THE INTERNATIONAL CONFERENCE ON THE 120TH
ANNIVERSARY OF THE BULNAY EARTHQUAKE:
ADVANCES IN ASTRONOMY AND GEOPHYSICS

FRACTAL DIMENSION OF SOLAR FLARES

D. Khongorzul, D. Batmunkh, B. Nyamsuren

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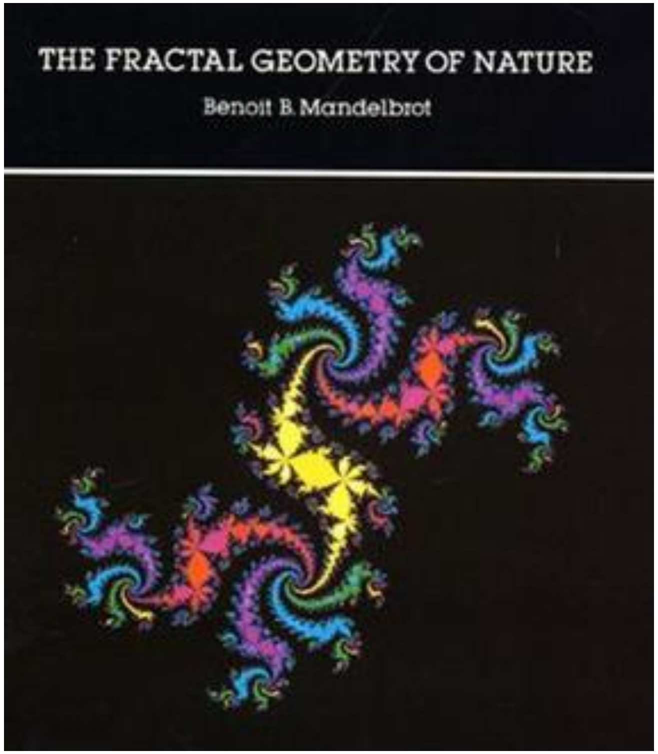
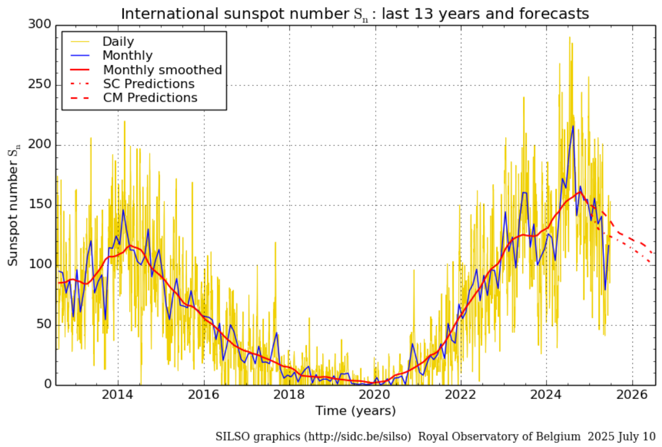


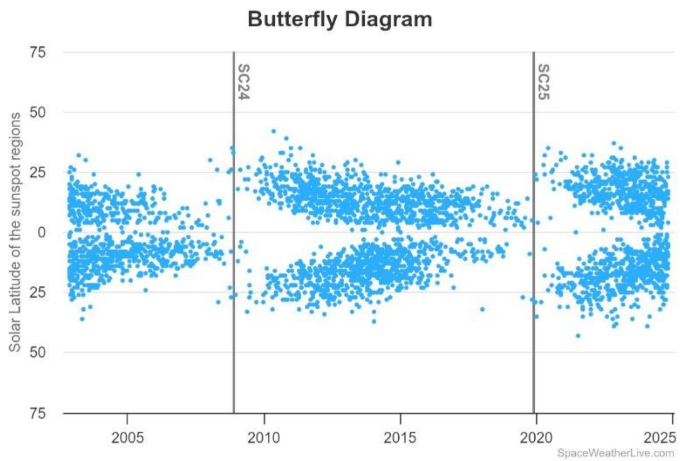
"Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in astraight line" (Benoit Mandelbrot 1977).

Solar cycle

- **The solar cycle** is an approximately 11-year cycle of solar activity.
- It's driven by the Sun's magnetic field and is marked by the frequency and intensity of **sunspots** on the surface. Leads to more solar flares, CMEs, and solar wind.
- The current cycle — **solar cycle 25** — began in December 2019 (NASA). Now reaching **maximum activity**.

