ON THE ROLE OF ROTATING SUNСПOTS IN THE ACTIVITY OF SOLAR ACTIVE REGION NOAA 11158

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ABSTRACT

We study the role of rotating sunspots in relation to the evolution of various physical parameters characterizing the non-potentiality of the active region (AR) NOAA 11158 and its eruptive events using the magnetic field data from the Helioseismic and Magnetic Imager (HMI) and multi-wavelength observations from the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory. From the evolutionary study of HMI intensity and AIA channels, it is observed that the AR consists of two major rotating sunspots, one connected to a flare-prone region and another with coronal mass ejection (CME). The constructed space–time intensity maps reveal that the sunspots exhibited peak rotation rates coinciding with the occurrence of major eruptive events. Further, temporal profiles of twist parameters, namely, average shear angle, \( \alpha_{av} \), \( \alpha_{best} \), derived from HMI vector magnetograms, and the rate of helicity injection, obtained from the horizontal flux motions of HMI line-of-sight magnetograms, correspond well with the rotational profile of the sunspot in the CME-prone region, giving predominant evidence of rotational motion causing magnetic non-potentiality. Moreover, the mean value of free energy from the virial theorem calculated at the photospheric level shows a clear step-down decrease at the onset time of the flares revealing unambiguous evidence of energy release intermittently that is stored by flux emergence and/or motions in pre-flare phases. Additionally, the distribution of helicity injection is homogeneous in the CME-prone region while in the flare-prone region it is not and often changes sign. This study provides a clear picture that both proper and rotational motions of the observed fluxes played significant roles in enhancing the magnetic non-potentiality of the AR by injecting helicity, twisting the magnetic fields and thereby increasing the free energy, leading to favorable conditions for the observed transient activity.

Key words: Sun: activity – Sun: coronal mass ejections (CMEs) – Sun: flares – magnetic fields – sunspots

Online-only material: color figures

1. INTRODUCTION

The activity level of the Sun is defined by eruptive events like coronal mass ejections (CMEs) and flares occurring in the active regions (ARs). These regions consist of groups of sunspots with positive and negative magnetic polarities. During the evolution of ARs, the sunspots exhibit motions, both proper and rotational, that lead to the storage of energy in the AR by increasing its magnetic non-potentiality. The eventual release of stored energy then occurs in the form of the eruptive events, such as flares and CMEs. An investigation of the characteristics of sunspots can thus help toward the understanding of transient solar activities.

Rotational motions of and around sunspots have been observed by several authors in the past (Evershed 1910; Bhatnagar 1967; McIntosh 1981). More recent studies have reported sunspot rotations around the umbra and as well as around another sunspot with the availability of high spatial and temporal resolution data from space-borne as well as ground-based observatories (Brown et al. 2003; Zhang et al. 2007; Yan et al. 2009). Rotational motions can shear and twist the overlying magnetic field structures, thereby storing excess energy. Vertical current, current helicity, and transport helicity are some of the quantitative parameters derived from observations that are related to the twisting of field lines anchored in the moving footpoints. CMEs that disturb the space environment are thought to occur due to an overaccumulation of helicity and its ejection from the corona to interplanetary space. Recently, Zhang et al. (2008) reported that helicity injection as inferred from the rotational motion of sunspots can be comparable to that as deduced for the entire AR by the local correlation tracking method. They also found good spatial and temporal correlation of sunspot rotational motion with two homologous flares.

The consequences of sunspot rotations and related changes, both in photosphere and corona, have been investigated by several researchers. Some studies examine the relationships between the sunspot rotation and coronal consequences (Brown et al. 2003; Tian & Alexander 2006; Tian et al. 2008), flare productivity (Yan et al. 2008; Zhang et al. 2008), statistics of the direction of rotating sunspots, helicities (Yan et al. 2008, and references there in), and the association of flares with abnormal rotation rates (Hiremath et al. 2005).

In this study, we report on the rotating sunspots observed during 2011 February 11–16 in AR NOAA 11158. We present the results related to the changes in various parameters, namely, vertical current, twist parameters, helicity injection, and the free energy of the AR during its evolution. Further, we examine whether the rotating sunspots were associated to the eruptive flare and CME events of the AR. Our aim is toward finding association of the observed uncommon rotation of the sunspots of this AR in terms of changes in various physical parameters. We have organized the paper as follows: observational data and analysis procedure are described in Section 2, followed by the results and a discussion of them in Section 3. Finally, the summary of the study is presented in Section 4.

2. OBSERVATIONAL DATA AND ANALYSIS

PROCEDURE

The observational data used in this study are obtained from the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012)
and the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO).

AIA observes the Sun in 10 different wavelengths in soft X-ray, EUV, and UV regimes to study the processes occurring at various atmospheric layers, i.e., chromosphere, transition region, and corona, at a pixel size of 0′′.6 and 12 s cadence. In addition, we also obtained high-resolution G-band 4300 Å and Ca II H 3970 Å images from Solar Optical Telescope (SOT; Tsuneta et al. 2008) on board the Hinode to understand the associated chromospheric structures. Data on the CME and flare initiation times were obtained from relevant web sites.3,4

HMI observes the full solar disk in the Fe I 6173 Å spectral line with a spatial resolution of 0′′.5 pixel−1 and provides four main types of data at a cadence of 12 minutes: Dopplergrams (maps of solar surface velocity), continuum filtergrams (broad-wavelength maps of the solar photosphere), and both line-of-sight (LOS) and vector magnetograms. Filtergrams are obtained at six wavelength positions centered at the Fe I line to compute Stokes parameters I, Q, U, and V. These are then reduced with the HMI science data processing pipeline to retrieve the vector magnetic field using the Very Fast Inversion of the Stokes Vector algorithm (Borrero et al. 2011) based on the Milne–Eddington atmospheric model. The inherent 180° azimuthal ambiguity is resolved using the minimum energy method (Metcalfe 1994; Leka et al. 2009). Data processing is carried out by the HMI vector team (Hoeksema et al. 2012) and the products are made available to the solar community.

