National Aeronautics and Space Administration

The Heliophysics Big Year

Dr. Sten Odenwald, Astronomer

NASA Heliophysics Education Activation Team

NASA's Big Questions

1. **What causes the Sun to vary?**
2. **How do the Earth and the heliosphere respond?**
3. **What are the impacts on humanity?**

These Big Questions form the basis for the

Framework for Heliophysics Education

https://science.nasa.gov/learn/heat/big-ideas/

The Framework for Heliophysics Education

What are the impacts of the Sun on humanity?

1.1 The Sun is really big and its gravity influences all objects in the solar system. (PS2, ESS1)

1.2 The Sun is active and can impact technology on Earth via space weather. (PS1, PS2, PS4, ESS2, ESS3)

1.3 The Sun's energy drives Earth's climate, but the climate is in a delicate balance and is changing due to human activity. (PS1, PS2, PS3, LS4, ESS2, ESS3)

How do the Earth, the solar system, and heliosphere respond to changes on the Sun?

2.1 Life on Earth has evolved with complex diversity because of our location near the Sun. It is just right! (PS3, PS4, LS1, LS2, ESS2)

2.2 The Sun defines the space around it, which is different from interstellar space. (PS2, ESS1, ESS2)

2.3 The Sun is the primary source of light in our solar system.(PS1, PS2, PS3,PS4, ESS1)

What Causes the Sun to Vary?

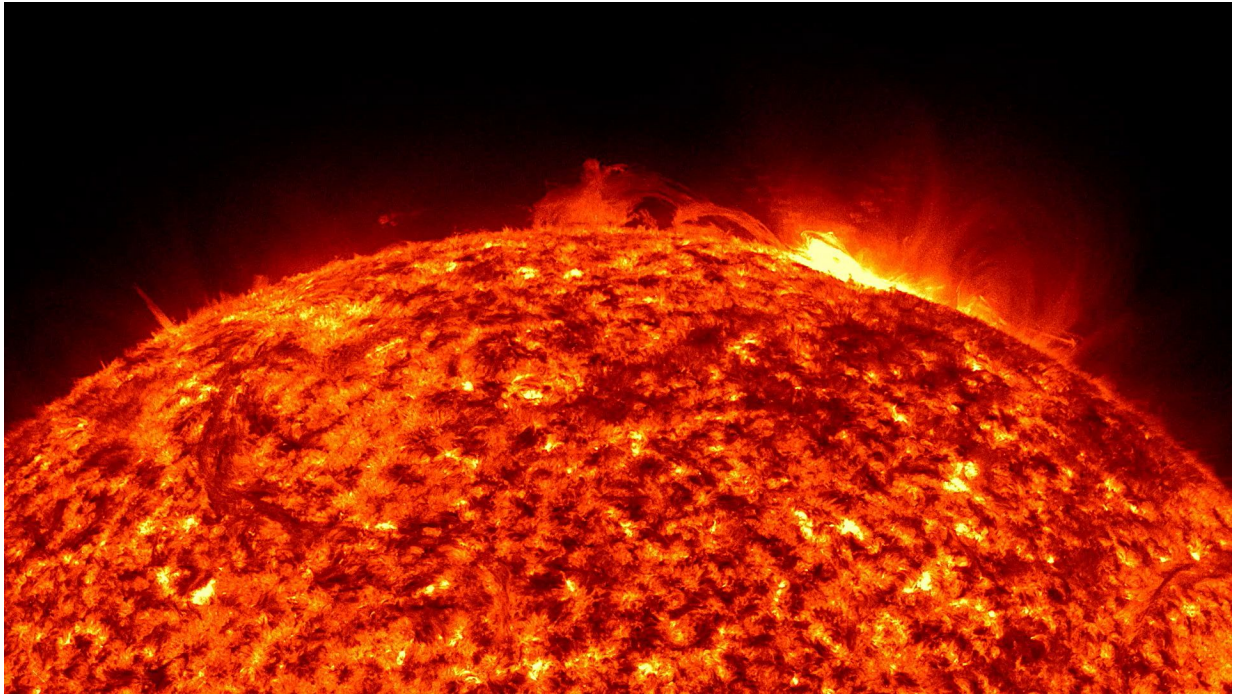
3.1 The Sun is made of churning plasma, causing the surface to be made of complex, tangled magnetic fields. (PS1, PS2, ESS1, ESS2)

3.2 Energy from the Sun is created in the core and travels outward through the Sun and into the heliosphere. (PS1, PS3, PS4, ESS1, ESS2, ESS3)

3.3 Our Sun, like all stars, has a life cycle. (PS1, LS1, ESS1)

Is there a solar superflare in our future?

Ordinary flares are pretty common, especially around Sunspot Maximum.



FHE Connection to Solar Superflares

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Math Problems on Solar Superflares

Introductory

Intermediate

Advanced

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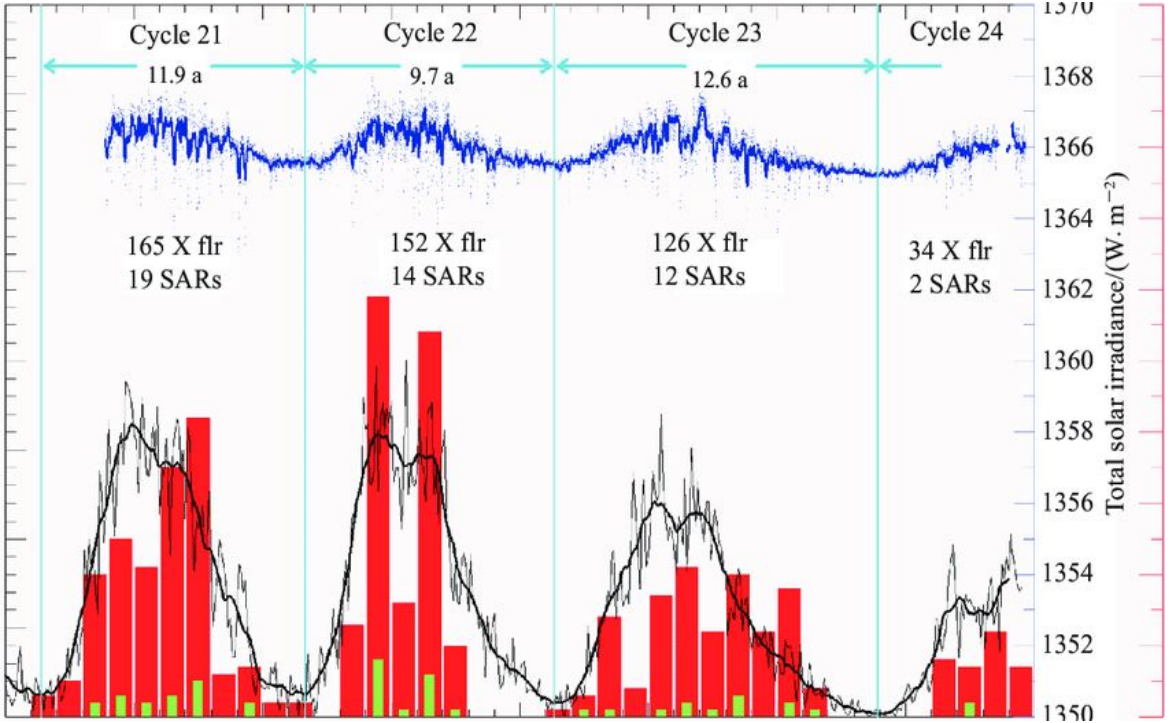