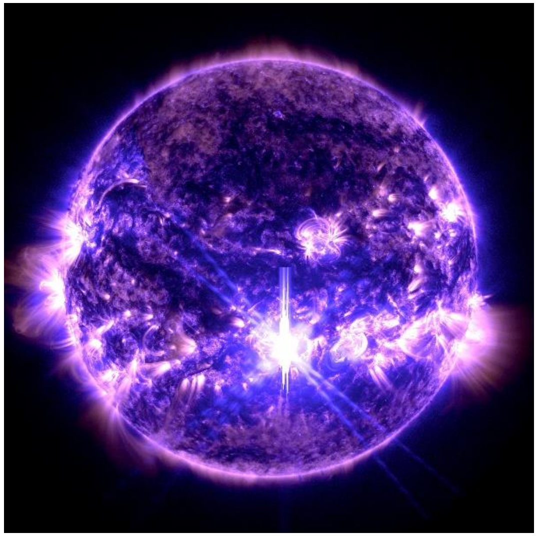


Shows increase in sunspot numbers since 2020. Peak expected around 2024-2025.



Sunspots start at high latitudes, then move toward the equator. Pattern repeats each cycle forms "butterfly wings"

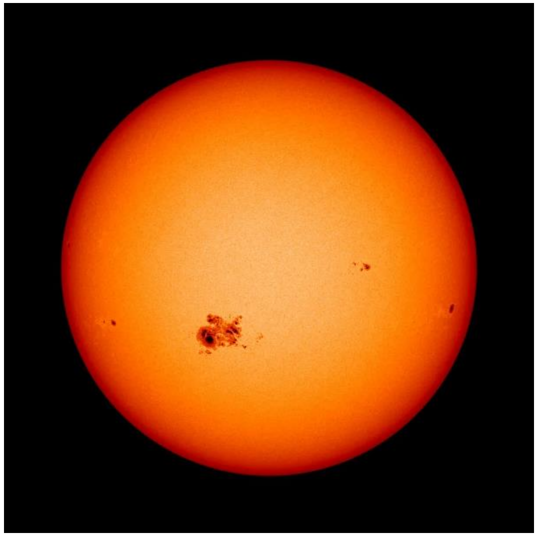
Solar activity

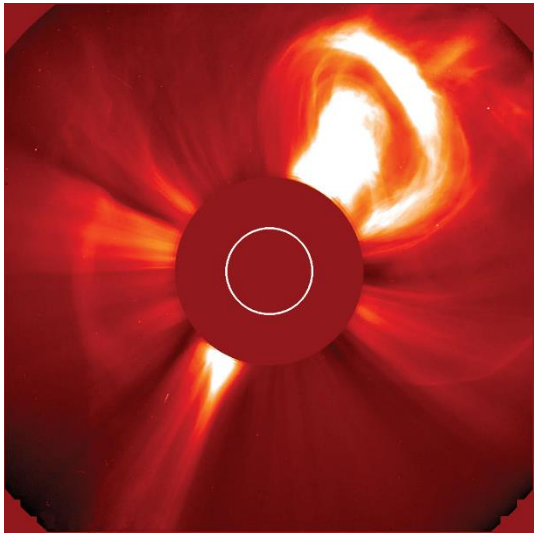


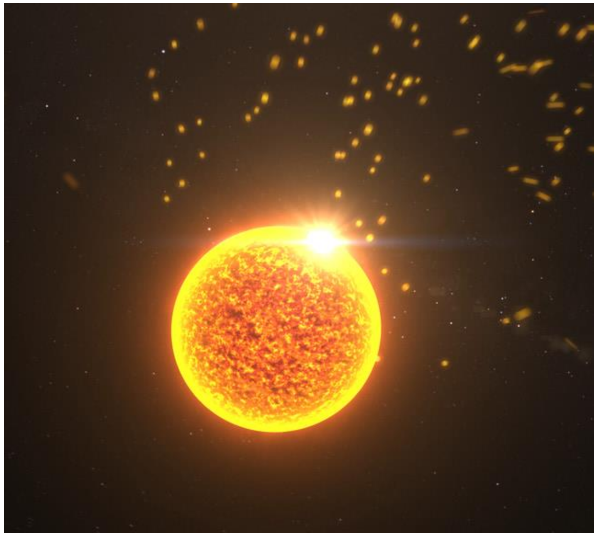
Solar activity refers to the various dynamic and often violent phenomena that occur on the Sun’s surface and in its atmosphere. These include:

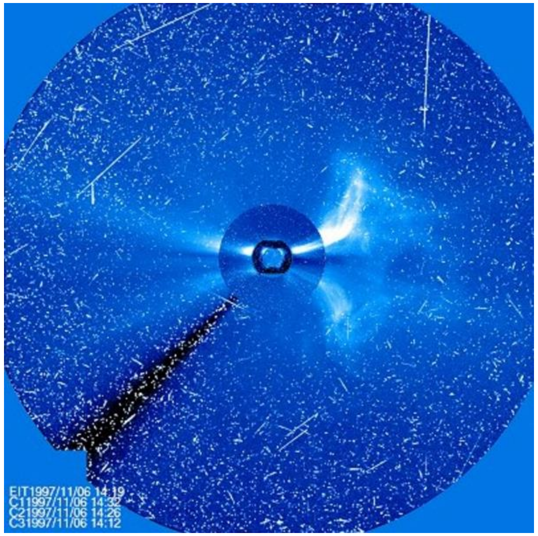
- Solar flares
- Sunspots
- Coronal Mass Ejections (CMEs)
- High-speed solar wind
- Solar energetic particles

All solar activity is driven by the Sun’s magnetic field.









