Sunspot Rotation and the M-class Flare in Solar Active Region AR 11158

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Abstract
In this paper, we measure the rotation of a sunspot in solar active region AR 11158 that produced a M-class flare. The flare occurred when the rotation rate of the sunspot reached its maximum. We further calculate the energy in the corona produced by the sunspot rotation. The energy accumulated in the corona before the flare reached $5.5 \times 10^{32}$ erg, sufficient for energy requirements for a moderately big solar eruption. This implies that sunspot rotation, which is often observed in solar active regions, is an effective mechanism for building up magnetic energy in the corona.

Keywords: Solar active region, sunspot rotation, solar flare

1. Introduction
It is generally accepted that the released energy in flares and Coronal Mass Ejections (CMEs) is from the magnetic field in the solar corona (e.g., Forbes, 2000). Understanding how energy builds up and is stored in the corona and why the stored energy is released rapidly is the key to forecasting solar events. Two mechanisms are suggested to build up magnetic energy in the corona: magnetic flux emergence and surface flows. Magnetic energy in the corona comes from the twisted magnetic flux tubes emerging from the solar interior into the corona, and is generated by shearing and braiding the field lines by the surface motions on the solar surface (e.g., Berger, 1984, Kusano et al., 2002, Liu and Schuck, 2012). There are several surface motions observed in the Sun. Among them is the rotation of the sunspots. This rotation braids field lines in the sunspots, generating twist in the sunspot’s magnetic tubes that contain higher magnetic energy. Rotating sunspots are often observed in solar active regions (e.g., Brown et al., 2003). Intensive studies have been carried out to analyze properties of the rotating sunspots (e.g., Yan et al., 2008, Zhu et al., 2012, Komm et al., 2012,

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Li & Liu, 2012), the relationship between rotating sunspots and solar eruptions (e.g., Zhang et al., 2008, Jiang et al., 2012, Török et al., 2013, Wang et al., 2014), and the cause of sunspot rotation (Longcope and Welsch, 2000; Fan, 2009).

However, a key question in understanding solar eruptions in rotating sunspots, the energy budget in the corona generated by the rotation of sunspots, is not well investigated. Does sunspot rotation generate sufficient energy for energy requirements in a moderately large solar eruption? This study will address this question.

Solar active region AR 11158 is chosen for this study. This is an emerging active region, quickly beginning to emerge on 12 February 2011 and finally developing into a complex, multipolar active region. This active region produced several major flares during its disk passage, including five M-class flares and one X-class flare, the first X-class flare in Solar Cycle 24. Because it is the first active region that has produced multiple major flares in solar cycle 24, a variety of research has been conducted to study sunspot formation (Toriumi et al., 2014), emergence and evolution of the active region (e.g., Liu and Schuck, 2012, Cheung and DeRosa, 2012, Jing et al., 2012), energy buildup in the corona (e.g., Sun et al., 2012a, Liu and Schuck, 2012, Tziotziou et al., 2013, Tarr et al., 2013, Aschwanden et al., 2014), instability of the magnetic field (e.g. Wang et al., 2014, Liu et al., 2013, Sun et al., 2012b), solar eruptions (e.g. Wang et al., 2012, Sun et al., 2012a, Sun et al., 2012b, Inoue et al., 2014, Yang et al., 2014), and the impact of the eruption to the interplanetary space and the Earth (e.g. Huang et al., 2014). There are several rotating sunspots in this active region. One sunspot that has produced an X2.2 flare at 01:27 UT 15 February 2011 has been well studied (Jiang et al., 2012; Wang et al., 2014). In this study, we analyze another rotating sunspot and its association with an M2.2 flare at 17:26 UT 14 February 2011 in this active region.

The paper is organized as follows: Section 2 describes data used and the method for measuring rotation of the sunspot. Results are shown in Section 3. We conclude this study in Section 4.

2. Data and Methods

2.1. Data

The observational data used in this research are taken by the Helioseismic and Magnetic Imager (HMI; Scherrer et al., 2012, Schou et al., 2012) aboard NASA’s satellite Solar Dynamics Observatory (SDO; Pesnell et al., 2012). The HMI instrument is a filtergraph with full disk coverage at 4096×4096 pixels. The spatial resolution is about 1” with a 0.5” pixel size. The width of the filter profiles is 76 mÅ. The spectral line is the Fei 6173Å absorption line formed in the photosphere (Norton et al., 2006). The measurement is taken at 6 wavelength positions in the spectral line. The continuum intensity is obtained by reconstructing the spectral line from the measurements at the 6 positions (Couvidat et al., 2012). The vector magnetic field is derived from the measurements of the linear and circular polarizations (Hoeksema et al., 2014). The Stokes parameters
Figure 1. Intensity (left) and vector magnetic field (right) of AR 11158 at 17:12 UT on 14 February 2011. The rectangle in the left panel encloses the rapidly rotating sunspot of interest. The black-white image in the right panel represents the vertical magnetic field with positive polarity in white and negative in black. The image is saturated at ±1000 G. The arrows refer to the horizontal field. Twisting field lines surrounding the sunspot are visible.

