A High-resolution Study of Magnetic Field Evolution and Spicular Activity around the Boundary of a Coronal Hole

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Abstract

In this study, we analyze high-spatial-resolution (0\".24) magnetograms and high-spatial-resolution (0\".10) Hα off-band (± 0.8 Å) images taken by the 1.6 m Goode Solar Telescope to investigate the magnetic properties associated with small-scale ejections in a coronal hole boundary region from a statistical perspective. With one and a half hours of optical observations under excellent seeing, we focus on the magnetic structure and evolution by tracking the magnetic features with the Southwest Automatic Magnetic Identification Suite (SWAMIS). The magnetic field at the studied coronal hole boundary is dominated by negative polarity with flux cancellations at the edges of the negative unipolar cluster. In a total of 1250 SWAMIS-detected magnetic cancellation events, ~39% are located inside the coronal hole with an average flux cancellation rate of 2.0 × 10^{15} Mx Mm^{-2} hr^{-1}, and ~49% are located outside the coronal hole with an average flux cancellation rate of 8.8 × 10^{17} Mx Mm^{-2} hr^{-1}. We estimated that the magnetic energy released due to flux cancellation inside the coronal hole is six times more than that outside the coronal hole. Flux cancellation accounts for ~9.5% of the total disappearance of magnetic flux. Other forms of its disappearance are mainly due to fragmentation of unipolar clusters or merging with elements of the same polarity. We also observed a number of significant small-scale ejections associated with magnetic cancellations at the coronal hole boundary that have corresponding EUV brightenings.

Unified Astronomy Thesaurus concepts: The Sun (1693); Solar photosphere (1518); Solar magnetic fields (1503); Solar chromosphere (1479); Solar spicules (1525)

1. Introduction

In general, network field, intranetwork (IN) field, and ephemeral regions form the magnetic field of the quiet Sun (QS). Coronal holes (CHs) in the QS regions are usually seen as dark regions in X-ray and EUV observations due to reduced emissivity at X-ray and EUV wavelengths (for reviews see, e.g., Cranmer 2009; Wang 2009). Formation of nonpolar CHs can result from decay of active regions (Karachik et al. 2010; Golubeva & Mordvinov 2016) and eruptive activities (Heinemann et al. 2018). One of the most important photospheric magnetic characteristics is the highly unbalanced magnetic flux residing in the concentrated flux tubes in CHs (Hofmeister et al. 2017), which leads to dominance of a certain polarity in the CHs and forms an open field topology for the fast solar wind. Plumes—fountain-like coronal structures—are often observed in the unipolar magnetic concentrations in CHs (Wilhelm et al. 2011). Although unipolar magnetic flux tubes are generally believed to dominate the evolution of CHs, high-resolution magnetograms show that vertical magnetic fluxes in the QS have a salt-and-pepper type of distribution, as they do in CHs (Lites et al. 2008; Hofmeister et al. 2019). Magnetic elements of opposite polarity in line-of-sight (LOS) magnetograms are generated by convection in the photosphere and often reside in intergranular lanes. Wiegelmann & Solanki (2004) studied the magnetic properties of twelve CHs and eight QS regions using magnetograms taken by the Michelson Doppler Imager (MDI) on the Solar and Heliospheric Observatory for comparison. The authors found that a significant amount of signed magnetic flux (77% ± 14%) in the CH is stored in open field, while a short and low-lying closed-loop field is reported in both the CH and QS regions. These closed loops in the CHs may play an important role in producing the “switchbacks” in the solar wind (Fisk 2005), if the interchange reconnection between the coronal loop and open field results in magnetic flux transport. With new observations by the Parker Solar Probe, Fisk & Kasper (2020) suggested that open magnetic flux is transported by interchange reconnection, and that the accompanying spikes occur in all types of solar wind (e.g., slow solar wind, fast solar wind, Alfvénic slow solar wind near the CH boundary).