Solar Flare

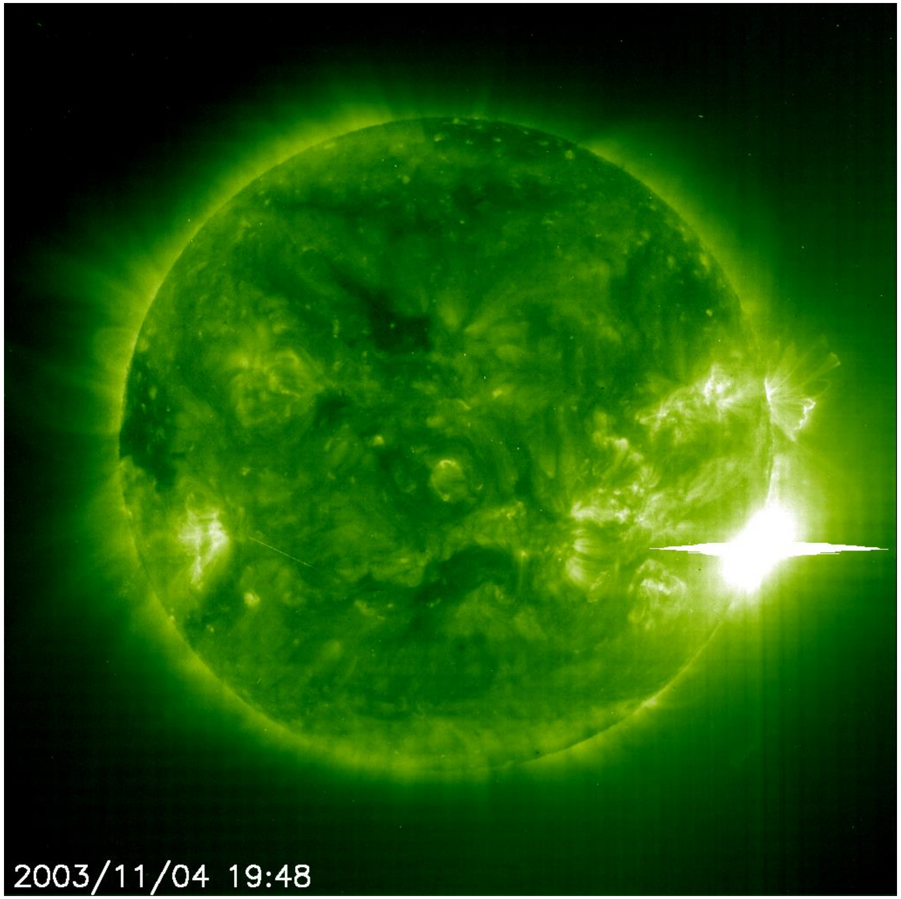
- **Solar flares** are large eruptions of electromagnetic radiation that occur near sunspots, usually at the dividing line between areas of opposite magnetic fields.

- Solar flares are classified according to their intensity, or energy output (in SXR):

Class	Intensity (erg cm^{-2} s^{-1})	I (W m^{-2})
A	10^{-5}	10^{-8}
B	10^{-4}	10^{-7}
C	10^{-3}	10^{-6}
M	10^{-2}	10^{-5}
X	10^{-1}	10^{-4}

Flare classes A through M are divided further using numbers 1 through 9, with 9 being the strongest. X-class flares can go even higher and have no upper limit.

- The most powerful flare ever measured was in 2003, **Halloween solar storm** was recorded as an **X28**.



