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The Dynamics of AR 12700 in Its Early Emerging Phase. I. Interchange Reconnection

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Abstract

The emergence of active regions (ARs) leads to various dynamic activities. Using high-resolution and long-lasting H α observations from the New Vacuum Solar Telescope, we report the dynamics of NOAA AR 12700 in its emerging phase on 2018 February 26 in detail. In this AR, constant interchange reconnections (IRs) between emerging fibrils and preexisting ones were detected. Driven by the flux emergence, small-scale fibrils observed in H α wavelength continuously emerged at the center of the AR and reconnected with the ambient preexisting fibrils, forming new longer fibrils. We investigate three IR scenarios that occurred over two hours. Specially, the third scenario of reconnection resulted in the formation of longer fibrils that show pronounced rotation motion. To derive the evolution of the magnetic structure during the reconnections, we perform nonlinear force-free field extrapolations. The extrapolated three-dimensional magnetic fields clearly depict a set of almost potential emerging loops, two preexisting flux ropes at 03:00 UT before the second reconnection scenario, and a set of newly formed loops with less twist at 03:48 UT after the third reconnection scenario. All of these extrapolated structures are consistent with the fibrils detected at the H α wavelength. The aforementioned observations and extrapolation results suggest that the constant IRs resulted in the magnetic twist being redistributed from preexisting flux ropes toward the newly formed system with longer magnetic structure and weaker twist.

Key words: magnetic reconnection – Sun: activity – Sun: atmosphere – Sun: chromosphere – Sun: evolution – Sun: magnetic fields

Supporting material: animations

1. Introduction

The emergence of active regions (ARs) is of fundamental importance in solar physics. Observations of how ARs emerge reveal the transport processes that bring magnetic fields to the solar atmosphere. The emergence of ARs is a multi-stage process (van Driel-Gesztelyi & Green 2015). Initially, toroidal magnetic fields are generated close to the base of the convection zone. Then, presumably triggered by deep convective flows and buoyant instabilities, magnetic flux tubes rise toward the surface as Ω -shaped loops, break through it, and leave footprints in the forms of sunspots and plages (Zwaan 1987; Moreno-Insertis 1997, 2007; Fan 2009a). The evolution of emerging flux tubes from below the solar surface to the corona is associated with various phenomena such as moving magnetic features (Zhang & Wang 2002; Zhang et al. 2003), plages, Ellerman bombs (Nelson et al. 2013), arch filament system, micro-pores (González Manrique et al. 2017), rotational bipoles (Fan 2009b; Kumar et al. 2013), and jets/ surges (Vargas Domínguez et al. 2014). The relationships between the aforementioned phenomena and flux emergence are shown in the review of Schmieder et al. (2014). Recent high-resolution observations of small-scale emergence events illustrate how ARs appear on the solar surface. Otsuji et al. (2011) studied the nature of flux emergence with *Hinode* (Kosugi et al. 2007)/Solar Optical Telescope (Tsuneta et al. 2008) data. Centeno (2012) presented the naked emergence of

Original content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. ARs observed by the *Solar Dynamics Observatory* (*SDO*; Pesnell et al. 2012).

The emergence of ARs leads to various dynamic activities. Observations and numerical simulations have shown that the interaction of newly emerging magnetic flux with preexisting magnetic fields leads to coronal heating (Shibata et al. 1991; Moore et al. 2002; Pevtsov & Kazachenko 2004; Galsgaard & Parnell 2005) and redistribution of helicity (Zhang & Low 2001, 2003). When magnetic flux emerges from beneath the photosphere, it may reconnect with the preexisting fields. Interchange is one model of reconnection, which often occurs between closed and open fluxes (Crooker et al. 2002). Here, we define the interchange reconnection (IR) as the process in which two sets of magnetic loops interact with each other and interchange their footpoints. Observational evidence supportive of IR between emerging ARs and coronal holes (CHs) include corona dimming (Baker et al. 2007) and the retreat of the CH boundary (Kong et al. 2018). Li et al. (2014) reported the detailed IR process as a way to convert mutual helicity to selfhelicity by employing observations from the Interface Region Imaging Spectrometer (De Pontieu et al. 2014).