Small-scale magnetic cancellation is also ubiquitous in the photosphere outside CHs. It often occurs in the network field of granules, mesogranules, and supergranules with convergence of opposite polarities. The problem of chromospheric and coronal heating can be addressed by studying cancellations of magnetic flux and convection flows associated with small-scale jet-like ejections. For decades, the study of spicules has been a hot topic, and such small-scale jet-like ejections are characterized as short-lived eruptive plasma bounded at the network boundary of opposite magnetic polarities (for a review see, e.g., Tsioropoula et al. 2012). Wang (1998) proposed Ho macro-spicules as a manifestation of magnetic reconnection, likely caused by network–ephemeral region or network–IN interactions. With high-resolution observations from the Solar Optical Telescope of Hinode, de Pontieu et al. (2007) found two types of spicules: “Type-I” spicules that are driven by shock waves through global oscillation and convective flows leaked into the solar atmosphere on timescales of 3–7 minutes, and dynamic “Type-II” spicules that are formed through the magnetic
reconnection process in the vicinity of magnetic flux concentrations in plage and network.

Recent observations by the Interface Region Imaging Spectrograph found that the small-scale network jetlets propagate at speeds of 70 km s$^{-1}$ over average lifetimes of 3 minutes (Panesar et al. 2018). The authors speculated that such network jetlet eruptions are small-scale analogs of large-scale coronal jets. Using high-resolution H$\alpha$ and magnetic field observations by the Goode Solar Telescope (GST; Goode & Cao 2012) at Big Bear Solar Observatory (BBSO), Samanta et al. (2019) found close connections between the generation of fine-scale spicules and intersections of the underlying network field with the ambient weak field of opposite polarity, in forms of magnetic flux cancellation and emergence. Sterling et al. (2020) argued that the emergence episodes that initiate enhanced spicular activities might actually be preparing for magnetic cancellations. They proposed a microfilament eruption model of solar spicules, which is morphologically similar to erupting minifilaments that drive coronal jets. However, it is not fully understood whether the properties of the magnetic energy budget through small-scale magnetic flux evolution are universal or differ between QS and CH regions, or whether the heating of plasma through small-scale reconnection is sufficient for coronal heating.

In this study, we present statistical properties of magnetic cancellation events and investigate small-scale H$\alpha$ ejections associated with magnetic evolution around the boundary of a low-latitude CH on 2018 July 29. Data of the high-resolution observations are taken by BBSO/GST. The structure of the paper is organized as follows. We describe observation and data processing in Section 2. Magnetic properties of the CH and the surrounding QS regions and jet-like ejections associated with magnetic cancellations are presented in Section 3. We summarize and discuss key findings of the study in Section 4.

2. Data and Processing

On 2018 July 29, BBSO/GST observed the boundary section of a quiet-Sun CH located at (604° E, 125° S) on the solar disk with on-site post-focus instrumentation, including the Broadband Filter Imager (BFI), Visible Imaging Spectrometer (VIS), and Near-infrared Imaging Spectropolarimeter (NIRIS; Cao et al. 2012). Taking advantage of high-order correction by an adaptive optics system with 308 subapertures (Cao et al. 2010) and a reconstruction technique for solar speckle interferometric data (Wöger et al. 2008), the observation during ~16:34–18:38 UT achieved diffraction-limited resolution under a favorable seeing condition. There is a gap of ~20 minutes in observations with no data obtained between 17:07 and 17:27 UT due to a variation in seeing. The obtained data include images in a TiO filter (705.7 nm; 10 Å bandpass) by BFI with a field of view (FOV) of 77″ at 0′′1 resolution and 20 s cadence, Fabry-Perot spectroscopic observations of the H$\alpha$ line at ±1.0, ±0.8, ±0.6, ±0.4, ±0.2, and 0.0 Å (0.08 Å bandpass) by VIS with a 70″ circular FOV at 0′′1 resolution and 40 s cadence, and spectroscopic polarization measurement of the Fe I 1565 nm line (0.25 Å bandpass) by NIRIS with a round FOV of 80″ at 0′′24 resolution and 42 s cadence. Each burst takes 100 frames and 60 frames for speckle reconstruction of TiO and H$\alpha$ lines, respectively. The normal Stokes inversion did not work with NIRIS data due to the very weak polarization signal in the QS region. LOS magnetograms are reduced by performing an area integration of the Stokes V profile in wavelength using the weak-field approximation. A QS area of 16 × 16 pixels that is away from the magnetic network in the center of the FOV and has a minimal flux variation is selected for noise evaluation. For the data set of the GST observation, we evaluate the total noise of the magnetic field measurement by finding the FWHM of a Gaussian profile fitted to the field strength of the QS field. The noise consists of the instrument error of NIRIS in a typical QS region (4 G) and the effect of a variation in seeing, resulting in an FWHM of 10 G. EUV data at 171 and 193 Å from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the Solar Dynamic Observatory are used to identify the CH and any connection to chromospheric eruptions. The CH boundary is identified based on the intensity gradient of EUV filtergrams in the 193 Å channel with the CATCH catalog (Heinemann et al. 2019).

