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Magnetic Polarity Distribution and Evolution of an Active Region Moss Areas; a Case Study

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Abstract

Moss regions, that are the footpoints of the hot coronal loops and seen as the brightest emission areas in the EUV solar active regions with 1 MK temperatures, are studied in a quasi-steady phase of an active region with NOAA number 12010. Studying the moss regions are important to probe the heating mechanism(s) of the active region cores. Using the 193 Å extreme-ultraviolet (EUV) images of the AIA/SDO along with the magnetograms of HMI and employing the feature tracking code, YAFTA, the magnetic features of the HMI images are identified and tracked and their locations are compared with respect to the positions of the selected moss regions. Results show that 68% and 32% of the moss areas are located over the borders and inside the magnetic patches, respectively. Moreover, 90% of the moss boxes are located above the uni-polarity magnetic regions that could be due to the low resolution and sensitivity of the HMI instrument. In continue three pairs of moss boxes at the opposite ends of the three hot coronal loops are selected and studied in more detail. Results show a global magnetic field increase at one end of the loop along with magnetic field decrease at the opposite side of the loops. Either a magnetic reconnection process near the flux cancelling leg of the loop, or a uni-directional siphon flow could be responsible to produce this behavior. Doppler-shift analysis is needed to distinguish which scenario is happening. Unfortunately, the spectral data are not present for these six moss boxes.

Keywords: Sun: EUV radiation - Sun: coronal heating, - Sun: magnetic field

Introduction

Active region “moss” areas appear as a reticulated network of bright emission with many tiny dark holes (due to the presence of spicules, which are cooler) in the extreme ultraviolet (EUV) images of the solar corona with temperatures about one MK. Indeed, moss regions are the footpoints of hot coronal loops (with temperatures in the range of 3 to 5 MK). Unlike the plage regions that appear in the chromospheric networks with strong unipolar magnetic fields, the moss regions trace the interface between the chromosphere and corona and therefore build an appropriate diagnostic tool to investigate the energy transfer mechanism(s) from the photosphere to the corona (Berger et al., 1999a,b; Fletcher & De Pontieu, 1999; Berger et al., 2004).

Photospheric granules with life-time of 5 - 10 min and widths of about 1 Mm are the top view of the small convection cells transferring the convection flows (with 0.5 to 1.5 km/s velocities) from the convection-zone (inside the sun) to the solar visible surface. The emission from the inside of granules are brighter respect to its surroundings because the hot plasma rising up and emerging into the solar surface due to buoyancy effect (and appear brighter) and then get cold after evacuating its energy into the photosphere (darker boundaries) and return back into the convection layer. Photospheric granules repeatedly merge with the newly emerging convection cells or split into smaller ones and create a very dynamic pattern all over the solar photosphere (Priest, 2014). Granules cover the all photosphere areas except of the sunspot regions. The downward convection flows concentrate the weak magnetic elements at the borders of the granules and increase the magnetic tension at these locations.

Choudhuri et al. 1993 showed that the mechanical work performed by convective motions on the magnetic field lines would increase the free energy in the solar corona and this budget of energy is more than enough to heat the corona and keep it hot, as it is (Tripathi 2013).

Moss emission is observed by Berger et al. 1999a,b in the TRACE Fe IX/X 171 Å images of an active region with NOAA number 8651, for the first time. They described the moss as thin layer with about 1 Mm thickness that occur almost 2 Mm above the photosphere having 2 to 3 times higher pressure respect to an ordinary coronal loop. Antiochos et al. 2003 found the intensity variations of the moss regions (~10 to 20 Mm) to be less than 10%. Warren et al. 2008, 2011 studied the emission of the active region cores by using the X-ray images for about 6 hours and found a well steadiness in the intensity. Tripathi et al. 2010 realized the density and temperature structures of the moss regions does not change significantly over a couple of hours in five continuous days. These findings strongly support the steady heating mechanism in the active region core loops.

Berger et al. 1999a suggested that the moss emissions are got produced by the downward heat conduction flux from the hot loops in the higher layers. Berger et al. 2004 showed the moss areas are associated with the edges of the chromospheric plage regions with weak magnetic fields. Testa et al. 2014 found the observational evidence of highly varying (in the time scale of 20 to 60 sec) intensity and velocity in the moss regions with spatial scales less than 500 km (small-scale). Running a numerical simulation code, they realized their observations support the heating by non-thermal particles (electrons), which produced out of some coronal nanoflare events with time scales smaller than 30 s. The common view was that the energy driving source for moss region coming from the top parts of the hot coronal loops. However, Chitta et al. 2018, 2019 showed that rapidly footpoint reconnections due to flux cancellation phenomena could produce high variability in the moss emission. Smitha et al. 2017 found an order of magnitude larger magnetic flux cancellation rate at the border of the photospheric granules. Based on this founding, Priest et al. 2018 developed a heating model for the solar chromosphere and corona based on flux cancellation that was able to predict the solar wind acceleration.

In continue the magnetic polarity distribution and evolution of an active region moss area along with their positional information are investigated and their structure and possible mechanisms are discussed.