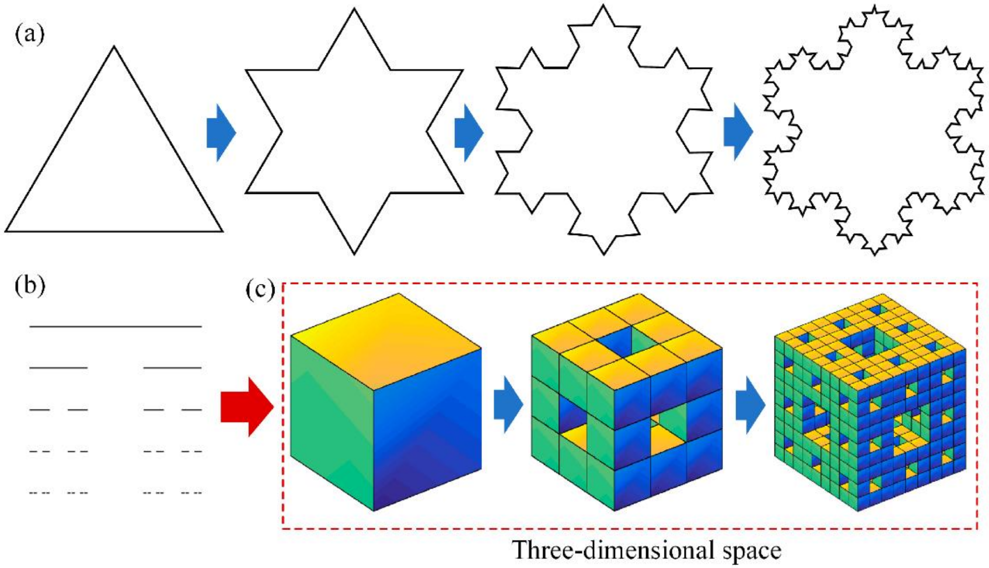
On Nov. 4, 2003, this solar flare saturated the X-ray detectors on several Sun-observing spacecraft.
NASA/ESA/SOHO

Fractal

- A **fractal** is a geometric shape that has a *fractional dimension*. Many famous fractals are ***self-similar***, which means that they consist of smaller copies of themselves. Fractals contain patterns at every level of magnification, and they can be created by repeating a procedure or iterating an equation infinitely many times.
- The Fractal dimension is defined by this formula:

$$D = -\log_{\varepsilon} N = -\frac{\log N}{\log \varepsilon}$$

Where ε is the scaling factor, D the dimension, and N the resulting number of units in the measured object. And this is how fractal geometry differs from Euclidean geometry.



The construction process of fractal a). Koch curve, b). Cantor set c). Menger sponge

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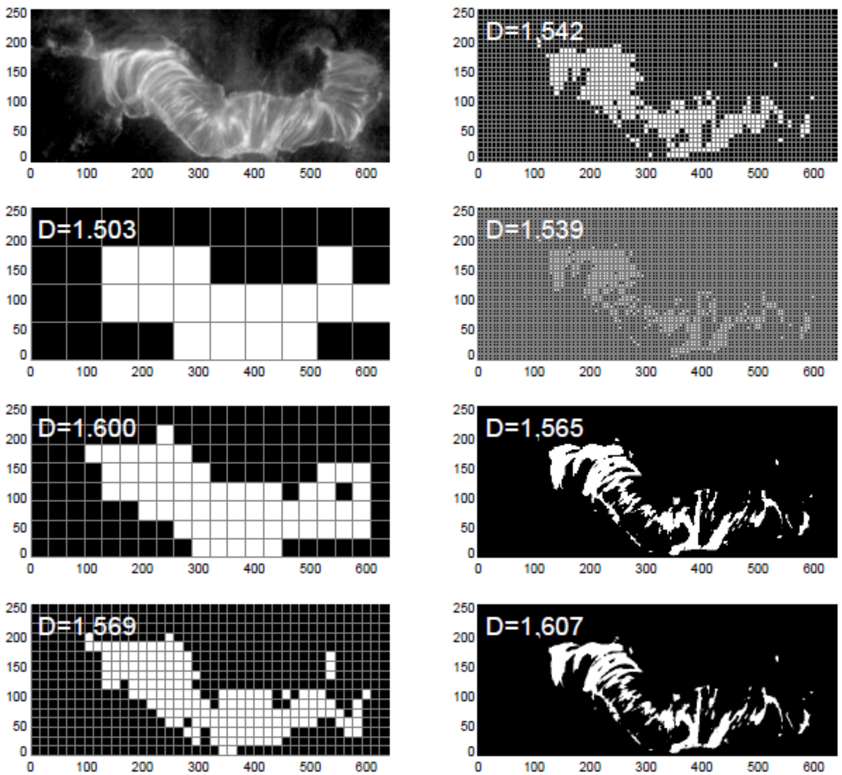
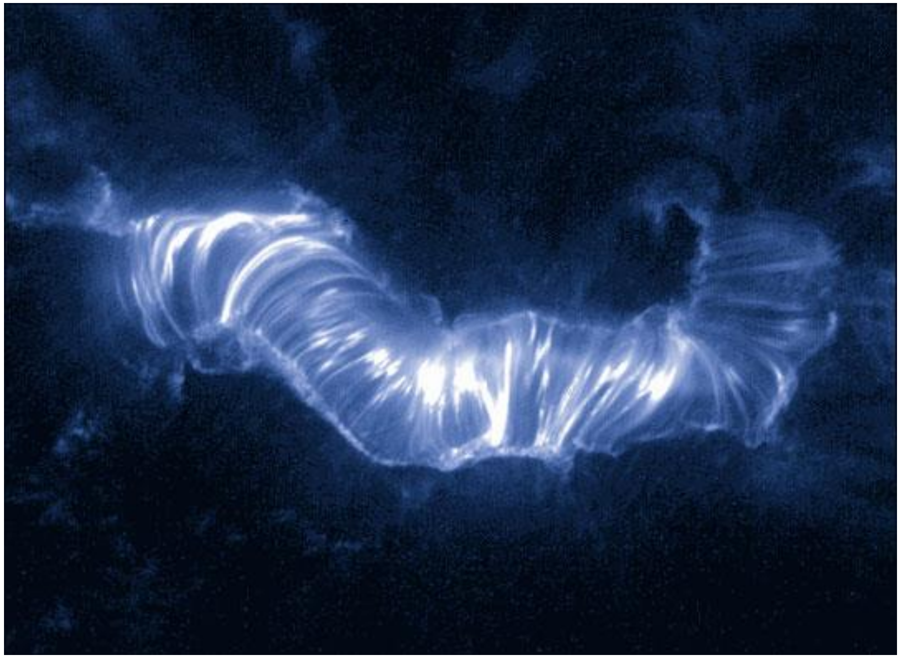
Bastille Day solar flare

