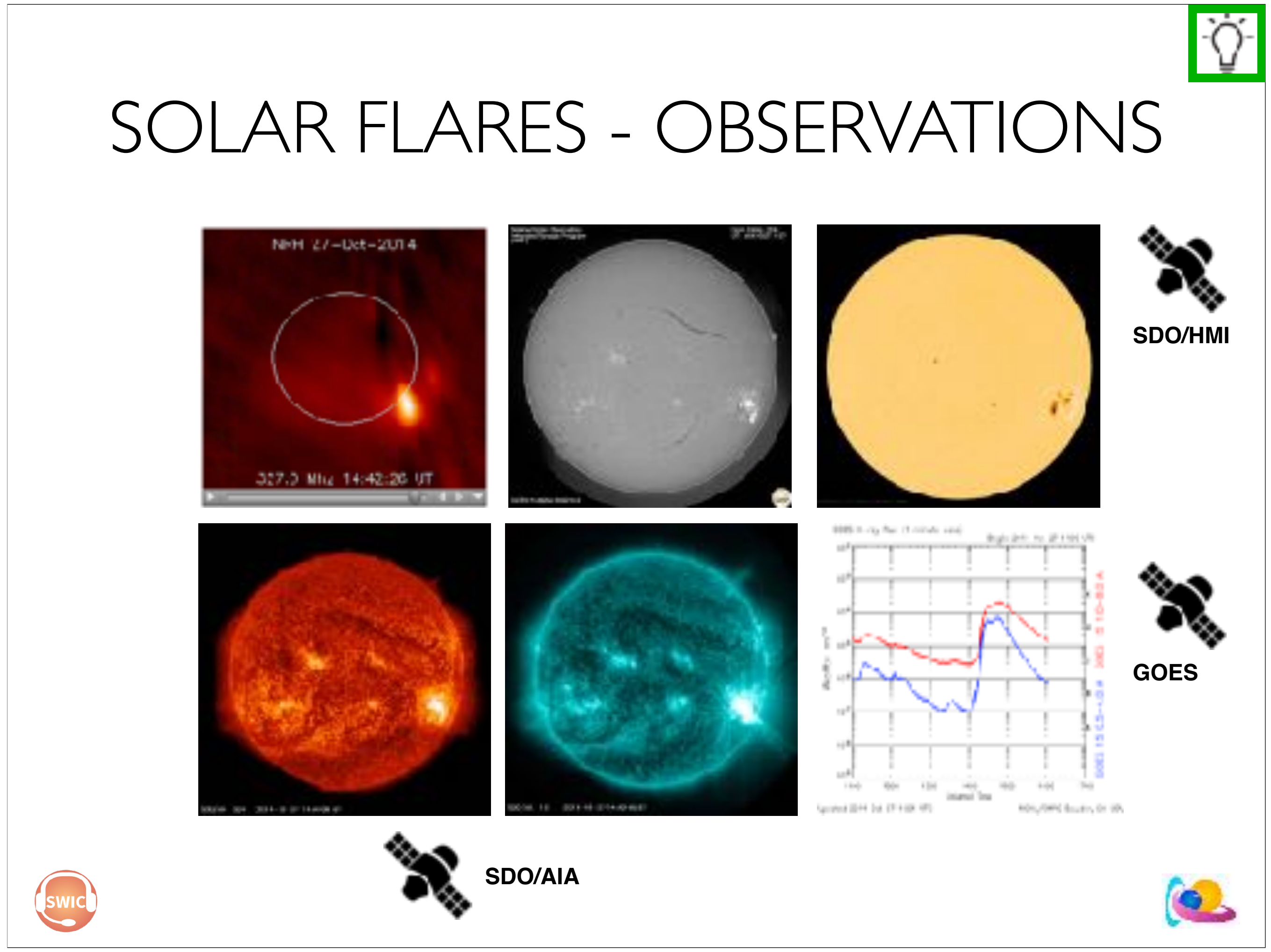
Magnetic energy is converted to thermal/radiative energy (flare, radio bursts) and kinetic energy (mass movement from CMEs and Solar Energetic Particles).

Flares in the visible continuum are particularly called white-light flares (WLFs), first observed by Carrington (1859). **Solar WLFs are usually rare** events compared to the Halpha and soft X-ray (SXR) flares because of the **short durations** (typically a few minutes; Hudson et al. 1992; Xu et al. 2006) and the **low contrast** (typically 5%-50%, at most 300%; Lin & Hudson 1976; Jess et al. 2008). (https://iopscience.iop.org/article/10.3847/1538-4357/aa9b34)

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

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

Images taken from https://iopscience.iop.org/article/10.3847/1538-4357/aae47c
Carrington's sunspot drawings on August 28 and September 1, shown in projected images. The whole disk drawings on August 28 and September 1 are shown above. The relevant parts of his logbook on August 28 and September 1 are shown below. These manuscripts are currently preserved in the archive of the Royal Astronomical Society.

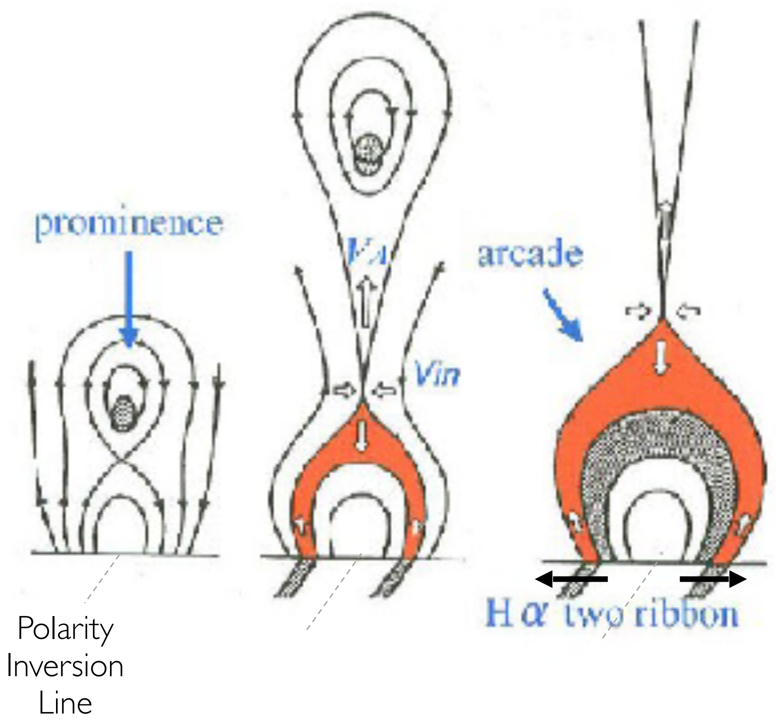


Solar flares are sudden bursts of radiation lasting minutes - hours at wavelengths over the entire electromagnetic spectrum: Gamma-rays, HXR, SXR, EUV; H-alpha, radio

The total irradiance enhancement is dominated by white light and infra-red emission (77%). UV and soft X-ray emissions <200 nm amount to 23%.
(Living Reviews in Solar Physics - Flare Observations (Benz, 2017), https://link.springer.com/article/10.1007/s41116-016-0004-3)

Sources:
http://bass2000.obspm.fr/home.php (Nançay Radio Heliograph)
http://www.stce.be/news/279/welcome.html

STANDARD FLARE MODEL



The CSHKP model is a model of solar flares that explains their observable features on the basis of magnetic reconnection. The basic idea of this model was proposed and developed by Carmichael, Sturrock, Hirayama, Kopp and Pneuman (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976), which is why this model is named CSHKP after these five scientists.

The model was originally proposed by Kopp and Pneuman and then refined. In broad lines it consists of the following phases:

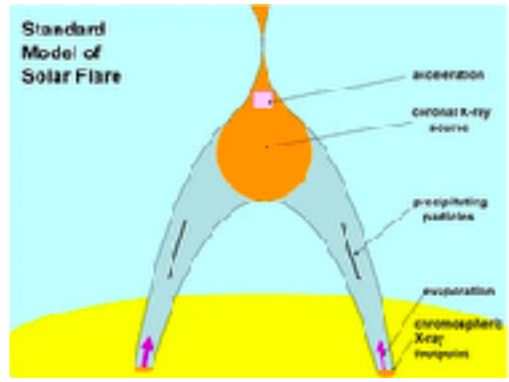
0) Magnetic reconnection occurs
1) It requires a „transient“ that opens up the magnetic field lines.
2) As they close down and reconnect, energy is released that goes into accelerating electrons which travel down the magnetic field lines.
3) These highly energetic particles will heat the dense chromosphere at the footpoints
4) and this plasma is heated and conducted into the loops
5) Post-eruption loop arcade appears successively high, because of the reconnection site rises with time
6) The ribbon separates with time because of the increasing distance between footpoints due to higher loop arcades

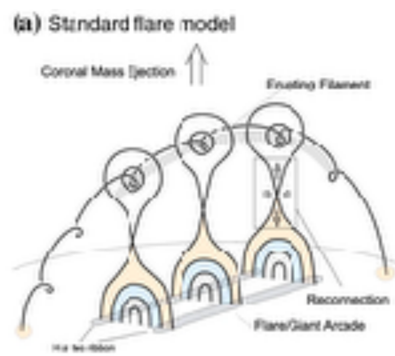
Polarity inversion line (PIL, also called neutral line): The line that separates solar magnetic fields of opposite polarity, typically determined from solar magnetograms.
From: https://www.swpc.noaa.gov/content/space-weather-glossary#n

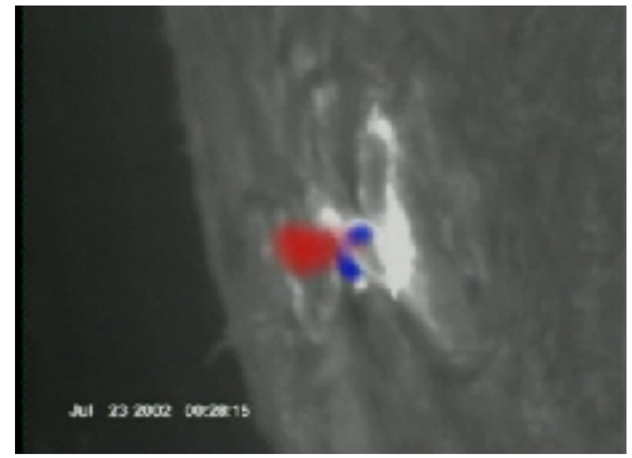
<u>Sources:</u>
From Maria Massi (What is a solar flare?)
http://www3.mpifr-bonn.mpg.de/staff/mmassi/#coronae1

An animated model from a solar flare can be found at:
Cheung et al. (2018): A comprehensive three-dimensional radiative magnetohydrodynamic simulation of a solar flare
http://adsabs.harvard.edu/abs/2018NatAs...3..160C
YouTube movie at https://www.youtube.com/watch?v=kyhsBqB2x_Y&feature=youtu.be

STANDARD FLARE MODEL







RHESSI

Top left: A schematic drawing of the standard flare scenario assuming energy release at high altitudes

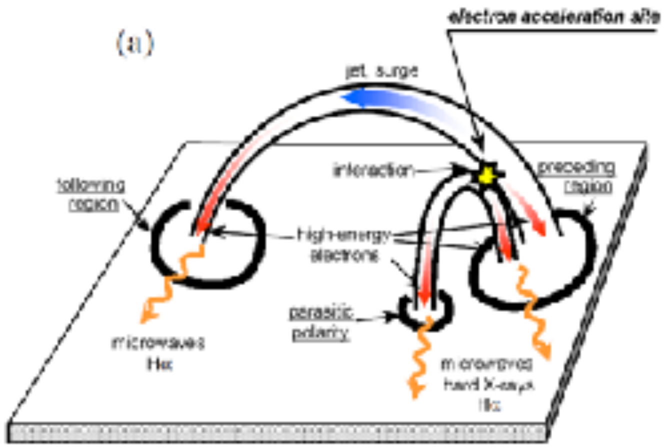
Right: **Soft X-rays (red), hard X-rays (blue)** and gamma-rays (purple) observed by the RHESSI satellite are overlaid on an optical Hα image. The movie starts in white light zooming into an active region. The color then changes to the **Hα line** of hydrogen, emitted in the **chromosphere**. Its brightening indicates the start of the flare. Note the high-energy footpoints moving apart on the Hα flare ribbons. Visualization by RHESSI scientists.

Source: Living Reviews in Solar Physics - Flare Observations (Benz, 2017), https://link.springer.com/article/10.1007/s41116-016-0004-3

Bottom left: standard flare model in 3D (https://link.springer.com/article/10.1007/s41116-019-0019-7)

TRIGGERS OF SOLAR FLARES

- Magnetic restructuring
- Magnetic flux emergence
- Helical energy storage
  - Sigmoid
  - Kink instability
- Instability surrounding fields
  - Long/high filaments
- Interaction with nearby CH
- …



There are various processes that can trigger a solar flare, but the underlying basic principle remains the same: magnetic reconnection transforms stored magnetic energy into kinetic and radiative energy.

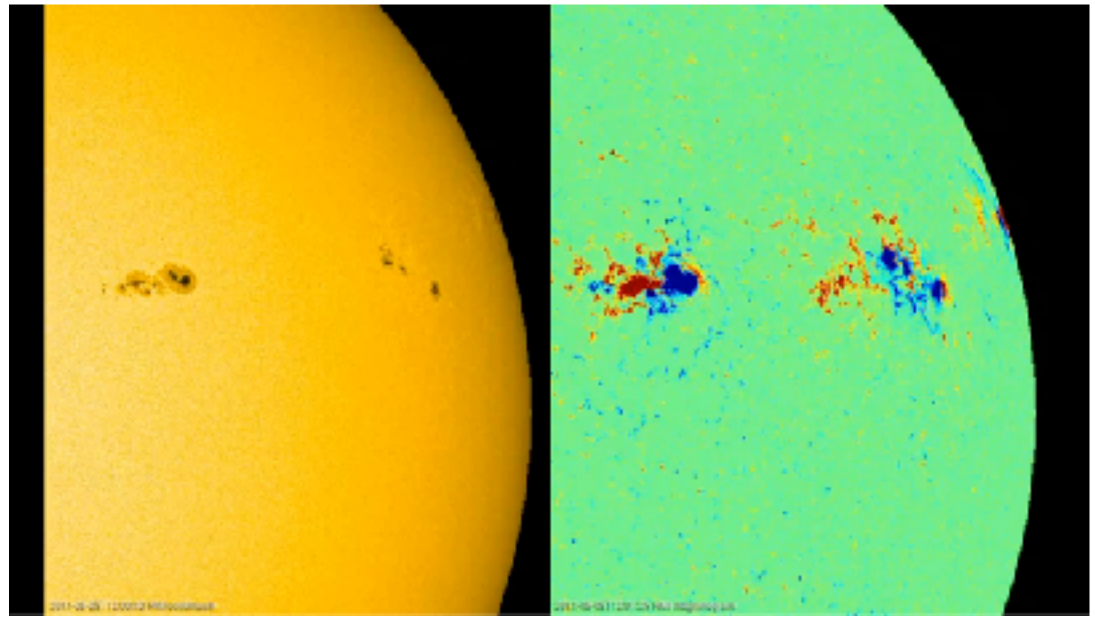
Sources:
Image from Hanaoka et al., 1999: Radio and X-ray Observations of the Flares Caused by Interacting Loops
http://solar.nro.nao.ac.jp/meeting/nbym98/PDF/hanaoka_2.pdf

Other example: Solar flare mechanism: http://www.stce.be/news/265/welcome.html

TRIGGERS OF SOLAR FLARES

SDO/HMI

Magnetic flux emergence



This movie shows how magnetic flux is emerging in the trail of the sunspot regions. This emerging field interacts with the existing magnetic configuration. When it creates an instability, an X-flare is observed.

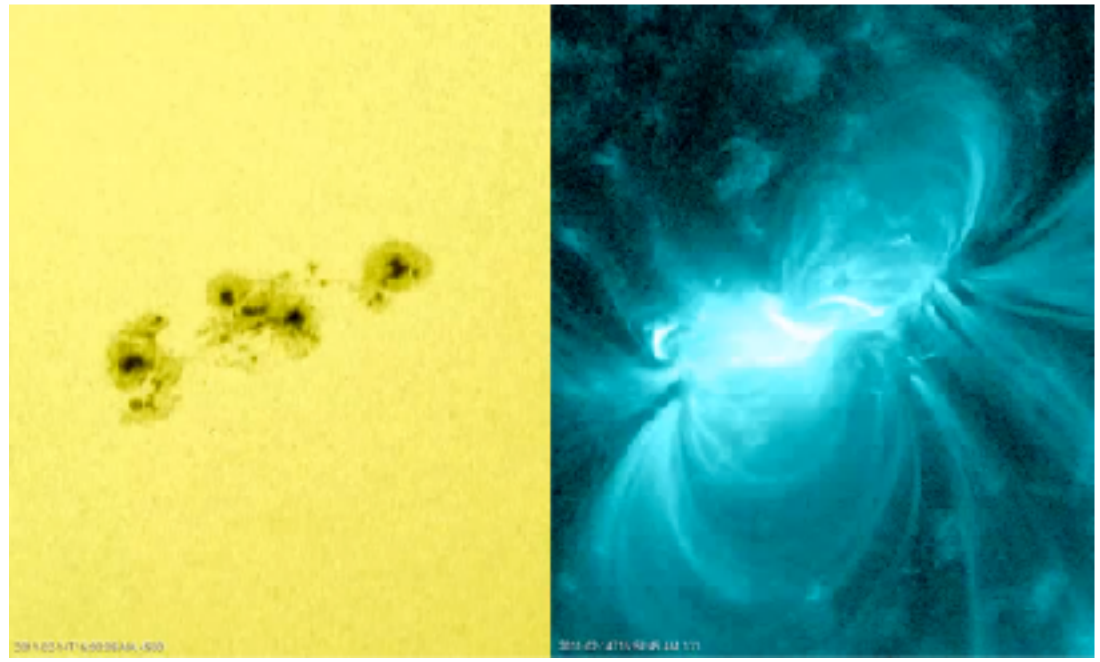
X6.9 flare on 9 August 2011: http://www.stce.be/news/353/welcome.html

Blue/black is negative (inward) magnetic polarity, red/white is positive (outward) polarity.

TRIGGERS OF SOLAR FLARES

Helical energy storage

SDO/AIA



This movie shows rotating sunspots that cause a solar flare.
Rotating sunspots are an extremely efficient way to inject energy into the magnetic field of the Sun's atmosphere. Twisting the Sun's magnetic field is like twisting an **elastic band**. At first you store energy in the elastic, but if you twist too much the elastic band snaps, releasing the stored energy. Similarly, rotating sunspots store energy in the Sun's atmospheric magnetic field. If they twist too much, the magnetic field breaks releasing energy in a flare.

X2.2 flare on 15 February 2011

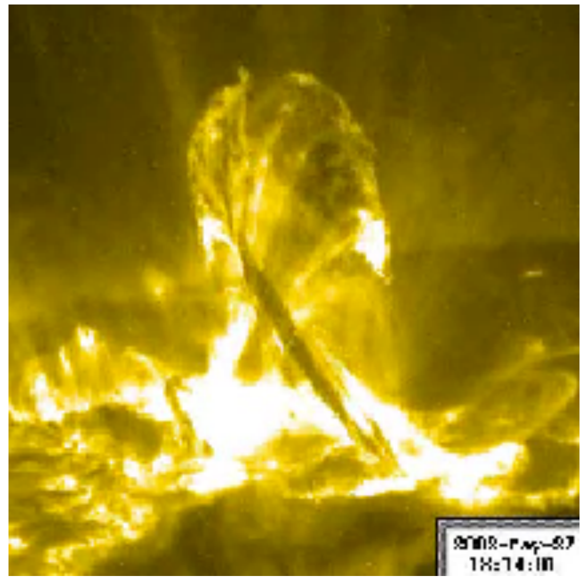
Sources:
Velareddi et al. (2012): On the role of rotating sunspots in the activity of solar active region NOAA 11158
http://iopscience.iop.org/article/10.1088/0004-637X/761/1/60/pdf

Jiang et al. (2011): Rapid sunspot rotation associated with the X2.2 flare on 2011 February 15
http://iopscience.iop.org/article/10.1088/0004-637X/744/1/50

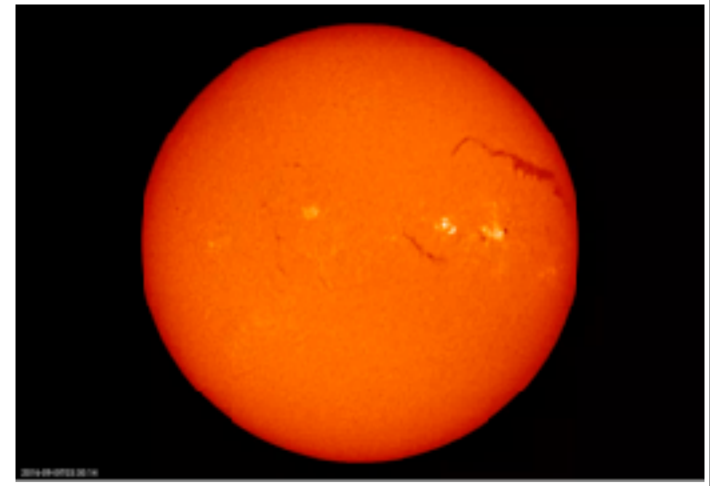
Also at PhysOrg: https://phys.org/news/2011-04-rotating-sunspots-super-solar-flare.html

TRIGGERS OF SOLAR FLARES

Kink instability



Unstable magnetic fields

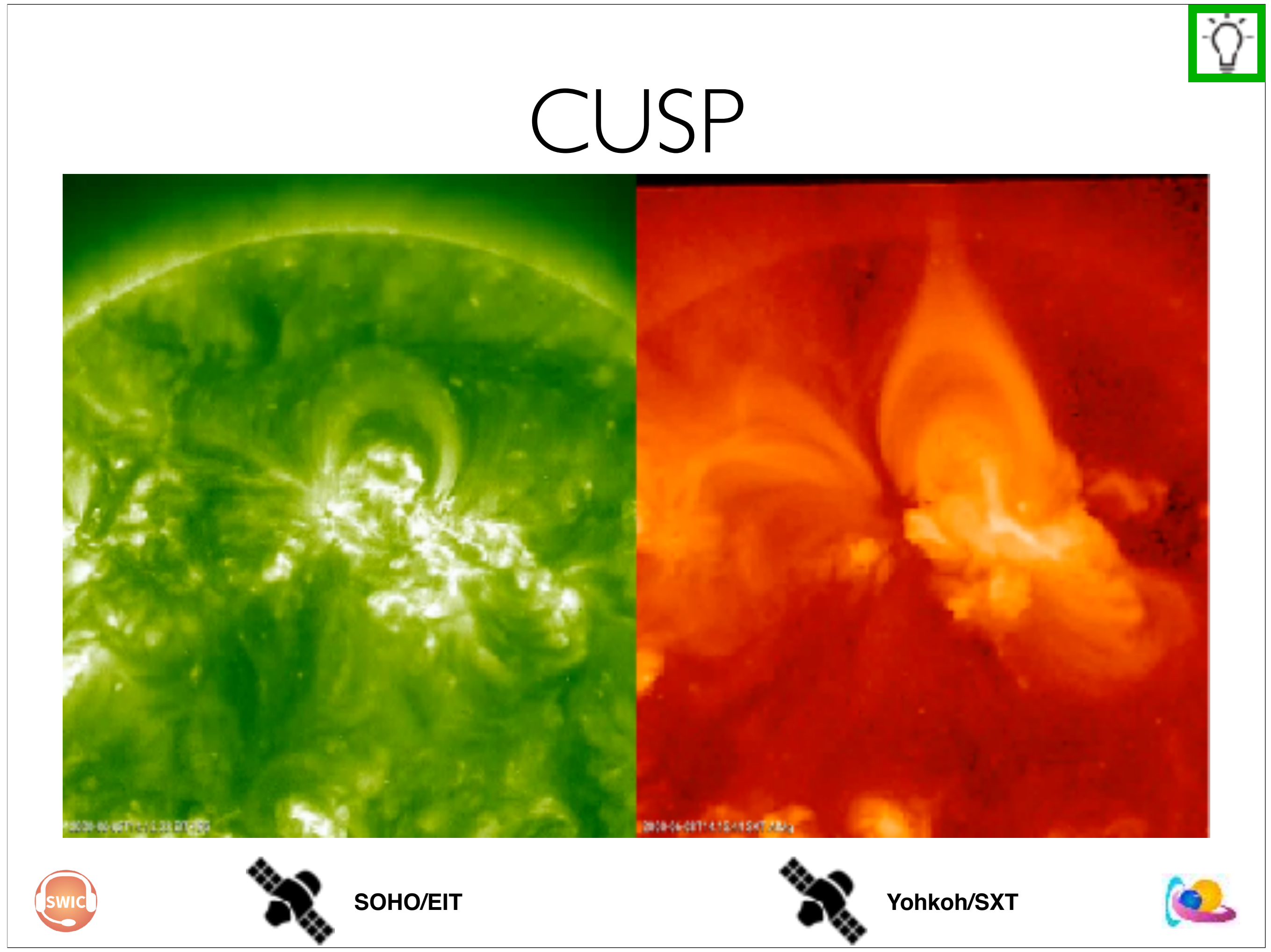


The left movies shows a kink magnetic flux tube, this is a bunch of magnetic strands that are intertwined. If it twist too much, it breaks.
The movie on the right is taken in H-Alpha and shows a B7 flare that did not only produce electromagnetic radiation. It apparently also created an imbalance in the magnetic fields. As a result, about an hour after the B7 flare, first the middle portion and then the western portion of the nearby filament disappeared entirely from view in H-alpha. The 40-degrees long filament to the upper right remained unchanged.