Credit: Wang, 2014: https://www.researchgate.net/publication/280207724_Magnetohydrodynamic_process_in_solar_activity

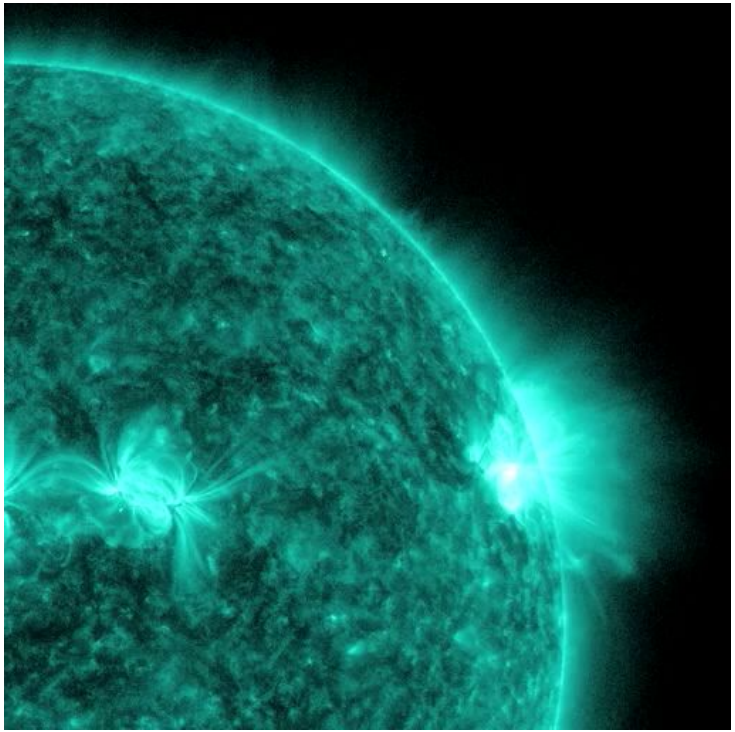
NASA HEAT

Is there a solar superflare in our future?

The biggest solar flares Emit huge amounts of x-ray radiation.

C = 1
M = 10
X = 100

X5 = 500 times C1



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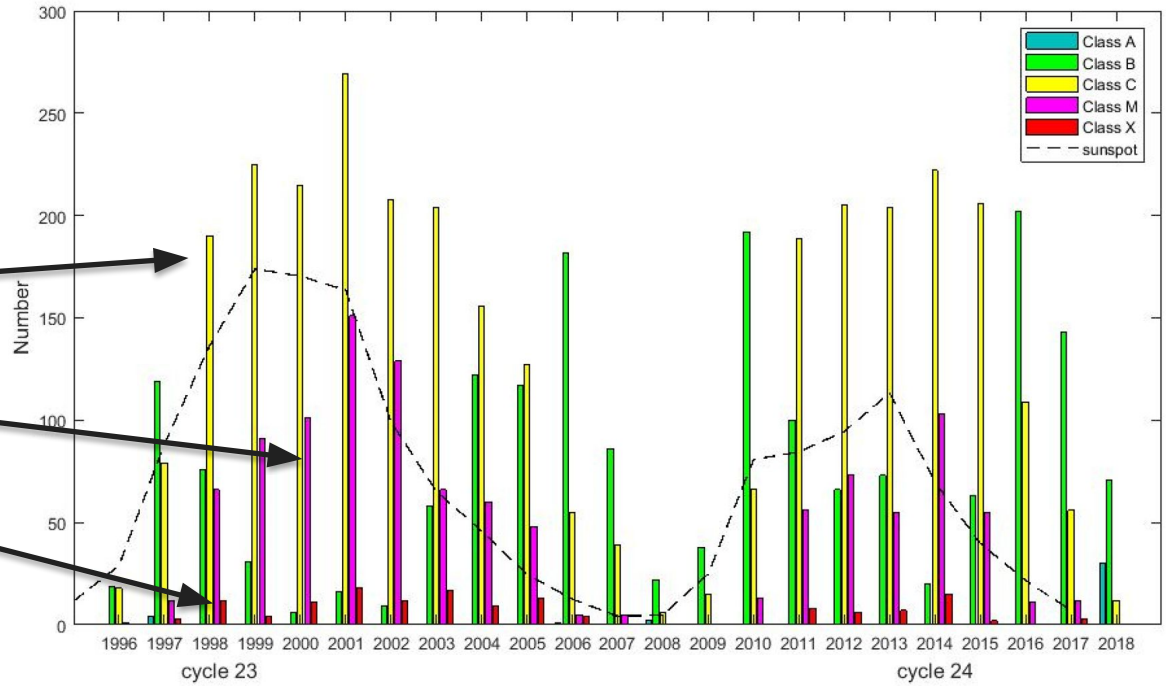
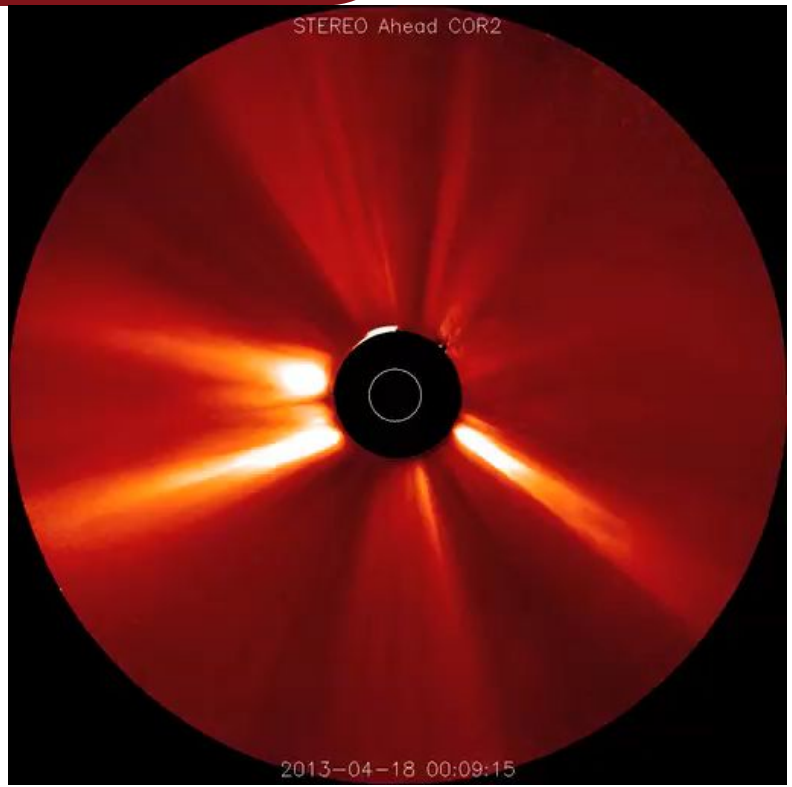


Credit: Grodji et al, 2021, *Atmosphere* **2022**, *13*(1), 69; https://doi.org/10.3390/atmos13010069

NASA HEAT

Is there a solar superflare in our future?

Coronal mass ejections are another form of solar storm that ejects billions of tons of magnetized plasma into interplanetary space.



