PROPERTIES OF SOLAR EPHEMERAL REGIONS AT THE EMERGENCE STAGE

SHUHONG YANG AND JUN ZHANG

Key Laboratory of Solar Activity, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; shuhongyang@nao.cas.cn, zjun@nao.cas.cn

Received 2013 May 12; accepted 2013 December 1; published 2013 December 24

ABSTRACT

For the first time, we statistically study the properties of ephemeral regions (ERs) and quantitatively determine their parameters at the emergence stage based on a sample of 2988 ERs observed by the Solar Dynamics Observatory. During the emergence process, there are three kinds of kinematic performances, i.e., separation of dipolar patches, shift of the ER’s magnetic centroid, and rotation of the ER’s axis. The average emergence duration, flux emergence rate, separation velocity, shift velocity, and angular speed are 49.3 minutes, $2.6 \times 10^{15}$ Mx $s^{-1}$, 1.1 km $s^{-1}$, 0.9 km $s^{-1}$, and 0.6 minute$^{-1}$, respectively. At the end of emergence, the mean magnetic flux, separation distance, shift distance, and rotation angle are $3.9 \times 10^{18}$ Mx, 4.7 Mm, 1.1 Mm, and 12°9, respectively. We also find that the higher the ER magnetic flux is, (1) the longer the emergence lasts, (2) the higher the flux emergence rate is, (3) the further the two polarities separate, (4) the lower the separation velocity is, (5) the larger the shift distance is, (6) the slower the ER shifts, and (7) the lower the rotation speed is. However, the rotation angle seems not to depend on the magnetic flux. Not only at the start time, but also at the end time, the ERs are randomly oriented in both the northern and the southern hemispheres. Finally, neither the anti-clockwise-rotated ERs nor the clockwise rotated ones dominate the northern or the southern hemisphere.

Key words: Sun: activity – Sun: evolution – Sun: magnetic fields – Sun: photosphere

Online-only material: color figures

1. INTRODUCTION

The magnetic flux of dipolar regions emerging from below the solar surface ranges from less than $10^{18}$ Mx to more than $10^{23}$ Mx. The small-scale dipolar regions with short lifetimes are called ephemeral regions (ERs) and their maximum total flux is $\sim 10^{20}$ Mx and their typical lifetimes are 1–2 days, as found in the early study of Harvey & Martin (1973). Schrijver et al. (1998) examined the observations from the Solar and Heliospheric Observatory (SOHO) and noted that the mean total unsigned flux per ER is $1.3 \times 10^{19}$ Mx. Using the Hinode magnetograms, Wang et al. (2012) quantified the characters of intranetwork (IN) ERs. Their results reveal that the IN ERs have a lifetime of 10–15 minutes and a total maximum unsigned magnetic flux of the order of $10^{17}$ Mx. To differentiate active regions and ERs, a size limitation of the dipolar area of about 2.5 deg$^2$ can be used (Harvey 1993). In a study by Hagenaar et al. (2003), the ERs were defined as dipoles with a total unsigned flux less than $3 \times 10^{20}$ Mx.

In the quiet Sun, ERs emerge continuously and thus replenish the loss of magnetic flux caused by the dispersion and cancellation (Schrijver et al. 1998). In the initial emergence phase that lasts about 30 minutes, the ER’s opposite polarity patches rapidly separate up to about 7 Mm with a velocity of about 4 km $s^{-1}$ (Schrijver et al. 1998). Then, the dipolar patches drift with the supergranular flow, slowing down to about 0.4 km $s^{-1}$ (Schrijver et al. 1998; Simon et al. 2001; Priest et al. 2002). With the magnetograms from the Solar Dynamics Observatory (SDO), Pesnell et al. (2012), Zhao & Li (2012) studied the properties of 50 ERs. They selected as their sample the ERs that are isolated and near the disk center with a continuous emergence phase longer than at least 1 hr. Their results show that the emerged flux has a range of $(0.44–11.2) \times 10^{19}$ Mx and the emergence duration ranges from 1–12 hr. For the IN ERs, Wang et al. (2012) noted that, during magnetic flux emergence, most of them displayed axial rotation with a rotation angle of more than 10°.

Although ERs have been extensively studied (Golub et al. 1977; Martin & Harvey 1979; Martin 1988; Webb et al. 1993; Chae et al. 2001; Hagenaar 2001; Hagenaar et al. 2008), their origin is still under debate. Some studies (Harvey et al. 1975; Hoyng 1992) suggest that ERs may be the small-scale tail of a wide spectrum of magnetic activity and that they are also generated by the global dynamo, which has been commonly considered to be the production mechanism of active regions (Kosovichev 1996; Dikpati & Gilman 2001; Mason et al. 2002). This means that ERs are speculated to come from the bottom of convective zones. However, many authors have argued that ERs are generated in local turbulent convection, i.e., by a local dynamo populating everywhere near the solar surface (Nordlund et al. 1992; Cattaneo 1999; Hagenaar et al. 2003; Stein et al. 2003). In addition to the above models, some authors (Nordlund et al. 1992; Ploner et al. 2001) have also proposed another possible origin, i.e., the recycling of magnetic flux from decayed and dispersed active regions.

