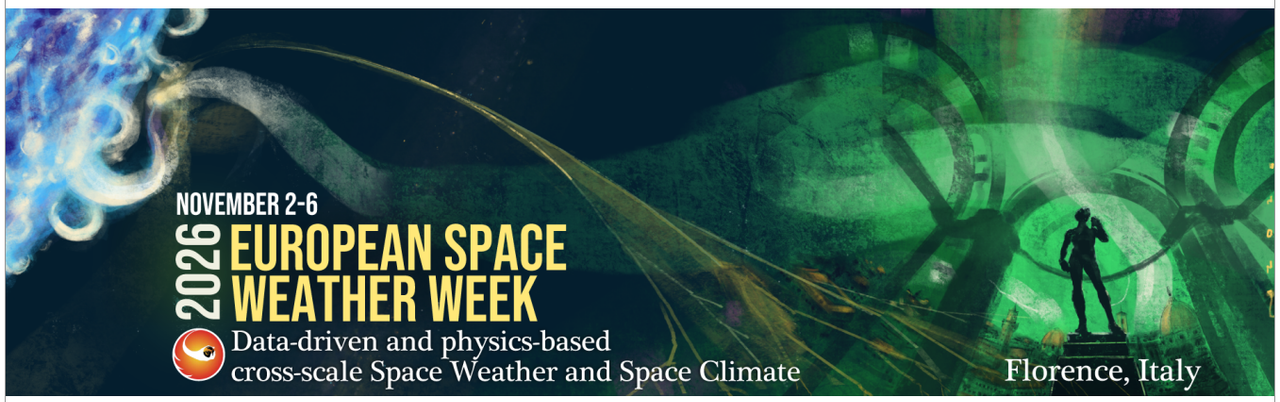
Space Weather Training Course



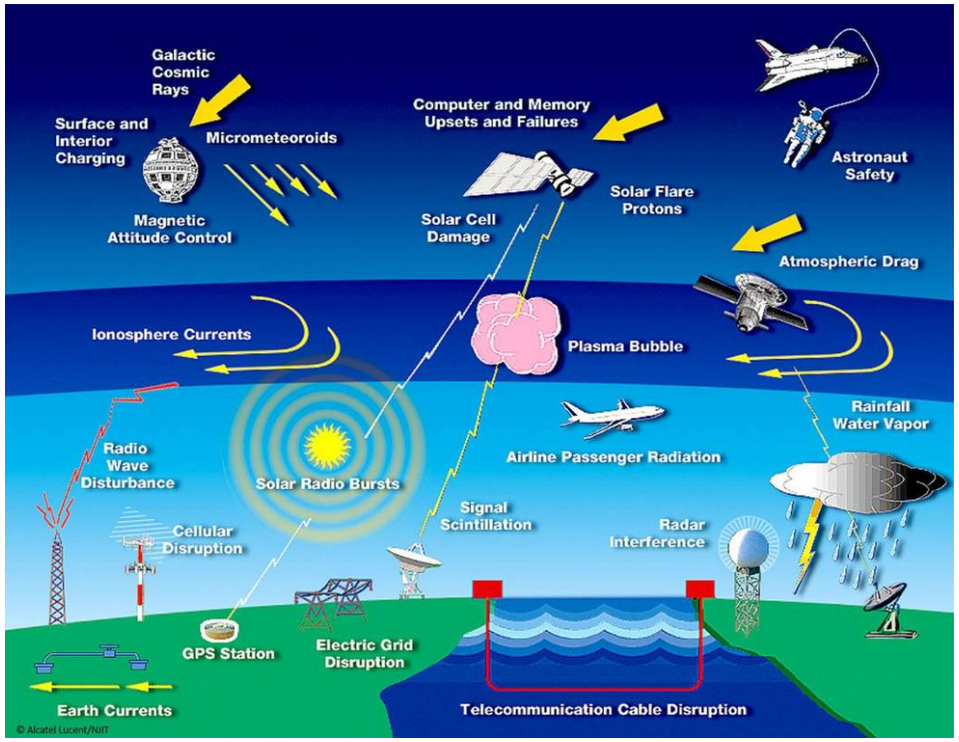
Collaboration of

e-SWAN

SWEC
Space Weather Education Centre

COMMUNITY COORDINATED MODELING CENTER

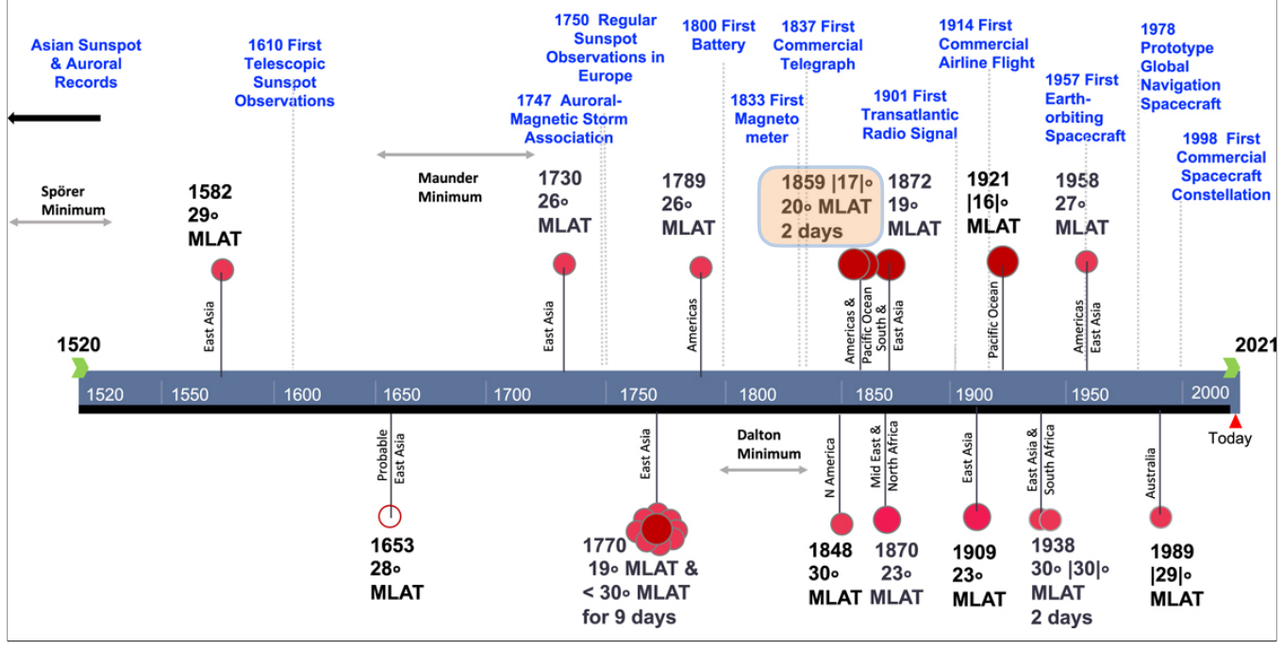
Space Weather Impacts



Instead of going through each of these effects and their causes separately, we will discuss a few famous space weather events and their effects

Timeline - 1859

500 Years of Space Weather Storms with Aurora Visible at or Equatorward of 30° Magnetic Latitude



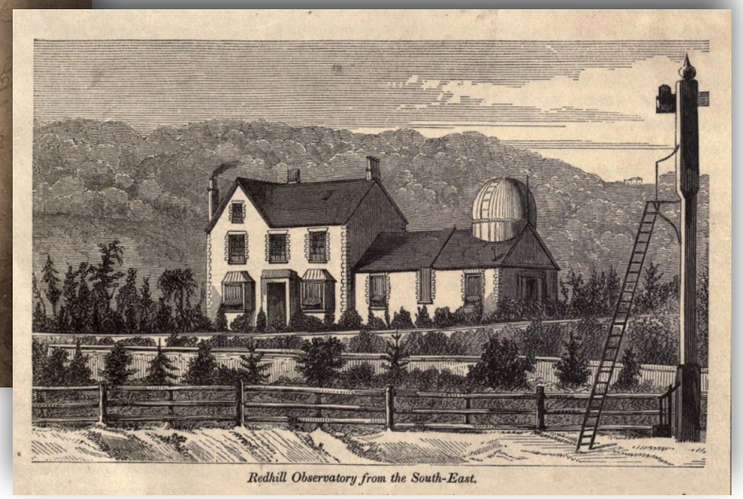
https://www.swsc-journal.org/articles/swsc/full_html/2021/01/swsc200106/swsc200106.html

Year and approximate magnetic latitude of lowest latitude report of visible aurora for storms spanning 500 years (1520–2020). The 14 events are placed above and below the timeline to avoid overlap. Brackets indicate southern latitudes. All MLAT values have been rounded to the nearest whole degree. Large circles correspond to more equatorward auroral visibility. An open marker indicates a probable event. See references in Table 1. Several technology developments are listed, as are the approximate intervals of grand/ secular solar minima.

MLAT = magnetic latitude

Carrington Event



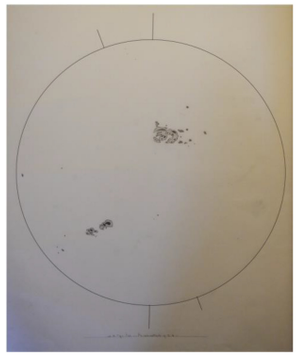


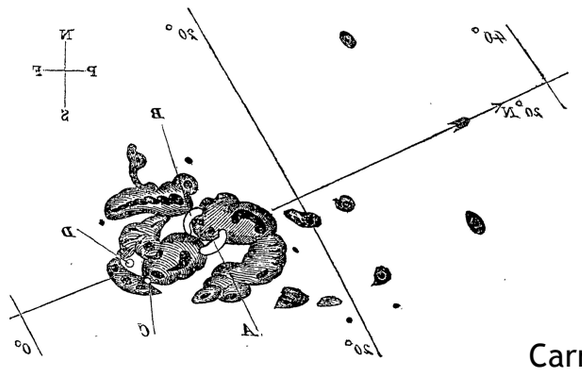
Redhill Observatory from the South-East.

Only known photograph of Carrington

Carrington's house and observatory on Furze Hill, Redhill, Surrey (between 1852 and 1857)

Carrington Event - 1 September 1859





Carrington, 1959

Flare is suggested to be of order of X45

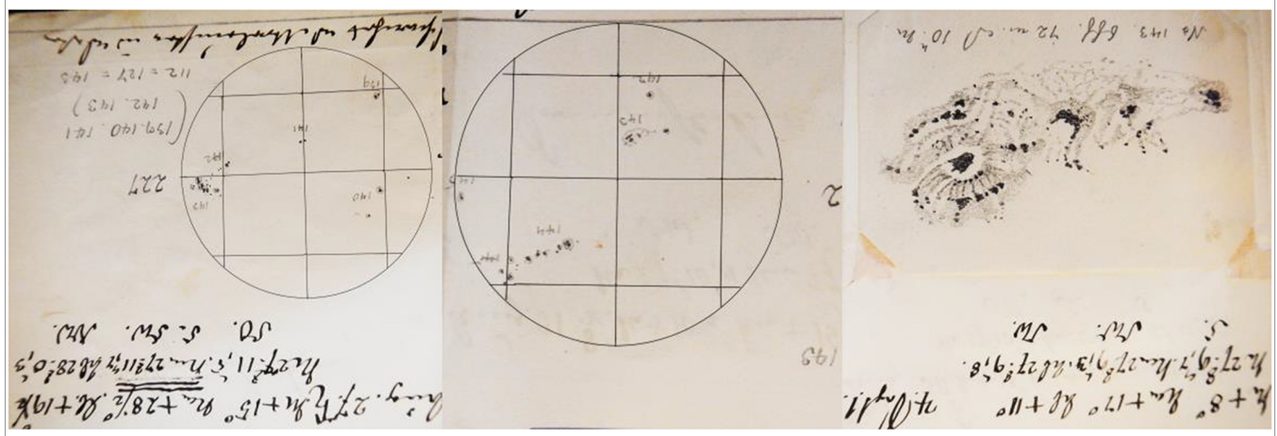
Carrington drawing of the sets of sunspots of September 1, 1859, the zones marked A and B was the location of a white flash lasting at least five minutes.

During this enhanced phase near the first peak in Solar Cycle 10, a significantly large and complex sunspot group appeared on the solar disk, which was visible even without a telescope (Crookers, 1859, p. 68; cf. Vaquero & Vázquez, 2009, pp. 57–102; Hayakawa et al., 2017, Hayakawa, Willis, et al., 2019). This large sunspot group was monitored by a number of contemporary astronomers such as Secchi, Carrington, and Schwabe. Among them, Father Angelo Secchi was the director of Collegio Romano and a prominent scientist and sunspot observer at that time. He mentioned this group's association with the great auroral display: “It is extremely remarkable that these great perturbations should have coincided with a maximum of solar spots, and should have happened precisely at a moment when an immense spot was visible on the disc of the Sun, even without the aid of the telescope” (Crookers, 1859, p. 68).

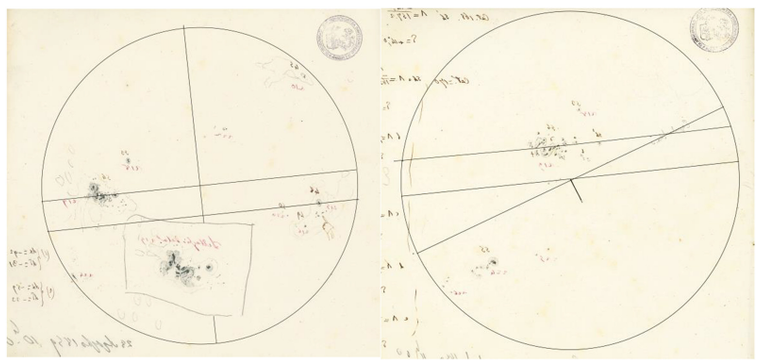
Within this large sunspot group, Carrington (1859) and Hodgson (1859) witnessed the earliest white-light flare in observational history on 1 September. This flare was recorded at 11:18–11:23 UT on 1 September

Drawings of a whole solar disk (top) and of the sunspot generated the strongest white-light flares (bottom) made by Richard Carrington on 1 September with its limb enhanced (RAS MS Carrington 3.2, f. 313a; Image courtesy of the Royal Astronomical Society). In both of panels, drawings are reversed from the originals in the horizontal direction as seen in the original solar disk. In the top panel, the Sun's rotational axis is drawn as an oblique line, and the sunspot that caused the Carrington flare is in the upper-right quadrant of solar disk.

Carrington Event - 1 September 1859



Schwabe, 1959



Secchi, 1959

Sunspot drawings by Heinrich Schwabe on 27 August (left), 1 September (center), and close-up figure of 1 September (right), reproduced from RAS MS Schwabe 31 (p. 131 and p. 136; Image courtesy of the Royal Astronomical Society). Circles in the upper halves correspond to the solar disk, on which the sunspots are drawn with the numbers. The sunspot group that caused the Carrington flare is numbered 143 (on left side of the disk in the left panel and a little upper right of the disk center in the middle panel). Note that Schwabe separated Carrington's Group 520 to Groups 143 and 142. Close-up drawing in the right panel reveals the details of the Group 143. They are reversed as they were seen on the sky. The solar rotational axis is not shown in these drawings. Their limb and contrast have been enhanced here

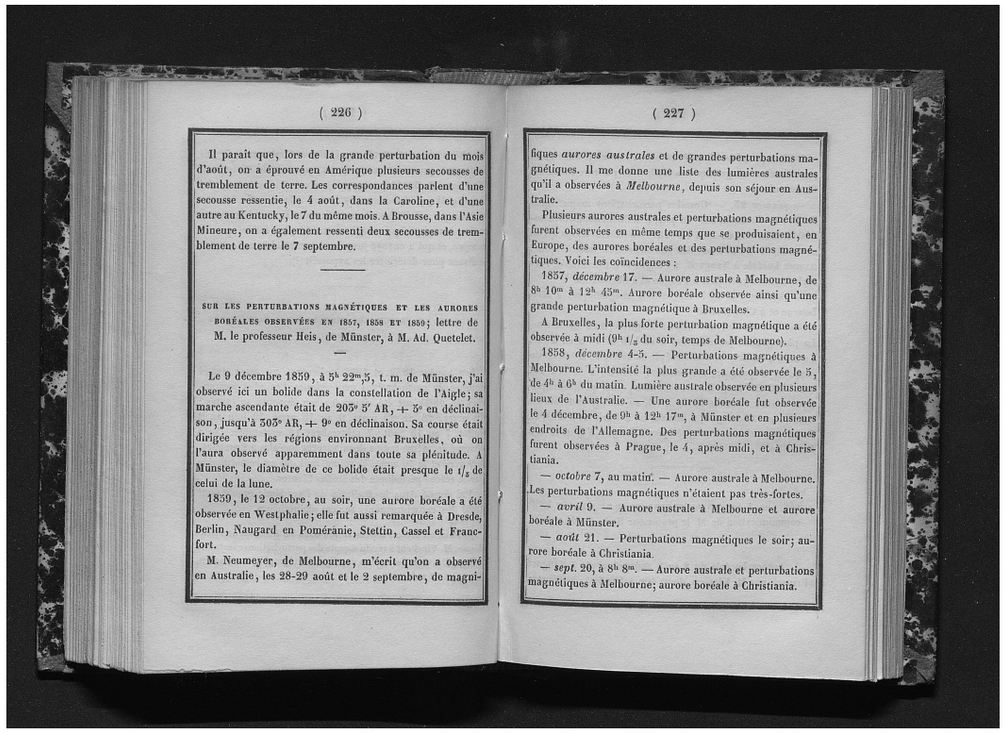
Drawings of the solar disk by Father Angelo Secchi on 28 (left) and 31 (right) August 1859 (OAR MS B13 in Archivio INAF Osservatorio Astronomico di Roma). The left observation includes close-up drawing of the source region of the Carrington event. In both of panels, drawings are reversed from the originals in the horizontal direction as seen in the original solar disk. The solar rotational axis is shown as a short oblique line in the right drawing. Their limb and contrast have been enhanced here.

