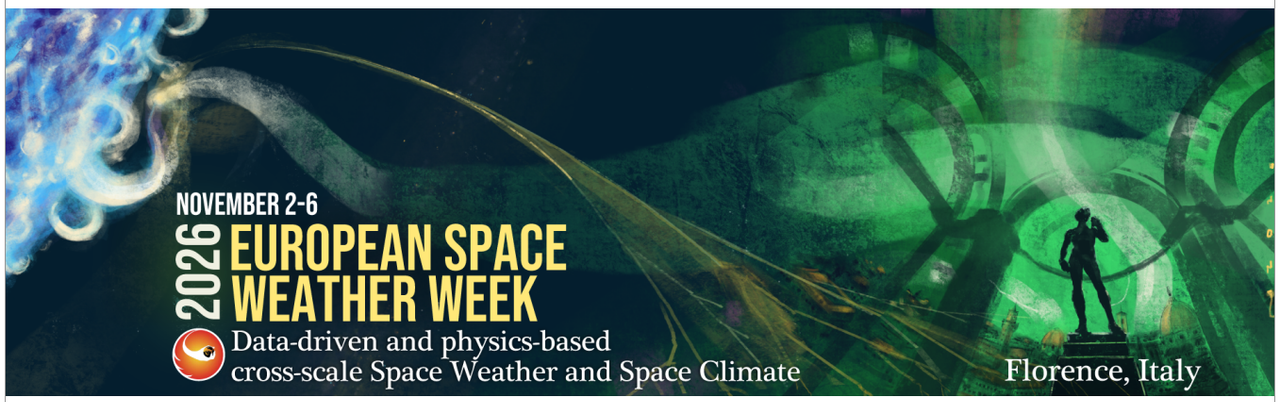
Space Weather Training Course



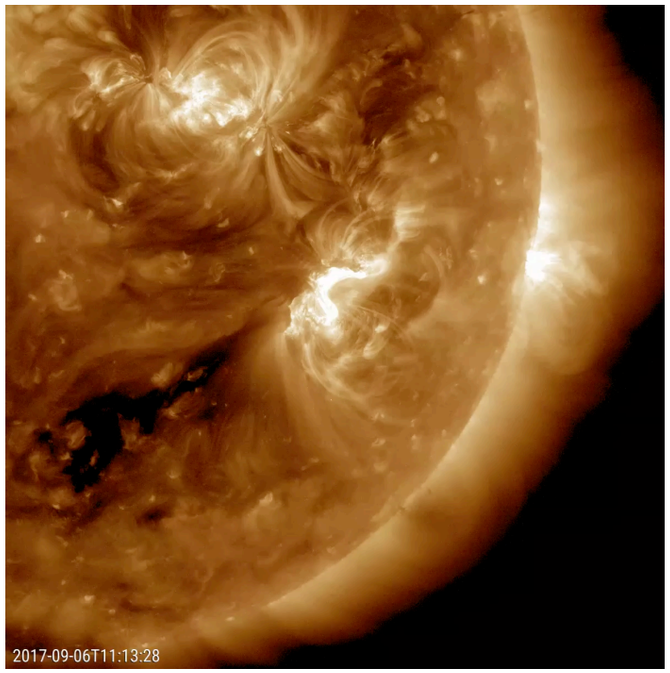
Collaboration of

e-SWAN

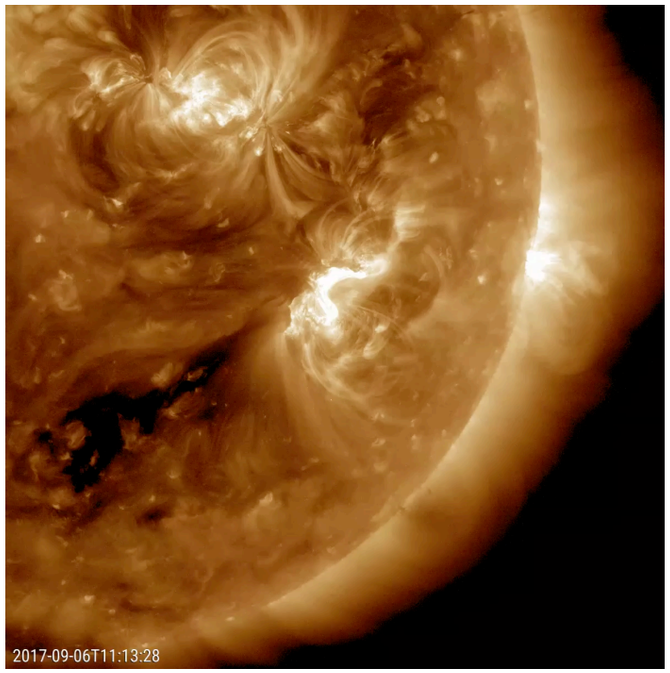
SWEC
Space Weather Education Centre

COMMUNITY COORDINATED MODELING CENTER

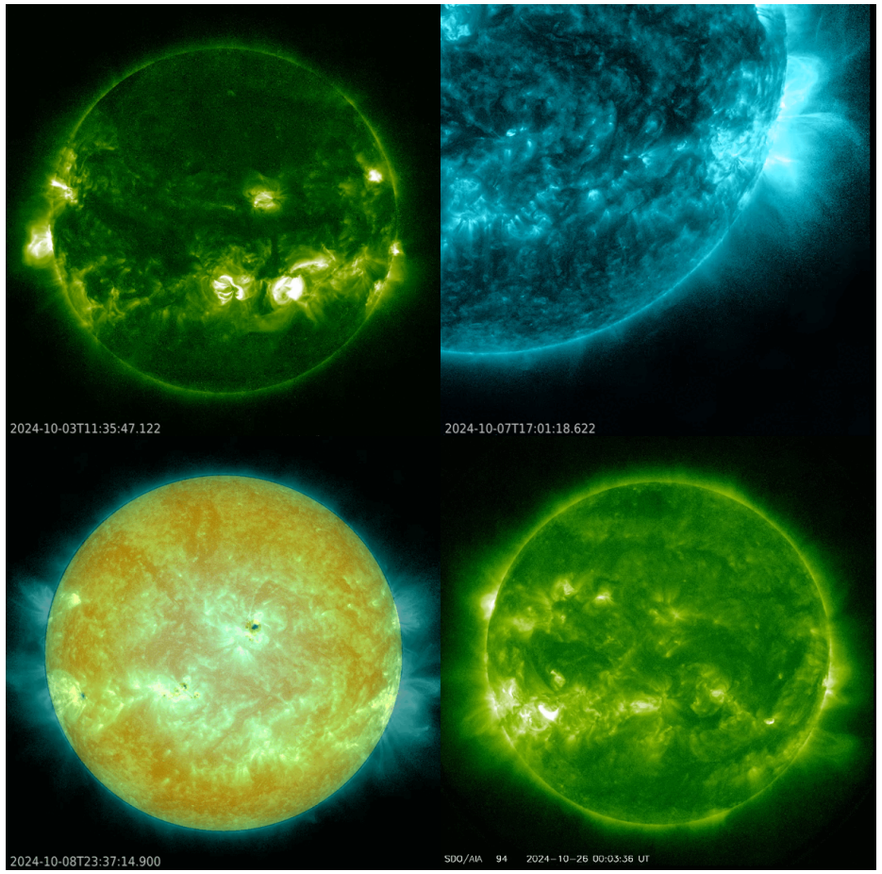
SOLAR FLARES



SOLAR FLARES



Introduction



A solar flare is a bright flash of light, caused by a reconfiguration of the solar magnetic field. This so-called reconnection can also send a plasma cloud into space. Solar flares and coronal mass ejections often, but not always, form part of one event.

Chances for a strong flare are highest when the Sun is very active. Solar flares often occur in regions with rapidly changing and complex magnetic field, which we can see in the magnetogram observations.

Compilation of strong flares that occurred in October 2024

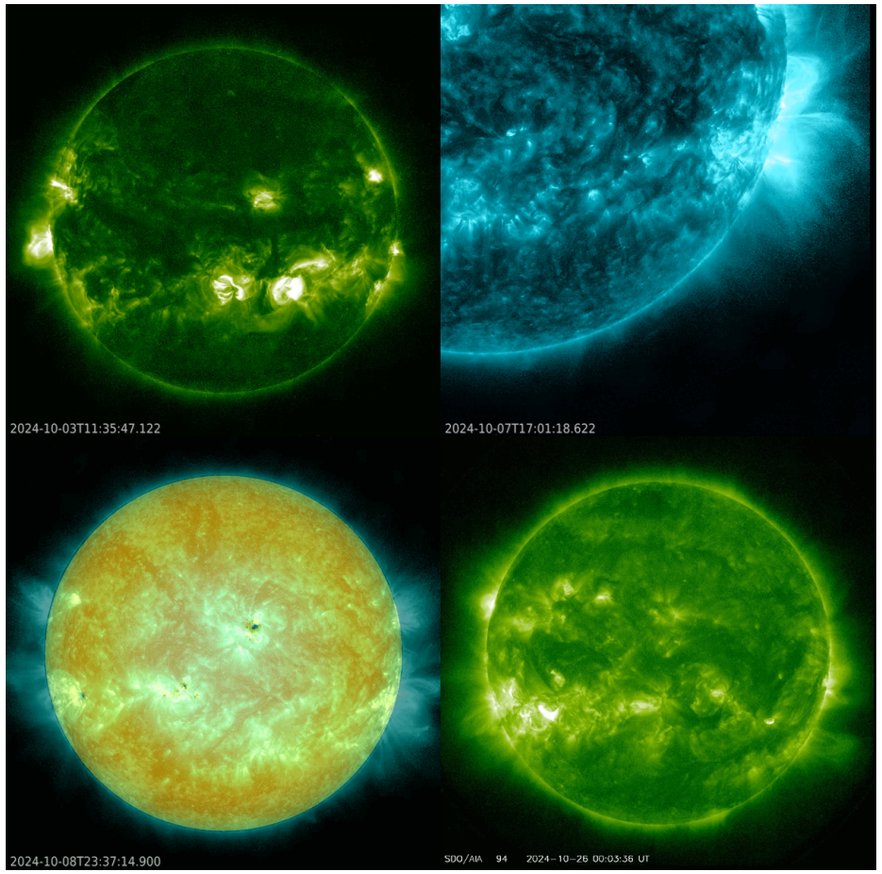
Oct 3: NOAA 3842 produced the strongest flare of solar cycle 25 (SC25). The **X9.0** flare peaked at 12:18UTC. This was already the second strong X-class flare in as many days by this sunspot group. The flare was associated with a halo CME, that was directed to Earth
Also impact on the sensor is visible

Oct 7: NOAA 3842 produced its third X-class flare, this time an X2.1 peaking on 7 October at 19:13UTC. The image top right was taken by GOES/SUVI 131 near the flare's maximum
Diffraction pattern visible

Bottomleft: a long duration X1.8 solar flare peaking on 9 October at 01:56UTC (GOES). This is an overlay of extreme ultraviolet imagery (SDO/AIA 131) on top of white light imagery (SDO/HMI) highlighting the strength of the flare and its location with respect to sunspot region NOAA 3848.