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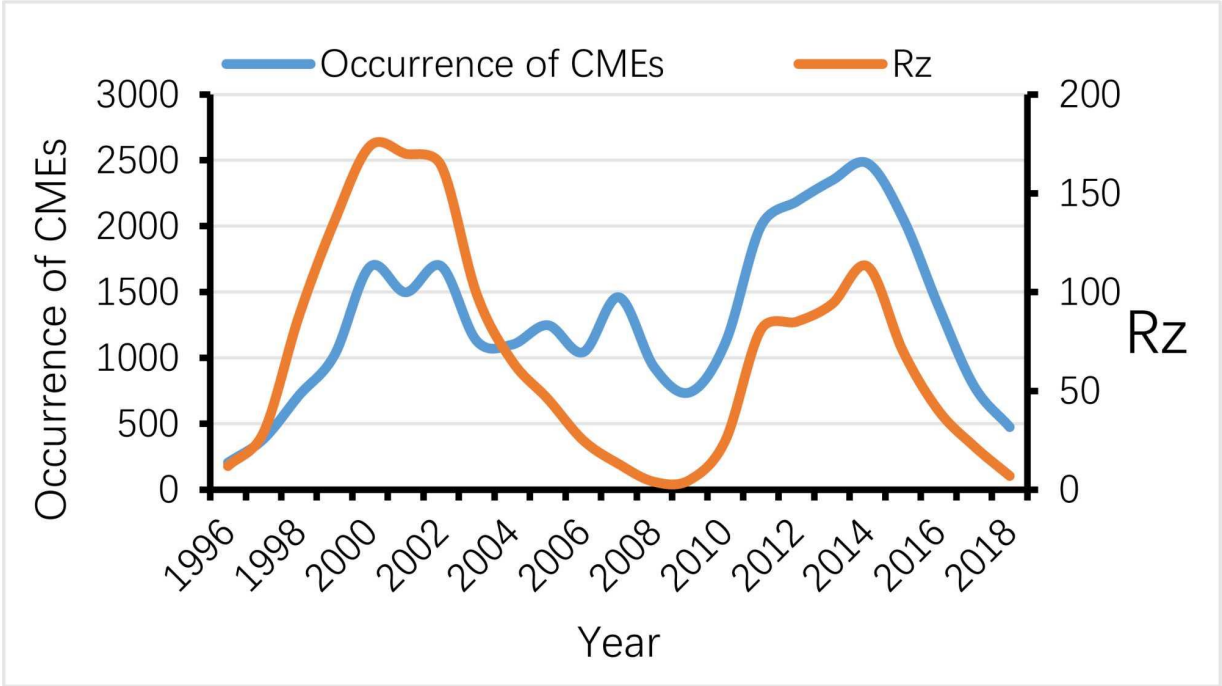

Credit: Kabore et al 2024; https://www.scirp.org/journal/paperinformation?paperid=137364

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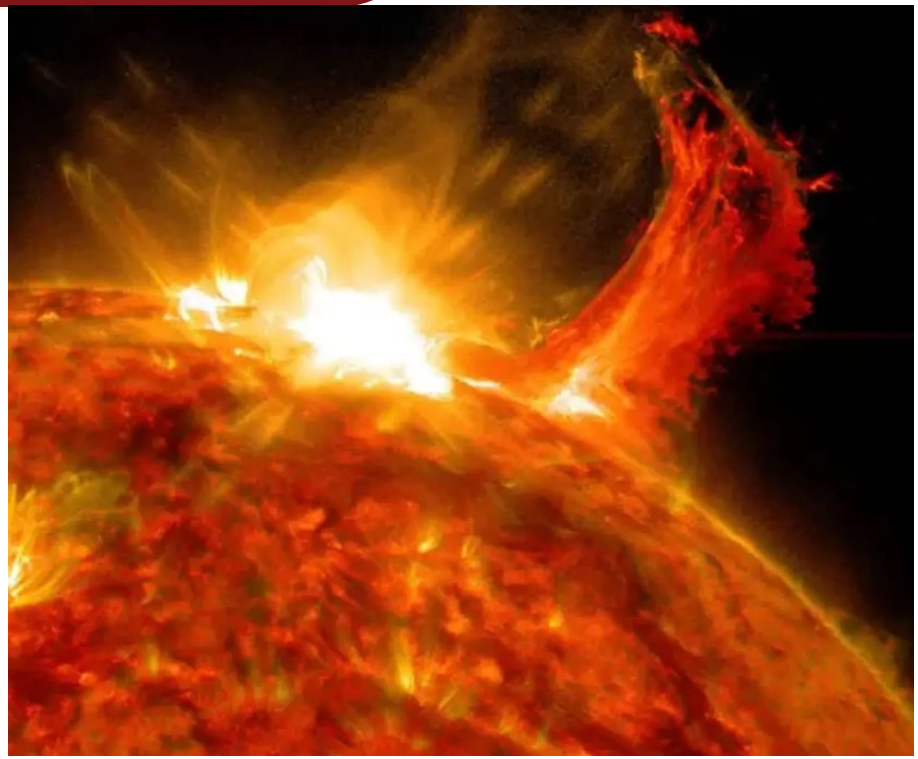
Is there a solar superflare in our future?

The most powerful X-class solar flares are often associated with coronal mass ejections but not always



Is there a solar superflare in our future?

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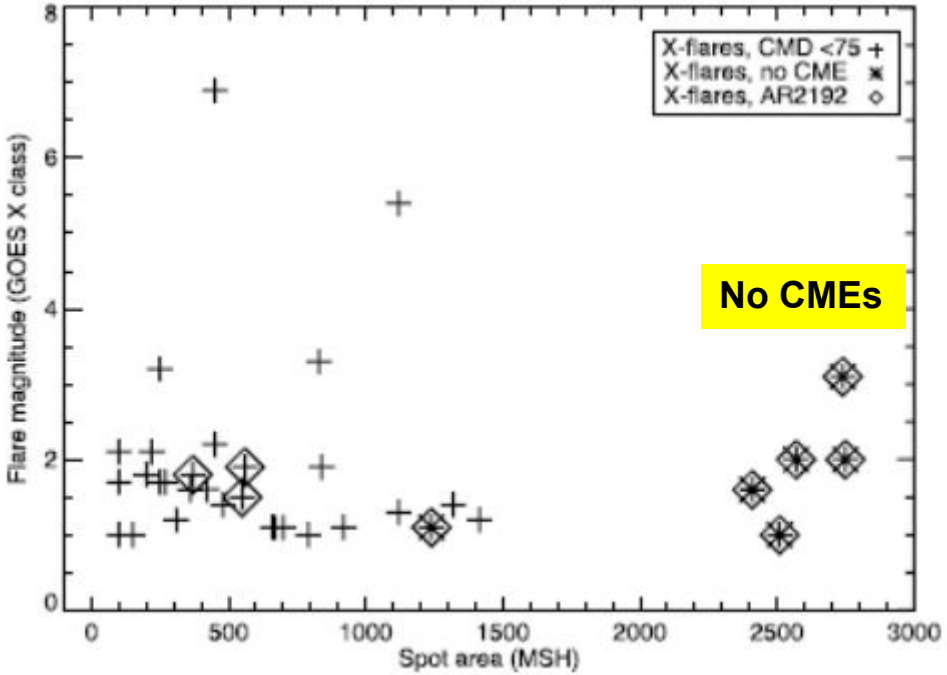
Among the Earth-facing 42 X-class flares observed between 2011 and 2014 by the *Solar Dynamics Observatory* 9 had no associated CMEs.