In a study (Yang et al. 2012) using observations from the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012; Scherrer et al. 2012) on board SDO, we have reported that ERs can be classified into two types: normal ERs and self-canceled ones. Both types have the same early evolution process: emerging and growing with separation of the opposite polarities. After that, the dipolar patches of normal ERs cancel or merge with the surrounding magnetic fields, while for self-canceled ones, a part of the magnetic fields with opposite polarities move back, meet together, and cancel with each other gradually, performing a behavior termed “self-cancellation.” Considering the same emergence process of the normal ERs and the self-canceled ones, we can combine them together and investigate their properties at the emergence stage.

The properties of ERs during the emergence process help us to provide the necessary parameters for numerical simulations for understanding the nature of ERs. For example, we wish to know the ratio of emergence duration to lifetime. In previous studies,
only several ER parameters at the emergence stage have been roughly determined just based on small samples (e.g., Schrijver et al. 1998; Wang et al. 2012; Zhao & Li 2012). Hagenaar (2001) studied some basic properties (including magnetic flux, emergence rate, separation distance, and separation velocity) of 38,000 auto-detected ERs, however, the data she adopted are SOHO Michelson Doppler Imager magnetograms with low tempo-spatial resolution, so ERs are still worth studying with high-quality observations (e.g., SDO/HMI magnetograms). So far, no study has quantitatively determined the parameters of ERs, such as emergence duration, flux emergence rate, area, flux density, separation distance, separation velocity, shift distance, shift velocity, orientation, especially rotation parameters, and relationship with the ER magnetic flux precisely at the emergence stage based on a large sample. This paper aims to statistically study for the first time the properties of ERs and to quantitatively determine their parameters at the emergence stage (the start time and the end time are definitely defined by us) with a large sample of ERs observed by SDO. In Section 2, we describe the observations and data analysis and in Section 3 we present the parameters and behaviors of ERs. The conclusions and discussion are given in Section 4.

2. OBSERVATIONS AND DATA ANALYSIS

The SDO/HMI uninterruptedly observes the Sun and records the line-of-sight magnetic fields with a cadence of 45 s in 6173 Å line. The full-disk magnetograms have a pixel size of 0.5" and are free of atmospheric distortions. These advantages are helpful for us to statistically study the properties of ERs. In this study, we use a sequence of line-of-sight magnetograms observed by the HMI over a four-day period (from 2010 June 11 12:00 UT to June 15 12:00 UT). In addition, the 171 Å image observed by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) at 12:00 UT on June 13 is also adopted. Since the noise is large for areas far away from the disk center, only the pixels with heliocentric angles α smaller than 60° are considered (outlined by the red circle in Figure 1). All of the magnetograms are derotated differentially to a reference time, June 13 12:00 UT. The blue curves highlight on our target where α < 60° over the observational period of four days. In the derotated magnetograms, the area S of one pixel is corrected to S/\cos(α_0), where α_0 is the heliocentric angle of the pixel. The magnetic flux density B is converted to B/\cos(α_1), where α_1 is the heliocentric angle at the time of the observation.

We first produce animations with the HMI magnetograms and then try our best to carefully examine them visually. ERs are identified as dipolar patches with opposite polarities emerging simultaneously or one following the other, which then grow and separate. Each ER is identified and tracked visually, which makes our results very reliable. We define the time when both the positive and the negative patches are detected as the start time (t_0) of the emergence. If the strength of a magnetic patch exceeds the noise level, 10.2 Mx cm^{-2} (Liu et al. 2012), we consider the patch as being detected. When the total unsigned magnetic flux of the two polarities reaches the maximum, the time is defined as the end time (t_1) of the emergence stage. The ER area is calculated from the pixels with magnetic fields above the noise level. The separation distance is measured along the great circle on the solar surface between the magnetic centroids of positive and negative patches. Similar to the separation distance, the shift distance is also calculated on the sphere, but between the magnetic centroid of the entire ER at t_0 and that at t_1. The definition of the ER's orientation angle γ is illustrated in the inserted circular area in Figure 8(a). “P” and “N” represent the magnetic centroids of ER’s positive and negative polarities, respectively. γ is defined as the azimuth of “P–N” in heliographic coordinates, where west is 0° and north is 90°, instead of in Cartesian coordinates. The range of γ is (0°, 360°).

The flux emergence rate, separation velocity, shift velocity, and angular speed of rotation are the average values during emergence.