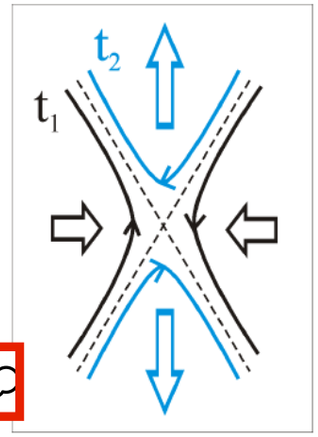
Oct 26, Bottom right: An X1.8 flare was observed from NOAA 3873, Coronagraphic imagery show the flare was associated with a asymmetric halo coronal mass ejection (CME). Assessment of the SOHO/LASCO C3 imagery indicate this is a quite fast CME with a true speed around **1600 km/s**.

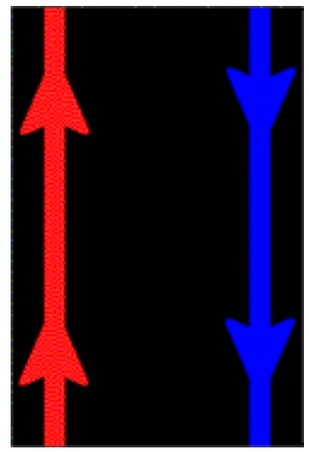
Introduction



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.

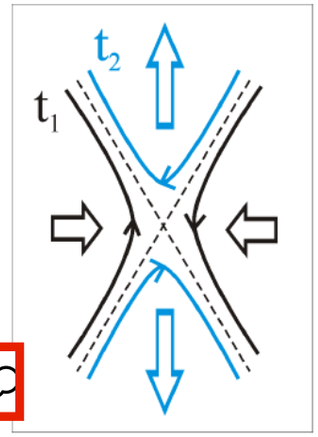
Sources:
Text from the CISM Summer School (Boulder, August 2013) – SW101_4_Flares
https://www.bu.edu/cism/SummerSchool/summerlist.html

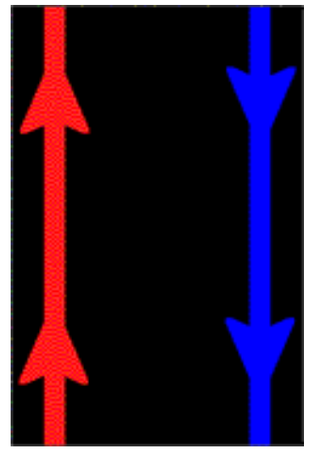
Animation from ESA: http://sci.esa.int/cluster/36447-direct-observation-of-3d-magnetic-reconnection/

Magnetic Reconnection

- Conversion of magnetic energy into kinetic energy and radiation

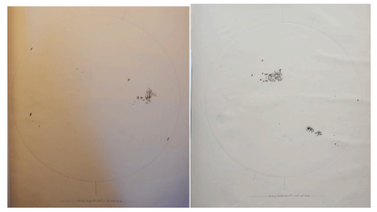
- Where
  - Solar flares
  - CME release from the Sun
  - Geomagnetic storms at Earth

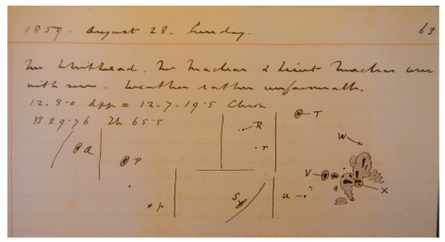


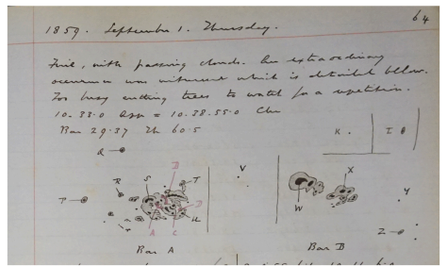


Solar Flares - WHAT?

- 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)

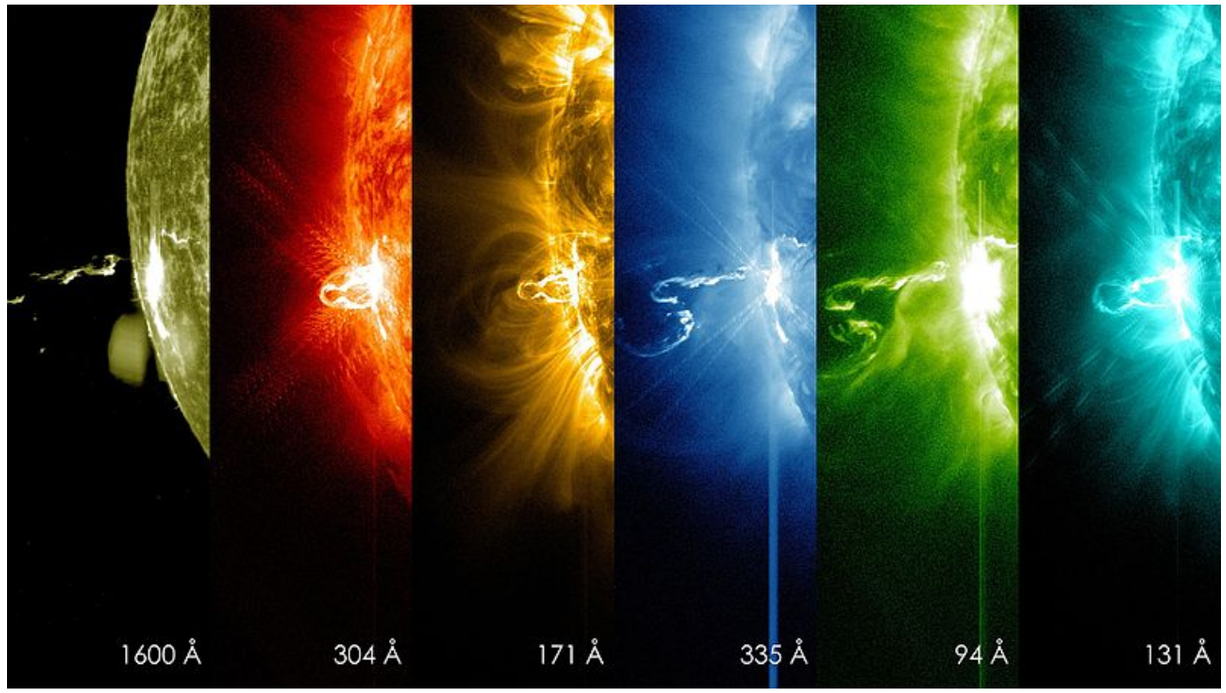
Sources:
From the CISM Summer School (Boulder, August 2013) – SW101_4_Flares
https://www.bu.edu/cism/SummerSchool/summerlist.html

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 - Observations

SDO/AIA

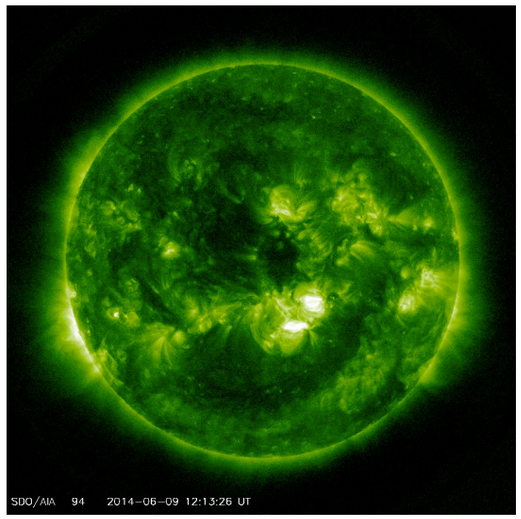


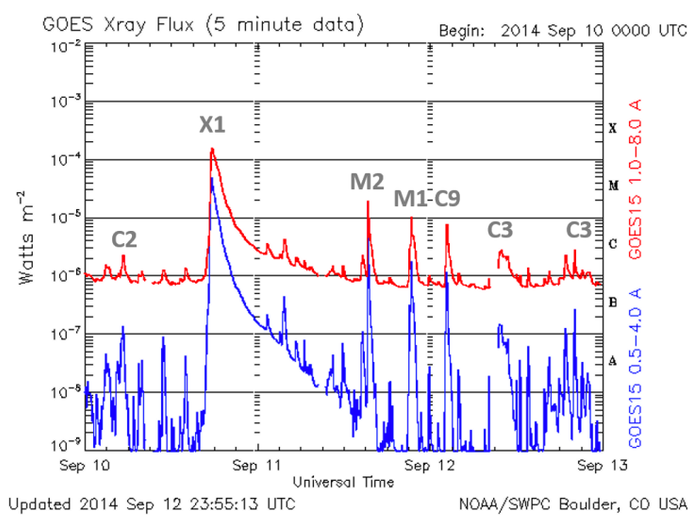
From left to right we go to higher temperatures, and see different parts of the flare (plasma that is more heated)
Solar flares are sudden bursts of radiation lasting minutes – hours at wavelengths over the entire electromagnetic spectrum: Gamma-rays, HXR, SXR, EUV; H-alpha, radio

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

Solar Flares - Observations





SDO/AIA **GOES**

First we come to solar flares. As you know a flare is a sudden flash of light which we can see in movies of the solar disk. We also measure the excess radiation coming from a flare for example with the GOES spacecraft. And then we classify the flares in different classes depending on the amount of X-ray flux we receive from them. Note that this is a logarithmic scale, so one step up means 10x more radiation received.
A_B_C_M_X flares - THIS IS OUR **STORM SCALE**
Background during solar min and solar max

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

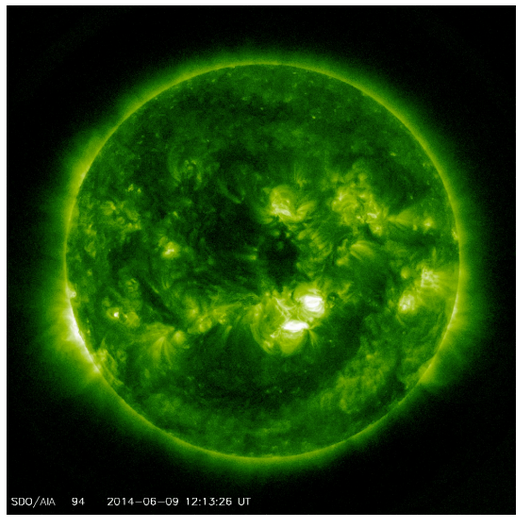
The letter designates the order of magnitude of the peak value and the number following the letter is the multiplicative factor. A C3.2 event for example, indicates an x-ray burst with 3.2x10-6Wm-2 peak flux. Solar flare forecasts are usually issued only in terms of the broad C, M, and X categories.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

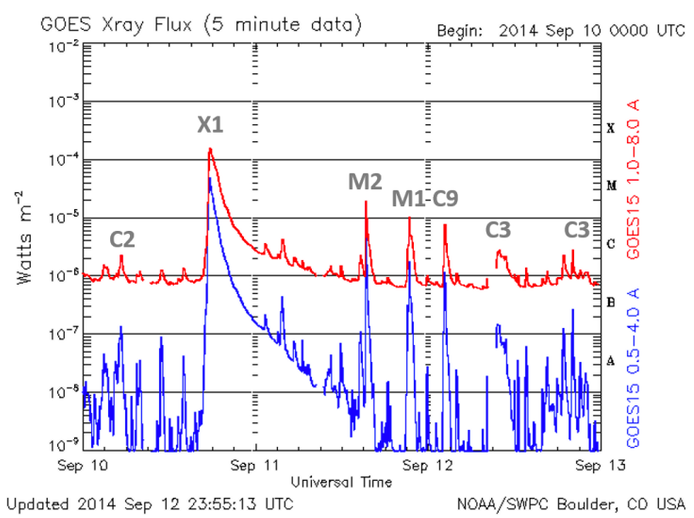
The C is often referred to as « Common » , M as « Medium (or moderate) », and X as « eXtreme