Numerical simulations of AR emergence bring insight into the magnetic and dynamic properties of the emergence process. Recent three-dimensional (3D) magnetohydrodynamics (MHD) simulations are able to produce an AR based on different emergence conditions (Archontis & Hood 2012; Rempel & Cheung 2014; Toriumi et al. 2015; Chen et al. 2017 and references therein). It is noteworthy that the model of Cheung et al. (2010) has rather successfully explained some observational properties associated with ARs' emergence, including elongated granules, mixed polarity patterns in the emergence zone, pore formation, and light bridges. In addition, flux emergence experiments often see the magnetic reconnection between emerging magnetic flux and the preexisting ambient fields. Edmondson et al. (2010) investigated the effect of IR on the dynamics and topology of CH boundaries. Based on 3D MHD calculations, Edmondson (2012) argued that IR plays a defining role in the evolution of the coronal magnetic field, and therefore the generation of the slow solar wind.

Despite preexisting MHD models for explaining AR emergence, observational evidence of the detailed emergence process has rarely been reported. Previous studies focused more on the photospheric layer and coronal response of the emergence events. Okamoto et al. (2009) reported the emergence of a flux rope at the polarity inversion line (PIL) in AR 10953, which was controversial. MacTaggart & Hood (2010) constructed a dynamic flux emergence model and found that the signatures of Okamoto et al. (2009) are not sufficient to uniquely identify an emerging flux rope. Vargas Domínguez et al. (2012) argued that the emergence of the flux rope did not take place at the PIL. Yan et al. (2017) observed a small-scale emerging flux rope near a large sunspot and the entire process from its emergence to its eruption using Big Bear Solar Observatory (BBSO)/Goode Solar Telescope (GST; Goode & Cao 2012). In addition, limited by the low resolution of previous observations, distinct detections of IR in the emerging ARs are rare. In the present work, using the high-resolution and long-lasting H α observations acquired at the New Vacuum Solar Telescope (NVST; Liu et al. 2014) and the simultaneous observations from the SDO, we present the detailed processes of three scenarios of IR in AR 12700 on 2018 February 26. It is noteworthy that the H α observations we adopted last for 5 hr, covering the early emerging phase of AR 12700. These observations provide a complete view of the IR, as they cover all the atmospheric layers from the photosphere to the corona at high temporal and spatial resolution. In particular, the H α observations clearly depict the emergence of flux tubes, and the rotational motion of fibrils that formed via reconnection between the emerging flux tubes and the preexisting fibrils (PF). Moreover, the results derived from the nonlinear forcefree field (NLFFF) extrapolations are consistent with the observations, providing more details on the changes of magnetic structures during the IRs.

Our paper is organized as follows. Section 2 describes the observations and data analysis taken in our study. In Section 3, we investigate three scenarios of IR between emerging flux and preexisting field in great detail. Finally, we summarize the major findings and discuss the results in Section 4.

2. Observations and Data Analysis

On 2018 February 26, NOAA AR 12700 emerged with a β configuration at solar disk location N04W01. The NVST was pointed at this region on February 26, and one series of H α 6562.8 Å observations was taken from 02:01:00 UT to 06:56:00 UT with a cadence of 8 s, a field of view (FOV) of 152" × 151", and a spatial sampling of 0."136 pixel⁻¹. These H α observations clearly reveal the detailed emergence process in the chromosphere, including fibrils emergence, interactions between different groups of fibrils, and untwisting motion of fibrils.

Moreover, we have also analyzed the data taken by the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) and Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the *SDO* to figure out the photospheric magnetic field

evolution and coronal response during the emergence of AR 12700. The HMI data adopted here were obtained from 2018 February 25 to 26, with a cadence of 45 s and a pixel size of 0."5. The AIA provides successive full-disk images of the multi-layered solar atmosphere with 10 passbands, 7 of which are in the extreme ultraviolet (EUV) channel and observed with a cadence of 12 s and a pixel size of 0."6. Here we focus on the 171 Å wavelength, which manifests the coronal brightenings clearly. All the data are calibrated with standard solar software routines, and all images observed by the *SDO* are differentially rotated to a reference time (04:00:00 UT on February 26). Moreover, data from all telescopes and instruments are carefully co-aligned, and the region of interest is spatially and temporally extracted from the different channels.

In order to investigate the evolution of the magnetic structures during the reconnections, we perform NLFFF extrapolations at 03:00 UT and 03:48 UT on February 26 with HMI photospheric vector magnetic fields as the boundary condition. The extrapolations use the "weighted optimization" method (Wiegelmann 2004; Wiegelmann et al. 2012). The vector magnetograms are preprocessed by a procedure developed by Wiegelmann et al. (2006) to remove the force and noise. Both NLFFF extrapolations are performed in a box of $288 \times 168 \times 256$ uniformly spaced grid points $(104 \times 61 \times 93 \text{ Mm}^3)$.