In this study, H$\alpha$ images and magnetograms by GST are aligned to subpixel precision by matching the chromospheric network. NIRIS magnetograms are validated with LOS magnetic field measurements provided by the Helioseismic Magnetic Imager (HMI; Schou et al. 2012). The results show a correlation coefficient of 0.98 in strong field areas and an overall correlation coefficient of 0.72. The latter number reflects that NIRIS detects many smaller magnetic elements that are absent from HMI data. To identify on-disk spicules, H$\alpha$ intensity images at ±0.8 Å are used to calculate two-dimensional pseudo-Doppler maps, in which the upward moving chromospheric materials are represented as bright strands. The evolution of small-scale magnetic elements is tracked with the Southwest Automatic Magnetic Identification Suite (SWAMIS; DeForest et al. 2007), by which magnetic cancellation events are detected and their corresponding magnetic fluxes are calculated. The applied tracking technique sets 2σ and 6σ of measured noise as lower and upper thresholds respectively for magnetic element detection. Each magnetic element is identified by finding local maxima and tracking their evolution, in which 6σ is set in a search for new elements while 2σ is applied to expand the boundary of previously detected elements. Only detected elements that survive more than three frames after being associated in consecutive frames are taken into account. Thus the minimum lifetime is 126 s. In SWAMIS, we set 3 × 3 pixels (~0.06 arcsec$^2$) as the minimum area of magnetic field elements for detection. Validation of the minimal magnetic flux elements (~3.3 × 10$^{15}$ Mx) detected by the tracking method is performed by visual inspection of a sample of randomly selected magnetic flux evolution events. Artifacts in the original data set make up 14% of the tracking results, which have either flux or lifetime lower than the preset limit, or both. Such artifacts are removed in results and analysis. Magnetic flux is calculated by integrating the measured flux density over the areas of detected magnetic elements. The uncertainty of magnetic flux measurement is estimated by calculating the unsigned flux density in a region away from strong network magnetic fields and then multiplying it by the measured element size of converging magnetic polarities.

3. Results

With the ~90 minutes of high-resolution data taken by GST observations near the targeted CH, we have observed small-scale magnetic field evolution and H$\alpha$ ejections. With magnetic fields of mixed polarities filling the IN around CH boundary
networks, chromospheric spicules are observed to actively evolve with time. The FOV of GST observations is centered on the southeast edge of the CH. This CH is in its end phase of boundary growth. The time lapse of magnetic evolution in the following results is with respect to the start time (16:34:18 UT) of GST observation.

Figure 1 shows the magnetic field, EUV image, and corresponding Hα blue-wing images at 16:46:44 UT. Hα spicular activities can be seen in Figures 1(a), (c), and (d), and are mostly anchored at boundaries of the magnetic network. Plume-like features are also observed outside the CH near the southeastern corner of the FOV from ~17:00 UT to 17:40 UT. In Figure 1(b) the purple contour defines the CH boundary using the 193 Å image, with small EUV bright loops lying along the CH boundary. The CH is located northwest of the CH boundary, which is shown in Figure 1(e). The CH boundary region is dominated by negative magnetic field with an averaged flux density (defined as total flux divided by area of magnetic element) of 220 G, which is about twice the strength of the positive field. The total flux is $3.6 \times 10^{21}$ Mx in the positive magnetic elements and $6.3 \times 10^{21}$ Mx in the negative magnetic elements. Magnetic elements of positive and negative polarities are labeled as blue and red features in Figure 1(c). 1434 cancellation events are identified in the total of 33,580 episodes of magnetic evolution, including emergence, cancellation, appearance, and disappearance of magnetic elements.