Credit: Harra et al, 2016, https://doi.org/10.1007/s11207-016-0923-0

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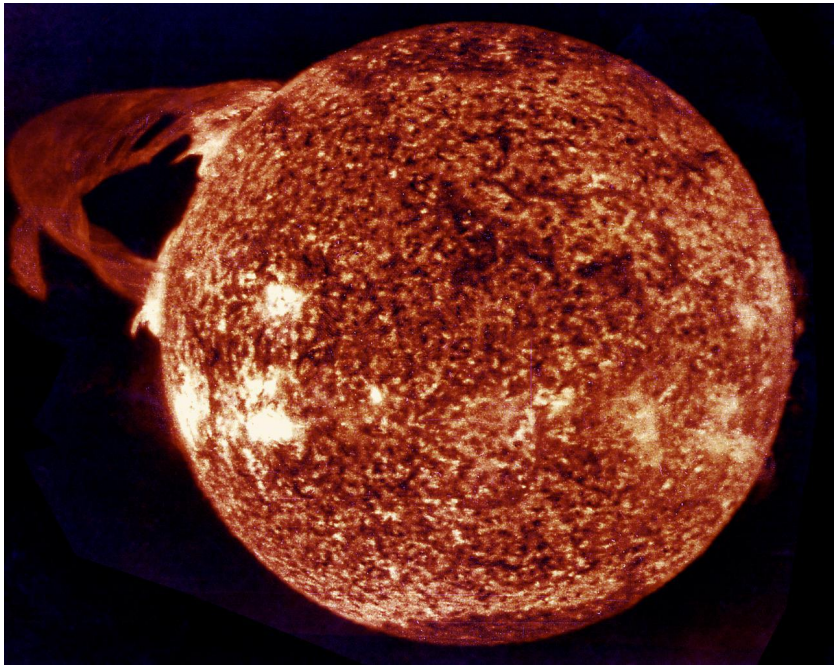
Is there a solar superflare in our future?

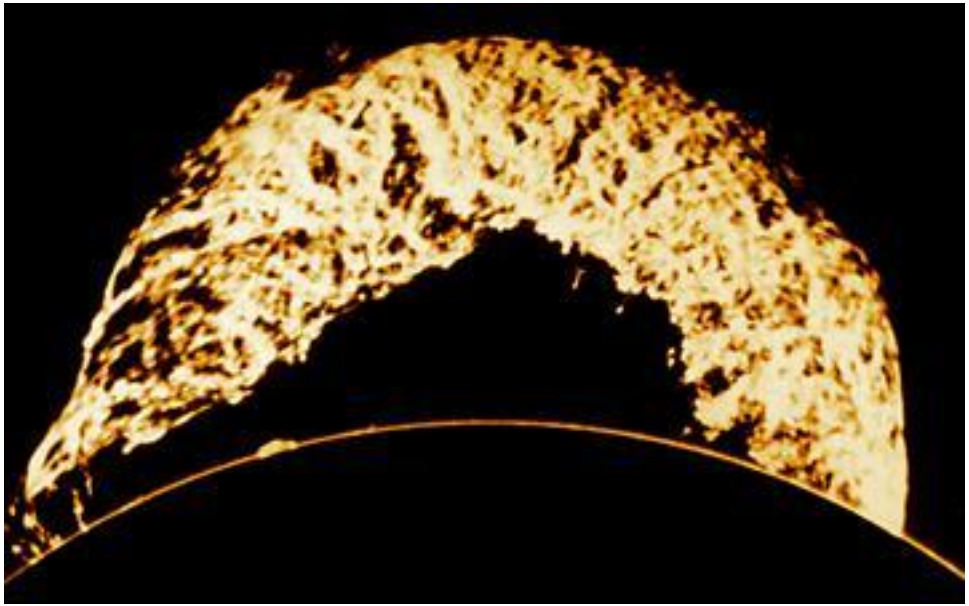
Other phenomena such as **eruptive prominences** can look spectacular and menacing, but in fact carry so little mass and energy that they are not much of a hazard to us.

This photograph of the Sun, taken on December 19, 1973, shows the famous ‘Skylab Flare’. It ejected matter ‘sideways’ to Earth’s orbital location and none of the matter reached Earth.



Is there a solar superflare in our future?

Here is another eruptive prominence spotted on June 4, 1946



Is there a solar superflare in our future?

The 1859 Carrington-Hodgson Event was the most troubling solar storm in the last 200 years.

The aurora it produced, along with magnetic and telegraph disturbances, was seen world-wide even near the Equator.

https://mind4survival.com/the-carrington-event/

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The 1859 Carrington-Hodgson Event was the most troubling solar storm in the last 200 years.

The aurora it produced, along with magnetic and telegraph disturbances, were seen world-wide even near the Equator.

But wait…there's more!

https://mind4survival.com/the-carrington-event/

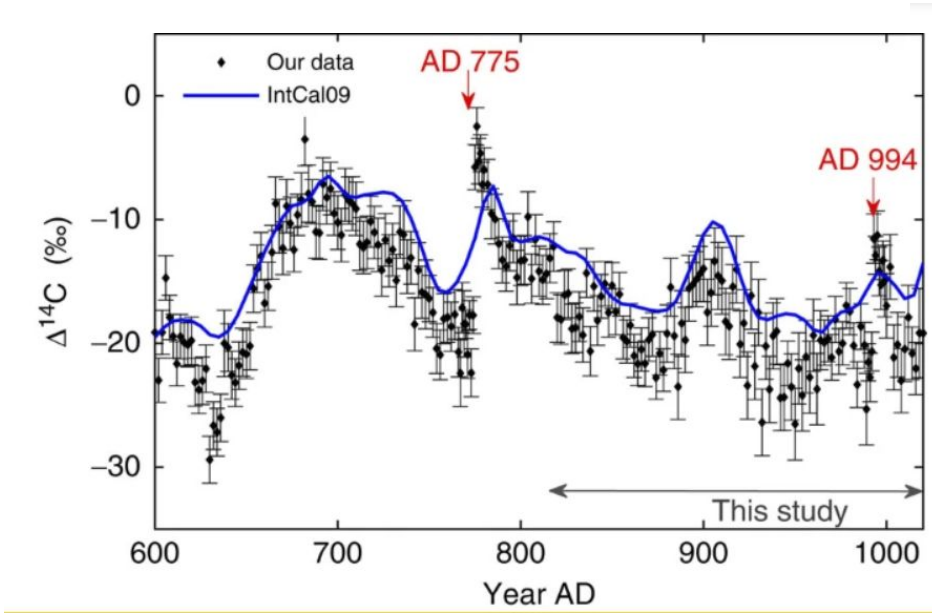
Is there a solar superflare in our future?