3. RESULTS

3.1. Latitudinal Distribution and Magnetic Flux of ERs

In the target delineated by the blue curve (see Figure 1), we identified 2988 ERs in total. After projection corrections, the real area of our target outlined by the blue curve in Figure 1 is 8.0 \times 10^5 Mm^2 and thus the average number density in the whole target is 9.32 \times 10^{-4} day^{-1} Mm^{-2}. This value is larger than that determined by Wang (1988; 8.7 \times 10^{-4} day^{-1} Mm^{-2}) and that determined by Martin (1989; 6.7 \times 10^{-4} day^{-1} Mm^{-2}). However, it is smaller than the values determined by Chae et al. (2001), Harvey (1993), and Hagenaar (2001; 17 \times 10^{-4} day^{-1} Mm^{-2}, 27 \times 10^{-4} day^{-1} Mm^{-2}, and 71 \times 10^{-4} day^{-1} Mm^{-2}, respectively). The different values of the average number density are marked with dashed horizontal lines in Figure 2(a). In our opinion, the different data from different instruments and different sample sizes may lead to the difference of the results. The latitudinal distribution of these ERs is presented in Figure 2(a). The ERs are not uniformly distributed in the range of (S60°, N60°). There are two regions with larger number densities; one is located around S15° and the other one is located around N25°. These distributions were also seen in the study of Hagenaar et al. (2003). The number densities at these two regions exceed 10 \times 10^{-4} day^{-1} Mm^{-2}.
higher than the density at the equatorial region between S10° and N10° (8.8 × 10⁻⁴ day⁻¹ Mm⁻²). The regions at latitudes above 40° have much lower densities, only about (5 ~ 6) × 10⁻⁴ day⁻¹ Mm⁻². The probability density function (PDF) of the ERs with a bin size of 0.6 × 10¹⁸ Mx is plotted in Figure 2(b). We can see that there is a PDF peak at 3.6 × 10¹⁸ Mx and the mean magnetic flux is 9.27 × 10¹⁸ Mx. This value is close to the results of Hagenaar (2001; 1.3 × 10¹⁸ Mx), Schrijver et al. (1998; 1.3 × 10¹⁸ Mx), and Wang (1988; 1.5 × 10¹⁹ Mx), but it is not fully consistent with several other results (2.5 × 10¹⁸ Mx, Martin 1989; 2.8 × 10¹⁹ Mx, Chae et al. 2001; 3.3 × 10¹⁹ Mx, Harvey 1993; 3.9 × 10¹⁹ Mx, Zhao & Li 2012), especially the very early study (∼10²⁰ Mx) by Harvey & Martin (1973). The mean values reported by different studies are marked with dashed vertical lines in Figure 2(b). This difference may be due to the better sensitivity and higher spatial resolution of SDO/HMI. Although Zhao & Li (2012) also used HMI data, they only selected large ERs, so they obtained a higher ER magnetic flux. Wang et al. (2012) investigated ERs using Hinode data with high spatial resolution, however, they just focused on IN ERs. They found that the IN ERs have magnetic fluxes from several 10¹⁶ Mx to 1.5 × 10¹⁸ Mx and the average flux is about 0.8 × 10¹⁸ Mx, more than one order of magnitude smaller than our result. The magnetic fluxes of the ERs range from smaller than 10¹⁸ Mx to larger than 10²⁰ Mx, but none of the fluxes are larger than 3 × 10²⁰ Mx, the upper limitation of ER flux defined by Hagenaar et al. (2003).

3.2. Separation and Growth of ERs with Opposite Polarities

The most conspicuous feature of ERs at the emergence stage is the separation and growth of the dipolar patches. Figure 3 shows three magnetograms exhibiting the separation and growth of opposite polarities of an ER on 2010 June 14. The start time t₀ of the ER emergence was 04:23 UT. At that time, both of the positive (white patch with blue contour) and negative (black patch with red contour) polarities were strong enough to be detected (panel (a)). The total unsigned magnetic flux of the ER was 4.3 × 10¹⁷ Mx, the area occupied by the two patches was 2.7 Mm², and the mean absolute flux density was 15.9 Mx cm⁻². The distance (marked by the green curve) between the two magnetic centroids (indicated by the blue and red plus signs) was 1.9 Mm. Then, six minutes later, the ER area expanded conspicuously and the strength was much stronger compared with the initial appearance at the start time (panel (b)). At 04:32 UT, the total unsigned magnetic flux of the ER reached the maximum, 2.7 × 10¹⁸ Mx. According to the definition, it was the end time t₁, indicating the end of emergence. Thus, the duration of emergence was nine minutes. The area expanded to 12.3 Mm², the mean flux density changed to 21.8 Mx cm⁻², and the separation distance reached 3.2 Mm. During the emergence period, the average separation velocity was 2.5 km s⁻¹ and the average flux emergence rate was 4.2 × 10¹⁵ Mx s⁻¹.