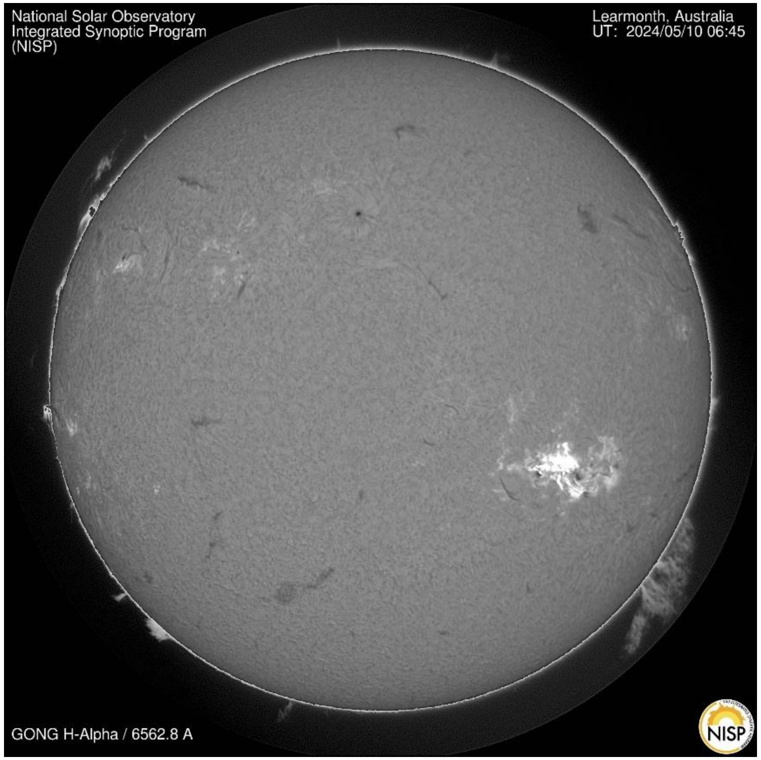


Measurement of the fractal area of the Bastille-Day flare, observed by TRACE 171 Å on 2000-Jul-04, 10:59:32 UT. The Haussdorff dimension is evaluated with a box-counting algorithm for pixels above a threshold of 20% of peak flux value. Note that the Haussdorff dimention is invariant when rebinned with different marco-pixel sizes (from 1 to 64), indicated with a mesh grid. The full resolution image is in the top left frame. (**Aschwanden & Aschwanden 2008**)