In this article, we have revised the temporal and spatial evolutions of the auroral displays during the stormy interval around the Carrington event. The contemporary sunspot drawings by Richard Carrington, Heinrich Schwabe, and Father Angelo Secchi showed a large and complex source AR between 25 August and 7 September. Schwabe and Secchi's sunspot drawings let us confirm the sunspot topology detailed in Carrington's (1859) sunspot drawings (Hayakawa, Ebihara, Hand, et al., 2018) with their resemblance, even though Schwabe's methodology is different from Carrington's for the solar observation. This resemblance is important because the scientific discussions of the Carrington event have been based on Carrington's drawing, and now they are strengthened by these additional contemporary observations. This AR probably caused a significant ICME on 27 August resulting in the first magnetic storm on 28/29 August, despite the AR's unfavorable location on the eastern side of the solar disk. The source AR rotated to the disk center on 31 August to 1 September and caused the white-light flare on 1 September, associated with the second extreme magnetic storm with low latitude aurorae.

https://www.sciencealert.com/powerful-solar-storms-may-be-much-more-common-than-we-thought
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2019SW002269

Through this comprehensive analysis, the team discovered something new about the Carrington Event; namely, that it wasn't just one huge belch of plasma. Rather, the team believes that the sunspot group erupted several times over the weeks before and after the event itself, from an earlier coronal mass ejection on 27 August 1859, and continuing through early October.

Carrington Event - 1 September 1859



(226)

Il paraît que, lors de la grande perturbation du mois d'août, on a éprouvé en Amérique plusieurs secousses de tremblement de terre. Les correspondances parlent d'une secousse ressentie, le 4 août, dans la Caroline, et d'une autre au Kentucky, le 7 du même mois. A Brousse, dans l'Asie Mineure, on a également ressenti deux secousses de tremblement de terre le 7 septembre.

SUR LES PERTURBATIONS MAGNÉTIQUES ET LES AURORES BORÉALES OBSERVÉES EN 1857, 1858 ET 1859; lettre de M. le professeur Heis, de Münster, à M. Ad. Quetelet.

—

Le 9 décembre 1859, à 5h 22m,5, t. m. de Münster, j'ai observé ici un bolide dans la constellation de l'Aigle; sa marche ascendante était de 205° 5′ AR, + 5° en déclinaison, jusqu'à 505° AR, + 9° en déclinaison. Sa course était dirigée vers les régions environnant Bruxelles, où on l'aura observé apparemment dans toute sa plénitude. A Münster, le diamètre de ce bolide était presque le 1/5 de celui de la lune.

1859, le 12 octobre, au soir, une aurore boréale a été observée en Westphalie; elle fut aussi remarquée à Dresde, Berlin, Naugard en Poméranie, Stettin, Cassel et Francfort.

M. Neumeyer, de Melbourne, m'écrit qu'on a observé en Australie, les 28-29 août et le 2 septembre, de magnifiques *aurores australes* et de grandes perturbations magnétiques. Il me donne une liste des lumières australes qu'il a observées à *Melbourne*, depuis son séjour en Australie.

(227)

Plusieurs aurores australes et perturbations magnétiques furent observées en même temps que se produisaient, en Europe, des aurores boréales et des perturbations magnétiques. Voici les coïncidences :

1857, *décembre* 17. — Aurore australe à Melbourne, de 8h 10m à 12h 45m. Aurore boréale observée ainsi qu'une grande perturbation magnétique à Bruxelles.

A Bruxelles, la plus forte perturbation magnétique a été observée à midi (9h 1/2 du soir, temps de Melbourne).

1858, *décembre* 4-5. — Perturbations magnétiques à Melbourne. L'intensité la plus grande a été observée le 5, de 4h à 6h du matin. Lumière australe observée en plusieurs lieux de l'Australie. — Une aurore boréale fut observée le 4 décembre, de 9h à 12h 17m, à Münster et en plusieurs endroits de l'Allemagne. Des perturbations magnétiques furent observées à Prague, le 4, après midi, et à Christiania.

— *octobre* 7, au matin. — Aurore australe à Melbourne. Les perturbations magnétiques n'étaient pas très-fortes.

— *avril* 9. — Aurore australe à Melbourne et aurore boréale à Münster.

— *août* 21. — Perturbations magnétiques le soir; aurore boréale à Christiania.

— *sept.* 20, à 8h 8m. — Aurore australe et perturbations magnétiques à Melbourne; aurore boréale à Christiania.

The Carrington Event: a spectacular solar storm

In 1859, an exceptional solar phenomenon took place. This immensely powerful solar eruption is now known as the Carrington Event. It was the first time such an event was observed and documented scientifically. The geomagnetic storm lasted several days, beginning on the 28th of August and reaching its peak on the 1st and 2nd of September of that year.

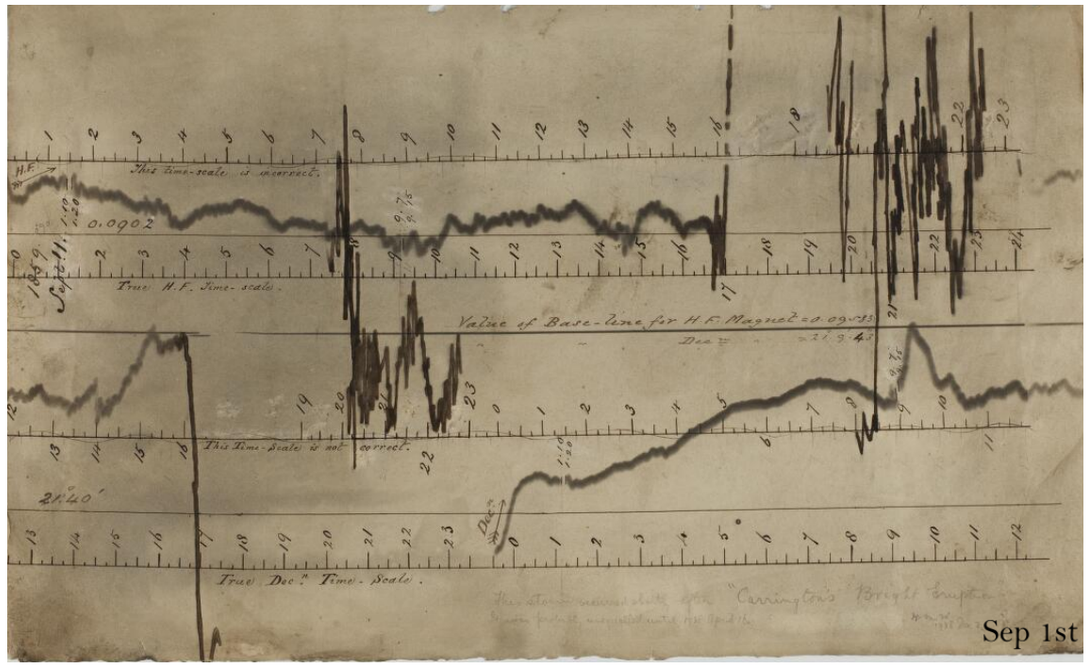
The English astronomer Richard Carrington witnessed this solar eruption and even produced a drawing of it at its maximum. The explosion was so intense that it triggered auroras visible as far south as Spain and Belgium, an extremely rare occurrence.

But above all, this solar storm had major technical consequences: it disrupted the telegraph network of the time for several hours. Electrical systems were still new in that era, so the event revealed just how vulnerable they were to magnetic disturbances originating from the Sun.

Adolphe Quetelet, director of the Royal Observatory of Brussels, played an essential role in documenting the event. Unlike Carrington, who observed but described the phenomenon only briefly, Quetelet wrote a detailed **scientific report** about the effects observed, notably the electrical disturbances. He published this report in 1860. His work is considered **one of the first complete scientific descriptions of a phenomenon of this kind.**

Although several other people also observed the effects of the solar storm, sometimes drawing or narrating what they saw, few provided an **analysis** as rigorous as that of Quetelet.

Carrington Event - 1 September 1859



This great magnetic storm is characterized by an extreme negative magnetic excursion. For example, a value of ≈ −1,600 nT was measured at Bombay

Magnetogram: The 'Carrington Event' on Sept 1 Recorded at Greenwich Observatory, London

The day after Carrington observed the impressive flare, Earth experienced an unprecedented geomagnetic storm, with telegraph systems going haywire and auroral displays — normally confined to polar latitudes — visible in the tropics, according to NASA Science.
Carrington put two and two together and realized that the solar flare he'd seen was almost certainly the cause of this massive geomagnetic disturbance. This was a connection that had never previously been made, according to NASA Spaceflight. The solar storm of 1859 is now known as the Carrington Event in his honor.
The Carrington Event sparked a huge geomagnetic storm that wreaked havoc with technology. Earth fell silent as telegraph communications around the world failed.

According to History.com, there were reports of sparks showering from telegraph machines, operators receiving electric shocks and papers set ablaze by the rogue sparks.
Striking auroras dazzled skywatchers around the world as polar light shows stretched far beyond their usual ranges. The northern lights (aurora borealis) were witnessed as far south as Cuba and Honolulu, Hawaii, whilst the southern lights (aurora australis) were seen as far north as Santiago, Chile, according to National Geographic.

For many people around the world, this was the first time they'd ever witnessed the aurora and didn't know what to make of the brighter than usual skies. Whilst some believed the end of the world had arrived, others began to start their day after hearing the birds chirping, seeing the bright skies, and believing the sun had begun to rise, according to History.com.

When telegraph workers returned to work the following day, the effects of the Carrington Event were still being felt as the **atmosphere was still very charged**. History.com reported that American Telegraph Company employees found it impossible to transmit or receive dispatches. Alarmingly, they found that they could however unplug their batteries and transmit messages to Portland, Maine, using only the auroral current according to Ars Technica.

the great geomagnetic storm that followed 17.6 h later and drove the record off scale

https://geomag.bgs.ac.uk/education/carrington.html

Carrington Event - 1 September 1859


Daily Evening Traveller.

Conversation between two operators of the telegraph line between Boston and Portland on the night of 2 September 1859

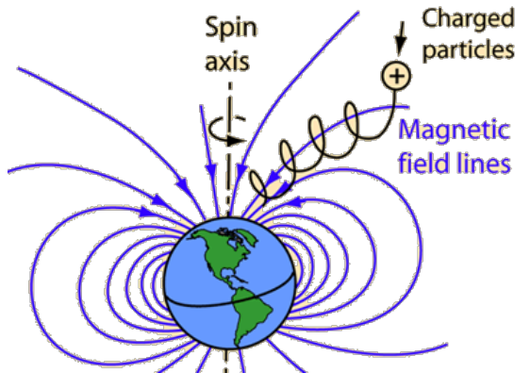
Boston operator: "Please cut off your battery entirely for fifteen minutes."
Portland operator: "Will do so. It is now disconnected."
Boston: "Mine is disconnected, and we are working with the auroral current. How do you receive my writing?"
Portland: "Better than with our batteries on. – Current comes and goes gradually."
Boston: "My current is very strong at times, and we can work better without the batteries, as the aurora seems to neutralize and augment our batteries alternately, making current too strong at times for our relay magnets. Suppose we work without batteries while we are affected by this trouble."
Portland: "Very well. Shall I go ahead with business?"
Boston: "Yes. Go ahead."

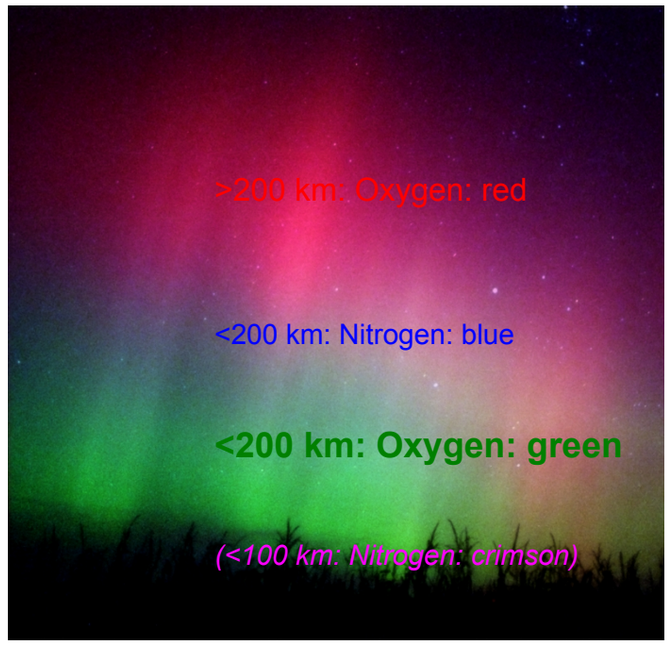
Distance Portland -Boston, roughly 5000 km
Start of space weather studies, first time link was made between solar activity and geomagnetic storm effects

Radio propagation was enhanced due to changes in the ionosphere, leading to good long-distance reception

Carrington Event - Effect: Aurora

- Aurora as far down as the tropics





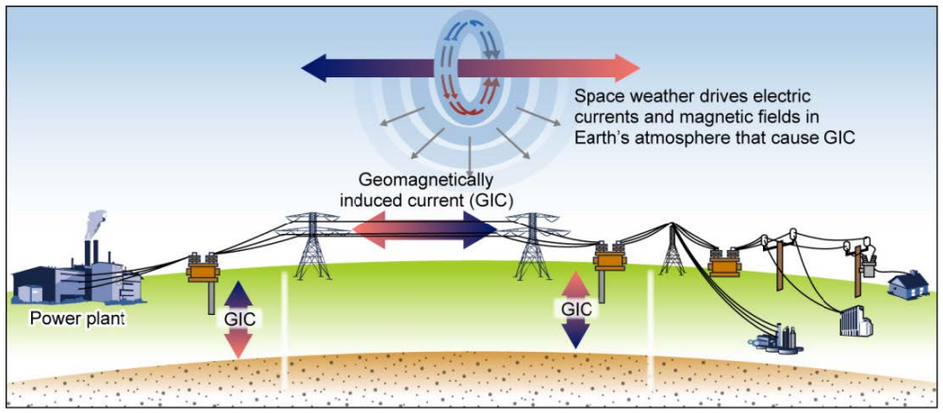
The visual auroral reports from the Russian Empire and Japan enable us to fill the apparent gap of auroral observations in the Eastern Hemisphere and complimentarily show a long and intermittent auroral visibility through the stormy period from 28/29 August to 4/5 September, when compared with the known visual auroral reports.

Auroras are generated in the ionosphere by the excitation of specific atmospheric gas species by energetic charged particles. As the gas transitions to its normal, unexcited state, it emits energy, some in the form of visible light. Auroras have a characteristic suite of emission lines in the visible spectrum. Each emission line is associated with a transition in a specific gas species. The emission line's color reflects the energy of the transition (Fig. 1B) and its intensity depends on the flux of the exciting particles and on the excitation potential of the gas species (Fig. 1A). Many visible-light auroral emissions are due to trace gasses that require different excitation energies than major components of the atmosphere, so that some important auroral emissions do not originate with the gases N2 and O2 that compose 99% of the bulk atmosphere. Atmospheric composition varies both with elevation and time. Thus, the mix of emission lines changes, depending on the mixture of gases that are being excited, the relative intensities of excitation and the depth range of the excitation within the ionosphere. The perceived color of an aurora is determined by the response of the human visual system to the mix of emission lines.

