SPECTROPOLARIMETRIC OBSERVATION OF AN EMERGING FLUX REGION: TRIGGERING MECHANISMS OF ELLERMAN BOMBS

H. Watanabe,1,2 R. Kitaï,2 K. Okamoto,1,2 K. Nishida,2 J. Kiyohara,2 S. Ueno,2
M. Hagino,2 T. T. Ishii,2 and K. Shibata2

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ABSTRACT

A high spatial resolution observation of an emerging flux region (EFR) was made using a vector magnetograph and a Hα Lyot filtergraph with the Domeless Solar Telescope at Hida Observatory on 2006 October 22. In Hα wing images, we could see many Ellerman bombs (EBs) in the EFR. Observations in two modes, slit scan and slit fixed, were performed with the vector magnetograph, along with the Hα filtergraph. Using the Hα wing images, we detected 12 EBs during the slit scan observation period and 9 EBs during the slit fixed observation period. With the slit scan observation, we found that all the EBs were distributed in the area where the spatial gradient of vertical field intensity was large, which indicates the possibility of rapid topological change in the magnetic field in the area of EBs. With the slit fixed observation, we found that EBs were distributed in the areas of undulatory magnetic fields, in both the vertical and horizontal components. This paper is the first to report the undulatory pattern in the horizontal components of the magnetic field, which is also evidence for emerging magnetic flux triggered by the Parker instability. These results allow us to confirm the association between EBs and emerging flux tubes. Three triggering mechanisms for EBs are discussed with respect to emerging flux tubes: 9 out of 21 EBs occurred at the footpoints of emerging flux tubes, 8 occurred at the top of emerging flux tubes, and 4 occurred in the unipolar region. Each case can be explained by magnetic reconnection in the low chromosphere.

Subject headings: Sun: chromosphere — Sun: magnetic fields — sunspots — techniques: spectroscopic

1. INTRODUCTION

Ellerman bombs (EBs) are short-lived, small-scale bright points observed best in the wings of chromospheric lines such as the Hα and Ca ii H lines. EBs were first discovered by Ellerman in 1917 (Ellerman 1917). The spectral profile of EBs consists of an absorption core at the Hα line center and asymmetric wide emissions in both the red and blue wings of Hα (Severny 1968; Engvold & Melbø 1968; Koval & Severny 1970; Bruzek 1972; Kitaï 1983).

The mean lifetime of an EB is estimated to be 10–20 minutes (Kurokawa et al. 1982; Nindos & Zirin 1998; Qiu et al. 2000). The typical size of an EB is on the order of 1″, and their shapes are mostly elliptical (Kurokawa et al. 1982; Nindos & Zirin 1998; Georgoulis et al. 2002; Pariat et al. 2007). The energy of an EB is estimated to be in the range 1025–1028 ergs (Bruzek 1972; Hu et al. 1995; Hénoux et al. 1998; Georgoulis et al. 2002; Fang et al. 2006).

It is reported that EBs are associated with chromospheric upflows with a velocity of about 6–8 km s−1 (Kurokawa et al. 1982; Kitaï 1983). On the other hand, Georgoulis et al. (2002) found that almost all EBs were also accompanied by photospheric downflows with a velocity of 0.1–0.4 km s−1. EBs are also related to Hα surges (Rust 1968; Matsumoto et al. 2008), which are thought to be evidence of magnetic reconnection in the low chromosphere. It has been suggested that some of the chromospheric anemone jets observed with Ca ii H filters are associated with EBs (Shibata et al. 2007).

It is important to study the relationship between EBs and magnetic fields, because EBs generally occur in areas of flux emergence and strong magnetic fields. In previous studies, it has been reported that several EBs appear at the boundaries of well-defined magnetic features, i.e., near magnetic-neutral lines (Roy & Leparuskas 1973; Dara et al. 1997), bipolar emerging fluxes (Zachariadis et al. 1987), or moving magnetic features (Nindos & Zirin 1998). In an emerging flux region (EFR), EB production is enhanced in the vicinity of sunspots, in areas near magnetic-neutral lines, and at the boundaries of neighboring supergranular cells (Qiu et al. 2000; Georgoulis et al. 2002). Georgoulis et al. (2002) suggested that EBs occur preferentially on separatrix or quasi-separatrix layers in the low chromosphere.