The PDFs of the separation distance at t₁, emergence duration, separation velocity, flux emergence rate, area at t₁, and flux density at t₁ are displayed in Figure 4. Each PDF has a peak value. The separation distance ranges from 1.3 Mm to 19.2 Mm with a peak at 3.2 Mm and the mean value is 4.7 Mm (panel (a)). The peak of the emergence duration is at 12 minutes and the mean duration is 49.3 minutes (panel (b)). During the emergence, the separation velocities of ERs varied between 0.03 km s⁻¹ and 5.5 km s⁻¹ and their PDF peaked at 0.4 km s⁻¹ (panel (c)). The mean separation velocity is 1.1 km s⁻¹. The peak value and mean value of flux emergence rate are 1.0 × 10¹⁵ Mx s⁻¹ and 2.6 × 10¹⁵ Mx s⁻¹, respectively (panel (d)). The areas at the end of emergence have a distribution peak at 10.0 Mm² and the mean area is 23.1 Mm² (panel (e)). The magnetic flux densities of the ERs are also determined at the end of emergence. Most ERs are not strong, only several reach 10 Mx cm⁻², and the peak value of PDF is at 28.0 Mx cm⁻², as shown in panel (f). The mean flux density of ERs is 35.3 Mx cm⁻². Schrijver et al. (1998) found that the initial emergence phase lasts about 30 minutes, the separation distance extends up to about 7 Mm, and the separation velocity is about 4 km s⁻¹ (marked with dashed vertical lines labeled “2” in Figure 4). In the study of Hagenaar (2001), the average distance between the opposite polarities is 8.9 Mm and the expanding velocity is 2.3 km s⁻¹ (marked with lines “4”). As reported by Chae et al. (2001) and Harvey & Martin (1976), the values of average separation of fully developed ERs are 7.4 Mm (marked with line “3”) and 2–3 Mm (line “6”), respectively. The separations of IN ERs obtained by Wang et al. (2012) are 3°–4° and the average value is 3.3°, i.e., 2.4 Mm (line “7”). At the very beginning phase of emergence, the separation velocity determined by Title (2000) is of the order of 5 km s⁻¹ (line “8”). The peak fluxes and the corresponding mean values of emergence durations are summarized in Table 1 and are displayed with different colors in Figure 4. The number density at t₁ of the fluxes is 4.3 × 10¹⁷ Mx, the area occupied by the two patches was 2.7 Mm², and the mean absolute flux density was 15.9 Mx cm⁻². The distance (marked by the green curve) between the two magnetic centroids (indicated by the blue and red plus signs) was 1.9 Mm. Then, six minutes later, the ER area expanded conspicuously and the strength was much stronger compared with the initial appearance at the start time (panel (b)). At 04:32 UT, the total unsigned magnetic flux of the ER reached the peak value and mean value of flux emergence rate are 1.0 × 10¹⁵ Mx s⁻¹ and 2.6 × 10¹⁵ Mx s⁻¹, respectively (panel (d)). The areas at the end of emergence have a distribution peak at 10.0 Mm² and the mean area is 23.1 Mm² (panel (e)). The magnetic flux densities of the ERs are also determined at the end of emergence. Most ERs are not strong, only several reach 10 Mx cm⁻², and the peak value of PDF is at 28.0 Mx cm⁻², as shown in panel (f). The mean flux density of ERs is 35.3 Mx cm⁻². Schrijver et al. (1998) found that the initial emergence phase lasts about 30 minutes, the separation distance extends up to about 7 Mm, and the separation velocity is about 4 km s⁻¹ (marked with dashed vertical lines labeled “2” in Figure 4). In the study of Hagenaar (2001), the average distance between the opposite polarities is 8.9 Mm and the expanding velocity is 2.3 km s⁻¹ (marked with lines “4”). As reported by Chae et al. (2001) and Harvey & Martin (1976), the values of average separation of fully developed ERs are 7.4 Mm (marked with line “3”) and 2–3 Mm (line “6”), respectively. The separations of IN ERs obtained by Wang et al. (2012) are 3°–4° and the average value is 3.3°, i.e., 2.4 Mm (line “7”). At the very beginning phase of emergence, the separation velocity determined by Title (2000) is of the order of 5 km s⁻¹ (line “8”). The mean flux emergence rates determined by Hagenaar (2001),
Figure 3. Sequence of HMI magnetograms illustrating the separation and growth of the dipolar patches of an ER at the emergence stage. The blue and red curves are contours of the ER’s positive and negative polarities at +10.2 G and −10.2 G levels, respectively. The blue and red plus symbols mark the magnetic centroids of the positive and negative polarities, respectively, and the green curves are the distance between them along the great circle of the solar surface. The dotted curves are the heliographic grids with a grid spacing of 0.5°.

(A color version of this figure is available in the online journal.)

Figure 4. PDFs of separation distance (panel (a)) at $t_1$, emergence duration (panel (b)), separation velocity (panel (c)), flux emergence rate (panel (d)), area (panel (e)) at $t_1$, and flux density (panel (f)) at $t_1$. The values obtained by different studies are marked with dashed vertical lines: “1” (Present study), “2” (Schrijver et al. 1998), “3” (Chae et al. 2001), “4” (Hagenaar 2001), “5” (Zhao & Li 2012), “6” (Harvey & Harvey 1976), “7” (Wang et al. 2012), “8” (Title 2000), and “9” (Wang 1988).

(A color version of this figure is available in the online journal.)

