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ORIGINAL ARTICLE

A new technique for the calculation and 3D visualisation of magnetic complexities on solar satellite images

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Abstract In this paper, we introduce two novel models for processing real-life satellite images to quantify and then visualise their magnetic structures in 3D. We believe this multidisciplinary work is a real convergence between image processing, 3D visualisation and solar physics. The first model aims to calculate the value of the magnetic complexity in active regions and the solar disk. A series of experiments are carried out using this model and a relationship has been indentified between the calculated magnetic complexity values and solar flare events. The second model aims to visualise the calculated magnetic complexities in 3D colour maps in order to identify the locations of eruptive regions on the Sun. Both models demonstrate promising results and they can be potentially used in the fields of solar imaging, space weather and solar flare prediction and forecasting.

Keywords Active regions · Solar disk · Solar flares · Magnetic complexity · Energy · Satellite images · 3D Sun

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Abbreviations

MDI	Michelson Doppler Imager
SOHO	Solar and Heliospheric Observatory
ESA	European Space Agency
NASA	National Aeronautics and Space Administration
NGDC	National Geophysical Data Center
GIF	Graphic Interchange Format
NOAA	National Oceanic and Atmospheric Administration
OpenGL	Open Graphics Library
ASAP	Automated Solar Activity Prediction

1 Introduction

Research and interest in the field of space weather and solar activities is growing because of the significance of their potential impact on human lives and activities. The term space weather is applied to the space environment around the Earth and all the way to the Sun. Space weather is defined as the "conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-born and ground-based technological systems and can endanger human life or health. Adverse conditions in the space environment can cause disruption of satellite operations communications, navigation, and electricity power distribution grids, leading to a variety of socioeconomic losses" [1–3]. In the past, few solar activities have affected the Earth and caused notable damage. In March 1989, power grids in north-east Canada collapsed during a great geomagnetic storm which left millions of people without electricity [4]. Another large event occurred during the end of October beginning of November 2003 period, when the largest ever recorded X-ray

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flare occurred, known as the Halloween solar storm. It damaged 28 satellites, knocking two out of commission, causing airplane routes to be diverted and power failures in Sweden and other countries [5, 6]. Thus, there is an urgent need to develop preventive measures capable of reducing the risks associated with space weather events, by introducing either a system design or efficient warning and prediction systems [3, 7]. This will allow industries at risk to take preventive measures to avoid or mitigate the consequences of these events. Space weather and solar activities are both directly influenced by the Sun. As such it is important to study the Sun and its activities in order to have a good understanding of its influence on space weather [1]. Solar flares are the most remarkable solar activities which drive space weather and affect the terrestrial environment as they spew vast quantities of radiation and charged particles into space [8, 9]. Flares are defined as sudden, rapid, and intense variations in brightness that occurs when the magnetic energy that has built up in the solar atmosphere is suddenly released, over a period lasting from minutes to hours. Flares emit strong radiation such as radio waves, X-rays and gamma rays, and energetic particles (protons and electrons) [10]. Solar flares mostly occur in active regions, as such, it is important to study active regions in order to have a good understanding of flares. Active regions are regions on the Sun usually form with sunspots, and they are studied in order to forecast solar activities. Solar active regions are associated with particularly strong and complex magnetic fields, which emerge through the photosphere into the chromosphere and corona. This creates suitable conditions for the release of enormous amounts of energy in the form of solar flares. Understanding this energy is important as it aids the prediction of solar eruptions, such as solar flares as well as other solar activities.

The work presented here demonstrates recent developments in our ongoing efforts to design a web-based, automatic and real-time system for predicting and forecasting solar flares. Two new models are introduced in this paper. Both models were executed using daily solar images captured by MDI (Michelson Doppler Imager) instrument on board of the SOHO (Solar & Heliospheric Observatory) satellite [11]. The first model introduces a method to calculate the magnetic complexity in active regions and in the solar disk for the purpose of solar flare prediction. The magnetic complexity calculation model is based on the famous physical Ising model [12]. The Ising model has been modified to fit the nature of this application. The method introduced here is the latest updated version, which is better fitted to imitate the property of the magnetic fields connections in active regions. More details about the original Ising model and the earlier models can be found in our previous publications [13, 14]. The magnetic complexities were calculated for number of different groups of active regions and solar disk samples. Then, their values were plotted against flare events that have occurred during the same period and location. This has revealed a clear relationship between the recorded magnetic complexities and flare events. The second model visualise the solar disk, active regions, and the calculated magnetic complexity in 3D colour maps. This model reconstructs the studied magnetogram image and represents it for 3D view. Also the model can view a 3D colour map of active regions according to their polarity or to the calculated magnetic complexity. This can identify the potentially eruptive regions. The models proposed in this paper offer a new approach to observe solar images for the purpose of solar flare prediction and forecasting.

This paper is organised as follows: solar data sources are introduced in Sect. 2. Section 3 introduces the magnetic complexity calculation model and how it has been used to calculate the magnetic complexity in active regions and in the solar disk. Section 4 describes the 3D visualisation model. Finally, the conclusion and future work is discussed in Sect. 5.

