SELF-CANCELLATION OF EPHEMERAL REGIONS IN THE QUIET SUN

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ABSTRACT

With the observations from the Helioseismic and Magnetic Imager aboard the Solar Dynamics Observatory, we statistically investigate the ephemeral regions (ERs) in the quiet Sun. We find that there are two types of ERs: normal ERs (NERs) and self-canceled ERs (SERs). Each NER emerges and grows with separation of its opposite polarity patches which will cancel or coalesce with other surrounding magnetic flux. Each SER also emerges and grows and its dipolar patches separate at first, but a part of the magnetic flux of the SER will move together and cancel gradually, which is described with the term “self-cancellation” by us. We identify 2988 ERs, among which there are 190 SERs, about 6.4% of the ERs. The mean value of self-cancellation fraction of SERs is 62.5%, and the total self-canceled flux of SERs is 9.8% of the total ER flux. Our results also reveal that the higher the ER magnetic flux is, (1) the easier the performance of ER self-cancellation is, (2) the smaller the self-cancellation fraction is, and (3) the more the self-canceled flux is. We think that the self-cancellation of SERs is caused by the submergence of magnetic loops connecting the dipolar patches, without magnetic energy release.

Key words: Sun: activity – Sun: photosphere – Sun: surface magnetism

Online-only material: animations, color figures

1. INTRODUCTION

Ephemeral regions (ERs) are short-lived small-scale dipolar magnetic regions which were described by Harvey & Martin (1973) for the first time. According to the early results, ERs have a typical lifetime of one to two days and a dimension of 30,000 km, with a maximum total flux of the order of \(10^{20}\) Mx (Harvey & Martin 1973). In the following years, the lifetime of ERs determined with higher cadence observations was found to be much shorter, from around 12 hr (Harvey et al. 1975) to less than 3 hr (Title 2000), and the magnetic flux was found to be smaller (~\(10^{19}\) Mx; Schrijver et al. 1998; Chae et al. 2001).

In the quiet Sun, magnetic flux disappears due to cancelation and dispersion, but at the same time it is continuously replenished by newly emerged ERs. It takes only about one day for one replacement of the flux in the quiet photosphere (Schrijver et al. 1998; Hagenaar et al. 2003). Harvey et al. (1975) compared the parameters of ERs and regular active regions and argued that ERs are the small-scale end of a broad spectrum of magnetic activity. The results from Martin (1988) and Hagenaar et al. (2003) reveal that ERs likely vary in anti-phase with the solar cycle. The origin of ERs is still not well known. The source may be the recycled flux from decayed active regions (Nordlund et al. 1992; Ploner et al. 2001). Alternatively, they may be produced through local dynamo processes, i.e., formed as a consequence of convective motions closer to the surface (Hagenaar et al. 2003; Stein et al. 2003). Hagenaar et al. (2008) studied the distribution and evolution of network magnetic elements in the quiet Sun and found that the emergence rate of ERs depends on the imbalance of magnetic flux surrounding the emergence sites.

Yang et al. (2009) investigated magnetic field evolution in a coronal hole region. They reported that an ER emerged and its dipolar patches separated first and then moved together and canceled with each other. With the help of vector magnetic fields and Doppler observations from the Hinode, they concluded that the cancellation between the opposite polarities of the ER was due to the submergence of the original loops that emerged from below the photosphere. Recently, Wang et al. (2012) studied the solar intranetwork magnetic elements in a quiet region and an enhanced network area using the Narrowband Filter Imager magnetograms from the Hinode, and found an intranetwork dipolar flux emergence followed by cancellation of its two poles with opposite polarities. They believed that, after emergence, the dipolar flux indeed submerged, i.e., retracted back into the sub-photosphere again, because they had tracked the dipole continuously in the magnetograms with high-temporal and spatial resolutions.

Then one question is raised: in the quiet Sun, how often and to what extent do ERs perform the behavior as reported by Yang et al. (2009) and Wang et al. (2012), i.e., an ER canceling itself after emergence? The present Letter is dedicated to answering this question based on statistical results.

2. OBSERVATIONS AND DATA ANALYSIS

The Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012; Schou et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) provides magnetic fields in the full disk of the Sun with a pixel size of 0.5" and a cadence of 45 s uninterruptedly. In this Letter, we adopt the HMI full-disk line-of-sight magnetograms with a three minute cadence, i.e., one frame in four, from 2010 June 11 12:00 UT to 2010 June 15 12:00 UT.