Based on observations, several triggering models for EBs have been proposed. The most generally accepted of these is magnetic reconnection in the low chromosphere (Hénoux et al. 1998; Georgoulis et al. 2002; Fang et al. 2003; Pariat et al. 2004; Fang et al. 2006). Chen et al. (2001), using a two-dimensional MHD simulation, confirmed that magnetic reconnection in the lower solar atmosphere can explain the main characteristics of EBs. On the other hand, Qiu et al. (2000) found that the majority of the Hα-UV (ultraviolet continuum at 1600 Å) well-correlated EBs were located at the boundaries of unipolar areas, and argued that EBs located in unipolar magnetic areas could be triggered by a mechanism other than magnetic reconnection in the low chromosphere. From a topological analysis, Pariat et al. (2004) found that EBs and bald patches were linked by a hierarchy of elongated flux tubes showing aperiodic spatial undulations, whose wavelengths were typically above the threshold of the Parker instability. These findings led to a resistive emergence model of magnetic flux tubes, as EBs are the signature of resistive emergence of undulatory flux tubes provoked by the Parker instability. Isobe et al. (2007) confirmed the validity of this model with a two-dimensional MHD simulation.

Our motivation is to test the magnetic reconnection model of EBs by analyzing time series data of magnetic and velocity fields in an EFR. In this paper, we use high-resolution data from a spectropolarimetric observation of NOAA 10917, taken with a vector...
magnetograph at the Domeless Solar Telescope (DST). Observational information and data reduction are presented in §2. The analysis of morphological characteristics from the slit observation is described in §3. Temporal evolutions of magnetic and velocity fields around EBs observed in the slit fixed observation are shown in §4. Finally in §5, we give a discussion and our conclusion about the triggering mechanism of EBs.

2. OBSERVATION AND DATA REDUCTION

We observed a β sunspot in NOAA active region (AR) 10917 from 2006 October 21 through October 22 for about 2.5 hr. Figure 1 (left) shows a full-Sun image of October 21 taken with the Solar Magnetic Activity Telescope (SMART) at Hida Observatory. With the DST, we performed on- and off-band imaging observations of the region in Hα, and a Fe i spectroscopic observation with the vector magnetograph. The AR consisted of two main preceding and following spots, and several small spots (see Fig. 1, right). In the Hα line center images (Fig. 1c), there were several dark filaments connecting the leading spot to the following one. The dark filaments showed redshift at their footpoints and blueshift at their tops; therefore, they were rising flux tubes. Beneath the dark filaments, numerous EBs appeared in the Hα wing images (Figs. 1a, 1b). The heliocentric coordinate of NOAA 10917 at 00:00 UT on October 22 was 5° S and 33° W. The AR was rather stable and in its developing phase during our observation period. No flare activity during our observation was reported by the Space Environment Center.

2.1. Hα Filtergram

A 10 wavelength set of Hα images (line center, ±0.3, ±0.5, ±0.8, ±1.2, and −5 Å) was obtained repeatedly with the DST from October 21 22:50 UT through October 22 01:27 UT. In our analysis, we used Hα ± 0.8 Å images for the identification of EBs. The pixel size of the Hα filtergram was 0.256", and the field of view (FOV) was 261" × 261". The time cadence of each wave-length frame was ~40 s. All the data were corrected by dark current subtraction and flat fielding.

