Signatures of Untwisting Magnetic Field in a Small Emerging Bipole in the Solar Photosphere

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Abstract

We perform a study of fluid motions and its temporal evolution in and around a small bipolar emerging flux region using observations made by the Helioseismic and Magnetic Imager on board the Solar Dynamics Observatory. We employ local correlation tracking of the Doppler observations to follow horizontal fluid motions and line-of-sight magnetograms to follow the flux emergence. Changes in vertical vorticity and horizontal divergence are used to derive signatures of evolving twists in the magnetic field. Our analysis reveals that the two polarities of the magnetic flux swirl in opposite directions in the early stages of flux emergence indicating an unwinding of the pre-emergence twists in the magnetic field. We further find that during the emergence, there is an increase in swirly motions in the neighboring nonmagnetic regions. We estimate the magnetic and kinetic energies and find that magnetic energy is about a factor of 10 larger than the kinetic energy. During the evolution, when the magnetic energy decreases, an increase in the kinetic energy is observed indicating transfer of energy from the unwinding of the magnetic flux tube to the surrounding fluid motions. Our results thus demonstrate the presence of pre-emergence twists in an emerging magnetic field that is important in the context of the hemispheric helicity rule warranting a detailed statistical study in this context. Further, our observations point to a possible widespread generation of torsional waves in emerging flux regions due to the untwisting magnetic field with implications for upward energy transport to the corona.

Unified Astronomy Thesaurus concepts: Solar photosphere (1518); Solar magnetic fields (1503); Solar magnetic flux emergence (2000); Solar activity (1475); Solar evolution (1492)

1. Introduction

The emergence and dynamics of magnetic flux play a pivotal role in the formation and evolution of various structures in the solar atmosphere as well as have a direct impact on space weather and climate. On the one hand, they are considered to be the prime candidates for the transfer of mass and energy within the solar atmosphere (e.g., Benz 2017 and references therein). On other hand, they are known to be closely associated with eruptive events at various scales such as flares (e.g., Sun & Norton 2017; Verma 2018 and references therein), jets (Mulay et al. 2016; Zheng et al. 2018), coronal mass ejections (CMEs; Tripathi et al. 2004; Chifor et al. 2007; Syntelis et al. 2017; Yan et al. 2017), UV bursts (Gupta & Tripathi 2015; Tian et al. 2018; Guglielmetti et al. 2019), and Ellerman Bombs (Pariat et al. 2004; Isobe et al. 2007).

The emergence of magnetic flux occurs at various spatio-temporal scales. Some emerge and evolve into prominent active regions (ARs), whereas some get fragmented during the early phase. ARs, when observed on the solar surface, exhibit a well-known characteristic pattern: those in the northern hemisphere show counterclockwise superpenumbral structures, whereas those observed in southern hemisphere show clockwise superpenumbral structures as was first discovered by Hale (1927). This pattern has been well studied since then and is attributed to the helicity of magnetic field, and is now known as the hemispheric helicity rule (Pevtsov et al. 1995, 2014; Longcope et al. 1998; Liu et al. 2014b).

In recent years, with the advent of long-term vector magnetic field measurements statistical studies have been performed to understand the hemispheric helicity rule. Wang (2013) has shown that about 60%–82.5% of the active regions follow the hemispheric helicity rules. By taking a sample of 151 active regions, Liu et al. (2014b) have found that 75% ± 7% of the active regions obey the hemispheric helicity rule. The question then arises that what happens to the other 25% that they do not follow this pattern. We emphasize that Liu et al. (2014b) did not discriminate between newly emerging and fully evolved active regions. In a study of a sample of 28 ARs, which focused on newly emerging ARs, Liu et al. (2014a) found that only 61% obeyed the hemispheric helicity rules, which is a significant drop in the percentage of active regions following the hemispheric pattern. The authors suggest that this could be due to small sample size and therefore may not be statistically significant. However, such a result also suggests that emerging flux regions may go through complex processes that may prevent them from exhibiting the peculiar behavior. Therefore, this warrants further detailed studies on emerging flux regions.