2 Solar data

2.1 Satellite images

SOHO/MDI magnetogram images have been used in this work. These images are captured by MDI (Michelson Doppler Imager) instrument, which is on board the SOHO (Solar and Heliospheric Observatory) satellite. SOHO is a project of international cooperation between ESA (European Space Agency) and NASA (National Aeronautics and Space Administration). SOHO/MDI magnetogram images are available publicly online[1] in GIF format (Graphic Interchange Format). The magnetogram images record the line-of-sight components of the magnetic fields on the solar disk [15] as shown in Fig. 1. These images are used in this work because they show the strength and location of the magnetic fields on the Sun, which makes them well suited for magnetic complexity calculation method. There are around 15 SOHO/MDI magnetogram images available per day. Every two images are separated by approximately a 90 minute gap. This is beneficial for the use of the proposed models in terms of tracking the changes in the magnetic complexity values of the active regions in relation to flare occurrence. MDI magnetogram images are in greyscale, where pixel intensities range from 0–255. The minimum pixel intensity value represents black, while the maximum pixel intensity value represents white. Each colour represents the magnetic polarity distribution on the solar disk. The grey areas indicate regions with minimum magnetic energies, while the black

[1] http://soi.stanford.edu/production/mag_gifs.html

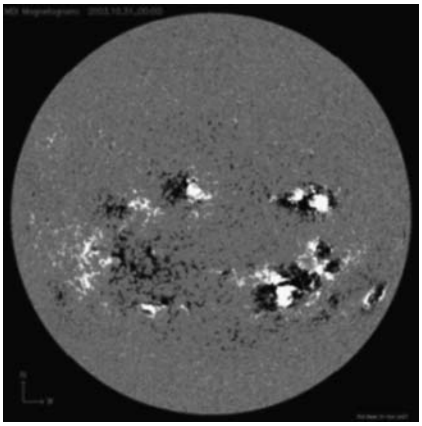


Fig. 1 SOHO/MDI magnetogram image

and white regions indicate strong magnetic fields. The black regions indicate "south" magnetic polarity (pointing towards the Sun), while white regions indicate "north" magnetic polarity (pointing outwards) [16].

2.2 NGDC flare catalogues

Solar flare catalogues obtained from the National Geophysical Data Center (NGDC) have also been used in this work. These catalogues are available for public access online.[2] NGDC holds one of the most comprehensive public databases for solar features and activities records from several observatories around the world. The NGDC flare events catalogues include full details about flares, such as flare's date, time, location, classification, intensity and NOAA number. Flares are classified according to their X-ray brightness as follows: A, B, C, M, or X. A and B flares are the weakest, while M and X flares are the strongest. C flares are weak in comparison to M and X flares and they could have few noticeable impacts on space weather. M and X flares are more related to major impacts on space weather, especially X flares. The NOAA number is a unique number, for each active region, given by the National Oceanic and Atmospheric Administration (NOAA). Using the NOAA number, flares can be assigned to the active regions that they have originated from. However, not all of the recorded flares are assigned to a NOAA number. This could be related to the difficulty of assigning a flare to the right active region, especially during solar maximum when in some scenarios active regions could be attached to or in a group of complex active regions, or the recorded flare might have occurred on the far side of the Sun.

[2] ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA

3 The magnetic complexity model

The idea of the magnetic complexity calculation model is based on the relationship between the energy stored in the magnetic fields of active regions and flares erupting from these regions. The magnetic complexity calculation model is derived from the Ising model. The Ising model is used for the analysis of magnetic interactions and structures of ferromagnetic substances [12]. This model allows for the simplification of complex interactions, since it has been successfully employed in several areas of science. The Ising model has been applied to many physical systems such as: magnetism, binary alloys, and the liquid-gas transition [17]. The model was also used in biology to model neural networks, flocking birds and beating heart cells [18–20]. Between 1969 and 1997, more than 12,000 papers were published using this model in different applications, which shows the importance and potential of this model [21]. For the first time, the Ising model has been modified and then applied to model the properties of magnetic fields formation in active regions and calculate the magnetic complexity of active regions. More details about the original Ising model and the first attempts of the modified model can be obtained in our previous publications [13, 14]. However, further modifications have been applied to the model since the first attempts in modifying the Ising model. To avoid confusion, it is worth mentioning that the "magnetic complexity" have also been declared as the "energy" in our previous publications. However, the new model imitates the magnetic configurations in active regions, which are the key factor in flare occurrence, to provide more accurate results. The calculated values should provide a new way to indicate the flaring and non-flaring active regions, or even flare classifications. Also, the magnetic complexity calculation model has been applied to calculate the overall magnetic complexity on the solar disk. This will provide a measure of the overall magnetic activities on the front side of the Sun, and therefore can be an important indicator for flare occurrences in general.

SOHO/MDI magnetogram images are used in this work. The magnetogram images are processed and represented in a 2D grid, according to pixel intensities. Each pixel value in the magnetogram image is represented in the grid as follows.

- Pixel intensity values between 0 and 30 represent the *black* areas in the image. These areas indicate a south magnetic polarity and are represented as -1 in the grid.
- Pixel intensity values between 230 and 255 represent the *white* areas in the image. These areas indicate a north magnetic polarity and are represented as $+1$ in the grid.
- Pixel intensity values between 31 and 229 represent the *grey* areas in the image. These areas indicate minimum magnetic energies and are represented as 0 in the grid.

The magnetic complexity is calculated using (1), which only takes the following values as an input: $+1$ and -1.