Sources:
Kink instability
Török et al. (2010): The writhe of helical structures in the solar corona
https://www.aanda.org/articles/aa/full_html/2010/08/aa13578-09/aa13578-09.html
http://www.lmsal.com/TRACE/POD/TRACEpodarchive14.html#movie61 (27 May 2002; M2 ; NOAA 9957)
Unstable if twist ~2.5pi (Török et al., 2003: https://www.aanda.org/articles/aa/pdf/2003/30/aah4206.pdf).

Unstable magnetic fields
Collateral damage: http://www.stce.be/news/361/welcome.html

Shen et al. (2014): A Chain of Winking (Oscillating) Filaments Triggered by an Invisible Extreme-ultraviolet Wave
http://adsabs.harvard.edu/abs/2014ApJ...786..151S



Observations of the cusp were important as direct evidence to confirm the standard flare model. What we see is the bottom part of the reconnection site (the **X-region**) in X-ray observations.
This cusp-shaped flare loop increases its height and the distance between the footpoints, as expected from the model.

<u>Sources:</u>
JHV: Flare from 06 June 2000 (SOHO, Yohkoh: X1.1 in NOAA 9026)
More on this and other cusps: http://solar.physics.montana.edu/takeda/evt_archive/cusp_flare.html

Another example of a cusp: http://www.stce.be/news/298/welcome.html (06 March 2015)
Another example of a cusp: http://www.stce.be/news/173/welcome.html (19 January 2012)
Another example of a cusp: http://www.stce.be/news/238/welcome.html (25 February 2014; X4.9)

Yokoyama et al. (2001): Clear Evidence of Reconnection Inflow of a Solar Flare
http://adsabs.harvard.edu/abs/2001ApJ...546L..69Y

: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.

Flare features

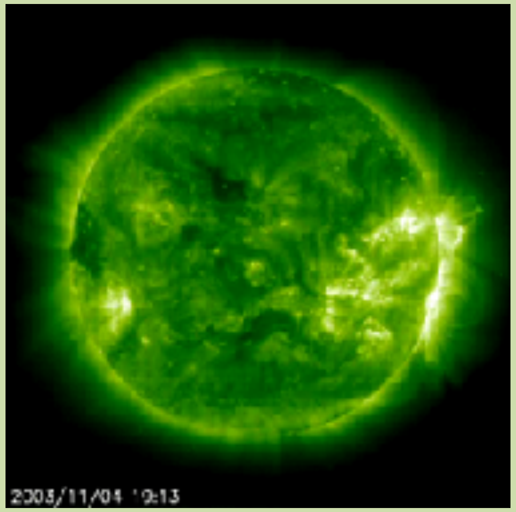
NOTICEABLE EVENTS SUMMARY

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 FLARES - OVERVIEW

- Characteristics
- **Classification**
  - H-alpha
  - X-ray
  - Radio bursts
- Flare predictions



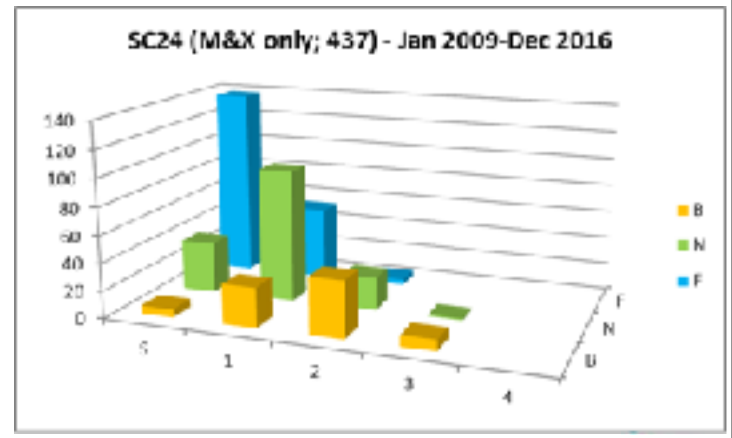
SOHO/EIT

SOLAR FLARES CLASSIFICATION

H-alpha

- Visual classification
- Importance
  - Area at max. brightness
- Brightness
  - Faint, Normal, Brilliant
- Optical class
  - E.g. SF, 3B,…
- Limited correlation with geophysical effects
- Depends strongly on seeing conditions

Importance	A_e (MH)	A_e ($°^2$)
S	$10 \leq A_e < 100$	$0,2 \leq A_e < 2,1$
1	$100 \leq A_e < 250$	$2,1 \leq A_e < 5,2$
2	$250 \leq A_e < 600$	$5,2 \leq A_e < 12,4$
3	$600 \leq A_e < 1200$	$12,4 \leq A_e < 24,7$
4	$1200 \leq A_e$	$24,7 \leq A_e$



Optical Information (Op): The optical classification and location of an associated flare, observed in Hα. It contains an importance and a Brightness parameter:
* Importance is the corrected area of the flare in heliospheric square degrees at maximum brightness, observed in the Hα line (656.3 nm).
S – Subflare (area ≤ 2.0 deg.2)
1 – Importance 1 (2.1 ≤ area ≤ 5.1 deg. 2)
2 – Importance 2 (5.2 ≤ area ≤ 12.4 deg. 2)
3 – Importance 3 (12.5 ≤ area ≤ 24.7 deg. 2)
4 – Importance 4 (area ≥ 24.8 deg. 2)
* Brightness is the relative maximum brightness of flare in Hα.
F – faint ; N – normal ; B – brilliant
In photometric observations: **If a flaring region reaches a brightness of 1.6 times (160%) the surrounding quiet sun background brightness, then it is considered a faint (F) flare.** If the flaring region reaches a brightness **between 160% and 360%** the background brightness, it is catalogued as a flare of **normal** intensity (N). Finally, in order to be considered a "brilliant" flare (B), the flaring region should reach an intensity of 360% the background brightness and its are should cover at least 10 millionths of the solar hemisphere.

* Location (ºLat. ºCMD) gives the spherical, heliographic coordinates of the solar flare in Hα. The field is blank for x-ray events with no optical correlation (no optical flare observed or no optical patrol at the time) and for flares that occasionally occur in unassigned regions).

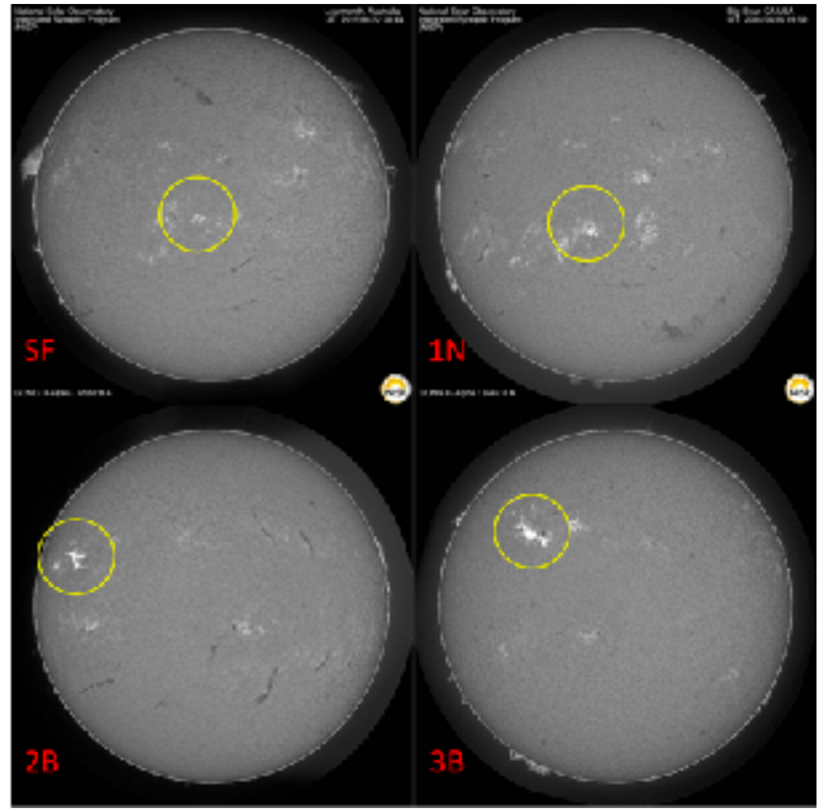
Note however, that the observed intensity is **strongly dependent on the seeing conditions**, and only a slight amount of atmospheric pollution can drastically alter the measured intensity.

This classification is still **widely used**, e.g. in the daily SWPC (event) reports, The Weekly, the SIDC's Ursigrams and weekly bulletins,…

Sources:
H-alpha flare classification: Australian SWS: http://www.sws.bom.gov.au/Educational/2/4/2
H-alpha observing: http://users.telenet.be/j.janssens/Halpha/Halfaeng.html#Flares
From SWPC 's « The Weekly » User guide (https://www.swpc.noaa.gov/sites/default/files/images/u2/Usr_guide.pdf ; page 4)
A detailed analysis of H-alpha flare properties is by Temmer et al. (2001): Statistical analysis of solar H flares
https://www.aanda.org/articles/aa/pdf/2001/33/aa1413.pdf

See also: https://www.stce.be/educational/classification

SOLAR FLARE CLASSIFICATION: H-ALPHA

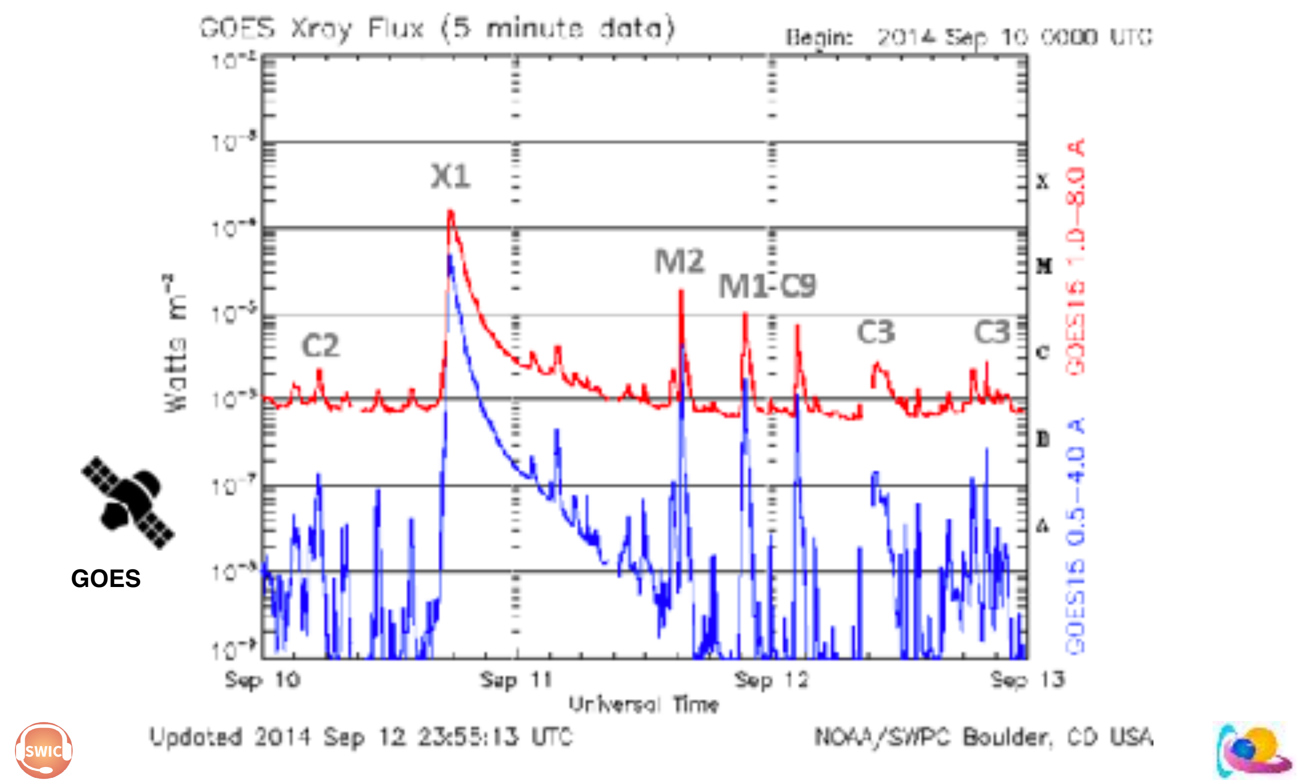


NOTICABLE EVENTS SUMMARY

	DAY	BEGIN	MAX	END	LOC	XRAY	OP	10CM	Catania/NOAA	RADIO_BURST_TYPES
SF:	22 Apr 2015 –	0830	0844	0858	S09E05	**M1.1**	SF			
1N:	16 Apr 2014 –	1954	1959	2004	S14E09	**M1.0**	1N		24/2035	II/2
2B:	02 Apr 2014 –	1318	1405	1428	N14E53	**M6.5**	2B	3700	09/2027	II/1IV/2
3B:	07 Mar 2012 –	0002	0024	0040	N17E27	**X5.4**	3B	7200		IV/1,II/2,V/2

Data are from the SIDC / Daily Ursigrams (http://www.sidc.be/archive)
Images are from GONG/NSO H-alpha Network (ftp://gong2.nso.edu/HA/hag/)

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 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

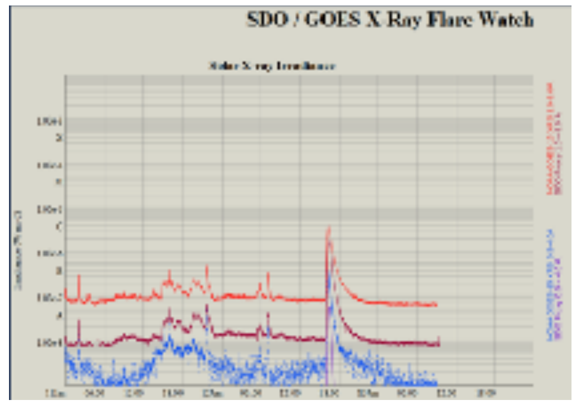
The letter designates the order of magnitude of the peak value and the number following the letter is the multiplicative factor. A C3.2 event for example, indicates an x-ray burst with 3.2x10-6Wm-2 peak flux. Solar flare forecasts are usually issued only in terms of the broad C, M, and X categories. 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

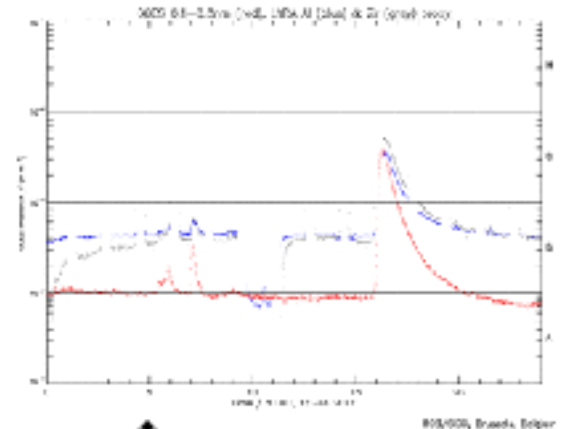
See also: https://www.stce.be/educational/classification
Note the peak intensity of a flare is based on the 1-minute averages by GOES, not on the **5-minute averages** which are often used for the graphs. Also, the peak intensity may not be rounded up, as the true flux never reached that level (e.g. a C5.8 is a C5 flare, not a C6 event).

SOLAR FLARE CLASSIFICATION: X-RAY

Back-up for GOES x-ray



SDO/EVE



PROBA2/LYRA

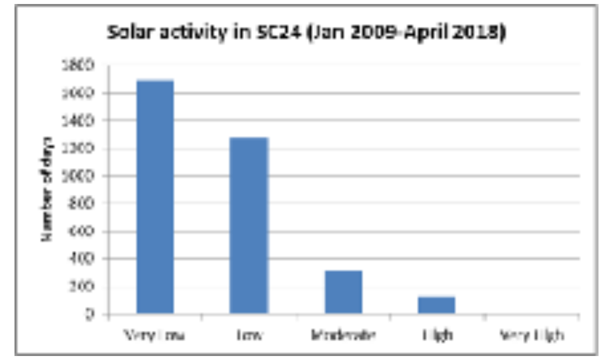
SDO/EVE: http://lasp.colorado.edu/eve/data_access/sdo-goes-eve-flare-watch/index.html
PROBA2/LYRA: http://proba2.oma.be/ssa

These instruments measure the solar EUV output which is then scaled to GOES so that they can be reliably compared and substituted. In that sense, the scaled EUV measurements are proxies for the GOES x-ray measurements.

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.

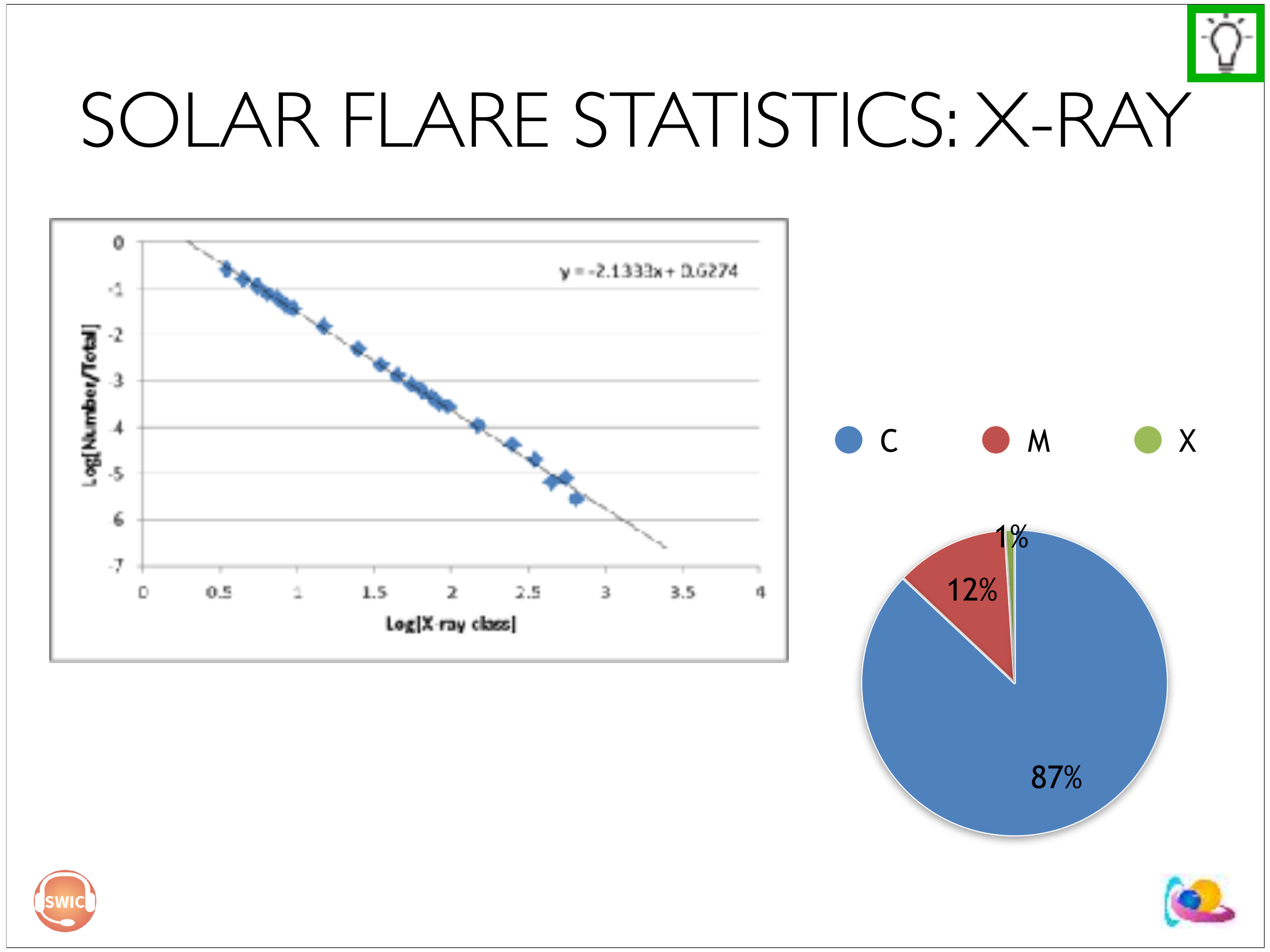
High: several (5 or more) M-class x-ray events, or isolated (one to four) M5 or greater x-ray events.

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

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 days
Low 1214 days
Moderate 299 days
High 118 days
Very High 0 days

See also: https://www.stce.be/educational/classification



The above chart shows for each bin of solar flare intensity (C3-X6) the ratio of the number of flares for that bin vs. the total number of flares (25031 flares; January 1976 - May 2016). Both axes are logarithmic in nature. The C2 and lower classes were omitted as these numbers are affected during high solar activity (high x-ray background). The X7 and higher intensities were omitted for not sufficient data.

The linear expression between these two quantities is y=0.6274-2.1333x
This means that **the number of flares N for a bin can be calculated from a power law equation**: N = 25031. delta . 4.24 ^I-2.13 , with delta equalling 1, 10 or 100 for the resp. class C, M or X.