2. Methods

2.1 data properties

The studied data is taken from the NOAA 12010 active region on 2014 March 21 from 11:34:28 UT to 13:42:39 UT (Figure 1). The extreme ultraviolet (EUV) images of AIA/SDO in 171, 193, and 94 Å channels are used with spatial resolution of 0.6 arcsec/pixel and cadence of 12 sec (Lemen et al. 2012; Pesnell et al. 2012). The 1600 and 1700 Å AIA images with time cadence of 24 sec are used for co-alignment of the AIA channels with HMI/SDO (Helioseismic and Magnetic Imager) magnetograms (Scherrer et al. 2012; Schou et al. 2012). The level 2 data, that are corrected for bad-pixels, flat-field, differential rotation and other quality checks, are utilized in this study. The cross-correlation method used for co-alignment of AIA 1600 images with HMI magnetogram images. Intensity contours of AIA 1600 (in yellow and orange colors) are over-plotted on HMI line-of-sight magnetograms at the starting time of the study (Figure 2). Black and white colors in the HMI images represent the negative and positive magnetic polarities, respectively. The NOAA 12010 active region during the 17th to 19th March 2014 and 22rd to 27th March 2014 was in its flaring-mode with 9 and 15 flares in the ranges of C1.0-C9.9 and C1.1-C4.1, respectively. Almost 24 hours before and after our study (~20-21 March), the active region was in the non-flaring quasi-stable mode.

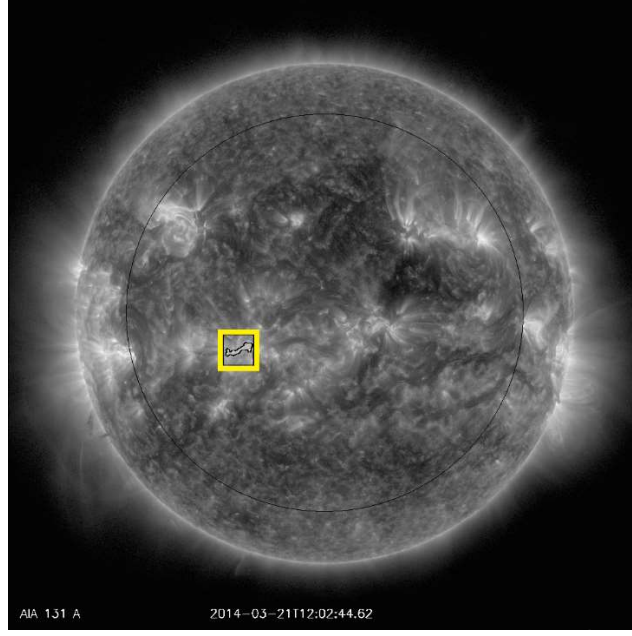


Figure 1. AIA 131 Å image of the sun recorded by AIA/SDO on 2014 March 21 at 12:02 UT. The studied active region (NOAA 12010) is located in the yellow box.

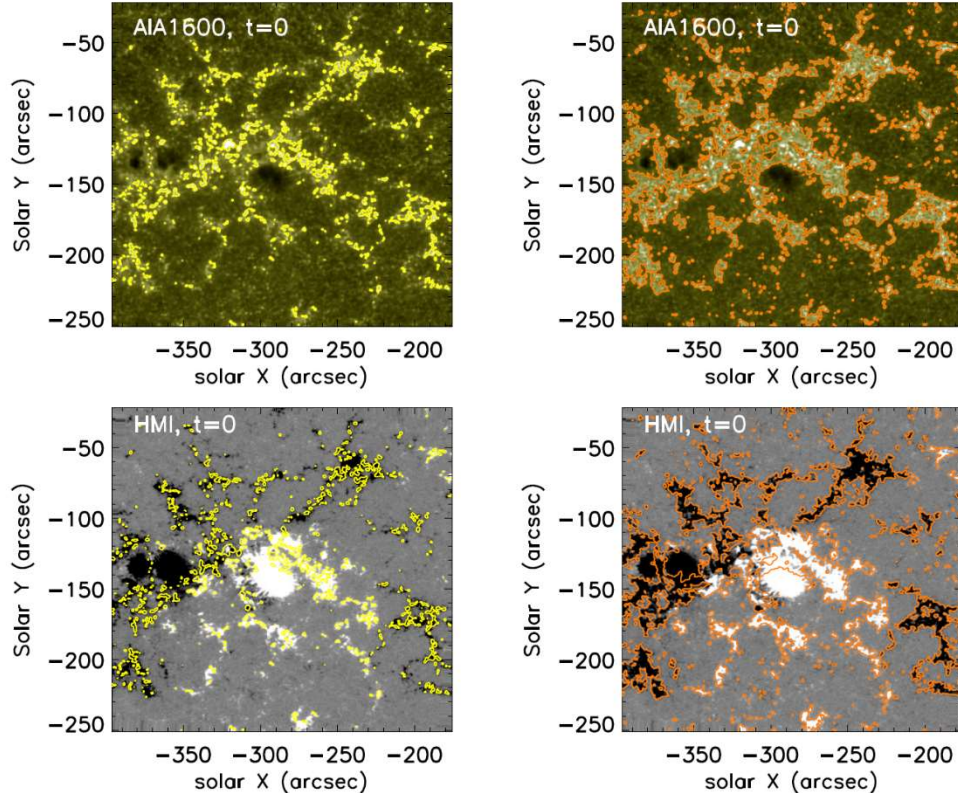


Figure 2: AIA and HMI co-alignment; the intensity contours of AIA 1600 (in yellow and orange colors) are overlaid on HMI magnetograms at the start time of the study. Black and white colors in the HMI images represent the negative and positive magnetic polarities, respectively.