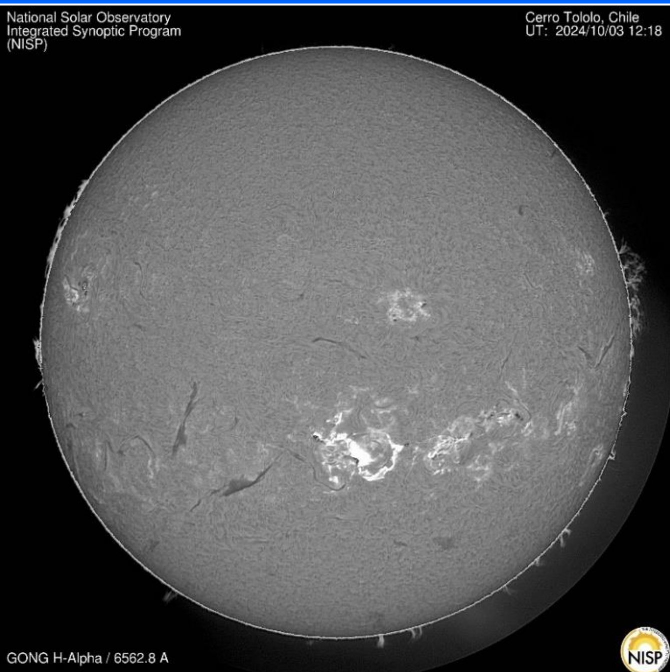
- The solar flare event of July 14, 2000, also known as the **Bastille Day solar flare**, was a powerful eruption that occurred during the solar maximum of Solar Cycle 23. GOES satellites detected a very strong **X5.7** class solar flare.
- As shown in the images on the left, the dimension was determined using the **Box Counting method**.
- The fractal flare area A can be described by the Haussdorff dimension D_2, i.e., $\boldsymbol{A(L) \propto L^{D_2}}$, and can be directly measured from imeges using a box-counting method.
- In this study, we analyze the solar flare using H-alpha chromosphere images and apply the box-counting method (same method) to calculate its fractal dimention.

- At the chromospheric level, in the **H-alpha spectral line**, we determined the fractal dimension of solar flares. When the electrons return to their original orbits, the absorbed energy is released as light, such as the H-alpha line with a wavelength of 6562.8Å (656 nm). For comparison, previous studies by other authors—for example, Aschwanden—have investigated the fractal dimension at the coronal and photospheric levels, using different spectral lines.
- In our analysis, the box-counting method was applied to a selected sample of 12 X- and M-class solar flares. The calculations were performed using the ***FracLab 2.2*** software package, with observational data obtained from the **GONG Data Archive**.

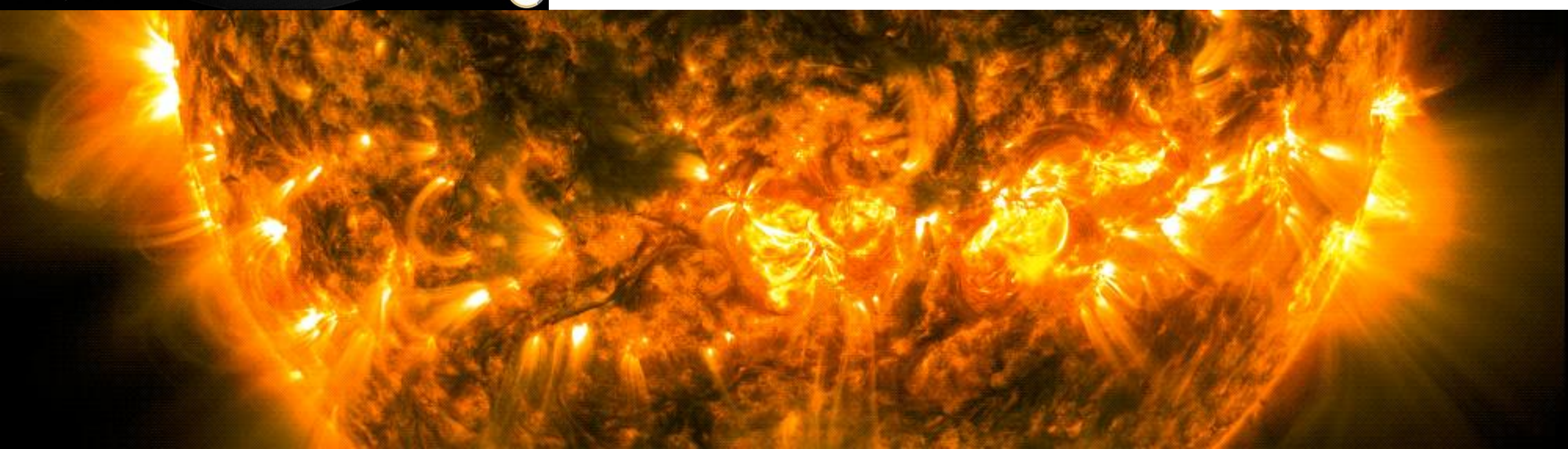


FracLAB
Small Breakthroughs, Big Impact

An X9.0 flare from Active Region 13842 - October 3, 2024



Among the selected events, the most powerful was an **X9.0 flare** launches from active region 13842 on October 3, 2024. NASA's Solar Dynamics Observatory, which watches the Sun constantly, captured imagery of the event.