Another rule of thumb: Since 1976, there have been a total of 55000 x-ray flares. About 48000 were C-class flares, 6500 were M-class flares, and 500 were X-class flares.
Or in percentages: **For every 100 solar flares, there are 87 C-class flares, 12 M-class flares, and 1 X-class flare.**

More on this (for the period 1976-1993) is at the Australian SWS: http://www.sws.bom.gov.au/Educational/2/4/5

SOLAR FLARE CLASSIFICATION: X-RAY

NOAA-scales: R-scale

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

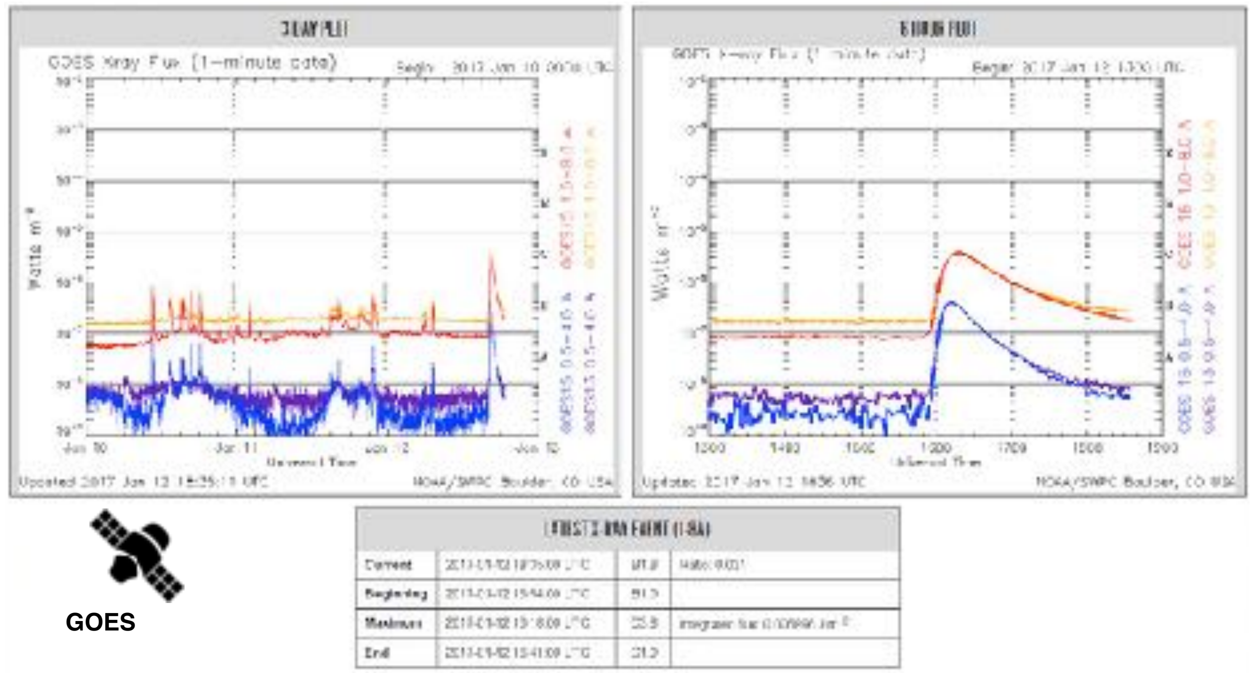
From the SWPC webpage:

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

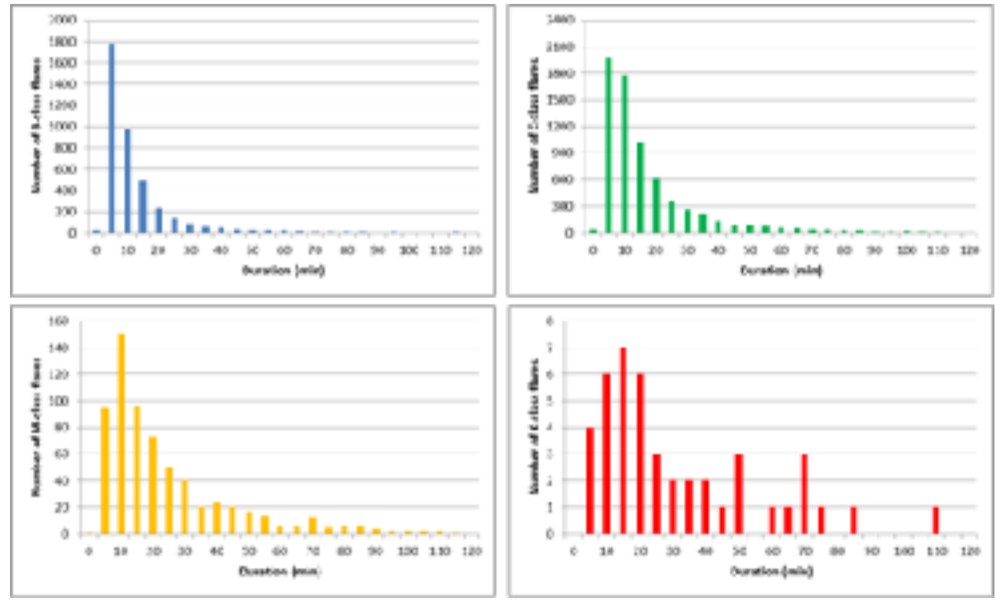
SOLAR FLARE DURATION



From SWPC 's « The Weekly » User guide (https://www.swpc.noaa.gov/sites/default/files/images/u2/Usr_guide.pdf ; page 15)

The **start** of an x-ray event is defined as the f**irst minute in a sequence of 4 minutes** of steep monotonic increase in 0.1-0.8 nm flux. The time of x-ray maximum is defined as the time tag of the peak 1-minute averaged value x-ray flux. The **end time** is the time when the flux level **decays to a point halfway** (1/2 peak) **between the maximum flux and the pre-flare background level.**

SOLAR FLARE DURATION



Jan 1976 - Dec 2000			Jan 2009 - Nov 2015		
Class	Number	Median	Class	Number	Median
B	8844	10	B	4041	10
C	16507	12	C	7015	14
M	1331	24	M	659	19
X	63	30	X	45	24
T	*26745*	***12***	*T*	*11760*	***13***

These graphs show the distribution of the duration (in minutes) of flares in the different categories. It is clear that stronger flares tend to last longer.

Sources:
From SWPC 's « The Weekly » User guide (https://www.swpc.noaa.gov/sites/default/files/images/u2/Usr_guide.pdf ; page 15)
From **Temporal aspects and frequency distributions of solar soft X-ray flares**
Veronig et al. (2002): https://www.aanda.org/articles/aa/pdf/2002/06/aa1910.pdf
And from **The duration of solar flares**
http://www.stce.be/news/332/welcome.html

SOLAR FLARE DURATION

Impulsive flare

- M- and X-class only
- Duration
  - Total duration < 10 minutes
- Usually NOT associated with CMEs
- Compact

Long Duration Event

- All flare classes
- Duration
  - Total duration > 1 hour
  - Decay time > 30 minutes (SWPC)
- Association with CMEs increases with increased duration

From the SWPC glossary at https://www.swpc.noaa.gov/content/space-weather-glossary#longduration (operational definition)

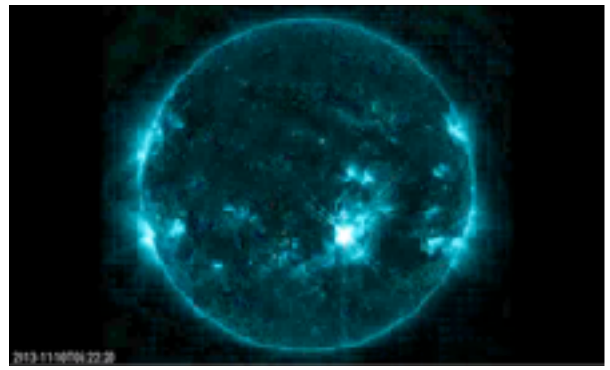
Long duration X-ray events (LDE) are not impulsive in appearance. The exact time threshold separating impulsive from long-duration events is not well defined, but **operationally**, any event requiring 30 minutes or more to decay to one-half peak flux is regarded as an LDE. It has been shown that the likelihood of a coronal mass ejection increases with the duration of an x-ray event, and becomes **virtually certain for durations of 6 hours or more**.

SOLAR FLARE DURATION

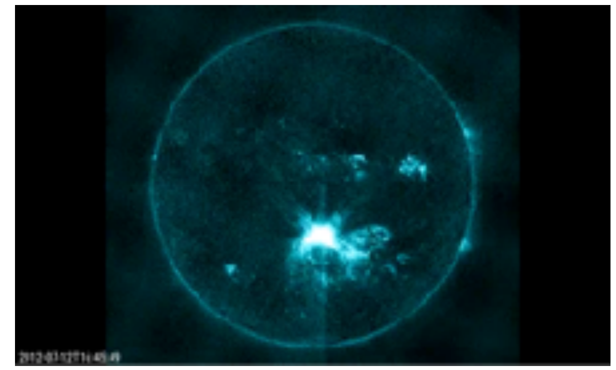
Impulsive flare

Long Duration Event

SDO/AIA



X1 - NOAA 1890 - 10 Nov 2013 (duration: 10 minutes)



X1 - NOAA 1520 - 12 July 2012 (duration: 113 minutes)

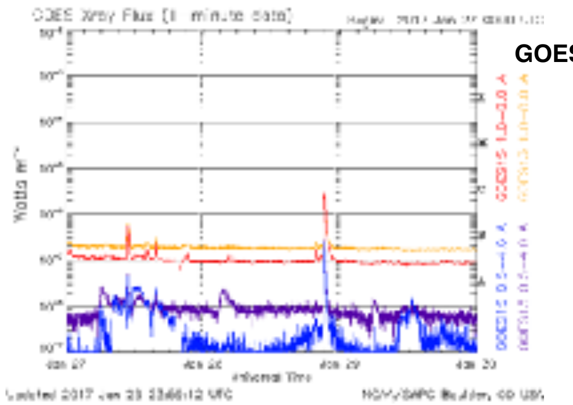
Imagery from STCE: http://www.stce.be/news/332/welcome.html

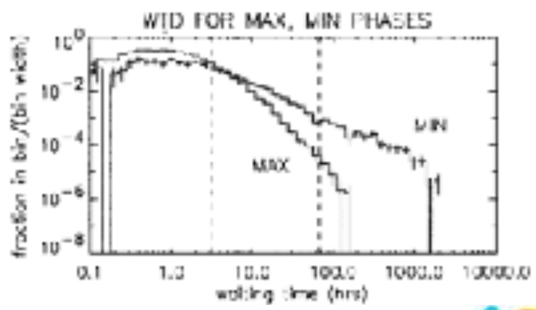
A short and a long duration X1 flaring event. These took place resp. in NOAA 11890 on 10 November 2013 (duration: 10 minutes) and in NOAA 11520 on 12 July 2012 (duration: 113 minutes or nearly 2 hours). The latter was accompanied by a full halo CME (no surprise), but also the 2013 X1 flare was associated with a partial halo CME.

SOLAR FLARE FREQUENCY

Isolated flare

- Usually specified per class (B, C, M, X)
- From entire Sun
  - 1-4 per day
- In practice
  - 1 event in 24 hours
- Average waiting time
  - 6.5 hours ($\geq$ C1)
  - SCmax: 3 hours
  - SCmin: 3 days





From SWPC 's « The Weekly » User guide (https://www.swpc.noaa.gov/sites/default/files/images/u2/Usr_guide.pdf ; page 1)

Terms Used to Describe Solar Activity
Very Low: x-ray events less than C-class.
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Very High: several (5 or more) M5 or greater x-ray events.

Wheatland et al. (2002): Understanding solar flare waiting-time distributions
http://www.physics.usyd.edu.au/wheat/papers/pdfs/understanding_WTD.pdf

The bottom figure shows the Waiting Time Distribution for all years 1975-2001, and reproduces the power-law tail reported by Boffeta et al. (1999). The distribution for the maximum phase of the solar cycle has a steeper distribution, because the rate of flaring is higher around solar maximum, and so the average waiting time is less. The average waiting times for the two phases are indicated by the dashed vertical lines (average waiting time for all flares regardless the phase of the cycle is 6,5 hours). The maximum and minimum distributions both exhibit approximate power-law tails.

From http://users.telenet.be/j.janssens/Archives/Archives.html#021109
The longest stretch without C-class flares was from 3 April till 3 November 2008, that's 214 consecutive days of very low activity.
Since the start of systematic GOES observations, there have been only 9 periods with more than 60 consecutive days with no C-class flares, 6 of those happened during the most recent SC23-SC24 minimum… The longest stretch without M-class flares was from 25 March 2008 till 19 January 2010 (665 days). … The longest stretch without X-class flares was from 14 Dec 2006 till 15 February 2011 (1524 days).

: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.

Flare classification

NOTICEABLE EVENTS SUMMARY

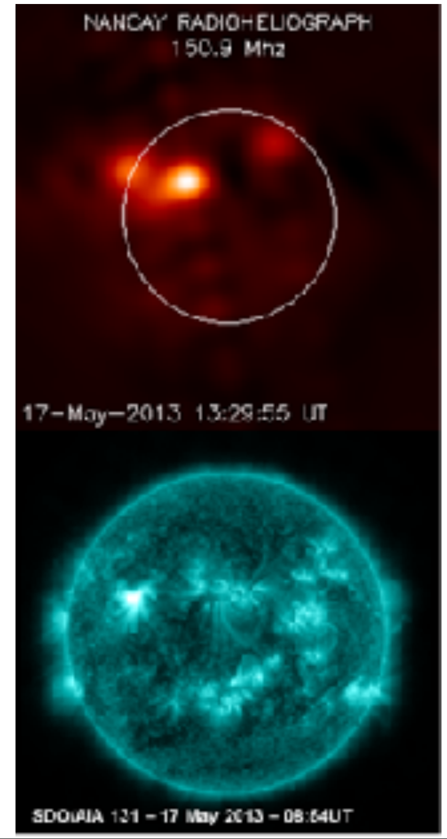
DAY	BEGIN	MAX	END	LOC	XRAY	OP	10CM	Catania/NOAA	RADIO_BURST_TYPES
16	1954	1959	2004	S14E09	M1.0	1N		24/2035	II/2

END

RADIO BURSTS

Tenflare

- Compared to pre-flare background levels, the 10.7cm (2800 MHz) radio flux suddenly increases by at least 100%
- Example: 17 May 2013
  - M3 flare in NOAA 1748
  - From +/- 140 sfu to > 400 sfu
- May affect daily 10.7cm radio flux values
- Radio flares are also observed at other wavelengths



SDO/AIA

1 sfu = 10-22 Wm-2 Hz-1

Tapping (2013): The 10.7 cm solar radio flux (F10.7)
http://onlinelibrary.wiley.com/doi/10.1002/swe.20064/epdf

A 10.7 cm solar flux measurement is a determination of the strength of solar radio emission in a 100 MHz-wide band centered on 2800 MHz (a wavelength of 10.7 cm), averaged over an hour. It is expressed in solar flux units (sfu), where 1 sfu = 10-22 Wm-2 Hz-1. It is daily measured at Penticton, British Columbia, Canada (DRAO: Dominion Radio Astrophysical Observatory). Measurements are taken at 17UT, 20UT and 23UT (winter period: 18-20-22UT), with the local noon value (20UT) as the value for that day. It is uncorrected for any flare influence. The daily values are at http://www.spaceweather.ca/solarflux/sx-4a-en.php

From SWPC Glossary at https://www.swpc.noaa.gov/content/space-weather-glossary#t
Tenflare: A solar flare accompanied by a 10cm radio burst of intensity greater than 100% of the pre-burst value.

RADIO BURSTS

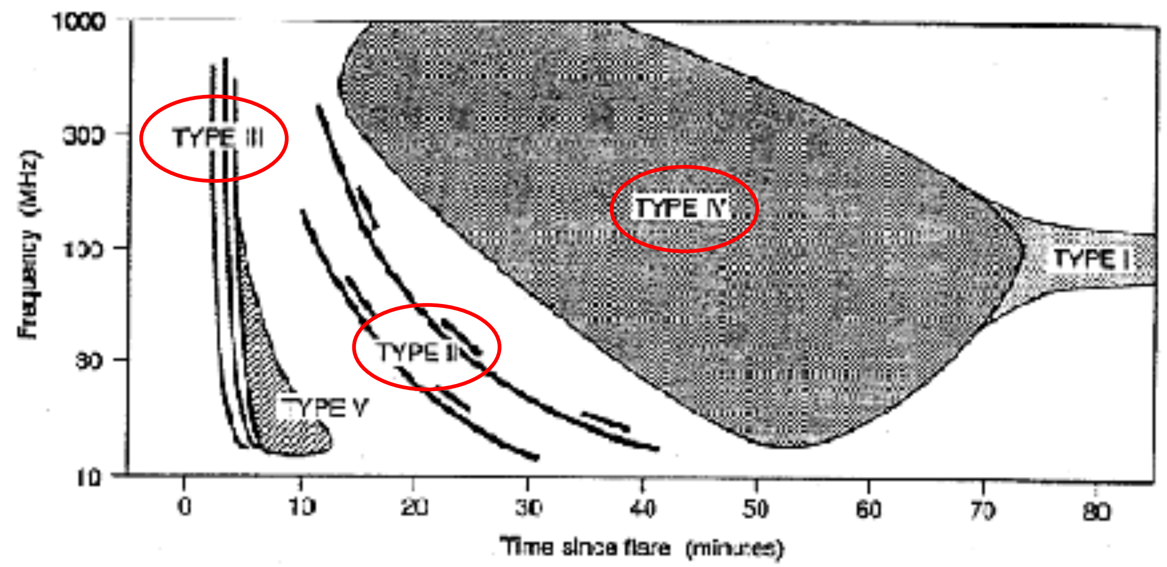


Figure 1. Schematic Radiospectrogram of Events Following a Large Solar Flare. This diagram illustrates each major type of solar radio burst in a typical configuration following a large flare. It should be noted that not all of these features are observed following every flare. (Source: *The New Culgoora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

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
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
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.]

See also: https://www.stce.be/educational/classification

RADIO BURSTS

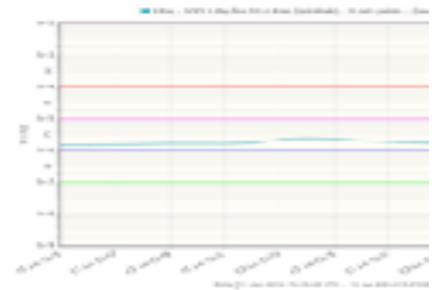
Type III

- Source:

  accelerated electrons propagating along open magnetic field lines
- During impulsive phase of flares
- Duration

  Seconds (isolated) to minutes (groups)
- Frequency

  10 kHz-1GHz



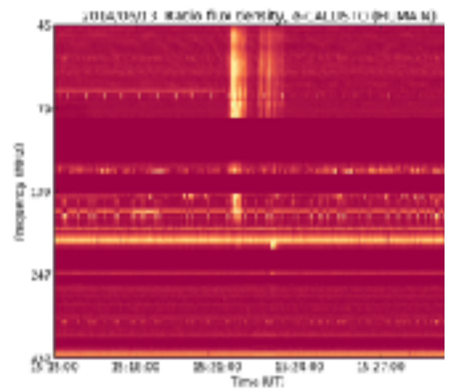


Image courtesy:
GOES-curve: STAFF viewer, http://www.staff.oma.be
Radio plot: ROB/Humain Radio Observatory, http://www.sidc.be/humain/

13 June 2014

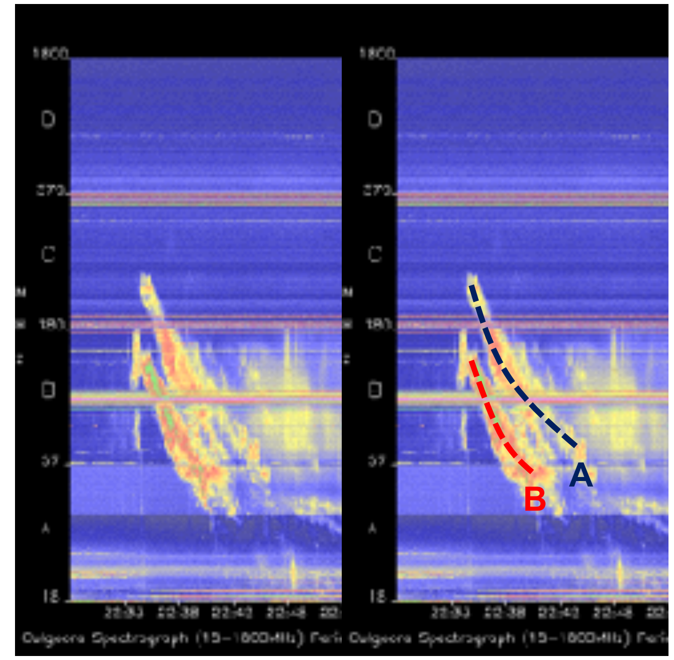
3940.	1521	1524	1527	G15	5	XRA	1-8A	C2.4	5.2E-04	2087
3940 +	1521	1522	1523	SAG	G	RBR	245	290		2087
3940 +	1521	////	1523	SAG	C	RSP	025-180	III/2		2087
3940 +	1522	1522	1525	HOL	3	FLA	S19E38	SF		2087

Solar Radio Bursts and Space Weather, S.M. White
https://www.nrao.edu/astrores/gbsrbs/Pubs/AJP_07.pdf
Type III bursts are brief radio bursts that drift very rapidly in frequency versus time (Fig. 1). For example, it can drift from 50 to 20 MHz in about 3 seconds, or 10 MHz s−1. Type IIIs are commonly seen in the impulsive phase of solar flares, and the connection they imply between the acceleration region in solar flares and open field lines that reach the solar wind makes them important for understanding field line connectivity in flares and the access of flare-accelerated particles to the Earth.

RADIO BURSTS

Type II

- Source:
  - electrons accelerated in shocks
  - Indicates CME
  - Shock speed can be derived from fundamental band (B)
- Start at peak in soft X-ray flux of flare
- Duration
  3-30 minutes
- Frequency
  20-150 MHz



Culgoora spectrograph at 01 Nov 2003 – http://www.sws.bom.gov.au/Solar/2/2/1 (Type II/2, 1079 km/s)

Solar Radio Bursts and Space Weather, S.M. White
https://www.nrao.edu/astrores/gbsrbs/Pubs/AJP_07.pdf
Type II bursts typically occur at around the time of the soft X-ray peak in a solar flare and are identified by a slow drift to lower frequencies with time in dynamic spectra, the frequent presence of both fundamental and **second-harmonic** bands (with a frequency ratio of 2), and splitting of each of these bands into two traces. The frequency drift rate is typically two orders of magnitude slower than that of the ("fast-drift") Type III bursts, so the two burst types are readily distinguished.

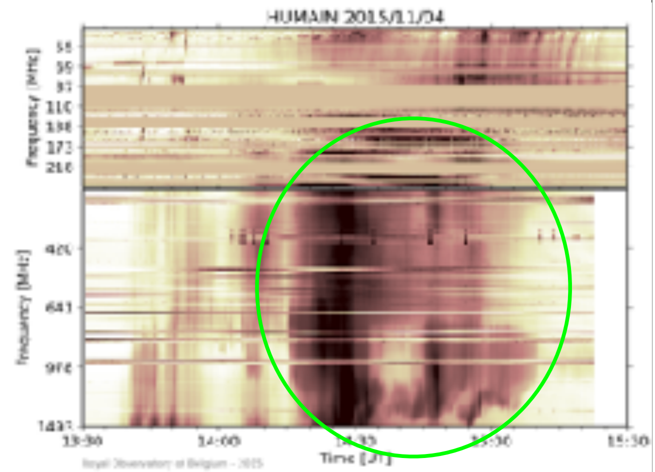
The fundamental band is the one provoked by the shock of the CME and is the one that reaches the lowest frequencies first (track « B » in the image). It is the fundamental track that is used to calculate the (true) speed of the shock as it moves through the corona and away from the Sun (density decrease => frequency decrease).