2.2 Moss Area Selection

Using the top 20% intensity contours of AIA 193 Å ($T \sim 1.2$ MK) the moss area is distinguished. Within this area 40 pairs of 3×3 pixel² boxes are selected and labeled as east (E)/west (W) moss boxes regarding their locations. Using the AIA hotter channels, such as 211, 335, 94, and 131 Å, each pair of the moss boxes is selected in a way to be at the two opposite ends (footpoints) of a hot coronal loop. The selected moss boxes are shown in Figure 3.

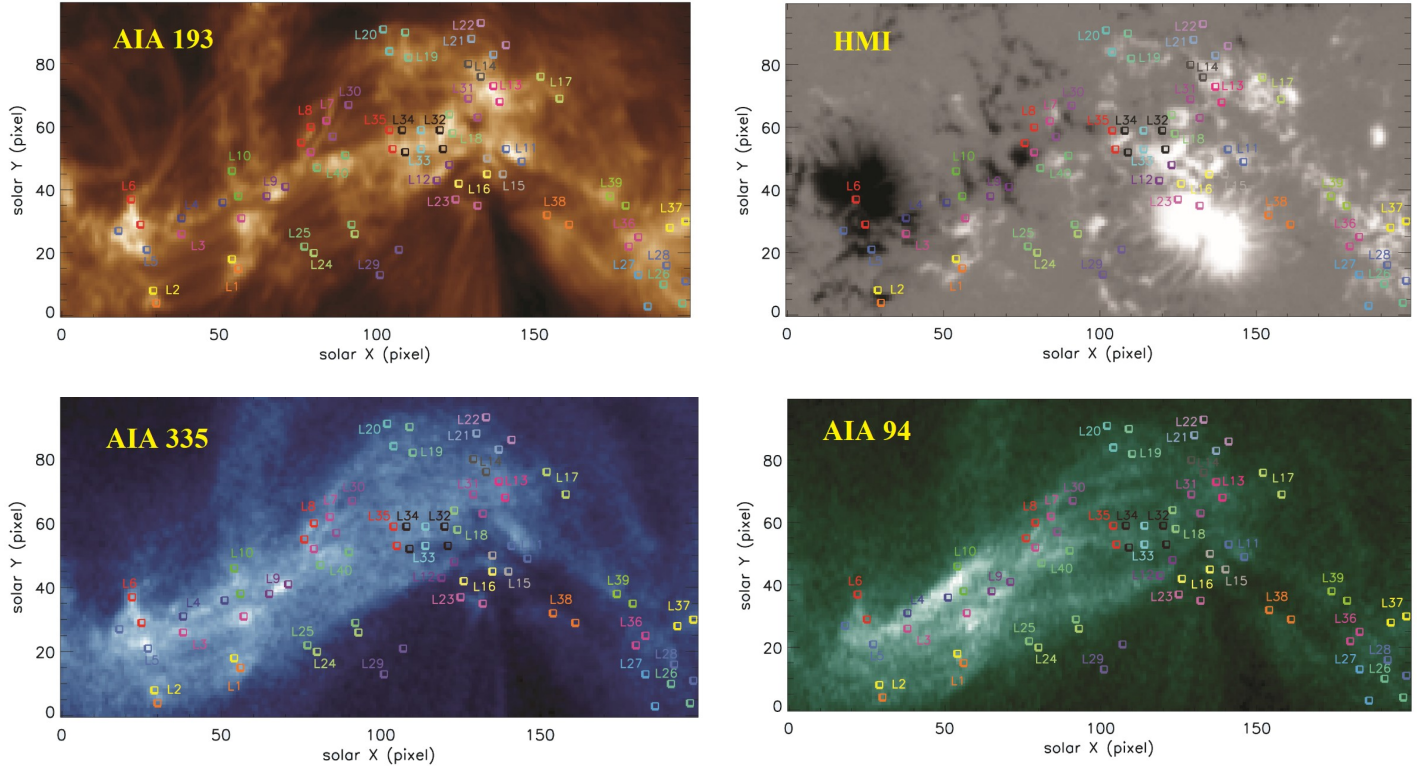


Figure 3: Boxes of moss areas are selected and labeled (in pair) from AIA 193 Å images and over-plotted on the AIA 335 and 94 channels that have higher temperatures, along with HMI magnetogram. .

2.3 YAFTA Algorithm

YAFTA (Yet Another Feature Tracking Algorithm) routine written in IDL language, is a 2-D region growing algorithm developed by DeForest et al. 2007 to identify and track magnetic features in the line-of-sight magnetograms. YAFTA groups the neighboring pixels that sit on a same hill of magnetic field strength, then, rank them regarding their flux and label the identified magnetic patches. Fourier Local Correlation Tracking (FLCT) code is used to (Welsch 2004; Fisher & Welsch, 2008) track the identified magnetic patches.

3. Results and Discussion

Forty pairs of 3×3 pixel² moss boxes are selected at opposite ends of hot coronal loops. Results show only 10% of the selected moss box pairs are rooted in the opposite (positive-negative) magnetic polarity configurations. About 60%, 13%, and 3% of the selected moss box pairs have positive-positive, negative-negative, and neutral-neutral magnetic fields. The rest 3% and 13% correspond to positive-neutral and

negative-neutral magnetic configurations. The results are summarized in the Table 1. In subsection 3.1 we study the evolution of 3 pairs of the positive-negative moss areas in more detail.