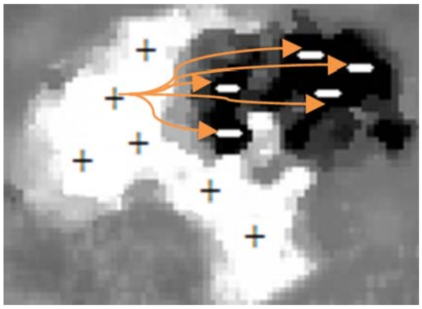


Fig. 2 A sample of an active region showing the interaction between opposite polarity areas according to the magnetic complexity model. Each spin within the *white area* (+) will be multiplied by all the spins in the *black area* (−)

In the equation, S_i represents the north polarity areas only (+1), and S_j represents the south polarity areas only (−1). The magnetic fields in active regions loop from the positive magnetic fields to the negative magnetic fields. This property has been applied to the calculation method. The multiplication goes only from the values representing the positive magnetic fields ($S_i = +1$) to the negative magnetic fields ($S_j = -1$), ignoring the weak polarity areas (0) as shown in Fig. 2, taking into consideration the distance (d) between the interacting spins. N is the number of the total spins (the size of the 2-D grid). E is the total energy or the magnetic complexity, and it is unit-less.

$$E = -\sum_{ij}^{N} \frac{S_i S_j}{d^2} \tag{1}$$

3.1 Calculating the magnetic complexity in active regions

A number of image processing techniques are applied to the MDI magnetogram images, prior to calculating the magnetic complexity in active regions. These procedures are summarised as follows.

- MDI magnetograms record the line-of-sight component of the magnetic fields on the solar disk. In this work it is important to have the magnetic fields of the MDI magnetogram images represented accurately. Due to the projection effect, it was noticed that active regions located near the solar limb were distorted and it was difficult to observe and record the line-of-sight component of the magnetic fields in these regions. Data far from the solar disk are less reliable because of the observing angle correction factor [22]. This leads to inaccurate representations of the active regions located near the solar limb. In order to resolve this problem, the MDI magnetogram image has been re-mapped using the method conducted in [23]. The magnetogram image is re-mapped from heliocentric Cartesian coordinates to Carrington heliographic coordinates. Then, the solar disk is shifted so the investigated active region located in the centre of the image. This is done by selecting the solar disk image which has the active region under investigation located on around zero longitude, in order to use the active region time and location information as a reference point in the shifting process. Finally, the solar disk is re-mapped again to heliocentric Cartesian coordinates. The resulting image shows that the solar disk is shifted and the active region under investigation is located in the centre of the image, as shown in Fig. 3.
- Despite the remapping process, it was noticed that several active regions located near the solar limb were still distorted. Therefore, active regions located above 45° from the centre of the solar disk were discarded.
- Most of the MDI magnetogram images used in this work included a random noise. Hence, it was necessary to apply an image filtering method to reduce the noise in these images. A (3 × 3) Median filter was applied for this purpose. This filter is quite popular due to the excellent noise reduction capability it can provide for certain types of random noise [24]. An example of an active region image before and after applying the median filter is shown in Fig. 4. This means that the new algorithm is more likely to achieve reliable results because better quality images are used.
- The active region under investigation is detected and cropped from the magnetogram image in order to calculate the magnetic complexity using (1), as explained previously.

A number of active regions candidates selected from different period of times, during solar minimum and solar maximum, were experimented with. The NOAA number and date of these active regions are: (*10308* 08/03/2003–18/03/2003), (*10314* 13/03/2003–18/03/2003), (*10365* 20/05/2003–01/06/2003), (*10482* 17/10/2003–27/10/2003), (*10484* 17/10/2003–30/10/2003), (*10486* 25/10/2003–03/11/2003), (*10488* 25/10/2003–03/11/2003), (*10507* 19/11/2003–30/11/2003), (*9393* 24/03/2001–02/04/2001), (*10956* 17/05/2007–21/05/2007). The calculated magnetic complexity values for each of the investigated active regions were compared to the flares that erupted from the same region, and they are both plotted against time. As a conclusion, these active regions have been classified according to their magnetic complexity values as follows:

1. *Non-Flaring Active Regions, Magnetic Complexity < 500*. These active regions were holding very low energy and occasionally were accompanied with few B flares. This can be seen in region 482 as shown in Fig. 5.
2. *Steady Increase Regions, 500 < Magnetic Complexity <10,000*. Active regions within this range usually had a gradual increase in their energy. Flares of type C, M and X

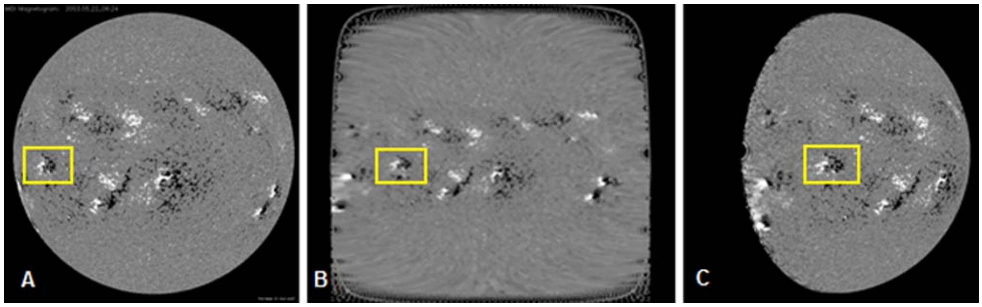
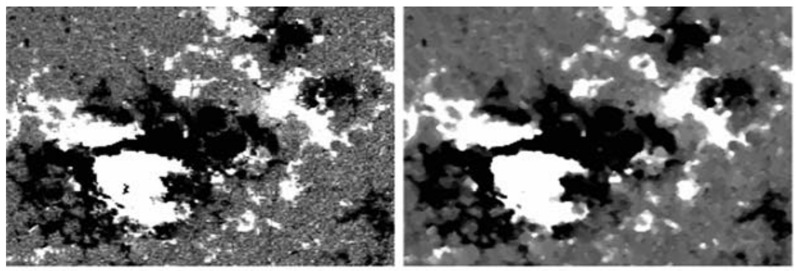