Auroral emissions are dominated by monatomic nitrogen (N1), molecular nitrogen (N2) and molecular oxygen (O2) at altitudes of 90–150 km. From altitudes of 150 to 900 km, the most important gas is monatomic oxygen (O1). Above 900 km, the most important gases are helium (He) and monatomic hydrogen (H1) (Russell, 2005b).

Carrington Event - Effect: GIC

- Aurora as far down as the tropics
- Geomagnetically Induced Currents (GICs) in telegraph wires



Sources: GAO (presentation); Art Explosion (images). | GAO-19-98

Electrons from magnetotail cause ionospheric currents -> Generate magnetic field -> Generates electrical field -> Generates currents at the surface

Geomagnetically induced currents (GIC) are electrical currents induced at the Earth's surface by rapid changes in the geomagnetic field caused by space weather events. GICs can affect the normal operation of long electrical conductor systems such as electric transmission grids and buried pipelines.

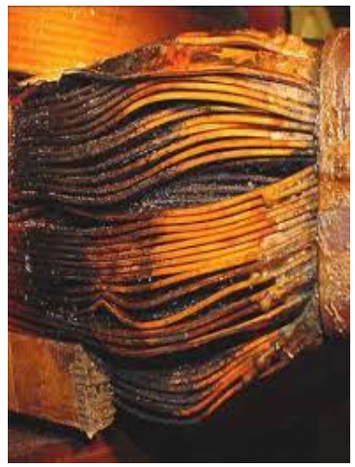
A time-varying magnetic field external to the Earth induces telluric currents—electric currents in the conducting ground. These currents create a secondary (internal) magnetic field. As a consequence of Faraday's law of induction, an electric field at the surface of the Earth is induced associated with time variations of the magnetic field. The surface electric field causes electrical currents, known as geomagnetically induced currents (GIC), to flow in any conducting structure, for example, a power or pipeline grid grounded in the Earth. This electric field, measured in V/km, acts as a voltage source across networks.

Geomagnetically Induced Currents

- Telegraph
- Affects all long conductors
- Power grid: transformer damage, blackout
- Pipelines: corrosion -> leaks



March 1989





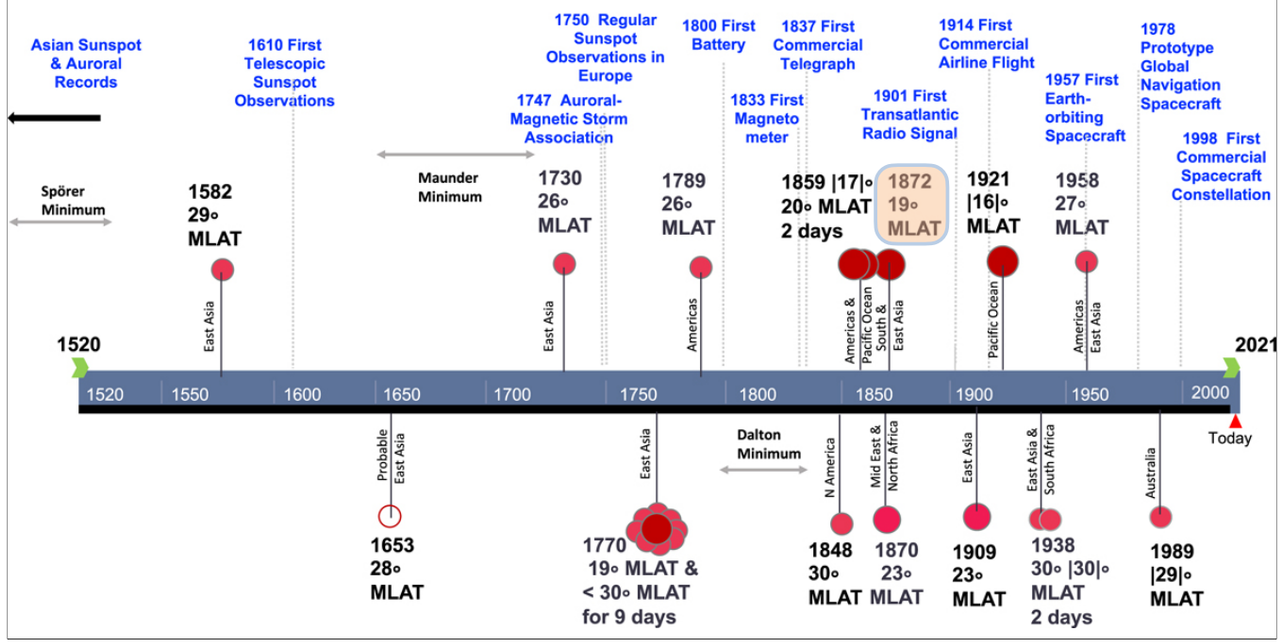
March 1989: Quebec, Canada

The variations in the Earth's magnetic field tripped circuit breakers on Hydro-Québec's power grid.[11] The utility's very long transmission lines and the fact that most of Quebec sits on a large rock shield prevented current flowing through the earth, finding a less resistant path along the 735 kV power lines.[12]

The James Bay network went offline in less than 90 seconds, giving Quebec its second massive power outage in 11 months.[13] The power failure lasted nine hours and forced the company to implement various mitigation strategies, including raising the trip level, installing series compensation on ultra high voltage lines and upgrading various monitoring and operational procedures. Other utilities in North America and Northern Europe and elsewhere implemented programs to reduce the risks associated with geomagnetically induced currents (GICs).[12]

Timeline - 1872

500 Years of Space Weather Storms with Aurora Visible at or Equatorward of 30º Magnetic Latitude

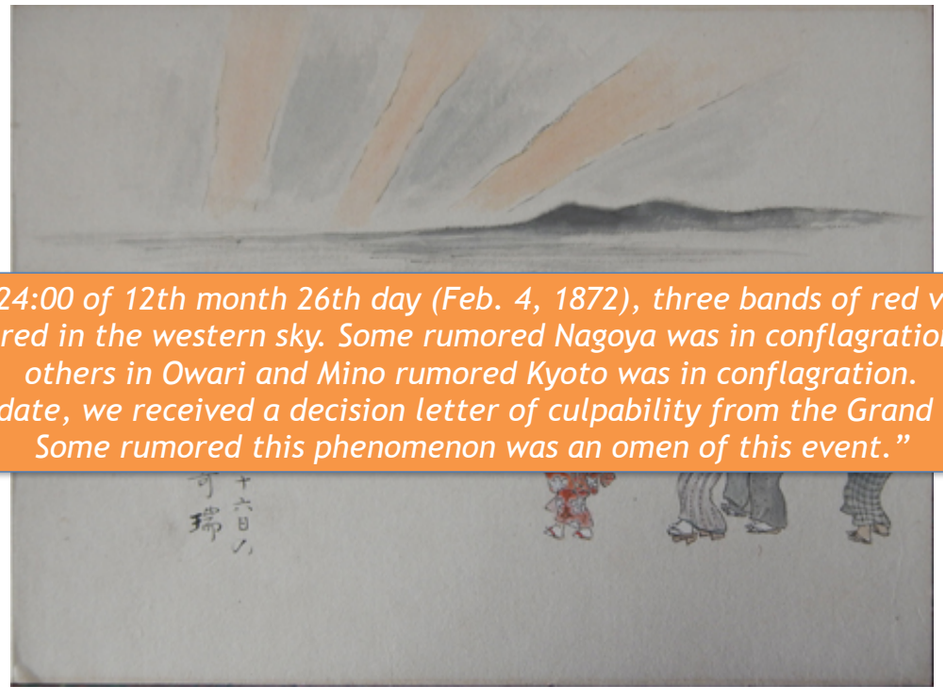


https://www.swsc-journal.org/articles/swsc/full_html/2021/01/swsc200106/swsc200106.html

Year and approximate magnetic latitude of lowest latitude report of visible aurora for storms spanning 500 years (1520–2020). The 14 events are placed above and below the timeline to avoid overlap. Brackets indicate southern latitudes. All MLAT values have been rounded to the nearest whole degree. Large circles correspond to more equatorward auroral visibility. An open marker indicates a probable event. See references in Table 1. Several technology developments are listed, as are the approximate intervals of grand/ secular solar minima.

MLAT = magnetic latitude

February 1872



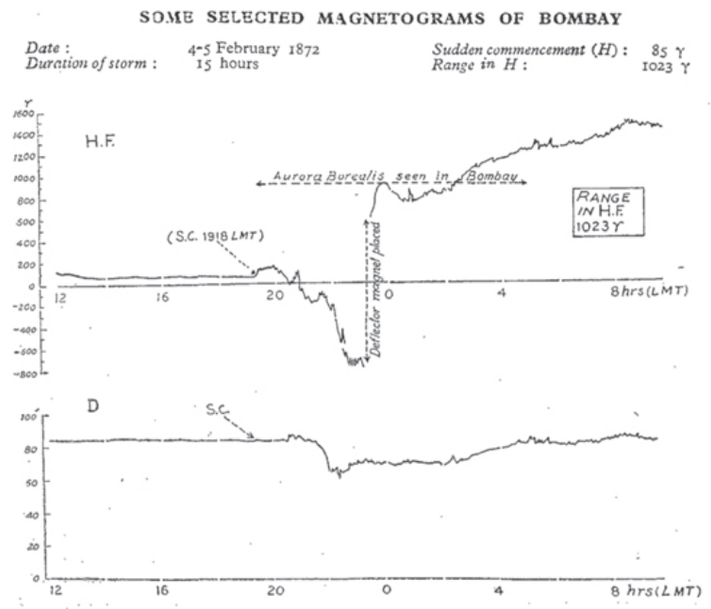
“At 24:00 of 12th month 26th day (Feb. 4, 1872), three bands of red vapor appeared in the western sky. Some rumored Nagoya was in conflagration, and others in Owari and Mino rumored Kyoto was in conflagration.
On this date, we received a decision letter of culpability from the Grand Council. Some rumored this phenomenon was an omen of this event.”

Junkyo Eshi, 1872

https://iopscience.iop.org/article/10.3847/1538-4357/aaca40
The study of historical great geomagnetic storms is crucial for assessing the possible risks to the technological infrastructure of a modern society, caused by extreme space-weather events. The normal benchmark has been the great geomagnetic storm of 1859 September, the so-called “Carrington Event.” However, there are numerous records of another great geomagnetic storm in 1872 February. This storm, which occurred about **12 years after** the Carrington Event, resulted in comparable magnetic disturbances and auroral displays over large areas of the Earth. We have revisited this great geomagnetic storm in terms of the auroral and sunspot records in historical documents from East Asia. In particular, we have surveyed the auroral records from East Asia and estimated the equatorward boundary of the auroral oval to be near 24fdg2 invariant latitude, on the basis that the aurora was seen near the zenith at Shanghai (20° magnetic latitude, MLAT). These results confirm that **this geomagnetic storm of 1872 February was as extreme as the Carrington Event**, at least in terms of the equatorward motion of the auroral oval. Indeed, our results support the interpretation of the simultaneous auroral observations made at Bombay (10° MLAT). The East Asian auroral records have indicated extreme brightness, suggesting unusual precipitation of high-intensity, low-energy electrons during this geomagnetic storm. We have compared the duration of the East Asian auroral displays with magnetic observations in Bombay and found that the auroral displays occurred in the initial phase, main phase, and early recovery phase of the magnetic storm.

Auroral drawing of Junkyo Eshi (J9) representing the auroral display on 1872 February 4. The original figure is currently preserved in the Shounji Temple. This figure is reproduced with permission of the Shounji Temple.

February 1872 - Magnetic Observations



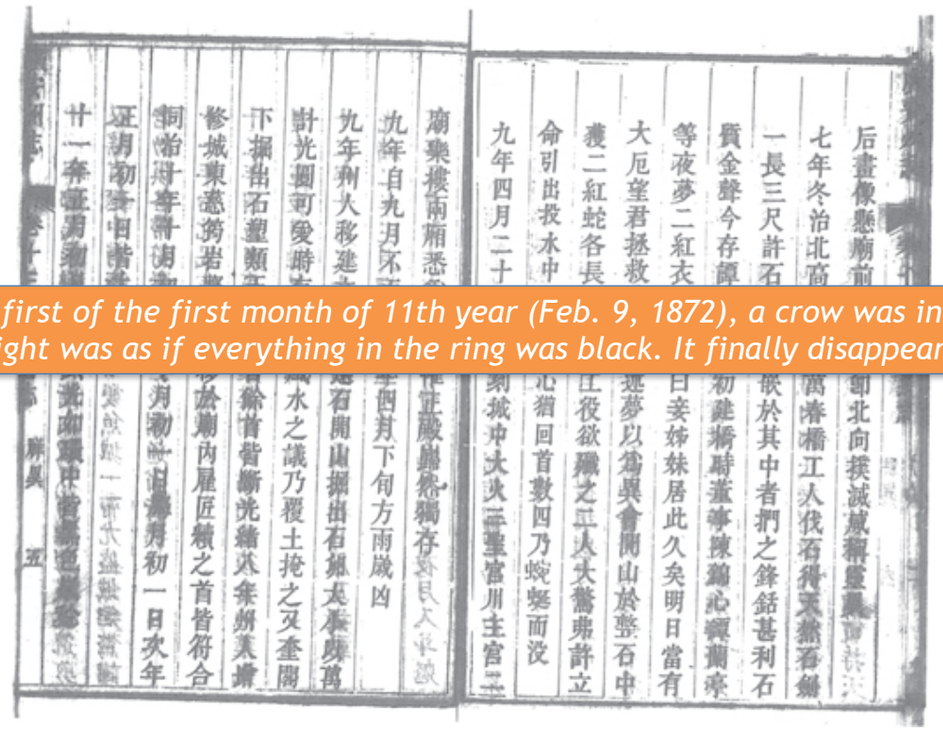
A magnetic storm of great intensity was recorded by Colaba on this day. It was one of the most violent storms since 1857 listed by Chapman and Bartels (*Geomagnetism* Vol. I page 328).

Very intense Aurora Borealis was seen in many places and even in low latitudes like Bombay from the evening of 4th to the morning of 5th. The Aurora Borealis of this date is one of the most brilliant on record. Internal telegraphic Communication and cable communication with England were interrupted for some hours as a result of the storm.

(Bombay LMT is 4 hours 51 minutes ahead of G M T)

February 4-5

February 1872 - Sunspot Observations



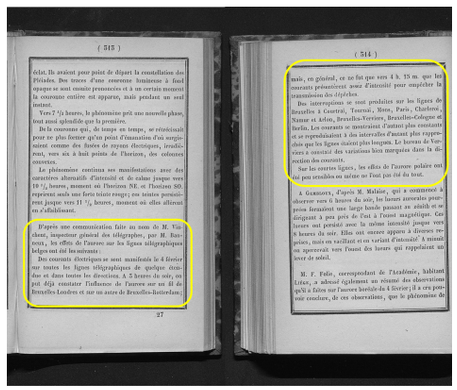
"On the first of the first month of 11th year (Feb. 9, 1872), a crow was in the sun. Its light was as if everything in the ring was black. It finally disappeared."

a Chinese local intellectual reports a naked-eye sunspot observation at Guǎngān (N30°28′, E106°38′) on 1872 February 9.

The date of the event is converted to 1872 February 9, where a considerably large number of sunspots were visible, with a few major sunspot groups on the right part of the Sun image. This might allow us to speculate that a large flare event could have happened a few days before the storm, due to the high activity of those Sun regions, when the sunspot groups were still on the left side of the Sun image according to the Sun rotation.

February 1872 - Reported Impacts

"... electrical currents were present on 4 February on all telegraph lines and in all directions. Affecting already from 3 pm local time the messagery between Brussels and London and between Brussels and Rotterdam, it was not until 4:15 pm that the currents were strong enough as to prohibit the sending of telegraphic messages. Interruptions were observed on all lines, not only in Belgium (e.g. Brussels-Namur, Brussels-Kortrijk), but also on the lines to Paris, Berlin and Cologne. It was noted that the longer the lines, the more constant the currents were and the more they recurred at increasingly shorter intervals."