3. Results

AR 12700 emerged near the center of the solar disk on 2018 February 26, which is shown in Figure 1. Prior to the NVST H α observations, the sequence of HMI magnetograms shows remarkable rotation of magnetic patches and separation of the fields with opposite polarities in this AR. At 22:04:10 UT on February 25, the negative patch denoted by the white contour in Figure 1(a) owned an elongated shape and a 19° angle between its main axis and the horizontal direction. Then, the elongated patch rotated counterclockwise, increasing the angle up to 166° at 00:55:55 UT on February 26. The mean rotating speed was about 0°.85 minute⁻¹. In addition, a bipole (marked by white brackets in panel (b)) emerged at 23:05:40 UT on February 25 and its positive patch (denoted by the red triangle) shifted northeastward with a velocity of 0.5 km s⁻¹ in the following hour.

The H α observations reveal that constant IRs occurred in the central region of AR 12700, which is approximately outlined by the blue dashed rectangle in Figure 1(a) and extended in Figures 2-5. From 02:00 UT to 04:00 UT on February 26, three scenarios of IR were observed between the emerging fibrils (EF) and the preexisting ones. Figure 2 (also see its animation) shows the first scenario of reconnection, which occurred from 02:12 UT to 02:32 UT. The H α observations (panels (a1)–(a3)) clearly show that two groups of chromospheric fibrils, i.e., PF and EF, successively interacted with each other from 02:24 UT to 02:30 UT. As a result, a new group of fibrils (NF) was formed (see panel (a3)). The corresponding HMI magnetograms reveal that EF and PF were rooted in magnetic fields with opposite polarities, the southwest footpoint of EF was rooted in the main negative polarity of the AR, and its northeast footpoint was located in the positive fields emerging between the main polarities. After interaction, the west leg of NF was close to the EF's southwest footpoint and its east leg was close to PF's northeast footpoint (see panels (b) and (d)). It is consistent with the condition of IR. Moreover, AIA 171 Å



Figure 1. Sequence of *SDO*/HMI magnetograms displaying the evolution of AR 12700 from 22:00 UT on 2018 February 25 to 01:00 UT on February 26. The white contours outline the magnetic patch with negative polarity, which shows obvious rotation motion. The green solid line shows the axis of this patch, the yellow dashed line represents the horizontal direction, and the angle between them is α . The blue dashed rectangle approximates the FOV of Figures 2–5. The white square brackets in panel (b) highlight a newly emerging bipole, and the red triangle marks the positive magnetic element of the bipole. The triangles in panel (c) play the same role, with the red one indicating the present location and the blue one indicating the previous location in panel (b).

observations revealed brightenings appearing at the intersection of PF and EF, and lasting from 02:21 UT to 02:32 UT, which further implies that the IR occurred between EF and PF.

In Figure 3 (also see the animation in Figure 5), the second reconnection scenario is displayed, which occurred from 03:00 UT to 03:17 UT. At 03:02:09 UT, there were three groups of chromospheric fibrils: small-scale emerging fibrils (EF: EF1 and EF2) and two groups of PF (PF1 and PF2). The magnetic connections of EF and PF1 (see panel (b1)) here are similar to that shown in Figure 2(b). The western legs of EF and PF1 were rooted in the main negative polarity of AR 12700. Interactions between EF and PF1 started at 03:02 UT, continued for about 15 minutes, and then a new group of fibrils (NF1) formed. As shown in panel (b2), NF1 connected two main polarities of the AR, with its west leg close to EF's southwest footpoint and its east leg close to PF1's northeast footpoint. The changes of the magnetic connections of these two groups of fibrils are representative IR signatures.

Figure 4 displays the emergence of the small-scale fibrils and its associated thermal properties at the onset of the second reconnection. The newly EF were clearly observed at 03:03 UT (see panel (b2)). During the EF emergence, brightening in the 171 Å channel appeared in EF, the west footpoint of PF1, and the intersections of PF1 and EF, lasting from 03:03 UT to 03:06 UT. Note that the brightenings were first observed in the north part of EF and then in the south part (see panels (a1)– (a4)). To investigate the detailed process of the EF emergence, we make time slices (panels (c1)–(c2)) in the H α channel along vertical cut "A–B" and slit "C–D" shown in panel (b1). Panel (c1) shows that EF initially rose at a projected velocity of 13 km s⁻¹, which is comparable to the previous studies (Chou & Zirin 1988; Cheung & Isobe 2014). EF's rising projected height was 1.5 Mm. At 03:03 UT, H α brightenings began appearing at the two sides of EF. The light curve of H α superposed in panel (c2) shows that the average emission strength peaked around 03:05:30 UT. Significant brightenings in the H α channel and EUV channels at the interaction sites between EF and PF1 indicate the occurrence of reconnection.