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 Flares - Observations

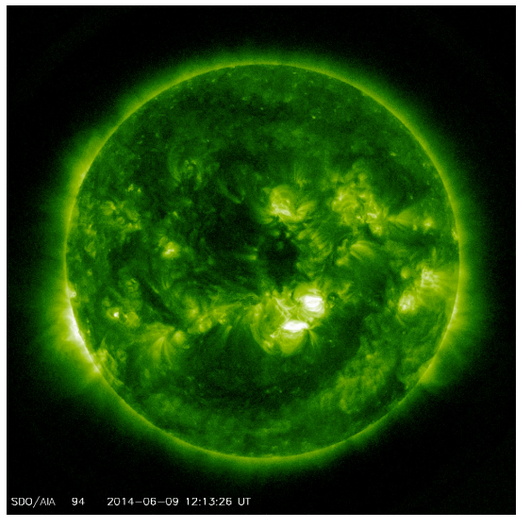


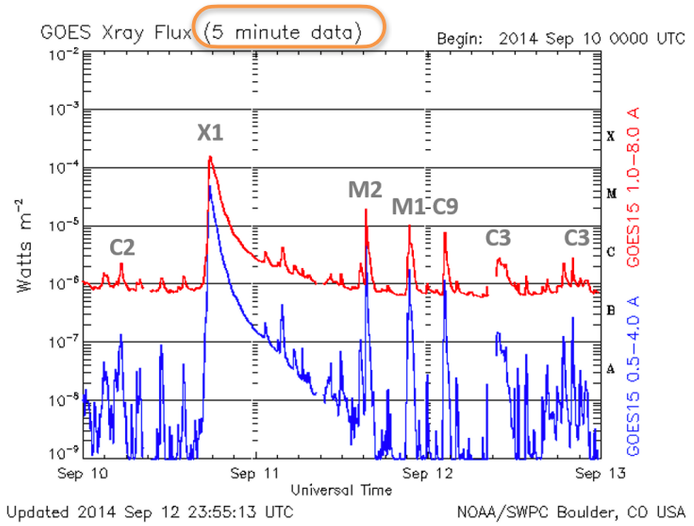


SDO/AIA

GOES

Solar Flares - Observations



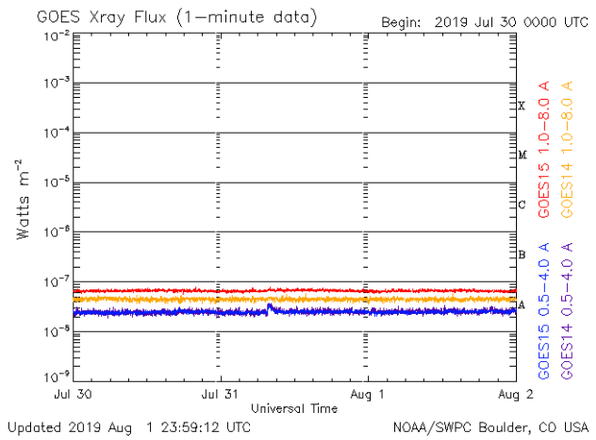


SDO/AIA

GOES

Solar Flares - Solar cycle

Solar minimum



Solar maximum

GOES

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A_B_C_M_X flares
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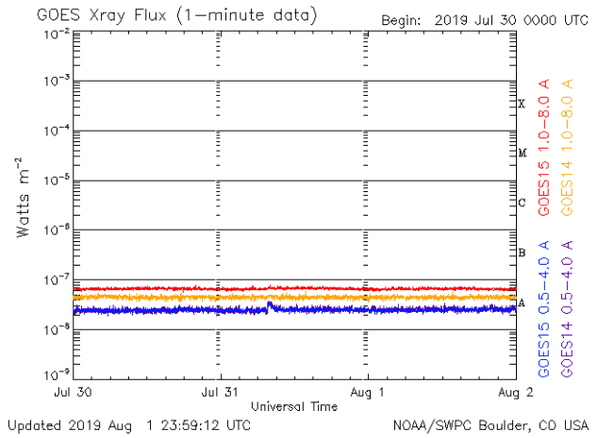
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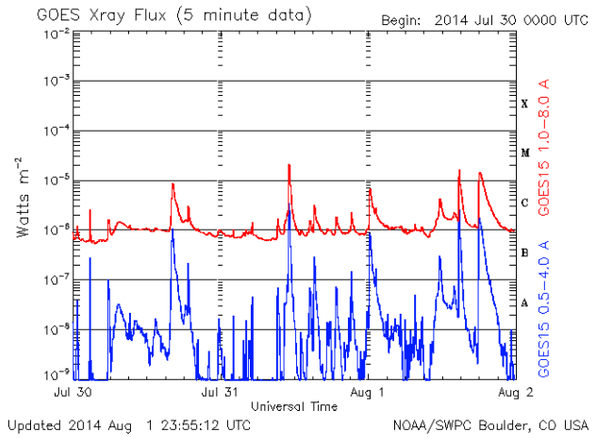
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Solar Flares - Solar cycle

Solar minimum



Solar maximum



GOES

Solar Flares - Automated detection

https://www.sidc.be/solardemon/

Solar Demon Flare Detection (qlk)

Quick-look! running in real time on SDO/AIA 94 QKL data
3 minute cadence, typical delay 15 minutes
(detection version 1.00)
(view all Solar Demon detection tools)

Detector 24h operating status:

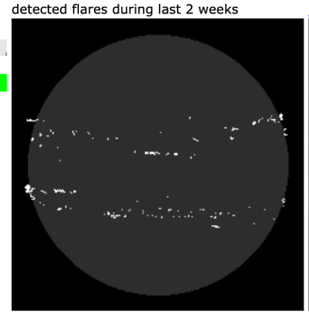
Last processed image:
0 hours and 34 minutes ago (2023-11-09 13:33 UTC)

Last detected flare:
2 hours and 46 minutes ago (2023-11-09 11:21 UTC)

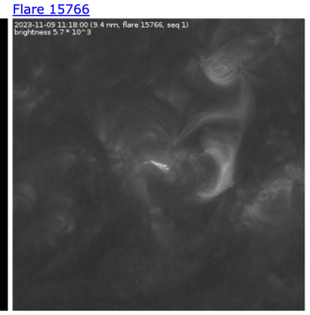
Filters (category)
-- *All classes*
Only C class flares and above
Only M class flares and above
Only X class flares and above

Filters (time)
Last 7 days
-- *Last 14 days*

detected flares during last 2 weeks



Flare 15766

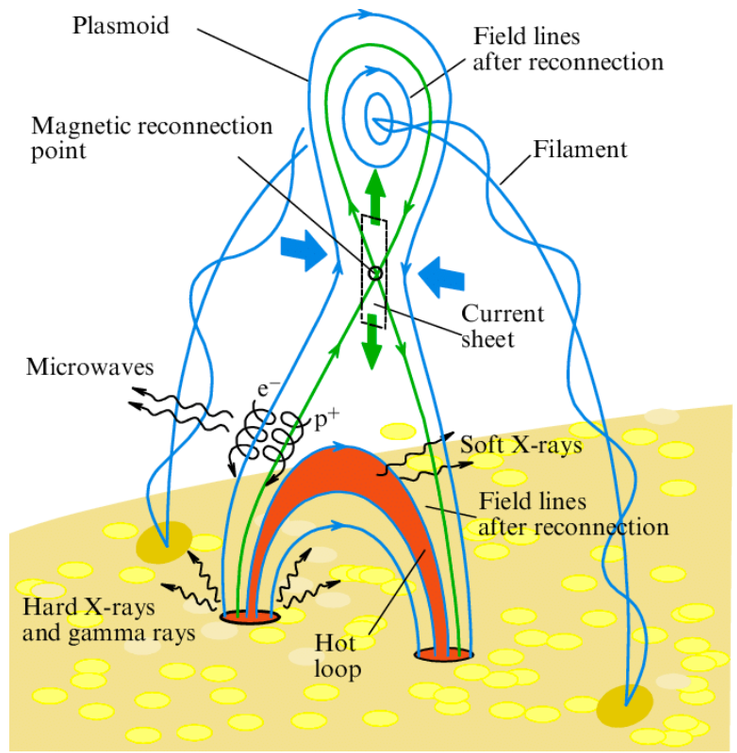


Overview of flares

	est. class	start	peak	end	#	lat	lon	dist. R⊙	AR	est. flux	GOES flux	GOES peak time	COMESEP	# det.	dimming
November, 2023															
9	B3	11:18	11:21	11:21	15766	-10	4	0.25	AR 3480	2.6	**N/A**	N/A	0	2	-1,899
9	B1	10:48	10:51	10:51	15765	25	15	0.44		1.4	**N/A**	N/A	0	2	
9	A8	08:30	08:33	08:33	15764	8	16	0.29	AR 3483	0.8	**N/A**	N/A	0	2	
9	B2	01:15	01:15	01:21	15763	7	14	0.26	AR 3483	1.8	**N/A**	N/A	0	3	-19
9	B2	00:51	00:51	00:51	15762	23	70	0.95	AR 3479	1.6	**N/A**	N/A	0	1	
8	C2	20:09	20:18	21:00	15761	9	7	0.16	AR 3483	20.1	**N/A**	N/A	0	18	-44
8	B3	14:48	14:48	14:54	15760	8	4	0.11	AR 3483	2.8	**N/A**	N/A	0	3	-29
8	C3	08:30	08:51	09:36	15759	9	0	0.09	AR 3483	28.3	**N/A**	N/A	0	20	
8	B6	07:06	07:24	08:03	15756			1.01		5.8	**N/A**	N/A	0	19	-266
8	A7	07:24	07:24	07:24	15757	23	59	0.88	AR 3479	0.7	**N/A**	N/A	0	1	-266

Solar flares are usually defined by their X-ray flux, but we can also observe them in the images themselves.
Solar Demon is one tool that uses the AIA 94 data to detect flares automatically and estimates their class

Solar Flares - Standard 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 that 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

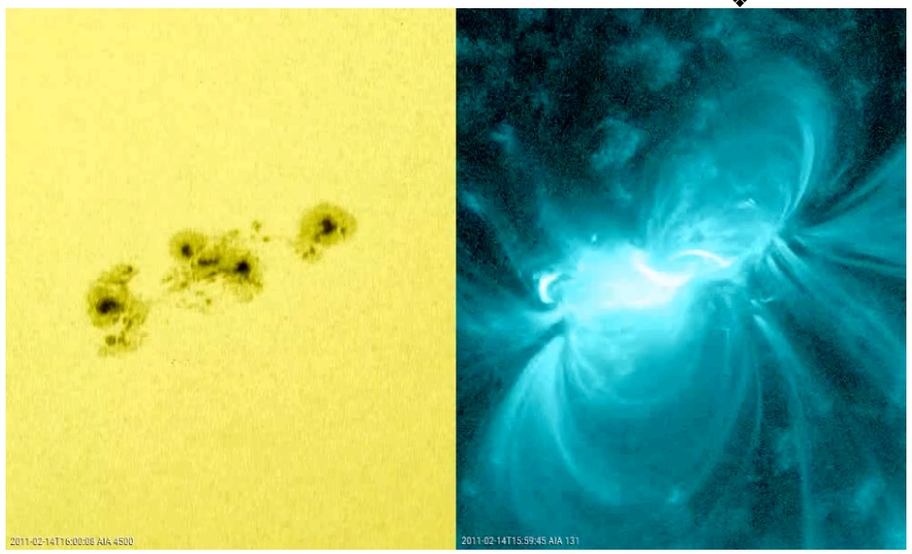
Sources:
From Maria Massi (What is a solar flare?)
http://www3.mpifr-bonn.mpg.de/staff/mmassi/#coronae1
Image:
https://www.researchgate.net/publication/341075910_X-ray_and_gamma-ray_emission_of_solar_flares