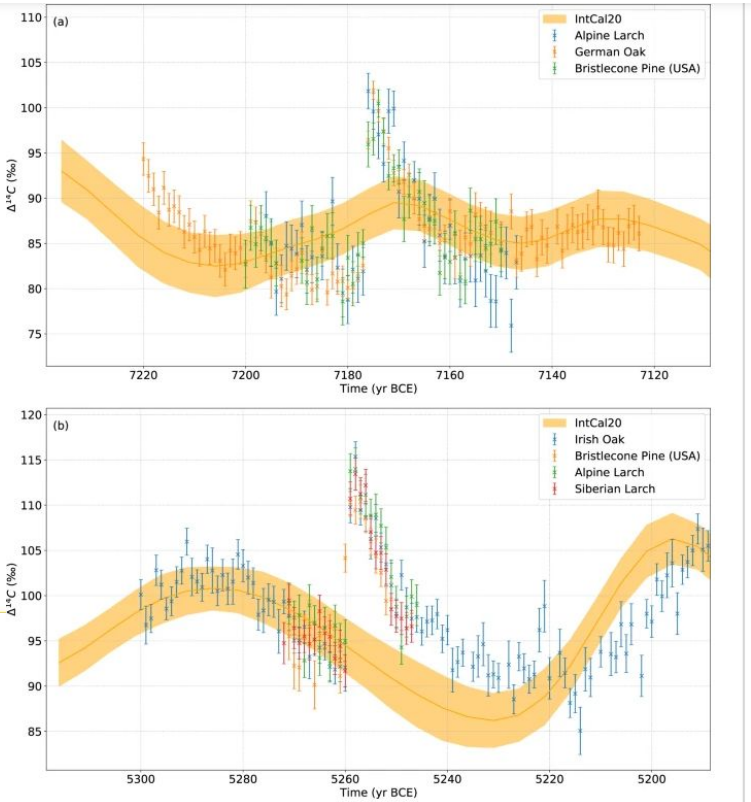
Ice cores reveal huge solar storm struck Earth around 660 BCE

Similar peaks are associated with intense solar storms believed to have occurred in the years 775 CE and 994 CE.

https://physicsworld.com/a/ice-cores-reveal-huge-solar-storm-struck-earth-around-660-bc/

Is there a solar superflare in our future?





https://www.nature.com/articles/ncomms2783

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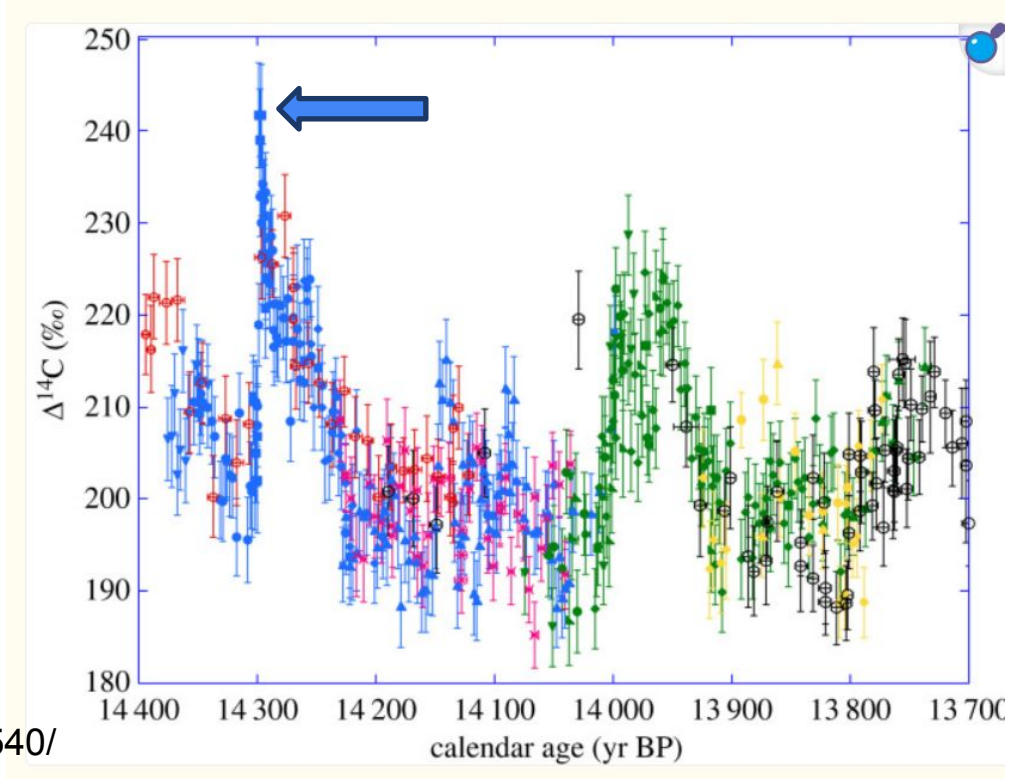
Is there a solar superflare in our future?

Another recent event discovered in 2023.

The asymmetric shape of the 14,300 BP spike is similar in shape to the 775 CE event, but twice as large in amplitude.



https://pmc.ncbi.nlm.nih.gov/articles/PMC10586540/

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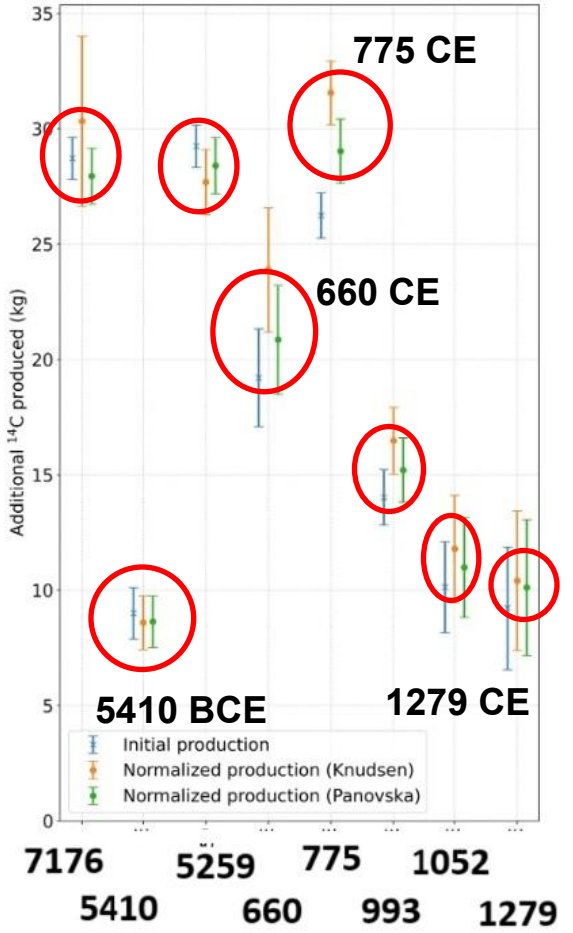
Is there a solar superflare in our future?

Further back in time, ice cores also seem to reveal events taking place in 7176 BCE and 5259 BCE.

https://www.nature.com/articles/s41467-022-28804-9

The increasing number of discoveries of strong SEP events that hit Earth over the past 12,000 years indicates they cannot be considered as extremely rare anymore.



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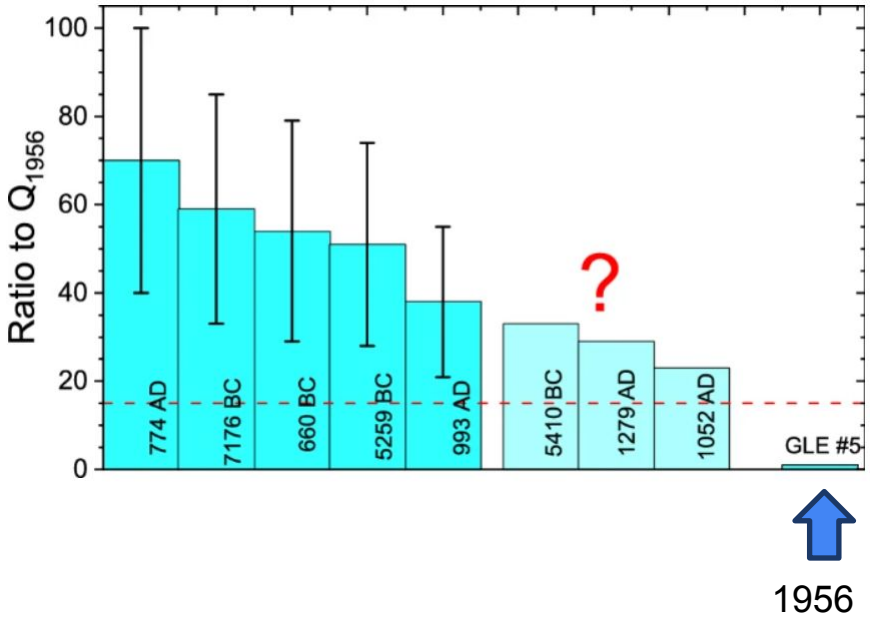
Is there a solar superflare in our future?