[I, Q, U, V], determined by the polarizations, are inverted to retrieve the vector magnetic field using a Milne-Eddington (ME) based inversion algorithm, Very Fast Inversion of the Stokes Vector (VFISV; Borrero et al., 2011, Centeno et al., 2014). The 180° degree ambiguity of the azimuth is resolved using a “minimum energy” algorithm (Metcalf, 1994; Metcalf et al., 2006; Leka et al., 2009). The location and extent of the ARs are automatically identified and bounded by a feature recognition model (Turmon et al., 2010), and the disambiguated vector magnetic field data of ARs are deprojected to heliographic coordinates (Bobra et al., 2014). Here the Lambert (cylindrical equal area) projection method centered on the region is used for the remapping. The continuum intensity images are also mapped to heliographic coordinates using the same projection method. In this study, the continuum intensity and vector magnetic field data are used to analyze the rotating sunspot in the active region AR 11158.

Fig. 1 shows the intensity continuum image (left) and the vector magnetic field (right) of this active region at 17:12 UT 14 February 2011. The image in the right panel is the vertical magnetic field saturated at ±1000 G, with the positive field in white and the negative in black. The horizontal field is presented by arrows. The rotating sunspot analyzed here in this research is enclosed by the rectangle on the left panel; the horizontal field (right panel) shows an obvious rotation pattern, indicating field lines twisted around the sunspot.

The 17:26 UT 14 February M2.2 flare was produced by this rotating sunspot, as shown in Fig. 1 of Sun et al. (2012b). Sun et al. (2012b) analyzed the magnetic topology structure involved in this event, and suggested that a coronal null point, setting above the erupting flux tube, likely led to magnetic reconnection, triggering the eruption. A special field geometry guided this eruption propagating non-radially.

Evolution of the sunspot is shown in Fig. 2. From the intensity continuum images in the top panels, one can clearly see that the sunspot rapidly rotates counter-clockwisely until 06:00 UT 15 February. The sunspot also grows gradually with time. The vector magnetic field in the bottom panels shows an increase of magnetic twist that surrounds the sunspot, and this twist relaxes significantly lately as seen in the 06:00 15 February data. The rotation rate of this sunspot
Figure 2. Evolution of the rotating sunspot. Top: intensity; Bottom: vector magnetic field. The sunspot grows and rotates rapidly in this time period. The images in the bottom panels, the vertical component of the magnetic field, are saturated at ± 1000 G.

is measured with the intensity continuum data that is described in detail in the following Section.

2.2. Methods

The intensity continuum data from 13 to 17 February 2011 are used to measure the rotation rate of the aforementioned sunspot in AR 11158. The data cadence is 720 seconds. For each frame, a square shaped window measuring 75 pixels by 75 pixels, is cropped around the sunspot. For the first frame, the center of mass for this sunspot is found, and its coordinates recorded. Taylor cross correlation is then performed between the first frame and the second frame to find the shift between the two frames and align them. The aligned frames are mapped to a polar coordinate system with the center of mass as the origin, where the X-axis in the mapped frames represents the angle and the Y-axis refers to the distance to the origin, as shown in Fig. 3. Taylor cross correlation is applied again to the mapped frames to derive the relative shifts of the two frames. The shift in the X-axis is the rotation angle of the sunspot within the time interval of the two frames. This procedure repeats by including the third frame. The second and the third frames are aligned each other using Taylor cross correlation, and then mapped to the polar coordinates with reference of the center of mass of the second frame. Taylor cross correlation is applied again to the mapped frames to measure the rotation angle. Rotation angle of this sunspot is determined by repeating this procedure on each frame. This angle is adjusted by the time interval of two adjacent frames to derive the rotation rate. Fig. 3 shows examples of mapped frames of the sunspot at several representative times. The slice of each mapped frame used for performing the cross correlation has a range of 0° – 360° in X-axis and 0 – 12 pixels in Y-axis. This approach is called Method 1 hereafter.