We used the high-resolution continuum images of NOAA 11158 obtained from the HMI for the rotation measurement of sunspots. In order to estimate the twisting in various sites of the AR, we used vector magnetograms projected and remapped to heliographic coordinates. The intensity images obtained from the AIA were used to examine the coronal changes associated with the photospheric motions. All images both from the AIA and HMI taken at different times were aligned by differentially rotating to an image at central meridian by the nonlinear remapping method (Howard et al. 1990). For our analysis, we have used the standard SolarSoft routines (Freedland & Handy 1998) implemented in Interactive Data Language.

In order to further characterize the association of rotational motion with non-potentiality and in turn with the observed transient activity of the AR, we examine the evolution of magnetic fluxes and the derived parameters (see Leka & Barnes 2003 for definitions of various non-potential parameters) therefrom. We evaluate the vertical currents and shear or twist parameters to estimate the extent of non-potentiality. The complexity developed through the flux motions by the helicity injection rate and consequent magnetic energy storage are also analyzed. Procedures for these calculations are briefly outlined below.

1. We evaluate the total absolute flux in sub-regions R1 and R2 by summing all the pixels \( F = \sum |B_z| \). The vertical current is computed from Ampere’s law \( \nabla \times B = \mu_0 J_z \), where the permeability of free space \( \mu_0 = 4\pi \times 10^{-7} \) Henry m−1. Using the \( z \)-component of this relation, one can deduce the total absolute vertical current as \( J_z = \sum |(\nabla \times B)_z|/\mu_0 \).

2. Magnetic shear. Non-potential nature of a magnetic field is characterized by magnetic shear defined as the difference between directions of observed transverse fields and potential transverse fields (Ambastha et al. 1993; Wang et al. 1994) and is given by

\[
S = B \cdot \theta = B \cdot \left( \cos^{-1} \frac{B \cdot B_p}{BB_p} \right),
\]  

where \( B = |B| \) is the magnitude of the observed magnetic field and \( B_p = |B_p| \) is the magnitude of the potential field computed from the Fourier method (Gary 1989). The weighted shear angle (WSA) in a region of interest with \( N \) pixels can then be obtained as

\[
WSA = \frac{\sum_{i=1}^{N} S_i}{\sum_{i=1}^{N} B_i}
\]

and will estimate the overall angle of departure from the potential field configuration.

3. Alpha best (\( \alpha_{best} \)). The force-free parameter \( \alpha_{best} \) is used as a proxy to monitor the extent of twist of the magnetic field lines in an AR. For this parameter, the extrapolated force-free fields best fit the observed transverse fields in the sense of a minimum least-squared difference on the photosphere. The procedure of the fitting method for calculating \( \alpha_{best} \) (Pevtsov et al. 1994; Hagino & Sakurai 2004) is as follows. For a given \( \alpha \) and with an observed \( B_z \), we compute a linear force-free field whose transverse component is \( B_{t,cal} \). We then search for the \( \alpha \) that gives a minimum residual (\( R(\alpha) \)) of the transverse component in a range of values through the following equation:

\[
R\alpha = \sum (B_{t,obs}(x, y) - f B_{t,cal}(x, y, \alpha))^2
\]

\[
\sum B^2_{t,obs}
\]

where \( f = \frac{\sum B^2_{t,obs}}{\sum B^2_{t,cal}(x, y)} \).

The error in the fitting of the residual and \( \alpha \) that is effected in estimating \( \alpha_{best} \) is given by

\[
\delta \alpha_{best}^2 = \frac{2\delta B_1 \sqrt{R_0}}{R' \sqrt{\sum B^2_{t,obs}}}.
\]

4. Average alpha (\( \alpha_{av} \)). Another proxy for representing the twist is obtained by taking the average of \( \alpha \) from the force-free assumption of photospheric fields, i.e., \( \nabla \times B = \alpha B \). Following Pevtsov et al. (1994) and Hagino & Sakurai (2004), it is given by

\[
\alpha_{av} = \frac{\sum J_z(x, y) \text{sign}(B_z(x, y))}{\sum |B_z|}.
\]

The error in \( \alpha_{av} \) is deduced from the least-squared regression in the plot of \( B_z \) and \( J_z \) and is given by

\[
\delta \alpha_{av}^2 = \frac{\sum (J_x(x, y) - \alpha_{av} B_z(x, y))^2}{|B_z(x, y)|} - (\frac{1}{N-1}) \sum |B_z(x, y)|.
\]

where \( N \) is the number of pixels where \( |B_z| \geq 150 \) G (with 150 G assumed as the lower cutoff for the transverse field).

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3 http://spaceweather.gmu.edu/seeds/
4 http://www.solarmonitor.org
5. Helicity injection. One uses the helicity injection rate to quantify the twist due to photospheric flux motions. Following Pariat et al. (2005):

\[
\frac{dH}{dt} = -\frac{1}{2\pi} \int_{S} \int_{S'} \frac{[\mathbf{x} - \mathbf{x}'] \times (\mathbf{u} - \mathbf{u}')]_{n}}{|\mathbf{x} - \mathbf{x}'|^2} \cdot B_n(x') \times B_n(x) dS' dS,
\]

where \(\mathbf{u}(x')\) is the footpoint velocity at position vector \(x(x')\), and \(B_n\) is the normal component of the observed magnetic field. This equation shows that the helicity injection rate can be understood as the summation of rotation rates of all the pairs of elementary fluxes weighted with their magnetic flux. Integration of the above equation in the observed time interval provides the accumulated helicity \(\Delta H = \int (dH/dt) d\tau\), which is injected due to footpoint shear motions.

6. Magnetic free energy. One can obtain the estimate of non-potentiality by the magnetic virial theorem (Chandrasekhar 1961; Molodensky 1974; Low 1982), which gives the total force-free magnetic energy as

\[
E_m = \int_{z>0} \frac{B^2}{8\pi} dV = \frac{1}{4\pi} \int_{z=0} (x B_x + y B_y) B_z dxdy,
\]

where \(B_x, B_y\) are the horizontal and \(B_z\) the vertical components of magnetic field \(B\) at position \((x, y)\) on the solar surface \(z = 0\). The applicability of this equation to a realistic situation like solar photospheric boundary must be restricted by force freeness of the field and flux-balance conditions. Despite its applicability limitations, it should provide some useful information about energy storage and release. Since the potential field state is a minimum energy state, by subtracting the potential field energy from the force-free energy one obtains the upper limit of the free energy available in the AR to account for the flares and CMEs.