### 3.1. Magnetic Cancellations at the CH Boundary

Figure 2(a) shows the sites of cancellation events (marked as green symbols) in the entire FOV. The midpoint between closest points on the edges of two adjacent magnetic features of opposite polarity is identified as the cancellation site, which is also on the path travelled by the canceling elements. The cancellation sites are also marked in Figures 2(b) and (c). It is noticeable that cancellation is more probable in the weak field region than in the concentrated negative unipolar field at the CH boundary. There are 767 magnetic flux cancellation events inside the CH, 619 in the QS outside the CH, and 48 in the CH boundary region (defined here as the belt region between the gray lines). The highest occurrence rate of flux cancellations is $1.5 \text{ Mm}^{-2} \text{ hr}^{-1}$ inside the CH, and the occurrence rate is 1.2 and $0.5 \text{ Mm}^{-2} \text{ hr}^{-1}$ at the QS and CH boundaries, respectively. At the CH boundary, the yellow and purple symbols in Figures 2(b) and (c) show locations of cancellation events that are associated with strong eruption-like events in Hα (see Figures 3 and 4). Details of the two events located in the CH (Figure 2(b)) and at the CH boundary (Figure 2(c)) are discussed in Section 3.2.

Figure 5 shows properties of magnetic elements in the CH boundary region. We define a proxy of magnetic energy as

$$E = \frac{1}{8 \pi} \int_0^L \int_A B^2 \, dA \, dl,$$

where $L$ represents photospheric density scale height derived by Sturrock et al. (1999) using a correction factor in range 1–2. The correction factor is used in estimating the height of a small range of an approximately vertical flux tube. $L$ implemented in the results has an estimated constant value of 100 km, which is a good proxy to describe to the rapid change in flux density and magnetic energy (Liu et al. 2016). All calculations are at the lower limit with the above implementation of $L$. The negative unipolar magnetic cluster along the CH boundary contains $(1.2 \pm 0.4) \times 10^{29}$ erg of magnetic energy $E$. The above magnetic energy makes up 63% of the total energy in the CH.
boundary region. Figure 5(a) shows the change in magnetic field at the CH boundary, in which the blue curve represents the total magnetic energy. The magenta curve represents the total magnetic energy stored in the elements that experience flux cancellations, and the red curve shows the cumulative magnetic energy released through flux cancellations. Figures 6(a) and 7(a) show the magnetic properties similar to Figure 5(a) but inside and outside the CH regions. The energy released by magnetic flux cancellation over the period of 90 minutes is in total $9.9 \times 10^{27}$ erg (red curve), with a corresponding energy release rate of $5.3 \, \text{erg cm}^{-3} \, \text{s}^{-1}$. This is comparable with the energy release rate of IN flux cancellations ($\sim 4.7 \, \text{erg cm}^{-3} \, \text{s}^{-1}$; Gošić et al. 2018). The main statistical results of the magnetic properties around the coronal hole boundary are summarized in Table 1. As shown in Figure 5(b), the net flux of the cancellation events increases in the negative polarity. The average net flux, which is calculated from the canceling magnetic elements detected by SWAMIS, changes from $1.6 \times 10^{16}$ Mx at beginning of the cancellations (blue bar) to $-3.0 \times 10^{16}$ Mx at end (yellow bar). The change in measured net flux in the selected region is due to flux concentration and dispersion of the detected magnetic elements, which results in some concentrated magnetic elements rising above detection and some dispersed magnetic elements falling below detection. The effect of a sensitivity limit of flux measurements and the accuracy of the feature tracking technique are not taken into account in the calculation so that net flux is not conserved in the process of cancellation. Similarly, such variance of net flux is observed inside and outside the CH. The size distribution of detected canceling magnetic elements is shown in Figure 5(c). The lower limit of flux element size is 0.03 Mm$^2$, which is set by the parameter of magnetic feature size in the SWAMIS method. It is seen that 97.7% of the canceling magnetic elements have a size of less than 3.0 Mm$^2$. The mean size of the magnetic flux elements is $0.73 \pm 0.03$ Mm$^2$ after cancellations, which is 0.8 Mm$^2$ smaller in area as than before cancellation. The lifetime of the magnetic elements has a low threshold of 126 s as limited by the SWAMIS tracking technique. Figure 5(d) shows that 43% of flux cancellations have a lifetime of less than 6.5 minutes, with a mean value of 3.7 minutes. As a result, the averaged magnetic flux cancellation rate is $1.02 \times 10^{18}$ Mx Mm$^{-2}$ hr$^{-1}$.