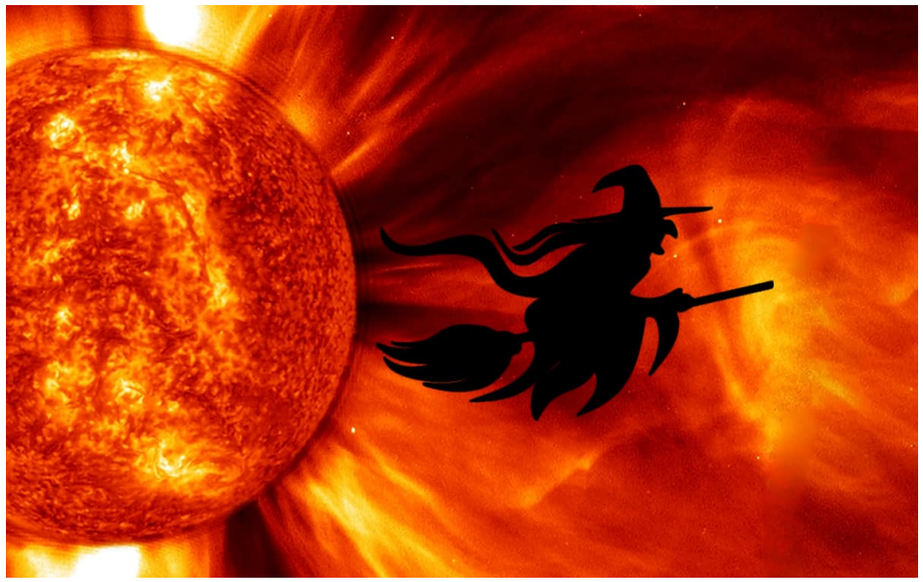


https://www.sidc.be/article/great-geomagnetic-storm-4-february-1872

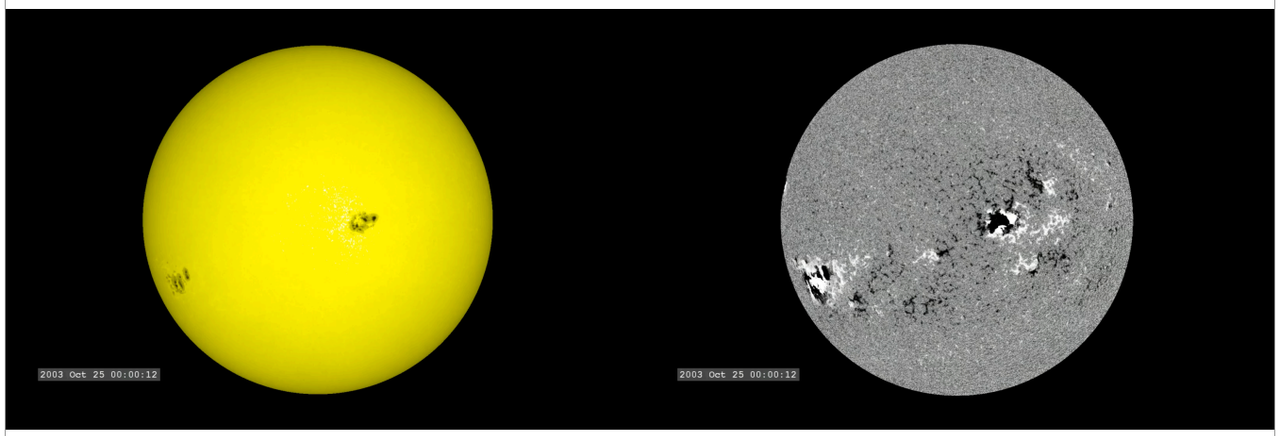
The third of these "superstorms" is the one from 4 February 1872, also known as the **Chapman-Silverman** storm (C-S storm). It occurred in the declining phase of the very strong solar cycle 11 which had a smoothed maximum of 234 (!) in August 1870 (SILSO). A study by Hayakawa and his collaborators a few years ago (2023) indicated that the minimum Dst during the C-S storm reached a value of -834 nT, and that this was a conservative estimate. The source region was most likely a moderately sized sunspot group about 3 times the surface are of the Earth, and located close to the Sun's central meridian.

The C-S storm has become famous for the intense and dynamic auroras that were visible at that time. Many observers commented on the bright red pillars ("columns of fire") shooting from the horizon all the way up to the zenith. In Hamada (south-west Japan), the brightness of the auroral display enabled observers to count the trees on the mountains and in the forests. Some villagers thought that big cities such as Kyoto and Nagoya were ablaze (Hayakawa et al. 2018). The auroras were seen overhead from locations as far south as Jacobabad (Pakistan; British India at that time) and Shanghai (China), both at about 20° in magnetic latitude (MLAT). Auroral visibility was reported from 13 locations with MLAT between -20° and +20°, many more than the single location recorded for the 1859 and 1921 storms. Mind-boggling examples are Aden (Jemen), Mecca (Saudi Arabia), Bombay (Mumbai, India), and Khartoum (Sudan). Other quite equatorial locations were Mauritius (near Madagascar), Sifook (Mozambique) and Tobago (just north of Venezuela!). In Bloemfontein (South-Africa), the bright red streamers frightened the natives considerably (Stone, 1872). In Havana, a correspondent from the New York Times wrote that "...the number of men and women who read the destruction of the world in this sign, was large and the latter took great care to go to church and pray that the calamity might be averted." (Sten Odenwald). The map above depicts the more equatorial locations from which aurora were observed, based on a selection of stations from the Hayakawa et al. papers and the Silverman 2008 article. The auroral extension and conservatively estimated storm intensity are good indicators that this geomagnetic storm was of comparable strength as the extreme storms of September 1859 and May 1921. This places the 1872 storm amongst the three largest geomagnetic storms yet observed.

Halloween Storms

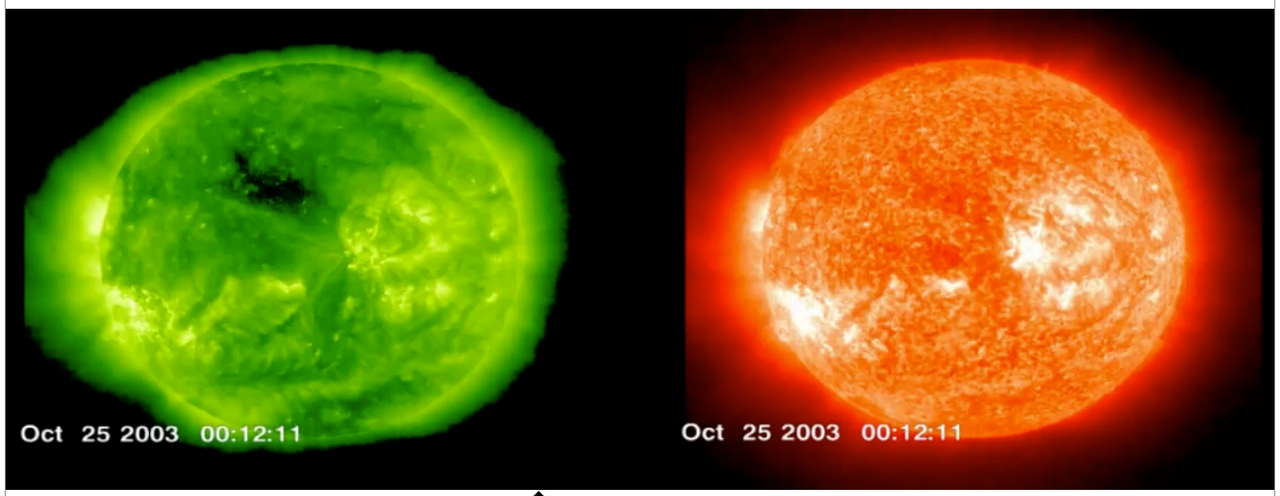


Halloween Storms – Oct/Nov 2003



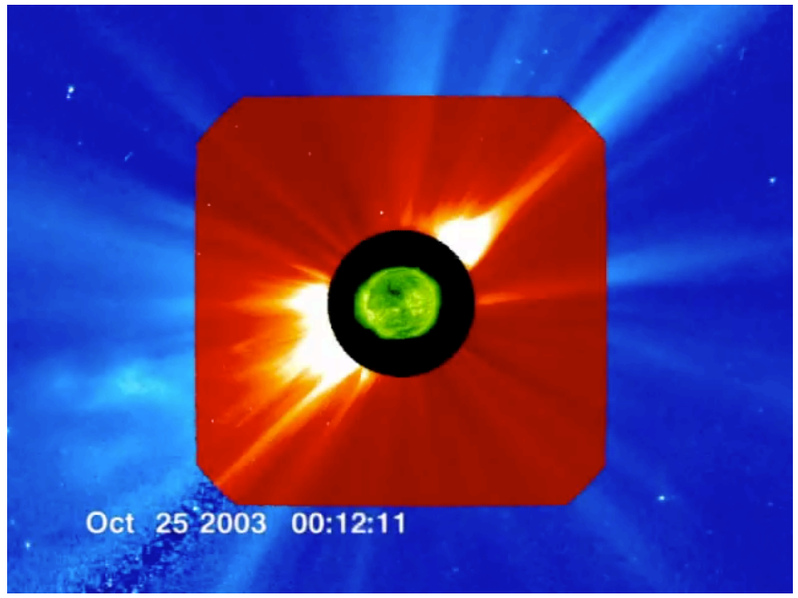
SOHO/MDI

Halloween Storms - Flares and particles



195 A SOHO/EIT 304 A

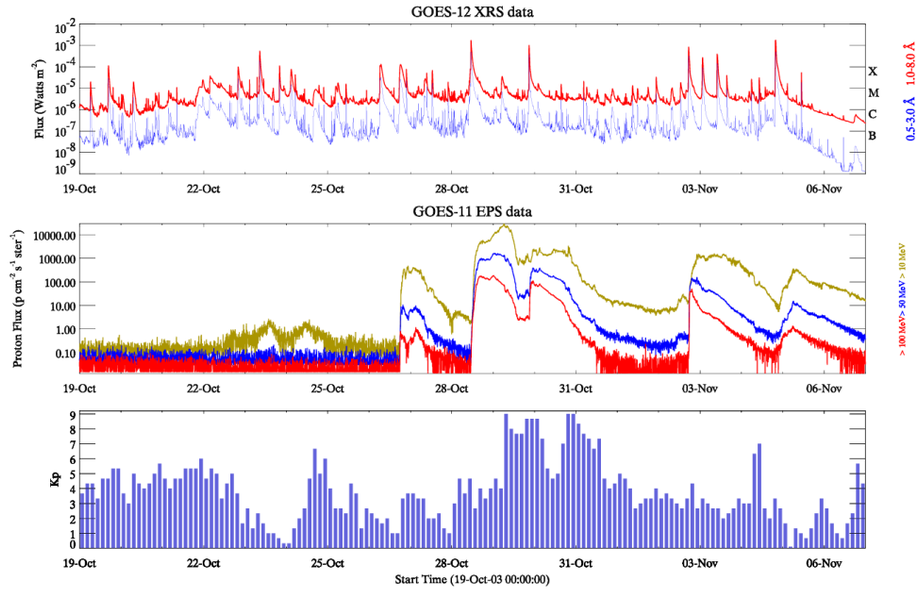
Halloween Storms - CMEs and particles



SOHO/LASCO

Very strong proton event causing noise in optical sensors, aging of satellites and instruments, single event effects, solar array efficiency decrease

Halloween Storms - Observations



X-ray

Proton Flux

Kp

Figure 1: Summary plot of GOES-12 X-ray flux, GOES-11 proton flux, and Planetary Kp index for 23 October to 7 November 2003.

[NOAA report]

In October and November of 2003, well **into the declining phase of Solar Cycle 23**, the Sun produced a significant display of solar activity, including one of the most intense solar flares ever recorded. The activity produced by the Sun during this period originated from large and complex sunspot groups. Major solar flare activity was often accompanied by fast Coronal Mass Ejections (CMEs) and strong energetic particle events. The arrival of transient solar wind from Earth directed CMEs produced extreme geomagnetic storming. Common effects of these space weather phenomena included prolonged high-frequency (HF) communication outages, fluctuations in power transmission systems, and minor to severe impacts on space satellite systems. This technical memorandum outlines the activity observed on the surface of the Sun, the resultant effects in the nearEarth space environment, and the impacts to human-made systems in orbit and on Earth.

Impacts were wide ranging. Geomagnetically induced currents (GIC) were sufficiently strong over Northern Europe to cause electrical transformer problems and even a power system failure and subsequent blackout. Radiation storm levels were high enough to prompt NASA officials to issue a **flight directive to the International Space Station (ISS) astronauts to take precautionary shelter. Airlines took unprecedented actions in their high latitude routes** to avoid the high radiation levels and communication blackout areas. **Numerous anomalies were reported by deep space missions and by satellites at all orbits.** Due to the variety and intensity of this solar activity, most industries vulnerable to space weather experienced some degree of impact to their operations.

Halloween Storms – Observations

Table 1a: Solar Activity Summary

X-ray Event and Region					Radio Emissions			Coronal Mass Ejections				NOAA Scales		
Flare Max Date Time	Xray Class	Opt Class	Reg	Location	245 MHz (SFU)	2695 MHz (SFU)	Type II (km/s)	Transit Time (hrs)	Halo Type	Plane of Sky Spd. (km/s)	Shock @ ACE			
19 Oct 1650	X1.1	1n	484	N08E58	650	510	625		P	458		R3		
22 Oct 0351	(Note 1)		484	N07E25		320		59.6	P	651	24/1450	R1		G3
22 Oct 2007	M9.9	Sf	486	S18E78	100	240			P			R2		
23 Oct 0835	X5.4	1b	486	S21E88	10000	1500	967		F	1110		R3		
23 Oct 2004	X1.1	1n	486	S17E84	2500	77						R3		
24 Oct 0254	M7.6	1n	486	S19E72	6800	73						R2		
26 Oct 0654	X1.2	3b	486	S15E44	14000	4000	1302		P	1245		R3		
26 Oct 1819	X1.2	1n	484	N02W38	1100	2000	950	31.8	F	1432	28/0130	R3	S2	G1
26 Oct 2140	M7.6	2n	484	N01W38		57						R2		
27 Oct 0927	M5.0	Sf	486	S16E26		65						R2		
27 Oct 1243	M6.7		486	S17E25	420	59						R2		
28 Oct 1110	X17.2	4b	486	S16E08	490000	13000	1250	19.0	F	2125	29/0559	R4	S4	G5
29 Oct 2049	X10.0	2b	486	S15W02	360000	2500	775	19.0	F	1948	30/1620	R4	S3	G5
02 Nov 1725	X8.3	2b	486	S14W56	24000	7700	1691	37.0	F	1826	04/0600	R3	S3	G3
03 Nov 0130	X2.7	2b	488	N10W83	100	240	1400		P			R3		
03 Nov 0955	X3.9	2f	488	N08W77	3900	4400	869		P			R3		
04 Nov 1950	X28.0	3b	486	S19W83	4800	20000	1268	47.8	F	2381	06/1915	R5	S2	G2
05 Nov 1052	M5.3	Sf	486	S16W90								R2		
Note 2								Note 3, 4			Note 2			

The X28 event shown here is the most powerful solar flare ever recorded. There is some debate that this event was actually as high as X40.