However, the photospheric field is not strictly force free (Metcalfe et al. 1995; Gary 2001), and flux balance in the region of interest is not fully satisfied. Therefore, one obtains incorrect estimates of the free energy. To derive the error estimate for the force-free energy measurement, we have adopted the pseudo-Monte Carlo method (Metcalfe et al. 2005), which gives the mean and variance of energy estimate by changing the origin of the coordinate system in all possible ways. It includes both the statistical error as well as the error due to the departure from the force-free state of the fields.

We have examined the errors given with the vector field data after inverting the Stokes profiles. The maximum error in transverse field \(B_t\) in the entire data set varied in the range of 20–35 G. The total field strength was observed to vary by 50 G over a day due to various factors (Hoeksema et al. 2012). Therefore, we simultaneously carried out the calculations with \(|B_t| \geq 150\) G and \(|B_t| \geq 15\) G and neglected the pixels having magnetic fields below these thresholds.

As required by Equation (8), the horizontal motions of photospheric fluxes using LOS magnetic field data are obtained at a cadence of 12 minutes by the method of differential affine velocity estimator (DAVE; Schuck 2006). It is a local optical flow method that determines the mass velocities within the windowed region. Further, it adopts an affine velocity profile, specifying the velocity field in the windowed region around a point and constrains that profile to satisfy the induction equation.

The maximum rms velocities of flux motions in the entire AR were found to be distributed in the range 0.6–0.9 km s\(^{-1}\). These velocity maps of mass motions revealed strong shear flows that included both proper and rotational motions. With the velocities of these flux motions, we computed the helicity flux density maps of the whole AR at pixels above 10 G to reduce computation time, then the helicity injection rate, and accumulated helicity using Equation (8).

3. RESULTS AND DISCUSSION

The AR NOAA 11158 was a newly emerging region that first appeared as small pores on the solar disk on 2011 February 11 at the heliographic location E33S19. Subsequently, it grew rapidly by the merging of small pores to form bigger sunspots and developed to \(\beta < \gamma < \delta\)– magnetic complexity on 2011 February 13. The HMI intensity maps in Figure 1 show the spatiotemporal evolution of AR 11158 during 2011 February 11–16. The prominent negative and positive polarity sunspots are labeled in frame (d) as SN1–SN3 and SP1–SP3, respectively. The overlaid LOS magnetic field contours in frame (e) depict the polarity distribution of the AR. The overall configuration of the AR is seen to be of quadrupolar nature. The proper motion of individual sunspots during February 13–16 is marked by arrowed curves traced by centroids of the sunspots as shown in frame (f).

In what follows, we shall present the evolution of the AR during 2011 February 13–15 using coronal observations in different wavelengths along with the changes in its magnetic and velocity field structures, the related physical parameters, and the flare/CME activities.

3.1. Evolution and the Activity of the AR

A careful examination of the animations of magnetogram and intensity maps revealed significant counterclockwise (CCW) rotation of SN1 and clockwise (CW) rotation of SP2 during February 13–15. We selected two sub-regions based on distinctive flux motions and associated transient activities. These are sub-region R1 covering SN1 and R2 around SN2, SN3, and SP2, as shown in the rectangular boxes in Figure 1(d).

The spatial evolution in R2 displayed a large shearing motion of SP2, which itself rotated CW during February 13–15. It then detached from SN2 and moved toward SP3 with small patches of both polarities appearing and disappearing over short periods of time. In R1, a small positive polarity site, SP1, emerged to the north of SN1 and rotated in a similar CCW direction along with a proper motion away from SN1. The rotation of SN1 and its associated SP1 twisted the field lines. These motions appeared to have resulted in a large magnetic non-potentiality in this sub-region. This followed the first X-class event of the current solar cycle 24, an X2.2 flare in R2 on February 15. In addition, several flares of smaller magnitude, including four M-class and several C-class, occurred during this period. All of these were associated with R2 except the M2.2 flare of 14 February which was observed to originate from R1. Many intermittent CMEs were also launched from this AR. These flares and CMEs (listed in Table 1) appear to be related to the observed motions in the AR. We have manually traced the QuickLook AIA images to look for mass ejections in 304 Å channel locating the sub-region they belonged to and found that most of the CMEs originated from R1 (except the one associated
Figure 1. HMI intensity images showing the evolution of AR NOAA 11158 during a six-day time period. The main sunspots are labeled SP/N* in (d) and the LOS magnetic field contours are overlaid in red (blue) at 150 (−150) G levels in panel (e) (also in subsequent figures unless specified). Proper motions of individual sunspots are traced along the arrowed curves as in panel (f). The two rectangular boxes mark the selected sub-regions R1 and R2 for further study. (A color version of this figure is available in the online journal.)

Table 1

| AR (NOAA) | Date (dd/mm/yyyy) | Flares Magnitude(Time UT) | CMEs (Time UT) |
|-----------|------------------|----------------------------|----------------|
| 11158     | 13/02/2011       | C1.1(12:36), C4.7(13:44), M6.6(17:28) | 21:30, 23:30 |
|           | 14/02/2011       | C1.6(02:35), C8.3(04:29), C6.6(06:51) | 02:40, 07:00, 12:50 |
|           |                  | C1.8(08:38), C1.7(11:51), C9.4(12:41) | 17:30, 19:20 |
|           |                  | C7.0(13:47), M2.2(17:20), C6.6(19:25) |                |
|           | 15/02/2011       | C1.2(23:14), C2.7(23:40) |                |
|           |                  | C2.7(00:31), X2.2(01:44), C4.8(04:27) | 00:40, 02:00, 03:00 |
|           |                  | C1.0(10:02), C4.8(14:32), C1.7(18:07) | 04:30, 05:00, 09:00 |
|           |                  | C6.6(19:30), C1.3(22:49) |                |

with the X2.2 flare from R2). This inference is further confirmed by the STEREO spacecraft information.5