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

Solar Flares - Triggers

Magnetic restructuring

SDO/AIA



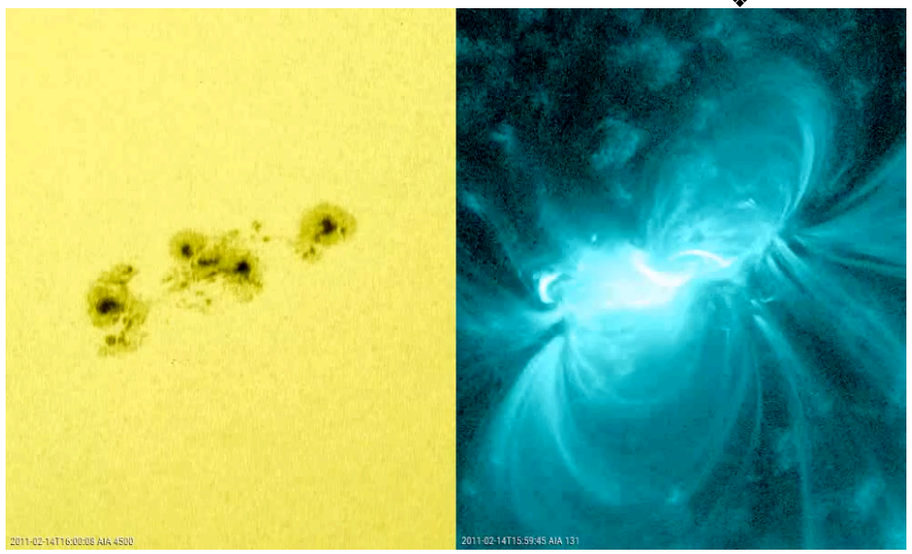
Solar flares are triggered by a restructuring of the magnetic field. When field lines are pushed together and magnetic reconnection occurs, and enormous amount of stored magnetic energy can be converted into radiation (heat, flare) and kinetic energy (CME).
We can spot this in the observations by looking for signs of magnetic restructuring, such as turning and interacting sunspots, growing regions, increasing in complexity. Instability in one region can also cause instability in another nearby region, …

Magnetic restructuring
Magnetic flux emergence
Helical energy storage
Instability in the surrounding field
Interaction with nearby CH
…

Solar Flares - Triggers

Magnetic restructuring

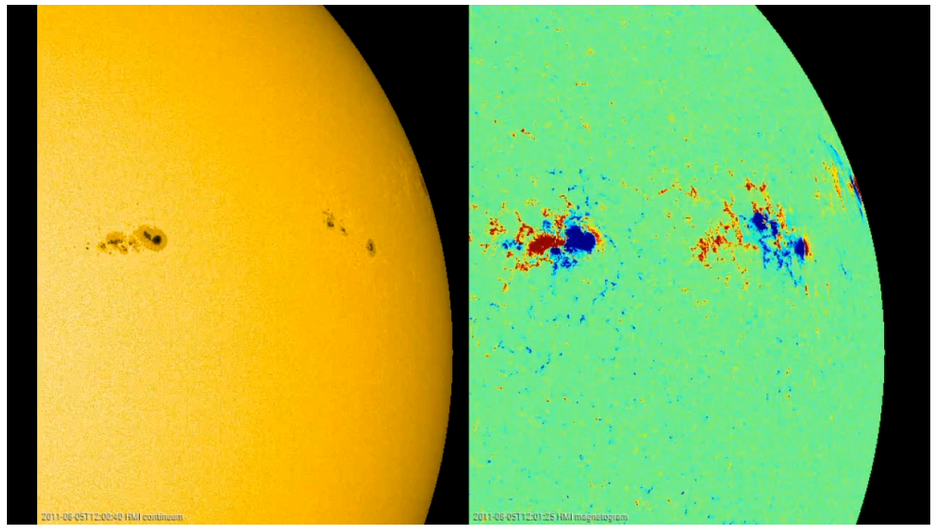
SDO/AIA



Solar Flares - Triggers

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.

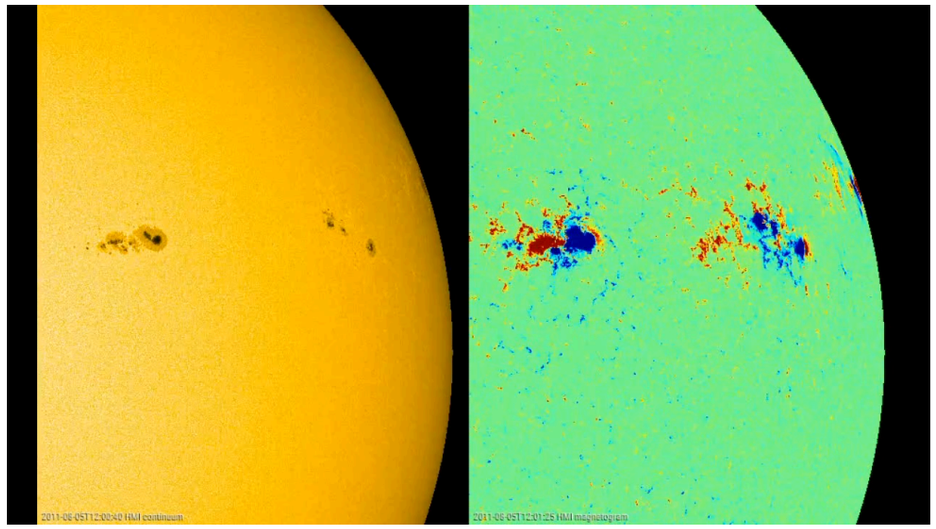
X6.9 flare on 9 August 2011: http://www.stce.be/news/353/welcome.html

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

Solar Flares - Triggers

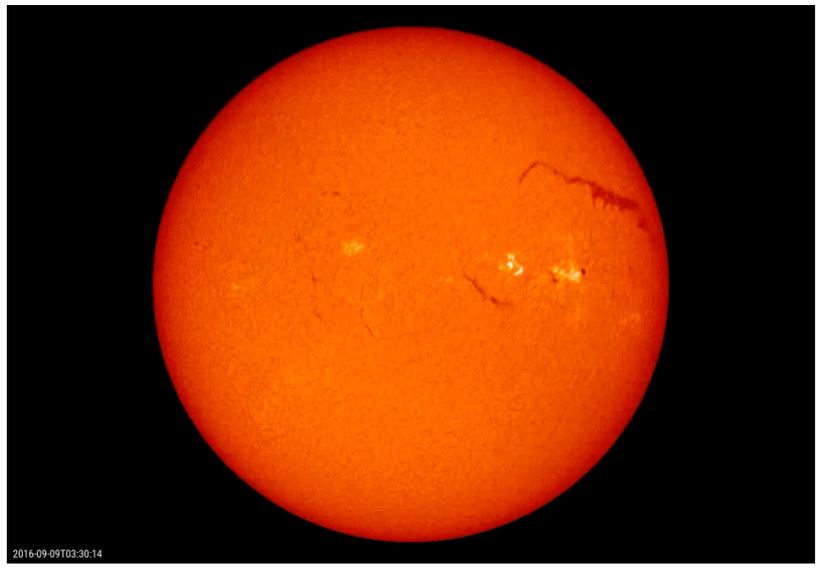
SDO/HMI

Magnetic flux emergence



Interaction with other features

Instability elsewhere



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.

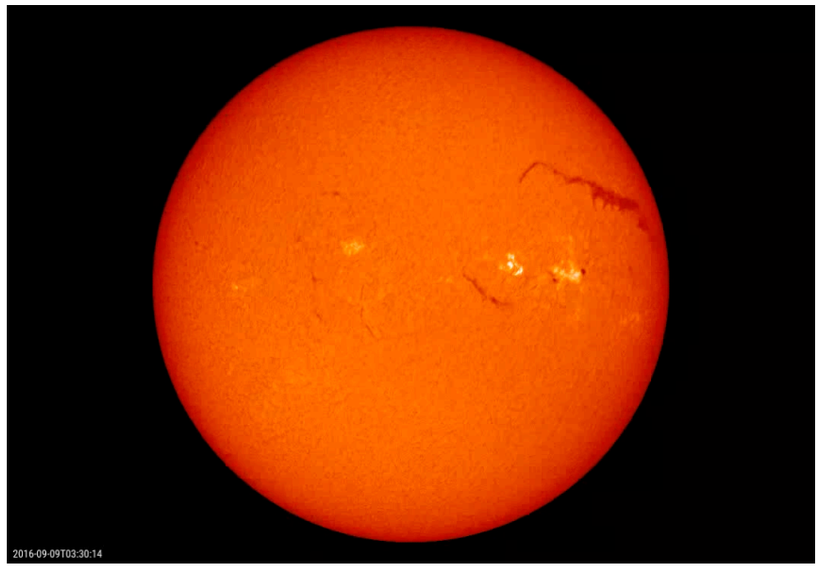
Sources:
Kink instability
Török et al. (2010): The writhe of helical structures in the solar corona
https://www.aanda.org/articles/aa/full_html/2010/08/aa13578-09/aa13578-09.html
http://www.lmsal.com/TRACE/POD/TRACEpodarchive14.html#movie61 (27 May 2002; M2 ; NOAA 9957)
Unstable if twist ~2.5pi (Török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

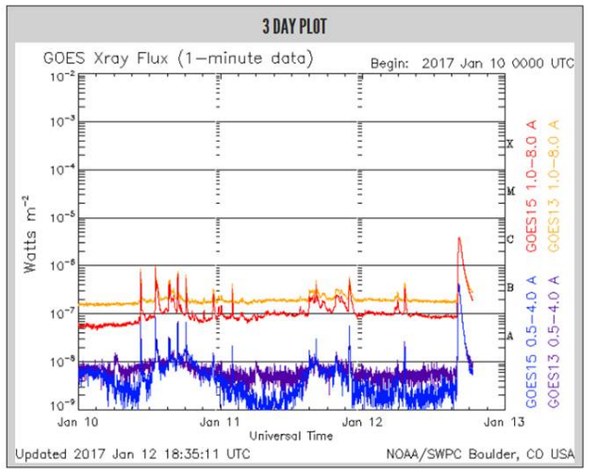
Shen et al. (2014): A Chain of Winking (Oscillating) Filaments Triggered by an Invisible Extreme-ultraviolet Wave
http://adsabs.harvard.edu/abs/2014ApJ...786..151S