Wang 2016 and Wang et al. 2019 are reported the observations of these unipolar loop-like configurations (positive-positive, negative-negative, positive-neutral, and negative-neutral) in the plage and moss areas. They suggest these unipolar flux concentrations could be unresolved structures due to low spatial resolution or low sensitivity of the HMI instrument. They provided some evidence of existing multiple fine structure loops inside the moss region. Moreover, they argued the inverted-Y structures that have null point at their dome top (and minority-polarity at their base) could be another feature associated with unipolar moss region.

Table 1. Photospheric magnetic polarity of the moss pair boxes

	Positive-Negative	Positive-Positive	Negative-Negative	Neutral-Neutral	Positive-Neutral	Negative-Neutral
Abundance (total 40 pair of boxes)	4	24	5	1	1	5
Abundance percentage	10%	60%	13%	3%	3%	13%

On the other side, about 66% and 24% of the selected moss boxes are found to be locating on top of the HMI positive and negative magnetic polarity regions, respectively. Only, 10 % of the moss boxes are from the neutral polarity regions ($-10 \text{ G} < B < 10$; close to the noise level of HMI magnetograms $\sim \pm 7 \text{ G}$).

Using YAFTA algorithm and FLCT technique on the HMI images the major magnetic patches in the study region are identified and tracked. The minimum size of the magnetic patches and the upper threshold of the magnetic field strength (to avoid inside the sunspot regions) are selected to be 4 pixel and 120 G, respectively. The locations of the selected moss boxes are plotted over the identified magnetic patches and got labelled as “inside” or at the “border” of the magnetic patches. It seems that most of the selected moss boxes fall into the borders of the magnetic patches. The results show that 68% of the moss boxes sit on the borders of the magnetic patches, while 32% of them repose inside the magnetic patches, during the whole study time. Figure 4 represent the locations of the all selected moss boxes on top of the YAFTA identified magnetic patches in the HMI magnetogram at the starting time of the study ($t=0$).

Chitta et al. 2017, 2018, and 2019 analyzing the high-resolution magnetographs of IMAX/SUNRISE realized the footpoints of hot coronal loops were mainly located at the minority-polarity regions (nearby the edges of strong plage regions), which was invisible in the corresponding HMI magnetograms because of its lower resolution. These observations could explain why only 10% of the selected moss box pairs exhibit to have visible bipolarity (positive-negative) situation.

On the other side, borders of the magnetic patches that are found to be the most abundant locations of the moss boxes in our analysis are in agreement with their findings, as well. Presence of the fibrillary magnetic canopies overlying the borders of the magnetic patches (granular cells) is another possible picture that agrees with our findings.

3.1 Moss Boxes at Opposite Footpoints of Hot Coronal Loops

Six moss boxes (1E, 1W, 2E, 2W, 3E, and 3W) at the opposite ends of three hot coronal loops (L1, L2, and L3) are selected to investigate more. Figure 5 represents the locations of these six moss boxes over the HMI magnetogram (left panel) and AIA 193 Å channel image (right panel) at the starting time of the study ($t=0$). The areas inside the orange, pink, and blue boxes are selected as background emission, with a neutral

average magnetic flux (in the range of ± 5 G), and subtracted from the AIA light curves of the moss boxes. The average intensity of each AIA channel along with the average strength of magnetic field related to each moss box are calculated at each time step.

