A Fractal Analysis of Solar Active Regions

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Abstract

Using white light and magnetogram images for 16 active regions (ARs), the fractal dimensions for umbral and penumbra regions as well as the underlying strong and weak magnetic fields were found to be 2.09 ± 0.42, 1.72 ± 0.40, 1.79 ± 0.49 and 1.96 ± 0.29 respectively, using the area-perimeter method. Utilizing the fractal dimensions as an indicator for complexity, it was observed that less complex, strong magnetic fields produced more complex umbral regions while the more complex, weak magnetic fields produced less complex penumbral regions. These observations support a recent model of sunspot formation where strong magnetic fields are trapped within the umbra resulting in a reduced freedom of motion, therefore forming less complex structures indicated by the lower fractal dimensions. However, trapped, strong magnetic fields reduce the temperature in umbral regions leading to more complex umbral structures. In the penumbral regions, unbound, weak magnetic fields are free to form complex structures indicated by the higher fractal dimension while the higher temperatures form more complex penumbral structures. It was also determined, through an initial temporal analysis, that the changes in complexity between the umbral and penumbral regions may be linked.

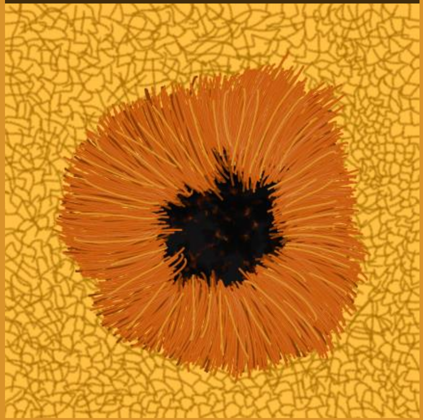
Related publications:

- Rajkumar, Brandon, and Shirin Haque. 2020. "A Fractal Analysis of Magnetograms Within Active Regions." *Solar Physics* 295 (2):10.
- Rajkumar, B., S. Haque, and W. Hrudey. 2017. "Fractal Dimensions of Umbral and Penumbral Regions of Sunspots." *Solar Physics* 292.

View of the sun from the SATU Observatory, UWI, St. Augustine, Trinidad and Tobago.

AR 12670 taken from the SATU Observatory.

Sunspot Drawing by Brandon Rajkumar.



Introduction

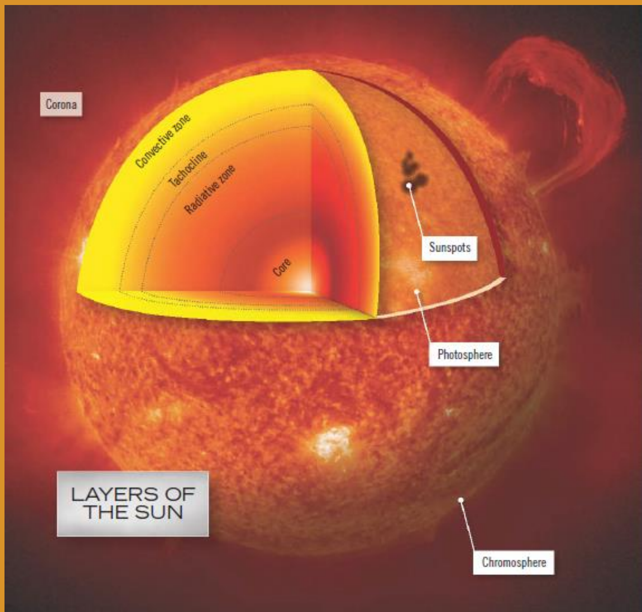


Figure 1 (left) : Diagram showing main layers and some phenomena of the sun (Cooper 2013)

The Sun is complex and dynamic with many features being driven by the underlying solar magnetic fields, the most prominent of which are sunspots. Sunspots are observed on the photosphere (visible surface) of the sun.