### 3.2. Magnetic Cancellations inside and outside the CH

Magnetic flux emergence and cancellation in the CH are related to the CH’s decay and growth. The AIA 193 Å observation shows that the CH experiences a growth in area from 2018 July 28 10:00 UT to 2018 July 29 16:00 UT. During the GST observation period under study (from 2018 July 29 16:34:18 to 18:04:54 UT), the boundary of the CH remains stationary. We divide the FOV of GST observations into the CH region and the exterior QS region, and study their magnetic field properties and evolution separately.

Figure 8(a) shows the magnetogram averaged over 90 minutes in the CH. The average flux densities of positive and negative magnetic elements within the CH are 80 G and $-130$ G, respectively. The strong negative flux concentrations close to the curved edge are labeled as part of the unipolar cluster at the CH boundary in SWAMIS tracking results. The
positive polarity of magnetic elements dominates the CH away from the negative network field, and most events centralize in the positive field region at 17:15 UT. Hα images in Figures 1(a) and (d) show that flux cancellations are often not associated with enhanced spicular activities except in the network field that was previously observed by Samanta et al. (2019). Figure 6(a) shows time profiles of photospheric magnetic energy evolution. The corresponding magnetic energy release rate is 15.7 erg cm⁻³ s⁻¹, which is ~2 times larger than that at the CH boundary. Figure 6(b) shows the distribution of net flux at the beginning (blue bar) and end (yellow bar) of magnetic flux cancellations. It shows a tendency of enhancement in negative polarity after cancellations. The average net flux changes from 4.6 × 10¹⁶ Mx before flux cancellations to −2.2 × 10¹⁷ Mx afterwards. The size distribution of canceling magnetic elements is shown in Figure 6(c). The mean size is 0.53 Mm² (0.39 Mm²) before (after) flux cancellations. As shown in Figure 6(d), 32.5% of the cancellation flux elements have a lifetime shorter than 8 minutes, and the average lifetime is 4.7 minutes. The flux cancellation rate in the CH is 2.0 × 10¹⁸ Mx Mm⁻² hr⁻¹.

Figure 8(b) shows the average magnetogram in the QS region outside the CH. The studied region excludes an area of ~100 Mm² outside the CH centered at about [53°, 20°] (see Figure 2(a)), because magnetic evolution in this area is not fully covered by NIRIS magnetograms. The average longitudinal flux densities of positive and negative magnetic elements in the QS region are 65 G and −160 G, respectively. The artificial dark lines in the lower left corner are due to rotation and shift of the GST’s pointing. Enhanced spicular activities are observed to be anchored at the edges of strong negative flux concentrations. Figure 7(a) shows that the photospheric magnetic field changes. The total magnetic energy increases by 1.9 × 10²⁹ erg in ~20 minutes from +22 minutes of the observation, which is followed by 30 minutes of magnetic energy dissipation (blue curve). The energy is released through small-scale magnetic flux cancellations at a rate of 8.2 × 10²⁶ erg Mm⁻³ hr⁻¹ (red curve).
Figure 7(b) shows the distribution of net flux before (blue bars) and after (yellow bars) the occurrence of magnetic flux cancellation events. The numbers of positive and negative magnetic elements remain the same after flux cancellations become balanced, whereas the average net flux changes from $7.8 \times 10^{16} \text{ Mx}$ to $-1.0 \times 10^{17} \text{ Mx}$. The size distribution of canceling magnetic elements in this region is similar to that in the CH. The mean size is 0.45 Mm$^2$ after cancellations but 0.82 Mm$^2$ at the beginning. Figure 7(d) shows that $\sim 97\%$ of cancellation events occur in 8 minutes. The average lifetime of cancellation events is 4.5 minutes. The flux cancellation rate in the QS region is $8.8 \times 10^{17} \text{ Mx Mm}^{-2} \text{ hr}^{-1}$. To calculate the small-scale energy release rate per unit area, we only consider magnetic elements with flux under $\sim 10^{19} \text{ Mx}$, which excludes the network field along the CH boundary and elements below the noise level ($3 \times 10^{15} \text{ Mx}$). The energy release rate due to cancellation is $3.7 \text{ erg cm}^{-3} \text{ s}^{-1}$.