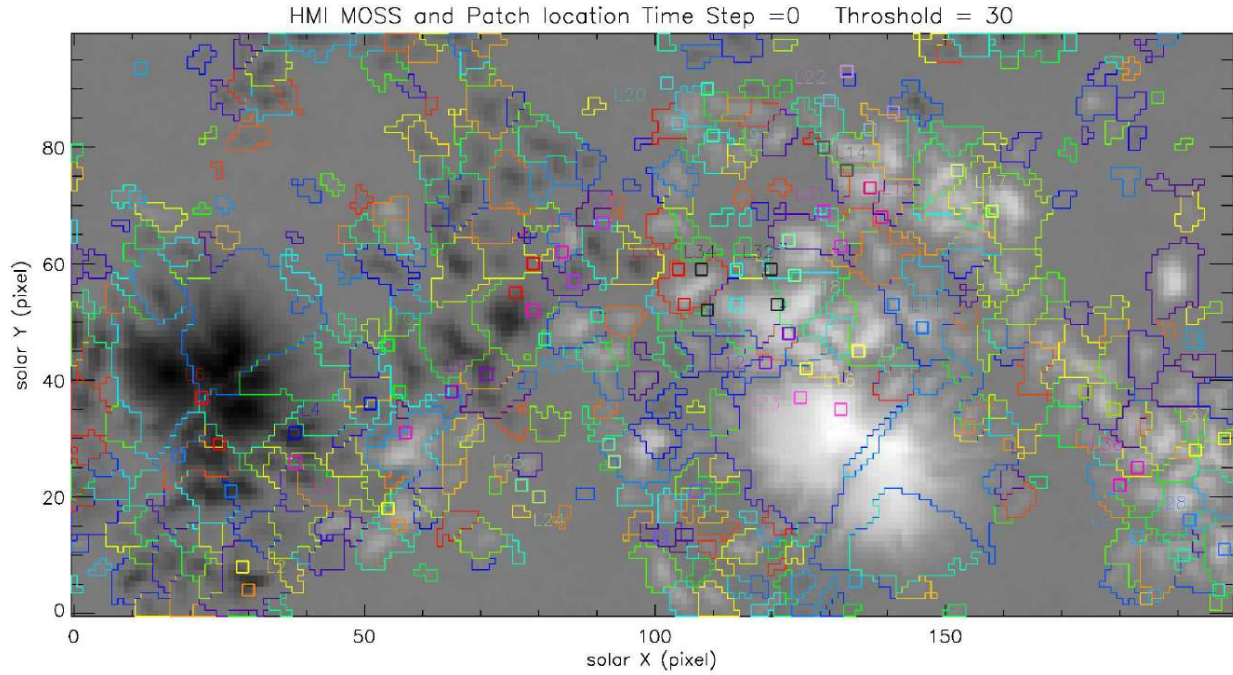


Figure 4: Locations of the moss boxes and the YAFTA identified magnetic patches over-plotted on the HMI magnetogram image at the starting time of the study ($t=0$).

Loop 1: Panel (a) of Figure 6 represent the magnetic field strength variation with time over the moss boxes 1E and 1W at the two opposite ends of the loop 1. Panel (b) shows the scatter plot of the magnetic field strength of 1W moss box versus the 1E one. Panels (c) and (d) demonstrate the scatter plots of the magnetic field strength of 1E and 1W moss boxes versus the corresponding various AIA channel intensities and the corresponding correlation coefficients are shown on top of each plot.

As panel (a) of Figure 6 shows, in the first 20 min of the study the magnetic field strength at the both 1E and 1W moss boxes increase simultaneously, representing an opposite-polarity emergence phenomena. However, between the time instances of 20 min to-150 min, an average decrease in the magnetic field strength of the 1E moss box is visible, while the 1W moss box experiencing an average increase. Considering the whole 150 min of the study duration, 86% negative correlation is obtained (panel (b)). The magnetic field strength versus the intensity in various AIA channel plots for the 1E moss box shows almost 80% correlation in 211, 131, 335, 304, 193, and 94 Å AIA channels that means decreasing the magnetic field strength occurring along with decreasing the EUV intensity in the AIA channels (panel (c)). However, increasing the magnetic field in the 1W moss box, the 335, 211, and 131 Å AIA channel intensities decrease with about 70% correlation. Other AIA channels at 1W box show some sorts of different behavior at different study time intervals (panel (d)).

Loop 2: Figure 7 is as Figure 6, but for the moss boxes 2E and 2W. As it is seen in the panel (a), in the first 30 min of the study the 2E moss box experience no considerable change in its magnetic field

strength, while the 2W moss box experience decreasing magnetic field about 100 G. In continue, until the end of the study time interval the 2E moss experience an average decrease, while the 2W moss experience an average increase in the magnetic field strength. The similar behavior was observed in the moss boxes of 1E and 1W. Panel (b) shows 69% of negative correlation between the magnetic fields in the 2E and 2W moss boxes. Panel (c) shows almost 70% correlation between the magnetic flux in the 2E moss box with the intensity of AIA 193, 211, and 94 Å channels; Decreasing negative polarity magnetic field at 2E moss box following the decrease in the AIA hot line intensities. Cooler AIA channels like 1600 and 1700 Å show no significant correlations. Panel (d) shows the scatter plots relating to 2W moss box; The AIA 211 and 94 Å lines shows a small negative correlation of 30% and 24% between the magnetic field and AIA intensity, respectively. While, the 171, 131, 1600 and 1700 channels represent a small positive correlations of 40% to 30%. Investigating the AIA light curves shows the presence of a couple of jet-like events that represent a sudden increase in the intensity at both 2E and 2W moss boxes.