We can rank these SEP events by comparing their fluences to that of a well-studied major SEP event in 1956.



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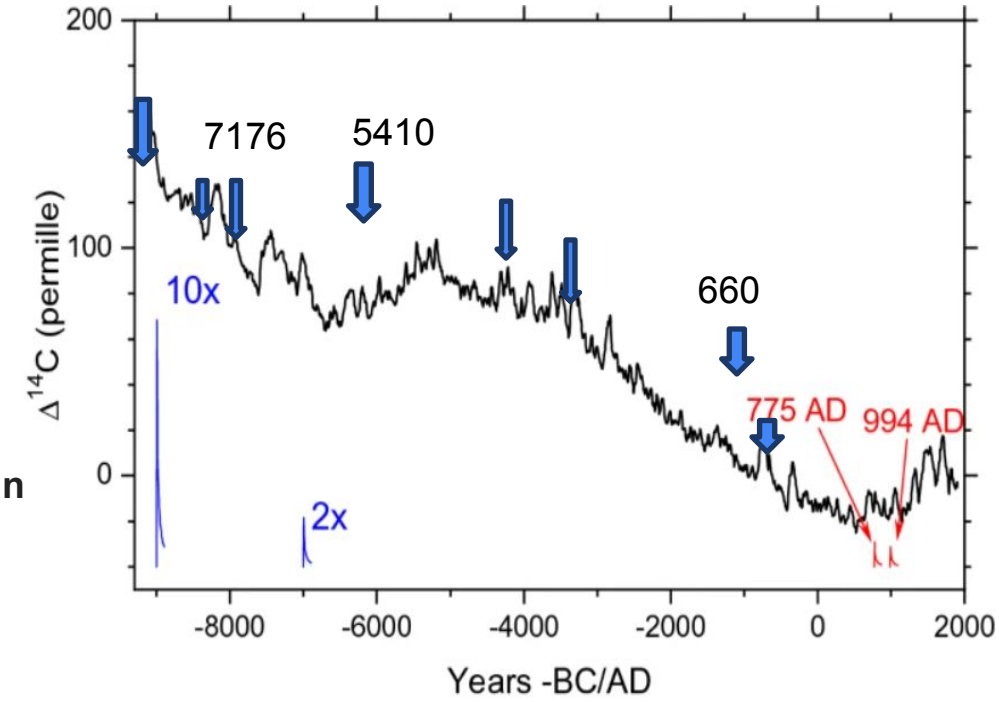
Is there a solar superflare in our future?

Combining this statistical data it is estimated that the probability of an event stronger than the strongest event seen thus far, over the entire Holocene Period (11,700 BP) is lower than 1 event per 5,000 years.

$P(> 10^{11}\ (\text{cm}^2\ \text{year})^{-1}) \leq 1.9 \times 10^{-4}\ \text{year}^{-1}$.

However, we have seen 10 major events in the last 10,000 years so that works out to one Super Carrington Event every 1000 years.



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Is there a solar superflare in our future?

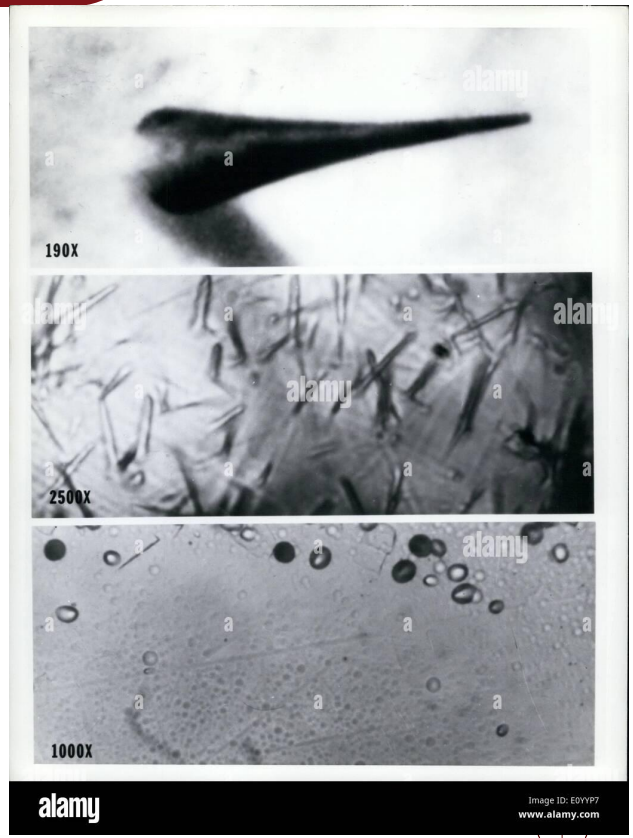
How typical is the current era?

Lunar cosmic ray studies: The flux of SEP above 10 MeV has not changed over the last 5 million years.

*Poluianov, S.; et al. (2018). "Solar Energetic Particles and galactic cosmic rays over millions of years as inferred from data on cosmogenic 26Al in lunar samples". Astronomy and Astrophysics. V.**1618**: p.A96.*

^{14}C data over the last 11,000 years shows no period significantly higher than the present.

https://www.aanda.org/articles/aa/full_html/2018/10/aa33561-18/aa33561-18.html



Is there a solar superflare in our future?

How powerful are these historical ‘super flares’?

774 CE flare ranged from 10^{34} to 10^{36} erg would imply a ~ X3000 to X300000 SXR flare.

Miyake F, Nagaya K, Masuda K, Nakamura T (2012) A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan. Nature 486:240. https://doi.org/10.1038/nature11123

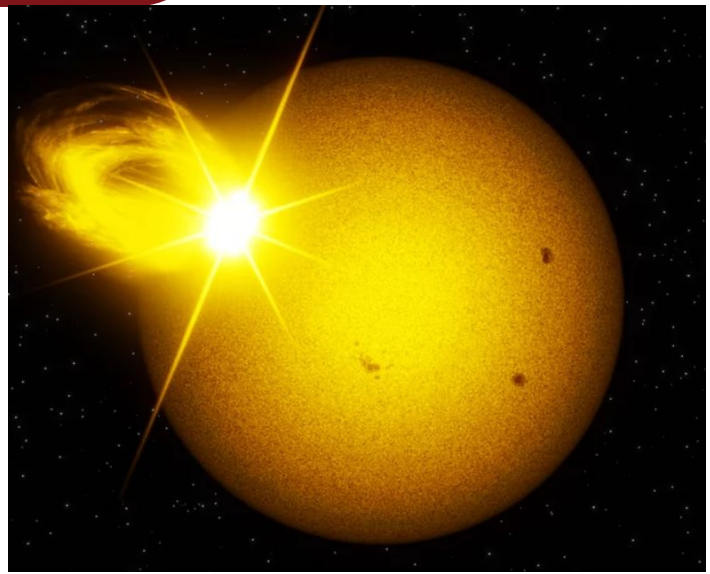
For comparison the 1859 Carrington flare is ~ X45 and ~ 5×10^{32} erg.