In summary, the canceled magnetic flux in the CH and in the QS (outside the CH) is $5.4 \times 10^{20} \text{ Mx}$ and $2.1 \times 10^{20} \text{ Mx}$, respectively. The sizes considered in those areas are similar. However, 19.5% of the cancellation events start with the emergence of magnetic flux of opposite polarities, which contributes to the increase in net flux. In addition, flux emergence inside the CH has an occurrence rate comparable to that of cancellation events. The net flux of negative polarity increases by $9.7 \times 10^{19} \text{ Mx}$ in 30 minutes.

### 3.3. H$\alpha$ Larger Eruption Events Associated with Magnetic Cancellations at the Boundary of the CH

H$\alpha$ spicules in the observation are mainly located at the CH boundary, where there is the unipolar negative magnetic cluster. We observe recurrent spicular activities that seemingly stem from this negative magnetic network as shown in Figure 1. The spicules observed in Doppler signals are mostly rooted at the edges of the strong negative magnetic concentrations with weak ambient positive fields. Previous studies found a close connection between spicules and opposite-polarity magnetic fluxes. (Yurchyshyn et al. 2013; Samanta et al. 2019). We use Doppler signals from H$\alpha \pm 1.0$ Å images to locate eruptive spicules, in which positive values of Doppler signals indicate H$\alpha$ upflows. During the phase of magnetic flux emergence, small brightening loops are observed at the CH boundary, which indicates chromospheric heating due to magnetic reconnection. In this section we present details of magnetic evolution associated with jetlet eruptions and spicular activities.

Figures 3(a) and (b) show H$\alpha$ eruptions in event 1 at the western footpoints of EUV brightening loops along the CH boundary. At 16:42:33 UT, two strands of H$\alpha$ spicules rooted between the opposite polarities, which later erupt in opposite directions, are observed to be cospatial with the brightening. Both spicules are elongated across the adjacent opposite polarities. About 1.4 minutes later, arched H$\alpha$ dark material (indicated by a yellow arrow) is formed between the roots of the two spicules, with a faint spire (indicated by a red arrow) extending southwest. This resembles CH jets depicted by...
Panesar et al. (2018), except that the present events are on a much smaller scale. At the same time, both of the preexisting spicules pointing in opposite directions experience eruptions sequentially from north to south. As seen in Figure 3(c), the photospheric magnetograms show positive magnetic elements surrounded by the semicircular negative network field where the spicules are rooted. A small segment of a negative magnetic element separates from the network field and converges with the positive magnetic element. Figure 9 shows the evolution of the average positive (negative) magnetic flux of the converging elements as the blue (red) curve. The black and red vertical dashed lines mark the times of formation of the arched Hα dark feature and the onset of the Hα eruptions, respectively. The time profiles show that the positive magnetic flux enhances until the onset of the eruption of the north-pointing spicule, then decreases from (3.9 ± 0.5) × 10^{18} Mx to (2.5 ± 0.4) × 10^{18} Mx in ∼3.4 minutes. The rapid decrease in negative flux occurs 2 minutes before the decrease in positive flux and is cotemporal with the formation of arched Hα dark material. The AIA images at 171 Å in Figure 3(d) show that EUV brightenings appear at the edge of the negative magnetic polarity (centered at (5″, 2″/5′)) when the two spicules become noticeable. Then the brightenings associated with eruptions evolve roughly northward along the spicules. The transverse speed is ∼18 km s^{-1}. The chromospheric counterparts of the magnetic reconnection are seen to continue moving northward, and later a small loop brightening is observed at 16:51:41 UT.