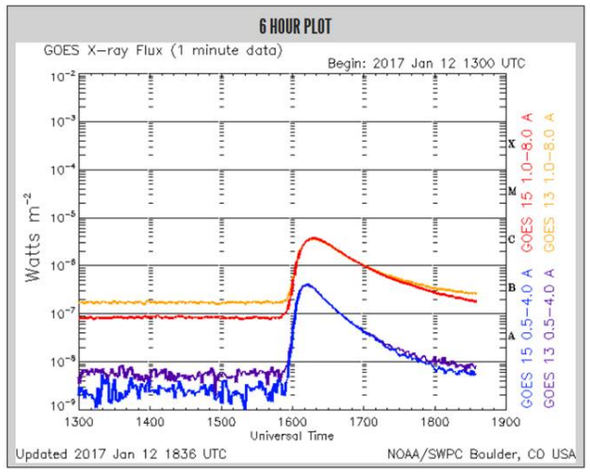
Interaction with other features

Instability elsewhere



Solar flares - Duration







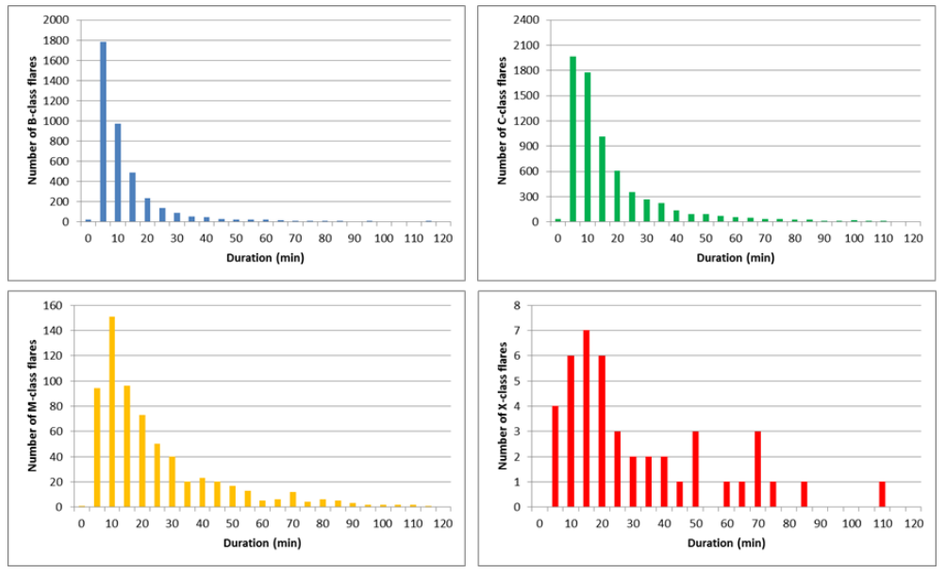
GOES

LATEST X-RAY EVENT (1-8Å)			
Current	2017-01-12 18:35:00 UTC	B1.8	Ratio: 0.031
Beginning	2017-01-12 15:54:00 UTC	B1.0	
Maximum	2017-01-12 16:18:00 UTC	C3.8	Integrated flux: 0.006896 J m^{-2}
End	2017-01-12 16:41:00 UTC	C1.9	

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 **first 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 flares - 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)

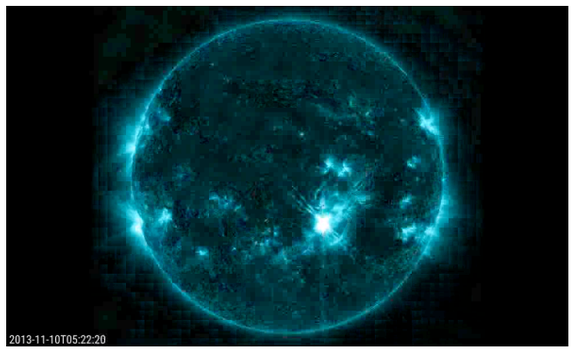
Long duration X-ray events (LDE) are not impulsive in appearance. The exact time threshold separating impulsive from long-duration events is not well defined, but **operationally**, any event requiring 30 minutes or more to decay to one-half peak flux is regarded as an LDE. It has been shown that the 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

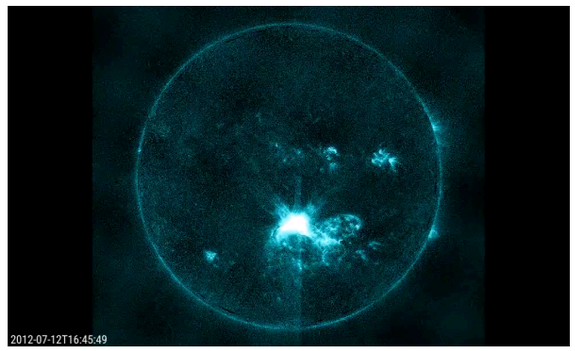
Impulsive flare

Long Duration Event

SDO/AIA



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



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

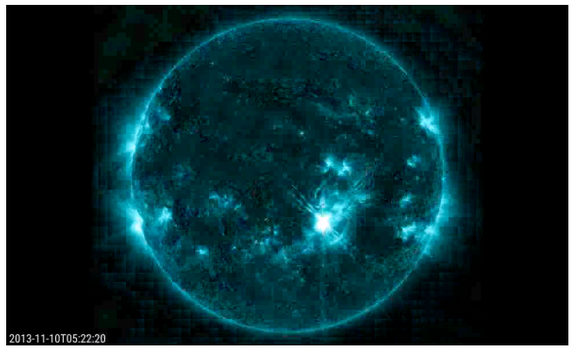
Imagery from STCE: http://www.stce.be/news/332/welcome.html
A short and a long duration X1 flaring event. These took place resp. in NOAA 11890 on 10 November 2013 (duration: 10 minutes) and in NOAA 11520 on 12 July 2012 (duration: 113 minutes or nearly 2 hours). The latter was accompanied by a full halo CME (no surprise), but also the 2013 X1 flare was associated with a partial halo CME.

Solar flare - Duration

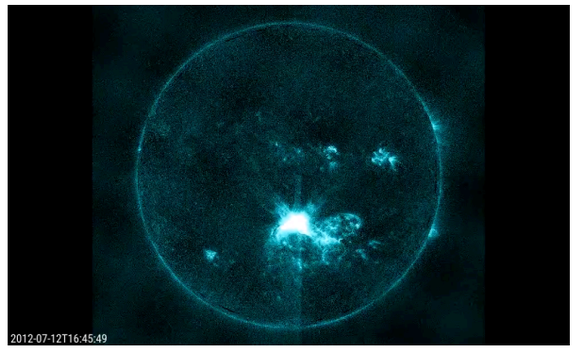
Impulsive flare

Long Duration Event

SDO/AIA



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



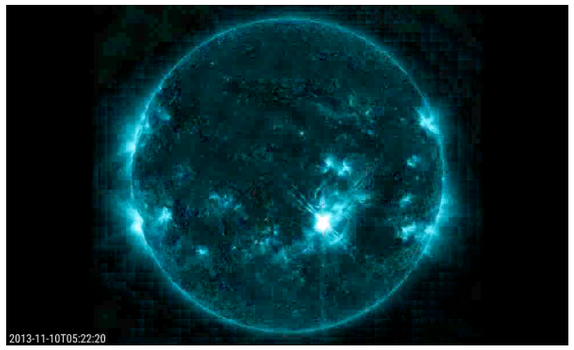
X1 - NOAA 1520 - 12 July 2012 (duration: 113 minutes)

Solar flare - Duration

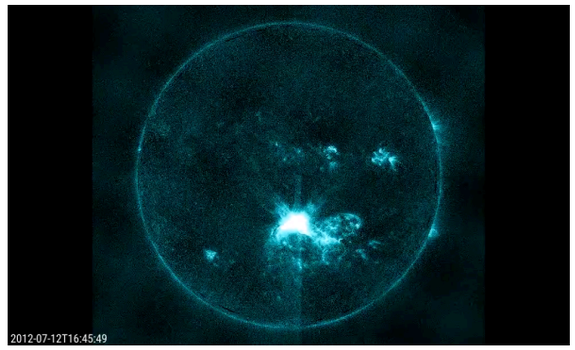
Impulsive flare

Long Duration Event

SDO/AIA



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



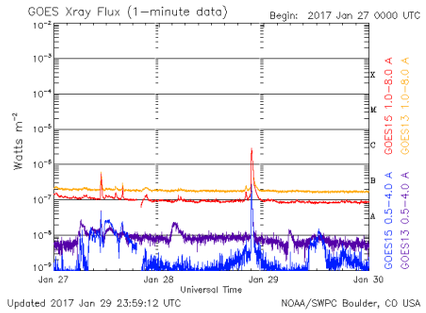
X1 - NOAA 1520 - 12 July 2012 (duration: 113 minutes)

Solar flares - Frequency

- From entire Sun
  1-4 per day

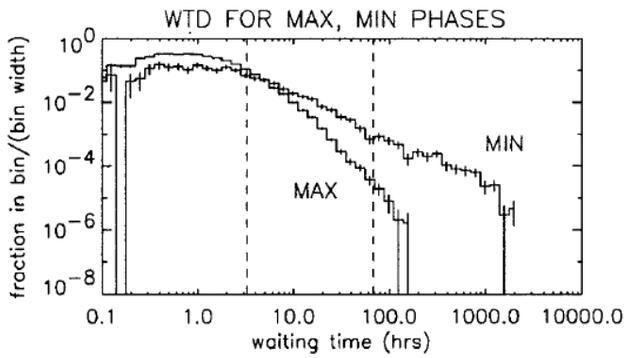
- In practice
  1 event in 24 hours

- Average waiting time
  - 6.5 hours (≥ C1)
  - SCmax: 3 hours
  - SCmin: 3 days





GOES



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

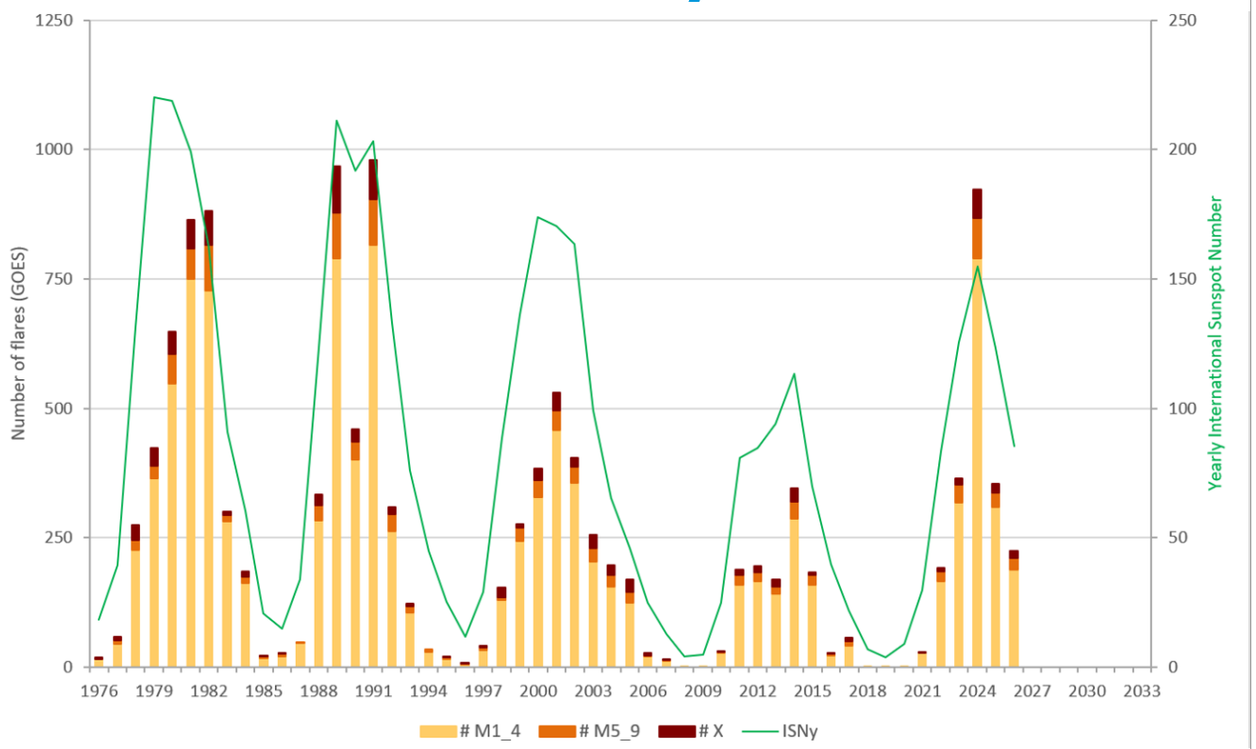
Terms Used to Describe Solar Activity
Very Low: x-ray events less than C-class.
Low: C-class x-ray events.
Moderate: isolated (one to four) M-class x-ray events.
High: several (5 or more) M-class x-ray events, or isolated (one to four) M5 or greater x-ray events.
Very High: several (5 or more) M5 or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

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).