Morphological changes observed in chromosphere, transition region, and coronal regions corresponding to some of the transient events are shown in Figure 2 using AIA observations in 304, 193, and 94 Å wavelengths. We further examine the characteristics of non-potentiality in the selected sub-regions. Figures 2(a1)–(a3) show a large mass expulsion from sub-region R1 that turned into a large CME on February 14 at 18:00 UT, with the associated flare M2.2 at 17:20 UT. It appeared to occur when the rotation of SN1 attained the maximum speed. This CME began at 17:30 UT and continued well past 19:30 UT as observed from the AIA/304 Å movies. The ejected plasma (marked by an arrow in Figure a1) is visible in 304 Å as it is sensitive to the chromospheric temperature (≈10⁴ K). However, it is only partially visible in 193 Å and not discernible in 94 Å except for the cusp-shaped field lines filled with hot bright plasma at ~10⁶ K. Another such mass ejection of February 15 at 00:36 UT that ensued from the same location is shown in Figures 2(b1)–(b3). The LOS magnetic field contours are overlaid in frame (b2) for reference, depicting the field line connectivities from the magnetic footpoints in the labeled sunspots. From the animations of magnetic and intensity images and coronal field line connectivity, a significant role of new emerging flux at SP1 can be inferred in these expulsions.

Figures 2(c1)–(c3) show the intense X2.2 flare which occurred on February 15 in sub-region R2. This event was also associated with a halo CME that began at 01:44 UT. This flare produced abnormal magnetic polarity reversal and Doppler velocity enhancement during the flare’s impulsive phase (Maurya et al. 2012). As mentioned earlier, the rotating flux footpoints, i.e., the sunspots, twisted the overlying magnetic structures in opposite directions. The rotational motion of the positive polarity spot SP2 around its negative polarity counterpart SN2 developed strongly twisted field lines along the polarity inversion line (PIL), clearly visible as a “sigmoidal” structure (c3). As reported earlier, such sigmoidal magnetic field structures are more likely to erupt (Canfield et al. 1999).

5 http://spaceweather.gmu.edu/seeds/
3.2. Measurement of Sunspot Rotation

To derive the rotational parameters of the sunspots, we followed the procedure explained in Brown et al. (2003). Essentially, we pursued the motion of a distinct feature in the penumbra, as it is comparatively richer than the umbra. We uncurl the annular region of penumbra by transforming from the Cartesian \((x-y)\) frame to the polar \((r-\theta)\) plane. In this way, we can measure the position angle of the observed feature as displaced from its previous position as the sunspot rotated. We identified the centroid of the sunspot SN1 by setting a 50% contrast between the umbra and penumbra in the time sequence of intensity images around the region of a circular disk with a radius of 18 arcsec. This circular region was then remapped onto the polar coordinate system from the Cartesian frame, so that annular features appeared as straight strips from umbra to penumbra. Once this is done, any portion of the strip could be tracked in time to determine the angular distance by which a particular feature is displaced.

We constructed the space–time diagrams for both the rotating sunspots, SN1 and SP2, extracted at the radii of 11” and 7” from their umbral centroid, as shown in Figures 3(a) and (b), respectively. Rotational motion of the features in the penumbral regions can be seen as diagonal bright or dark streaks. The uncurling starts at the westward point chord connecting the centroid position and the outer circle of annular portion and proceeds CCW around the sunspot centroid. These diagrams clearly show the CCW rotation of SN1 in sub-region R1, and the CW rotation of SP2 in sub-region R2. A well observed streak is traced and plotted (as marked by “+” at the respective positions) as angular displacement \((\theta)\) and its time derivative, i.e., angular velocity \((d\theta/dt)\) with time, in Figures 3(c) and (d).

The sunspot SN1 started rotating early from February 14 until February 15 at 18:00 UT. During the 24 hr period of February 14, it rotated by over 100° at an average rotation rate of 4° hr\(^{-1}\), peaking at 7° hr\(^{-1}\) at around 23:50 UT, i.e., just 3 hrs before the X-flare. The timings of mass expulsions from this sub-region (cf. Figure 2(a1)) also coincided well with the fast rotation.
Figure 3. Space–time map of a strip in (a) the sunspot SN1 (at a distance of 7 arcsec from the sunspot’s centroid) and (b) sunspot SP2 (at a distance of 11 arcsec from the sunspot’s centroid), after remapping the annular region of the sunspot to the $r$–$\theta$ plane. Rotation angle ($\theta$) and rotation rate ($d\theta/dt$) of the sunspot’s umbrae are inferred from the well-appearing diagonal feature in (a) and (b) sampled along the path marked by “+” and plotted with time in (c) and (d), respectively.

rate of SN1. Except for the CME associated with the X2.2 flare, all other CMEs listed on February 15 were found to be associated with the sub-region R1 even in the decreasing phase of its rotation rate. This suggests that the new emerging flux SP1 and large rotation rate of SN1 might have played a role in the process of sigmoidal structure formation that gave rise to the CMEs that were often associated with flares.

A similar analysis was carried out for evaluating the rotation of SP2 in order to examine its role in the X2.2 flare reported by Jiang et al. (2012). For the sake of completeness and consistency,
we reproduced the results for SP2 in Figure 3. It exhibited rotation rates of 4.48 hr$^{-1}$ on February 14 (before the X2.2 flare) and 1.92 hr$^{-1}$ on February 15, which are consistent with the results deduced by Jiang et al. (2012). Moreover, SP2 rotated by 95$^\circ$ until February 15 at 04:00 UT, which is also within the error limits of our manually tracked feature to their reported value of 107$^\circ$. Notably, a small rotation rate of 0.9 hr$^{-1}$ was observed after the flare from the time profile, showing that it rotated by a total of 25$^\circ$ until the end of the day. As is evident, there existed proper motion in addition to the rotational motion of SP2 (Figure 1(f)). Therefore, it may not be appropriate to attribute the rotational motion alone to the X2.2 flare and other events observed in this region.

It is thus evident that the two sub-regions consisting of the sunspots with high rotation rates were essentially the sites from where flares and CMEs originated in NOAA 11158. We speculate that the rotational motion led to the adequate storage of energy and injection of helicity that subsequently played the predominant role in the eruptions. In what follows, we shall discuss these aspects in further detail using the physical parameters deduced from the velocity and magnetic field measurements.

