Analysis of Sunspot Groups Evolution Based on The Fractal Dimension of AR12192 and AR12209

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ABSTRACT

The area with a strong magnetic field on the Sun is an active region (AR). It is indicated by the presence of sunspots. The large AR has a long lifetime evolution and can produce recurrent sunspots (RS) and trigger lots of solar activities. AR12192 is the largest AR of the 24th solar cycle which occurred on October 18, 2014. AR12192 reemerged as the RS, AR12209 on November 13, 2014. This study analyzed the evolution of AR12192 and AR12209 by measuring their fractal dimension (FD) throughout their lifetimes. The analysis of FD was conducted on heliographic longitude ≤~60 to minimize the projection effect. The images of each AR were taken from Solar Dynamic Observatory (SDO) with Helioseismic and Magnetic Imager (HMI) Continuum filters. The evolution of ARs can be analyzed from the linear regression relationship between the FD value to time during their lifetimes. Based on this research, the FD value of AR12192 was increasing with the range of 1.31 to 1.52, but the FD value of AR12209 was decreasing with the range of 1.12 to 1.35. These results implied that the complexity level of AR12192 is greater at the beginning than at the end of its total evolution.

Keywords: *Sunspot – Evolution – Fractal*

1 INTRODUCTION

Sunspots are the region of the solar surfaces with a strong magnetic field that generally appear in groups called active regions (ARs). The strong magnetic field on sunspots triggers lots of solar energetic activities, such as solar flares and coronal mass ejections (CMEs). Sunspots within AR are evolving which indicates the magnetic field inside the AR is changing throughout their lifetime.

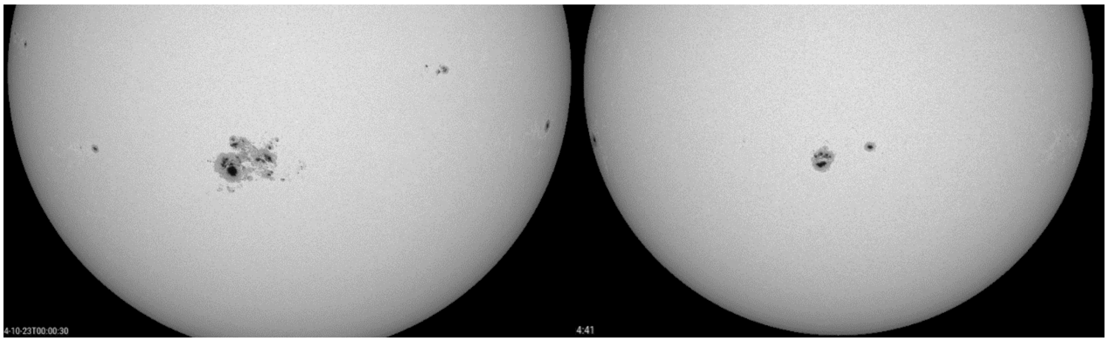
The evolution of sunspot groups is generally based on the size of AR and the magnetic complexity (Loughhead & Bray, 1961, and related literature therein; McIntosh, 1990; McAteer et al., 2005, and related literature therein). A previous study by (Loughhead & Bray, 1961; McIntosh, 1990; Klicik et al., 2018, and related literature therein) noted that larger and more complex ARs produce numerous and higher energy of solar flares. The size of an AR is evolving throughout its lifetime. It is increasing at the beginning of its evolution until it reaches the maximum value of the total area, and then decreasing at the end of its evolution. Also, the magnetic complexity of an AR is increasing at the beginning and then decreasing at the end of its evolution. It is implied that the evolution of sunspot groups determined the productivity of solar flares.