Roberts (1959): Solar Radio Bursts of Spectral Type II : http://adsabs.harvard.edu/abs/1959AuJPh..12..327R
Gopalswamy: Coronal Mass Ejections and solar radio emissions : http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.708.626&rep=rep1&type=pdf

RADIO BURSTS

Type IV

- Source
  - Electrons trapped in post-eruption arcades behind CMEs
  - Related to very energetic CMEs
    (average speed: 1200 km/s)
- During decay phase of solar flares
  Connection with SEPs
- Duration
  Hours (to days)
- Frequency
  - 20 to >1000 MHz
  - Lowest: 8 +/-5 MHz



Gopalswamy: Coronal Mass Ejections and solar radio emissions
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.708.626&rep=rep1&type=pdf
The type IV bursts are associated with very energetic CMEs (average speed 1200 km/s), confirming the earlier finding by Robinson [1986] for the **continuum** events at metric wavelengths. The radio emission should originate from a heliocentric distance 3.5 to 4.5 Rs, depending on whether the radio emission occurs at the fundamental or harmonic of the plasma frequency. When the type IV burst attains the lowest frequency, the IP type II burst occurs at frequencies well below 1 MHz, which means the shock is much farther away. This suggests that the energetic electrons responsible for the type IV burst might come from the continued reconnection occurring beneath the CME.
[Comment by Dr Christophe Marqué (ROB): The height of type IV reported by Gopalswamy concerns the low frequency ones. The one for example observed in Humain (04 Nov 2015) is really taking place in the post flare loops close to the flare site.]

Solar Radio Bursts and Space Weather, S.M. White
https://www.nrao.edu/astrores/gbsrbs/Pubs/AJP_07.pdf
Type IV bursts are broadband quasi-continuum features associated with the decay phase of solar flares. They are attributed to electrons trapped in closed field lines in the post-flare arcades produced by flares; their presence implies ongoing acceleration somewhere in these arcades, possibly at the tops
of the loops in a “helmet-streamer” configuration. Type IV bursts have long been of interest in Space Weather studies because they have a high degree of association with solar energetic particle events.

Example: 04 Nov 2015: http://www.stce.be/news/326/welcome.html
2340B1327 U1339 A1348 SVI 2 FLA N09W04 2B ERU 2443
2340 + 1331 1352 1413 G15 5 XRA 1-8A M3.7 5.9E-02 2443
2340 + 1336 1341 1438 SVI G RBR 4995 740 2443
2340 + 1337 1341 1442 SVI G RBR 2695 340 2443
2340 + 1337 1341 1429 SVI G RBR 8800 560 2443
2340 + 1338 1341 1414 SVI G RBR 15400 210 2443
2340 + 1343 //// 1358 SAG C RSP 048-180 II/2 955 2443
2340 + 1351 //// 1531 SVI C RSP 025-171 IV/1 2443
2340 + 1404 1426 1502 SAG G RBR 410 1400 2443
2340 + 1405 1433 1507 SAG G RBR 245 1400 2443
2340 + 1406 1427 1456 SAG G RBR 1415 5800 2443
2340 + 1406 1427 1458 SAG G RBR 610 1000 2443

: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

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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.

Radio bursts

NOTICEABLE EVENTS SUMMARY

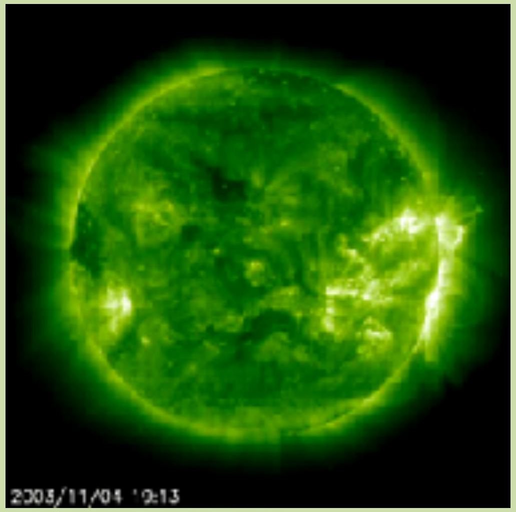
DAY	BEGIN	MAX	END	LOC	XRAY	OP	10CM	Catania/NOAA	RADIO_BURST_TYPES
16	1954	1959	2004	S14E09	M1.0	1N		24/2035	II/2

END

The type of radio burst is followed by a number indicating its importance.
The importance is a scale from 1 to 3 indicating how well the radio burst was observed: 1 is weak, 2 is normal, 3 is strong.

SOLAR FLARES - OVERVIEW

- Characteristics
- Classification
- **Flare predictions**
  - McIntosh
  - Hale

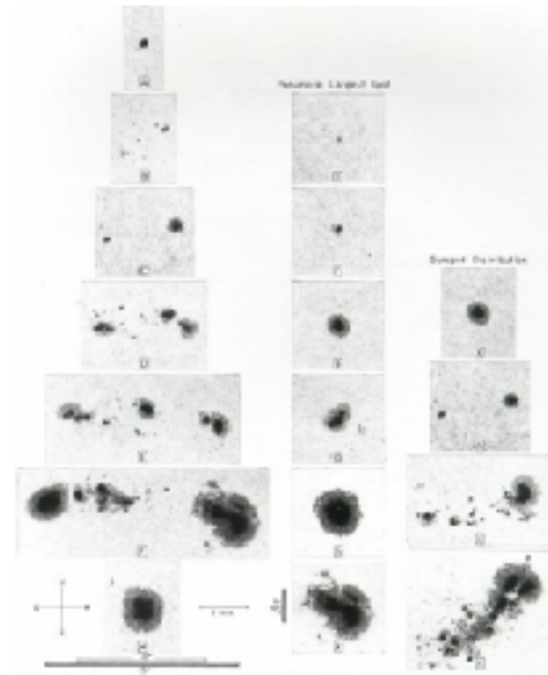


SOHO/EIT

FLARE PREDICTIONS

McIntosh classification

- Zpc *(3-letter code)*
  - Z - Modified Zürich classification
  - p - Penumbra largest spot
  - c - Interior sunspot distribution
- 60 possible combinations
  - Linked to flare intensity
  - Rather large uncertainties
- Used worldwide



See: https://www.stce.be/educational/classification

The McIntosh classification for sunspot groups was developed by Patrick McIntosh (McIntosh, 1990) based on an earlier scheme devised by Max Waldmeier in 1947, called the Zürich classification. The general form of the McIntosh classification is Zpc (overview image above), where Z is the modified Zurich class, p is the type of principal spot, primarily describing the penumbra, and c is the degree of **compactness** in the interior of the group.

The 3 component McIntosh classification (McIntosh, Sol. Phys. 125, 251-267,1990) is based on the general form 'Zpc', where 'Z' is the modified Zurich Class, 'p' describes the penumbra of the principal spot, and 'c' describes the distribution of spots in the interior of the group.

The modified **Zurich classes** are defined on the basis of whether **penumbra** is present, how penumbra is distributed, and by the **length** of the group.

McIntosh, P.S. (1990): The classification of sunspot groups
http://adsabs.harvard.edu/abs/1990SoPh..125..251M

https://wwwbis.sidc.be/educational/classification.php#:~:text=The%203%20component%20McIntosh%20classification,the%20interior%20of%20the%20group.

McIntosh, P.S. (1990): The classification of sunspot groups
http://adsabs.harvard.edu/abs/1990SoPh..125..251M

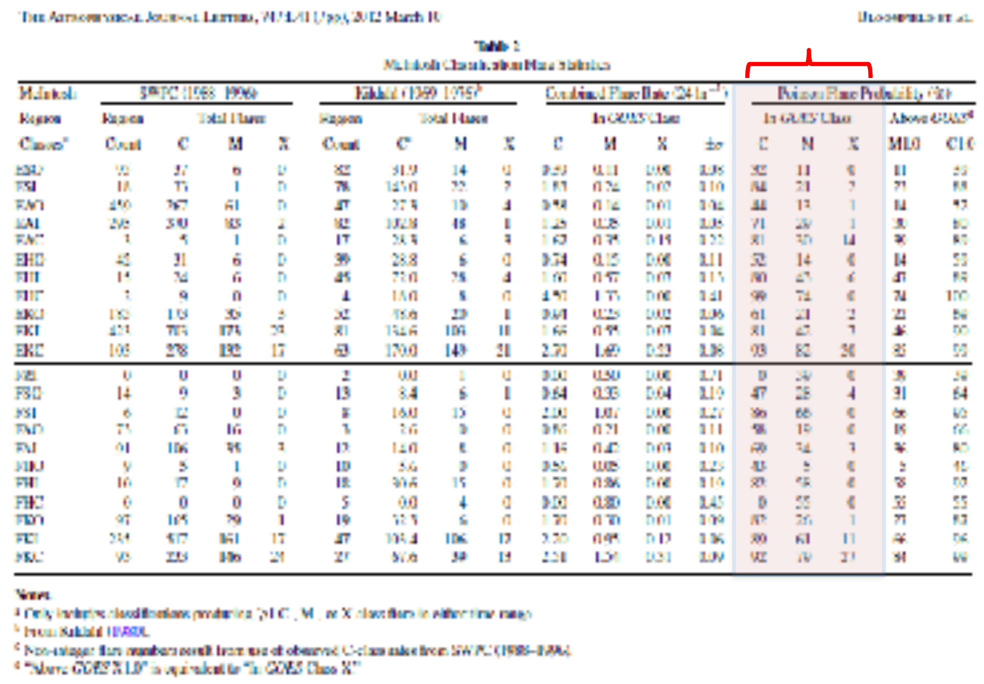
Questions to ask (Table 1 from McIntosh paper)
Z – **General outlook of the sunspot group:**
=> Unipolar or bipolar group?
=> Penumbra or no penumbra?
=> Penumbra on one or both sides of the group?
=> Length of the group (>10°? >15°?)
* 7 options: A, B, C, D, E, F, H

p – Penumbra largest spot
=> Rudimentary or mature penumbra?

=> Symmetric or asymmetric penumbra main spot?
=> N–S–diameter of the largest spot (>2,5°?)
* 6 options: x, r, s, a, h, k

c – Sunspot distribution interior (“compactness”)
=> Several spots between leading and trailing main spot?
=> Internally, is there at least one spot with a mature penumbra?
* 4 options: x, o, i, c (open, intermediate, compact)

FLARE PREDICTIONS



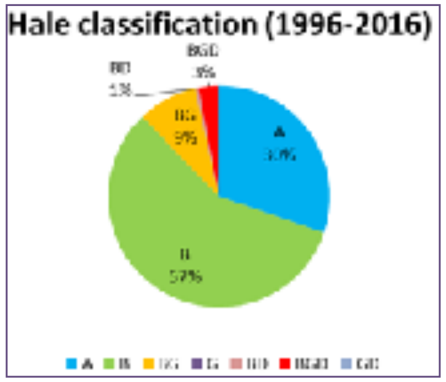
For space weather forecasting it is important to know how this classification relates to the probability of producing a flare.

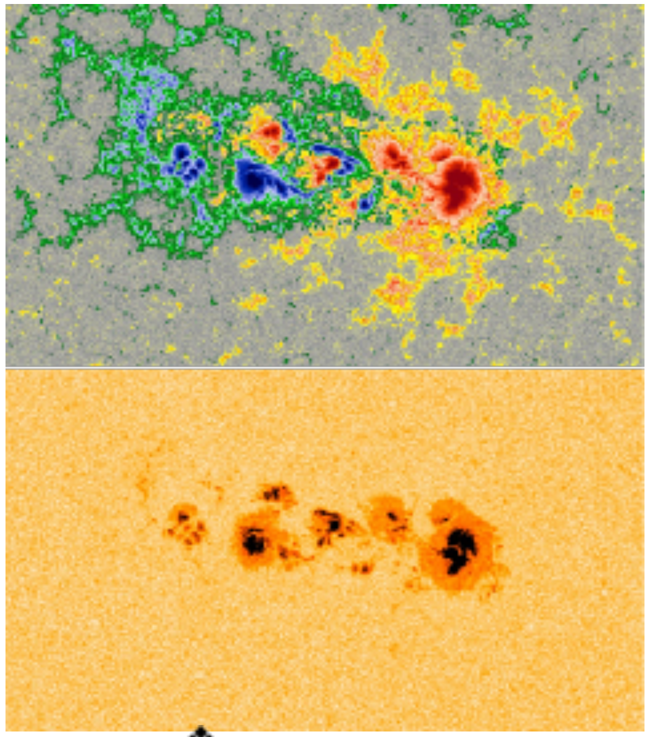
Bloomfield S. et al. (2012): Toward Reliable Benchmarking of Solar Flare Forecasting Methods
http://adsabs.harvard.edu/abs/2012ApJ...747L..41B

FLARE PREDICTIONS

Mount Wilson (Hale) classification

- Based on the magnetic properties of a sunspot group
- 7 options:
  - A (α)
  - B (β), BG (βγ), G (γ)
  - BD (βδ), BGD (βγδ), GD (γδ)





SDO/HMI

Jaeggli and Norton (2016): The Magnetic Classification of Solar Active Regions 1992-2015
http://adsabs.harvard.edu/abs/2016ApJ...820L..11J
http://iopscience.iop.org/article/10.3847/2041-8205/820/1/L11/pdf

Magnetic classifications provide a simple way to describe the configuration of the magnetic flux and sunspots in a solar active region (AR). The Mount Wilson (or Hale) classification system for sunspot groups put forward by Hale et al. (1919) has been used for nearly a century. In the original Hale classification scheme, the designation (**alpha**) is given to regions that contain a single sunspot or sunspot group all having the same polarity. Generally, these also have a weaker opposite polarity counterpart that is not strong or concentrated enough to produce sunspots. (**beta**) is assigned to regions that have two sunspots or sunspot groups of opposite polarity. The classification (**gamma**) is appended to the above classes to indicate the AR has a complex region of sunspots with **intermixed polarity**. This classification can also be used individually to describe an AR that has no organized magnetic behavior. As an addendum to the original scheme, Kunzel (1965) proposed an additional classification to modify the existing three. (**delta**) indicates that at least one sunspot in the region **contains opposite magnetic polarities inside of a common penumbra** separated by no more than 2° in heliographic distance (24 Mm or 33″ at disk center).

Also at STCE: http://www.stce.be/news/222/welcome.html

Make sure to avoid classifying too quickly a sunspot group as a delta or a gamma type when this sunspot group is still very close to the limb. Indeed, line-of-sight may come into play that show an unipolar spot as if it would have a delta structure.
See STCE: http://www.stce.be/news/188/welcome.html

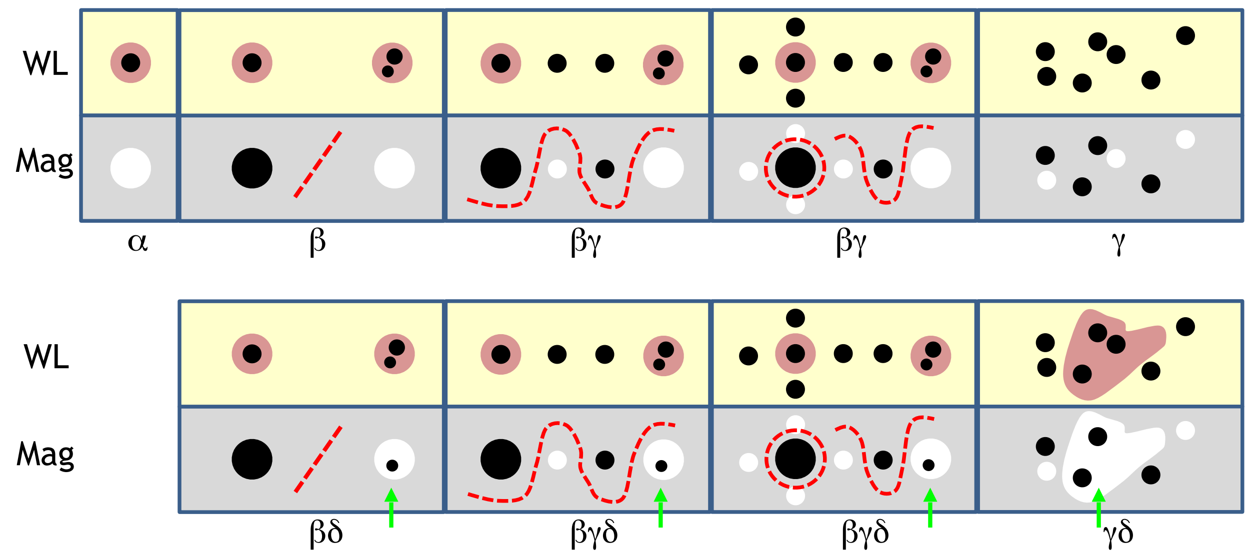
The pictures to the right are from SDO/HMI and show a magnetogram and a white light image of NOAA 1875 on 23 October 2013.

The chart with the % of Hale classification was based on the NOAA reports at https://solarscience.msfc.nasa.gov/greenwch.shtml for the period Jan 1996-September 2016. A total of 32965 classifications were made. The percentage of reported delta's in the sunspot groups is 3.5%.

See also: https://www.stce.be/educational/classification

FLARE PREDICTIONS

Mount Wilson (Hale) classification - Sketches

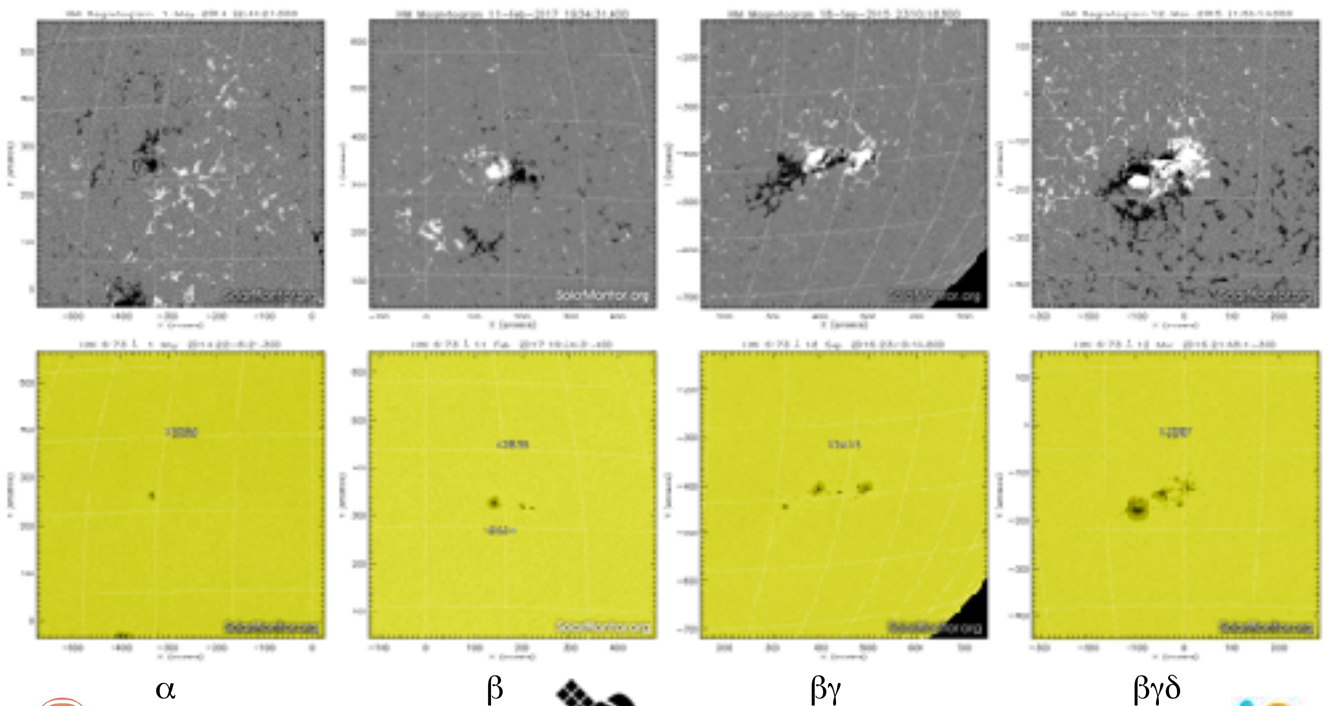


Text underneath based on SWPC User Guide, SWPC Glossary (https://www.swpc.noaa.gov/content/space-weather-glossary#m), Mount Wilson (http://obs.astro.ucla.edu/spotlgnd.html) and SIDC old webpages (http://sidc.oma.be/educational/classification.php#magnetic).

Alpha – Unipolar group; that is, all plus or all minus magnetic field
Beta – A bipolar group; that is a mix of plus and minus magnetic polarities exist, with the plus well divided from the minus with one polarity in each end (E-W) of the group, i.e. “easily divided by a simple line”.
Beta-Gamma – A group which is generally bipolar but which is lacking a well marked dividing line between the opposite polarity regions (“you need to lift your pencil to divide the polarities” or “no single, continuous line can be drawn between spots of opposite polarities”).
Gamma – a group in which the polarities are so completely mixed that **no bipolar structure** can obviously be recognized.
Delta – This is a sub-classification for non-unipolar regions. It means at least two opposing polarity umbrae are within two heliographic degrees of each other and share the same penumbra.

[The determination of the Hale class is done on the (magnetic polarity of the) sunspots, NOT the magnetograms!]