On November 4, 2003 we experienced an X35 flare – the strongest during the Space Age.

Is there a solar superflare in our future?

Surveys of other sun-like stars.

- Study of 56,450 Kepler stars similar to our Sun
- Four years of Kepler observations,
- 10^{26} to 10^{29} joules : 10 to 10,000 times a typical solar flare.
- Equivalent of being able to observe the Sun for **220,000 years**



Vasilyev et al,**2024**, **Sun-like stars produce superflares roughly once per century**, Science, Vol 386, Issue 6727, pp. 1301-1305, DOI: 10.1126/science.adl5441

Wichmann, Fuhrmeister, Wolter and Nagel, **2014**, **Kepler super-flare stars**, Astron. Astrop, v. 567.

Maehara, H., Shibayama, T., Notsu, S., et al. **2012**, **Super flares on solar-type stars**, Nature, 485, 478

Image credit:MPS/Alexey Chizhik; https://www.mpg.de/23854476/solar-superflares-once-per-century

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Let's do the math!

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You observe a family of 5 humans for one year.
Humans have a life span of 100 years.

Let's do the math!

If we observe 5 humans randomly selected across this one year, it is as though we studied one human for (100 yrs/5) x 1 sample = **20 years.**

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You observe a family of 5 humans for **two** years.
Humans have a life span of 100 years.

Let's do the math!

If we observe 5 humans randomly selected across this one year, it is as though we studied one human for (100 yrs/5) x 2 samples = **40 years.**

Is there a solar superflare in our future?

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The survey selected Sun-like stars similar in age to our sun to within about 3 billion years.

If we observe 56,450 stars randomly selected across 4 years of time, it is as though we statistically observed our sun for about

$$\frac{\text{3 billion years}}{\text{56,400 stars}} \times \text{4 samples} = \text{about } \mathbf{213{,}000\ years}.$$ Close enough.

Is there a solar superflare in our future?

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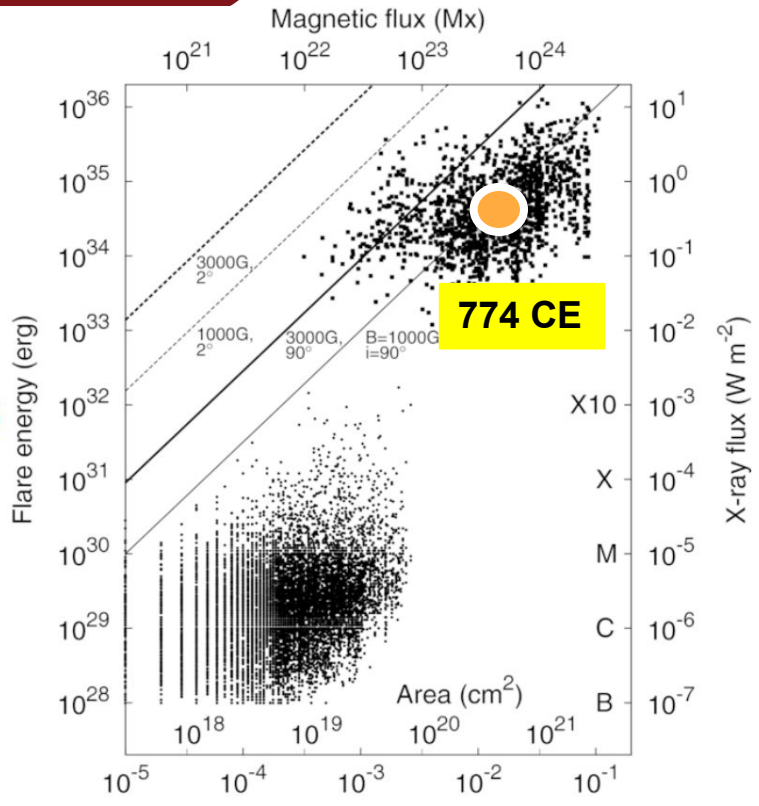
✔ **Flare behavior similar to the Sun over a span of about 220,000 years.**
✔ **Many small flares, fewer big flares, and very few enormous flares.**
✔ **Sun-like stars produce superflares roughly once per century.**

Is there a solar superflare in our future?

Here is a plot showing solar flares versus Kepler-star flares.

Kepler

Solar



Super flares on other sun-like stars
https://iopscience.iop.org/article/10.1088/0004-637X/771/2/127

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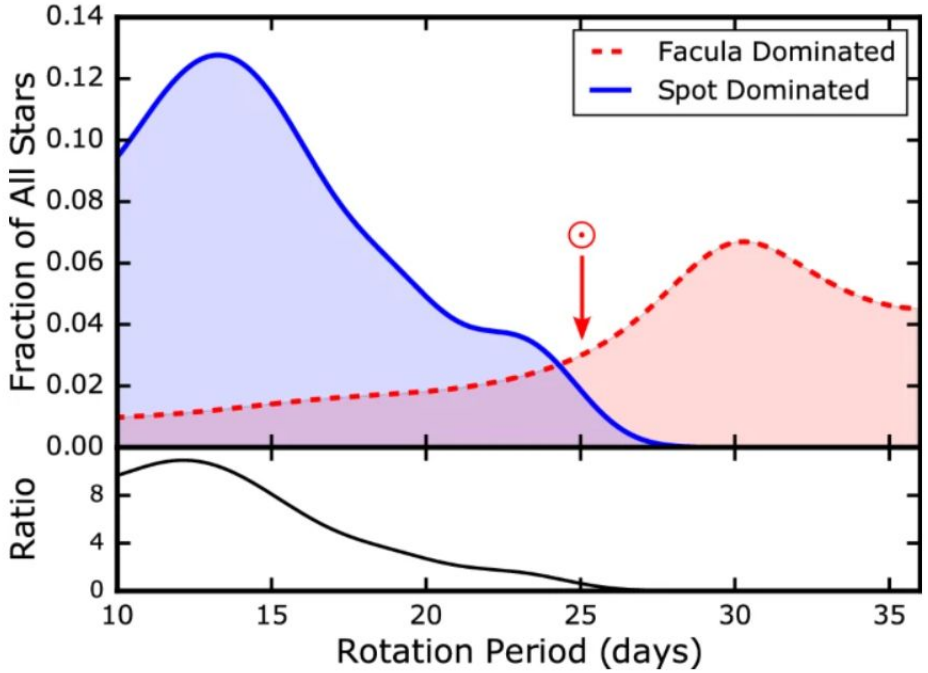
Is there a solar superflare in our future?

When the sun-like stars are plotted against their rotation periods and type of flaring activity, our sun is in a curious location.

Powerful spot-dominated flares more common in fast rotators.

Less-powerful facula-dominated flare more common in slow rotators.