Fig. 3 The three images above shows the re-mapping stages and how it affects an investigated region. Image date: 2003.05.22 06:24. Region NOAA number: 365. (**A**) The original magnetogram image in heliocentric Cartesian coordinates. (**B**) The solar disk represented in Carrington heliographic coordinates. (**C**) The solar disk re-mapped and represented in heliocentric Cartesian coordinates, showing the active regions under investigation near the centre

Fig. 4 An active region before (*left*) and after (*right*) applying the 3 × 3 median filter



NOAA 10486 2003.10.30 00.00

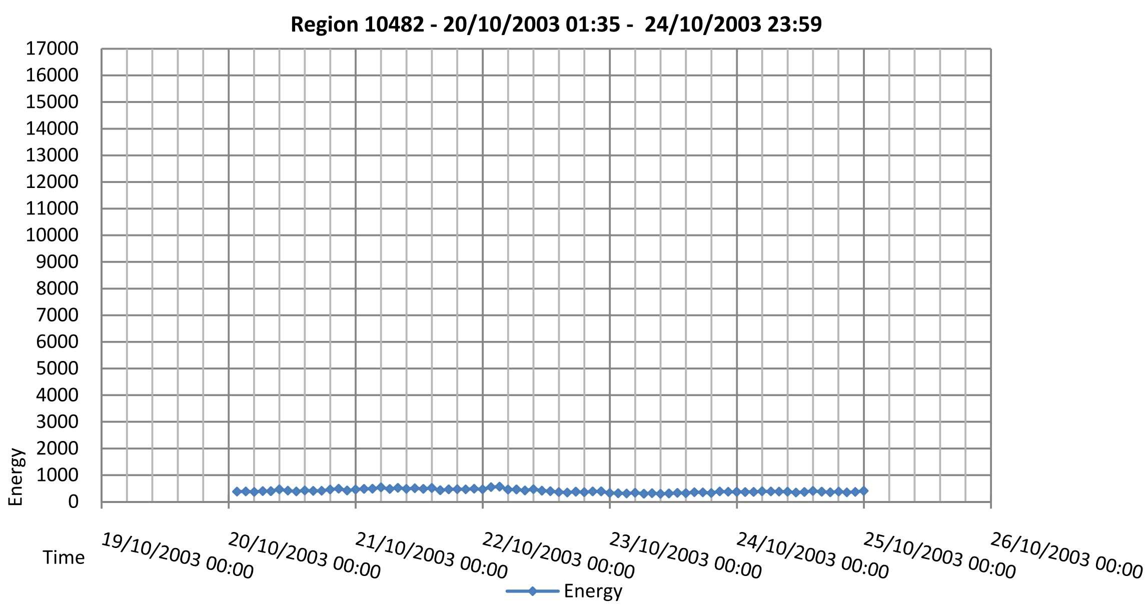


Fig. 5 The curve represents the energy (magnetic complexity) of active region 482. Very low energy and no flares were recorded within the region

erupted as the energy increased. Also, it has been noticed that flares occurred as groups separated by approximately 10 hours. This can be seen in region 365, shown in Fig. 6.

3. *Highly Energetic Regions, Magnetic Complexity > 10,000*. These active regions were holding very high energy, accompanied by high number of flares of type C, M and X. Also, it has been noticed that erupted flares were separated by short time intervals. This can be seen in region 9393, shown in Fig. 7.

Also, it was noticed that the number of flares increases as the energy (magnetic complexity) increases. As a conclusion, these outcomes show a good indication of the state of active regions in relation to flare occurrences.