In terms of magnetic helicity, the observed hemispheric pattern corresponds to negative (positive) magnetic helicity in the northern (southern) hemisphere (Seehafer 1990; Pevtsov et al. 1995; Abramenko et al. 1997; Bao & Zhang 1998; Pevtsov et al. 2014). Duvall & Gizon (2000) and Gizon & Duvall (2003a) suggested that the large-scale converging flows toward active regions with the action of Coriolis force are consistent with the observed hemispheric pattern (Pevtsov et al. 2014; Braun 2019). Therefore, we may deduce that the magnetic helicity of ARs showing the hemispheric rule could primarily be due to the swirling fluid, which converts its kinetic helicity to the magnetic helicity. However, the large-scale converging flows develop as a consequence of the thermal imbalance due to the establishment of fully grown sunspots (Wu et al. 1986;
Khodachenko & Zaitsev 2002). Therefore, the hemispheric pattern may not be unambiguously observed in newly emerging active regions. The reduced trend in the hemispheric pattern in the case of emerging active regions observed by Liu et al. (2014a) is consistent with such a picture. However, we stress that the origin of helicity is still not established, and that the above inferences based on large-scale inflows is only suggestive of a possible origin.

An essential diagnostic of the above-suggested scenario is then to study the signatures of pre-emergence magnetic helicity (twist and writhe) in emerging ARs. If the sign of pre-emergence twist does not match with what is expected from the hemispheric pattern, then the emerging AR would undergo untwisting motion to follow the hemispheric pattern after complete emergence. Therefore, a careful analysis is warranted to fully comprehend the nature of flux emergence and its interaction with the surrounding fluid. For example, if we study the fluid vorticity during the process of the flux emergence, we may observe signatures of winding or unwinding of flux tubes.

In addition to the above, several studies show that magnetic regions on the Sun are associated with vortex motions (Brandt et al. 1988; Bonet et al. 2010; Wedemeyer-Böhm et al. 2012; Yan et al. 2014; Zheng et al. 2016). These motions are of particular significance because they can generate torsional Alfvén waves (Giovannelli 1972; Jess et al. 2016; Leonard et al. 2018; Felipe et al. 2019), which are important for solar coronal heating. Due to this reason, a search on these torsional motions is underway (Brandt et al. 1988; Wang et al. 1995; Zhang 2006; Attie et al. 2009; Bonet et al. 2010; Wedemeyer-Böhm et al. 2012; Gosain et al. 2013; Sangeetha & Rajaguru 2016). However, studies are sparse on the nature of twists observed in the early stages of flux emergence (Leka et al. 1996; Portier-Fozzani et al. 2001; Pevtsov et al. 2003).

For the above purposes, we observe a small bipolar region during its emergence in the photosphere. This region was a part of the data used in the analysis of the work carried out by two of the authors of this paper (Sangeetha & Rajaguru 2016). The region showed different behavior than the rest of the regions used for analysis. When investigated on this further, we realized that it was due to the small flux emergence in the southern hemisphere. This motivated us to investigate this region further using continuous observations provided by the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory (SDO; Scherrer et al. 2012) to study the changes in vorticity during the emergence. The data used for this analysis are discussed in Section 2. The analysis and results are discussed in Section 3. Finally, we present the summary and conclude in Section 4.

2. Observation and Analysis Method

2.1. Data

A small bipolar region that is studied in this paper started to emerge on 2011 May 8 in the southern hemisphere of the Sun, and was later identified as NOAA 11211 on 2011 May 10. The focus of this work is to study the evolution of this emerging flux region and its effects on the plasma motions in its vicinity. For this purpose, we have used the Doppler velocity ($v_D$) and line-of-sight (LOS) magnetic field ($B_{LOS}$) recorded by the HMI instrument on board SDO. The HMI provides measurements of these quantities with a cadence of 45 s and pixel size of 0\textdegree.5. The whole region taken for the analysis is 512\textdegree $\times$ 512\textdegree, which is centered around Carrington longitude 16\textdegree.1 and Carrington latitude $-3\textdegree.5$. Figure 1 displays the LOS magnetic field maps showing emerging bipole located with a yellow arrow. The overplotted blue box encloses the region that is considered for further detailed analysis.