3,5 years after solar max

11 X class flares, 2 major ones
6 CMEs that arrived, storms ranging from G1 to G5 (extreme)
2 very fast full halo CMEs

Mixture of effects from flare, ICME and particles: strong ICME arriving when new flaring is going off

http://www.nuevatribuna.es/media/nuevatribuna/files/2016/10/28/2004_-noaa_halloweenstorms2003_assessment.pdf

Halloween Storms - Observations

Table 1b: Solar Activity Summary

X-ray Event			Geomagnetic Response				>10 MeV Proton Event				>100 MeV Proton Event			
Flare Max		Xray Class	SI Time	SI Ampl (nT)	Max Kp	Max Ap	Start Time	Peak Flux (PFU)	Peak Time	Dur. (hr)	Start Time	Peak Flux (PFU)	Peak Time	Dur. (hr)
19 Oct	1650	X1.1												
22 Oct	0351	M3.7	24/1529	105	7-	43								
22 Oct	2007	M9.9												
23 Oct	0835	X5.4												
23 Oct	2004	X1.1												
24 Oct	0254	M7.6												
26 Oct	0654	X1.2					26/1825	466	26/2235	24.8				
26 Oct	1819	X1.2	28/0207	10										
26 Oct	2140	M7.6												
27 Oct	0927	M5.0												
27 Oct	1243	M6.7												
28 Oct	1110	X17.5	29/0613	140	9_0	252	28/1215	29525	29/0615	94.7	28/1150	186	29/0015	61.9
29 Oct	2049	X10.0			9_0	221	29/2150	3298	29/1935	61.1	29/2150	110	29/2310	27.9
02 Nov	1725	X8.3	04/0627	72	7_0	39	02/1745	1570	03/1345	51.6	02/1740	49	02/1905	23.7
03 Nov	0130	X2.7												
03 Nov	0955	X3.9												
04 Nov	1950	X28.0	06/1937	31	6-	20	04/2225	353	05/0600	62.1	05/0535	1.3	05/0540	1.5
05 Nov	1052	M5.3												
Note 2			Note 5		Note 2, 6		Note 2, 7		Note 2, 8		Note 2			

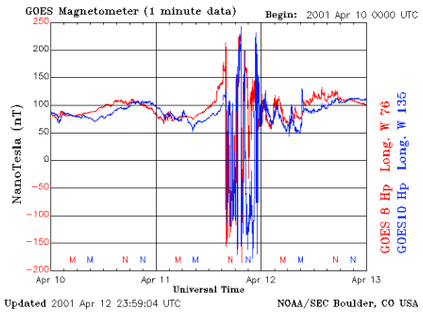
X17 event: associated proton event lasted for 4 days (more flaring occurred in those days, raising the proton level)

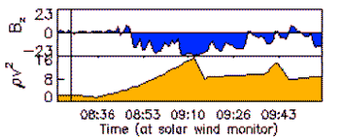
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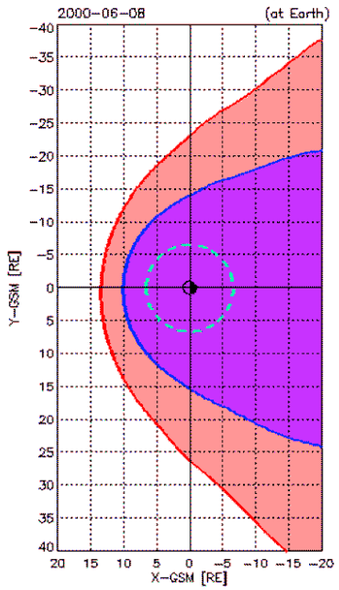
Halloween Storms - Impacts on Satellites

- Magnetopause crossings

Table 6: Magnetopause Crossing Times				
	GOES-8	**GOES-9**	**GOES-10**	**GOES-12**
24 October 2003			1832-1858	1525-1857
29 October 2003	2030-2400	0645-0650 1812-2400	1739-2327	1349-2057
30 October 2003	0000-0112 2006-2320	0000-0130 2035-2320	0004-0005 1736-2239	0033-0034 1737-2353
These estimated times (in UTC) are approximate and based on negative excursions of the Hp magnetic field component in the GOES 0.5 second sampled data. During some of these intervals, the magnetopause moved in an out over GOES many times.				







http://www.nuevatribuna.es/media/nuevatribuna/files/2016/10/28/2004_-noaa_halloweenstorms2003_assessment.pdf

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

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

Animation from ESA/Cluster: http://sci.esa.int/cluster/36447-direct-observation-of-3d-magnetic-reconnection/
Top panel: z-component of the IMF (Bz), displayed in blue, and the **dynamic pressure** (ρv2), displayed in orange, measured by the ACE spacecraft in the solar wind on 8 June 2000 (see text for details). Bottom panel: magnetopause position (blue line) and bow shock position (bright red line) estimated from the solar wind data as displayed in the top panel. Pink area between these two borders depicts the magnetosheath, while the purple area symbolises the magnetosphere. The dashed green circle, located at 6.6 RE, depicts where many communication and weather satellites orbit the Earth.(Acknowledgments: S.M. Petrinec, Lockheed Martin)

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

Halloween Storms - Impacts on Satellites

- Magnetopause crossings
- Sensor noise
- Star tracker issues
- Safe mode/shutdown/suspended operations
- Loss of ADEOS-2 (JAXA) after one year in orbit
- Loss of instruments (e.g. Marie on Mars Odyssey)
- …

http://www.nuevatribuna.es/media/nuevatribuna/files/2016/10/28/2004_-noaa_halloweenstorms2003_assessment.pdf

GOES magnetopause crossings

Spacecraft entered safe mode during the severe radiation storm. During downloading on 29 October, the spacecraft had a memory error that was corrected with a cold reboot on 31 October. The MARIE instrument on the Mars Odyssey had a temperature red alarm which required it to be powered off on 28 October. Recovery is not expected.

Japan Aerospace Exploration Agency (JAXA) lost contact with the ADEOS-2 satellite, following an intense CME, which impacted Earth's magnetic field on 24 October. ADEOS-2 is an environmental observation satellite, launched in December 2002 by the Japanese Space Agency. It was designed to collect data on global warming and other climate-change phenomena. The spacecraft was developed at a cost of 70 billion yen ($640 million), and it had an expected lifespan of three years. Recovery is not expected.

Halloween Storms - Impacts

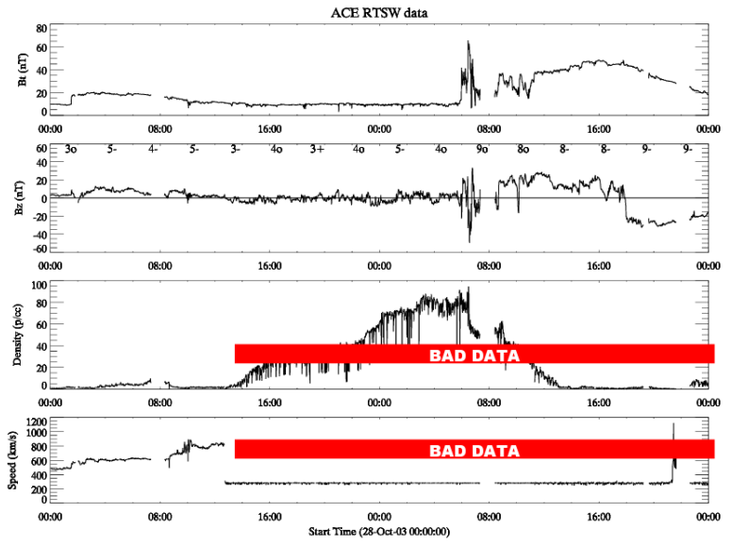


Figure 15: ACE RSTW and Magnetic Field Data for 28-29 October 2003 (speed and density data are invalid after 1200 UTC on 24 October due to contamination from high fluxes of high energy particles)

unavailable from 1220 UTC on 28 October until 0100 UTC on 31 October due to contamination from high fluxes of energetic particles from the proton event

At 1100 UTC on 28 October, an X17 flare erupted on the Sun, with an associated full-halo CME. The ACE EPAM particle flux increased steadily several hours before the shock arrival with a notably sharp increase at the time of the shock. The shock from this CME was observed at ACE at 0559 UTC on 29 October (see Figure 15). A sudden impulse at Earth was observed at 0613 UTC, and was followed by periods of extreme geomagnetic activity (Kp=90). The total interplanetary magnetic field increased dramatically at the time of shock arrival, with the southward Bz peaking at –50 nT. By 1800 UTC, after an extended interval of northward orientation, Bz rotated southward to near –30 nT for a period of several hours. ACE solar **wind plasma measurements from the ACE/SWEPAM were unavailable** from 1220 UTC on 28 October until 0100 UTC on 31 October, **due to contamination from high fluxes of energetic particles from the proton event** associated with the X17 flare. During the outage, a different non-real-time data mode on the SWEPAM sensor was used to approximate the maximum solar wind speed at approximately 2,000 km/s (see Section 3.b. below).

Halloween Storms - Aviation

- Communication: degraded HF service (including blackouts) led to rerouting of polar flights
- Navigation: Wide-Area Augmentations System (WAAS) was seriously impacted
- GNSS: companies delayed high resolution land surveying, postponed airborne and marine survey operations, cancelled drilling operations,…



The polar routes used by commercial airlines are impacted significantly by solar activity. Airlines on polar routes must contend with degraded communications; potential biological impacts from radiation storms; impacts to navigational systems (generally a lesser concern); and as avionics evolve, a potential impact to electronic systems. The October-November solar storms created a significant disruption to airline operations. Some polar flights were **diverted, requiring additional stop-offs and resulting in additional fuel, flight time, and also costly crew exchanges.**

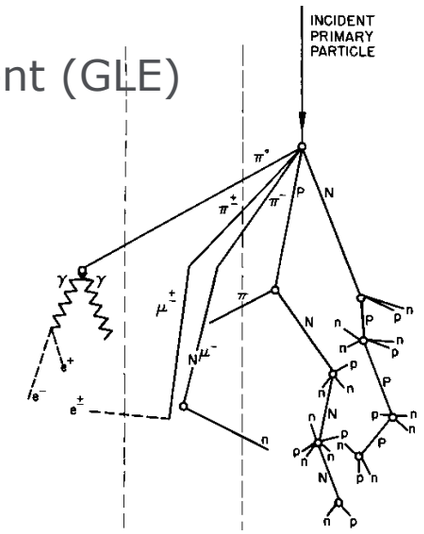
Radiation storm levels were high enough to prompt NASA officials to issue a flight directive to the International Space Station (ISS) astronauts to take precautionary shelter.

Sudden increase in EUV and X-ray radiation leads to higher ionisation in D-region of the ionosphere -> Short wave radio waves (in the HF range) are absorbed by the increased particles in the low altitude ionosphere causing a complete blackout of radio communications. This is called a short-wave fading.

The Wide Area Augmentation System (WAAS) is a satellite-based navigation aid developed by the U.S. Federal Aviation Administration (FAA) to improve the accuracy, integrity, and availability of the Global Positioning System (GPS)

Halloween Storms - Impacts

- Radiation: flights on the U.S. to Europe routes flew at lower altitudes during the severe radiation storm
- Ground Level Enhancement (GLE)



GLE: **Sharp increase in number of neutrons at ground**
Result of a particle shower, measured with neutron monitors
Tens of minutes to hours
Glitches: computers, pacemakers, medical devices
Radiation: astronauts, aircraft crew and passengers

Particles with even greater energies (>500 MeV) are recorded on the ground by a cosmic-ray detector; these events are called Ground Level Enhancement (GLE) (Davies, 1990).
Result of a particle shower, measured with neutron monitors
Glitches: errors increase with altitude, More errors during SC min than SC max
Protection for astronauts: No EVA, Sheltering inside ISS
Protection in aviation: Lower altitudes and Rerouting via lower latitudes, but both increase the cost for the airlines

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Power companies in North America experienced some problems during the October-November high solar activity. Impacts and actions reported by grid operators included less use and switching between systems, high levels of neutral current observed at stations throughout the country, a capacitor trip in the northwest (known to be GIC susceptible), and transformer heating in the Eastern U.S. Precautions were implemented. For example, a 'growling' transformer was backed down to help cool it. GIC impacts were more significant in Northern Europe where **heating in a nuclear plant transformer** was reported and a power system failure occurred on 30 October in Malmo, Sweden resulting in blackout conditions for about one hour.

GPS operations are affected by changes in total electron content (TEC) of the ionosphere along the path to the satellite during large flares and geomagnetic storms. Significant storms can cause large increases and decreases in TEC, which impact the accuracy of single-frequency GPS. Dualfrequency GPS receivers can better adjust to a disturbed ionosphere, but still experience some degraded signals and position errors. Many GPS users will experience little or no impact during TEC disturbances, but those requiring precise GPS measurements have a great need for SEC alerts and warnings. Those with the greatest concerns include surveying companies using GPS measurements for land surveying, topographic work, and property boundary analysis, deep-sea drilling operations, land drilling and mining, and various DoD operations. Operators relying on GPS can and will take important actions during geomagnetic storms. During the October-November activity, companies delayed high resolution land surveying, postponed airborne and marine survey operations, cancelled drilling operations, and some, as was the case with the C.R. Luigs deep water drill ship, resorted to backup systems to ensure continuity of operations.

The Aurora Borealis and Aurora Australis (northern and southern lights) are the visible manifestation of geomagnetic disturbances. With the advent of the Internet and other advances in communications, entrepreneurs are seizing commercial opportunities to provide aurora alerts, image galleries and photo sales, and even aurora viewing tours. The public's interest in aurora viewing generated numerous contacts from media and the general public. Though it is not a part of SEC's product line, SEC staff assisted with numerous inquiries about aurora viewing. The extreme and prolonged geomagnetic storms on 29 and 30 October ensured widespread middle and even low latitude aurora. Aurora sightings occurred from California to Houston to Florida. Tremendous aurora viewing was also reported from mid-Europe and even as far south as the Mediterranean countries.

Halloween Storms - Impacts

- GIC: power system failure occurred on 30 October in Malmö, Sweden resulting in blackout conditions for about one hour

- Aurora



http://www.nuevatribuna.es/media/nuevatribuna/files/2016/10/28/2004_-noaa_halloweenstorms2003_assessment.pdf

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Halloween Storms - What would the effects be today?



"No story tonight; the wi-fi's out. Good night, sweetie."

Halloween storms were 20 years ago. We are now far more dependent on technology
Need for awareness, forecasts and sector specific bulletins

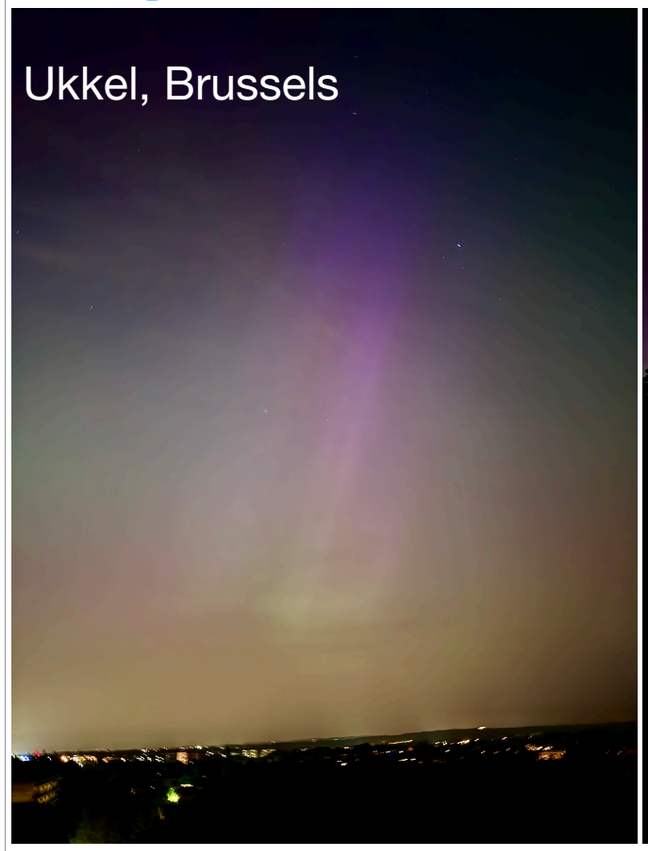
Now we move on to some, maybe unexpected, effects