Another approach to measure the rotation of the sunspot is to trace representative features of the sunspot frame by frame. An effective way to trace features
Figure 3. Stack of representative remapped intensity images of the rotating sunspot in polar coordinates. The X-axis refers to the angular coordinate in degrees; the Y-axis refers to the radial coordinate in Mm. Time runs from top to bottom. The cross correlation technique is applied to the remapped images to derive the shift in angle. Rotation rate is further determined by this shift in angle (Method 1 hereafter).

is to make a time-slice image of the features. This is the most common method used in previous papers (e.g. Brown et al., 2003, Jiang et al., 2012, Wang et al., 2014). The method to generate the mapped frames in a polar coordinates system is the same as in Method 1. To avoid a shift of the features along the radial direction (Y-axis in the mapped frame), we take an average of five pixels in the Y-axis, from 10 pixels to 14 pixels. A stack with one average slice per frame forms the time-slice image, as shown in Fig. 4. The center of mass of each column in this time-slice image (green dots in the image) is found. This is identified to be the center of the tracked feature. The rotation rate is determined from those
identified locations using a linear fit to every 10 location data. This approach is called Method 2 hereafter. In Method 1, the cross correlation is applied to two frames that enclose the entire sunspot. The shift of the angle measured is deemed to be an average of the rotation for the entire sunspot. In other words, it is representative of bodily rotation rate for the sunspot. Method 2, on the other hand, measures the rotation rate by tracing special features. It requires that the features be representative for the sunspot and have a fairly long lifetime. Additionally, evolution and proper motion of the features add uncertainty to the measurement with Method 2.

Fig. 5 exhibits a comparison of the rotation rates from the two methods. A 10-point running average is applied to the rate of Method 1 to match the 10-point...
linear fit in Method 2. The error bar in Method 1 is estimated by measuring the rotation rate from 11 different values of radial coordinate (Y-axis in mapped frames). The selection ranges from 11 to 21 pixels. The error reported in Fig. 5 is the standard deviation of the 11 measurements. The error bar in Method 2 represents the error of the linear fit to the 10-point data. Both methods measure a positive rotation rate (counter-clockwise) during most of the time and also capture the rapid spinning of the sunspot in the time period of 12:00 – 20:00 UT 14 February 2011. This indicates that both methods are effective in measuring rotation for the time periods when the sunspots rotate significantly. In other time intervals, however, Method 2 measures the rotation rate as oscillating around the zero line, such as in the intervals of 20:00 UT 13 February to 04:00 UT 14 February and 22:00 UT 14 February to 12:00 UT 15 February, when the sunspot obviously rotates counter-clockwise when viewed from a movie of the sunspot. It appears that Method 1 performs better. In this study, we use Method 1 to measure the rotation rate.

3. Results

Results are shown in Fig. 6. From top to bottom are temporal profiles of magnetic flux, rotation rate, electric current, and energy flux (Poynting flux) across the photosphere (green curve, bottom panel), respectively, for the rotating sunspot from 13-17 February 2011. The light blue curve in the bottom panel represents accumulated energy in the corona that is computed by integrating the energy flux over time. The error bars in each panel refer to the standard deviation of the variables (1-σ). The red vertical lines in each panel denote the occurrence time of the M-class flare. The temporal profile of the magnetic flux Φ (top panel) is computed by,

\[ \Phi = \int_S B_z dS, \]

where \( B_z \) represents the vertical component of the magnetic field. Integration is done over the area of interest. It exhibits a monotonous increase from 00:00 UT 13 February to 06:00 UT 14 February, indicating the sunspot underwent quick emergence in this time period. The sunspot rotated rapidly in this time period (see the second panel). The rotation continues after the emergence stops, and reaches its maximum just before the occurrence of the flare.

It is often observed that the sunspots rotate when they are emerging (e.g. Brown et al., 2003). Longcope and Welsch (2000) proposed a dynamical model that suggests that only a fraction of the electric current carried by a twisted flux tube will pass into the corona. This leads to torsional Alfven waves that propagate along the flux tube, transporting magnetic twist from the highly twisted portion of the flux tube under the photosphere to the less twisted portion of the flux tube that emerged and expanded in the corona. This process is manifested on the photosphere with rotational motions of sunspots. Pevtsov et al. (2003) tested this model with six emerging active regions. They found reasonable agreement between the model prediction and observation. MHD simulations successfully
reproduced the processes the model predicts (e.g. Magara and Longcope, 2003, Fan, 2009). Thus, the rotation of the sunspot propagates magnetic twist into the corona and builds up free energy in the emerged magnetic field.