We have tracked the marked bipolar region from 2011 May 8 until 2011 May 11. To study the evolution of flows and magnetic field, we subdivided the full length of observations into five shorter segments, namely, T1, T2, T3, T4, and T5 as noted in Table 1. Each observation set covers 14 hr, except T4 which includes only 12 hr, due to unavailability of data. In order to avoid large uncertainties due to projection effects, we demanded that the region of interest should be located within 30\textdegree latitude and longitude. The error due to projection effect would be less than 15\%. Moreover, the duration for each time series is taken so as to be not influenced by the effects of dying and newly generated supergranular flows (see, e.g., Sangeetha & Rajaguru 2016).

Figure 2 displays the HMI LOS magnetic field maps corresponding to the blue box in Figure 1 at the beginning of each observation set. We note here that the leading polarity is positive, whereas the trailing polarity is negative. As the figure reveals, with passing time, the bipolar region spreads and shows enhanced magnetic field. In Figure 3, we plot the evolution of magnetic field derived within the area indicated by Figure 2 for all the observation data sets. Figure 3 reveals that the magnetic field continuously increases and reaches the highest values of $\sim 18 \times 10^{18}$ Mx during the third observation set. Thereafter, the flux starts to decrease and continue to decline throughout our

| Time Series | Start of Observation | End of Observation |
|-------------|----------------------|--------------------|
| T1          | 02:00 on 2011 May 8  | 16:00 on 2011 May 8|
| T2          | 16:00 on 2011 May 8  | 06:00 on 2011 May 9|
| T3          | 06:00 on 2011 May 9  | 20:00 on 2011 May 9|
| T4          | 20:00 on 2011 May 9  | 08:00 on 2011 May 10|
| T5          | 00:00 on 2011 May 11 | 14:00 on 2011 May 11|
observation. The missing data between T4 and T5 are marked as “no data” in the figure.

2.2. Analysis

The main aim of the paper is to study the interplay between the emerging flux and fluid motion. For this purpose, we have derived the vertical vorticity \( \omega_z \) and horizontal divergence \( d_h \), which are defined as

\[
(\nabla \times \mathbf{v})_z = \left( \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y} \right) = \omega_z \text{ (vertical vorticity),} \tag{1}
\]

\[
(\nabla \cdot \mathbf{v})_h = \left( \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} \right) = d_h \text{ (horizontal divergence),} \tag{2}
\]

where \( v_x \) and \( v_y \) are the horizontal velocities and are computed by applying Fourier Local Correlation Tracking (FLCT; Welsch et al. 2004) on the Doppler velocities obtained from HMI. The granular structures, which appear as upflows and downflows in the Doppler velocity maps, are used to track the horizontal motions on the Sun. For the application of FLCT procedure, we have used parameters such as the Gaussian window \( \sigma = 15 \) pixels and the time difference between the images as \( \Delta t \approx 2 \) minutes, similar to Sangeetha & Rajaguru (2016). Moreover, we have removed the \( p \) and \( f \) mode signals from the data before computing the velocities. This has been done by using a Gaussian-tapered filter that filters out all the signals above 1.2 mHz frequency. The nature of these physical quantities provides us with information on the fluid properties at the photosphere.

In Figure 4, we show two snapshots of Doppler velocity maps. The overplotted black arrows represent the horizontal
Figure 4. Snapshots of the Doppler velocities corresponding to three of observation sets, namely, T1, T3, and T4. Overplotted arrows are the horizontal motions tracked from fluid motions using FLCT. The overplotted contours correspond to the negative (black) and positive (yellow) magnetic field of ±50 G.
motions tracked from the Doppler velocity using the FLCT procedure. The length of the arrow indicates the flow speed. We have overplotted the contours of ±50 G positive (yellow) and negative (black) magnetic field. These plots clearly show the swirly pattern in the plasma. It is more evident in the positive field region than in the negative magnetic field region. It is to be noted that not just the swirly motions associated with fluids result in vorticity but also shearing motions in plasma. The horizontal velocities computed here are then used to compute $\omega_z$ and $d_h$ for all five data sets separately and are shown in Figures 5 and 6. We emphasize that these quantities are derived at each time step. However, for display purposes, a time average for each set is plotted in corresponding panels.