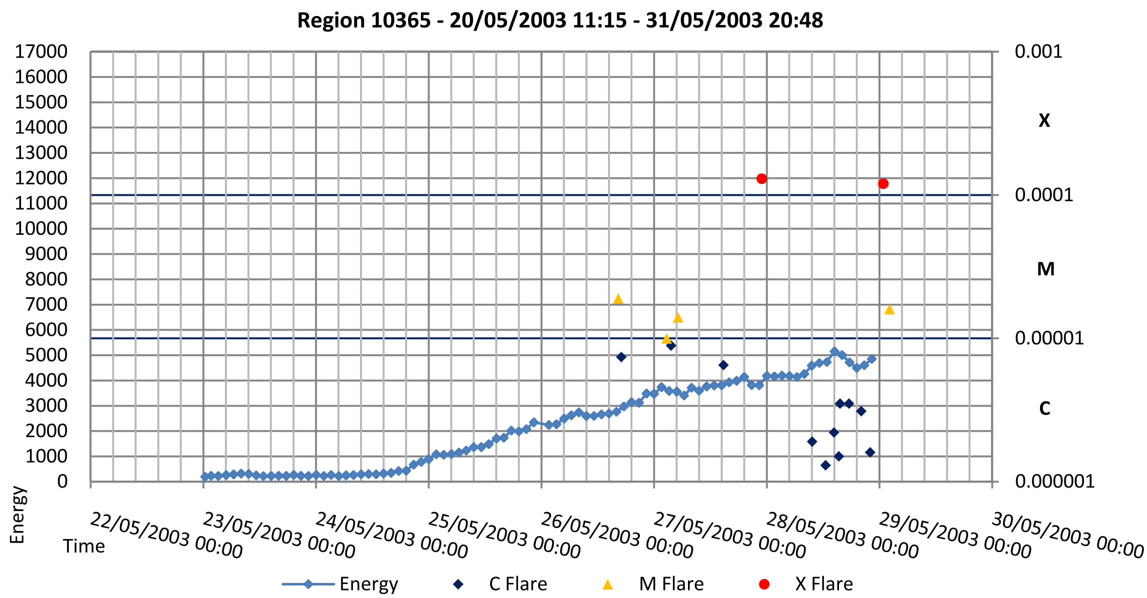


Fig. 6 The curve represents the energy (magnetic complexity) of active region 365. A gradual build up in energy with flares occurred as groups separated by a period of time

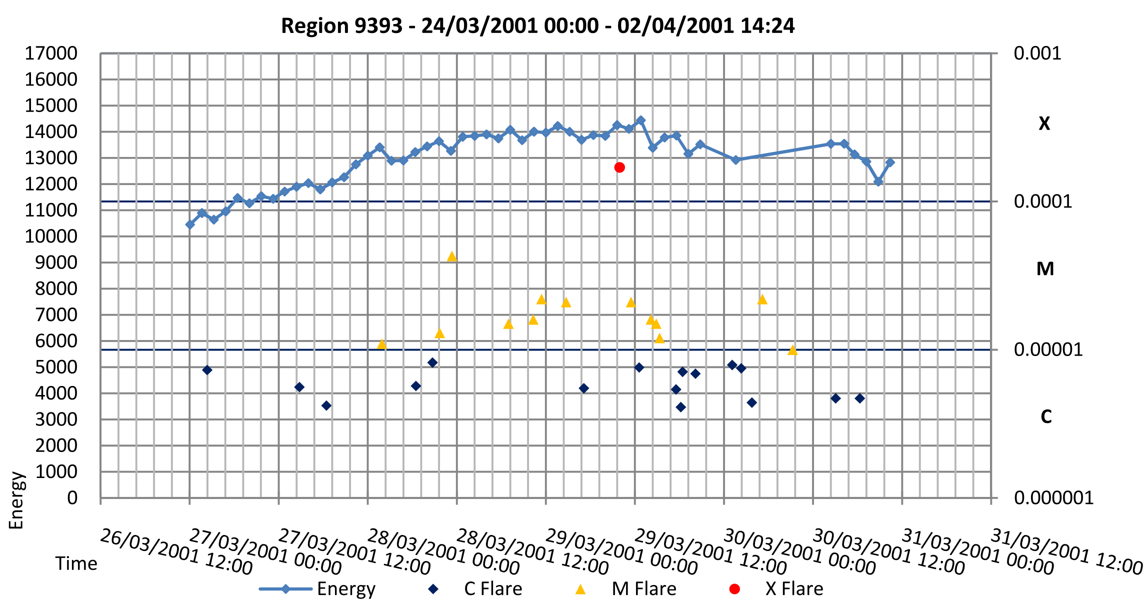


Fig. 7 The curve represents the energy (magnetic complexity) of active region 9393. The energy is very high, accompanied by a high number of flares with short time intervals

3.2 Calculating the magnetic complexity in the solar disk

On many occasions, especially during the solar maximum when the number of sunspots and active regions is high, it is difficult to assign some of the erupted flares to the active regions that they originated from. This is because either there are groups of complex active regions adjacent to one other, or the flare might have occurred on the back side of the Sun. Therefore it is important to have an indicator to reflect the overall status of the solar disk. Based on this, we are introducing a new technique to calculate the solar disk magnetic complexity. The ideology of this method is comparable to the solar cycle and it can be used to determining the overall solar activities on the Sun, which could be useful for flare prediction. A summary of the method's processes is now described.

- The MDI magnetogram image is filtered using the Median filter. This is similar to the approach explained in Sect. 3.1.