Zhao & Li (2012), Harvey & Harvey (1976), and Wang (1988; line “9”) are $1.6 \times 10^{15}$ Mx s$^{-1}$, $2.31 \times 10^{15}$ Mx s$^{-1}$, $3.4 \times 10^{15}$ Mx s$^{-1}$, and $2.2 \times 10^{15}$ Mx s$^{-1}$, respectively. These results are generally consistent with ours. However, there are also some differences that may be due to different observations. According to the results of Zhao & Li (2012; vertical lines labeled “5”), the values of some parameters (such as unsigned flux, duration, distance, and area) are consistent with those ERs with large magnetic fluxes in our study, since they selected their sample with three criteria and thus small ERs were ignored. According to the results of Harvey (1993), the lifetime of ERs is 4.4 hr. The emergence duration determined in the present study is about 50 minutes, so the birth stage is only about 19% of the lifetime.

Figure 5 shows the relationships among the parameters discussed above and the total unsigned magnetic flux of ERs. The red dots are the scatter plots of all the ERs. In order to clearly display the relationships, the data are processed with a “sort-group” method (Zhao et al. 2009). First, the data are sorted in ascending order according to the total unsigned flux. Then, each of the 300 ERs are grouped into 1 group and 10 groups are obtained in all. Finally, the parameters are correlated with the magnetic flux and the values of the 10 groups are plotted (marked
Figure 5. Scatter plots of separation distance, emergence duration, separation velocity, flux emergence rate, area, and flux density vs. the magnetic flux of ERs (red symbols) and sorted and grouped points (blue symbols; from panels (a)–(f), respectively). Each error bar represents the standard deviation of the corresponding group data.

(A color version of this figure is available in the online journal.)

by the blue symbols in each panel). Each error bars represent the standard deviation of the corresponding group data. We can see that the separation distance (panel (a)), emergence duration (panel (b)), flux emergence rate (panel (d)), area (panel (e)), and flux density (panel (f)) are positively correlated with the magnetic flux. On the other hand, the separation velocity has a negative correlation with the magnetic flux (panel (c)). The variation trends indicate that the higher the total unsigned magnetic flux is, (1) the further the two polarities separate, (2) the longer the emergence lasts, (3) the slower the separation is, (4) the higher the flux emergence rate is, (5) the larger the area is, and (6) the stronger the ER field is. Harvey & Harvey (1976) found that the flux emergence rate is large for larger ERs and Zhao & Li (2012) showed that the emergence duration and flux growth rate are positively correlated with the total emerging flux, which are supported by our results (see Figures 5(b) and (d)).

3.3. Shift of the Magnetic Centroids of ERs

We also compute the magnetic centroid of each ER using its total unsigned magnetic flux. During the emergence, the magnetic centroid is not stable and there exists a shift on the solar surface. Figure 6 shows the evolution of an ER as an example to illustrate this kind of movement. At 00:44 UT on June 12, the ER emergence began (panel (a)). The ER centroid was marked by the green plus symbol and it was located at (−6′5, 19′1). At 00:53 UT, the location of the magnetic centroid moved to (−7′3, 18′6), indicating that the ER moved in a southeast direction (panel (b)). When the emergence ended, the ER reached (−8′2, 17′4) (panel (c)). The shift movement relative to the heliospheric grids can also be easily found. From t₀ to t₁, the centroid shifted 1.76 Mm in 54 minutes with an average shift velocity of 0.54 km s⁻¹.

For the shift distance and shift velocity of ERs, their PDFs and their relationships with the total unsigned magnetic flux are presented in Figure 7. The shift distance is no more than several Mm and the mean distance is 1.1 Mm while the peak value is at 0.4 Mm (panel (a)). The PDF of the shift velocity peaks at 0.2 km s⁻¹ and the mean velocity is 0.9 km s⁻¹ (panel (b)). Similar to the relationship between the separation distance and the total unsigned magnetic flux shown in Figure 5(a), there is also a positive correlation for the shift distance, as seen in Figure 7(c). The increasing trend indicates that the higher the total magnetic flux is, the larger the shift distance is. The shift velocity is negatively correlated with the magnetic flux (panel (d)), indicating that the higher the total magnetic flux is, the slower the ER’s centroid shifts.

3.4. Orientation and Rotation of ERs

Besides the separation movement and shift movement, ERs also rotate during the emergence, leading to a change in orientation. An example of ER rotation is shown in Figure 8. At 10:02 UT on June 13, both the positive and negative polarities of the ER appeared. The initial orientation is shown in panel (a). The negative patch was located to the northeast of the positive patch and the orientation was 113′:1. Then, the axis of the ER rotated clockwise and, six minutes later, the orientation changed to 101′:1 (panel (b)), much smaller than the initial angle. The emergence continued and the clockwise rotation also did not...
Figure 6. Sequence of magnetograms illustrating the shift of magnetic centroid of an ER at the emergence stage. The blue/red curves are contours of the ER’s positive/negative polarities at +10.2 G and −10.2 G, respectively, and the green plus symbols mark the magnetic centroid of the ER. The dotted curves are the heliographic grids with a grid spacing of 0.5°.

(A color version of this figure is available in the online journal.)