### 3.3. Evolution of Physical Parameters in Sub-regions R1 and R2

We now present a detailed description of the magnetic and velocity field observations and their derived parameters, as discussed in Section 2, in the sub-regions containing the rotating sunspots, R1 and R2.

The vector magnetic field map of the sub-region R1 on February 14 at 18:00 UT is shown in Figure 4(a) along with the map of tracked horizontal velocities of magnetic fluxes in Figure 4(b). The magnetic transverse vectors are seen nearly aligned with the PIL (thick dashed curve), implying a large shear along the SP1–SN1 interface. The map of tracked velocities shows the velocity vectors both exhibiting spiral or vortical patterns in the penumbral region of SN1, as a result of its rotation, and aligned in the opposite direction to that of the magnetic field vectors.

The new emerging positive flux SP1 rotated in the CCW direction, along with a proper motion toward the main flare site R2. It is noteworthy that when the footpoints were dragged along one direction, the corresponding vector magnetic field pointed toward the opposite direction so as to retain its footpoint connectivity. In the process, the shear in magnetic structures built up. The shear motion along the PIL is an effective mechanism for enhancing the non-potentiality of magnetic fields. This can be identified as the alignment of transverse magnetic field vectors along the PIL (Ambastha et al. 1993). Clearly, the shear (Equation (1)) distribution map shows intense shear around the PIL with the rotation of SN1 and SP1 and proper motion of SN1 as well. This process enhanced the electric currents along PIL as is evident from the distribution of calculated vertical current $J_z$ in frame (c) of Figure 4. Following Zhang (2001), the $J_z$ is decomposed to current of chirality $J_z^{ch}$ and current of heterogeneity $J_z^{ch}$, and their trend is examined. Throughout the time interval the average ratio $J_z^{ch}/J_z^{ch}$ is deduced to be 1.11, implying the region is chirally dominated and is approximately consistent with force-free equilibrium. Interestingly, the shear current, i.e., $J_z^{ch}$, follows a similar increasing trend with $J_z^{ch}$, having a correlation coefficient of 0.97. This infers that the rotational motion leads to an increase of both twist as well as shear, which contribute to total current $J_z$. Moreover, the force-free parameter $\alpha = J_z/J_B$ has a negative distribution (of order $10^{-6}$ m$^{-1}$), explaining the chirality with the counter rotation of the constituent sunspots in R1. From the AIA observations of R1, as confirmed by STEREO, it is observed that the intermittent mass expulsions turned into fast CMEs in this sub-region.

A map of helicity flux density computed from horizontal flux motions is shown in Figure 4(d). Throughout the time interval, the helicity flux distribution is homogeneous with a negative (dark) sign and implies a left-handed sense of chirality, further conforming to the observed CCW rotation of SP1 and SN1. The bipolar flux system having such CCW rotations (SP1 and SN1) forms sigmoidal patterns, which are efficient energy storage mechanisms, that account for the flares/CMEs (Canfield et al. 1999). This is also evidenced by the high-resolution Hinode G-band continuum image showing filamentary structures (frame (e)) that are consistent with the rotational motion of SP1 and SN1. The corresponding Hinode chromospheric Ca ii image (frame (f)) shows the flare ribbons along the PIL and overlying bright flare loops across the PIL (dashed line) associated with an M-class event of February 14. These observations suggest that the rotational motion of SN1 played a significant role in creating favorable conditions for the eruptions.

The vector magnetic map of sub-region R2 is shown in Figure 5 at the time of the X2.2 flare with a smoothed PIL (thick dashed curve) separating a positive and negative LOS magnetic field. This sub-region gave rise to several flares (listed in Table 1) of varying magnitudes including the energetic X2.2 flare along with its associated CME. Importantly, a major portion of the flux (SP2 and SN2) is relatively associated with shearing motion, compared to flux within the rotating SP2 itself, and therefore the region R2 is shear-motion dominated. As in R1, the alignment of $B_i$ vectors with PIL in this sub-region also showed strongly sheared magnetic fields. The tracked horizontal velocities (cf. Schuck 2006) displayed strong shearing motion of SP2 along PIL. These motions led to the stressing of field lines and possible flux cancellation as SP2 and SN2 possessed opposite fluxes. The distribution of vertical currents ($J_z$), another indicator of the large non-potentiality of magnetic structures, too showed strong currents around the PIL in R2 in the form of J-shaped ribbons. High-order shear is polarized along the PIL probably due to the continuous shear motion of SP2 and rotation. This sub-region is roughly consistent with force-free equilibrium: The average ratio over the time $J_z^{ch}/J_z^{ch}$ = 1.29 indicates a dominant chirality associated current. Nevertheless, a dominant shear motion exists with magnetic shear and gradients; $J_z^{ch}$ does not show an increasing trend, but indeed we do observe one in $J_z^{ch}$ similar to that in the total current $J_z$. It means that both rotational as well as proper motions are contributing to $J_z^{ch}$, the component that is parallel to the magnetic field. Therefore, the boundary motions in the evolution of the system in force-free equilibrium retain it to be in same force-free equilibrium. Distribution of helicity flux is inhomogeneous, due to having mixed polarities, and, especially during the peak times of some flare events like M6.6 and X2.2, we noticed the negative helicity flux in the existing system of positive helicity flux around the PIL. Injection of such opposite signed helicity is indicative of imminent transient activity. Whereas twisted penumbral fibril structure is seen in the Hinode G-band image on the photosphere, the bright chromospheric ribbons from X2.2 flare lying on either side of the PIL are seen in the Hinode Ca ii image.
Temporal profiles of the deduced physical parameters for the sub-region R1 are plotted in Figure 6 (left column). The total absolute flux doubled from $5 \times 10^{21}$ Mx to $9 \times 10^{21}$ Mx from February 13 to February 15. Thereafter, it showed no significant increase. The emergence of SP1 and the gradual evolution of SN1 in a proportion of approximately 1:3 contributed to this gradual increase of flux. The absolute vertical current also increased along with the flux until February 15, and decreased afterward. There was a pronounced increase in $|J_z|$, from 2.0 to $2.6 \times 10^{12}$ A, after February 14 at 14:00 UT. The average of
shear ($\langle S \rangle$) and weighted shear angle showed a similar trend, which explains the $J_z$ temporal trend. This might be related to the increasing rotation rate of the sunspot, thereby increasing the shear of horizontal magnetic fields by dragging the footpoints accommodating large field gradients around the PIL.