2.2. Vector Magnetograph

Along with the Hα filtergrams, Fe i spectra were observed using a vector magnetograph (VMG). The spectral FOV includes both the 6301.5 Å and 6302.5 Å Fe i absorption lines. The spectral resolution was 0.0083 Å pixel−1 at 6302.5 Å, the slit length was 140.8", and the width was 0.275". A VMG consists of a rotating waveplate, three Wollaston prisms, and a high-dispersion spectrograph (Kiyohara et al. 2004). During one rotation of the waveplate, a pair of spectral images in orthogonally polarized states were taken at every interval of 22.5°. It took ~30 s for one rotation of the waveplate, and 16 pairs of data were demodulated into the Stokes parameters I, Q, U, and V with the method described in Kiyohara et al. (2004). The calculated Stokes I, Q, U, and V were inverted to generate parameters such as magnetic field intensity, magnetic inclination, magnetic azimuth, and line-of-sight velocity with the Advanced Stokes Polarimeter (ASP) inversion code (see Skumanich & Lites 1987). The ASP inversion technique adopts a Milne-Eddington atmosphere, so that parameters are assumed to be constant along the line-of-sight direction. Inversion was applied only in the area whose polarization degree was larger than 0.5%. The noise levels of the observed quantities, which were estimated from the temporal fluctuations at a relatively stable point near the center of the AR, were ±50 G for magnetic field intensity and ±3° for inclination and azimuthal angle.

We performed in two observation modes using the VMG: “slit scan” and “slit fixed.” In the slit scan mode, we scanned the AR by 2" intervals for 46 positions, so that we could generate one map with a FOV of 92" × 140.8". In the slit fixed mode, we tracked the AR manually, fixing the slit alignment along the axis of the AR, where EB production was active. The exposure time and the time cadence were 1500 ms and ~30 s, respectively, for
both observation modes. First, slit fixed observation was done from October 21 23:03 UT to October 22 00:53 UT. Next, slit scan observation was done from October 22 01:00 UT to 01:25 UT.

All spectral data were corrected by dark current subtraction and flat fielding. Slit fixed data were coaligned with reference to the positions of the main spots on the continuum images. We performed boxcar smoothing of 5 frames (2.5 minutes) on the slit fixed data to reduce high-frequency noise. For the time series data of Doppler velocity, we applied a low-pass filter (3 mHz) in order to eliminate the effect of photospheric 5 minute oscillations. To obtain the physical insights into the magnetic configuration more easily, we corrected for geometric projection effects to the vector magnetic field. To be more precise, the magnetic inclination was converted to the tilt angle from local normal to the solar surface, and the azimuth was converted to the tilt angle measured from the slit direction on the local horizontal plane.

2.3. Identification of EBs

As stated in § 1, EBs are characterized by their dark core and bright wing enhancements in Hα. To identify EBs, we calculated the contrast $I_\text{c}(x, t) = I(x, t) - I_0(t)/I_0(t)$ on Hα ± 0.8 Å images. Here, $I(x, t)$ is the intensity of a pixel at position $x$ taken at time $t$, and $I_0$ is the mean intensity of the entire frame at time $t$. We adopted an empirical threshold value of $I_c = 1.15$ for EBs; that is, we defined EBs as regions where intensity is more than 15% brighter than average. This value is consistent with earlier works, e.g., 5%–30% in Georgoulis et al. (2002) and 14% in Pariat et al. (2007). We made sure that the areas did not show any brightness enhancements at the positions of the EBs in Hα center images.

In order to know the EFR magnetic conditions around EBs, we analyzed only those EBs that were adjacent to the VMG slit. As a result, 12 EBs were detected during slit scan observation and 9 EBs during slit fixed observation. Figure 2 shows the temporal series of Hα wing and line center images, and the position of the 9 EBs detected during the slit fixed observation period. In Figure 2, the appearances of the dark filaments and their velocity distributions change rapidly with time. This may be due to new emerging flux tubes (EFTs) that pressed the dark filament from below the photosphere. Of the 9 EBs detected during the slit fixed observation, 7 were observed from their birth to their death, 1 EB was already in existence when the observation started, and 1 EB had not yet decayed when the observation stopped.

3. RESULTS OF THE SLIT SCAN OBSERVATION

Figures 3–6 show results obtained from the slit scan observation. The slit scanning direction was transversal, from left to right in each figure. The positions of 12 identified EBs are indicated by yellow or white diamonds. In this section, we mainly describe the morphological characteristics of the AR and the preferential locations of EBs.