3. Results

Figure 5 displays the time-averaged horizontal divergence maps corresponding to the five observation sets, namely, T1, T2, T3, T4, and T5. The overplotted contours correspond to the negative (red) and positive (blue) magnetic field of ±50 G.

Figure 5. Time-averaged horizontal divergence maps corresponding to the five observation sets, namely, T1, T2, T3, T4, and T5. The overplotted contours correspond to the negative (red) and positive (blue) magnetic field of ±50 G.

Moving flux due to emerging magnetic flux and the influence of emerging flux on the fluid vorticities inside the emerging magnetic field region due to flux expulsion (Proctor & Weiss 1982).

Time-averaged maps of vorticities obtained for the five observation sequences are shown in Figure 6, as labeled. The positive (negative) $\omega_z$ values represent the motion of the fluid in a counterclockwise (clockwise) direction. The overplotted contours are the negative (red) and positive (blue) contours of $B_{LOS}$ similar to Figure 5. Figure 6(a) distinctly shows that the two polarities of the emerging flux have opposite signs of vertical vorticity. The presence of the opposite sign of vorticity is suggestive of the fact that the fluid at the two polarities is swirling in opposite directions. With passing time, this pattern changes, and we observe a mixed sense of vorticities in subsequent observation sets. However, the existence of differently directed swirly motions at both the polarities is still observed. We further note that toward the end of the observation, the direction of these swirly motions at two polarities are opposite to that seen at the beginning of the observations (see panels (a) and (e) of Figure 6).

3.1. Influence of Emerging Flux on the Fluid Vorticity Inside the Emerging Magnetic Field Region

In order to have further quantitative measurements of vorticities and its time evolution at the two polarities of the emerging flux, we plot in the top panel of Figure 7 the spatially averaged signed vorticities for positive and negative
magnetic flux for all five sets of observations. In the bottom panel, we plot the evolution of the unsigned vertical vorticity. Note that for creating these plots we have only considered the pixels with magnetic flux density larger than \( \pm 10 \) G, due to associated errors. It has to be noted that we are using magnetic fields only to separate magnetic and nonmagnetic regions. We have not used magnetic fields to track velocities. Hence, a lower threshold of 10 G that is of the order of the error in magnetic field measurements was used. A higher threshold in magnetic field could affect the results of nonmagnetic regions. In the top panel, the black curve represents the vertical vorticity for positive magnetic flux regions (leading polarity), whereas the red curve shows that for negative flux regions (trailing polarity). The figure reveals that the leading polarity primarily shows negative vorticity, which is according to the hemispheric rule, whereas the trailing polarity does not. Therefore, it is plausible to conclude that the two polarities are swirling in opposite directions, indicating either unwinding or winding of the emerging flux tube. Similar to what was deduced from Figure 6(a), the plots reveal that at the beginning of the flux emergence, the vertical vorticities at the two polarities are of opposite signs, suggesting rotation in the opposite direction. During the course of the evolution, though there are changes and the magnitude of vertical vorticity reduces, the sense of twist remains almost opposite, up to T4. In T5, we observe that the vorticity is mostly negative at both the footpoints, indicating that the fluid is going back to the original state, which is typical for the southern hemisphere of the Sun. Moreover, all these changes observed are more than the standard error estimates that lies between 5 and \( 9 \times 10^{-7} \) s\(^{-1}\).

We add a caveat here on the breaks in vorticity observed in these time evolution plots. When horizontal velocities are derived from the Doppler velocities using FLCT, at the edges, i.e., at the start and end of the time series, we get incorrect velocity measurements. Hence, we remove velocity measured at the edges to derive vorticity and divergence. This creates a gap of 15 minutes between each data set. Additionally, to remove the small-scale evolving features, we have performed one hour of smoothening of the derived vorticity. This introduces a gap by an additional two hours in the data, so a total of 2.5 hr between the data sets.