These sunspots are also considered natural fractal phenomena as they exhibit many fractal properties. Fractals refer to a type of geometry which describes the complexity of shapes or objects in terms of a non-integer number.

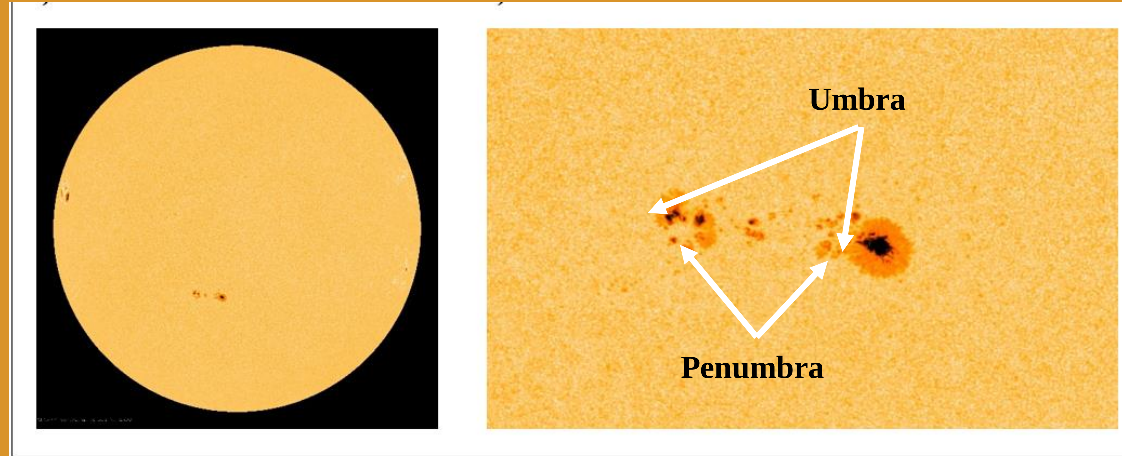


Figure 2: Flattened Intensity full disk and cropped image of AR 12367 on 16th June 2015

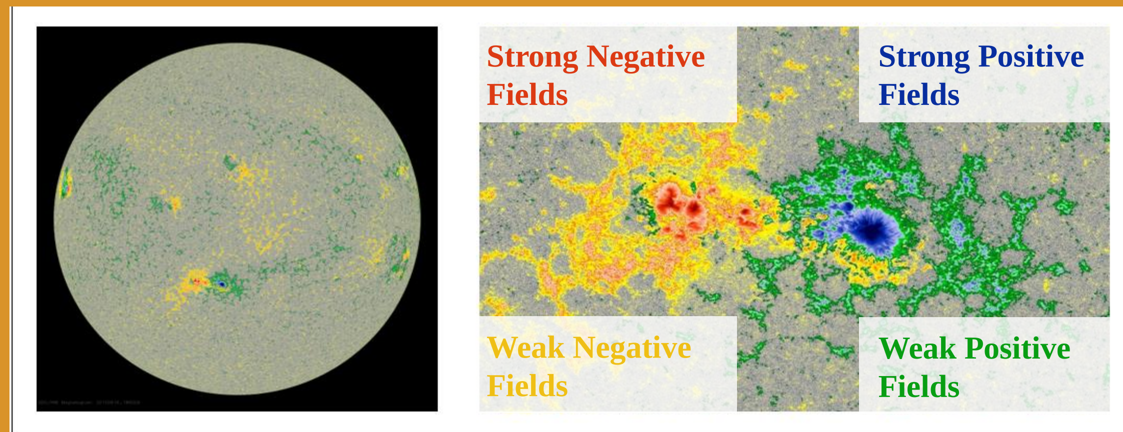


Figure 3: Colour Magnetogram full disk and cropped image of AR 12367 on 16th June 2015

Flattened Intensity images show the sunspot structures on the photosphere, such as the umbra and penumbra, while colour magnetogram images show the underlying magnetic fields that drive them. Colour magnetograms divide the magnetic fields into four main magnetic field groups: strong positive, weak positive, strong negative and weak negative magnetic fields.