The complexity level of an AR's image can be measured using the fractal dimension (FD) that was initially introduced by Mandelbrot (1983). FD is the complexity level of a fractal object. A fractal geometry object is an object that has roughness and irregular shape of the geometric structure with infinitely complex and has the self-similarity of a shape across multiple size scales. The study of FD is used to analyze the complexity and quantification of irregular shapes of the geometric structure, in this case, sunspot group or AR (Zaffar et al., 2020). The FD of the AR's image is determined by the magnetism aspect. It was characterized by the penumbral indebtedness of the sunspot (Milovanov & Zelenyi, 1992).

This study analyzes the total evolution of AR12192 as the largest sunspot group on the 24th solar cycle using FD. AR12192 occurred on October 18, 2014, and reemerged as the recurrent sunspot (RS) which is AR12209 that occurred on November 13, 2014. In this study, the measuring of FD value of each ARs was using the box-counting method. Further, the analysis of FD values of each ARs during their lifetime is not only a predictor of their evolution but also associated with solar energetic events like solar flares.

2 METHODS

The data of sunspot groups evolution in this research is originated from the solar disc images that consist of AR12192 and AR12209. The images of each ARs were taken from the database Institute D'Astrophysique Spatiale (IAS) SDO using an HMI Continuum filter. The images of each ARs measured on heliographic longitude ≤~60 degrees to minimize the projection effect that starts from October 19, 2014 to October 27, 2014 for AR12192 and November 16, 2014 to November 23, 2014 for AR12209. Figure 1 consists of sample images of AR12192 and AR12209 which are used in this research.



(a) **(b)**

Figure 1. Images of AR12192 (a) and AR12209 (b) that took from IAS SDO using an HMI Continuum filter.

AR12192 showed six X-class solar flares during its passage. But, it only released four X-class solar flares considering the projection effect. Instead, the AR12209 did not trigger any X-class solar flares, only C-class. However, AR12192 was more active than AR12209 as the Recurrent Sunspot group (RS) of AR12192. Therefore, study about sunspot group's evolution is vital to predict solar flares.

The analysis of sunspot groups evolution in this research is carried out by observing the linear regression relationship between FD value against time for each ARs during their lifetime using python Spyder. The FD value was measured by the box-counting method from ImageJ software.

Generally, FD represents the complexity level of a complex object that has a roughness, fragmentation pattern, and irregular shape of the geometric structure. It has the self-similarity of a shape across multiple size scales. The Hausdorff–Besicovitch box dimension or simply box-counting method is one of the techniques to calculate the FD (Zaffar et al., 2020). The box-counting method samples an image and counts how many boxes with a specific dimension can cover up the image. The process is repeated with different box dimensions and the rate of the number of box that can cover the image will define its dimension. The FD value is obtained from the slope of the curve between the log number of boxes (N) as the y-axis and the log scale of the box size (ε) as the x-axis. The FD of an object can be calculated by taking a ratio between the log number of the box (N) and log (ε) that can be express mathematically as,

$$FD = \frac{\log N}{\log \varepsilon}. \tag{1}$$

Note that a higher FD value represents a higher complexity of the image. Besides, FD expresses the space-filling property of the data whereas, the Hurst exponent (HE) is used to represent the smoothness of the data in this research (Hassan et al., 2014). The relation between FD and HE expressed as follows,

$$FD = 2 - HE. \tag{2}$$

HE lies between 0 to 1. Considering the relationship of FD and HE, HE particularly compares persistence, anti-persistency, and Brownian nature of the time series data (Salakhutdinov et al., 1998; Hassan et al. 2014; Zaffar et al. 2020). If HE value approaches 1, the data is quasi-regular (persistent). If it approaches zero, the data is irregular (anti-persistent). Meanwhile, HE=0.5, the data represented as a Brownian process.

3 RESULTS AND DISCUSSION

This research was conducted to analyze the evolution of AR12192 and AR12209. The analysis is based on FD using the box-counting method for both ARs during their lifetime. Linear regression is also performed to correlate the relationship between FD values to the days of the year (doy) for both ARs. Otherwise, HE used to define the natural behavior of the data.