From the bottom panel, we find that in the initial stages of flux emergence (T1), the vertical vorticity is fluctuating around \( 3.5 \times 10^{-5} \) s\(^{-1}\). However, from the start of the second set of observation (i.e., during the strong emergence of magnetic flux) until the end (T5) the unsigned vertical vorticity shows a monotonic increase. We note that precisely at the same time when the signed vertical vorticity is found to decrease. This result could primarily be attributed to the generation of more oppositely directed vorticities in the fluids during the strong emergence of the flux.

Figure 6. Same as Figure 5, but for vertical vorticity.
3.2. Influence of Emerging Flux on the Fluid Vorticity in the Surrounding Nonmagnetic Regions

We further study the effects of emerging flux to the surrounding nonmagnetic regions. For this purpose, we have defined the nonmagnetic areas to be regions with magnetic flux density less than 10 G. We perform a similar analysis as was done for magnetic regions in Section 3.1. In Figure 8, we plot the spatially signed averaged (top panel) and unsigned averaged vertical vorticity (bottom panel) as a function of time for all five sets of observations. While the signed averaged curve shows a significant fluctuation in the vertical vorticity that is highest at the peak of the emerging flux, the unsigned average plot shows a monotonic increase in the vertical vorticities in the nonmagnetic region. From the top panel, we note that most of the time, the negative vorticity is more dominant over the positive, whereas at the time of intense flux emergence, i.e., during T3 and T4, the positive vorticity is dominant. The bottom panel shows a monotonic increase in the vorticity, similar to that observed for the magnetic regions. It is interesting to note that the magnitude of the vorticity in magnetic and nonmagnetic regions is almost the same. We further note that the unsigned averaged vorticity, for both magnetic (bottom panel of Figure 7) and nonmagnetic regions (bottom panel of Figure 8), keeps increasing even after the flux emergence has come to a halt.

The next obvious step is to study the extent to which the emerging flux region affects the fluid motion in the quiet Sun ($B_{\text{LOS}} < 10$ G). For this purpose, we drew concentric circles around the emerging flux as shown in the top panel of Figure 9 and identify them as R1–R6 as labeled. The first circle has a radius of 25″ and the consecutive circles increase in radius by 25″. Since close to the equator the vorticity values tend to reduce toward zero, we have considered only up to about 60″ in the southern hemisphere for this analysis. In the bottom panel of Figure 9, we plot the evolution of the signed averaged vorticities within the concentric cells for all five sets of observations for the nonmagnetic region. As can be inferred from the plots, the vorticity in region R1, i.e., very close to the emerging flux region, the fluctuations in the vorticity is most substantial. These fluctuations reduce in the outer cells. This is suggestive of the fact that the effects of emerging flux on the fluid motion in the surrounding nonmagnetic region is strongest in close vicinity and gradually reduces as we move farther out.

3.3. Relationship between Fluid’s Vertical Vorticity and Horizontal Divergence

There have been several studies showing a linear correlation between vertical vorticity ($\omega_z$) and horizontal divergence ($d_h$) for the quiet-Sun region that has been attributed to Coriolis effects (e.g., Duvall & Gizon 2000; Gizon & Duvall 2003a; Sangeetha & Rajaguru 2016). However, such correlation gets
computed within the concentric cells as labeled. For that purpose, we have plotted in Figure 10 the time-averaged vertical vorticity as a function of horizontal divergence according to the criterion of emerging divergence obtained for five different sets of observations as labeled. For this purpose, we have identified all the quiet-Sun pixels in all five sets of observations with $|B_{\text{LOS}}| > 10$ G. For all these pixels, we have binned the $\omega_z$ within a bin size $20 \mu s^{-1}$ for divergence and plotted the variation of $\omega_z$ and $d_B$ for each observation set. For comparison with the quiet Sun, we have reproduced the vertical vorticity as a function of horizontal divergence curve (in red) for a quiet-Sun region from Sangeetha & Rajaguru (2016). The figure reveals that the solid black line corresponding to the first set of observation T1 (right at the start of flux emergence) shows the same behavior of linear correlation as that of the solid red line. However, this linear correlation starts to get altered for the observation set T2 that continues with emerging flux. The curve obtained for the last set, i.e., T5, shows behavior similar to that obtained for the northern hemisphere, i.e., for negative divergence vorticity is positive and vice versa (Duvall & Gizon 2000; Gizon & Duvall 2003a; Sangeetha & Rajaguru 2016).