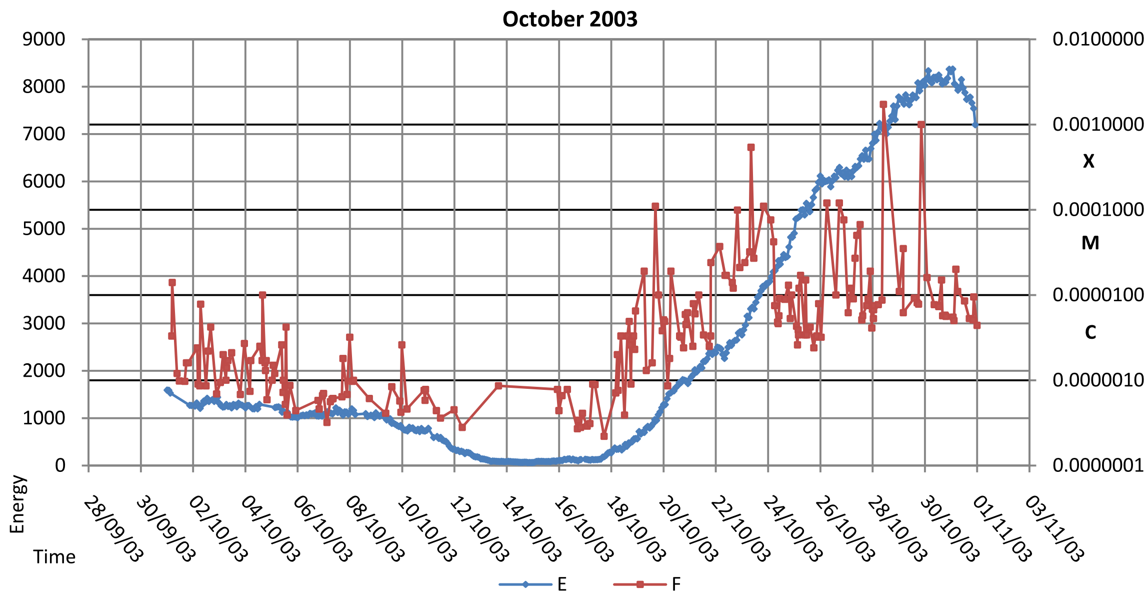


Fig. 8 This plot shows the solar disk energy (magnetic complexity) and flares which occurred in October 2003

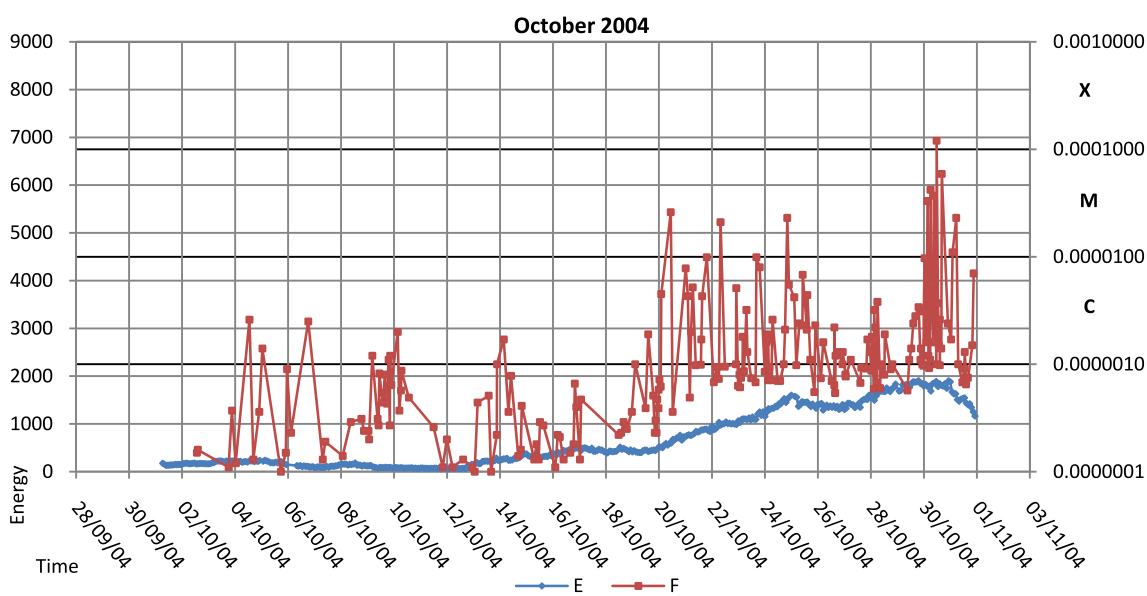


Fig. 9 This plot shows the solar disk energy (magnetic complexity) and flares which occurred in October 2004

- The solar disk is detected in order to exclude the black areas around the disk.
- The magnetic complexity of the solar disk is calculated using (1), as explained previously.

This method has been experimented using MDI magnetogram images over a number of months; April 2001, June 2003, March 2001, March 2003, May 2003, May 2005, May 2007, November 2003, October 2003 and October 2004. The calculated values have been plotted against flares that occurred during the same period. A clear relationship can be noticed between both curves in the plots. As a conclusion, it was noticed that the number of flare events increases with the increase of the solar disk magnetic complexity (energy), and vice versa. Some of the results are shown in Figs. 8, 9, and 10.

4 3D visualisation of the magnetic complexities on the solar disk

A new tool has been developed using OpenGL (Open Graphics Library) program to visualise the solar disk, active regions, and the calculated magnetic complexity in terms of