For each point \((x, y)\) on the solar disk, the heliocentric angle \(\alpha\) is defined as: \(\sin(\alpha) = \sqrt{x^2 + y^2}/R_{\odot}\), where \(R_{\odot}\) is the solar radius and the disk center is at \(x = y = 0\). Since the noise increases for large \(\alpha\), we do not consider the pixels with \(\alpha \geq 60^\circ\) in each magnetogram as Hagenaar (2001) and Jin et al. (2011) have done. In Figure 1, the red circle outlines the
area where $\alpha < 60^\circ$. Then, we derotate all the magnetograms differentially to a reference time (2010 June 13 12:00 UT). Our target area is outlined with the blue curve, within which $\alpha < 60^\circ$ at all the times during the observation period of our data set.

For each pixel in the rotated frame, there is a certain $\alpha_0$. The pixel area $S$ in the HMI magnetograms is $0.5 \times 0.5$, and one pixel at $\alpha_0$ corresponds to a real area $S' \cos(\alpha_0)$ on the solar surface. The observed flux density $B$ is assumed to be related to the flux density along the local normal direction, and then the corrected flux density is $B' / \cos(\alpha_1)$, where $\alpha_1$, instead of $\alpha_0$, is the real position at the observation time.

3. RESULTS

We track the ERs that emerged within the area outlined by the blue curve in Figure 1 and identify 2988 ERs during the four days. We find that these ERs can be classified into two types according to their performance during evolution: normal ERs (NERs) and self-canceled ERs (SERs). For each type, we provide one movie including three examples.

3.1. Type One: NERs

As can be seen from Movie 1 (available in the online edition), each NER emerged and grew with separation of its opposite polarity patches which canceled or coalesced with other magnetic flux at the end. Most ERs are NERs, and the number of NERs is 2798.

The first example of NERs is shown in Figure 2. In the ellipse region, the NER emerged and could be identified as a dipolar region at 20:32 UT on June 13 (denoted by arrows in panel (a)). The two patches with opposite polarities (labeled with “A” and “B”) grew and separated along the long axis (panel (b)). The negative patch moved toward the pre-existing positive magnetic field (indicated by arrow “C”) and they canceled with each other (panel (c)). At 02:05 UT on June 14, most of the flux of “A” had disappeared and the cancellation between “A” and “C” was still going on (panel (d)).

Along slit “M–N” marked in panel (c), we obtain the image profile by averaging 5 pixels in the magnetograms in the direction perpendicular to “M–N.” Then, we make the space–time plot of such profiles over time from June 13 17:29 UT to June 14 04:56 UT, as displayed in panel (e). The NER emerged around 18:30 UT and the two patches separated with an average velocity of 0.8 km s$^{-1}$ in the first 3 hours (marked by the dashed lines). Moreover, during the emerging stage, there was a rapid emergence with an expansion velocity of 3.9 km s$^{-1}$ from 20:29 UT (marked by the dotted lines). After 21:30 UT, when the NER was well developed, the separation slowed down, and patch “A” moved toward “C” and canceled with it.

We measure the magnetic flux ($\phi$) of the NER by calculating $\phi_+$ and $\phi_-$ in an area containing the two patches. The selected area is changed according to the expansion of the NER to ensure that the area has an appropriate size. After selection, the pixels with unsigned magnetic fields weaker than 10.2 Mx cm$^{-2}$ (noise level determined by Liu et al. 2012) are eliminated. The positive flux ($|\phi_+|$), negative flux ($|\phi_-|$), and total flux ($|\phi_+| + |\phi_-|$) are plotted as a function of time in panel (f). The total flux displayed a sharp increase at a rate of $4.2 \times 10^{19}$ Mx hr$^{-1}$ during the rapid emergence stage (20:29 UT–21:11 UT) and then appeared as a slow increase and reached $4.8 \times 10^{19}$ Mx. From 22:20 UT when the negative patch “A” collided and canceled with the pre-existing positive patch “C,” the negative flux of the NER began to decrease at a rate of $2.2 \times 10^{18}$ Mx hr$^{-1}$, while the positive flux of the NER mainly maintained at a steady level.

3.2. Type Two: SERs

As shown in Movie 2 (available in the online edition), each SER emerged and grew and its dipolar patches separated at first, but then a part of the magnetic flux of the SER moved together and canceled gradually, which is described with the term “self-cancellation” by us in this Letter. There are only 190 SERs, about 6.4% of the ERs.