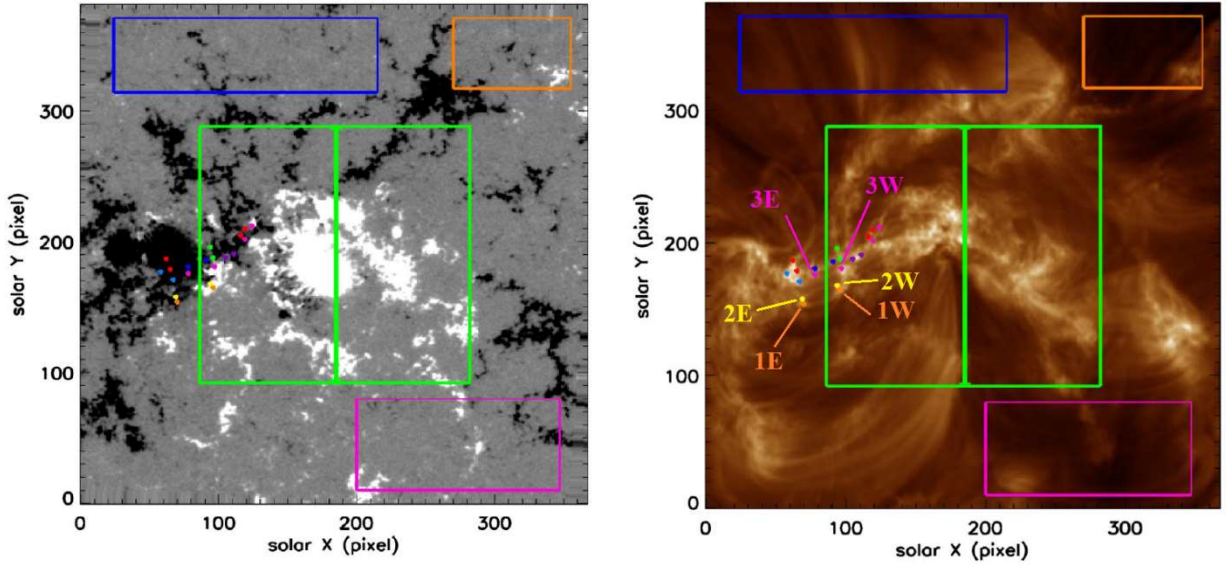


Figure 5. Six moss boxes (1E, 1W, 2E, 2W, 3E, and 3W) at the opposite ends of three hot coronal loops (L1, L2, and L3) are selected and demonstrated over the HMI magnetogram (left panel) and AIA 193 Å channel image (right panel) at the starting time of the study ($t=0$). The areas inside the orange, pink, and blue boxes are selected as background emission, with a neutral average magnetic flux (in the range of ± 5 G), and subtracted from the AIA light curves of the moss boxes. The light-green box shows the field of view of IRIS instrument.

Loop 3: Figure 7 is as Figure 6, but for the moss boxes 3E and 3W. In the first 50 min of the study, the 3E moss box experiences an increase of about 250 G of the negative magnetic field strength. However, the 3W moss box, at the same time, experience an increase of about 50 G of positive magnetic field strength. Then until the time instance $t=100$ min the magnetic field almost does not change at 3E moss box, but decreases for about 150 G at the 3W moss box. In the last time intervals (between 100 to 150 min), the 3E moss experience a decrease followed by an increase, while the 3W moss box experience a moderate decrease in the magnetic field strength. Scatter plots at (b) panel shows three linear parts with clear different slopes. However, the general behavior of this pair of opposite polarity moss boxes is similar to the previous ones; increasing the magnetic field in the positive polarity (moss box 3W) occurs along with decreasing the negative magnetic field (moss box 3E), but with a smaller correlation of 34%.

4. Conclusion

We analyzed 40 pairs of moss boxes that seems to settle at the two opposite ends of hot coronal loops using AIA/SDO and HMI magnetogram images. In the following, we summarize our findings as,

- Only 10% of the pairs of moss boxes seems to locate on bipolar (positive-negative) regions. While the 90% stand over the unipolar (positive-positive, negative-negative, positive-neutral, and negative-neutral) or neutral (neutral-neutral) regions. The results are in agreement with the findings of Wang 2016, Chitta et al. 2017, and Wang et al. 2019. They suggest the origins of the unipolar regions to be the low resolution and sensitivity of the HMI instrument. They suggest the existence of unresolved sub-structures such as tiny bundles of fine structure loops, inverted-Y structures, or the expanding fibrillary canopies in the moss regions would be a reason for this observed unipolarity.
- Using the YAFTA algorithm the magnetic patches of the HMI magnetogram images are identified and tracked. Results show that 68% of the moss boxes are locating at the boundary of the magnetic patches, while the rest 32% stand inside the magnetic patches. This result is also in agreement with the findings of Chitta et al. 2017, 2018, and 2019. Using the high-resolution IMAX magnetographs, they showed the footpoints of hot coronal regions (the moss area) are rooted in the minority-polarity regions at the edge of plage regions and this phenomenon is invisible to HMI magnetogram due to its low resolution and sensitivity.
- In the most time interval of the study, the three pairs of moss boxes at the opposite sites of the hot coronal loops L1 to L3 represent a similar behavior; For instance, one box experience increasing the magnetic field, while the other one experience decreasing. Cancelling at one end and emerging at another end of the hot coronal loop could be due to a magnetic reconnection process with the neighboring magnetic environment of the magnetic flux losing leg. Another possible mechanism is the uni-directional siphon flows that starts to move upward from one leg of the loop (flux increase) and then drain at the other side of the loop. Calculating the Doppler shifts at opposite ends of the loops could shed light to this problem. Unfortunately the spectra is not available for these six studied moss boxes.