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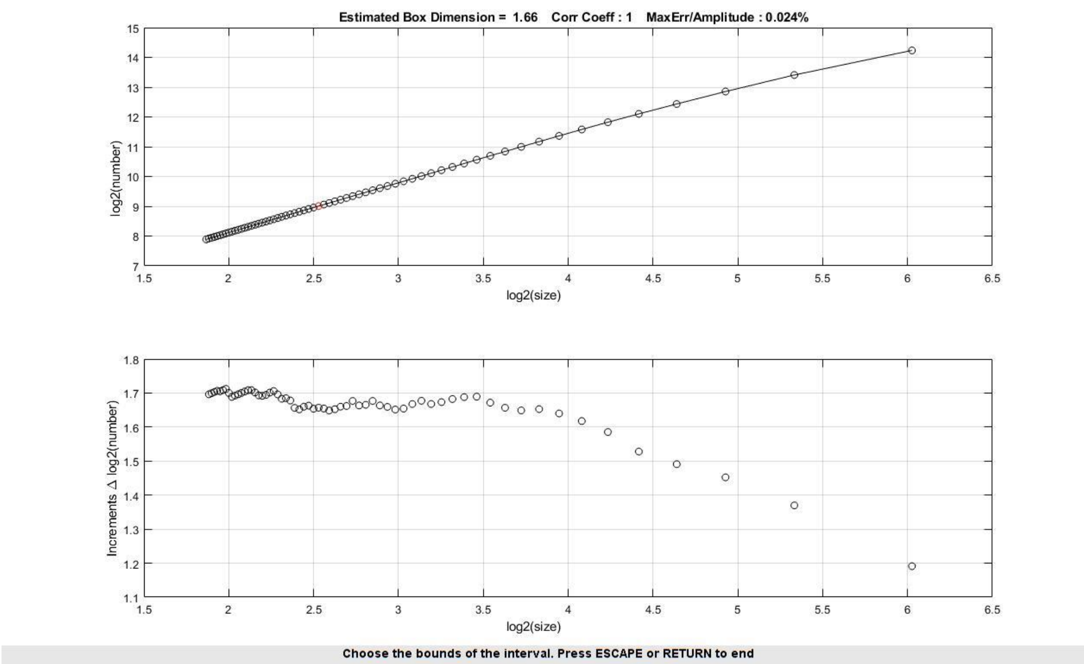
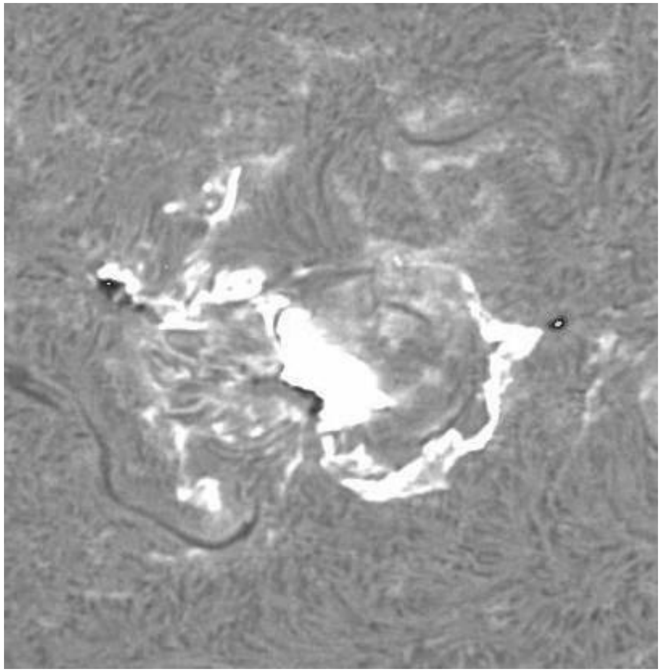
An X9.0 flare from Active Region 13842 - October 3, 2024





On October 3, 2024, a very powerful X9.0-class flare was observed from Active Region 13842. Using the *FracLab 2.2* software, the box-counting method was applied to its H-alpha imagery, yielding a fractal dimension of **1.66**. The correlation coefficient was 1.0, and the maximum error was 0.024%, indicating that the results are highly accurate and reliable.

This value shows that the spatial structure of the flare lies between one-dimensional filamentary patterns and two-dimensional surface structures. At small scales, fine and complex self-similar features dominate, whereas at larger scales, the structure becomes more uniform. These findings are consistent with previous studies at the coronal and photospheric levels, but in the case of chromospheric H-alpha emission, the structure may be denser.

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Fractal dimension of Solar flares (Chromosphere, H-alpha image)

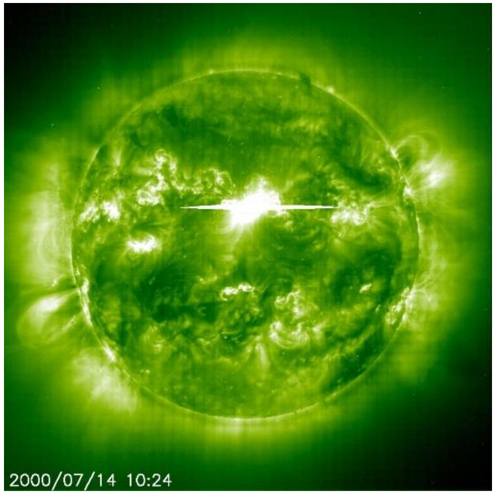
- We measured the fractal dimention of solar flares across 12 events, with a particular focus on data from the year 2024. The result indicate that fractal dimentions of the analyzed flares range between **1.64 – 1.83**.