The sign and magnitude of $\alpha_{av}$ and $\alpha_{best}$ are found to be consistent, as both the parameters are equivalent proxies representing the twist. The larger error bars in $\alpha_{best}$ arise due to the 150 G error in the transverse field given to propagate in the fitting procedure (see Equation (7)). The negative sign indicates the left-handed twist or chirality. This agrees well with the physically observed CCW rotation of the sub-region consisting of the sunspots SN1 and SP1. The twist proxies, $\alpha_{av}$ and $\alpha_{best}$, show an increasing trend (in magnitude) with the rotation profile of SP1 (see Figure 3), further corroborating the increase in non-potentiality, as is also evident from the absolute vertical current $|J_z|$. A similar trend also reflects the temporal profile of the helicity injection rate $dH/dt$ calculated from the physically derived horizontal velocity field of the flux motions. The distribution of helicity flux is homogeneous with a negative sign over the region R1 and the helicity injection rate increases (in magnitude) with the rotation rate, reaching a maximum of $-17.52 \times 10^{40}$ Mx$^2$ hr$^{-1}$. Thereafter, the helicity injection and the rotation rates decreased. As the corona cannot accommodate an amount of continuously accumulating helicity, it would try to expel it to the outer atmosphere in the form of
CMEs in order to make the system stable, therefore explaining the CMEs observed from region R1 of this AR. A total helicity accumulation of \(-4.44 \times 10^{42} \text{ Mx}^2\) was estimated in the sub-region R1 during this period. Since a major part of the flux (SN1) is associated to rotational motion, this accumulated helicity is mostly contributed by dominant rotational motion in this sub-region.

The three parameters are different representations of twist or magnetic complexity, though the manner in which they are estimated is similar. Increased rotation rate of SN1 seems to increase the twist, as does the increasing trend of the parameters. The strong mass expulsions observed in AIA/304 Å at 12:50, 17:30, and 19:20 UT on February 14, turning into CMEs, further strengthen this evidence. This correspondence of the twist
parameters $a_{av}$, $a_{best}(S)$, WSA, and $dH/dt$ to the rotational profile of SN1 suggests the predominant role of rotation in the observed expulsions/CMEs (refer to panels (a1) and (b1) in Figure 2).

Thus, we are able to identify the correspondence of the measured twist parameters to the observed rotation of the sunspot in sub-region R1. However, the free energy deduced for R1 does not show any obvious association with the observed CMEs. We believe that the broad peaks in free-energy profile seen during the CMEs (12:50, 17:30, 19:20 UT) might have some relation, but a rapid release of energy is not obvious. The maximum mean value of free energy is estimated around $10^{22}$ erg s, which is adequate to account for the large eruptions.

Temporal profiles of the deduced physical parameters for the sub-region R2 are plotted in Figure 6 (right column). Absolute flux for this sub-region was much larger in magnitude compared to that of R1; it increased monotonically from $10 \times 10^{21}$ Mx to $14 \times 10^{21}$ Mx. The magnitude of absolute current $J_e$ was also correspondingly larger and showed appreciable variations associated with local evolution. Peaks in the electric current profile are noticeable at the times of large flare events, i.e., M6.6 and X2.2. The currents decreased thereafter, implying that the build-up currents in the pre-flare phase lead to relaxation of the magnetic field structure by releasing energy during flares. These peaks are not reflected in the $\langle S \rangle$ and WSA profiles because of the averaging property of these parameters. Note that WSA is higher by about 7° compared to that of R1, implying a high level of non-potentiality over the region. Both the twist proxies, $a_{av}$ and $a_{best}$, agreed in sign and magnitude. Unlike in R1, the positive sign of these parameters represents a positive or right-handed twist in R2. A relatively large average value of $a_{av}$ at $8.5 \times 10^{-8}$ m$^{-1}$ is suggestive of a stronger twist presence in this sub-region. None of these parameters shows a corresponding trend with the rotational profile of SP2, and probably complexity in the flux system is not only due to twisting but also shearing of fluxes.

Unlike R1, the sub-region R2 showed positive helicity injection at a much higher rate, with a maximum of $29.11 \times 10^{10}$ Mx$^2$ hr$^{-1}$. The accumulated helicity was also comparatively larger. A total helicity of $10.27 \times 10^{12}$ Mx$^2$ was injected during the 60 hr period by the observed flux motions and, as a result the coronal helicity, is likely to be positive. Within R2, the shearing of the flux system between SN2 and SP2 is dominated by the twisting single-flux system of SP2. Therefore, it is likely that the accumulated helicity is mostly contributed by the shear motion. This observance is consistent with reports of Liu \\& Zhang (2006) in AR 10488, which has shearing and twisting phases. They claimed that shear motion between two different flux systems is indeed the major contributor of helicity injection in this AR.

At the epochs of the M6.6 and X2.2 flares, sharp dips in helicity rate occurred corresponding to the injection of opposite, negative helicity. Existence of such mixed signs of helicity flux in a single domain is supposed to be the sign of triggering transient flare events (Linton et al. 2001; Kusano et al. 2004). However, such observational evidence of negative or opposite helicity flux may not be a real change due to true helicity transfer; it could be flare-related transient change affecting the magnetic field measurements. The observed distribution of negative helicity flux coincides spatially and temporally to the reports of possible flare effects on Doppler and magnetic measurements in the X2.2 flare (Maurya et al. 2012). A specific study focusing on the helicity injection and its behavioral change during flares and CMEs from this AR 11158 is presented in Vemareddy et al. (2012). They showed that the change of helicity flux signal due to injection of opposite helicity could be a true change unless there is no impulsive effect of the flare on magnetic field measurements. In particular, the localized helicity flux distribution, having sudden dips in the helicity flux profile as drawn in the figure, is affected by flare-related transient effects during these M6.6 and X2.2 flare cases.