EXAMPLES OF HALE CLASSIFICATION



Examples from https://www.solarmonitor.org/index.php

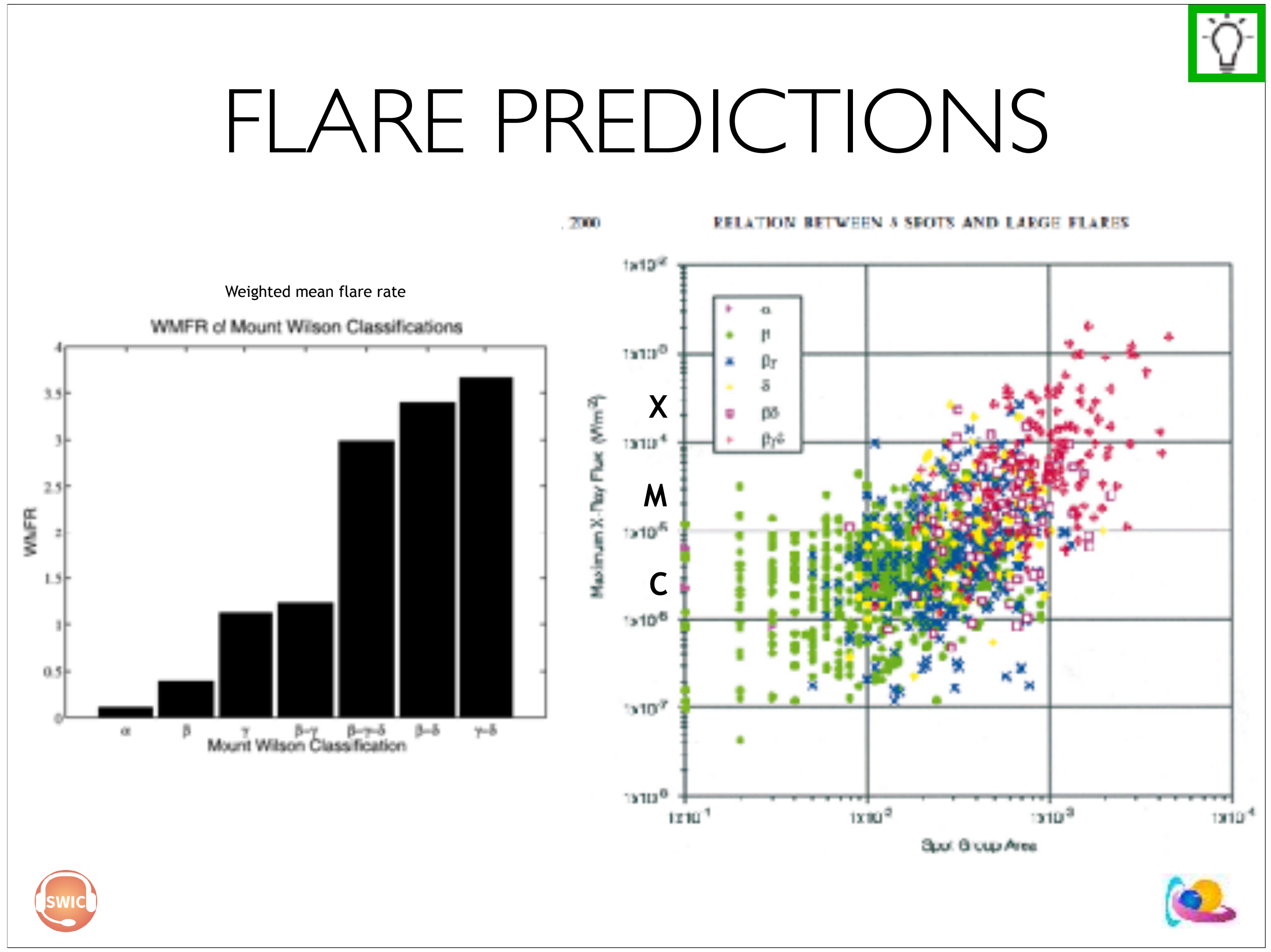


Figure left: Shin et al. (2016): Development of Daily Maximum Flare-Flux Forecast Models for Strong Solar Flares – http://adsabs.harvard.edu/abs/2016SoPh..291..897S

Most of the complex sunspots of the Mount Wilson magnetic classification that are characterized by gamma and/or delta show higher WMFR values (WMFR: weighted mean flare rate).

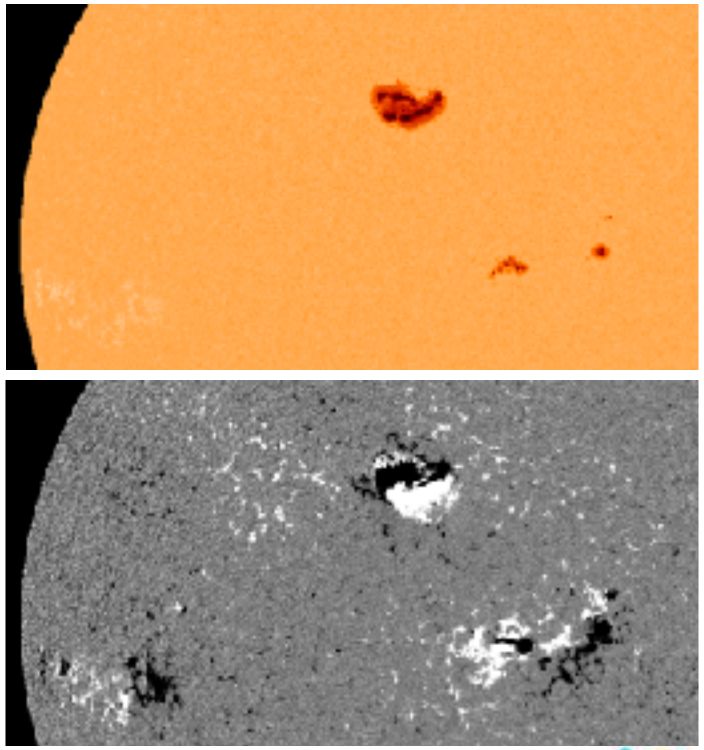
Figure right: Sammis et al. (2000): The Dependence of Large Flare Occurrence on the Magnetic Structure of Sunspots
http://adsabs.harvard.edu/abs/2000ApJ...540..583S
http://iopscience.iop.org/article/10.1086/309303/pdf

In Figure 2, we plot the largest flare from each active region against the largest reported area from that region, for each magnetic class. This shows a roughly linear connection between the logs of SXR flux and active region maximum areas. The general slope of Figure 2, upward and to the right, confirms the well-known fact that large active regions have more large flares than small ones and also tend to be more complex.

The increase in flare size with spot size shows that although the sharp gradient and currents of the delta configuration provide the appropriate situation for flare occurrence, the scale offered by a large spot is important in producing great flares. All large flares (X4 or higher) occur in spot groups of area greater than 1000 MH (micro hemispheres, **disk fraction**) classified bgd. Predictions that X1 flares will occur for such a class will enjoy a 41% probability of success with no other considerations. Adding some of the considerations mentioned by Zirin & Liggett (1987) and Zirin & Marquette (1991), particularly H-alpha brightness and flux emergence, should improve these predictions considerably.

FLARE PREDICTIONS

- Magnetic shear
- Magnetic helicity
- Flaring history
- Evolution of group
- Size of the spots
- …



Massi et al.: http://www3.mpifr-bonn.mpg.de/staff/mmassi/c4-Model.pdf
⇒Magnetic shear: the vector magnetic field is oriented more parallel to the neutral line than perpendicular to it.

From https://solarscience.msfc.nasa.gov/flares.shtml
Stable sunspots tend to be fairly symmetrical unless there is extensive magnetic shear nearby from emerging magnetic flux or the passing of an area of opposite magnetic polarity. Magnetic shearing can cause large portions of sunspot penumbras to distort or vanish.

Lee et al. (2012): Solar Flare Occurrence Rate and Probability in Terms of the Sunspot Classification Supplemented with Sunspot Area and Its Changes
http://adsabs.harvard.edu/abs/2012SoPh..281..639L
We used sunspot data from 1996 to 2010. We noted that sunspot area and its changes can be a proxy of magnetic flux and its emergence/cancellation, respectively.
When the sunspot area increases, the flare occurrence rates and probabilities noticeably increase, especially for major flares.This is statistical evidence that magnetic flux emergence is an important mechanism for triggering solar flares, because sunspot area can be a good proxy of magnetic flux.

Filament: e..g 7 June 2011:
STCE: http://www.stce.be/news/353/welcome.html
STCE: http://www.stce.be/news/x137x/welcome.html
Science at NASA: https://science.nasa.gov/science-news/science-at-nasa/2011/11jul_darkfireworks

: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

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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.

Flare prediction

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

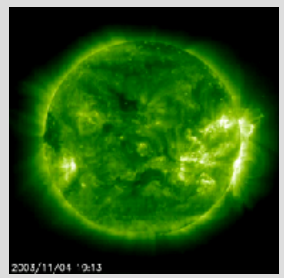
Radiation

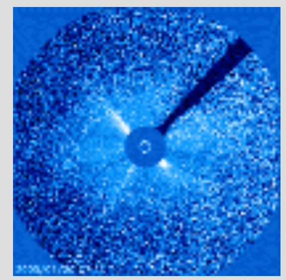
Particles

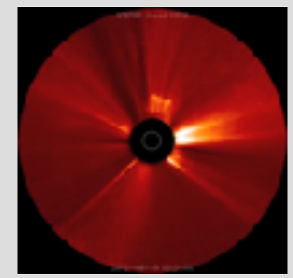
Solar flares

Proton events

Coronal Mass Ejections







SOHO/EIT

SOHO/LASCO

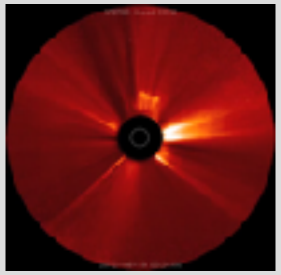
SOHO/LASCO

SOLAR ERUPTIONS

Magnetic Reconnection

Particles

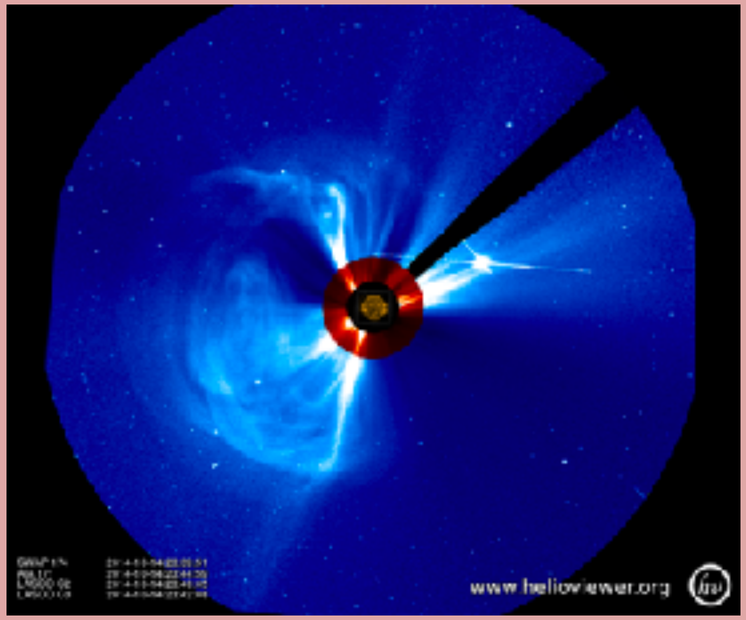
Coronal Mass Ejections



SOHO/LASCO

CME - OVERVIEW

- **Model**
- On-disk signatures
  - Filaments
  - Waves
  - Dimming
  - Post-eruption arcade
- Characteristics



PROBA2/SWAP
SDO/AIA
SOHO/LASCO

CORONAL MASS EJECTION

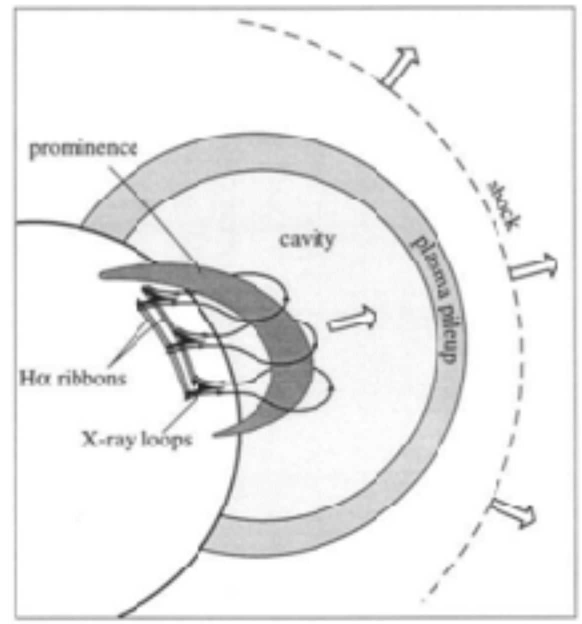


Figure 3. Schematic diagram showing the relationship between various features associated with a CME. The shaded region labeled "plasma pileup" refers to the outer circular arc seen in coronagraphs.

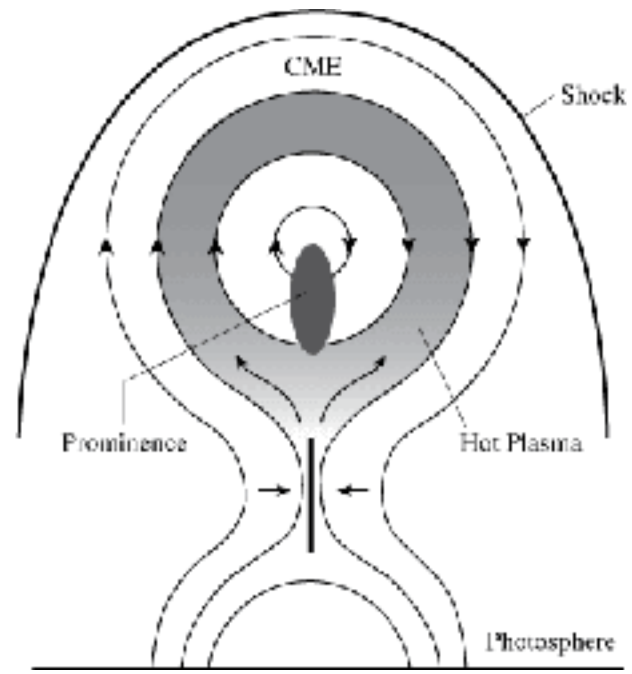


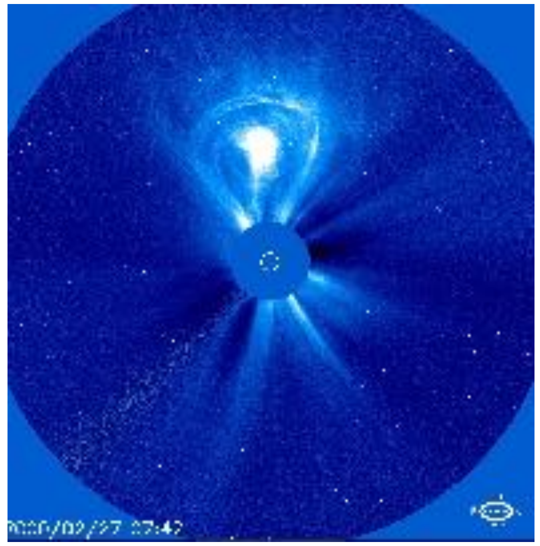
Figure to the right taken from https://ase.tufts.edu/cosmos/print_images.asp?id=27
A magnetic reconnection takes place at a current sheet (dark vertical line) beneath a prominence and above closed magnetic field lines. The coronal mass ejection (CME) traps hot plasma below it (hatched region). The solid 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.

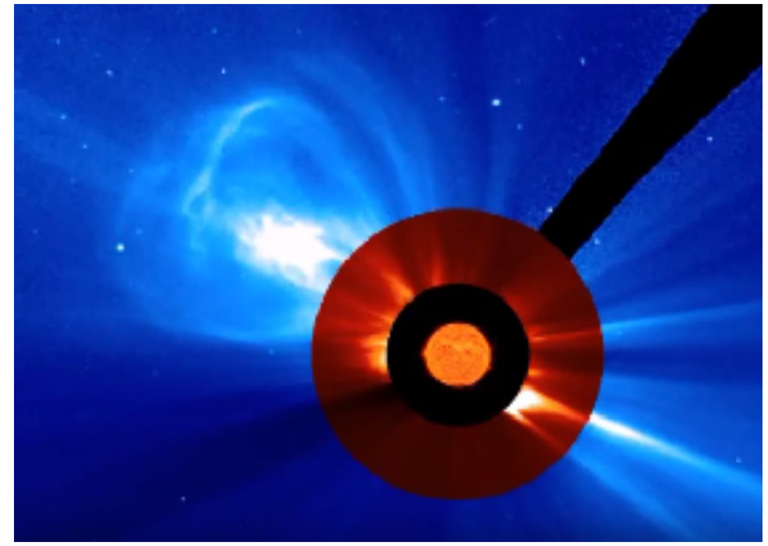
Left: In this model of a three-part coronal mass ejection, portrayed by Terry Forbes (2000), swept-up, compressed mass and a bow shock have been added to the eruptive-flare portrayal of Tadashi Hirayama (1974). The combined representation includes compressed material at the leading edge of a low-density, 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





SOHO/LASCO

SDO/AIA
SOHO/LASCO

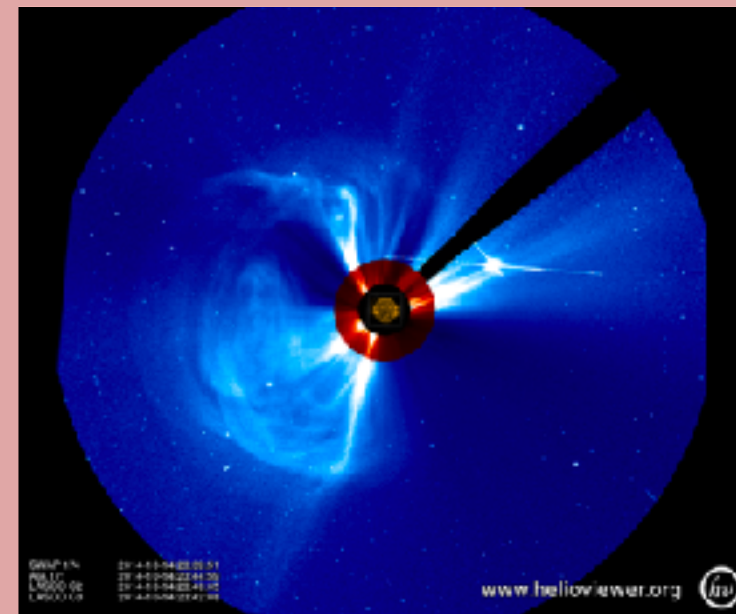
Left picture: SOHO Gallery: https://sohowww.nascom.nasa.gov/gallery/images/las02.html
Right picture: STCE: http://www.stce.be/news/342/welcome.html

Coronagraph 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

CME - OVERVIEW

- Model
- On-disk signatures
  - Filaments
  - Waves
  - Dimming
  - Post-eruption arcade
- Characteristics



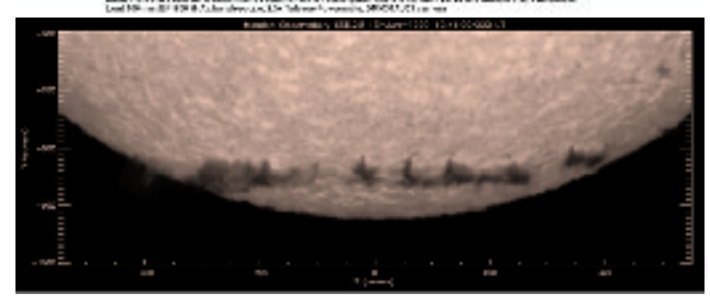
PROBA2/SWAP
SDO/AIA
SOHO/LASCO

FILAMENTS & PROMINENCES

Chromospheric features
- Protruding into corona
- H-alpha and EUV
- Relatively cool (10.000K)

Mark the transition between positive and negative magnetic areas
  Appear all over solar disk

Location
- In active region
  Group filament
- Outside active region
  Quiescent filament
- Polar crown filament



Prominences are observed at the limb, filaments on the solar disk, but these are in fact the same features.

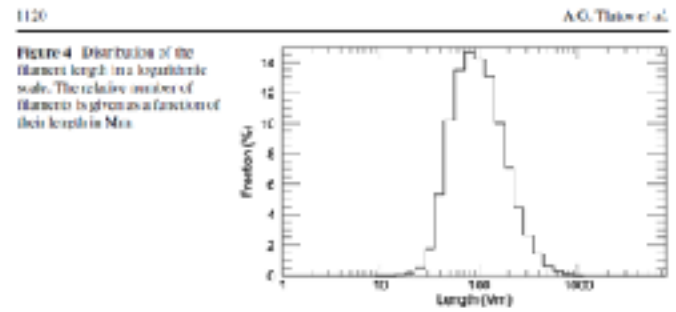
More info on filaments at http://www.stce.be/news/219/welcome.html

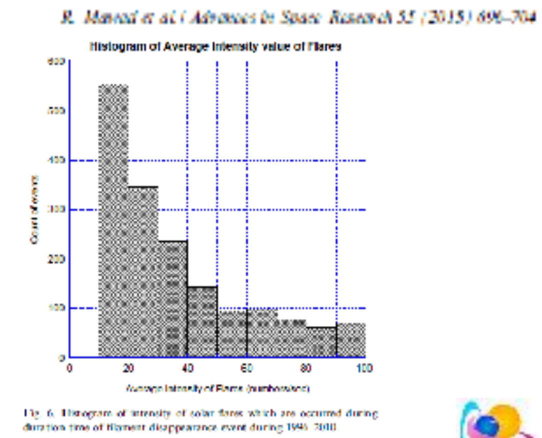
Polar crown filaments form above the polarity inversion line between the old magnetic flux of the previous cycle and the new magnetic flux of the current cycle. Studying their appearance and their properties can lead to a better understanding of the solar cycle.

More info on polar crown filaments at:
– http://solar.physics.montana.edu/wood/99Prom.html
– https://science.nasa.gov/science-news/science-at-nasa/2008/17sep_polarcrown

FILAMENTS & PROMINENCES

- Quiescent
  - Not associated to AR
  - Weeks to months
- Length
  - Long filaments (> 15°)
  - More prone to instabilities
    - Near (emerging) active regions
    - From Moreton/EIT waves
    - Near coronal holes
  - Flaring
    - 38% result in at least 1 flare
    - Intensity : C1-M1





Tlatov et al. (2016): Tilt Angles of Solar Filaments over the Period of 1919 – 2014
http://adsabs.harvard.edu/abs/2016SoPh..291.1115T

Mawad et al. (2014): Filaments disappearances in relation to solar flares during the solar cycle 23
http://adsabs.harvard.edu/abs/2015AdSpR..55..696M

Hao et al. (2015): Statistical Analysis of Filament Features Based on the Hα Solar Images from 1988 to 2013 by Computer Automated Detection Method
http://adsabs.harvard.edu/abs/2015ApJS..221...33H

FILAMENT/PROMINENCE ERUPTIONS

- Height
  - Zirin (1988)
    - If > 50.000 km, eruption likely within next 48 hours
  - Filippov (2008)
    - Height cannot exceed ciritical height
    - Related to strength of and change in magnetic field
- Other signs
  - Darkening filament
  - Change in tilt or length

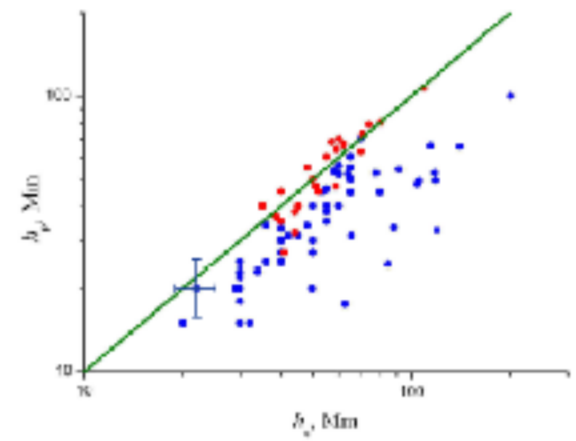


Fig. 7. The observed filament height above the chromosphere h_p versus the critical height of stable filament equilibrium h_c. The blue circles correspond to the filaments which safely passed the west limb. The red circles correspond to the filaments which disappeared from the disk. The straight green line corresponding to an equality of these quantities is the stability boundary.