Figure 3 shows the evolution of the first SER in Movie 2. The ellipse region in panel (a) outlines the location of the SER. At 08:11 UT on June 14, the SER (indicated by arrows in panel (a)) had exhibited a significant dipolar configuration. Then, the SER went on developing and its two patches (denoted by arrows “A” and “B” in panel (b)) separated. Gradually, the positive polarity patch “A” split into two major elements “A1” and “A2,” and “A2” moved toward to “B” while “A1” and “B” did not change their positions much (panel (c)). When “A2” met with “B,” the cancellation took place (see panel (d)), and at last, “A2” completely disappeared and part of “B” remained.

Along the separation and approach direction, i.e., “M–N” marked in panel (d), we obtain a series of image profiles as we have done in Figure 2, and stack them in panel (e). The changes of positive flux, negative flux, and total flux ($|\phi_+|$, $|\phi_-|$, and $|\phi_+| + |\phi_-|$), respectively during this period are shown in panel (f). The SER violently emerged with the negative patch followed by the positive one (the first three hours in panel (e)), leading to a rapid increase of the total flux to $1.1 \times 10^{20}$ Mx and an imbalance between the positive and the negative flux at the emergence stage (stage 1 in panel (f)). When the SER was well developed, expansion of the two patches (positive “A” and negative “B” in panel (e)) almost stopped, and patch “A”
Figure 2. Panels (a)–(d): sequence of HMI magnetograms displaying the evolution of an NER denoted by the arrows and outlined by the ellipse in panel (a). The field of view is 50″ × 50″ and the gray scale saturates at ±80 Mx cm⁻². Arrows “A,” “B,” and “C” denote the negative and the positive patches of the NER and the pre-existing positive magnetic fields, respectively. Panel (e): space–time plot along slit “M–N” marked in panel (c). The dashed lines indicate the separation of the NER patches, and the dotted lines a rapid emergence phase of the NER. Panel (f): temporal variations of the positive (dash-dotted curve), negative (dashed curve), and total (solid curve) magnetic flux of the NER. The dotted line indicates a sharp increase of total magnetic flux and the solid vertical line marks the flux maximum. (An animation and a color version of this figure are available in the online journal.)

began to split into two components, “A1” and “A2.” Component “A2” moved toward “B” (marked by the red dotted line in panel (e)) and met with “B” around 22:15 UT (marked by the dotted vertical line in panel (f)). Then, “A2” began to cancel with “B,” resulting in the total disappearance of “A2” and the shrinkage of “B.” This self-cancellation process led to the significant decrease of total magnetic flux from 6.4 × 10¹⁹ Mx to 4.4 × 10¹⁹ Mx at a rate of 1.3 × 10¹⁹ Mx hr⁻¹ (marked by the red dotted line in panel (f)).

3.3. Statistical Results of the ERs

The probability density functions (PDFs) of the ER (black curve) and SER (red curve) numbers are plotted in Figure 4(a). We find that the PDF peak of the ERs is at 5.0 × 10¹⁸ Mx, and there is also a peak of the SER PDF which can be seen clearly in panel (b). The PDF of SERs is peaked at 1.8 × 10¹⁹ Mx. The blue curve in panel (a) represents the number ratio of SER to ER. The dash-dotted vertical line is located at 5.5 × 10¹⁹ Mx, a general separation of abundant samples (before) and few samples (after). Thus, we think the ratio curve before the vertical line is statistically reliable. The ratio curve increases from 0 to 0.5, with the variation of ER flux from 0 to 5.5 × 10¹⁹ Mx, revealing that the higher the ER magnetic flux is, the easier the performance of ER self-cancellation is.

For SERs, only part of the magnetic flux is self-canceled. The scatter plots of self-cancellation fractions versus magnetic flux of SERs are shown with red symbols in Figure 4(c). The mean value of the self-cancellation fraction of SERs is 62.5%. We apply a “sort-group” method introduced by Zhao et al. (2009) to the SERs: (1) all the SERs are sorted according to the total magnetic flux of individuals, (2) the 190 sorted SERs are grouped into 10 data points with equal SER number and each data point is assigned with the mean value of the corresponding SER group, (3) the self-cancellation fractions and the magnetic flux values are correlated with each other and plotted with blue symbols in Figure 4(c). The statistical correlation shows a general tendency that the higher the ER magnetic flux is, the smaller the self-cancellation fraction is. We plot the PDF of self-cancellation fractions in panel (d). The dotted vertical line marks the PDF maximum at 75%. We can see that there are increase and decrease trends before and after the PDF peak, respectively.