Figure 4 shows the magnetic evolution and Hα activities at the east footpoint of the small EUV loop. As seen in Hα images (Figure 4(a)), there are multiple strands of recurrent spicules rooted at the Hα bright points, which correspond to network edges in magnetograms (see Figure 4(b)). At 16:45:21 UT, the enhanced positive magnetic element starts to merge with the strong negative network field, which is cotemporal with Hα eruptions in event 1. At 17:08:04 UT, enhanced spicular activities are observed to accompany the magnetic cancellation of opposite polarities. Such enhancement of Hα spicules is similar to the spicular activity observed by Samanta et al. (2019). AIA images in Figure 4(c) show an EUV brightening at the roots of the enhanced spicules. However, no EUV response is observed along the spicular spires.

3.4. Occurrence Rate of Flux Cancellation and Spicules inside the CH and in the QS Region

In the relatively weak field regions either inside or outside the CH, less magnetic flux evolution of the cancellation events (including event 1) is associated with Hα eruptions than at the CH boundary. In event 1, the Hα eruption is triggered by magnetic flux cancellation while both the positive and negative...
fluxes continue to emerge. The arched dark feature formed in Hα images is likely due to magnetic reconnection between two bipolar patches. We interpret the scenario as follows. When the negative field of the north-pointing spicule merges with the positive field of the south-pointing spicule, the two magnetic flux tubes reconnect at the location of merging opposite polarities and the plasma is temporarily trapped in the newly formed field. Then the microfilament erupts in a manner suggested by Sterling & Moore (2016). The loop brightening in EUV images (AIA 171 and 193 Å) becomes visible ∼4 minutes after the microfilament eruption, and continues to enhance with flux emergence at the loop footpoints. Such base brightenings of EUV associated with magnetic reconnection are rare in observations, with only seven of 88 enhanced spicules accompanied by detectable bright loops in AIA 171 Å. The occurrence rates of magnetic flux cancellation events inside and outside the CH are comparable, while fewer eruptive Hα spicules (six spicule enhancements) are observed inside the CH than outside it (15 spicule enhancements). This could be due to the fact that the vertical field topology in the chromosphere makes the Hα spicule in the CH less observable: the material moves in the line-of-sight direction. It is noticeable that the more enhanced Hα spicules (61 of 88) are rooted close to the network field cluster.

3.5. Energetics

In the total of 88 enhanced spicules observed in the FOV, there are three events originating from the unipolar magnetic elements that do not show magnetic cancellation. Other spicule events exhibit close temporal and spatial correlation with flux cancellation between their underlying magnetic elements and adjacent magnetic elements of opposite polarity. However, the magnetic cancellation detected by SWAMIS demonstrates ubiquitous characteristics of the small-scale reconnection, which has an exceedingly high occurrence rate (3127 events in ∼90 minutes). Therefore, more cancellations do not have associated spicules. The total magnetic energy released through magnetic cancellation in the FOV is $3.3 \times 10^{29}$ erg, of which $2.6 \times 10^{29}$ erg and $0.7 \times 10^{29}$ erg correspond to the events inside the CH and outside the CH, respectively. The energy release rate in the CH ($15.7 \text{ erg cm}^{-2} \text{s}^{-1}$) is four times as high as that in the QS ($3.7 \text{ erg cm}^{-2} \text{s}^{-1}$) region through cancellation. The results are in agreement with the energy release rate reported in the previous study of IN flux cancellations (∼4.7 erg cm$^{-3}$ s$^{-1}$; Gošić et al. 2018), which is regarded as sufficient for local chromospheric heating. The global energy release rate required for coronal heating is $(0.1–2) \times 10^{7} \text{ erg cm}^{-2} \text{s}^{-1}$ in the QS and $(0.5–1) \times 10^{7} \text{ erg cm}^{-2} \text{s}^{-1}$ in the CH (Aschwanden 2001). Based on the heating power requirement given by Aschwanden (2001), even the energy release of the individual cancellation events in the QS, which yields $\sim 3.7 \times 10^{7}$ erg cm$^{-2}$ s$^{-1}$ along
the photospheric column depths, provides sufficient energy to locally heat the corona. The average energy release rate of magnetic cancellations during the observation period is 0.5 erg cm\(^{-3}\) s\(^{-1}\) in the CH and is 0.1 erg cm\(^{-3}\) s\(^{-1}\) in the QS region. The global radiative loss of energy is at a rate of 0.1 erg cm\(^{-3}\) s\(^{-1}\) (Vernazza et al. 1981). Therefore, the energy release of magnetic cancellation in the QS region balances out the radiative loss when the lower correction factor of the density scale height is applied. With a higher correction factor (e.g., 2) applied there is extra energy through magnetic cancellation to further heat the corona. On the other hand, free energy budgeted in a coronal hole is \(\sim 4\) times higher than the heating power required to maintain the temperature in the chromosphere from radiative loss. Such excess free energy is sufficient in coronal heating and solar wind acceleration. Other mechanisms such as dissipation of waves would also play a significant role in the heating. In EUV observations, hot plasma is seen to be ejected to the upper atmosphere with enhancement of spicules. Seven events are associated with EUV brightening (as seen in AIA 171 Å) at the base of the enhanced spicules. In particular, with the dim background of AIA 171 Å in the CH, a faint spire becomes visible extending from the bright base in event 1 about 3 minutes after the spicule eruption. In one event, we see clear evidence of jet-like features combining with microfilament eruption, agreeing with the model of Sterling et al. (2020), in which small strands of chromospheric material embedded between opposite magnetic elements go through jet-like eruption without base brightening.