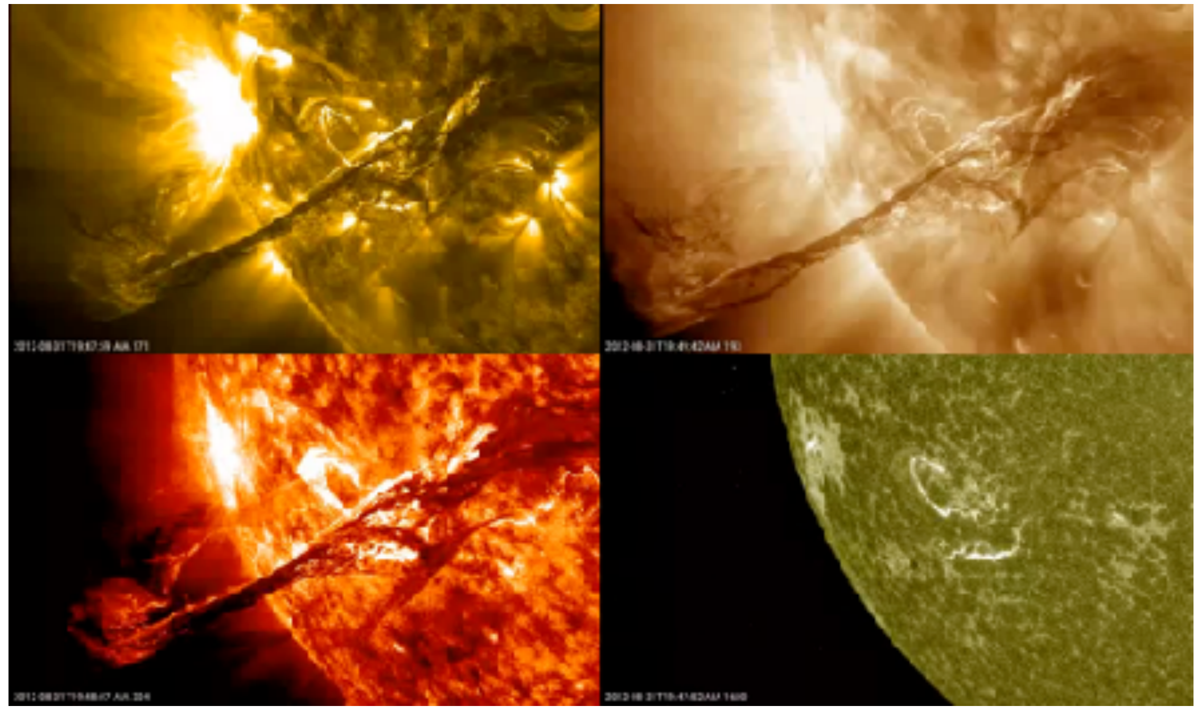
Data taken from:
Filippov et al. (2008): Causal relationships between eruptive prominences and coronal mass ejections
http://adsabs.harvard.edu/abs/2008AnGeo..26.3025F
http://www.ann-geophys.net/26/3025/2008/angeo-26-3025-2008.pdf

Zirin (1988): Astrophysics of the Sun

The critical height is a model based parameter depending on the strength of the magnetic field and describing how the equilibrium of a prominence will be unstable when it reaches a certain height (See Filippov & Den (2000)).

Most disrupted prominences become unstable at a height of 0.06-0.14 R⊙ from the solar surface, and there are two most probable critical heights at which a prominence is very likely to become unstable, the first one is 0.13 R⊙ and the second one is 0.19 R⊙. (https://iopscience.iop.org/article/10.1088/0004-637X/744/2/168)

TWO RIBBON FLARE



SDO/AIA

This movie shows a spectacular filament eruption, where a very long-living filament (that was already seen at the previous solar rotation) came back around the solar limb. Only, now the filament was not stable anymore and erupted causing a coronal mass ejection. Due to the location of the filament on the east limb, only a glancing blow (flank) of this relatively slow moving particle cloud (+/- 520 km/s) struck Earth, sparking a minor geomagnetic storm. Aurorae were visible in Scandinavia, Scotland, Canada and Alaska.

In the lower right panel, the **flare ribbons** are clearly seen to move apart.

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

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

filaments / prominences

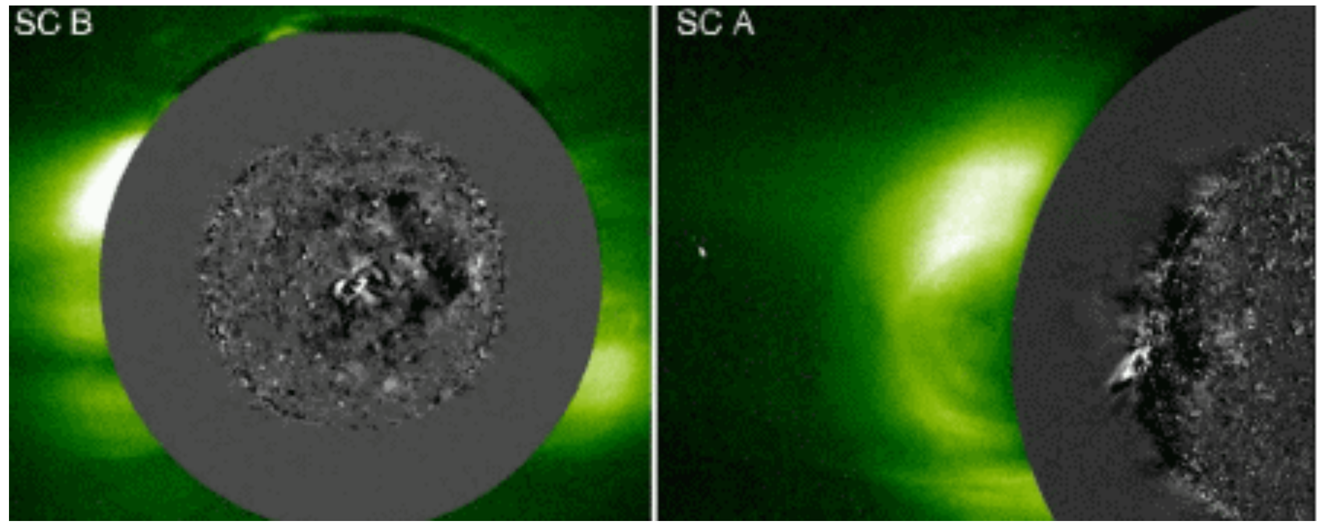
SOLAR INDICES FOR 16 Apr 2014
WOLF NUMBER CATANIA : ///
10CM SOLAR FLUX : 184
AK CHAMBON LA FORET : 012
AK WINGST : 004
ESTIMATED AP : 004
ESTIMATED ISN : 139, BASED ON 29 STATIONS.

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

EIT WAVE



STEREO/EUVI & COR1

There are expanding large-scale waves in the solar atmosphere usually associated to strong solar eruptions (flares and CMEs). We distinguish two kinds of waves, Moreton waves are observed in Halpha and mostly related to flares, while EIT waves are seen in EUV and mostly related to CMEs.

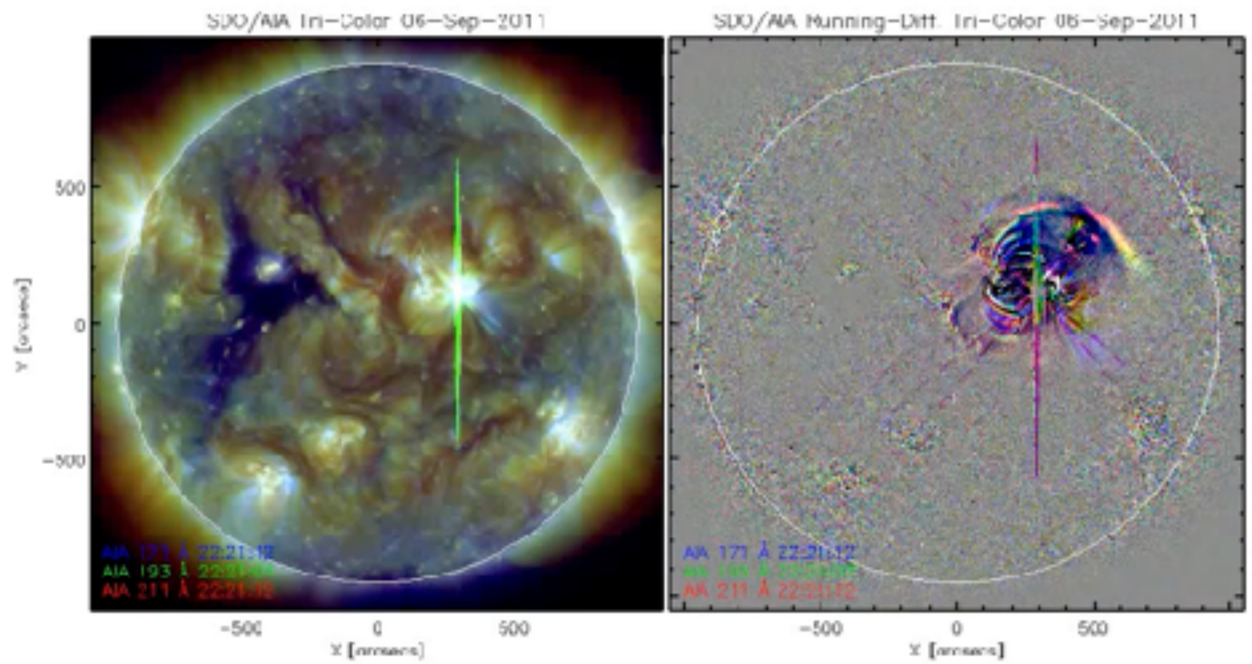
Another name for this kind of feature is "solar tsunami".

EIT waves are named after the SOHO/EIT instrument with which they were first discovered. They are coronal waves with rather low speeds (200-600 km/s) and are typically related to CMEs.

Example above on EIT wave from: https://cor1.gsfc.nasa.gov/
The twin STEREO spacecraft confirmed the existence of EIT waves in February 2009 when sunspot 11012 unexpectedly erupted. The blast hurled a billion-ton cloud of gas (a "CME") into space and sent a tsunami racing along the sun's surface. STEREO recorded the wave from two positions separated by 90 degrees,

More examples:
Moreton waves: http://www.stce.be/news/222/welcome.html
EIT waves: http://www.stce.be/news/222/welcome.html and http://www.stce.be/news/241/welcome.html

EIT WAVE



SDO/AIA

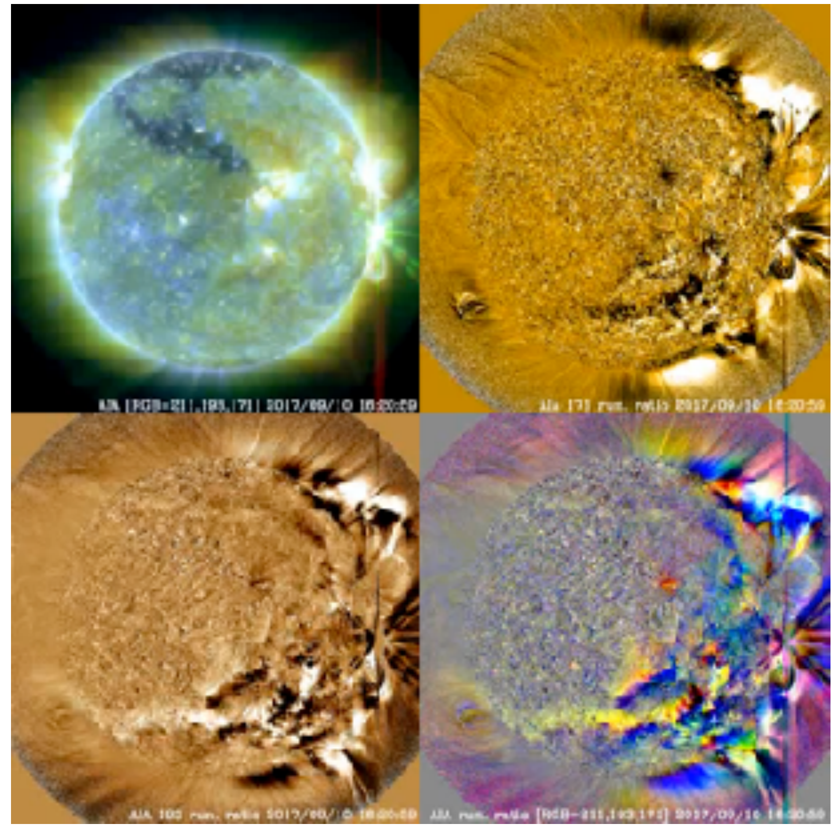
Shen et al. (2014): A Chain of Winking (Oscillating) Filaments Triggered by an Invisible Extreme-ultraviolet Wave
http://adsabs.harvard.edu/abs/2014ApJ...786..151S

In this paper, we present an interesting observational study of a chain of winking filaments that was in association with a GOES X2.1 flare in the NOAA active region AR11283 (N13W18) on 2011 September 6. The flare was produced with a remarkable EUV wave propagating mainly in the northwest direction, which not only triggered the oscillation of three filaments in the northwest of AR11283, but also launched the oscillation of a long filament and the occurrence of a small jet in the eastern hemisphere, where the wave signature is very weak or even invisible.

Based on our analysis results, we conclude that the EUV wave is a **good agent for triggering and connecting successive but separated solar activities** in the solar atmosphere.

GLOBAL EIT WAVE FROM X8 FLARE

SDO/AIA

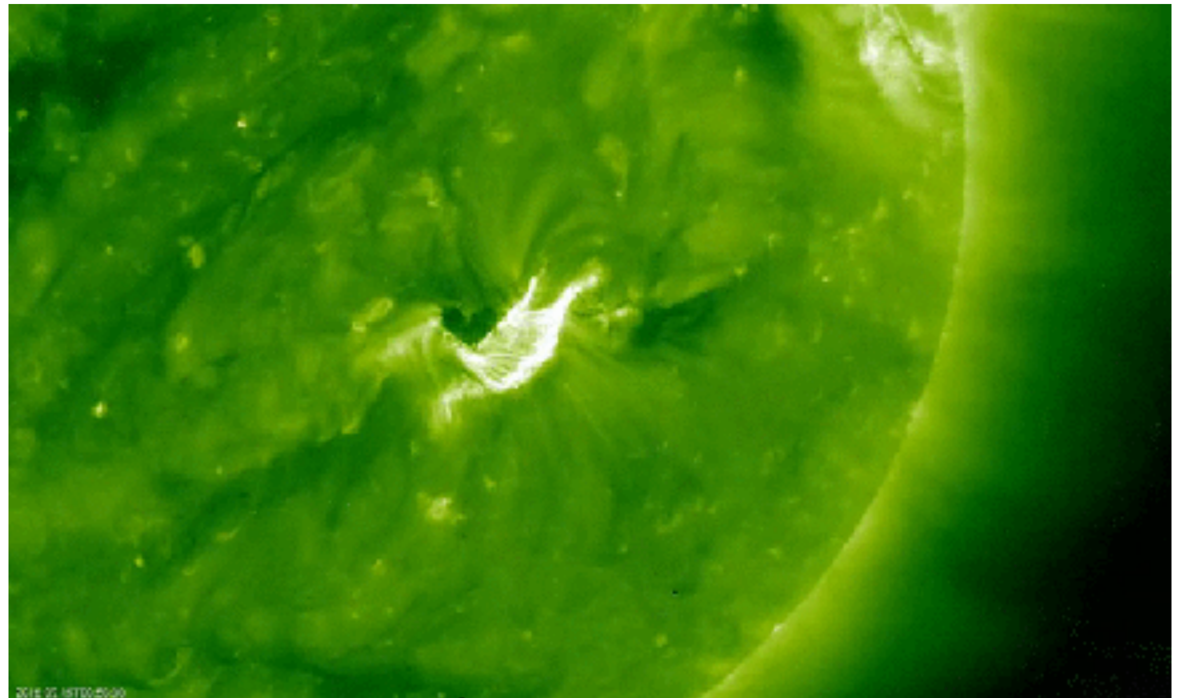


© Liu et al., 2018

EIT-waves can be **stopped**, **reflected** and **refracted** at the boundary of coronal holes or near active regions.

Liu et al. (2018): A Truly Global Extreme Ultraviolet Wave from the SOL2017-09-10 X8.2+ Solar Flare-Coronal Mass Ejection
http://adsabs.harvard.edu/abs/2018ApJ...864L..24L

CORONAL DIMMING
(TRANSIENT CORONAL HOLE)



STEREO/EUVI

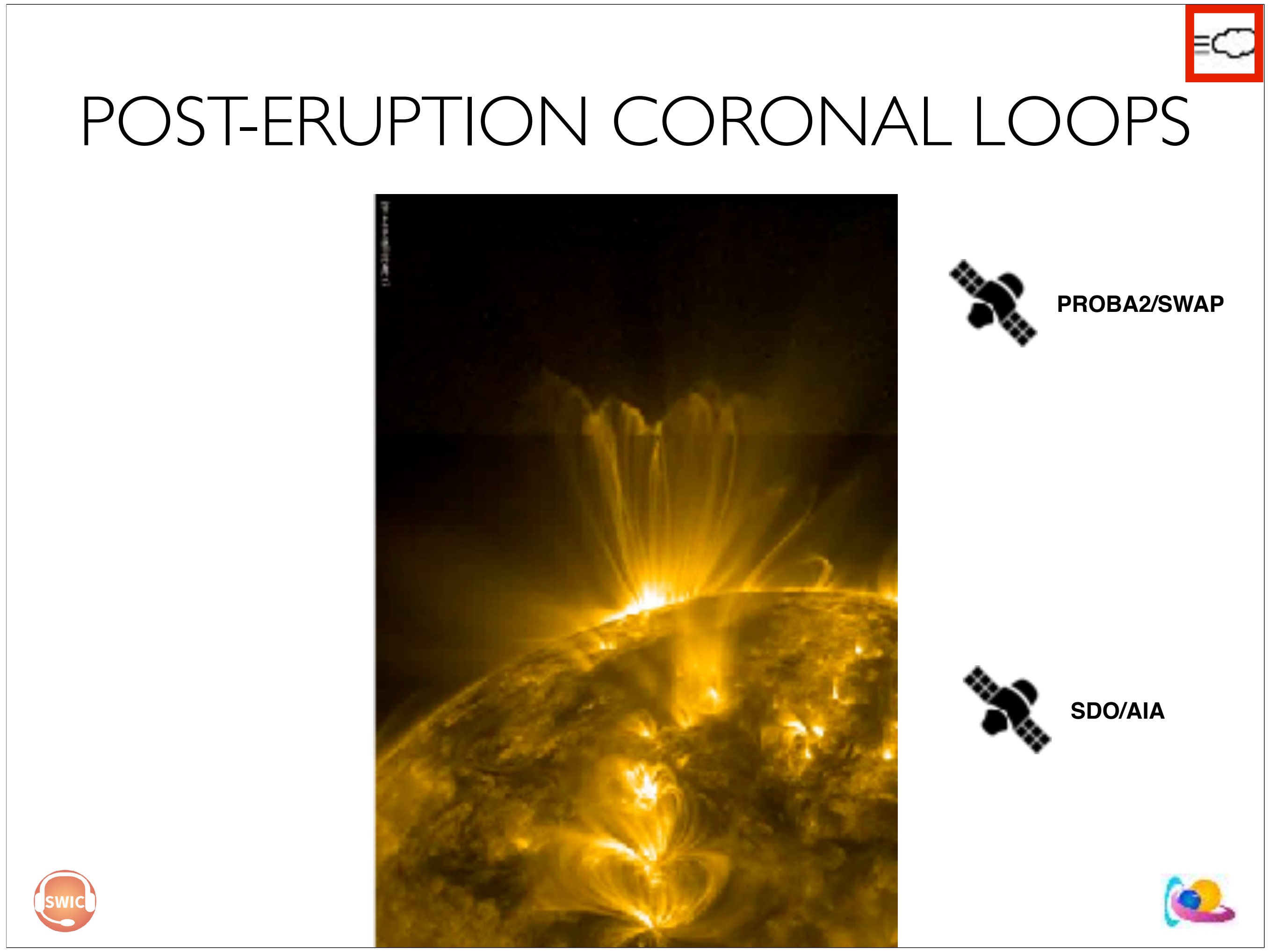
A coronal dimming occurs in the wake of coronal mass ejection and is usually interpreted as mass depletions due to the loss or rapid expansion of the overlying corona (the plasma is hurled away in the coronal mass ejection). This darkening is temporary as the plasma is supplemented again. That is why they are also called transient coronal holes.

Sources:
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

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

Cheng et al. (2016): The Nature of CME-flare-Associated Coronal Dimming
http://adsabs.harvard.edu/abs/2016ApJ...825...37C



Post-flare loops indicate a long duration event and thus the presence of a CME.

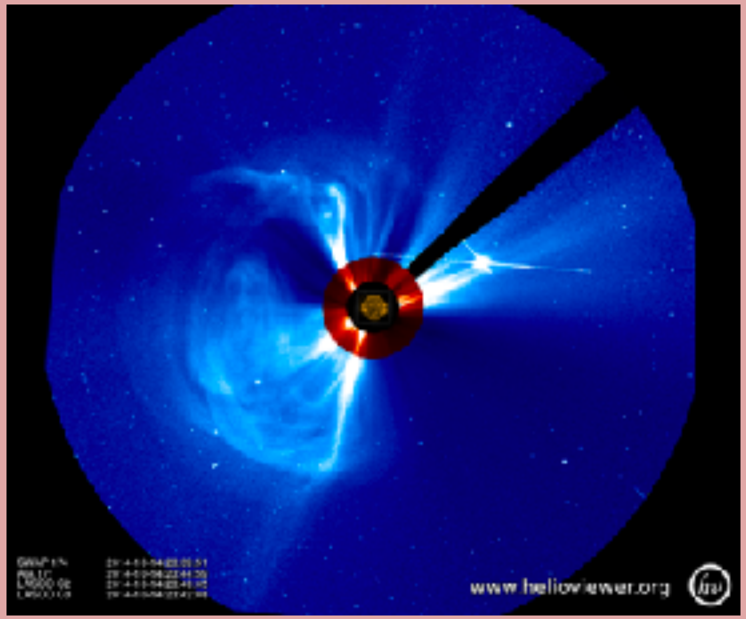
This M2-event finished with an **arcade**, which is the technical term for a series of post-flare coronal loops. Interestingly, these post-flare loops continued to grow, first reaching the limit of AIA's Field-Of-View (FOV), and then continuing to grow even beyond AIA's FOV. Fortunately, PROBA2's wider-field SWAP telescope was able to monitor this arcade in its full glory till its disappearance.
The loops of this long duration arcade were visible for about 2.5 days (60 hours!), and at their maximum height, they were towering at least 340.000 km above the solar surface. That's not far from the average Earth-Moon distance!