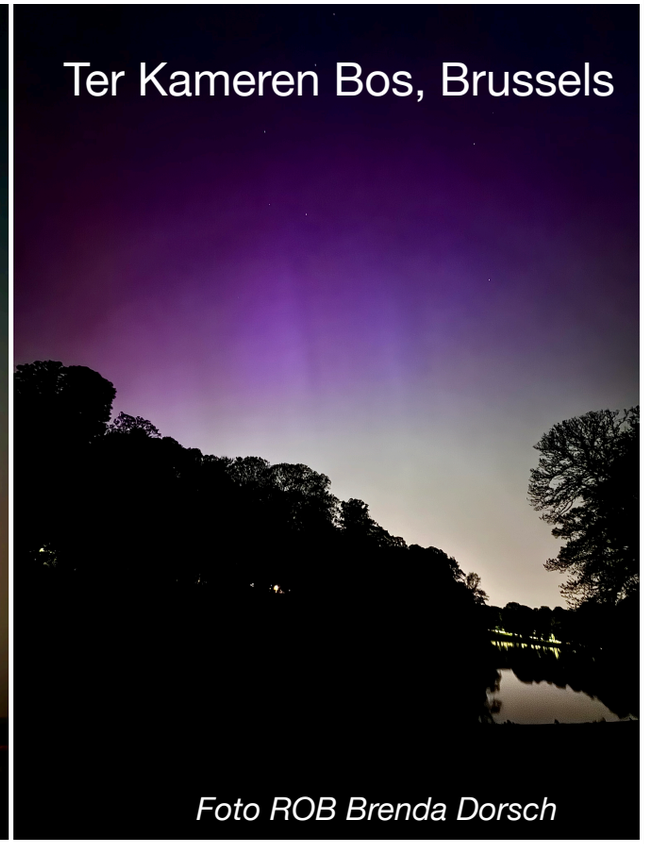
May 2024



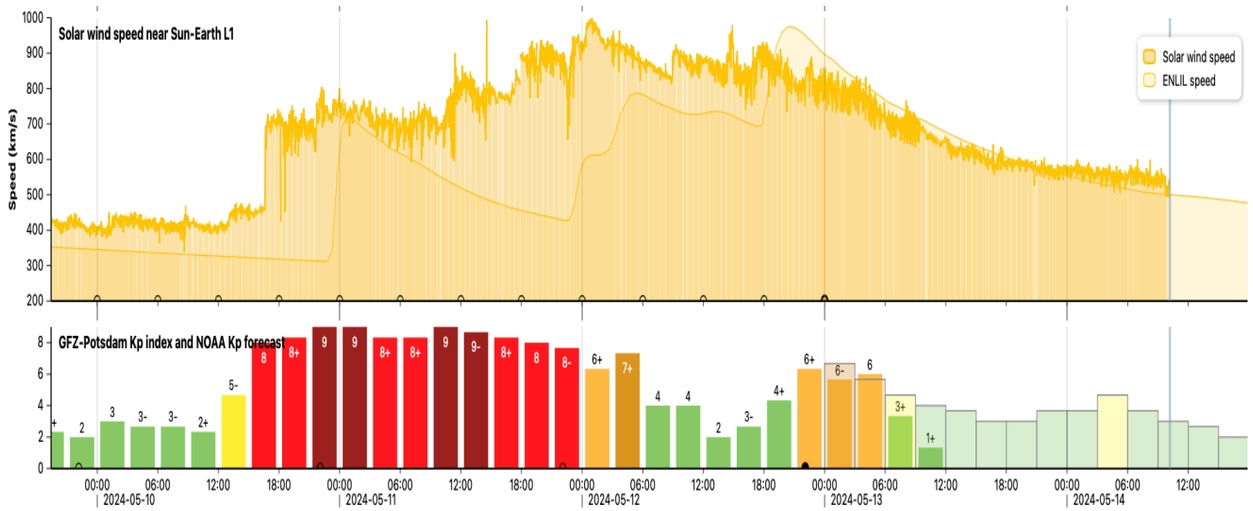
By StormChaserAmelia - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=148271060
Aurora at zenith, Onawa, Iowa, U.S. (42°N GLAT, 51°N MLAT)