Method and Results

The fractal dimension of each structure (umbra, penumbra, strong magnetic fields and weak magnetic fields) is determined by using the Area-Perimeter method which relates the area (S) of each structure to its respective perimeter (L) by

$$S \sim L^q$$

Therefore, $q = {}^{Log\ S}/_{Log\ L}$

Where q is related to the fractal dimension (d) by

$$d = {}^{2}/_{q}$$

A preliminary temporal analysis was performed on AR 12403 over a period of 8 days with a temporal resolution of 1 day. A correlation of r = 0.623, it suggests that changes in complexity between the umbra and penumbra may be linked.

Table 1: Fractal dimensions *d* determined for each structure

Structure	**Fractal Dimension**
Umbra	2.09 ± 0.42
Penumbra	1.72 ± 0.40
Strong Magnetic Fields	1.79 ± 0.49
Weak Magnetic Fields	1.96 ± 0.29

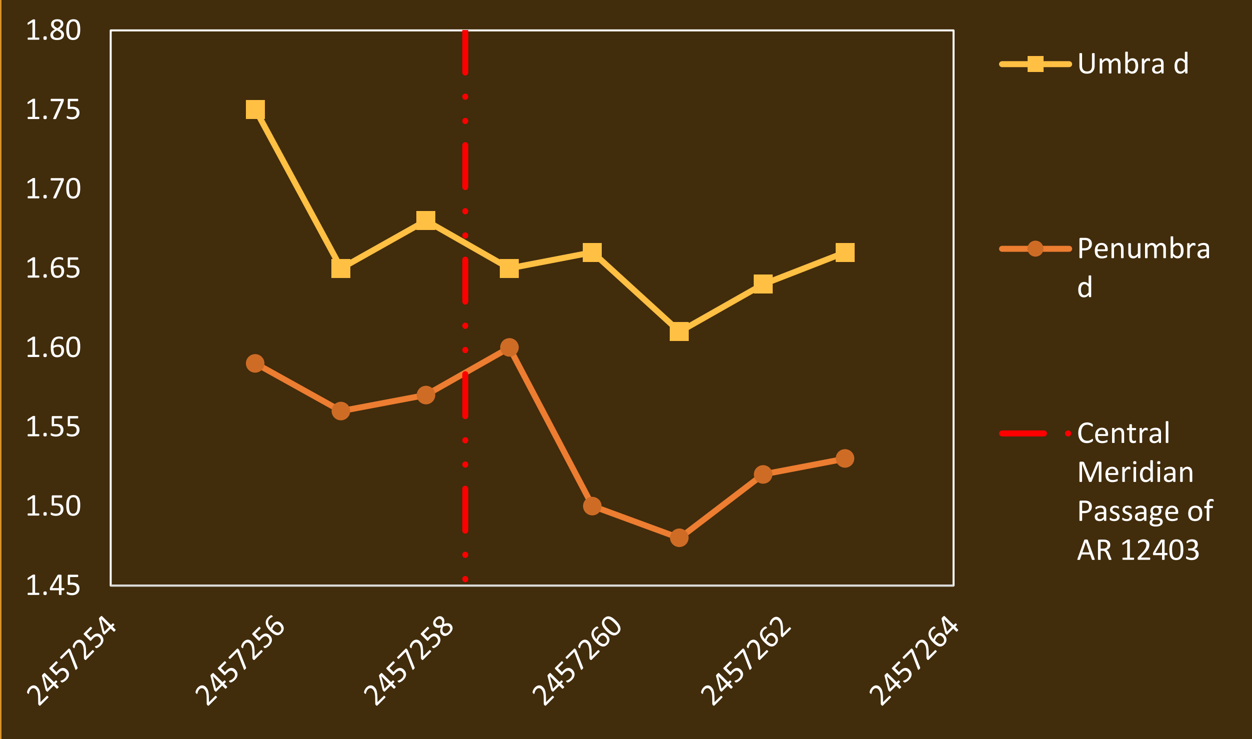
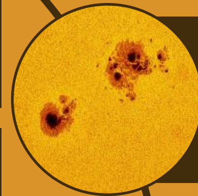