The third reconnection is shown in Figure 5 (also see its animation). From 03:18 UT to 03:34 UT, PF2 was split into two groups; one group interacted with EF and led to the formation of new longer fibrils similar to NF1, which showed a pronounced rotation motion from 03:24 UT to 03:33 UT. Note that the rotation originated from the intersection between EF and PF2. At 03:34 UT, the southernmost part of EF was lifted and interacted with the other group of PF2, leading to the formation of another group of fibrils. As a result, several groups of newly formed longer fibrils (NFs) are produced to connect the main polarities after the constant reconnections. Meanwhile, brightenings (denoted by the green contour and arrows)



Figure 2. First scenario of interchange reconnection between emerging fibrils and preexisting ones observed from 02:12 UT to 02:31 UT on February 26. Panels (a1)–(a3): NVST H α images displaying the scenes before, during, and after the reconnection. The blue and red curves indicate the preexisting fibrils (PF) and the newly emerging small ones (EF), which are duplicated in panel (b). The yellow curve indicates the newly formed fibrils (NF) resulting from the reconnection, which is overplotted on panel (d). Panels (b)–(d): *SDO*/HMI magnetograms and AIA 171 Å image corresponding to the top panels. The green contours mark the locations of AIA 171 Å brightenings, which are overplotted on panels (a1)–(a2). The animation displays NVST H α and *SDO*/AIA 171 Å images shown in Figure 2. The 10 s animation covers 29 minutes from 02:05 UT to 02:34 UT on 2018 February 26.

(An animation of this figure is available.)



Figure 3. NVST H α and SDO/HMI observations displaying the second reconnection scenario from 03:00 UT to 03:17 UT. The features marked here are similar to those in Figure 2.

in the 171 Å channel appeared in the intersections of different groups of fibrils, peaked around 03:31 UT (panel (b2)), and lasted from 03:27 UT to 03:39 UT. The corresponding HMI magnetograms (panel (c)) show that the footpoints of NFs were

anchored in the locations of the EF's negative footpoint and PF2's positive footpoint, suggesting the magnetic connections are consistent with the IR model.



Figure 4. Characteristics of the emergence of the small-scale fibrils during the second reconnection scenario. Panels (a1)–(a4): brightenings at 171 Å during the EF emergence. The red arrows denote the EF brightenings that appeared successively. The blue arrows denote the brightening around footpoints of PF1. Panels (b1)–(b2): NVST H α images acquired before and at the onset of H α brightenings. The blue and red curves delineate the preexisting fibrils (PF1) and the emerging ones (EF), respectively. Panels (c1)–(c2): Time-slice plots at H α wavelength along vertical cut "A–B" and slit "C–D" marked in panel (b1), respectively. The white dashed–dotted lines mark the onset of the H α brightening. The yellow arrows denote the brightenings at H α wavelength. The red curve is the light curve displaying the variation of the average emission intensity at H α wavelength in slit "C–D."

Based on the photospheric vector magnetic fields at 03:00 UT and 03:48 UT, we extrapolate the 3D structure of the target AR using NLFFF modeling. For visualizations of the EF and preexisting ones in the second and third reconnection scenarios mentioned above, we select a region with an FOV similar to Figure 1 from the NLFFF extrapolations and display the results in Figure 6. Figures 6(a) and (b) show the extrapolation results at 03:00 UT from the top view and side view, respectively. The emerging loops (EL) were overlaid by two magnetic flux ropes

(FR1 and FR2). The north part of EL (EL(N)) is higher than its south part (EL(S)). At 03:48 UT, a set of longer loops (NL) with weak twist was formed. The modeling results are consistent with the observations shown in Figures 3–5 for EL(N), EL(S), FR1, FR2, and NL, corresponding well to EF1, EF2, PF1, PF2, and NFs in H α images, respectively. In addition, the extrapolations show that the twist angles of FR1 and FR2 are about 2π and 4π , respectively.



Figure 5. Similar to Figures 2–3 but for the third reconnection scenario from 03:18 UT to 03:40 UT. The green contour and arrows in panels (b1)–(b2) denote the 171 Å brightenings during the reconnection. The animation displays NVST H α and *SDO*/AIA 171 Å images shown in Figures 3–5. The 17 s animation covers 50 minutes from 02:55 UT to 03:45 UT.

(An animation of this figure is available.)