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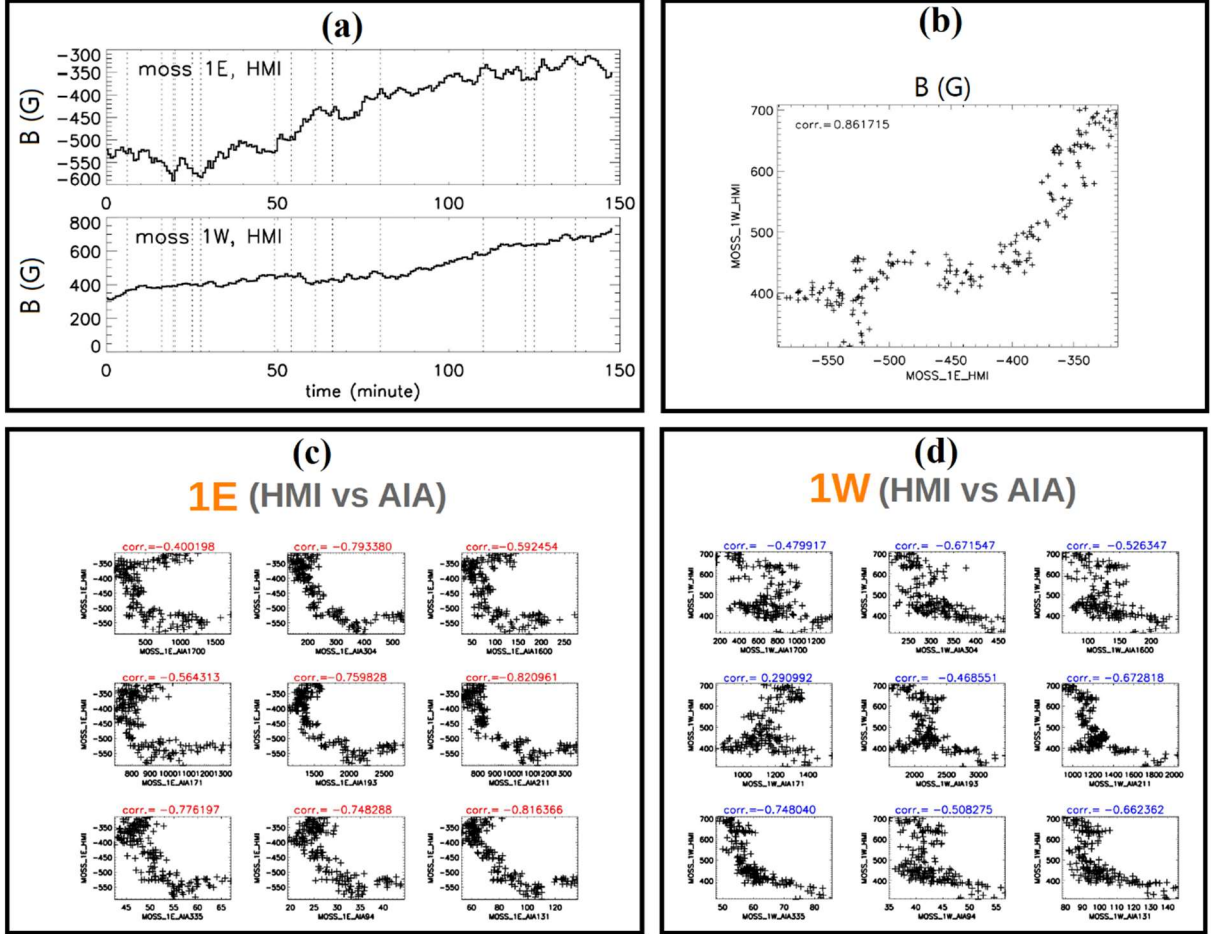


Figure 6. Panel (a) represent the magnetic field strength variation with time over the moss boxes 1E and 1W at the two opposite ends of the loop 1. Panel (b) shows the scatter plot of the magnetic field strength of 1W moss box versus the 1E one. 86% negative correlation is significantly visible. Panels (c) and (d) demonstrate the scatter plots of magnetic field strength of 1E and 1W moss boxes versus the corresponding various AIA channel intensities and the corresponding correlation coefficients are shown on top of each plot.