Electric current in vertical direction $I_z$ in an area of $S$ is computed by

$$I_z = \int_S \left( \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \right) dS,$$

where $B_x$ and $B_y$ are magnetic fields in X- and Y-axis, respectively. Integration is done over the area of interest. The vertical current in the rotating sunspot was calculated using vector magnetic field at the photosphere observed by HMI. As expected, the vertical current increases with time in the time period when the sunspot underwent emergence and quick spinning (see the third panel). It reaches its maximum just before occurrence of the flare. It drops dramatically
afterwards. This implies that magnetic twist and energy quickly built up as the sunspot emerged and rotated, and relaxed after the eruption.

It is interesting to examine if the rotation alone can build up enough energy in the sunspot to supply the need of the released energy in the flare. Energy flux, the Poynting flux \( S = \frac{c}{4\pi}E \times B \), where \( E \) is electric field and \( B \) is magnetic field. Consider purely rotation, and use cylindrical coordinates,

\[
B = B_r \hat{r} + B_\theta \hat{\theta} + B_z \hat{z}, \quad \mathbf{V} = V_\theta \hat{\theta}.
\]  

(3)

Electric field \( E \) is,

\[
cE = -\nabla \times \mathbf{B} = V_\theta B_z \hat{z} - V_\theta B_z \hat{r}.
\]  

(4)

Poynting flux in vertical direction (z direction), \( S_z \) is then,

\[
S_z = -\frac{1}{4\pi} V_\theta B_z B_\theta = -\frac{1}{4\pi} r \Omega B_z B_\theta,
\]  

(5)

where \( r \) is the distance from the pixel of interest to the rotation center. \( \Omega \) is rotation rate.

Equation (5) is used to compute the energy flux across the photosphere purely due to the rotation of the sunspot. The vector magnetic field used is the observational data; the rotation rate is measured as described in previous Section. Results are presented in the bottom panel of Fig. 6. The green curve represents the energy flux across the photosphere, while the light blue curve is the accumulated energy in the corona. Accumulated energy is computed by integrating over time the energy flux. It is clearly seen that the rotation continuously injects energy into the corona. The injection rate reached its maximum before the eruption of the flare. Energy built up purely by the rotation of the sunspot reached \( 5.5 \times 10^{32} \) erg before the flare, sufficient for energy requirements for a moderately large flare/CME (Forbes, 2000). It suggests that, for this sunspot, rotation alone can supply the released energy needed for this M-class flare.

4. Conclusions and Future Work

The rotation rate of a sunspot in solar active region AR 11158 is measured using continuum intensity data taken by HMI. This rotating sunspot produced a M2.2 flare at 17:26 UT 14 February 2011. It is found that the flare occurred when the rotation rate reached its maximum. Energy in the corona generated by rotating the sunspot is further estimated. It reached \( 5.5 \times 10^{32} \) erg, sufficient for energy requirements in a moderately big solar eruption. This suggests that rotating sunspots alone can be an effective mechanism for building up magnetic energy in the corona for solar eruptions.

Energy source is explored and discussed in this work. Triggering of this flare is still unclear. Reconnection at the null point might be one possibility (Sun et al., 2012b), but it fails to address the casual correlation of maximum rotation rate of the sunspot and the occurrence time of the flare observed in this event. This rapid rotation in the sunspot certainly twists field lines greatly. It may lead
to a kink instability in the sunspot flux tube, causing eruption of the flare, if the twist accumulated in the flux tube by the rotation is large enough. Theoretically, the threshold of the twist that leads to a kink instability is about $2.5\pi$ (Hood and Priest, 1981). Integrating the rotation rate over time yields a total twist of $0.74\pi$, much less than the threshold for kink instability. This is one difficulty for the scenario of kink instability. Perhaps the originally emerged field has already twisted significantly. Rotation could add additional twist so that total twist reaches the threshold for a kink instability. Or, perhaps the eruption of this flare was triggered by other mechanisms, such as a torus instability that requires that the overlying magnetic field have a large gradient, but does not require very high twist in the flux tube (Török and Kliem, 2005; Kliem and Török, 2006). For example, Török et al. (2013) discussed the possibility of raising the overlying field by rotating the footpoints of the fields. This leads to the increase of the magnetic gradient vertically in the overlying fields. All those scenarios deserve further investigation to understand the triggering mechanism in this event.

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