3.1. Magnetic Field

Figure 3 shows the distribution of magnetic field intensity. Some small spots had a large field intensity of ~2000 G (see Fig. 1 for
EBs were distributed in regions with a field intensity of 500–1000 G. The field inclination angle, shown in Figure 4, means the tilt angle from local normal to the solar surface, and the background gray scale in Figure 5 shows the vertical components of the magnetic field, i.e., \( B \times \cos(\text{field inclination}) \).

After correcting for projection effects, we solved the 180° ambiguity of the azimuthal angle with the hypothesis that the magnetic lines were similar to those of a dipole between the two main spots, because NOAA 10917 was a simple dipole in overview. The green arrows in Figure 5 indicate the horizontal vectors of magnetic lines whose lengths are proportional to log-scaled horizontal components of the magnetic field at each point. As seen in the background image of Figure 5, the EB production areas showed a large spatial gradient of vertical field intensity. This suggests the possibility of rapid topological change of the magnetic field in the area of EBs, probably due to new EFTs.

We found that most EBs were distributed in regions whose inclination angle is \( \pm 90^\circ \), that is, near the magnetic-neutral line. We found 8 out of 12 EBs near magnetic-neutral lines (squares and crosses in Figs. 4–6), and 4 EBs in the unipolar region. Here, we introduce two classifications of neutral lines, “top” and “dip.” These are defined by the sign of the field line curvature (Pariat et al. 2004). “Top” is a region of the photosphere \( (z = 0) \) where the field line curvature is negative,

\[
B_z = 0, \quad \text{and} \quad B \cdot \nabla B_z < 0, \quad (1)
\]

while “dip” is a region where the field line curvature is positive,

\[
B_z = 0, \quad \text{and} \quad B \cdot \nabla B_z > 0. \quad (2)
\]

Top is sometimes referred to as an \( \Omega \)-loop, and dip as a U-loop. Thus, the 8 EBs found on neutral lines are classified into 5 top EBs and 3 dip EBs. In Figures 4–6, the crosses represent top, and the squares represent dip.

### 3.2. Doppler Velocity

Figure 6 shows the Doppler, or line-of-sight, velocity field. Red regions are receding from us, while blue regions are approaching us. The effect of solar rotation velocity has already been subtracted. There was no significant velocity field with \( |v| > 2 \text{ km s}^{-1} \) around this AR. We assumed that the observed Doppler velocity consisted of large-scale flow and localized flow fields. In the large-scale view, the blue trend on the east side and the red trend on the west side were considered to be due to the horizontal flux segregation motion of the EFR or a supergranular horizontal diverging flow (Bernasconi et al. 2002; Kozu et al. 2006; Magara 2006). Because the target’s position was on the west side, the horizontal segregation motion is observed as blue on the east side and red on the west side. Using \textit{SOHO} MDI full-disk magnetogram images, we estimated the horizontal velocity around this AR based on the local correlation tracking method. The averaged horizontal velocity over our observational period was 0.16 km s\(^{-1}\), diverging from the center toward the east and west. Therefore, the effective component of horizontal velocity against the line-of-sight velocity was less than 0.1 km s\(^{-1}\).

Let us look at the localized relation between EB positions and the Doppler map in Figure 6. The EBs were mostly located on the red/blue boundary of Doppler velocity. This result also proved the existence of EFTs. One example is shown in the areas enclosed...
by a green rectangle in Figures 4 and 6, where an \( \Omega \)-shaped magnetic field line was observed. Its top showed blueshift, or upward motion, of the magnetic line, and its footpoints showed redshift because of the plasma sliding down along the loops. Thus, the observed local Doppler variation around the EBs can be interpreted as sketched in Figure 7. Therefore, the estimated amplitude of horizontal velocity (\(<0.1\ km\ s^{-1}\) from SOHO MDI magnetogram images) and the results of earlier works (Lites et al. 1998; Kozu et al. 2006) allow us to suppose that the localized line-of-sight velocities were predominantly influenced by vertical motion.