Figure 4: Time series of fractal dimension for AR 12403 for the umbrae and penumbrae

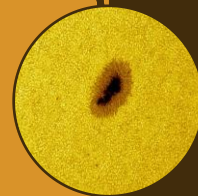
Discussion and Conclusion

It was observed that strong magnetic fields dominate the umbral regions while weak magnetic fields dominate the penumbral regions.

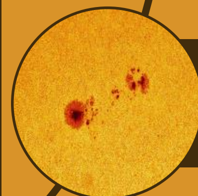
Using the fractal dimensions determined as an indicator for complexity of these regions, it was determined that more complex weak magnetic fields result in less complex penumbral structures while less complex strong magnetic fields result in more complex umbral structures. These results support a recent model of sunspot formation proposed by (Jaeggli, Lin, and Uitenbroek 2012).



Cooler temperatures within the umbra allow for the formation of molecular hydrogen. As they move toward the umbra/penumbra boundary, temperatures increase leading to an increase in ionised hydrogen.

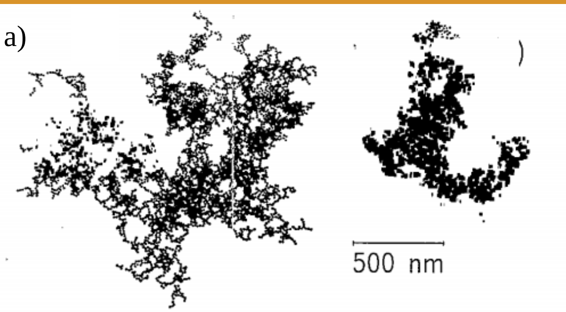


This results in an increased outer pressure which traps strong magnetic fields within the umbra region. Trapped magnetic fields suggest a reduced freedom of motion and thus the formation of less complex (strong) magnetic structures.



Unbound weak magnetic fields within the penumbral regions are free to move, twist and form more complex structures.

a)



b)

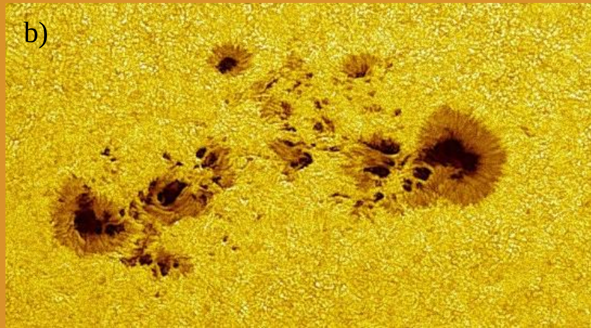


Figure 5 (left): Comparison of a) gold colloid structure and b) active region

Using an unrelated gold colloid analysis (Weitz et al. 1985) as an analogy for umbral and penumbral structure formation, it is suggested that an increased abundance of molecular hydrogen in the umbra leads to more complex umbral structures while the greater abundance of ionised hydrogen in penumbral regions result in less complex penumbral regions.

Further fractal analysis of active regions may present a quick and simple method for predicting their behaviour and thus the behaviour of solar magnetic activity.

References:

Jaeggli, Sarah A, Haosheng Lin, and Han Uitenbroek. 2012. "On molecular hydrogen formation and the magnetohydrostatic equilibrium of sunspots." *The Astrophysical Journal* 745 (2): 133. https://doi.org/10.1088/0004-637X/745/2/133.

Weitz, DA, JS Huang, MY Lin, and J Sung. 1985. "Limits of the fractal dimension for irreversible kinetic aggregation of gold colloids." *Physical review letters* 54 (13): 1416. https://doi.org/10.1103/PhysRevLett.54.1416.

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