Sources:
STCE: http://www.stce.be/news/316/welcome.html
STCE: http://www.stce.be/news/331/welcome.html

STCE: http://www.stce.be/news/274/welcome.html

CME - OVERVIEW

- Model
- On-disk signatures
  - Filaments
  - Waves
  - Dimming
  - Post-eruption arcade
- **Characteristics**

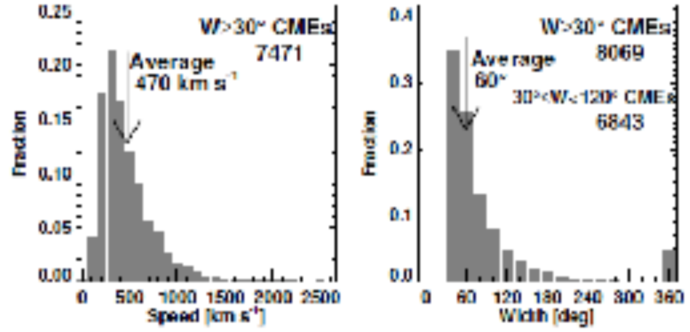


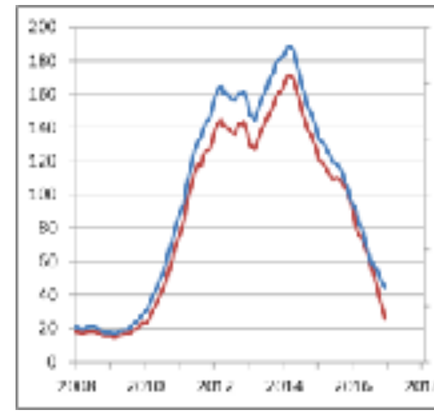
PROBA2/SWAP
SDO/AIA
SOHO/LASCO

CORONAL MASS EJECTION

Characteristics

- Average speed
  - 470 km/s
  - Fast transit event (<24h)
- Average width
  60 degrees
- Average Mass
  - 10^{12} kg
  - ~ medium sized mountain
- Number per day
  1-6 / day

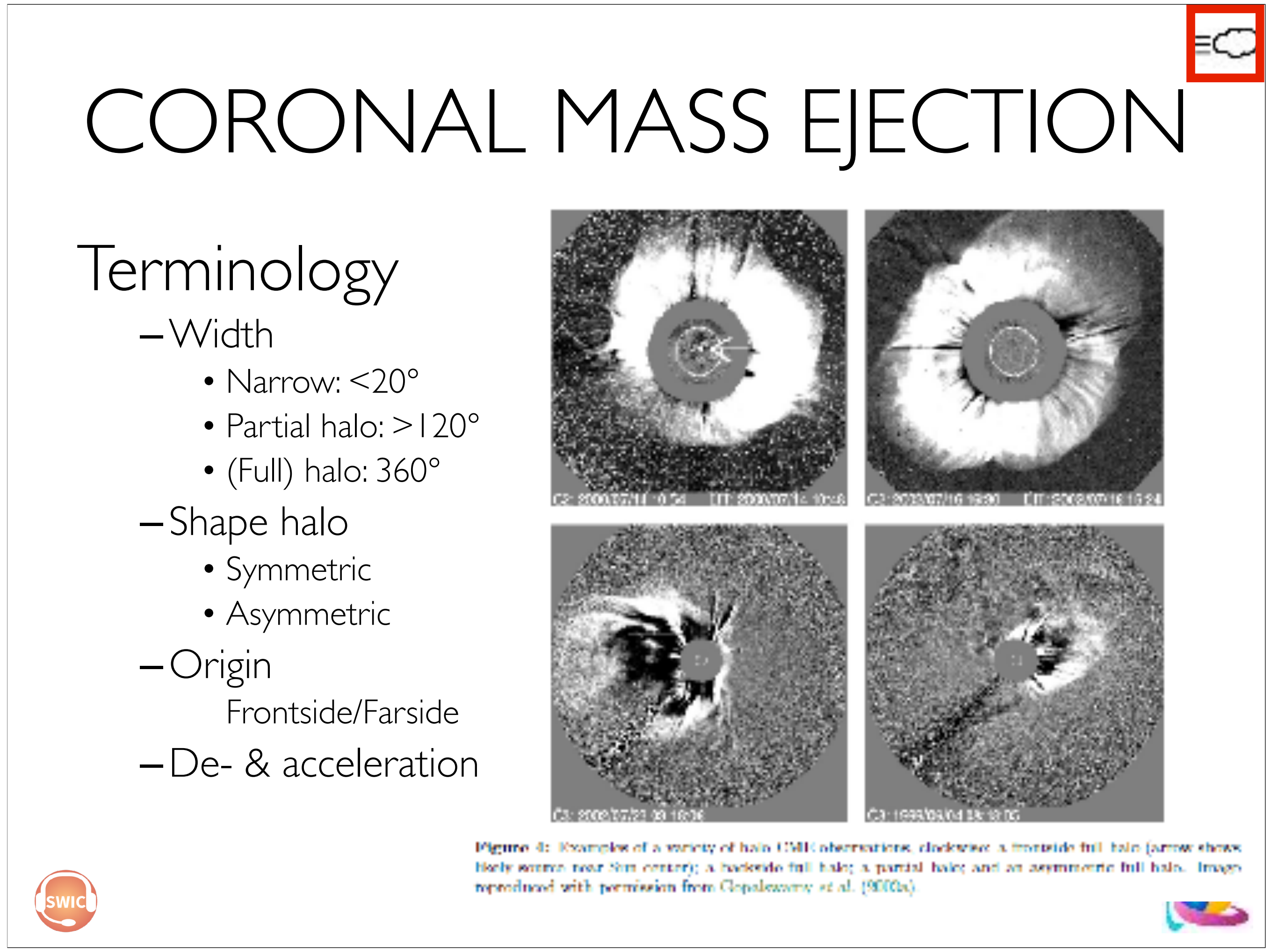




CACTus, ROB/SIDC

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

A nice example a fairly recent (2012) Fast Transit Event 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.



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

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. The CDAW CME catalog 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).

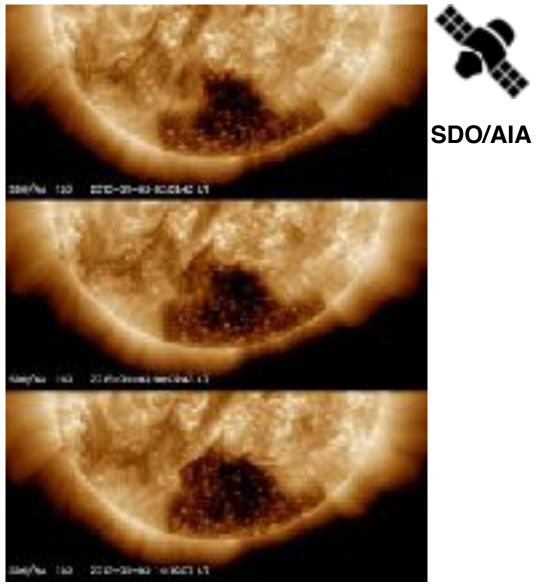
Because of their increased sensitivity, field of view and dynamic range, the SOHO/LASCO and STEREO/COR coronagraphs now frequently observe halo CMEs, which appear as expanding, circular brightenings that completely surround the coronagraphs’ occulting disks (Figure 4). Observations of associated activity 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.

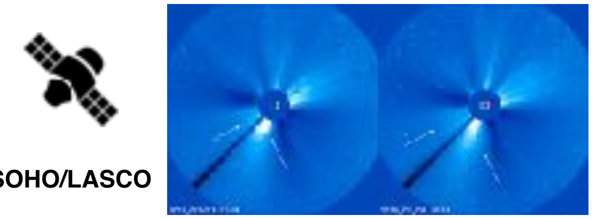
Yashiro et al. (2004) found that slow CMEs tend to accelerate and fast CMEs decelerated through the LASCO field of view, with those around the solar wind speed having constant speeds. Thus, CMEs attain fast acceleration low in the corona until gravity and other drag forces slow them further out. This process continues into the interplanetary medium.

CORONAL MASS EJECTION

Terminology

- Stealth CME
  - No obvious surface signature
  - Rather slow (<300 km/s)
  - Rather faint
- CME cannibalism
  - 2nd CME overtakes 1st
  - Enhanced geomagnetic storms
- Deflection
  - By corona holes, CME,…





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

The absence of solar surface activity with observed CME activity is not a new observation (Howard and Harrison, 2012). The launch of STEREO in 2006, however, afforded us the opportunity to study the origins of CMEs simultaneously from multiple lines of sight. Robbrecht et al. (2009a) presented a study of a streamer blowout CME without a clear source region. The STEREO spacecraft were sufficiently widely separated (53°) that the CME and its source region could be viewed edge-on in STEREO A and face-on in STEREO B. STEREO B saw the CME as a faint halo and it was detected in-situ as a magnetic cloud 5 days later. Robbrecht et al. suggested that the CME originated high enough up in the corona such that no surface signatures were evident. Subsequently, Ma et al. (2010) performed a statistical study of all CMEs observed during the first 8 months of 2009 when the STEREO lines of sight were nearly perpendicular to each other. They found that about a third of the CMEs were “stealth”, having no distinct surface association, and tending to be slow, i.e., < 300 km s-1. Faint coronal changes could be detected in about half of the stealth CMEs, again suggesting a higher launch site. It is noted that this period was during the recent unusual extended solar minimum, so the fraction of such CMEs may be different at other times.

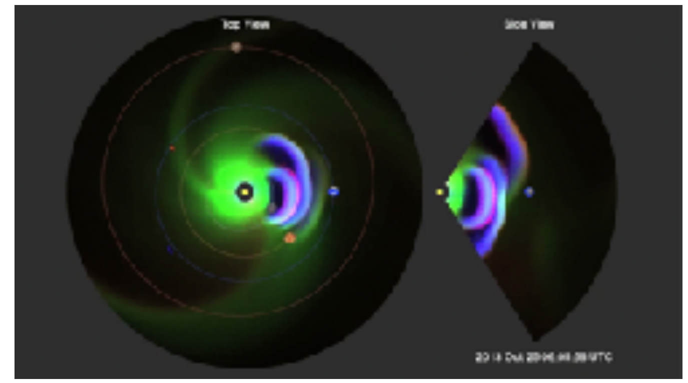
A good example is in this STCE Newsitem: The curious case of a strong storm
http://www.stce.be/news/290/welcome.html

More info at Howard et al. (2012): Stealth Coronal Mass Ejections: A Perspective
http://adsabs.harvard.edu/abs/2013SoPh..285..269H

CORONAL MASS EJECTION

Terminology

- Stealth CME
  - No obvious surface signature
  - Rather slow (<300 km/s)
  - Rather faint
- CME cannibalism
  - 2^{nd} CME overtakes 1^{st}
  - Enhanced geomagnetic storms
- Deflection
  - By coronal holes, CME,…



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

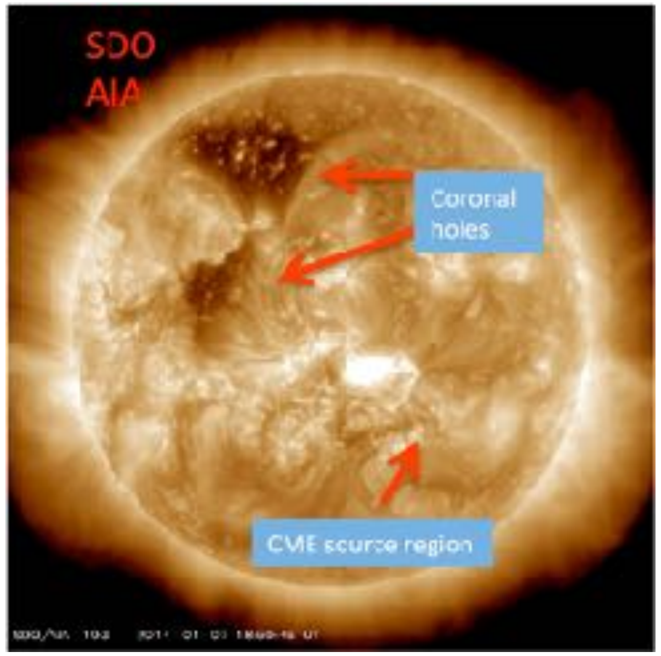
In this research model run, the Sun has launched three coronal mass ejections (CMEs) which may merge into a single front as it expands into the solar system. These events are sometimes called 'cannibal' CMEs.

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
- Stealth CME
  - No obvious surface signature
  - Rather slow (<300 km/s)
  - Rather faint
- CME cannibalism
  - 2nd CME overtakes 1st
  - Enhanced geomagnetic storms
- Deflection
  - By coronal holes, CME,…



SDO/AIA

A good example of deflections is at https://science.gsfc.nasa.gov/674/swl_research.html
Extreme Solar Wind Deflects CMEs
A very fast CME was observed on January 7, 2014. Preliminary data analysis and all 8 community forecasts reported in GSFC's Space Weather Scoreboard indicated rapid arrival at Earth and a major geo-magnetic storm. However, the CME arrived at Earth ~19 hr after the predicted time, and the geomagnetic storm was weak (Kp < 3). What happened? Detailed analysis by the CCMC/SWRC team identified possible causes for the gap between predicted vs. actual outcome. The solar wind coming from the nearby coronal holes was extremely fast - 950 km/s at Earth (very rare!) and deflected the CME away from the Earth. However, the solar wind speed assumed at the lower boundary of the CME transport model (WSA-ENLIL) was too low - 750 km/s (maximum allowed value). Therefore the model CME propagated to Earth much too slowly. Previously the same coronal hole did not produce such high speed wind, so the strong deflection was a surprise. We know that CMEs can be deflected by a coronal hole, so a CME that seems to be Earth-directed can be deflected from the Earth-Sun line. The simulations did not predict that the deflection would be so large that the CME only hit a glancing blow to the Earth.

Deflections
Kay et al. (2015): Global Trends of CME Deflections Based on CME and Solar Parameters
http://adsabs.harvard.edu/abs/2015ApJ...805..168K
Forecasting space weather effects relies on knowledge of the path of a CME. Observations commonly show significant non-radial deviations in the CME trajectories. Understanding these deflections will allow for more accurate space weather predictions. Coronal observations show that CMEs can undergo significant deflection close to the Sun, but it is often hard to disentangle the effects of deflection, rotation, and non-uniform expansion in the lower corona (Nieves-Chinchilla et al. 2012). Byrne et al. (2010) measure a latitudinal deflection of 30° below 7 ⊙ R for the 2008 December 12 CME. Kilpua et al. (2009) suggest that CMEs may not be able to penetrate the open magnetic field emanating from coronal holes (CHs). The CH magnetic field then guides CMEs toward the Heliospheric Current Sheet (HCS). Shen et al. (2011) and Gui et al. (2011) attribute the deflection to gradients in the background magnetic energy density, which would also cause CMEs to tend to deflect toward the HCS. As with the observed CMEs, the MHD CMEs tend toward regions of lower magnetic energy. In some cases, magnetic reconnection creates an imbalance in the magnetic energy, which causes a CME to deflect early in the eruption (Zuccarello et al. 2012; Lynch & Edmondson 2013). MHD simulations also show that CMEs can deflect due to interactions with other CMEs (Lugaz et al. 2012). Finally, there are also effects of CME rotation due to a torque created by differential forces along the CME’s toroidal axis.

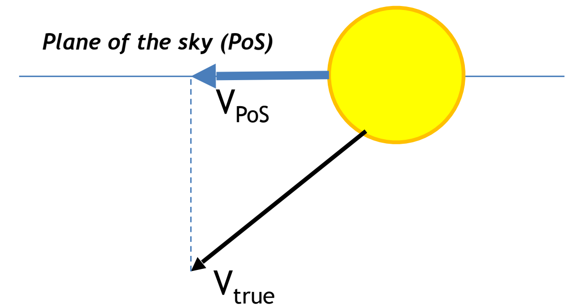
CORONAL MASS EJECTION

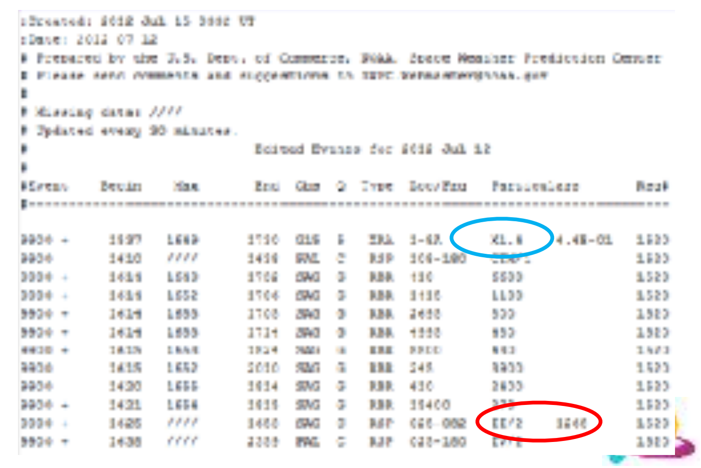
Speed

- We see the projected speed
  - Plane of the sky (PoS)
- We use the true speed
  - = Corrected PoS speed

    $V_{true} \geq V_{PoS}$
  - From Type II radio bursts

    = shock speed





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

Some additional information on the relation between CMEs, CME shocks and Type II radio bursts can be found at http://www.ovsa.njit.edu/fasr/Chapter_15.pdf (Gopalswamy: Interplanetary Radio bursts, in Solar and Space Weather Radiophysics - Chapter 15).
As well as in Gopalswamy et al. (2008): Coronal mass ejections, type II radio bursts, and solar energetic particle events in the SOHO era
http://adsabs.harvard.edu/abs/2008AnGeo..26.3033G
http://www.ann-geophys.net/26/3033/2008/angeo-26-3033-2008.pdf

Some good examples on how to calculate/deduce the CME speed:
- NASA: http://rodshome.com/TLA/sunspots/CMEveloctiry%20calc.pdf
- Pohjolainen et al. (2007): CME Propagation Characteristics from Radio Observations
http://adsabs.harvard.edu/abs/2007SoPh..244..167P

Data of Type II bursts with derived shock speeds:
NOAA: https://www.swpc.noaa.gov/products/solar-and-geophysical-event-reports
SWS: http://www.sws.bom.gov.au/Solar/2/3
Attention: The shock speed is usually (a bit / a lot) higher than the (corrected) CME speed.

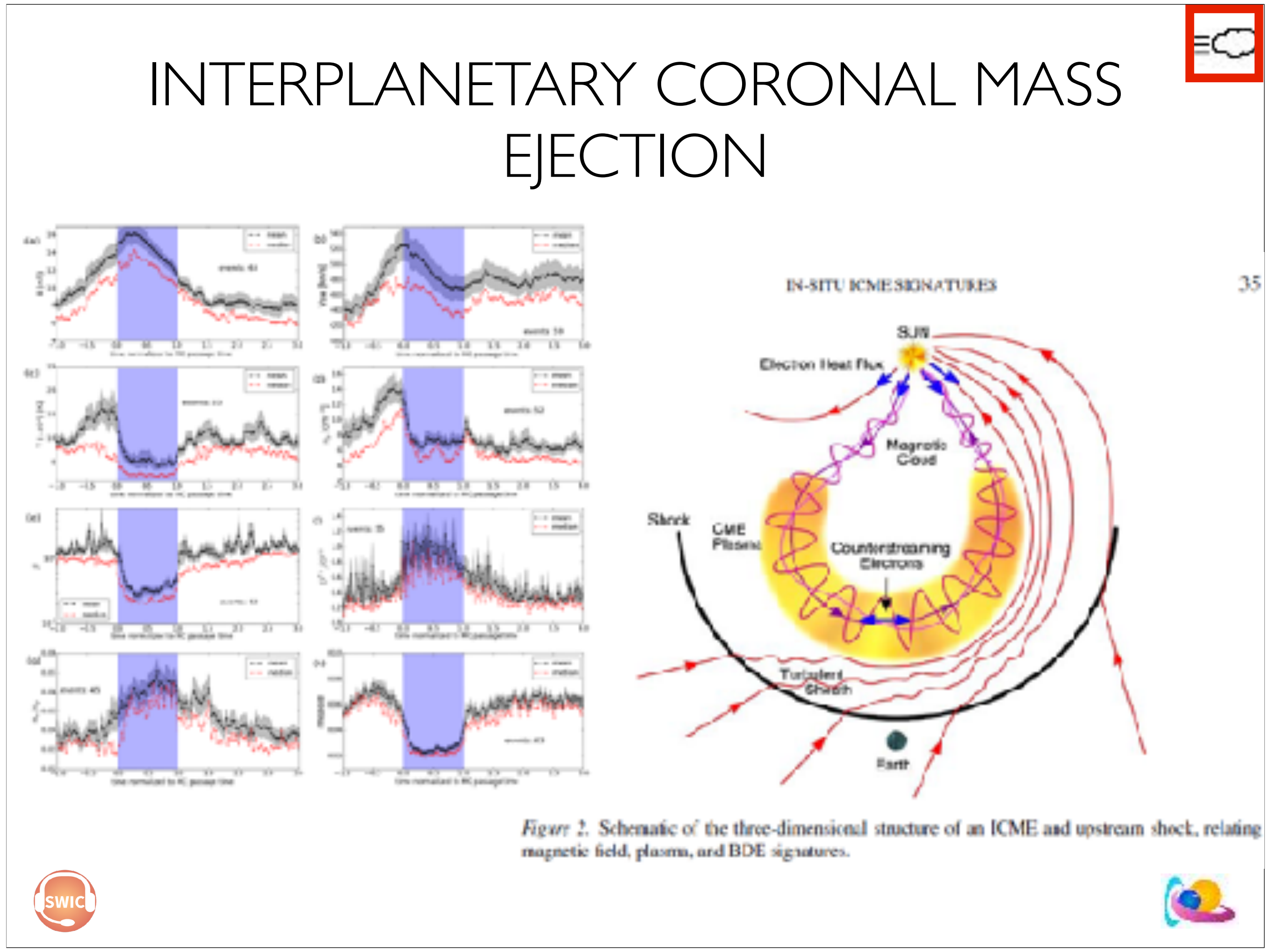


Figure right: Zurbuchen et al. (2006): In-Situ Solar Wind and Magnetic Field Signatures of Interplanetary Coronal Mass Ejections http://adsabs.harvard.edu/abs/2006SSRv..123...31Z

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.

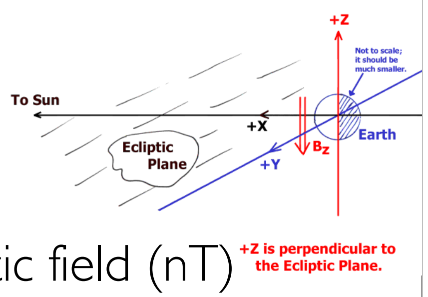
Rodriguez et al. (2016): Typical Profiles and Distributions of Plasma and Magnetic Field Parameters in Magnetic Clouds at 1 AU
http://adsabs.harvard.edu/abs/2016SoPh..291.2145R

Figure to the left: 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

Coronal mass ejections (CMEs) are large-scale solar eruptive events in which large amounts of plasma carrying magnetic flux and helicity (see e.g. Démoulin, Janvier, and Dasso, 2016, and references therein) are expelled into the interplanetary space. When sampled in situ by a spacecraft in the interplanetary medium, they are called interplanetary CMEs (ICMEs). Magnetic clouds (MCs) are an important subset of ICMEs that exhibit a particular internal magnetic field configuration resembling that of a flux rope. This is characterized by an enhanced magnetic field intensity, smooth rotation of its magnetic field vector, and low temperature (e.g. Burlaga, 1991).
The classical three-part structure of a CME (bright front, dark cavity, and dense core) is commonly also interpreted in terms of a magnetic flux rope propagating in the corona (see e.g. Illing and Hundhausen, 1986; Vourlidas et al., 2013). The bright front corresponds to the plasma pile-up in front of the flux rope, the cavity represents the bulk of the flux rope, and the dense core is the erupting prominence that is located in the bottom (concave-out) parts of the flux rope field lines. However, it is very difficult to identify the corresponding three-part morphology in ICMEs detected in situ (e.g. Kilpua et al., 2013a).

The plasma β and the level of fluctuations in the magnetic field vector are the best parameters to define the boundaries of MCs. We find that one third of the events shows a peak in plasma density close to the trailing edge of the flux ropes.

CORONAL MASS EJECTION



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**
- Need to predict both orientation and intensity

  Not easy and potentially changing during Sun-Earth transit!

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.