4. RESULTS OF THE SLIT FIXED OBSERVATION

Next, we proceed to the results obtained from the slit fixed observation. Figure 8 explains the coordinate system used in Figures 9–12. The left and right \(\text{H}_\alpha\) images are the \(\text{H}_\alpha - 0.8\ \text{Å}\) images taken at the beginning and end of the observation, respectively. For example, in the left \(\text{H}_\alpha\) panel, we can see a bright patch near the center of the slit, which is marked as “EB1” in the middle panel. The middle panels show the temporal variation of physical parameters on the slit. The dashed and dash-dotted rectangles are indicators of EB positions. The dashed rectangles show EBs found in the \(\text{H}_\alpha - 0.8\ \text{Å}\) images, while the dash-dotted rectangles show EBs found in the \(\text{H}_\alpha + 0.8\ \text{Å}\) images. As shown in the upper right corner of each figure, the width of the rectangle indicates its lifetime, and the height covers a zone of the EB position \(\pm 3.4''\). The mean lifetime of the 9 detected EBs was \(~20\ minutes\), which is comparable to those of previous works.

As in the slit scan observation, the 180° ambiguity of the azimuthal...
angle is resolved with a hypothesis that the magnetic lines were similar to those of a simple dipole.

The slit fixed Figures 9–12 appear to illustrate another important EB characteristic, i.e., that EBs appear to occur and recur at preferential locations. Because the slit’s position was fixed along the axis of the AR, we can easily classify the EBs into three groups that faded and reappeared at nearly the same locations. These groups are (EB3, EB5, EB9), (EB6, EB7), and (EB1, EB4, EB8).

This is a nice result that shows the occurrence and recurrence of EBs with temporally varying underlying magnetic conditions.

4.1. Magnetic Field Intensity

Figure 9 shows the temporal evolution of the magnetic field intensity on the slit. As mentioned in § 3.1, the EBs were distributed in regions with a magnetic field intensity of 500–1000 G. The magnetic field intensity near the EBs was evidently increasing, or at least changing in time. If a new EFT makes an appearance from beneath the photosphere, it presses the preexisting magnetic field, and the magnetic intensity gradually increases. Therefore, an area with strong magnetic intensity can be interpreted as an EFT production site. Of the 9 EBs, all except EB6, EB7, and EB9 showed signatures of increasing field intensity.

4.2. Magnetic Inclination

In Figure 10, the temporal evolution of the magnetic field inclination with respect to local normal (+z) is shown. A more detailed picture of the temporal variation of the inclination angle around each EB can be seen in Figure 13. In Figure 13, arrows indicate the magnetic vectors \((y, z) = [\cos(\text{inclination}), \sin(\text{inclination})] \) with unit length. As in § 3.1, almost all the EBs were distributed near magnetic-neutral lines.

According to the definition in § 3.1, EB1, EB2, EB4, EB6, EB7, and EB8 were of the “dip” type, no “top” EBs were found, and EB3, EB5, and EB9 belonged to neither category, but were in the unipolar region. Although EB3 and EB5 did not lie on a magnetic-neutral line, but stayed in the unipolar region, their distributions of inclination angles showed an apparent dip configuration, which is clearly seen in Figure 13. We shall henceforth call this kind of configuration a “local dip.”

At the locations of EB1 and EB3, we found temporal formation of magnetic dip structure. At first, the distribution of the magnetic field was uniform along the slit. As time passed, the inclination of field lines evolved such that the magnetic topology took the
dip structure in the photosphere. It is interesting that the Hα wing brightenings had already started when the magnetic field lines were still in a uniform state in the photosphere, which may indicate that the magnetic dips had already formed in the layers above the Fe i 6302.5 Å line formation heights, and started to produce an EB by magnetic reconnection.

In the central part of the active region, there was a clear undulatory pattern, which is seen as periodically blue and red regions along the slit in Figure 10. All the EBs were distributed in this undulatory field line area. This is supporting evidence for the resistive emergence model of Pariat et al. (2004).

4.3. Magnetic Azimuth

Figure 11 shows the temporal evolution of the magnetic field azimuth on the local horizontal plane. The azimuthal angle is the tilt angle measured from the slit direction (+y). Magnetic lines in orange regions are inclined to the right (+x), and magnetic lines in green regions are inclined to the left (−x). Azimuthal angles between the two main spots mostly took values ranging from −20° to +20°. Like the inclination angle, the azimuthal angle showed a clear undulatory pattern. Two plots of the inclination and azimuthal angles along the slit are shown in Figure 14. The

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**Fig. 10.**—Same as Fig. 9, but showing magnetic inclination variation with time (slit fixed). The plot along the black solid line is shown in Fig. 16b.