Figure 2 presents the change of FD value with respect to the doy for AR12192 together with the linear regression along its lifetime. It shows that the FD value of AR12192 ranges from 1.31 to 1.52 with mean value is 1.46. Therefore, the HE value of AR12192 ranges from 0.69 to 0.48 with mean value of 0.585. It indicates that the FD value of AR12192 is persistent. Meanwhile, the linear regression line has an equation as follows,

$$y = (12.1 \pm 3.5) \times 10^{-3} x + (-2.1 \pm 1.0), \tag{3}$$

where y is FD value and x is doy. From that equation, the correlation of FD value to doy of AR12192 is represented by its gradient. The value of the gradient is $(12.1\pm3.5)\times10^{-3}$. It means that the FD value to the time of AR12192 has a positive correlation.

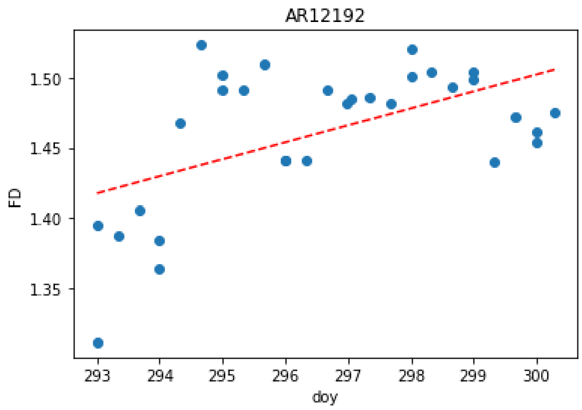


Figure 2. Linear regression relationship between FD value against doy of AR12192.

Whereas, Figure 3 shows the change in FD value with respect to the change of the doy for AR12209. Based on the data, the FD value of AR12209 ranges from 1.12 to 1.35 with mean value is 1.27. So, the HE value of AR12209 has range from 0.65 to 0.88 with mean value of 0.765 which indicates the data of AR12209 is persistent. Meanwhile, the linear regression line of AR12209 has an equation as follows,

$$y = (-5.6 \pm 4.6) \times 10^{-4} x + (-1.5 \pm 1.5), \quad (4)$$

where y is FD value and x is doy. The gradient of the linear regression equation is $(-5.6\pm4.6)\times10^{-4}$ which means the correlation of FD value to time on AR12209 data has a negative correlation.

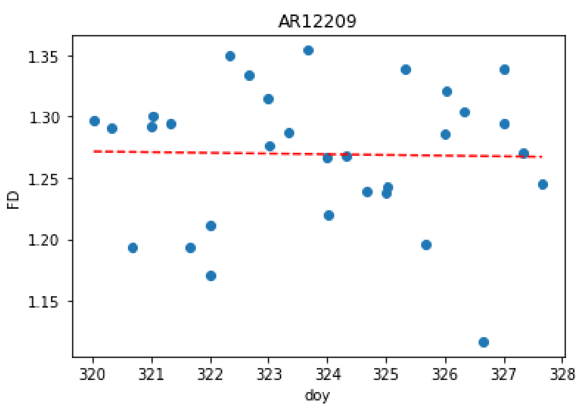


Figure 3. Linear regression relationship between FD value against doy of AR12209.

Based on those results, the complexity level of AR12192 is increasing during its lifetime which is shown from the positive value of the gradient. Besides, AR12209 as the RS of AR12192 was decreasing during its lifetime which is shown from the negative value of the gradient. That means the FD value or complexity level of AR12192 for total evolution was increasing in the beginning and decreasing at the end of its evolution. The range for the total evolution of AR12192 is from 1.12 to 1.52 with mean value about 1.37. It has a similar range as the previous study by (Zaffar et al., 2020) that had a range of AR12192 from 1 to 1.5 for its total evolution. They also used the Hausdorff-Besicovitch box dimension and correlation dimension for their research. Based on that result, they interpreted that AR12192 is persistent and correlated. Other studies by (Herdiwijaya and Indradjaja. 2002) found that the FD value for sunspot groups from January 1749 until December 2000 had a range from 0.5 to 1.5. They interpreted that the granulation dimension of the Sun correlated to the maximum area in its interior. Simply, the study of the solar cycle also can be analyzed using FD of the sunspots.