### 3.4. Energetics

In order to understand the involved energetics in the emerging flux region, we compute the magnetic ($B^2/(8\pi)$) as well as the kinetic energy densities ($\rho v^2/2$) during the emergence, where $B$ is the magnetic field and $\rho$ is mass density that is taken from FAL-93 (Fontenla et al. 1993) Model-C as $= 2.75 \times 10^{-7}$ g cm$^{-3}$. $v$ is the horizontal velocity that is obtained as $\sqrt{v_x^2 + v_y^2}$, which is computed using FLCT (as shown in Figure 4).

Table 2 lists the estimates of maximum magnetic energy density $E_B^{\text{max}}$ (column 2) and maximum kinetic energy density $E_K^{\text{max}}$ (column 4) obtained in each set of observation. Columns 3 and 5 are the spatially and temporally averaged magnetic and kinetic energies. We note that for this analysis we have only used pixels with magnetic flux density $B > \pm 50$ G. Regions with high magnetic fields were considered to avoid the small-scale field, which may or may not be related to the emerging flux region.

The analysis shows that the magnetic energy density is always higher than the kinetic energy density for all the sets of observations. Moreover, the magnetic energy increases with time until the third set of observations and decreases thereafter. This finding is consistent with the magnetic flux as seen in Figure 3. We further note that, while the magnetic energy

| Time Interval | $E_B^{\text{max}}$ | $E_B^{\text{avg}}$ | $E_K^{\text{max}}$ | $E_K^{\text{avg}}$ |
|---------------|-------------------|------------------|------------------|------------------|
| T1            | $7.45 \times 10^4$ | $1.27 \times 10^4$ | $2.83 \times 10^3$ | 57.3             |
| T2            | $7.87 \times 10^4$ | $1.94 \times 10^3$ | $1.87 \times 10^3$ | 27               |
| T3            | $8.2 \times 10^4$  | $2.04 \times 10^3$ | $2.8 \times 10^3$  | 58.9             |
| T4            | $6.44 \times 10^4$ | $1.61 \times 10^3$ | $2.98 \times 10^3$ | 58.9             |
| T5            | $2.4 \times 10^4$  | $9.28 \times 10^2$ | $4.22 \times 10^3$ | 90.11            |

Note. All the energy densities are in erg cm$^{-3}$.
increases, kinetic energy slightly decreases and vice versa in the later phase. The presence of higher magnetic energy at all times makes it plausible to conclude that the magnetic field has sufficient energy to alter surrounding fluid motions.

We would like to point out that, in an ideal situation, for a flux tube surrounded by a completely field-free plasma, there is no tangential force on the flux tube surface, i.e., the magnetic pressure force is perpendicular to the flux surface and the tangential tension force would not have any effect on the surrounding plasma. But in reality a flux tube in a stratified plasma is subject to instabilities like kink or sausage (Priest 2014). These would hence lead to tension forces tangential to the field. This can cause an exchange of vortical motions that are magnetic in origin, viz. the magnetic baroclinicity and tension terms of the vorticity evolution equation in MHD. In this work, we have measured and studied motions around an emerging flux region and have attempted to link their vortical nature to the above sources of magnetic origin. The details of how magnetic field generates vorticity is not aimed observationally in our work.

4. Summary and Conclusion

In this paper, we have studied the evolution of an emerging bipolar region from its birth using the observations recorded with HMI. For this purpose we have computed the vertical vorticity and horizontal divergences by tracking the horizontal motions using the FLCT methods (Welsch et al. 2004). We summarize the results below.

1. At the initial phase of flux emergence, the two bipolar footpoints of emerging flux harbor swirly motions or vorticities of opposite signs (see Figures 6 and 7). The sign of vorticity in the leading polarity confirms what the hemispheric rule would predict for the southern hemisphere of the Sun (i.e., clockwise rotation).