**Fig. 11.**—Same as Fig. 9, but showing magnetic azimuthal variation with time (slit fixed).
four crosses are indicators of EB generation sites. It is clearly seen that the magnetic fields around EBs were undulatory, and that EBs were located in the region where the inclination of magnetic lines was \( \approx 90^\circ \), and where their azimuthal angles changed their signs. The characteristic wavelength of the undulation pattern exceeded 5000 km, that is, it was longer than 4000 km. This result tells us an important fact, because 4000 km is the characteristic wavelength of the Parker instability at the photospheric layer. As far as we know, we are the first to report an undulatory pattern in azimuthal angles around EBs.

4.4. Emerging Flux Tubes

In the observed AR, there were signatures of many EFTs in the photosphere. The preferential position of EBs showed an undulatory pattern in their magnetic field components, probably due to new EFTs triggered by the Parker instability. We identified three small EFTs during the slit fixed observation. Figure 15 shows the positions of three EFTs and EBs. EFTs were identified by examining the distribution of magnetic field intensity, inclination, and Doppler velocity. Figure 16 shows three kinds of plots, magnetic field intensity, inclination, and Doppler velocity, along the black solid line in Figures 9–12. The field line inclination was \( \Omega \)-shaped, the field intensity was increasing, and the Doppler velocity changed its sign across the neutral line. The blueshifted area was found near the top of the \( \Omega \)-loop field lines. The blueshifted area can be interpreted as vertically upward motion, as suggested in §3.2. On both sides of the footpoints there existed redshifted (i.e., downward-moving) areas. We think that these downflows were due to the motion of plasma dragged from the top of the \( \Omega \)-loop along the field lines. Therefore, we conclude that this area was an EFT, and call it “EFT1.” EFT1 was located near EB1, started its emergence at about 23:10 UT, and had not yet decayed at the end of the observation. EFT3 made an appearance near EB3. It started its emergence at about 23:20 and had not yet decayed at the end of the observation. EFT3 induced magnetic field intensity enhancement in its early phase and a Doppler blueshifted velocity of \( \approx 1.0 \text{ km s}^{-1} \). However, unlike EFT1 and EFT2, EFT3 did not have redshifted areas at its footpoints.

5. DISCUSSION

5.1. Schematic Models

From the slit scan observation, we found that 8 out of 12 identified EB production areas had a large spatial gradient of vertical field components, which indicates the existence of new EFTs. The Doppler velocity map in Figure 6 shows that almost all the EBs had downward motion adjacent to upflow, which is also a signature of new EFTs. Thus, we confirmed that EBs have a strong relation to the emergences of the EFTs detected with the slit fixed observation. We also try to confirm a relation between the residual four EBs found in the unipolar region and the emergence of EFTs and magnetic reconnection, as will be discussed below.

During the slit fixed observation period, we identified three EFTs (Fig. 15). Each EFT invoked a gradual enhancement of magnetic field intensity. In regions where magnetic fluxes emerge continuously, new EFTs compress the preexisting fluxes, and the flux density increases. If oppositely directed (or at least sheared) magnetic lines are compressed and approach each other, a magnetic reconnection occurs. It is widely accepted that EBs are a signature of magnetic reconnection in the low chromosphere. Therefore, it is plausible that magnetic field intensity increases at the location of an EFT and an EB.

In Figure 17, we show schematically how our data are interpreted by magnetic reconnection. Models 1, 2, and 3 show EB mechanisms with different magnetic configurations: model 1 for the footpoint of an EFT, model 2 for the top of an EFT, and model 3 for the unipolar region. According to the definition of magnetic lines in §3.1, a dip EB is explained by model 1, a top by
model 2, and a unipolar by model 2 or 3. Due to the coarse scan step and lack of temporal information, we cannot clarify whether the four unipolar EBs found during the slit scan observation were located at the top of an EFT or not, and so these four unipolar EBs can be explained either by model 2 or model 3. In summary, the identified EBs are classified as follows: EB1, EB2, EB4, EB6, EB7, EB8, three dip EBs from the slit scan belonging to model 1, EB3, EB5, EB9, five top EBs from the slit scan belonging to model 2, and four unipolar EBs from the slit scan belonging to model 2 or 3.