Figure 7. Upper panels: PDFs of shift distance (panel (a)) and shift velocity (panel (b)). Lower panels: scatter plots of shift distance (panel (c)) and shift velocity (panel (d)) vs. the magnetic flux of the ERs.

(A color version of this figure is available in the online journal.)

stop. At the end of emergence, there was a significant change of the ER appearance (panel (c)). The orientation became 93°1, which means the ER rotated clockwise 20°0 with an absolute average angular speed of 2°2 minute⁻¹ at the emergence stage.

Due to the rotation, the orientations of ERs at t₀ and at t₁ are different. Figure 9 shows the spatial distribution of the orientations at the start time (panel (a)) and the end time (panel (b)) of flux emergence. In the whole target, the orientations both at t₀ and t₁ are randomly distributed, but in some sizable (100′′ × 100′′) areas, ERs are generally ordered. For example, as shown in panel (c1), the orientations of ERs outlined by the ellipse are mainly from positive to negative polarities (see panel (c2)). The inserted color image in panel (c2) is the AIA 171 Å observation and shows the overlying coronal
Figure 8. Sequence of magnetograms illustrating the rotation of an ER at the emergence stage. The contours, plus signs, and dotted curves have the same meanings as those in Figure 3. γ is the orientation that varies between (0° and 360°). The definition of γ is displayed in the inserted circular area in panel (a). “P” and “N” represent positive and negative polarities, respectively.

(A color version of this figure is available in the online journal.)

Figure 9. Spatial distribution of the ER orientations at the start time (panel (a)) and the end time (panel (b)) of flux emergence. Panel (c1) is the enlarged frame outlined by the square in panel (a) and panel (c2) is the corresponding magnetogram. Panels (d1) and (d2) are similar to panels (c1) and (c2) but for the area outlined by the square in panel (b). The inserted color image in panel (c2) is the AIA 171 Å observation and shows the overlying coronal loops (emphasized with dotted green curves) between the positive and negative magnetic fields. The ellipses outline the ERs that are generally ordered.

(A color version of this figure is available in the online journal.)
loops (emphasized with dotted green curves) between positive and negative magnetic fields. In panel (d1), the general pointing directions of the ERs located within the green circle are from northwest to southeast, consistent with the alignment of positive and negative polarities of the large-scale background fields (see panel (d2)). The black circle in panel (d1) contains ERs that mainly align in the southeast–northwest direction, also the direction of background fields, as shown in panel (d2). These results imply that, in some sizable areas, ER orientation may depend on the large-scale magnetic configuration.

The histograms of the orientations at $t_0$ and those at $t_1$ are presented in the left and the right columns in Figure 10, respectively. The histograms are shown in angular representation with a bin size of $45^{\circ}$ and the ERs located in the northern and southern hemispheres are considered separately. At the start time of emergence, the initial orientations are essentially randomly distributed for both the northern (panel (a)) and southern (panel (b)) ERs. At the end of the emergence stage, the orientations after rotation are still basically randomly oriented in the northern and southern hemispheres.

Figure 11 shows the PDFs of rotation angle and angular speed and their relationships with the magnetic flux. If one ER rotates anti-clockwise, its rotation angle and angular speed are assigned a plus sign. If it rotates clockwise, a minus sign is assigned. The PDF of rotation angle have a general balance between positive and negative values and the peak is at zero (panel (a)). The mean value of the absolute rotation angles is 12\(^{\circ}\)9 (marked with line “1”). This value agrees with that (> 10\(^{\circ}\); marked with line “2”) of IN ERs reported by Wang et al. (2012). The angular speed data also peak at zero and the mean absolute angular speed is 0\(^{\circ}\)6 minute\(^{-1}\) (panel (b)). The plots in panel (c) show that there is no close relationship between absolute rotation angle and magnetic flux, i.e., the rotation angle does not depend on the magnetic flux. The variation of absolute angular speed with magnetic flux is presented in panel (d). The decrease trend reveals that the higher the magnetic flux is, the lower the absolute angular speed will be.

Some ERs rotate clockwise while some rotate anti-clockwise. In Figure 1, the red dots represent the ERs with anti-clockwise rotation, while the blue dots represent the ERs with clockwise rotation. In order to examine if there exists a hemisphere rule for the ER rotation, the ERs at different latitudes should be considered separately. We define an imbalance parameter $\rho$ to describe the number imbalance between the
anti-clockwise- and the clockwise-rotating ERs. ρ is defined as

\[ ρ = \frac{N_{\text{anti-clockwise}} - N_{\text{clockwise}}}{N_{\text{anti-clockwise}} + N_{\text{clockwise}}} \]  

where “N” is the ER number. The parameter ρ as a function of latitude is shown in Figure 12. It shows that there is no significant domination of anti-clockwise rotation or clockwise rotation at different latitudes. The average value of |ρ| is about 0.03 and the maximum value is smaller than 0.07.