Finding your way in the URSIgram

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

CME & ICME

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

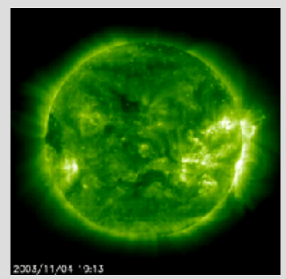
Radiation

Particles

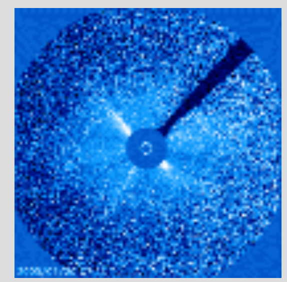
Solar flares

Proton events

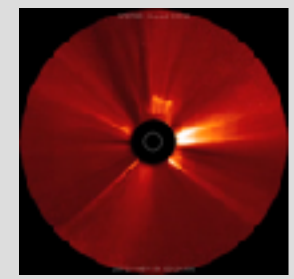
Coronal Mass Ejections



SOHO/EIT



SOHO/LASCO



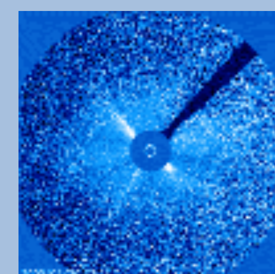
SOHO/LASCO

SOLAR ERUPTIONS

Magnetic Reconnection

Particles

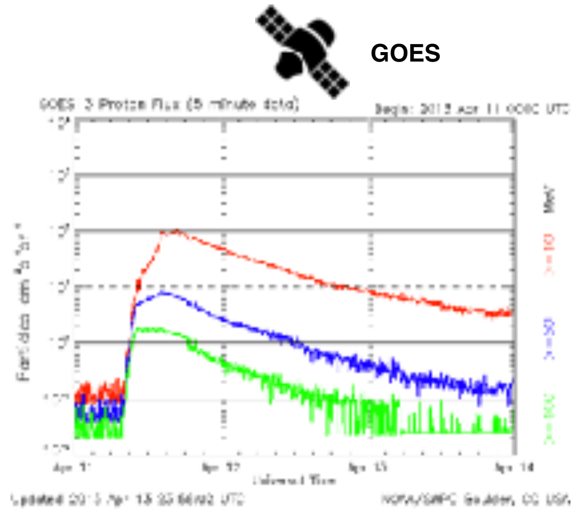
Proton events



SOHO/LASCO

PROTON EVENTS

Proton event
- > 10MeV proton flux
  5 min. average
- Start: ≥ 10 pfu
  Need at least 3 data points
- Peak: maximum value
  May take hours to days
- End: < 10 pfu
  NO new events as long as flux > 10 pfu



Proton enhancement
  Increased flux, but below 10 pfu

Solar Energetic Particles
  High energy (keV to GeV) protons, electrons and ions which come from the Sun

SWPC 's « The Weekly » User guide (https://www.swpc.noaa.gov/sites/default/files/images/u2/Usr_guide.pdf ; page 15) on Proton Events:
A proton event starts when the integrated proton flux (5-minute average) rises above a specific threshold for at least three points.

From: SESC: https://umbra.nascom.nasa.gov/SEP/ (contains list of all proton events since 1976)
The end of an event is the last time the flux was greater than or equal to 10 pfu. This definition 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.

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.

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 EVENTS

Impulsive

Associated with impulsive solar **flares** (electron rich)

The onsets are not necessarily fast, but the events are of rather **short** duration (1 to 20 hours)

Rather narrow propagation cones

Events from eastern hemisphere may not be observed

Gradual

Associated with **CME**-driven shocks

- Gradual solar flares (LDE)
- Wide and fast shocks
- Type II and IV radio bursts
- Usually proton rich

The onsets are not necessarily gradual, but the events are of **long** duration

- 1 to 3 days
- Partly due to continuing acceleration of shock

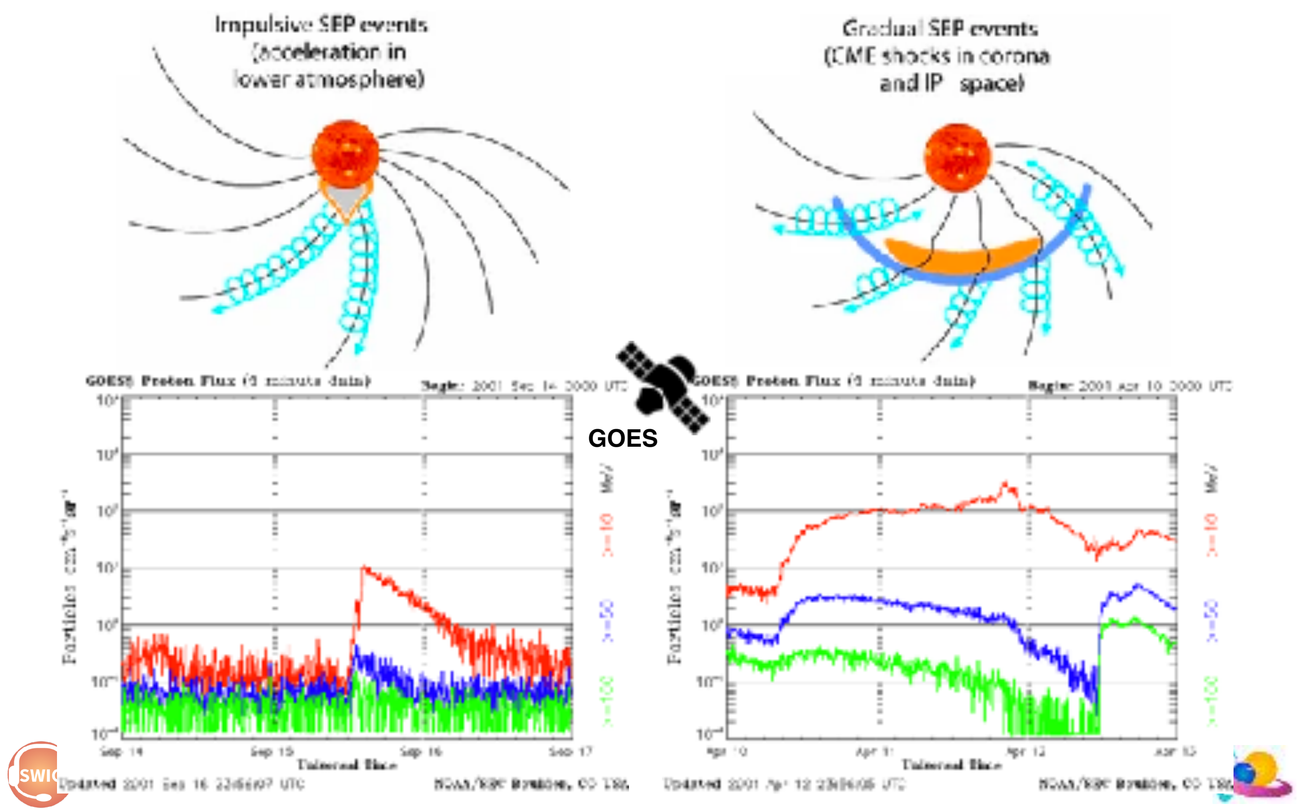
Park et al. , 2015: Study of Solar Energetic Particle Associations with Coronal Extreme-ultraviolet Waves
http://iopscience.iop.org/article/10.1088/0004-637X/808/1/3/pdf
Impulsive SEP events, having short durations of several hours, are associated with impulsive flares. They are electron rich and are generally distributed within a narrow propagation cone. Gradual SEP events are associated with gradual X-ray flares and type II and type IV radio emission. They are produced by wide and fast CME-driven shocks (Gopalswamy2003) and have a broad range of source longitudes (Kahler 1994; Reames 1999). Gradual events are proton rich in contrast to impulsive events.
Many events have characteristics of both gradual and impulsive events due to a combination of both flare- and shock-associated particles (Cane et al. 2006).

A very good site on the characteristics between gradual and impulsive events is at
SEPEM: http://dev.sepem.oma.be/help/sep_intro.html (alternate: http://sepem.eu/help/index_intro.html)

Papaioannou et al. (2016): Solar flares, coronal mass ejections and solar energetic particle event characteristics
https://www.swsc-journal.org/articles/swsc/pdf/2016/01/swsc150076.pdf

Reames, 2013: The Two Sources of Solar Energetic Particles
http://adsabs.harvard.edu/abs/2013SSRv..175...53R

PROTON EVENTS

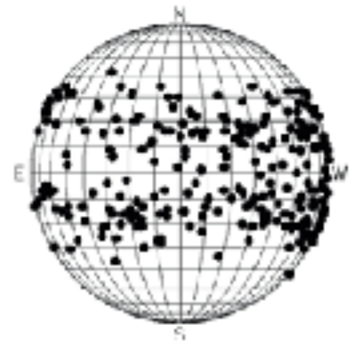


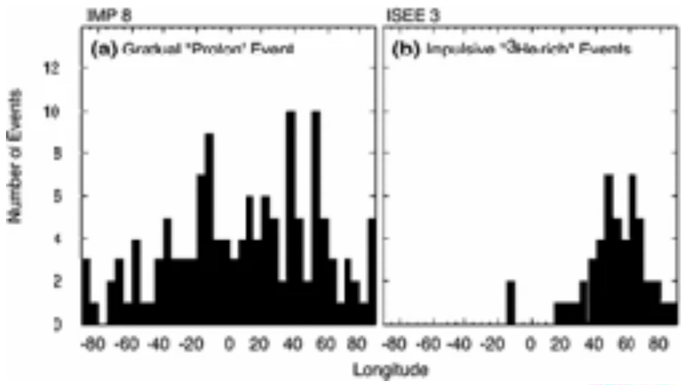
The cartoons were taken from:
Reames (1999): Particle acceleration at the Sun and in the heliosphere
http://adsabs.harvard.edu/abs/1999SSRv...90..413R
The 15 Sep 2001 event (11 pfu) resulted from an M1 (1N) flare on 11:28UT
The 10 Apr 2001 event (355 pfu) resulted from an X2 (3B) flare on 05:26UT. The (halo) CME arrived on 11 April around 15UT, hence the maximum proton flux (near 21UT) coincides with the passage of the ICME.

EFFECTS FROM LOCATION SEP SOURCE

There's a higher likelihood for SEP events from the western hemisphere

- Does not exclude SEPs from the eastern hemisphere or even from the Sun's backside!
  - E.g. Major flare on 23 July 2012
  - Mechanism?
- Eastern SEPs: slower rise





Papaioannou et al. (2016): Solar flares, coronal mass ejections and solar energetic particle event characteristics
https://www.swsc-journal.org/articles/swsc/pdf/2016/01/swsc150076.pdf
Top figure taken from their Figure 5 (D).

Bottom graph: Longitudinal distributions of the solar sources associated with a) gradual and b) impulsive SEP events. (Reames 1999)

Major farside flare from 23 July 2012: http://www.stce.be/news/152/welcome.html
Example from 29 October 2015 event: http://www.stce.be/news/325/welcome.html

https://spaceweather.com/archive.php?view=1&day=15&month=07&year=2021
https://www.stce.be/news/543/welcome.html

It is believed that the **coronal waves** associated to strong CMEs widen the access possibilities of the energetic particles to earth through the coronal Parker spiral magnetic field lines. This would allow some of the backside events still to create a proton event at Earth. But even then, there's still a problem of the eastern hemisphere events, in particular e.g. at locations E120.

Aside GOES, there are other satellites equipped with SREM that also measure proton fluxes:
http://space-env.esa.int/index.php/SREM_Plots.html
Currently (2017), only the Integral satellite has an operational SREM.

Finally, STEREO and SOHO also measure proton fluxes:
ACE: https://services.swpc.noaa.gov/images/ace-sis-3-day.gif
STEREO: https://stereo-ssc.nascom.nasa.gov/beacon/beacon_insitu.shtml (click plots, scroll down to « IMPACT »).

PROTON EVENT CLASSIFICATION

NOAA-scales: S-scale

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
S 4	Severe		10^4	3 per cycle
S 3	Strong		10^3	10 per cycle
S 2	Moderate		10^2	25 per cycle
S 1	Minor		10	50 per cycle

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

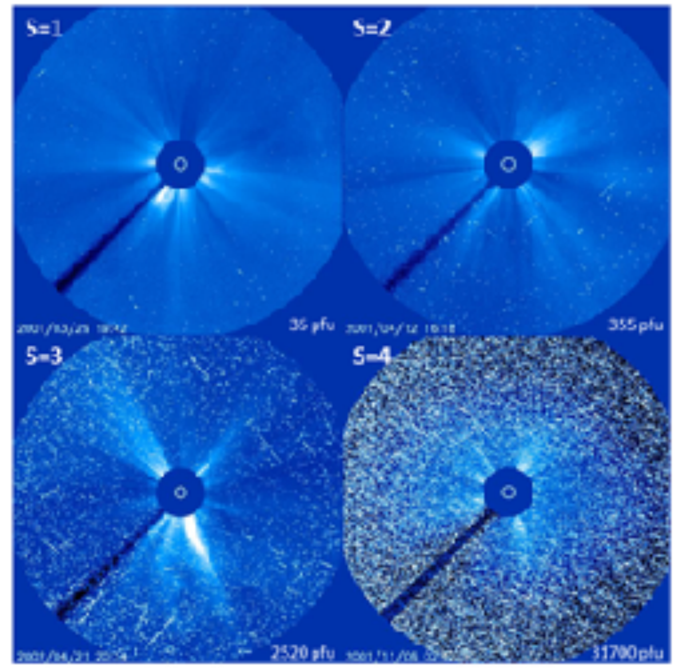
The « S » stands for **Solar radiation Storm**. Since observations started in 1976, no S5 event has been recorded.

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

PROTON EVENT CLASSIFICATION

NOAA-scales: S-scale

SOHO/LASCO



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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

FORECASTING PROTON EVENTS

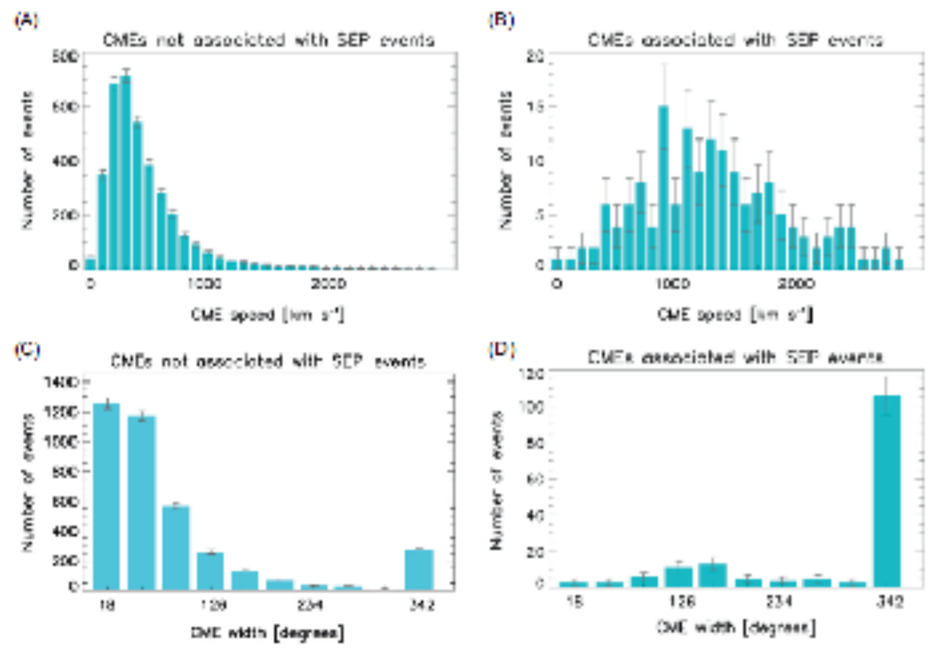


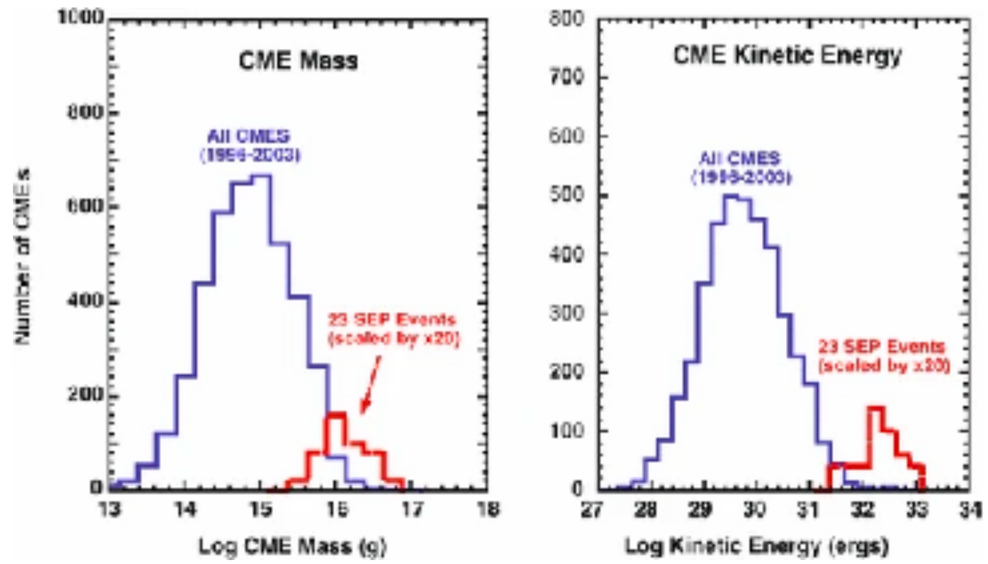
Fig. 6. Distribution of the CME velocity (in km s^{-1}) for all 3535 CMEs not associated with SEP events in our sample from 1997–2013 (A) and for the 158 SEP events, within the same time period (B). Distribution of the CME width (in degrees) for all 3535 CMEs not associated with SEP events in our sample from 1997–2013 (C) and for the 158 SEP events, within the same time period (D). The error bars denote the statistical error.

From these distributions we can conclude that coronal mass ejections associated with solar energetic particle events are generally wider and faster.

Papaioannou et al. (2016): Solar flares, coronal mass ejections and solar energetic particle event characteristics
https://www.swsc-journal.org/articles/swsc/pdf/2016/01/swsc150076.pdf

Dierckxsens et al., 2015: Relationship between Solar Energetic Particles and Properties of Flares and CMEs: Statistical Analysis of Solar Cycle 23 Events
http://link.springer.com/content/pdf/10.1007%2Fs11207-014-0641-4.pdf

FORECASTING PROTON EVENTS



Comparison of the mass distribution of all CMEs observed from 1996-2003 (Gopalswamy 2006) to the masses of CMEs associated with 23 of the 50 largest SEP events of solar cycle 23 (scaled up by 20). Right: Comparison between the distributions of the kinetic energy of CMEs associated with 23 large SEP events from solar cycle 23 and all CMEs observed from 1996-2003. Images reproduced from Mewaldt et al. (2008).

From Desai & Giacalone (2016, https://link.springer.com/article/10.1007/s41116-016-0002-5)
The largest SEP events are associated with the fastest ~1-2% of CMEs. The CMEs have typical speeds >1500km/s, although a few have speeds as low as ~700-800km/s (Kahler 2001). Figure 9 [above] compares the mass (left) and energy (right) distributions of all CMEs (in blue) with those associated with 23 of the 50 largest SEP events (in red) from solar cycle 23. Similarly, Yurchyshyn et al. (2005) found that the distributions of the plane-of-sky-speeds for >4000 CMEs, whether they are accelerating or decelerating, showed no physical distinction and exhibited log-normal forms similar to the ones shown in Fig. 9. The figure clearly shows that large SEP events are associated with CMEs that have masses >10ˆ15g and kinetic energies >3×10ˆ31ergs, with the kinetic energy of the CME being more indicative of whether the associated SEP event is also likely to be large and intense.

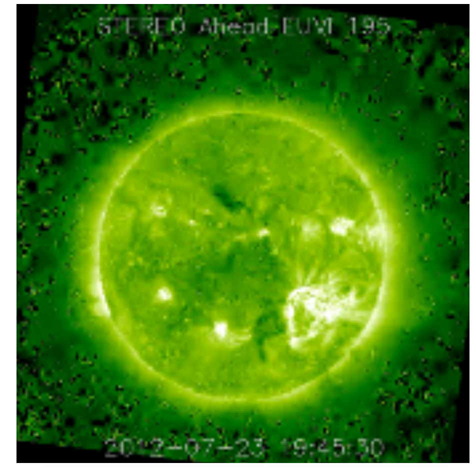
FORECASTING PROTON EVENTS

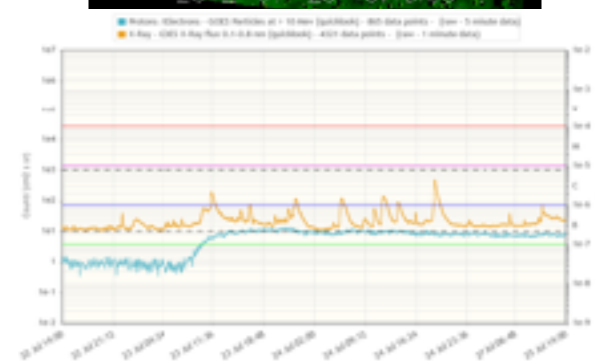
Look for active regions & filaments that can:

- Produce strong x-ray flares
- Fast CMEs (~1000 km/s or more)
- Wide CMEs (partial or full halo CMEs)
- Preferably on the western solar hemisphere

Finetune from history on farside/ eastern hemisphere

- Proton flux enhancements,…
- Observations by STEREO spacecraft





Probabilities and intensities for proton events for a variety of the above parameters can be found in:
Dierckxsens et al., 2015: Relationship between Solar Energetic Particles and Properties of Flares and CMEs: Statistical Analysis of Solar Cycle 23 Events
http://link.springer.com/content/pdf/10.1007%2Fs11207-014-0641-4.pdf

More info on SEP events at http://dev.sepem.oma.be/help/solpenco2_intro.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

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

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AK CHAMBON LA FORET : 012
AK WINGST : 004
ESTIMATED AP : 004
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Proton flux / events

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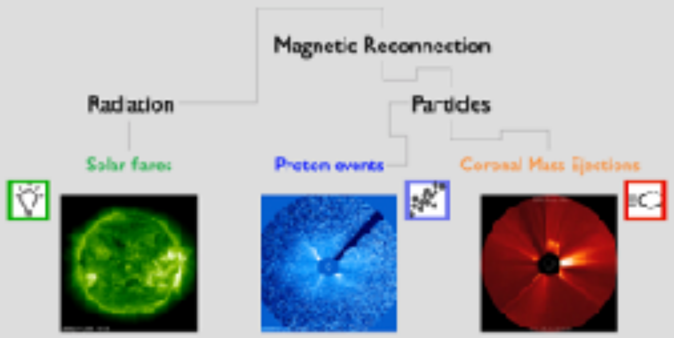
END

SUMMARY 1/2



Solar flares

- Standard model
- Classification
  - Hα, x-ray, NOAA scale (R)
- Radio bursts
- Flare predictions
  - McIntosh, Hale

SUMMARY 2/2

Proton events

- $\geq$10 MeV proton flux $\geq$ 10 pfu
- Classification
  - Impulsive vs. Gradual
  - NOAA Scale (S)
- Forecasting
  - Strong flare
  - Wide and fast CME
  - Western solar hemisphere

Coronal Mass Ejection

- Model
- On-disk signatures
- Classification & Terminology
  - Stealth, Cannibalism, Deflection
- True vs. Plane-of-the-Sky speed
- Interplanetary CME & Bz