The temporal profile of free energy is plotted in the bottom frame of Figure 6, along with the GOES X-ray flux. The onset times of flares from the sub-region R2 are marked in this frame. The error bars represent standard deviation of free energy obtained by changing the origin of the coordinate system (as explained before), representing the departure from force-freeness and flux balance. It is to note that the AR, as a whole, nearly fulfills the conditions for force-freeness and flux balance ($\leq 0.05$). Therefore, the constructed potential field from the extrapolation is not far from these conditions. The integration was carried out over the sub-regions of interest, R1 and R2, using Equation (9). Although the force-free condition was nearly satisfied, a part of the field lines from R2 were seen to be connected to R1 from the coronal AIA images. Hence, the condition for flux balance was not fully obeyed, which poses some problem for the applicability of the virial theorem. Therefore, the derived results are not conclusive enough unless the mean value of free energy is much larger than the error bars.

The most significant finding of the free-energy plot is the step-down decrease in free energy at the onset of the flares (indicated by the GOES X-ray profile). This provides unambiguous evidence of energy release during the flares. Magnetic energy is believed to be stored by flux emergence and force-freeness and flux balance. Therefore, the derived results are not conclusive enough unless the mean value of free energy is much larger than the error bars.

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The changes in potential and total energy estimated from the onset to the post-flare phase are given in Table 2 for those flares where we found the step-down decrease in the energy. The
difference in available free energy between the post-flare and the flare onset time, which gives the amount of energy released during the main flares, is described in the following.

The X2.2 flare of February 15/01:44 UT. The total energy \( E_T \approx [4.92 \pm 1.58] \times 10^{32} \text{ erg} \) was estimated on February 15/01:48 UT. It decreased to \([3.67 \pm 1.20] \times 10^{32} \text{ erg}\) after the impulsive phase of the flare, i.e., at 02:12 UT. The ratio \( E_T/E_P \), the total energy over the energy of the respective potential state, corresponds to 2.01 and 1.46 at these two time instants. During this short 24-minute period, the excess energy released was estimated as \([1.05 \pm 1.04] \times 10^{32} \text{ erg} \), sufficient to account for an X-class flare.

The M6.6 flare of February 13/17:28 UT. The ratio \( E_T/E_P \) of 1.6 at the onset time of the flare at 17:24 UT reduced to 1.08 at 18:12 UT, i.e., after the flare. This implies a release of free energy of \([4.3 \pm 1.7] \times 10^{32} \text{ erg} \), i.e., consistent with the magnitude of the flare.

Similarly, the free energies released for the C-class events, listed in Table 1 and shown by shaded bars, in Figure 6 are estimated as \([1.8 \pm 5.9] \times 10^{31}, [1.6 \pm 5.4] \times 10^{31}, [3.7 \pm 5.2] \times 10^{31}, \) and \([1.1 \pm 4.5] \times 10^{31} \text{ erg} \). These estimated values are not statistically significant as the mean values are smaller than the errors by a factor of two. Because the magnetic energy change is purely due to the change in the boundary conditions, it is expected that even minute changes in the magnetic field corresponding to a C-class flare would be reflected by the mean values retaining error bars without much change.

4. SUMMARY AND CONCLUSIONS

This study suggests that the rotational motions of major sunspots in NOAA AR 11158 were not only related to the transport of magnetic energy and complexity from the low atmosphere to the corona, but also appear to have played a major role in the onset of flares and CMEs. We have attempted to infer the relationship between the observed flux motions, variations in derived physical parameters in association with the dynamical transients, namely, flares and CMEs. A careful analysis of the flux motions leads us to better understand the dynamical nature of the photosphere at the interface between the convection zone where the basic dynamo originates and the tenuous corona.

The observations presented here provide direct evidence for the energization of the solar corona by the emergence and/or dynamics of magnetic flux tubes that appear as rotating sunspots. This phenomenon is important for understanding how the solar atmosphere attains the conditions necessary for the release of energy and helicity observed in solar flares and CMEs. For a detailed study of various physical parameters characterizing non-potentiality, we selected two sub-regions, R1 and R2 of AR NOAA 11158, which consisted of rotating sunspots. In R1, with the rotating sunspot SN1, the estimated rotation rate is found to have a good correspondence to twist parameters \( \alpha_{av} \) and \( \alpha_{best} \), \( \langle S \rangle \), and \( dH/dt \). It showed that the intrinsic rotation of the sunspot increased the overall twist in sub-region R1. Major CMEs in R1 occurred on 14 February at 12:50, 17:30 and 19:20 UT, which coincided well with the timings of high helicity injection rates and twist parameters. As the sunspot’s rotation rate reached the maximum, the fluxes moved with maximum velocities to provide larger complexity in the connectivity. The calculated free energies, however, did not show good correspondence to the observed CME events, except that broad peaks were observed during these CMEs. This is largely due to the violation of the flux-balance condition (80%). It is important to note that the occurrence of CMEs is also attributed to the new flux emergence (Martin et al. 1985; Zhang et al. 2008). However, the absolute flux profile of R1 does not show such sudden emergence of flux related to the emergence of SP1.

No clear relationship of the rotation rate is found with the twist parameters and \( dH/dt \) for the sunspot SP2 in R2. Shear motion of SP2 (cf. Figure 1(f)) seems to be the dominant factor, which obliterates the rotational effect of SP2 on the twist parameters and helicity rate. This shear motion caused the storage of magnetic energy by stressing the field lines. The intermittent release of energy during the observed flares is discernible. A total free energy of \([1.05 \pm 1.04] \times 10^{32} \text{ erg} \) is released during the X2.2 flare. This is three times larger than the derived energy from coronal magnetic field extrapolations by Sun et al. (2012) over the entire AR. Spectral line-profile reversals occurred during the impulsive phase of this flare, affecting the magnetic and velocity field measurements, as reported recently by Maurya et al. (2012). As a result, the injected helicity rate shows an impulsive negative peak because of the sudden appearance of negative helicity density, which indicates flare-related transient effect (cf. Figure 5(d)).