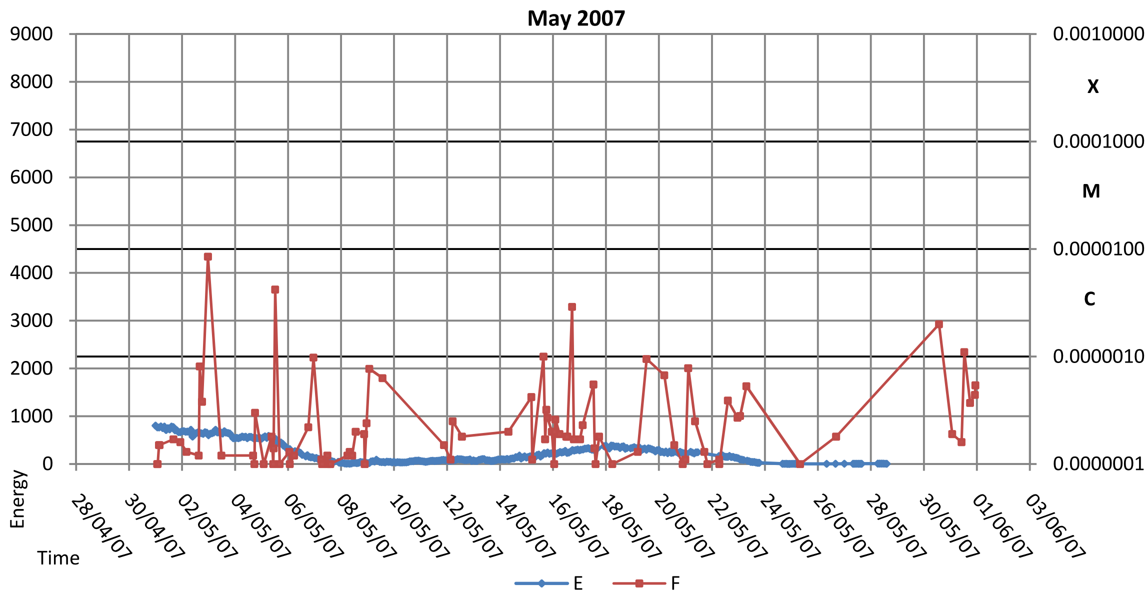


Fig. 10 This plot shows the solar disk energy (magnetic complexity) and flares which occurred in May 2007

3D colour maps. The 3D colour maps offer a new approach to visualise active regions across the solar disk according to their polarities or to their magnetic complexities. This is very useful in terms of identifying the potentially eruptive areas on the solar disk. Viewing the Sun in 3D is very advantageous in comparison with the regular 2D images, as it offers different viewing experience i.e. zooming in/out and navigating through the Sun and solar activities. Also it offers a better viewing of solar activities located near the solar limb. This tool is very constructive; it offers a new approach in visualising and investigating solar activities, and it can be used effectively in the field of space weather research.

The OpenGL-based tool reads a text file as an input, which includes the properties of the extracted features from the magnetogram image under investigation. The steps that have been undertaken to extract the required features are explained here.

- The SOHO/MDI magnetogram image is converted to the Carrington heliographic coordinates. Using the method employed in [23].
- Active regions are detected from the heliographic coordinate image, using intensity filtering. The intensity filtering threshold value T_f for each image is found automatically using (2), where, μ is the mean, σ represents the standard deviation, and α is a constant that is determined empirically based on the type of the features to be detected and the images.

$$T_f = \mu \pm (\sigma \times \alpha) \tag{2}$$

The value of the first threshold is determined using (2) with the plus (+) sign and α equal to 2. All pixels that have intensity values larger than this threshold are marked as active regions with north polarity. In the same manner, the second threshold is determined using (2) with the minus (−) sign and α equals to 2. Any pixel with intensity value less than this threshold is marked as an active region with south polarity.

- After detecting the pixels that represent active regions, the magnetic complexity values are calculated using (1) and represented as colours ranging from red to green. Here red represents the highest complexity and green represents the lowest complexity.
- Then using (3), 3D Cartesian coordinates of each pixel are calculated. In this equation, B is equal to latitude, L is equal to longitude of the detected solar pixel and r is equal to the radius of the solar disk that the new data are mapped to:

$$\begin{aligned} x &= r \sin(B)\cos(L) \\ y &= r \sin(B)\sin(L) \\ z &= r \cos(B) \end{aligned} \tag{3}$$

- All the calculated 3D coordinates of the pixels are recorded to text files along with their colour values and visualised using the OpenGL-based 3D tool.

This tool has been tested on the same active regions that had their magnetic complexities values investigated previously in Sect. 3.1. The results of this model are shown in Fig. 11 in three groups: (A), (B), and (C), and they can