Solar Flares - Solar cycle



https://www.stce.be/content/sc25-tracking#flares

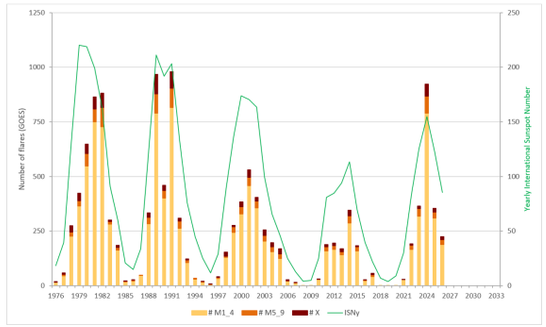
Solar flares are known to cause radio black-outs at high frequencies (HF; 3-30 MHz). Some flares may be accompanied by strong radio emission affecting radar and GNSS frequencies (see the ROB/GNSS and SIDC/Humain websites), thus causing problems with air traffic operations and with GPS-based communication and navigation services. Solar flares are recorded in the wavelength band from 1 to 8 Angstrom (0.1-0.8 nm) by the GOES (NOAA/SWPC). The 3 most often used classes are: C, M, and X standing for small (or "Common"), Medium, and large (or "eXtreme") flares. The range is logarithmic, each class being 10 times stronger than the previous one, and within each category ranging from 1 to 9 (e.g. a C9 flare, an M3 flare,...). See the STCE SWx Classification page for more details.

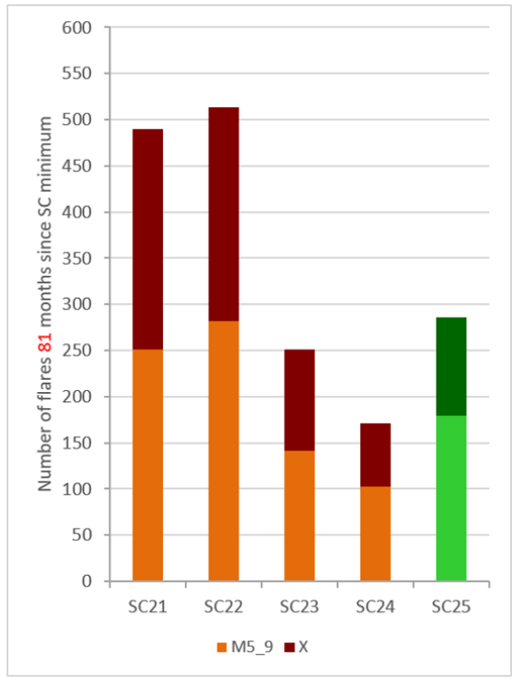
In the graph above, the yearly number of flares are **binned in 3 classes**: M1 to M4, M5 to M9, and the X-class flares. The thin green line represents the yearly International Sunspot Number (ISN). The values for the current year are obviously preliminary. The data sources are NOAA/NGDC (1976-July 2017), and the NOAA/SWPC Weekly bulletins (2017-present). Rescaling of the flares' peak intensity (pre-GOES-16 era) has been performed in accordance with guidelines at NGDC/NOAA.

Following the exceptional flaring activity by NOAA 13664 in **May 2024**, and the **very high solar activity during the second half of 2024**, SC25 has now (up to 30 September 2026) produced **1803 flares in the M1_M4 range, 179 in the M5_M9 range, as well as 107 X-class flares**.

* About 7% of these **2089 M- and X-class** flares were produced in May 2024, and we have to go back to March 1991 to find a month with even more M- and X-class flares (resp. 179 vs 143). March 1991 also has 2 X-class flares more than May 2024 (23 vs 21).
* May 2024 was also the **first month with more than 10 X-class flares in a single month since September 2005** with the famous active region NOAA 10808
* Note that also **August 2024** (122 M- and X-class flares) performed well above average. As such, 2024 is only the **third year with more than 900 M- and X-class flares in a single year, after 1989 and 1991** (resp. 922, 968 and 979). For comparison; SC24 produced only 1200 M- and X-class flares during its entire duration.
* Another important flare-productive group was NOAA 14366, which produced 66 M- and 6 X-class flares in **February 2026**. This active region ranks third in the list of flare-productive groups as observed during the GOES era as can be seen in this updated table. Note also new entry by SC25 in this table: NOAA 14479 was the source of 35 M- and 1 X-class flares early July 2026.

Solar Flares - Solar cycle

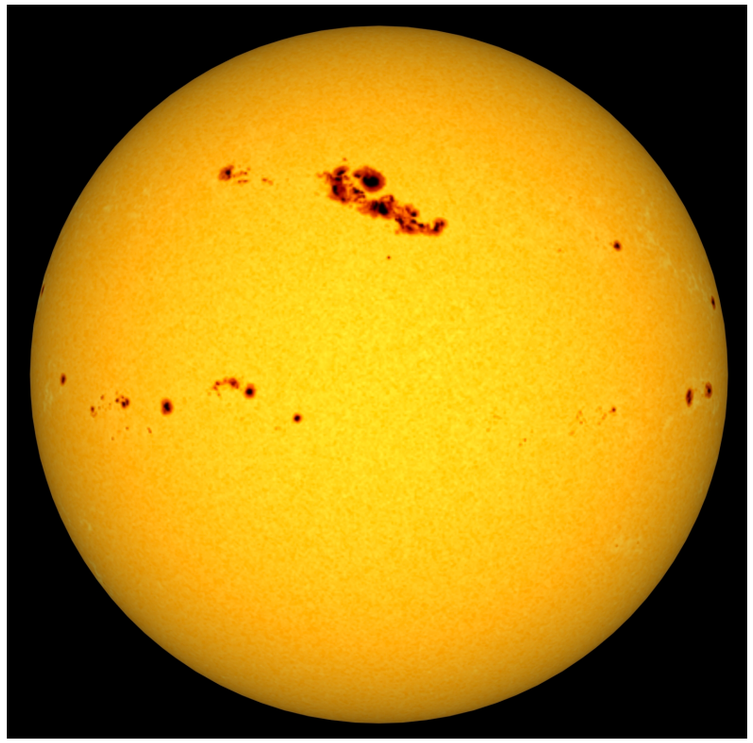




https://www.stce.be/content/sc25-tracking#flares

Comparing the current number of flares to that of previous solar cycles at the same stage (81 months since SC minimum ; bar-diagram above), **the number of strong (M5+) flares so far in SC25 (286) is higher than both SC23 (252) and SC24 (171), but well below the flaring numbers of SC21-22** (resp. 490 and 513). NOAA 13664 produced 17 of the 286 M5+ flares (12 X-class events!) in SC25, also NOAA 14366 (14, of which 6 X-class) contributed significantly, as well as NOAA 13663 and 13697 with 11 such flares each (resp. 5 and 6 X-class).

Flare Prediction - Sunspots



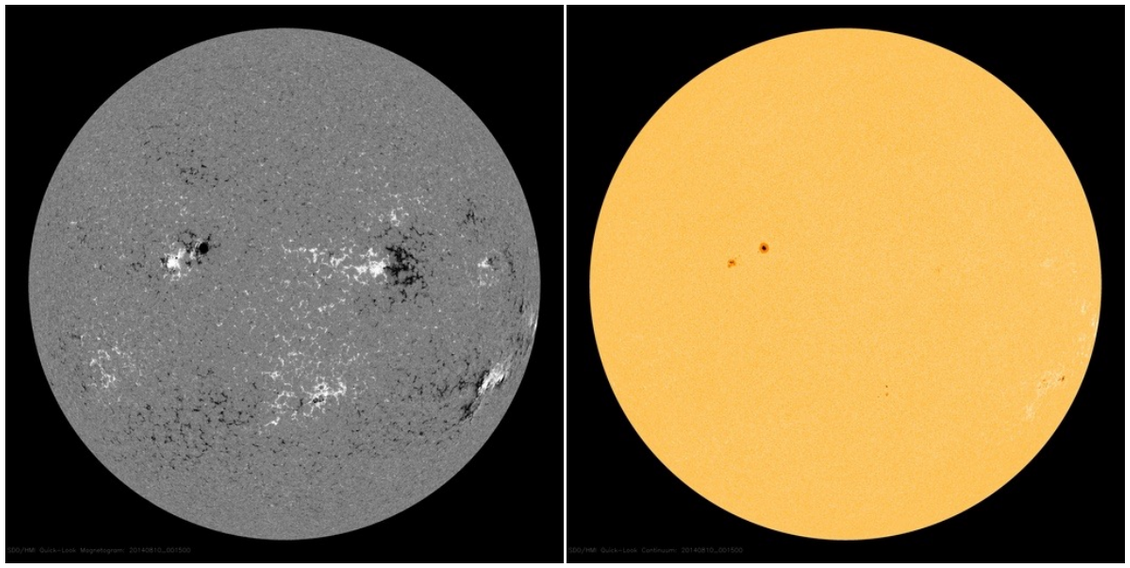
From ground we can image the photosphere in white light. The Sun then appears as a rather dull yellow ball, but sometimes shows dark spots called sunspots.

Sunspots are relatively dark area’s on the solar surface that indicate cooler regions in the solar photosphere. These area’s are slightly cooler compared to their surroundings because the intense magnetic fields in these regions inhibit the convection of plasma. This means that the heat that is produced in the core of the Sun is radiated outwards less efficiently in these locations, and thus they are somewhat cooler and appear dark. Note that sunspots are still very hot: their dark core has a temperature of ~4000K, while the bright photosphere has one of ~5800K.

Sunspots appear, change and evolve and then disappear again in time spans of days up to months. They usually come in pairs, each with a different polarity. The number of sunspots on the solar disk is an important measure of solar activity.