In model 1, new EFTs appear from below the preexisting uniform magnetic field. An antiparallel layer is produced in the low chromosphere, just above the photospheric dip region, and reconnection occurs at the point marked with an “X.” When reconnection occurs, a converging flow should exist across the antiparallel field lines. This speculative flow is shown in Figure 17 with dotted arrows. We could not detect this speculative horizontal flow in our observations, probably due to the small amplitude of the flow’s velocity, the compactness of the spatial extension of the velocity field, and so on.

Fig. 13.—Temporal evolution of magnetic field inclination around each EB. The time for each frame is shown at the upper left in UT. The circle at the center of each figure indicates the position of the EB.
Model 2 explains the triggering mechanism of an EB on top of an EFT. Model 2a is the case for the "local dip" configuration, which accounts for EB3 and EB5. As in model 1, a horizontal converging flow may exist across the local dip position (dotted arrows). Model 2b is the case for no local dip configuration. If there is a shear between neighboring magnetic lines, magnetic reconnection can occur at that point. In fact, Linton & Antiochos (2005) reported that reconnection can occur even at small contact angles between the interacting magnetic field lines. In model 2b, only upward motion will be observed. This may account for EB9. The six top EBs and four unipolar EBs on slit scan observation can be understood by both models 2a and 2b.

In model 3, there are no dips of magnetic field lines. If there is a shear between the neighboring magnetic lines, magnetic reconnection occurs at that point. This may account for the unipolar EBs from the slit scan observation. We are not sure how the velocity field is distributed in model 3.

As for EB1 and EB3, the inclination angles were at first uniform and gradually made dip configurations. These two EBs appeared in the early phase of the EFTs. The dip configuration may be observed only after the EFT has developed sufficiently, because of the spatial resolution or the formation height. Therefore, even if
we have a snapshot of the magnetic inclination angle around an EB that does not show dip configuration, there is still a possibility that this EB is related to dip areas.

Pariat et al. (2007) reported that EBs are located in regions called bald patches, where the field lines have a U-shape. This result is somewhat consistent with our models 1 and 2a. We extended the work of Pariat et al. (2007) by observing the temporal evolution of the magnetic configuration of an EFT. In our data, more than half of the observed EBs can be accounted for by models 1 or 2a. However, there were a non-negligible number of observed EBs located at the top of the \( \Omega \)-loop or the unipolar region. Therefore, models 2b and 3, that is, EB triggering without dip configuration, are also the effective mechanisms for EBs.

5.2. Evidence of Parker Instability

We found an undulatory pattern whose characteristic wavelength was longer than 4000 km in both the inclination and azimuthal data (Fig. 14). In Pariat et al. (2004), the mechanism of an EB is the magnetic reconnection of undulatory flux tubes emerging by the Parker instability (Parker 1966). If the undulatory magnetic fluxes emerge by the Parker instability, magnetic field lines become undulatory in its vertical components. Their wavelength \( \lambda \) should satisfy

\[
\lambda > 4\pi H \approx 2000 \text{ km.} \tag{3}
\]

Here, \( H \) is the pressure scale height and takes a value of 150–200 km in the photosphere. This is called a resistive-emergence model. The undulatory pattern in magnetic field inclination is direct evidence for this model. In addition, the undulatory pattern in the magnetic field azimuth also proves the Parker instability for the following reason. As the magnetic fluxes that emerge by the Parker instability go up, the atmospheric pressure decreases with increasing height, and the emerging flux expands horizontally (Shibata et al. 1989). However, the footpoints anchored in the photosphere are still compressed by their surroundings. When this EFT is observed from the top, the horizontal components of the magnetic field lines show wavy undulations with a wavelength characteristic of the Parker instability. We are the first to report an undulation of horizontal components of magnetic field, which is supporting evidence for the Parker instability.

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