4. CONCLUSIONS AND DISCUSSION

In this study, we have statistically investigated the properties of ERs. Based on almost 3000 ERs, we quantitatively determine their parameters at the emergence stage for the first time. During the emergence process, there are three kinds of kinematic performances, i.e., separation of dipolar patches, shift of the ER’s magnetic centroid, and the rotation of the ER’s axis. Several parameters, e.g., duration of emergence, flux emergence rate, and separation velocity, are measured. At the end of emergence, six parameters, i.e., magnetic flux, area, flux density, separation distance, shift distance, and rotation angle, are also determined. Moreover, we find that the higher the ER magnetic flux is, (1) the further the two polarities separate, (2) the longer the emergence lasts, (3) the slower the separation is, (4) the higher the flux emergence rate is, (5) the larger the area is, (6) the stronger the ER field is, (7) the larger the shift distance is, (8) the slower the ER’s centroid shifts, and (9) the lower the absolute angular speed is. In addition, we note that the regions

Figure 11. Upper panels: PDFs of rotation angle (panel (a)) and angular speed (panel (b)). Lower panels: scatter plots of absolute rotation angle (panel (c)) and absolute angular speed (panel (d)) vs. magnetic flux of ERs. Different values obtained by the present study and Wang et al. (2012) are marked with dashed lines “1” and “2,” respectively.

(A color version of this figure is available in the online journal.)

Figure 12. Number imbalance between anti-clockwise-rotated and clockwise-rotated ERs as a function of latitude.

(A color version of this figure is available in the online journal.)
with locations around $S15^\circ$ and around $N25^\circ$ have larger number densities.

There are at least three kinds of convective cells according to their sizes, i.e., granulation, mesogranulation, and supergranulation (Simon & Leighton 1964; Rast 2003). The horizontal velocity of supergranular flows is determined to be about 0.3–0.5 km s$^{-1}$ (Leighton et al. 1962; Simon & Leighton 1964). Magnetic elements that emerge within supergranular cells are advected toward the supergranular borders with a velocity of about 0.4 km s$^{-1}$ (Zhang et al. 1998). However, as revealed by our results and also observed by Schrijver et al. (1998), the separation velocity of dipolar patches at the emergence stage is much larger. We suggest that, when magnetic flux tubes rise from below the photosphere, the $\Omega$-shaped tubes are mainly affected by the buoyant force and can be ejected into the atmosphere of the Sun with a high velocity, leading to a rapid separation of the positive and negative polarities. After the emergence stage, the Sun with a high velocity, leading to a rapid separation of magnetic patches are mainly driven by horizontal supergranular flows and thus the separation slows down. We also find that the average shift velocity of the ERs (0.9 km s$^{-1}$) is larger than that of the supergranular flows. This fact may be due to the existence of configuration asymmetry of the ERs. When ERs emerge, the separation of dipolar patches is not symmetric, so the shifts are observed. Another possible interpretation is that the planes the flux tubes are located in are not vertical, i.e., there exists tilt angles relative to the solar radial direction. As soon as they rise and get through the photosphere, the flux tubes will become vertical, resulting in the magnetic centroid sideward shifts (see Figure 6). As shown in this study, ERs display a rotation of their axes. One possible reason is that the chaotic convective motions shear and distort the dipolar patches. Another reason may be that the rotation is caused by the relaxation of twisted ERs (Patsourakos et al. 2008), implying that the structures of ERs are quite complicated.

The most popular model for the formation of active regions is that they are generated by a dynamo action at the bottom of the convection zone, where the tachocline is located (Dikpati & Gilman 2001; Mason et al. 2002). The tachocline is a transition layer of solar rotation, from the solid-body rotation of the radiative interior to the differential rotation of the convection zone (Kosovichev 1996). The large shear in the tachocline can form and store large-scale fields, which will emerge through the solar surface due to the buoyant force (Parker 1993). Active regions are aligned generally in the east–west direction within a few degrees because of the effect of the Coriolis force during the emergence of flux tubes (Hale et al. 1919; Schmidt 1968). However, for the ERs in our study, not only at the start time, but also at the end time, their orientations are basically randomly oriented in both the northern and the southern hemispheres (Figure 10). Besides, neither the anti-clockwise-rotating ERs, nor the clockwise-rotating ones, dominate the northern or the southern hemisphere (Figure 12). The locations of the ERs spread all over the target from $S60^\circ$ to $N60^\circ$ (see Figure 1). These results imply that, distinct from active regions, it seems that ER flux is not generated by the global dynamo and it may be generated by a local dynamo. However, small flux systems are significantly affected by convective motion below the solar photosphere and will eventually have random orientations when they emerge, even if they have been generated by the global dynamo. So, we cannot exclude the possibility that they may be generated by the global dynamo. Figure 2(a) shows that, instead of the equatorial or the high-latitude regions, the regions at around $S15^\circ$ and $N25^\circ$ (the general latitudes of the active regions) have larger ER number densities, indicating that the recycling of magnetic flux from decayed and dispersed active regions may be another origin of the magnetic flux of ERs.