2. The unsigned average of vorticity computed for the magnetic region shows a monotonic increase with time, i.e., with emerging flux. The signed averages of vorticity show strong fluctuations in the early phases of flux emergence. In the nonmagnetic regions the increase in vorticity is found to be strongly correlated with the emerging magnetic flux (see Figures 7 and 8).

3. We have further studied the spatial extent until which the emerging flux affects the fluid motions in the quiet Sun. We find that the fluid close to the emerging flux region is most strongly affected. Such an effect reduces as we further move away from the emerging flux region (see Figure 9).

4. Our study further reveals that right at the beginning of flux emergence, there is a linear correlation between vortical vorticity and horizontal divergence. However, during the emergence, this correlation gets altered and becomes opposite to what is observed for the quiet Sun in the southern hemisphere (see Figure 10).

5. The magnetic energy density (both average and maximum) is found to be greater than the kinetic energy density at all times during the flux emergence (see Table 2).

In our analysis, we found that during the early phase of the flux emergence, the two footpoints of the magnetic field has twist in opposite directions, with only the leading polarity following a clockwise (negative vorticity) direction of the swirling motions typical for the southern hemisphere (Sangeetha & Rajaguru 2016) according to hemispheric helicity rules (Seehafer 1990; Pevtsov et al. 1995; Abramenko et al. 1997; Bao & Zhang 1998; Pevtsov et al. 2014), whereas the trailing polarity twists in a counterclockwise (positive vorticity) direction. Such disagreement in the vorticity (swirly motions) at the two footpoints can be attributed to a conclusive signature of the unwinding of the twisted flux tube. It has to be noted that the opposite direction of swirl at the two footpoints can either wind or unwind the flux tube. But since the signed vorticity was reducing over time, we have concluded that the magnetic flux tubes are unwinding. There could also be other mechanisms, for example, the plasma could be draining down the helical field lines resulting in a spiral-like structure with opposite vorticity or it could even occur due to a simple rotation of a flux tube as a whole without any change in its internal twist. But again, this would lead to the main question why is it that the footpoints have opposite vorticity observed. We further note that the observed opposite direction of twist is for about 1–2 days during the emergence, which is similar to the observed helicity injection rate observed in the corona during the time of flux emergence (see, e.g., Pevtsov et al. 2003). The observation of helicity injection in the corona during flux emergence has been attributed to torsional Alfvén waves generated due to the rotation of the emerging flux tubes (Pevtsov et al. 2003).

Another important fact is that we observe certain periodic variations in the vorticity with a period between 5 and 10 hr derived from the Doppler velocities. This periodic nature is observed in vorticity alone, i.e., this is not observed in the Doppler velocity data. Hence, we can rule out the fact that these are SDO orbital periodic variations observed in the data (Liu et al. 2012). These periodic behaviors observed in vortical motions are real and the origin of these is unknown.

Our results also display the linear correlation between the vertical vorticity ($\omega_z$) and the horizontal divergence ($d_\theta$) during the very initial stage of the flux emergence. This result is similar to that observed for the quiet Sun using time–distance helioseismology (Duvall & Gizon 2000; Gizon & Duvall 2003a) as well as FLCT (Sangeetha & Rajaguru 2016). Sangeetha & Rajaguru (2016) find that this behavior is only valid for nonmagnetic regions and the correlation is altered for magnetic regions. This is opposite to what is observed in our study during the emerging flux. This discrepancy could be attributed to the unwinding of the twisted flux tubes. In that scenario, the untwisting flux tube may impart its twist to the surrounding fluids. This scenario is also justified from the fact that at all times during the flux emergence, the magnetic energy density is at least 10 times greater than the kinetic energy density.

The observations of twisting and untwisting of flux tubes that may generate the torsional Alfvén waves are also important to address the problem of the heating of the solar atmosphere (Jess et al. 2016; Leonard et al. 2018). To the best of our knowledge, this is the first study reporting the unwinding of a flux tube during the flux emergence. Further work involving a statistical study is required to comprehend such phenomena fully.

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