The M6.6 flare of February 13/17:28 UT was another large, but less impulsive, event that released \([4.3 \pm 1.7] \times 10^{31} \text{ erg} \) of energy in a 48-minute period. Step-down decrease of free energy was found not only during the two large flares, but also in some flares of smaller magnitude. This reveals the storage and release of energy in the flares occurring in sub-region R2. It is important to mention that we have not carried out an analysis of errors due to the spectro-polarimetric and random noise and their effects on the free-energy estimation. At present, there is no established method available on the data set. Moreover, the estimation of free energy suffers due to the departure from the validity conditions of the virial theorem as a result of the selection of small-sized areas of the sub-regions.

The accumulated helicity contributed by the rotational motion of the sunspot can also be obtained as

\[
\Delta H = \frac{1}{2\pi} \Delta \theta \Phi^2,
\]

where \( \Phi \) is the magnetic flux and \( \Delta \theta \) is the total rotation angle of the sunspot. Since the sunspot SN1 rotated by \( \approx 160^\circ \) during the 60 hr period of our study, and assuming the average magnetic flux of this sunspot as \( 3.5 \times 10^{33} \text{ Mx} \), the accumulated helicity by rotation is estimated as \( -5.44 \times 10^{32} \text{ Mx}^2 \). This is consistent with the derived value of \( -4.44 \times 10^{32} \text{ Mx}^2 \) from the tracked velocities of the fluxes.

Thus, this study demonstrates that both shear (dominated in R2) and rotational (dominated in R1) motions of the observed fluxes enhanced the magnetic non-potentiality of the AR by injecting helicity. This helped to increase the free energy of the AR’s magnetic field by increasing the overall complexity, leading to the conditions favorable for the eruptions. The deduced physical parameters describing the level of magnetic non-potentiality and the free energy showed a reasonably good correspondence to the observed transient activity of the AR. This study also provides clear signatures of energy release during the major energetic transients of the AR.

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REFERENCES

Ambastha, A., Hagyard, M. J., & West, E. A. 1993, Sol. Phys., 148, 277
Bhatnagar, A. 1967, Kodaikanal Observ. Bull., A180
Borrero, J. M., Tomczyk, S., Kubo, M., et al. 2011, Sol. Phys., 273, 267
Brown, D. S., Nightingale, R. W., Alexander, D., et al. 2003, Sol. Phys., 216, 79
Canfield, R. C., Hudson, H. S., & McKenzie, D. E. 1999, Geophys. Res. Lett., 26, 627
Chandrasekhar, S. (ed.) 1961, Hydrodynamic and Hydromagnetic Stability (Oxford: Clarendon)
Evershed, J. 1910, MNRAS, 70, 217
Freeland, S. L., & Handy, B. N. 1998, Sol. Phys., 182, 497
Gary, G. A. 1989, ApJS, 69, 323
Gary, G. A. 2001, Sol. Phys., 203, 71
Hagino, M., & Sakurai, T. 2004, PASJ, 56, 831
Hiremath, K. M., Suryanarayana, G. S., & Lovely, M. R. 2005, A&A, 437, 297
Hoeksema, J. T., Liu, Y., Hayashi, K., et al. 2012, Sol. Phys., in press
Howard, R. F., Harvey, J. W., & Forgach, S. 1990, Sol. Phys., 130, 295
Jiang, Y., Zheng, R., Yang, J., et al. 2012, ApJ, 744, 50
Kusano, K., Maehiro, T., Yokoyama, T., & Sakurai, T. 2004, ApJ, 610, 537
Leka, K. D., & Barnes, G. 2003, ApJ, 595, 1277
Leka, K. D., Barnes, G., Crouch, A. D., et al. 2009, Sol. Phys., 260, 83
Lemen, J. R., Title, A. M., Akin, D. J., & Boerner, P. F. 2012, Sol. Phys., 275, 17

Linton, M. G., Dahlburg, R. B., & Antioco, S. K. 2001, ApJ, 553, 905
Liu, J., & Zhang, H. 2006, Sol. Phys., 234, 21
Low, B. C. 1982, Sol. Phys., 77, 43
Martin, S. F., Livi, S. H. B., & Wang, J. 1985, Aust. J. Phys., 38, 929
Maurya, R. A., Vemareddy, P., & Ambastha, A. 2012, ApJ, 747, 134
McIntosh, P. S. 1981, in The Physics of Sunspots, ed. L. E. Cram & J. H. Thomas (Sunspot, NM: Sacramento Peak Observatory), 7
Metcalfe, T. R. 1994, Sol. Phys., 155, 235
Metcalfe, T. R., Jiao, L., McClymont, A. N., Canfield, R. C., & Uitenbroek, H. 1995, ApJ, 439, 474
Metcalfe, T. R., Leka, K. D., & Mickey, D. L. 2005, ApJ, 623, L53
Molodensky, M. M. 1974, Sol. Phys., 39, 393
Pariat, E., Demoulin, P., & Berger, M. A. 2005, A&A, 439, 1191
Pevtsov, A. A., Canfield, R. C., & Metcalf, T. R. 1994, ApJ, 425, L117
Schou, J., Scherrer, P. H., Bush, R. I., & Wachter, R. 2012, Sol. Phys., 275, 229
Schuck, P. W. 2006, ApJ, 646, 1358
Sun, X., Hoeksema, J. T., Liu, Y., et al. 2012, ApJ, 748, 77
Tian, L., & Alexander, D. 2006, Sol. Phys., 233, 29
Tian, L., Alexander, D., & Nightingale, R. 2008, ApJ, 684, 747
Tsuneta, S., Ichimoto, K., Katsukawa, Y., & Nagata, S. 2008, Sol. Phys., 249, 167
Vemareddy, P., Ambastha, A., Maurya, R. A., & Chae, J. 2012, ApJ, in press (arXiv:1202.5195)
Wang, H., Ewell, M. W., Jr., Zirin, H., & Ai, G. 1994, ApJ, 424, 436
Yan, X.-L., Qu, Z.-Q., & Kong, D.-F. 2008, MNRAS, 391, 1887
Yan, X.-L., Qu, Z.-Q., Xu, C.-L., Xue, Z.-K., & Kong, D.-F. 2009, Res. Astron. Astrophys., 9, 596
Zhang, H. 2001, ApJ, 557, L71
Zhang, J., Li, L., & Song, Q. 2007, ApJ, 662, L35
Zhang, Y., Liu, J., & Zhang, H. 2008, Sol. Phys., 247, 39