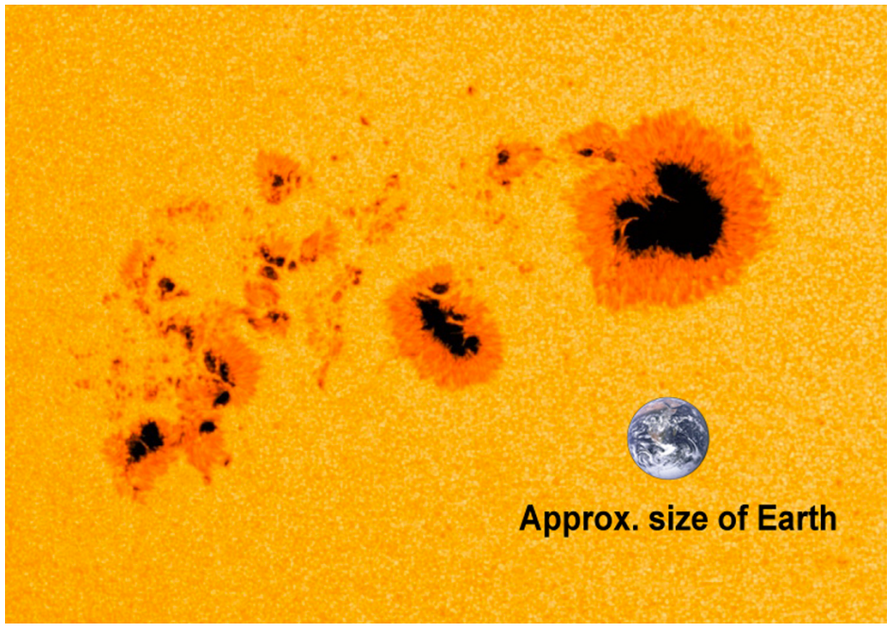
Magnetogram

SDO/HMI



A magnetogram images the strength of the magnetic field. When you compare them to the photospheric images you can clearly see the relation between magnetic field strength and the sunspots: sunspots are regions of very strong magnetic field.

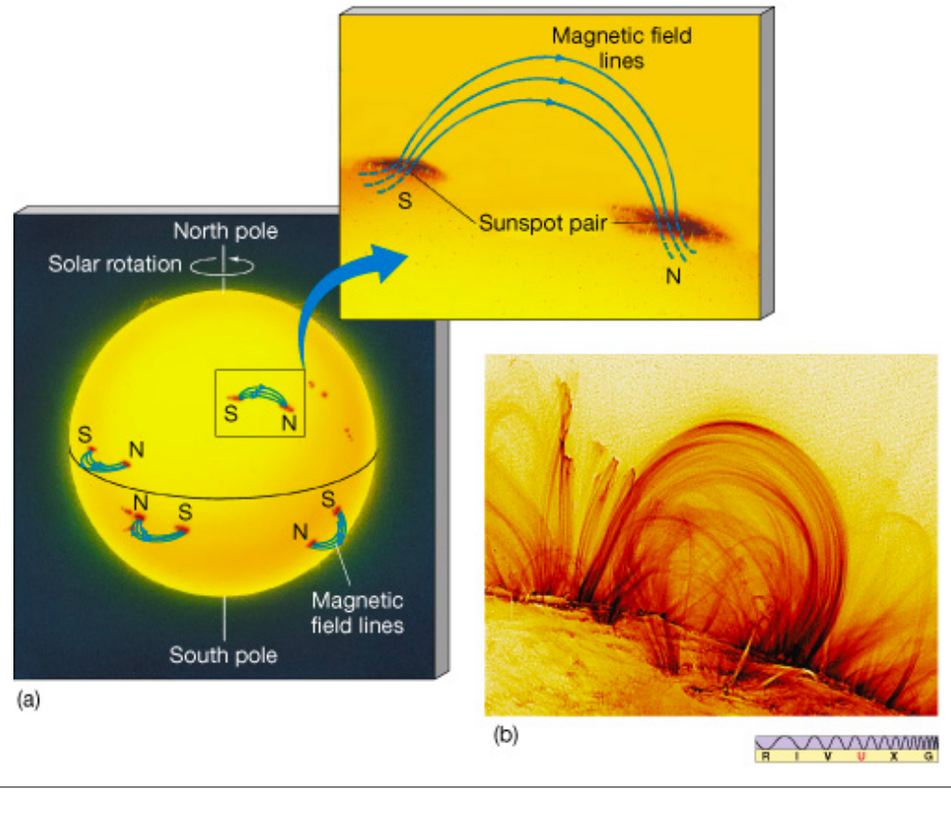
Sunspot size



Sunspots are huge!

Often two distinct regions can be seen in a sunspot: the dark core called the umbra (shadow in Latin) and the slightly less dark surroundings, called the penumbra.

Magnetic field

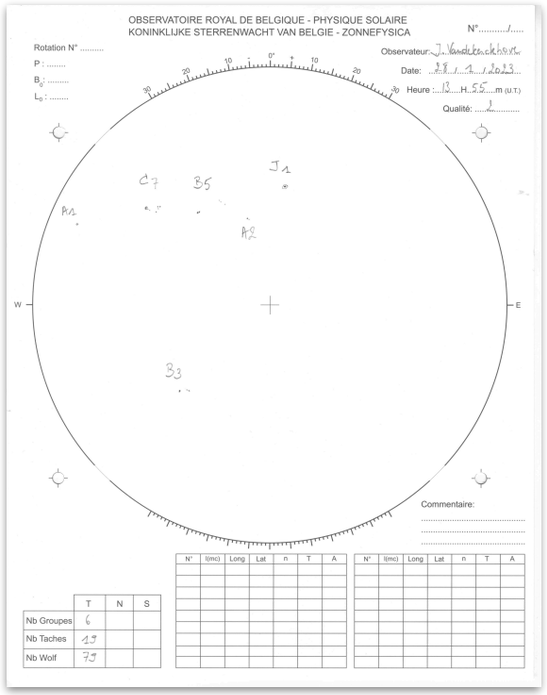


The solar magnetic field lines are made visible by the plasma that is attached to them (frozen in theorem). Think of the typical physics experiment where you can trace the fields lines of a magnet with iron filings.

The magnetic field lines connect the different polarities (From the positive to the negative pole).

Image from: http://ircamera.as.arizona.edu/NatSci102/NatSci102/lectures/sun.htm

Sunspot drawings


OBSERVATOIRE ROYAL DE BELGIQUE - PHYSIQUE SOLAIRE
KONINKLIJKE STERRENWACHT VAN BELGIE - ZONNEFYSICA

N°...../.....

Rotation N° .....
P : .....
B_0 : .....
L_0 : .....

Observateur: J. Vandekerckhove
Date: 28 / 4 / 2023
Heure : 13 H 55 m (U.T.)
Qualité: 1

W
E

Commentaire:

	T	N	S
Nb Groupes	6		
Nb Taches	13		
Nb Wolf	73		

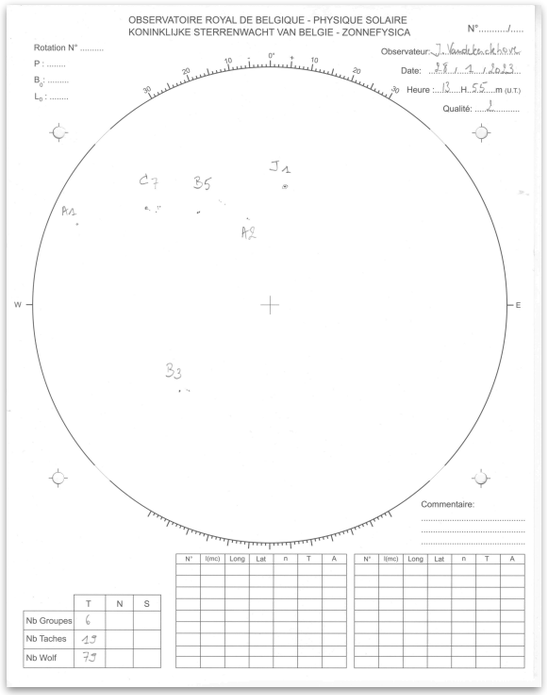
N°	l(mc)	Long	Lat	n	T	A

N°	l(mc)	Long	Lat	n	T	A

The Royal Observatory of Belgium hosts the World Data Center for the production, preservation and dissemination of the international sunspot number. (http://sidc.oma.be/silso/)

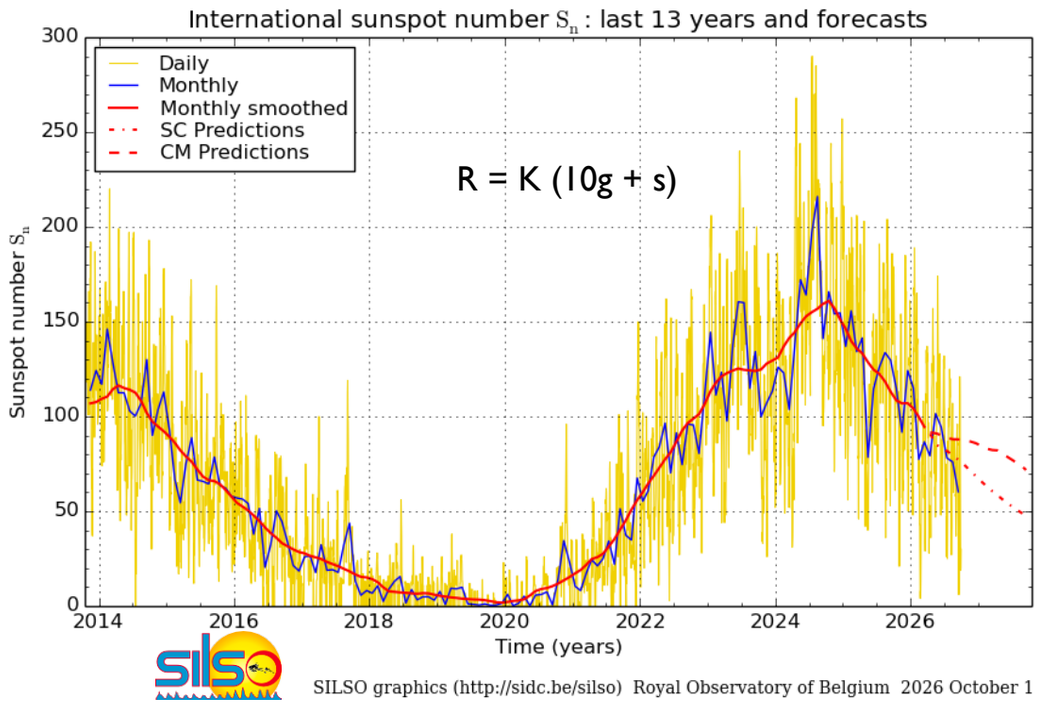
Each day (when weather permits) we make drawings of the sunspots that are seen on the solar disk. At ROB we have done this since **1955**, but sunspot records go back centuries. Some very big sunspots were observed with the naked by the ancient Greek, but more systematic observations only began when the telescope was invented (think e.g. of Galileo Galilei).
This long record allows us to study the evolution of solar activity over very long time scales. We now have satellites with much clearer observations of this activity, but to be able to properly correlate current with older observations, we keep on making drawings.