Figures 4(e) and (f) are similar to Figures 4(a) and (b), but for ER flux (black curve), self-canceled flux (red curve), and the ratio (blue curve) of self-canceled flux to ER flux. The PDF of ER flux is peaked at 7.0 × 10¹⁸ Mx (panel (e)), and the peak of self-canceled flux is at 3.3 × 10¹⁹ Mx (panel (f)). The flux ratio curve exhibits a variation from 0 to 0.3 in the range of 0–5.5 × 10¹⁹ Mx, indicating that the higher the ER magnetic flux is, the more the self-canceled flux is.
4. CONCLUSIONS AND DISCUSSION

With the observations from the SDO/HMI, we statistically investigate the ERs in the quiet Sun. We find that there are two types of ERs: NERs and SERs. Each NER emerged and grew with separation of its opposite polarity patches which finally canceled or coalesced with other magnetic flux. Each SER also emerged and grew and its dipolar patches separated at first, but then a part of the magnetic flux of the SER moved together and canceled gradually, which is described with the term “self-cancellation.” We identify 2988 ERs, among which there are 190 SERs, about 6.4% of the ERs. The mean value of the self-cancellation fraction of SERs is 62.5%, and the total self-canceled flux of SERs is 9.8% of the total ER flux. Our results also reveal that the higher the ER magnetic flux is, (1) the easier the performance of ER self-cancellation is, (2) the smaller the self-cancellation fraction is, and (3) the more the self-canceled flux is.

Magnetic flux cancellation is an observational phenomenon of flux disappearance when two magnetic patches with different polarities encounter each other (Livi et al. 1985; Martin et al. 1985; Zhang et al. 2001). As one of the three modes for removal of magnetic flux with opposite polarities from the photosphere illustrated by Zwaan (1978, 1987), the disappearance of magnetic flux can result from the retraction of magnetic loops into the sub-photosphere, if the two poles are still connected by initial loops. So in theory, the process where magnetic loops emerge into the solar atmosphere and then submerge below the subsurface is quite reasonable and possible. The submergence of part of an active region was studied by Rabin et al. (1984) and the submergence of a sunspot group was reported by Zirin (1985), who suggested that submergence of an active region may be common. To determine if cancellation is caused by the submergence of magnetic loops, it is important to check vector field data. With Hinode spectropolarimetric data, Yang et al. (2009) found that at the area where the two opposite polarities of the ER canceled, there were strong transverse fields pointing directly from the positive patch to the negative one. Moreover, they also observed larger Doppler redshifts between the canceling patches. They suggested that the cancellation of the ER was due to the submergence of the original loops. In the recent study of Wang et al. (2012), although there was a lack of vector field observations, they believed that the emergence and submergence of the ER they observed was a real behavior since the ER had been tracked in the high-tempospatial resolution photospheric magnetogram. Thus, we also think the self-cancellation of SERs is caused by the submergence of magnetic loops connecting the dipolar patches.

When magnetic patches of ERs separate and cancel with other magnetic elements, the connection between opposite polarities will be changed and the magnetic loops will be restructured to a lower potential configuration, which requires magnetic flux reconnection accompanied with energy release (Wang & Shi 1993). When the ER loops emerge through the photosphere
Figure 4. Panel (a): PDFs of ER (black curve) and SER (red curve) numbers and the number ratio (blue curve) of SER to ER. The bin size is $1 \times 10^{18}$ Mx. The dash-dotted vertical line is located at $5.5 \times 10^{19}$ Mx, a general separation of abundant samples (before) and few samples (after). Panel (b): PDF of SERs at an enlarged displaying scale with a bin size of $2 \times 10^{18}$ Mx. The dotted vertical line marks the PDF maximum. Panel (c): scatter plots of self-cancellation fractions vs. magnetic flux of SERs (red symbols) and of sorted and grouped points with error bars (blue symbols). Panel (d): PDF of self-cancellation fractions with a bin size of 5%. The dotted vertical line marks the PDF maximum before and after which there are increase and decrease trends (dashed lines). Panels (e) and (f): similar to panels (a) and (b), but for ER flux (black curve), self-cancelled flux (red curve), and the ratio (blue curve) of self-cancelled flux to ER flux.

layer from below and then submerge into the sub-photosphere again, no magnetic reconnection occurs and no magnetic energy is released.

Our results reveal a tendency that the higher the ER magnetic flux is, the easier the performance of ER self-cancellation is. We suggest that the behavior depends on the magnitude of magnetic flux and on the relative importance and balance between the magnetic pressure and the magnetic tension acting on the emerging flux tubes. In this study, we also note that the dipolar patches of most of the SERs split before the self-cancellation phase (e.g., as shown in Figure 3). It may be caused by plasma motions in the photosphere. When they emerge into the photosphere, they are drifted toward the supergranular boundaries by mesogranular and supergranular flow and split into smaller fragments due to granular convection (Simon et al. 2001; Priest et al. 2002).

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