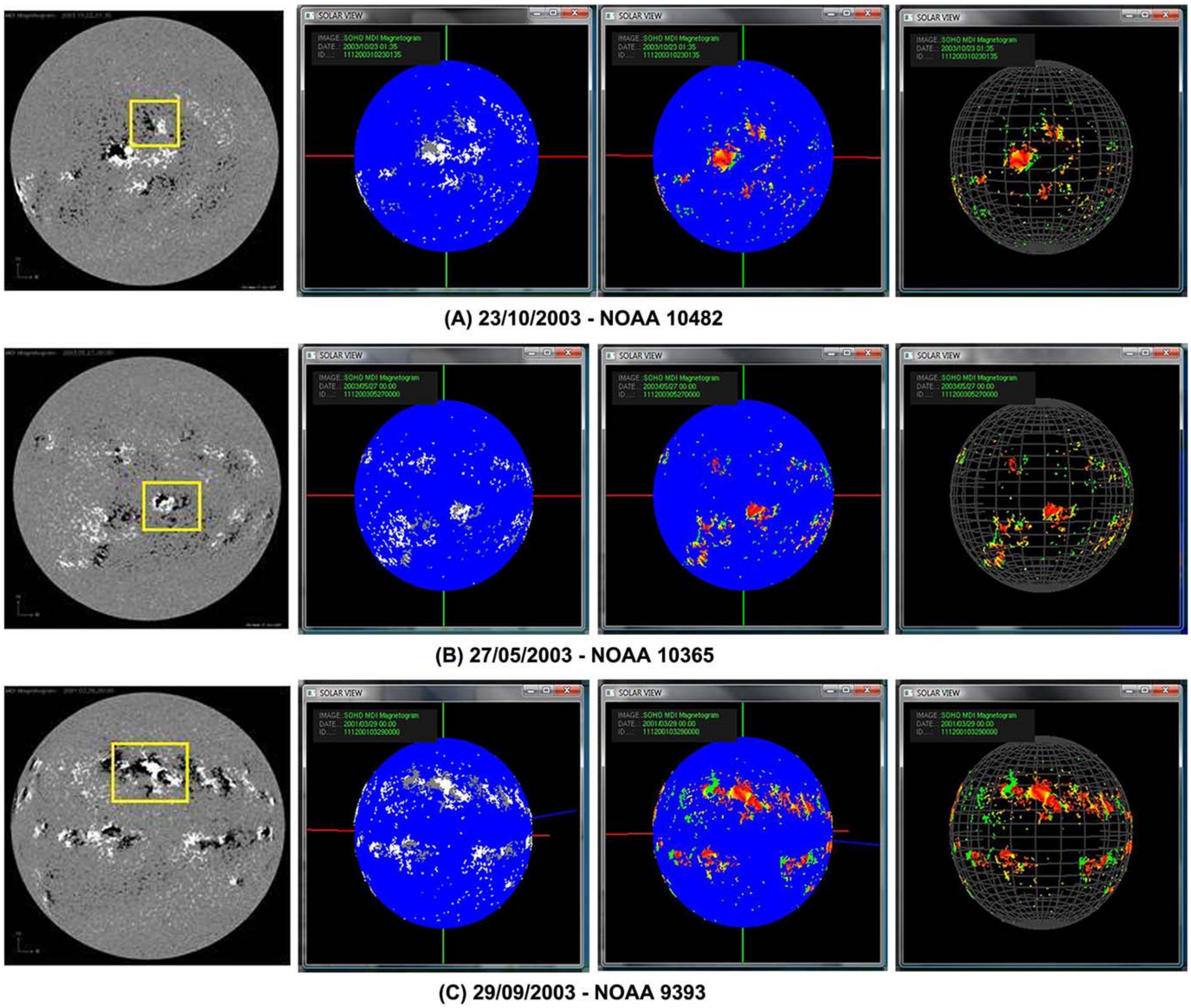


Fig. 11 For each group, the 1st image is a magnetogram image, with the active regions under investigation surrounded by a *yellow square*, as a reference point, so it can be compared with the related images in the group. The 2nd image present active regions in 3D colour map. The 3rd image presents magnetic complexity regions. The 4th image shows the solar disk in the 3rd image in wired view

be compared to the previous results, which discussed in Sect. 3.1 and presented in Figs. 5, 6, 7 respectively. Each group in Fig. 11 consists of four images. The first is a magnetogram image. The second image is a 3D colour map of the solar disk, which shows the active regions as white/grey areas, where white represents the north polarity regions, and grey represents the south polarity regions. The third image is a 3D colour map of the solar disk, which shows the high magnetic complexity areas represented as red colour and the low magnetic complexity areas represented as green colour. The red coloured areas indicate a potential flare eruption location, while the green coloured areas indicate quite locations. The fourth image is a 3D wired view of the solar disk, which shows another view of the third image.

5 Conclusion and future work

Two new models have been presented in this paper. The first calculates the magnetic complexity in active regions and the solar disk. This model is based on the famous physical Ising model, which has been modified to suit the properties of this application. The second is to visualise the solar disk, active regions, and the calculated magnetic complexity in 3D colour maps. SOHO/MDI magnetogram images are used for this research. Both models have been developed with the C++ programming language and OpenGL software for 3D applications. Also they have been tested on different groups of samples selected randomly from different time periods. The obtained results reveal a relationship between the calculated magnetic complexities in active regions and the solar disk with flares. Also, the calculated magnetic complexity values have been represented in a 3D model in order to visualise the flaring regions on the solar disk. These models demonstrate very significant findings and can be useful tools for solar imaging, space weather and applied imaging in general.

The aim of our research is to develop an automatic, real-time, and web-based system for solar flare forecasting. Currently, the models presented here can perform in real time. However, further work will be carried out on a large amount of data in order to establish the exact correlation between the calculated magnetic complexities and flares in order to evaluate the capability of the model to accurately predict flare classes. This will be investigated using statistical or machine learning methods. Also, the magnetic complexity model will be integrated with ASAP (Automated Solar Activity Prediction). ASAP is an automated solar forecasting system which predict flares based on the sunspot's McIntosh classification and area [25, 26], available online.[3] This step will enable us to determine number of solar activities parameters which are related to flare events, such as: *sunspot's McIntosh classifications*, s*unspots' area, active region's magnetic complexity,* and *solar disk magnetic complexity*, which can provide better flare prediction. Finally, the 3D visualisation model will be updated so it can be used to reconstruct and represent other solar images i.e. SOHO/MDI Continuum images, EIT images, etc., and represent the solar features that are presented in these images.

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[3] http://spaceweather.inf.brad.ac.uk

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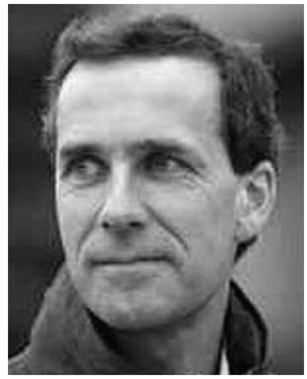

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