Sunspot drawings



USET

Sunspot number and solar cycle



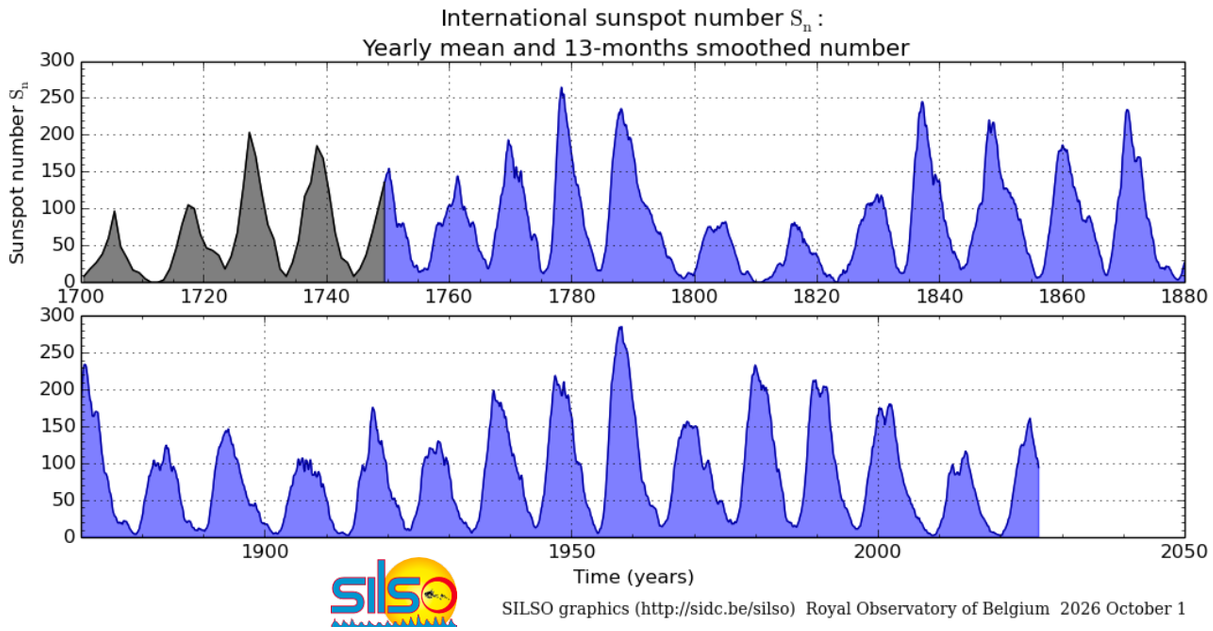
Every day we count the number of sunspots, combining different observations on different locations and correcting for the specifics of the observations. This is a weighted count: one single sunspot has much less weight than a complex group (the complex group is much more likely to cause activity).

The relative sunspot number is defined as R = K (10g + s), where g is the number of sunspot groups and s is the total number of distinct spots. The scale factor K (usually less than unity) depends on the observer and is intended to convert the observation back to the scale originated by Wolf in 1848. This weighing factor combines corrections for the observer, location, and instrumentation.

Combining all observations leads to a daily sunspot number. When we plot this number over time, we see a clear cyclical behaviour. The solar activity, for which the sunspot number is a proxy, increases and decreases over a time span of approximately 11 years. This is called the solar cycle.

The red lines indicate different predictions for the behaviour of the next solar cycle. As you can see, there is quite some discrepancy/uncertainty for the various predictions.

Long term solar activity
Solar seasons

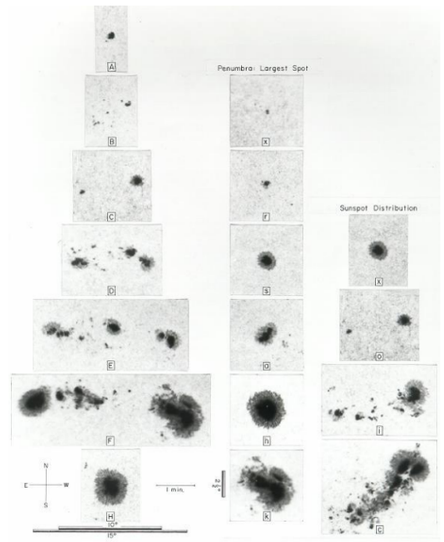


This graph shows you the solar activity over the last three centuries. Clearly, there is a large variation in solar cycles, some are shorter that others (more narrow), some are much stronger than others (higher).
To create this type of graph, we rely heavily on the old sunspot drawings as these are our main indication of how active the Sun was in the distant past.

Solar Flares - Classification

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

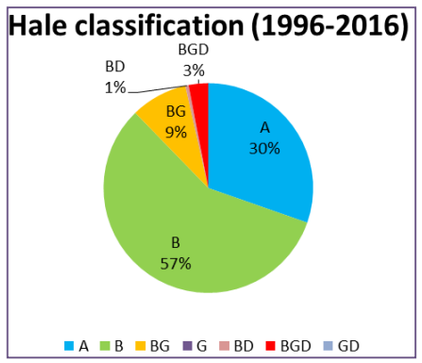


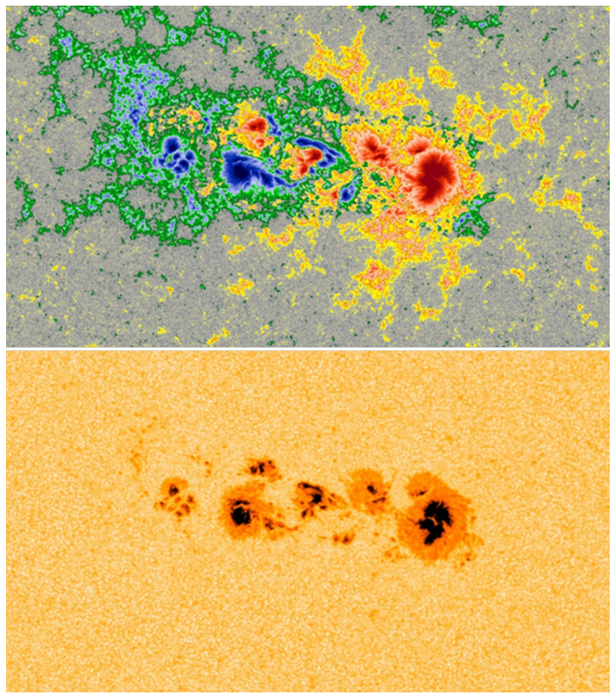
To quantify the complexity of the regions that are at the base of a solar flare, we divide them into different classes which can be linked to their likelihood to produce a flare
A very important, widely used type of classification is the McIntosh classification, which goes back to an original classification that was defined at the Zurich observatory. It was further refined into a three letter code where the first denotes the original classification, the second gives more information on the largest spot and the third specifies how compact the region is and how the sunspots are distributed between the two major polarities.
Some examples are shown on the right. We have 60 possible combinations which -through statistical studies- have been linked to flare probabilities, but with rather large uncertainties.

Solar Flares - Classification

Mount Wilson (Hale) classification

- Based on the magnetic properties of a sunspot group
- 7 options: α, β, βγ, γ, βδ, βγδ, 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.

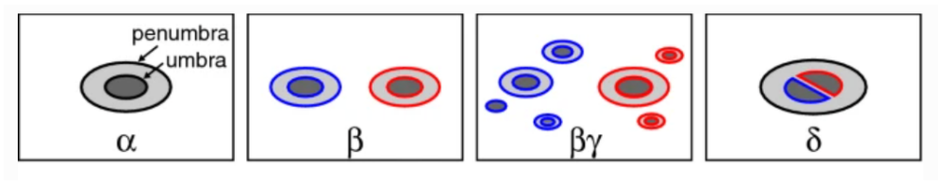
The chart with the % of Hale classification was based on the NOAA reports at https://solarscience.msfc.nasa.gov/greenwch.shtml for the period Jan 1996-September 2016. A total of 32965 classifications were made. The percentage of reported delta's in the sunspot groups is 3.5%.

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

Solar Flares - Classification

Table 3.1: Mount Wilson Scheme

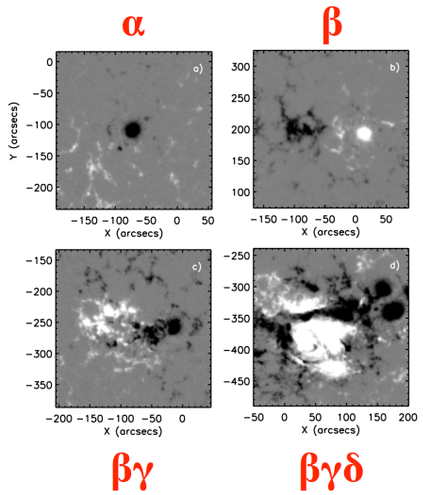
Magnetic Class	Description
α	Unipolar sunspot
β	Bipolar sunspot group
γ	Atypical mixing of polarities
$\beta\gamma$	Mixture of polarities within a predominantly bipolar group
δ	Opposite polarity umbrae ($< 2°$ separation) surrounded by a single penumbra
$\beta\delta$	Bipolar with delta configuration
$\beta\gamma\delta$	Bipolar, mixed & delta configuration

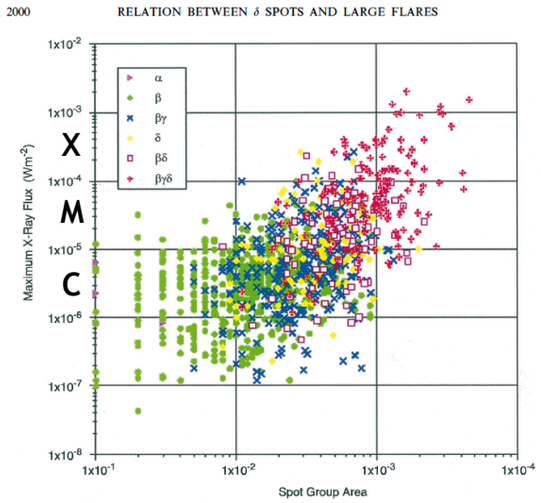


Bottom figure from https://link.springer.com/article/10.1007/s41116-019-0019-7
Based on the magnetic properties of a sunspot group

Also called the Hale classification

Solar Flares - Prediction





For space weather forecasting it is important to know how this classification relates to the probability of producing a flare. Intuitively, it is easy to understand that more complex regions, with mixed polarities, will allow for easier interactions of the magnetic field and thus a larger chance of a stronger flare.

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

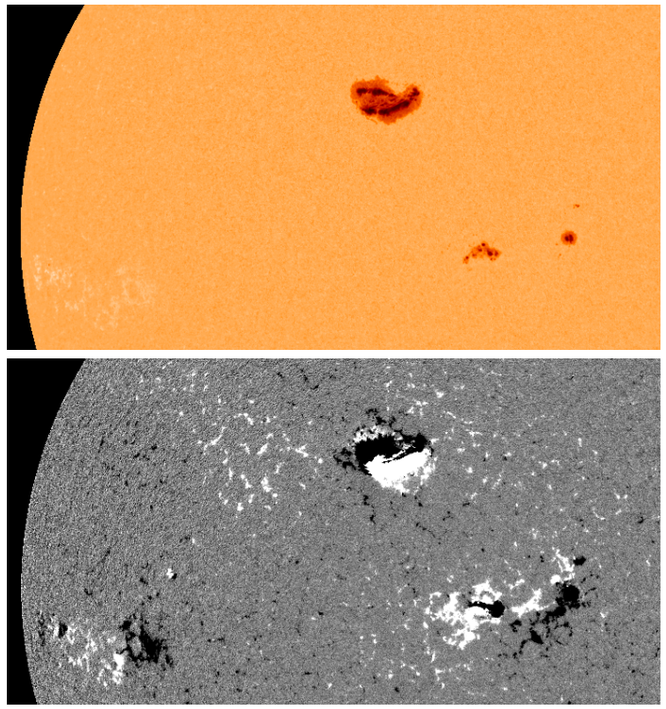
In Figure 2, we plot the largest flare from each active region against the largest reported area from that region, for each magnetic class. This shows a roughly linear connection between the logs of SXR flux and active region maximum areas. The general slope of Figure 2, upward and to the right, confirms 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.

Bottom figure from https://link.springer.com/article/10.1007/s41116-019-0019-7

Solar Flares - Prediction

- 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.
(Shear: laterally shifted in relation to each other.)

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