May 2024 - Aurora



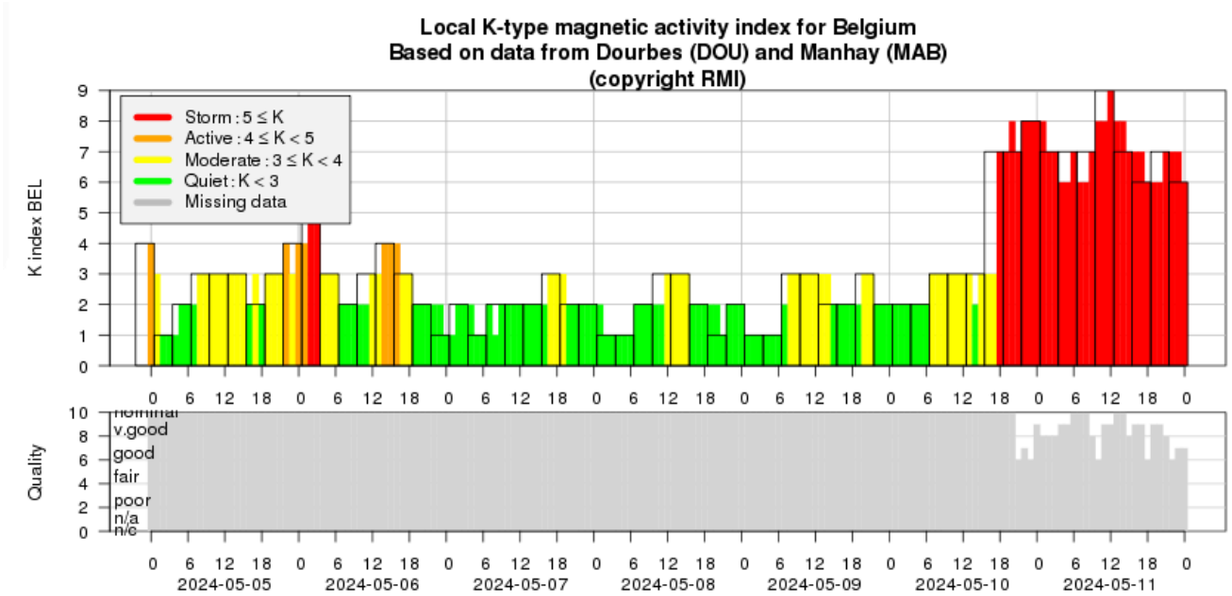


May 2024 - Observations

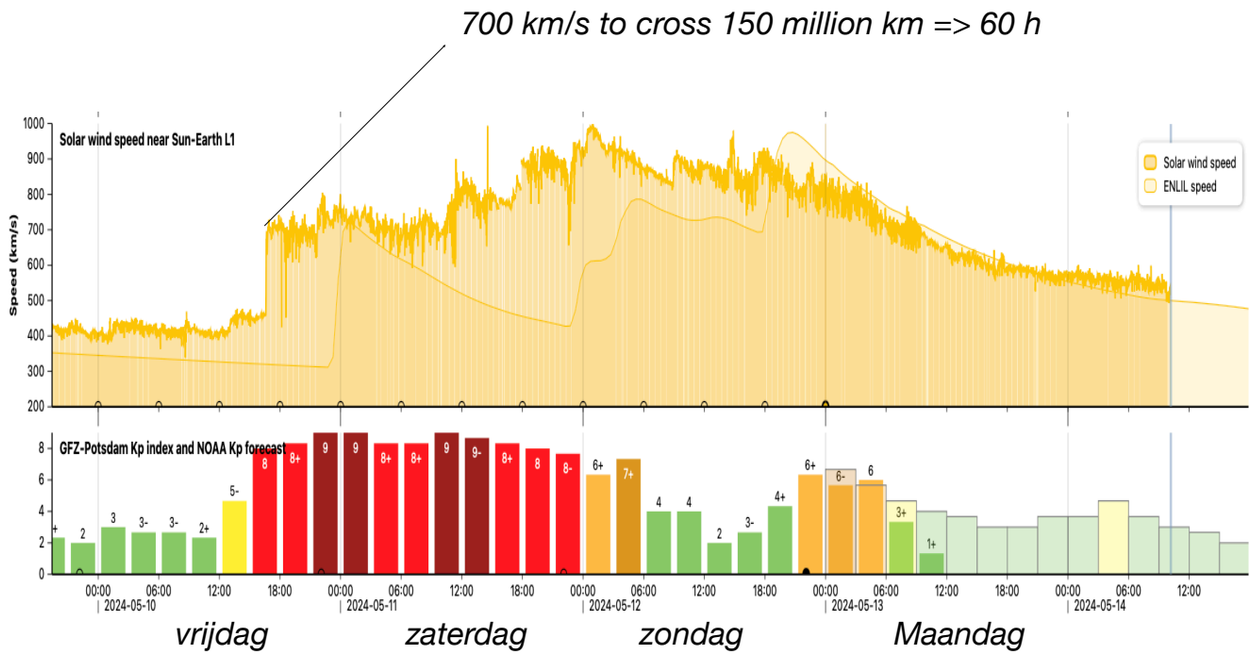


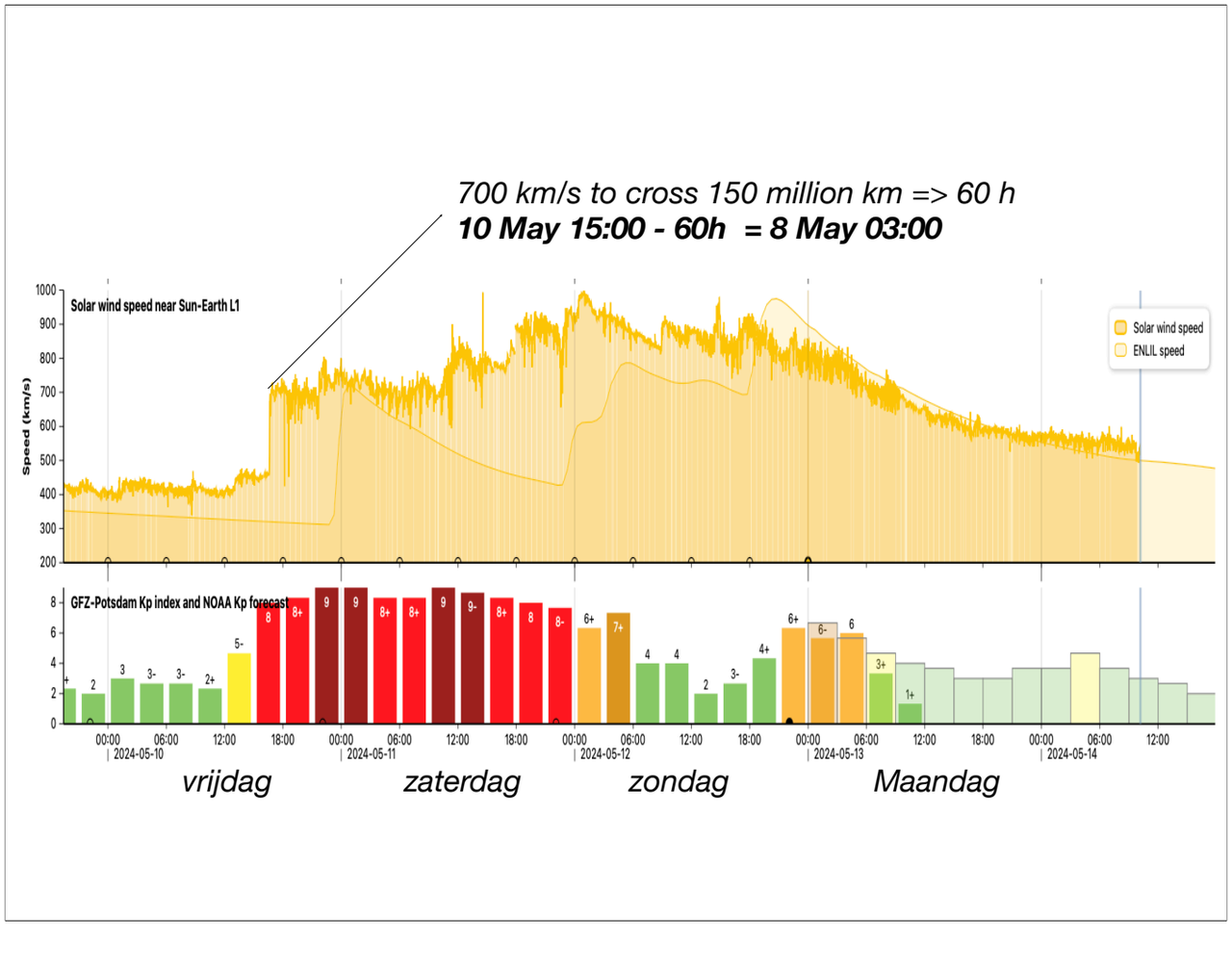
http://spaceweather.knmi.nl/viewer

May 2024 - Observations

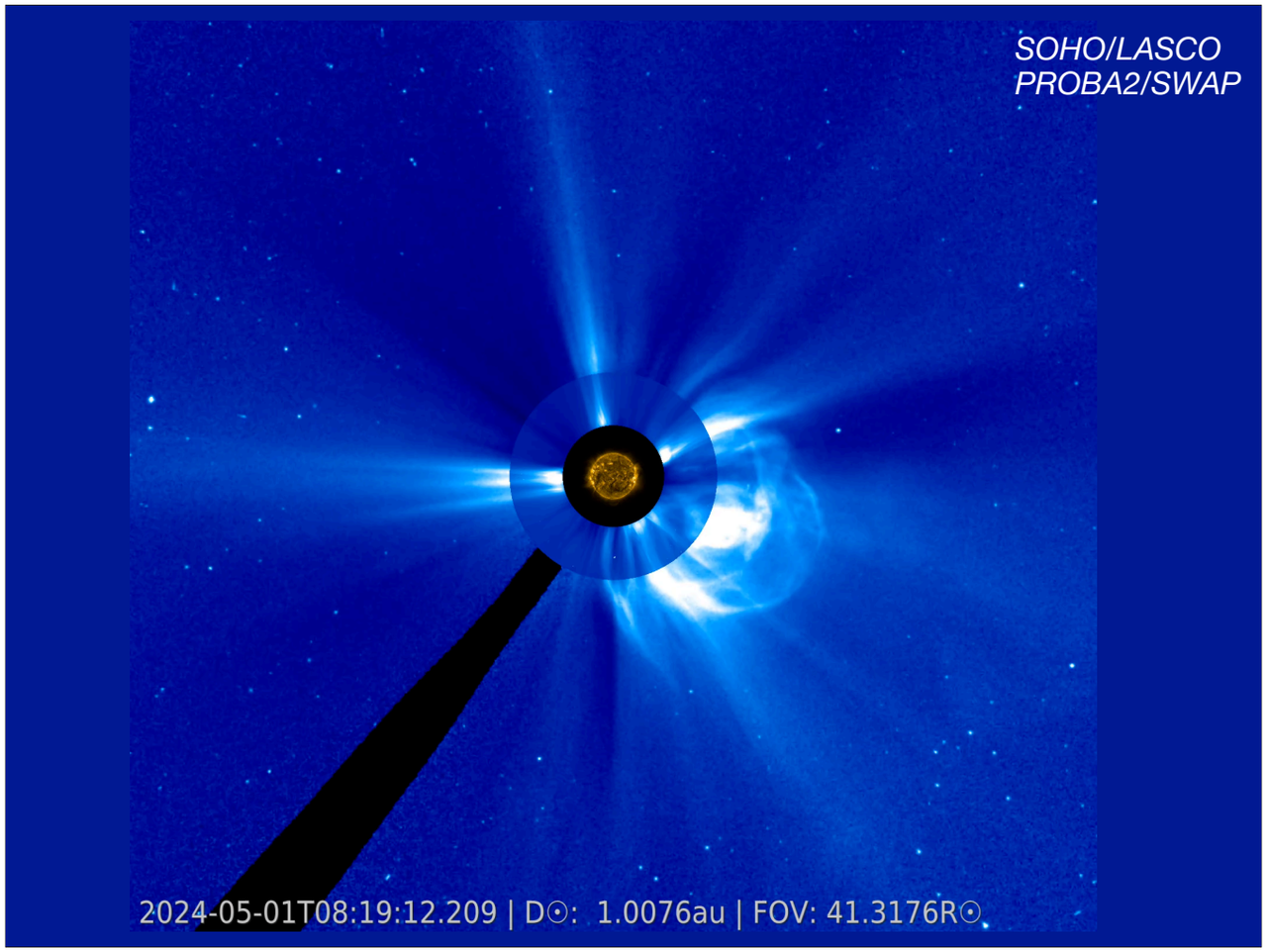


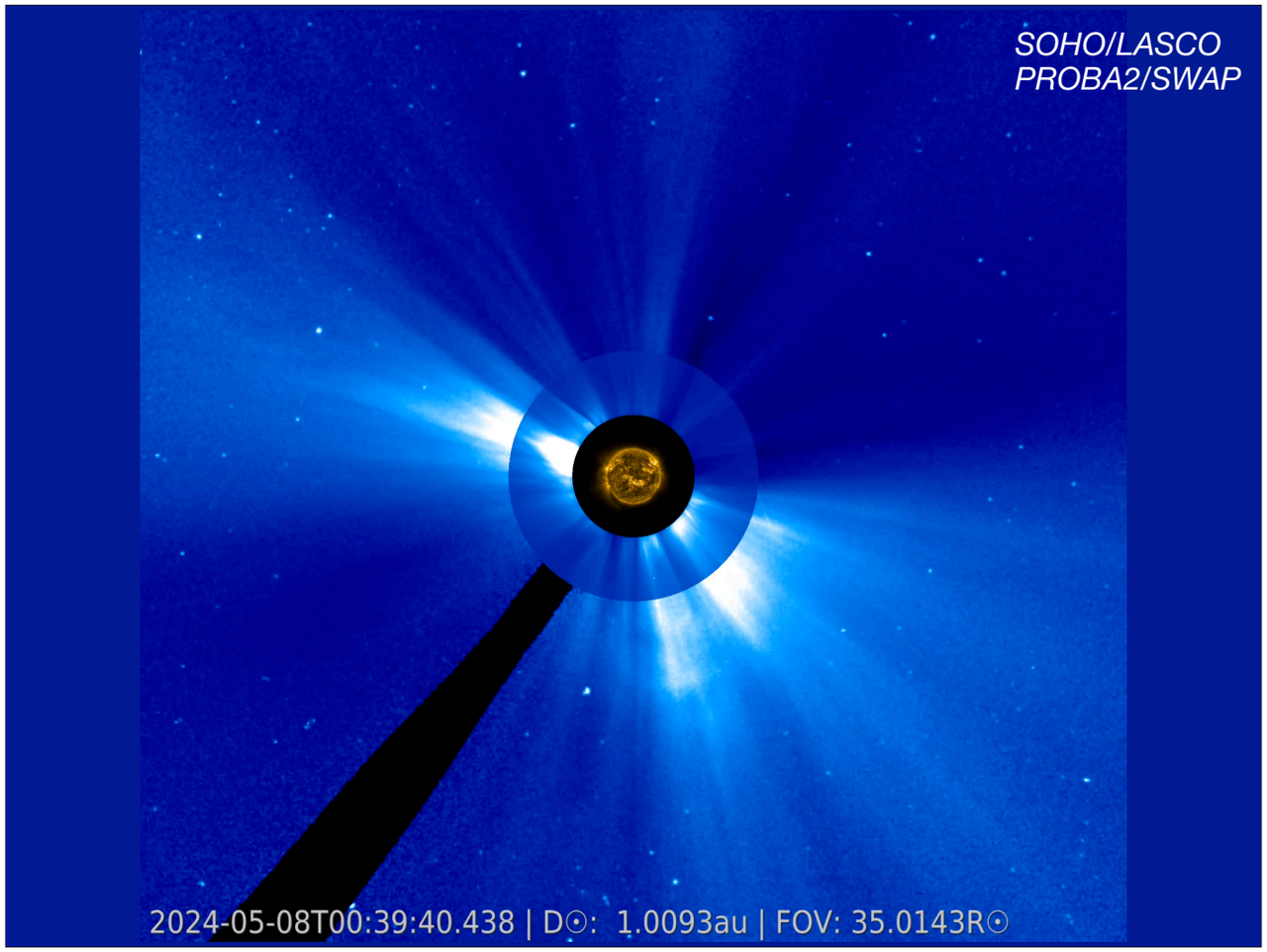
May 2024 - Observations

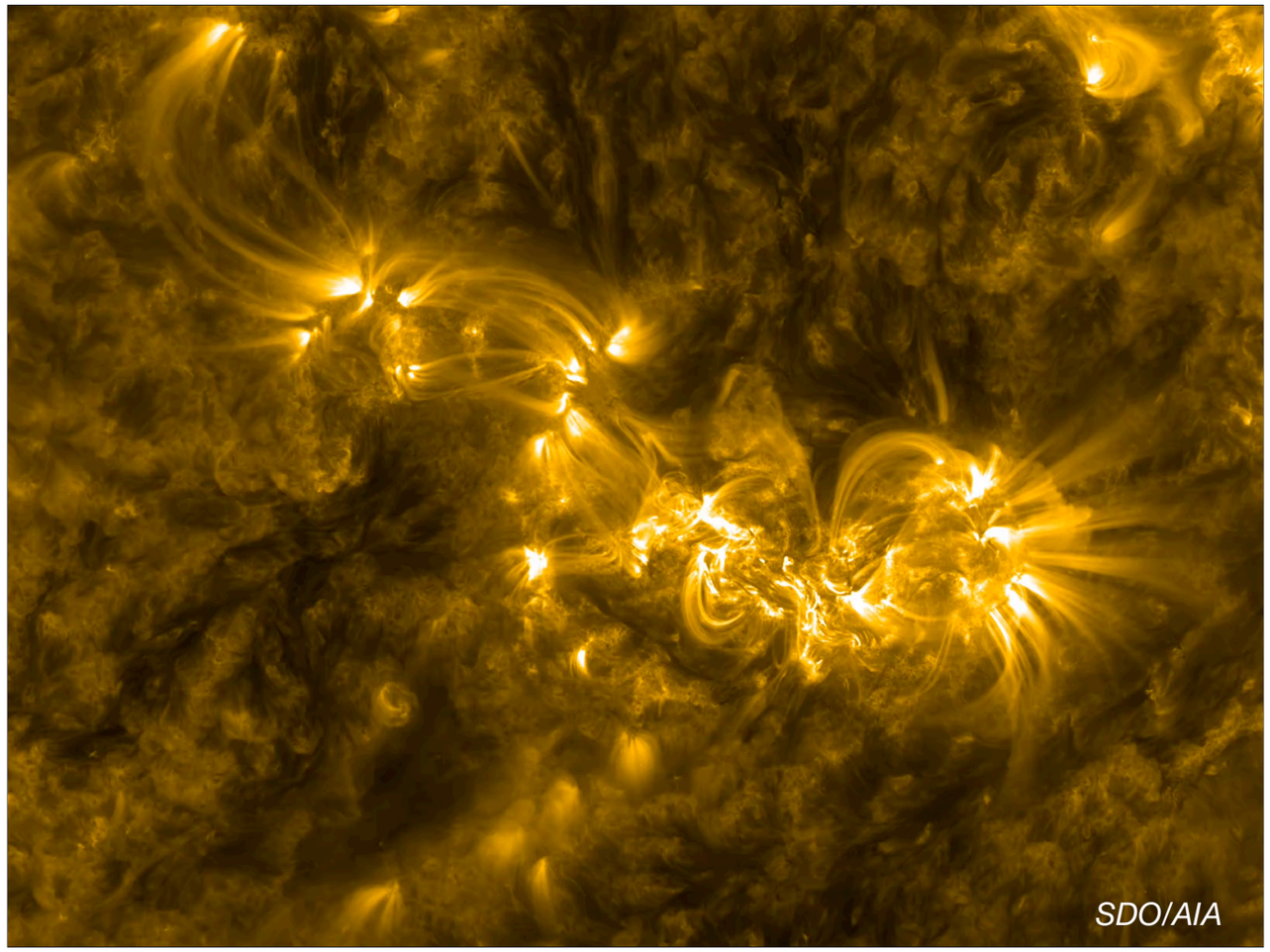




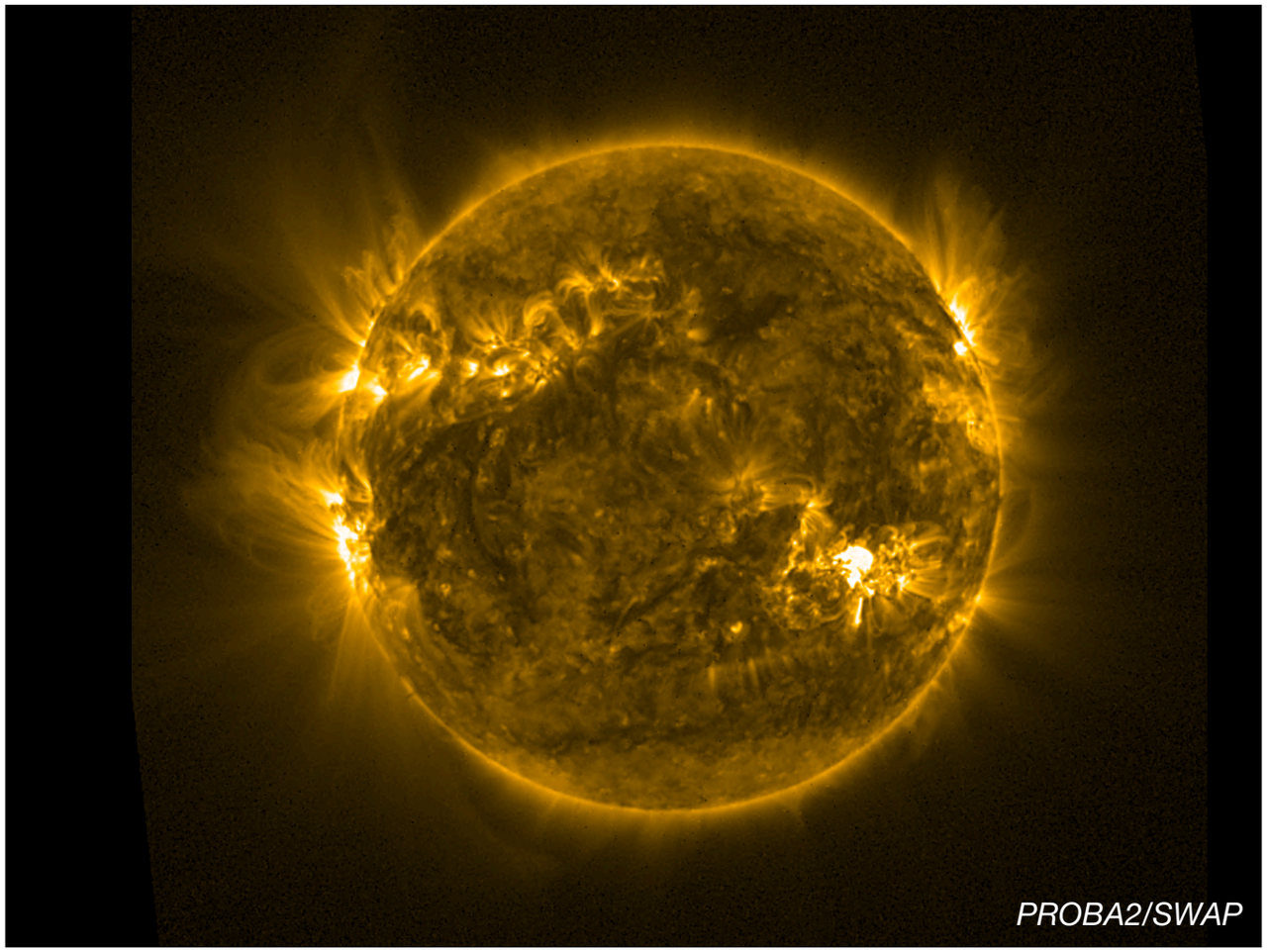
Mother Day’s storm


SOHO/LASCO
PROBA2/SWAP
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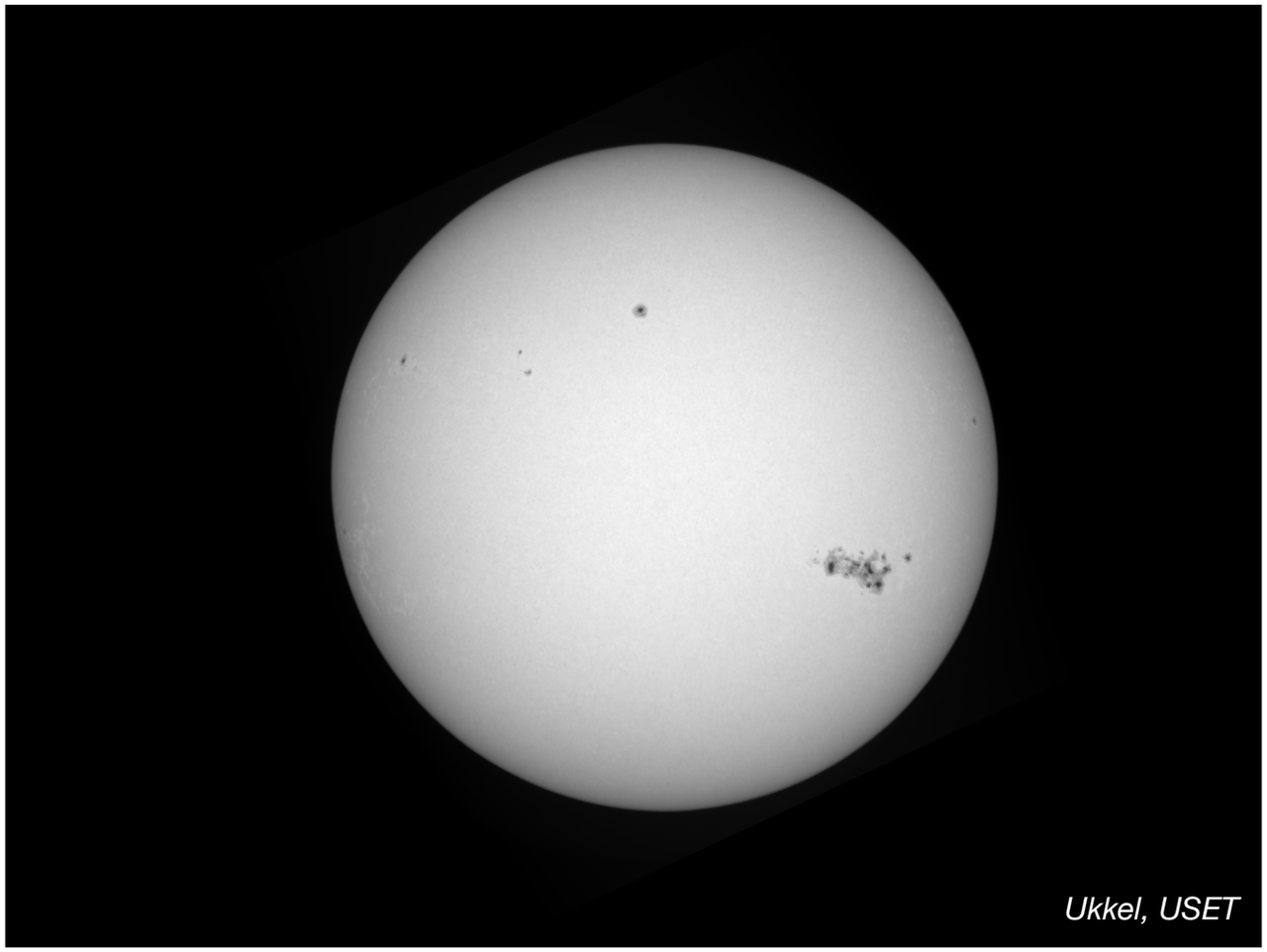

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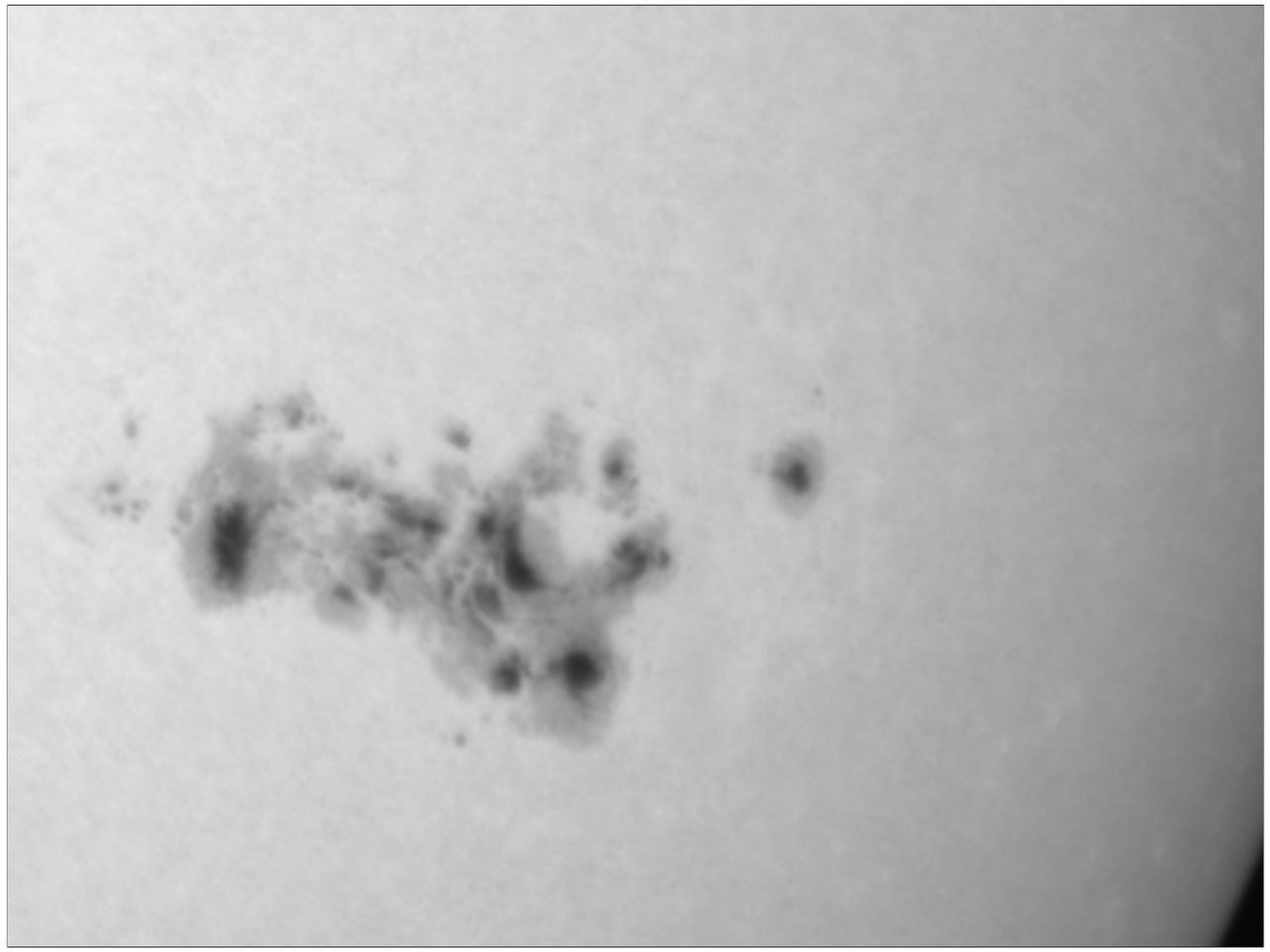