We thank the referee for constructive comments and Prof. Jingxiu Wang for his helpful suggestions. This work is supported by the Outstanding Young Scientist Project 11025315, the National Basic Research Program of China under grant 2011CB11403, the National Natural Science Foundations of China (11203037, 11221063, 11373004, and 11303049), and the CAS Project KJCX2-EW-T07. The data are used courtesy of the NASA/SDO and the HMI science teams.

REFERENCES

Cattaneo, F. 1999, ApJL, 515, L39

Chae, J., Martin, S. F., Yun, H. S., et al. 2001, ApJ, 548, 497

Dikpati, M., & Gilman, P. A. 2001, ApJ, 559, 428

Golub, L., Krieger, A. S., Harvey, J. W., & Vaiana, G. S. 1977, SoPh, 53, 111

Hagenaar, H. J. 2001, ApJ, 555, 448

Hagenaar, H. J., De Rosa, M. L., & Schrijver, C. J. 2008, ApJ, 678, 541

Hagenaar, H. J., Schrijver, C. J., & Title, A. M. 2003, ApJ, 584, 1107

Hale, G. E., Ellerman, F., Nicholson, S. B., & Joy, A. H. 1919, ApJ, 49, 153

Harvey, K. L. 1993, PhD thesis, Rijksuniv. Utrecht

Harvey, K. L., & Harvey, J. W. 1976, Air Force Rep. AFGL-TR-76-0225, Part II, 35

Harvey, K. L., & Martin, S. F. 1975, SoPh, 40, 87

Harvey, K. L., & Martin, S. F. 1973, SoPh, 32, 389

Hoyn, P. 1992, in The Sun, ed. J. T. Schmelz & J. C. Brown (NATO AISI Ser. C. 373; Dordrecht: Reidel), 99

Kosovichev, A. G. 1996, ApJL, 469, L61

Leighton, R. B., Noyes, R. W., & Simon, G. W. 1962, ApJ, 135, 474

Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, SoPh, 275, 17

Liu, Y., Hoeksema, J. T., Scherrer, P. H., et al. 2012, SoPh, 279, 295

Martin, S. F. 1988, SoPh, 117, 243

Martin, S. F. 1989, in IAU Symp. 138, Solar Photosphere: Structure, Convection, and Magnetic Fields, ed. J. O. Stenflo (Dordrecht: Kluwer), 129

Martin, S. F., & Harvey, K. H. 1979, SoPh, 64, 93

Mason, J., Hughes, D. W., & Tobias, S. M. 2002, ApJL, 580, L89

Nordlund, A., Brandenburg, A., Jennings, R. L., et al. 1992, ApJ, 392, 647

Parker, E. N. 1993, ApJL, 408, 707

Patsourakos, S., Pariat, E., Vorlida, A., Antiochos, S. K., & Wuelser, J. P. 2008, ApJL, 680, L73

Pesnell, W. D., Thompson, B. J., & Chamberlin, P. C. 2012, SoPh, 275, 3

Ploner, S. R. O., Schüssler, M., Solanki, S. K., & Gadun, A. S. 2001, in ASP Conf. Ser. 236, Advanced Solar Polarimetry—Theory, Observation, and Instrumentation, ed. M. Sigwarth (San Francisco, CA: ASP), 363

Priest, E. R., Heyvaerts, J. F., & Title, A. M. 2002, ApJ, 576, 533

Rast, M. F. 2003, ApJL, 597, 1200

Scherrer, P. H., Schou, J., Bush, R. I., et al. 2012, SoPh, 275, 207

Schmidt, H. U. 1968, in IAU Symp. 35, Structure and Development of Solar Active Regions, ed. K. O. Kiepenheuer (Dordrecht: Reidel), 95

Schou, J., Scherrer, P. H., Bush, R. I., et al. 2012, SoPh, 275, 229

Schrijver, C. J., Title, A. M., Harvey, K. L., et al. 1998, Natur, 394, 152

Simon, G. W., & Leighton, R. B. 1962, ApJ, 135, 474

Simon, G. W., & Leighton, R. B. 1964, ApJL, 140, 1120

Simon, G. W., Title, A. M., & Weiss, N. O. 2001, ApJL, 561, 427

Stein, R. F., Berlick, D., & Nordlund, Á. 2003, in ASP Conf. Ser. 286, Current Theoretical Models and Future High Resolution Solar Observations: Preparing for ATST, ed. A. A. Pevtsov & H. Uitenbroek (San Francisco, CA: ASP), 121

Title, A. M. 2000, RSPTA, 358, 657

Wang, H. 1988, SoPh, 116, 1

Wang, J. X., Zhou, G. P., Jin, C. L., & Li, H. 2012, SoPh, 278, 299

Webb, D. F., Martin, S. F., Moses, D., & Harvey, J. W. 1993, SoPh, 144, 15

Yang, S. H., Zhang, J., Li, T., & Liu, Y. 2012, ApJL, 752, L24

Zhao, J., & Li, H. 2012, RAA, 12, 1681

Zhao, M., Wang, J. X., Jin, C. L., & Zhou, G. P. 2009, RAA, 9, 933