Cliver et al, 2022, Extreme Solar Events, https://link.springer.com/article/10.1007/s41116-022-00033-8#Fig59

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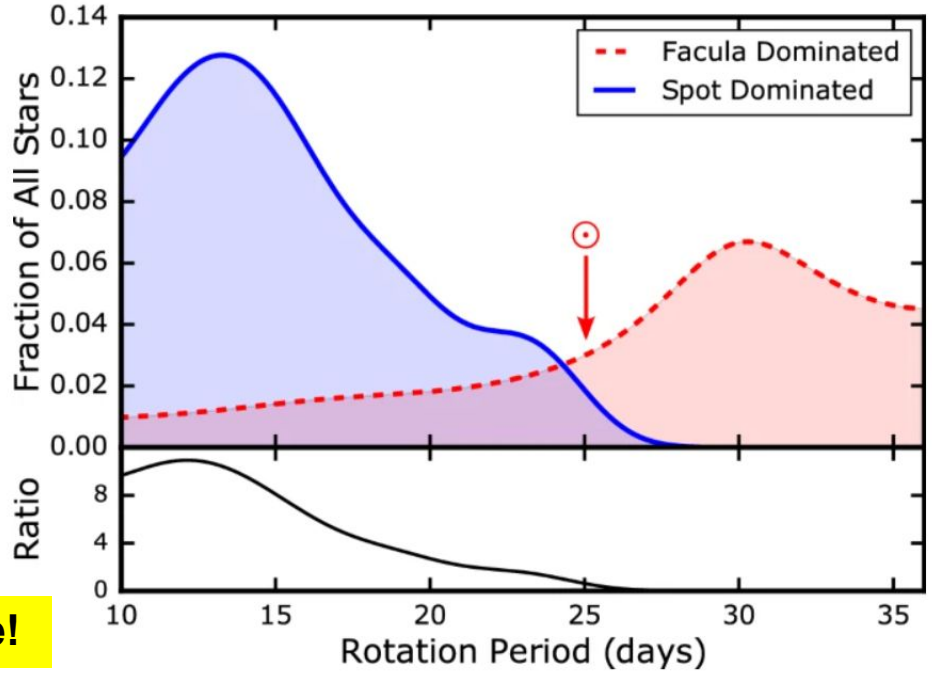


Fewer superstorms in our sun's future!

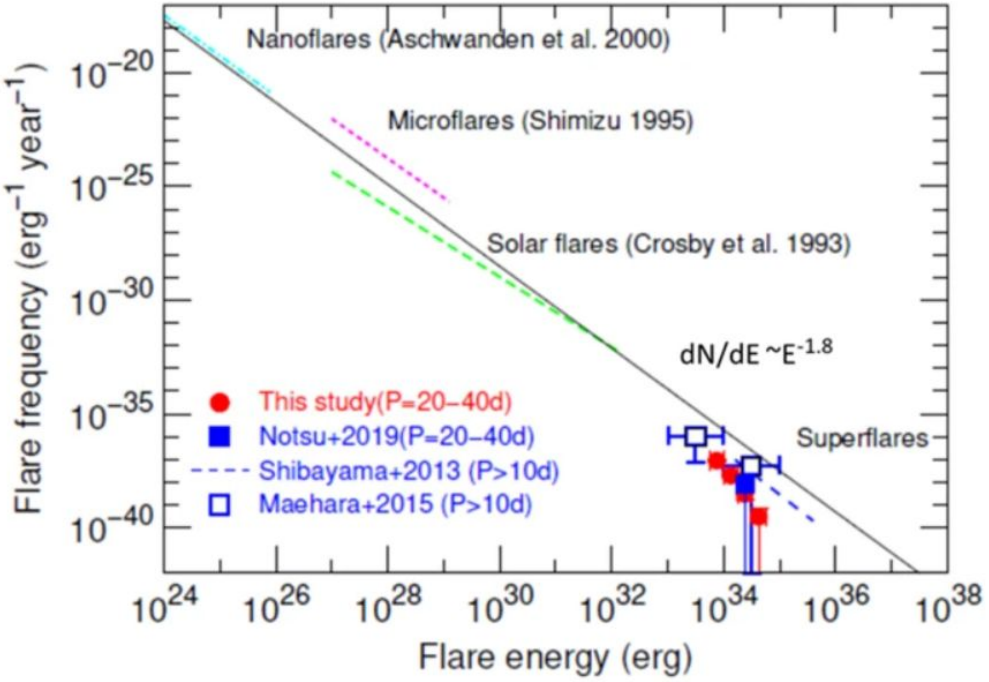
Cliver et al, 2022, Extreme Solar Events, https://link.springer.com/article/10.1007/s41116-022-00033-8#Fig59

NASA HEAT

Is there a solar superflare in our future?

Maehara et al. (2015) determined that occurrence frequency of 10^{33} erg solar flares would be **once every 500 years.**

Notsu et al. deduced that flares with 10^{34} erg occur on old (~ 4.6 Gyr), slowly rotating (P_{rot} ~ 25 days) Sun-like stars approximately **once every 2000–3000 years.**



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Is there a solar superflare in our future? Likely Impacts

Prototype =	Carrington	774 CE	12,300 BCE
Duration	Days	**Mo. To Yrs**	**5-10 years?**
Magnetosphere	Partial loss	Full loss	Full loss
Van Allen Belts	Partial loss	Full loss	Full loss
Astronauts	LD20?	LD50?	LD100?
Electric Grid	> 50% global loss	Full loss	Full loss
GEO Satellites	> 50% loss	Full loss	Full loss
LEO Satellites	< 50% loss	Ful loss	Full loss

Is there a solar superflare in our future? Likely Impacts

Prototype=	Carrington	774 CE	12,300 CE
Duration	Days	Mo. To Yrs	5-10 years
Ozone Layer	Total loss	Total loss	Total loss
Geomagnetic field at surface	Highly variable in some areas	Highly variable everywhere	Highly variable everywhere
UV-B and C	Minimal hazard	Major hazard	Major hazard
Atmosphere	No loss below 100 km	Some loss below 100 km	Significant loss above 20-km

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Surface and ocean life survives unaffected with proper UV shielding by day

Is there a solar superflare in our future?

The odds are **perhaps better than one-in-thirteen** we will see another Carrington-level event within your lifetime if you are under 20 years old.

Do the math!

Is there a solar superflare in our future?

The odds are **perhaps better than one-in-thirteen** we will see another Carrington-level event within your lifetime if you are under 20 years old.

C^{14} record shows as many as 8 events in the last 9,000 years, but there could be more.

Upper limit is one per 1,000 years.

Morina et al, 2019 estimate a ten-year rate as high as 0.02, which for our 80-year calculation is 0.16 or ***one-in-six.***

Time window: 100-20 = 80 years.

80 years/1000 years = 0.08 = 1/13

Odds are one in 13.

This is a lower limit because if more are discovered, say twice as many, the interval is 500 years and the odds are one-in-six.

Morina et al, 2019, Probability estimation of a Carrington-like geomagnetic storm. *Sci Rep* **9**, 2393 (2019). https://doi.org/10.1038/s41598-019-38918-8

Is there a solar superflare in our future?

The odds are **perhaps better than one-in-thirteen** we will see another Carrington-level event within your lifetime if you are under 20 years old.

The odds are perhaps **one-in- fifty six** that you might see another superflare in your lifetime.

Do the math!

Is there a solar superflare in our future?

The odds are **perhaps better than one-in-thirteen** we will see another Carrington-level event within your lifetime if you are under 20 years old.

The odds are perhaps **one-in- fifty six** that you might see another superflare in your lifetime.

- 774 CE and 7176 BCE would classify as Kepler super flare events.
- Two super flare events every 9,000 years.
- One super flare every 4,500 years.

Time window: 100 – 20 = 80 years.

80 yrs/ 4,500 yrs = 0.018 = 1/56

Odds are one in 56

Is there a solar superflare in our future?

For more about this, see my blog at Astronomy Café.

Next Time: March

The Solar Wind: How some planets lose their atmospheres