In this research, the mean value of FD is about 1.37. Another research by (Milovanov and Zelenyi. 1992) found the mean value of sunspots FD is about 1.24. This research has a higher value of FD than than that from the previous research. It is because AR12192 is the largest sunspot on the 24th solar cycle and was ranked as the 33rd largest region out of 32908 ARs since 1874. So, it has a more complex texture than other sunspots in general.

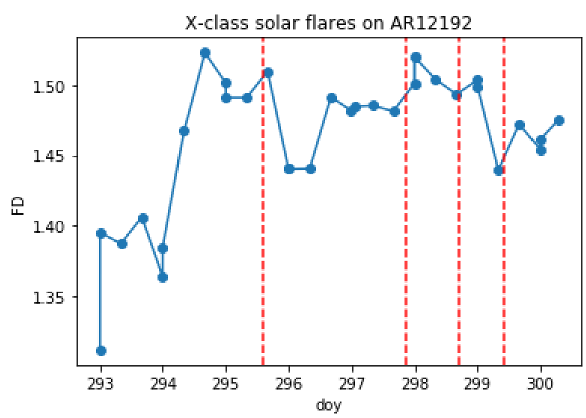


Figure 4. Plotting data of X-class solar flares which occured on AR12192. The dash-line represent the occuring time of X-class flares.

AR12192 as the largest sunspot group also produced many solar flares including X-class solar flare. It produced six X-class solar flares during its passage, but only four X-class solar flares that conducted due to the consequence of the projection effect, namely X1.6 on October 22, 2014, X3.1 on October 24, 2014, X1.0 on October 25, 2014, and

X2.0 on October 26, 2014. It indicates that AR12192 is more active than AR12209 that only produced C-class solar flares. It can also be interpreted that AR12192 which has a higher value of FD would produce energetic solar flares than the smaller one. Figure 4 shows the relationship of FD value to the doy with detection of X-class solar flares on AR12192. Based on the plotted data, this research found that the X-class solar flares on AR12192 occurred when the FD value >~1.42. Previous studies by (McAteer et al., 2005) found that X-class flares require a minimum FD value=1.25. Other results from minimum FD value for M-class flares was also performed and it requires FD value=1.2. Their research also used the box-counting method to measure the FD value. So, it indicates that this result is compatible.

Other research by (Dominiguez et al., 2014) who studied the complexity of geomagnetic – a solar magnetic activity made a conclusion that the FD value of solar magnetic is correlated with solar activity indexes, such as solar flare or CME. Therefore, a study about FD is also evidenced as guidance to predict solar energetic activity.

4 CONCLUSIONS

This study reveals the evolution of AR12192, AR12209, and the total evolution of AR12209 based on the FD value using the box-counting method. The FD value represents the complexity and roughness of the image of each ARs. Based on this research, the FD value of AR12192 was increasing with the range of 1.31 to 1.52, the FD value of AR12209 was decreasing with the range of 1.12 to 1.35. Therefore, the FD value for AR12192 total evolution has a range from 1.12 to 1.52. These results implied that the complexity level of AR12192 is greater at the beginning than at the end of its total evolution. The FD value depends on the magnetic aspects of the sunspot groups which show from the area of AR, the number of sunspots on AR, etc. The study about FD value also allows us to use it as the guidance to predict solar energetic activities, in this case, solar flares. Hence, analysis on FD value of AR is compatible to use for studying sunspot groups evolution. Furthermore, it can be used for predicting solar energetic activities.

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