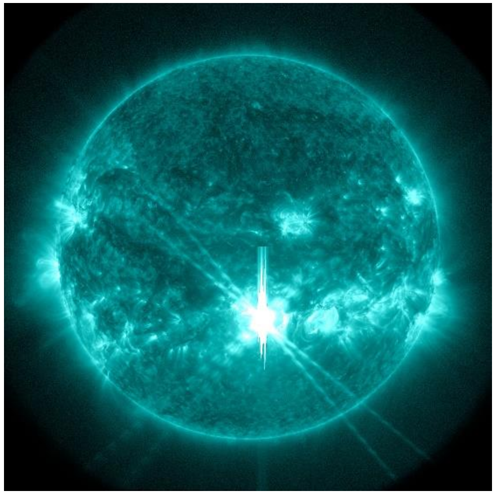
Here, we present a comparison with the results from the study by J. Aschwanden 2022.

- photospheric granulation: ~ 1.21 ± 0.07
- transition region plages: ~ 1.29 ± 0.15
- transition region sunspots: ~ 1.54 ± 0.16
- active region magnetograms: ~ 1.59 ± 0.08
- EUV nanoflares: ~ 1.56 ± 0.08
- large solar flares: ~ 1.76 ± 0.14
- Bastille-Day X5.7-class flare: ~ 1.89 ± 0.05

Our X9 solar flare is (Chromosphere, H-alpha) : ~ 1.67

	Observation Date	Star Time (UT)	Flare Duration τ_f (s)	GOES Class	Region	Fractal Dimension D_2
1	10/3/2024	12:08	1140	X9.00	3842	1.6708
2	10/1/2024	21:58	1860	X7.10	3842	1.8016
3	2/22/2024	22:08	2100	X6.37	3590	1.6718
4	9/14/2024	15:13	2040	X4.54	3825	1.769
5	5/6/2024	05:38	4140	X4.52	3663	1.8164
6	5/10/2024	06:27	2340	X3.98	3664	1.6451
7	5/9/2024	08:45	3060	X2.20	3664	1.6683
8	10/7/2024	19:02	1740	X2.10	3842	1.8295
9	10/31/2024	21:12	900	X2.03	3878	1.8246
10	1/3/2025	11:29	1140	X1.20	3947	1.7965
11	5/25/2025	16:18	1080	M8.90	4098	1.7998
12	5/31/2025	23:31	3660	M8.20	4100	1.7483





Application of fractal dimension to the determination of some physical parameters of a solar flare (examples).

1. The amount of energy released during a flare, E_{flare} , can be explained by the magnetic energy stored in the solar atmosphere,

$$E_{flare} = \frac{B^2}{8\pi} L^3$$

where $\boldsymbol{L}$ is the characteristic size of the flare and $\boldsymbol{B}$ is the characteristic magnetic flux density in the corona.

If we take fractality into account, we need to replace the Euclidean length with the fractal length, which is obtained from the area of the flare.

$L \propto A^{1/D} = A^{1/1.75}$. If we compare this with flat geometry $A^{1/1.75}/A^{1/2} > 1$. This means that with fractality L will be longer than usual.

2. We can estimate the inflow velocity Vin as

$$V_{in} \sim \frac{L}{\tau_{flare}} ,$$

τ_{flare}- the timescale of flare,

The plasma influx will be large.

3. The number density in the flare loop is $n_{loop} \sim 2\sqrt{\frac{EM}{L^3}}$, EM- emission measure.

n_{loop} will be less.

Conclusion

- For a large flare (magnitude X and M) at the level of the solar chromosphere, registered by the H-alpha line, the average fractal dimension is about 1.75.
- Compared to others, especially for the Bastille Day flare, the result of our calculation on the H-alpha image is acceptable.
- The ratio of fractal area to Euclidean area is defined as $l^D/l^2 = l^{7/8}$, (7:8)
- If such a dependence $N \sim \varepsilon^{-D}$ exists for a given object, then this means that it has fractal properties. However, in the case of strong solar flares, the fractal dimension fluctuates significantly.
- Calculation (from H-alpha images) shows that the fractal dimension of a large solar flare varies significantly with scale, indicating its proximity to multifractal properties.
- Indeed, for a quantitative analysis of the physical parameters of flares, it is necessary to take into account the fractal dimension.

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Thank you for your attention!