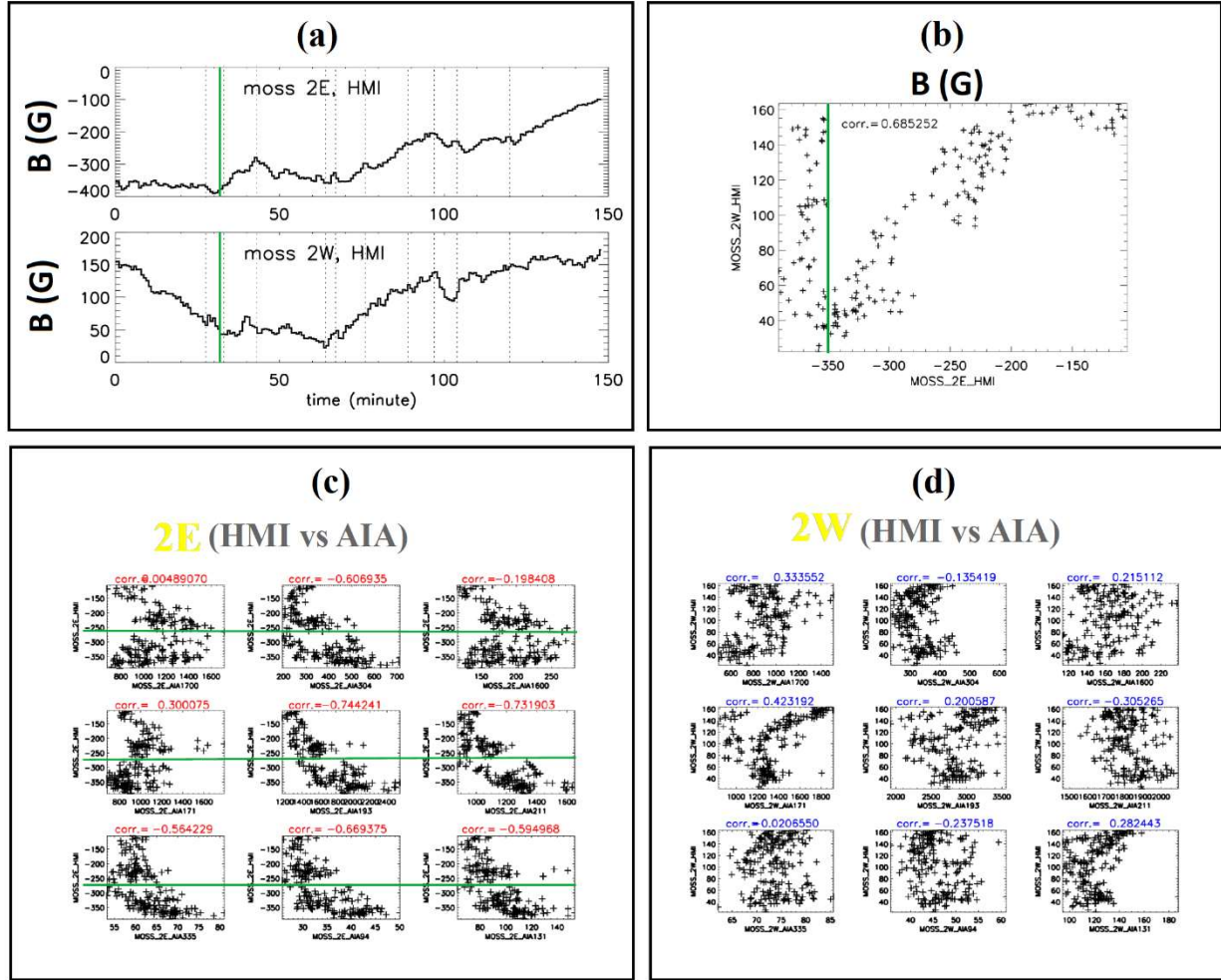


Figure 7. As Figure 6, but for the loop 2 (L2).

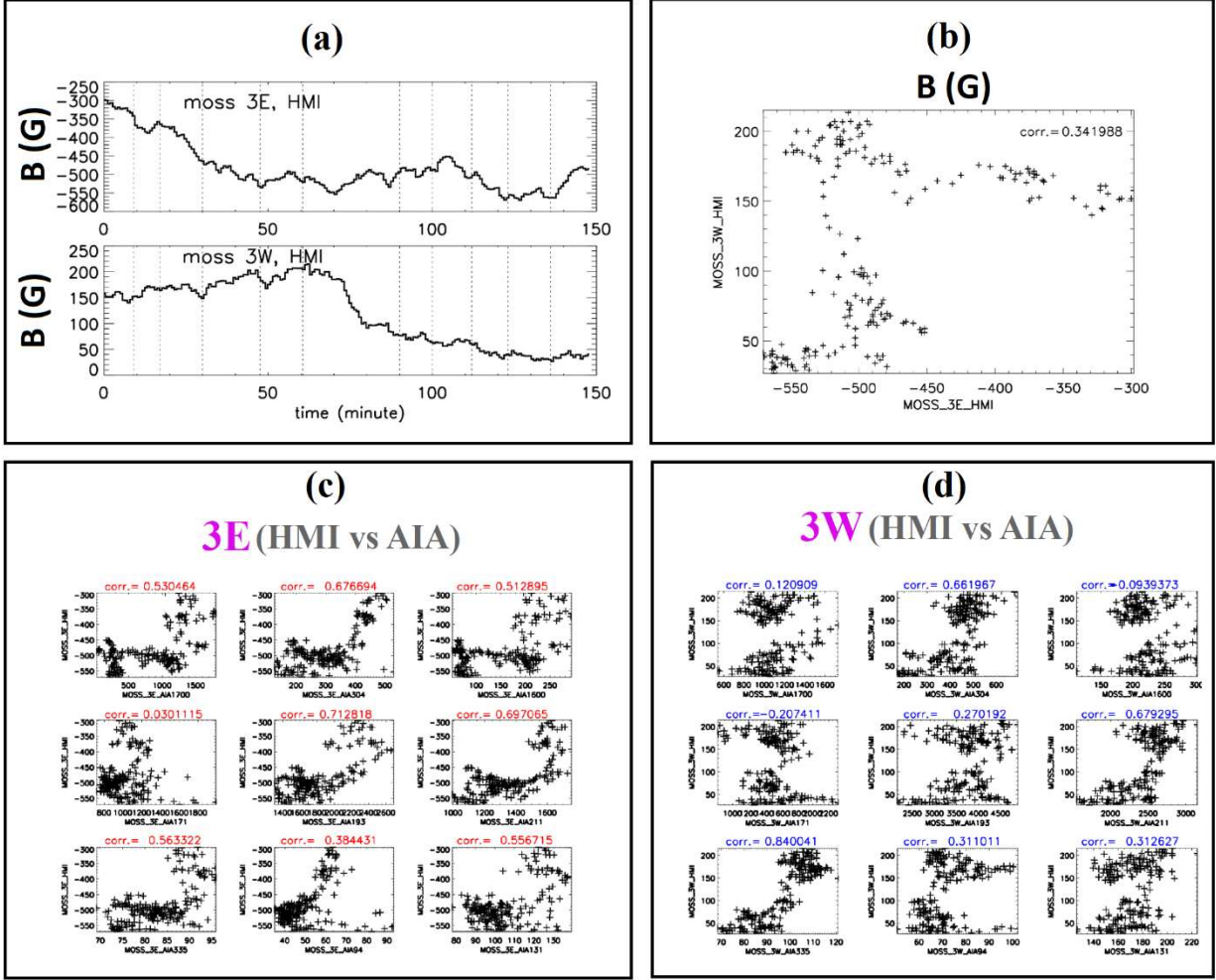


Figure 8. As Figure 6, but for the loop 3 (L3).