4. Summary and Discussion

In this paper, we study the dynamics of AR 12700 in its emerging phase on February 26 by using observations from the NVST and SDO. The photospheric evolution of the emerging AR is characterized by the rotation of magnetic patches and separation of emerging bipoles. Driven by the flux emergence, IR between emerging flux and preexisting fields constantly occurred in the upper atmosphere in AR 12700. At the center of this AR, we investigate three such processes in which smallscale EF reconnect with the overlying preexisting ones, accompanied by H α and EUV brightening, and forming new groups of fibrils. Specifically, during the third reconnection scenario, the formation of longer fibrils via reconnection shows remarkable rotation motion. In addition, the extrapolated 3D fields clearly depict the small-scale EL, two overlying flux ropes, and the newly formed loops. They coincide well with the observed EF, two groups of PF, and the newly formed longer fibrils, respectively.

The emergence of ARs is associated with various dynamic activities, such as jets and flares, which are triggered by reconnections (Shibata et al. 2007; Schmieder et al. 2013; Aulanier 2014). During the emergence of AR 12700, we detect

IRs and surge-like activities. Surge-like activities will be investigated in another upcoming paper. In the present work, three processes of IRs are investigated in detail. We confirm these reconnections are IR based on the following findings: (1) distinct interactions between constant EF and PF, (2) brightenings in H α and EUV wavelengths at their intersections, and (3) newly formed longer fibrils due the interactions between two groups of H α fibrils that show changes of magnetic connections.

The NLFFF modeling reveals that EL is almost potential, with its north part (EL(N)) higher than its south part (EL(S)). This coincides well with the observations shown in Figures 4(a1)–(a4), that is, brightenings in the 171 Å channel first appeared in the north part of EF and then in the south part of EF. Considering the extrapolation results and Figures 3–4, we suggest that PF1 first reconnected with EF1, which was higher and closer to PF1 at 03:00 UT, and then reconnected with EF2, which rose up to the height of PF1 at 03:03:33 UT. As shown in Figures 6(c)–(d) and the Figure 5 animation, the third reconnection scenario resulted in the formation of the twisted structure NL with a weaker twist than FR1 and FR2. Similar observations have been reported by Xue et al. (2016).



Figure 6. Magnetic structures revealed by the NLFFF extrapolations before the second reconnection scenario (panels (a)–(b)) and after the third reconnection scenario (panels (c)–(d)). The photospheric vertical magnetograms (Bz) are shown as the background. The first row is the top view of the structure, with north as up and west to the right. The second row is the side view. The red curves in panels (a)–(b) represent the emerging loops (EL), whose north part (EL(N)) is higher and south part (EL (S)) is lower. The two sets of green curves represent two magnetic flux ropes (FR1 and FR2). The green curves in panels (c)–(d) represent the newly formed twisted loops (NL) resulting from the reconnection.

They investigated the rotational motion of the erupted filament enabled by the reconnection with the chromospheric fibrils and proposed that the reconnection between the filaments and less twisted flux leads to the release of twist. Using BBSO/GST, Kumar et al. (2017) found that reconnection of cool loops caused the formation of an unstable flux rope that showed counterclockwise rotation, which was driven by the rapid flux cancellation in the decaying phase of AR 12353. However, in our case, the reconnections were driven by flux emergence in the AR emerging phase.

According to the twisted threads of NL shown in Figures 6(c)-(d), we estimate its twist angle to be less than 2π . As mentioned above, the twist angle of FR2 is about 4π . These extrapolation results suggest that the IR between potential emerging flux and preexisting flux ropes resulted in the magnetic twist being redistributed from preexisting flux ropes to a newly formed system with longer magnetic structure and weaker twist. As magnetic flux emergence occurs, the reconnections reconfigure the magnetic fields within the AR and redistribute the magnetic twist. Similar scenarios have been proposed by Pevtsov et al. (1996) and Canfield & Reardon (1998) with data of about 1" pixel size. In the present work, the observations with a 0."136 pixel size enable us to identify the details throughout the reconnection process. The result revealed in our work is different from the previous emerging-reconnection picture in that the emerging fields are twisted and then the twist is transported to the newly formed structure via reconnection with the potential overlying preexisting fields (Pevtsov et al. 2003; Fan & Gibson 2004). According to the work of Xue et al. (2016), when filaments reconnect with less

twisted flux, the twist tends to equilibrate along the new structure, resulting from a true propagation of twist from the more twisted to the less twisted part (as a torsional Alfvén wave packet). During the third reconnection scenario in our work, reconnections occurring between FR2 with a twist angle of 4π and the potential flux result in NL whose twist angle is less than 2π . This twist propagation process manifests as rotational motion of the newly formed longer fibrils.

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