X1 flare and several M flares



X1 flare and several M flares


Ukkel, USET



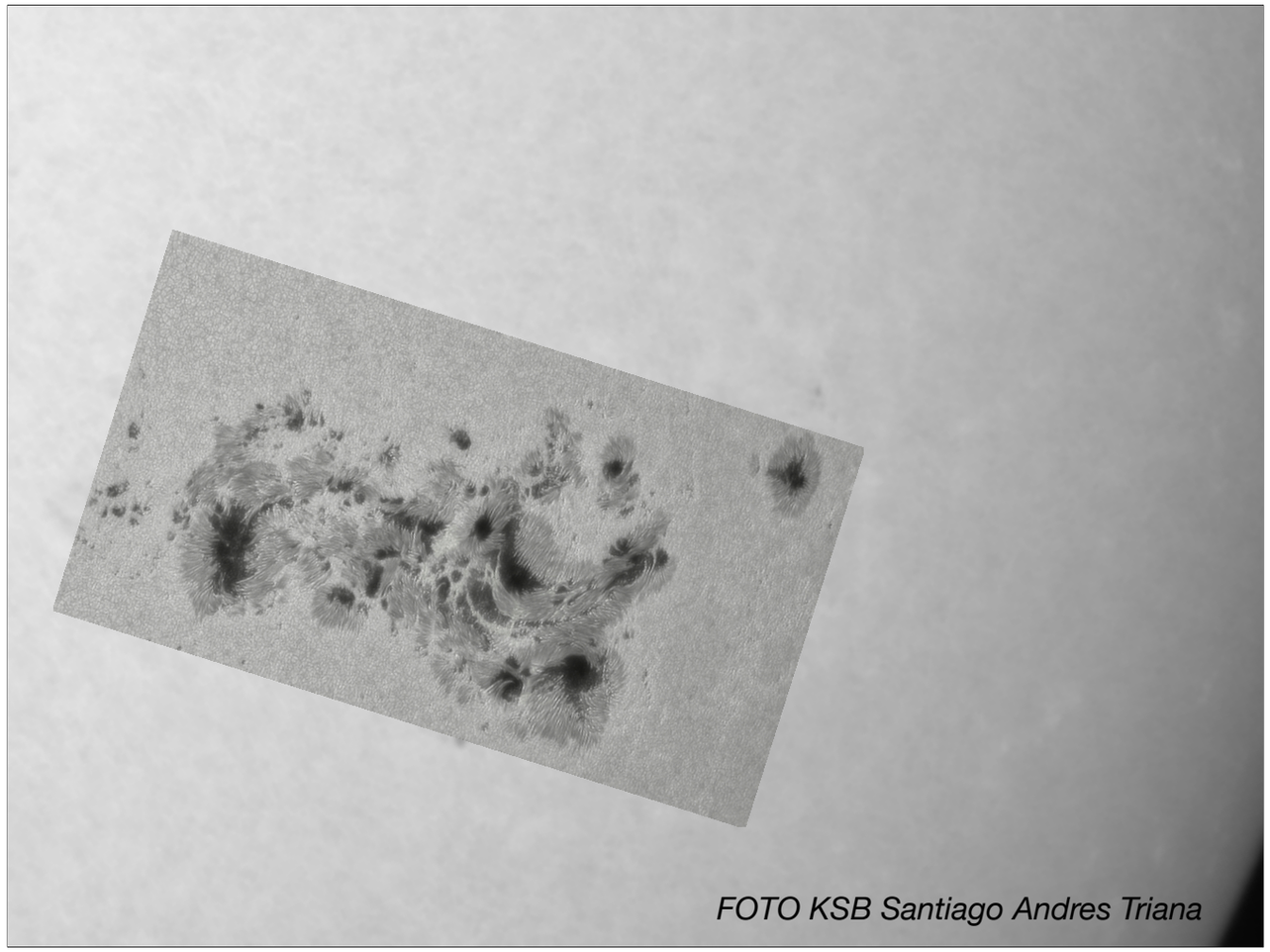
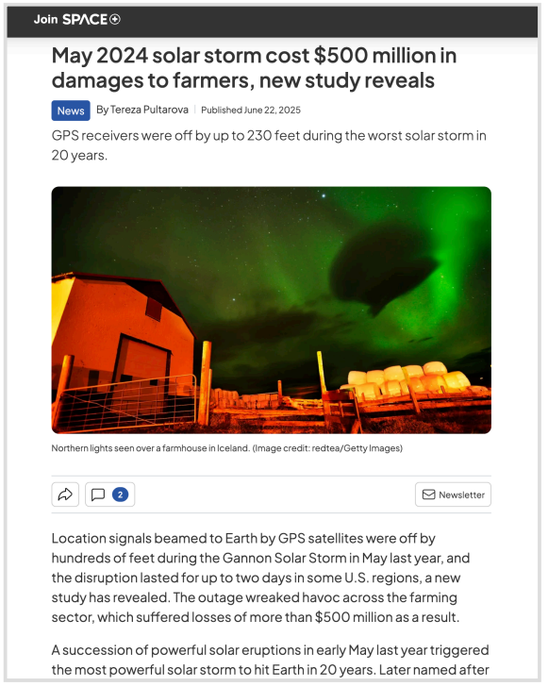


FOTO KSB Santiago Andres Triana

May 2024 - Agriculture



Join SPACE

May 2024 solar storm cost $500 million in damages to farmers, new study reveals

News By Tereza Pultarova | Published June 22, 2025

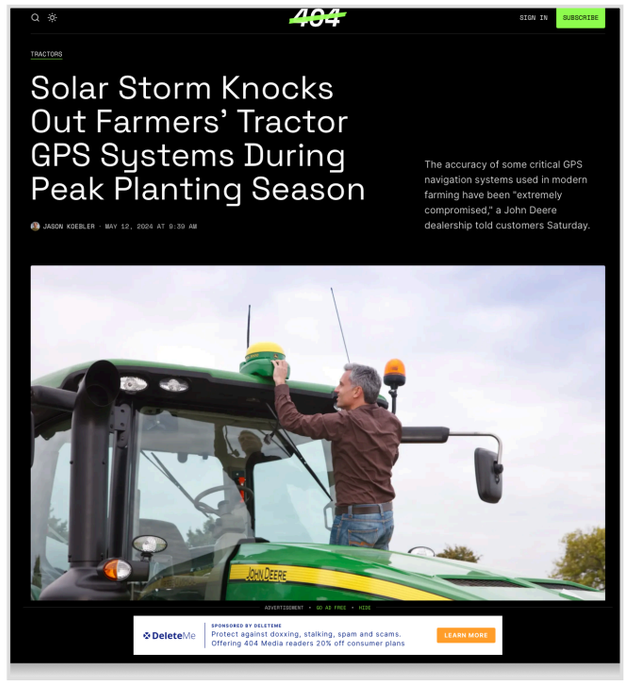
GPS receivers were off by up to 230 feet during the worst solar storm in 20 years.

Northern lights seen over a farmhouse in Iceland. (Image credit: redtea/Getty Images)

2 Newsletter

Location signals beamed to Earth by GPS satellites were off by hundreds of feet during the Gannon Solar Storm in May last year, and the disruption lasted for up to two days in some U.S. regions, a new study has revealed. The outage wreaked havoc across the farming sector, which suffered losses of more than $500 million as a result.

A succession of powerful solar eruptions in early May last year triggered the most powerful solar storm to hit Earth in 20 years. Later named after



404 Media

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TRACTORS

Solar Storm Knocks Out Farmers' Tractor GPS Systems During Peak Planting Season

The accuracy of some critical GPS navigation systems used in modern farming have been "extremely compromised," a John Deere dealership told customers Saturday.

JASON KOEBLER · MAY 12, 2024 AT 9:39 AM

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Farmers use GPS on their tractors, sprayers and harvesters to ensure they evenly distribute seeds, pesticides and fertilizer without overlap. Some vehicles even drive themselves, following the lines the GPS mapped out.

May 2024 Solar Storms
X1.2(X1.3)-class flares[100] and X4.5-class flare. The flares with a magnitude of 6–7 occurred between 30 April and 4 May 2024. On 5 May the strength of the solar storm reached 5 points, which is considered strong according to the K-index. The rapidly growing sunspot AR3663 became the most active spot of the solar cycle 25. On 5 May alone, it emitted two X-class (strongest) flares and six M-class (medium) flares. Each of these flares resulted in a short-term but profound disconnection of the Earth's radio signal, resulting in signal loss at frequencies below 30 megahertz (MHz).
An extreme (G5) geomagnetic storm alert was issued by the National Oceanic and Atmospheric Administration (NOAA) – the first in almost 20 years. The final storms reaching the highest level of NOAA's G-scale before solar cycle 25 occurred in 2005 in May, August, and September, respectively.

With a NOAA rating of G5, an estimated peak Dst of −412 nT, and aurorae seen at far lower latitudes than usual in both hemispheres, this geomagnetic storm was the most powerful to affect Earth since November 2003. A later study estimates a Dst peak of −518 nT, meaning the strongest storm since 1989 and the second strongest since 1921.

Global Positioning System (GPS) accuracy degraded significantly during the storm. GPS relies on precise timing signals from satellites to determine location, but geomagnetic storms can introduce delays and distortions in these signals as they pass through the disturbed ionosphere. During the peak of the May 2024 storm, GPS errors increased to 20 meters or more in some regions, affecting precision agriculture, surveying, and navigation systems

GPS-dependent sectors experienced widespread but difficult-to-quantify impacts. Precision agriculture, which relies on centimeter-level GPS accuracy for automated equipment, saw reduced efficiency during critical planting and harvesting operations. The construction and surveying industries reported project delays and increased costs due to temporary GPS accuracy degradation.

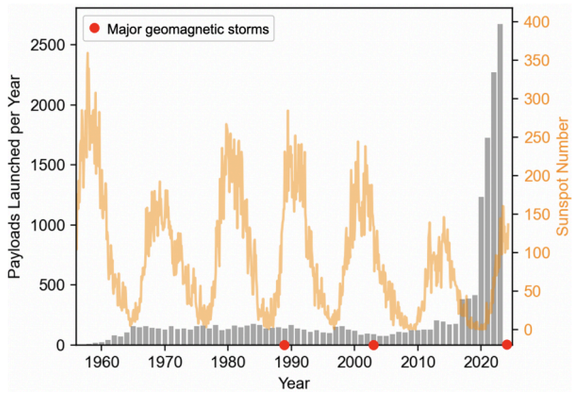
https://www.researchgate.net/publication/394717902_The_Extreme_Solar_Storms_of_May_2024_A_Comprehensive_Analysis_of_Causes_Effects_and_Historical_Context

https://www.space.com/astronomy/sun/may-2024-solar-storm-cost-usd500-million-in-damages-to-farmers-new-study-reveals

May 2024 - Impacts on satellites



February 2022



The 3 February 2022 launch of 49 of SpaceX's Starlink satellites has provided a fascinating example of how even modest space weather can have significant practical and financial consequences. This was the 36th in a series of launches that started in May 2019, but was the first to experience significantly enhanced atmospheric drag due to geomagnetic activity. That drag quickly led to the loss of many of the 49 satellites, with only 11 satellites surviving at the time of writing, as shown by the Space-Track satellite catalog (https://www.space-track.org/). The value of the 38 lost satellites, and of the largely wasted launch, is thought to be several tens of millions of dollars.

The launch took place at 18:13 UTC, on the trailing edge of one modest geomagnetic storm that reached G1 intensity earlier that day, and a few hours before another storm that reached G1 later the next day. Following its usual procedures, SpaceX launched its satellites into an initial orbit around 210 km altitude, from where they were due to use electric thrusters to raise their altitudes to an operational level around 500 km. SpaceX notes that it uses this low initial orbit altitude so that any satellites that fail initial post-launch checkout will quickly be deorbited by atmospheric drag. This is a good strategy for reducing the accumulation of space debris, a major concern for the long-term sustainability of space activities. However, it is also a strategy that is vulnerable to space-weather-driven changes in atmospheric drag—as happened on this occasion.

A subsequent Starlink launch on 21 February used a higher initial orbit at 300 km, reducing the payload from 49 to 46 satellites, and can be considered an agile response to the space weather losses experienced 2 weeks earlier.

https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2022SW003074

May 2024 - Impacts on satellites

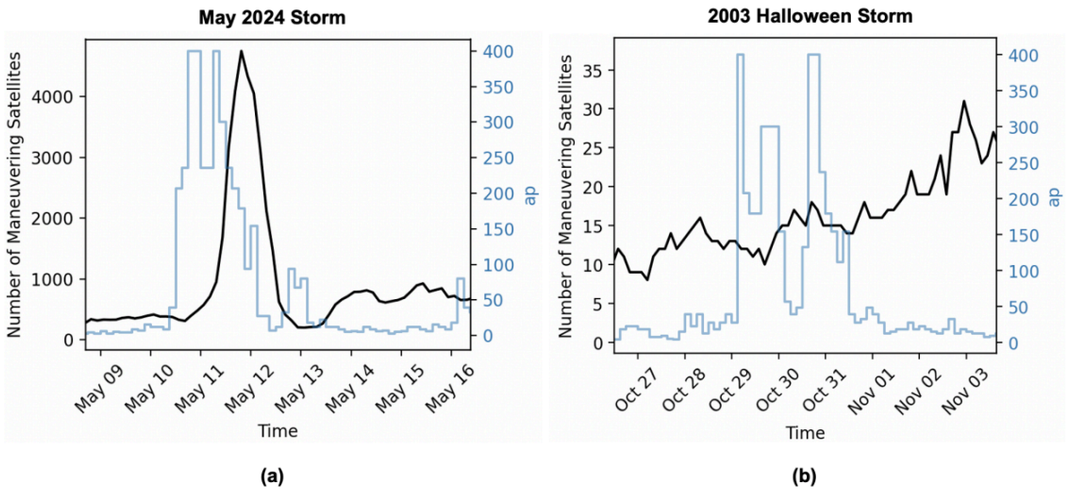


Fig. 6 (a) Satellites in LEO (mostly SpaceX) maneuver *en masse* in response to the sudden loss in altitude during the May 2024 Gannon storm. (b) During the 2003 Halloween storm, there was no comparable change in satellite maneuver activity (note the difference in scaling).

At 00:19 UTC on 13 May, the GOES-16 satellite, the primary operational geostationary weather satellite in the GOES East position, providing a view centered on the Americas, stopped transmitting all data. The transmission of data resumed nearly 2 hours later at 02:00 UTC.[88] There was a second loss of data transmission shortly after, lasting 11 minutes from 03:19 UTC to 03:30 UTC.[89]

Other impacts to satellite services include Starlink's fleet of low-orbiting satellites, which experienced degraded service because of the intensity of the solar storms, but remained operational. The extreme geomagnetic storm accelerated the re-entry of a Starlink satellite by approximately 11 days with respect to a reference altitude. About half of the ~10,000 LEO payloads—mostly Starlink satellites—performed a coordinated large-scale maneuver during the May 2024 event, the largest satellite migration on record.

The storm caused electrical problems for ESA's Gaia spacecraft.

Figure from https://arxiv.org/pdf/2406.08617

For the May 2023 storm, about 300 of the nearly 10,000 active payloads in LEO appear to be maneuvering during the quiet period leading up to the storm. After the storm hits, with some offset to account for the time it takes for drag decay to accumulate, thousands of satellites begin to maneuver en masse in response to the sudden increase in atmospheric density. For comparison, maneuver activity in LEO was not comparably impacted during the October 2003 Halloween storm. Most of the May 2024 maneuver activity is attributable to the **Starlink constellation**, which performs **autonomous orbit maintenance and thus responds quickly to perturbing events**.