![Graph](image)

**Figure 7.** Same as Figure 5 but for the QS region outside the CH. The red (black) line-filled bars in panels (b) and (c) represent histograms of corresponding properties before (after) cancellation events.

| Regions          | Number of Cancellations (1) | Occurrence Rate (Mm\(^{-3}\) hr\(^{-1}\)) (2) | Energy Release (erg cm\(^{-3}\) s\(^{-1}\)) (4) | Area (Mm\(^{2}\)) (5) | Lifetime (minutes) (6) | Flux Rate (Mx Mm\(^{-3}\) hr\(^{-1}\)) (7) |
|------------------|-----------------------------|-----------------------------------------------|-----------------------------------------------|------------------------|------------------------|-----------------------------------------------|
| CH               | 1245                        | 1.5                                           | 15.7                                          | 0.53                   | 4.7                    | \(2.0 \times 10^{16}\)                        |
| CH boundary      | 222                         | 0.5                                           | 5.3                                           | 0.73                   | 3.7                    | \(1.2 \times 10^{16}\)                        |
| Outside CH (QS)  | 1589                        | 1.2                                           | 3.7                                           | 0.82                   | 4.5                    | \(8.8 \times 10^{17}\)                        |

**Table 1.** Magnetic Properties of the Cancellation Events

Note. The table lists magnetic properties of flux cancellation around the coronal hole. The total number of cancellations and the occurrence rate are listed in columns (2) and (3). The average energy release rate, maximum area of canceled elements, lifetime from flux maximum to minimum, and flux cancellation rate are listed in columns (4)–(7), respectively.
4. Conclusions

We have investigated small-scale magnetic transients using high-resolution GST observations near a CH boundary. Use of the automatic magnetic feature tracking method (SWAMIS) in the magnetic field analysis enabled us to determine statistical properties of the small-scale flux cancellations inside and outside the CH, as well as the association of Hα spicules with underlying magnetic evolution. The main results in this work are summarized as follows.

1. Inside the CH, small-scale magnetic cancellation frequently occurs. The net decrease in the vertical component of magnetic flux is of the order of $10^{18} \text{ Mx Mm}^{-2} \text{ hr}^{-1}$, which is comparable to that in the QS intranetwork. The energy release of cancellation at the CH boundary has the same rate as in the QS intranetwork.

2. Despite comparable occurrence rates in the CH ($1.5 \text{ Mm}^{-2} \text{ hr}^{-1}$) and in the surrounding QS region ($1.2 \text{ Mm}^{-2} \text{ hr}^{-1}$) in similar analyzed areas, the energy released through small-scale magnetic flux cancellations in the CH is $2.6 \times 10^{29} \text{ erg}$, which is $\sim 4$ times as high as outside the CH ($0.7 \times 10^{29} \text{ erg}$).

3. The energy release rate of cancellation is above the global radiative loss rate in the CH, while it is equivalent to it in the QS region. Free energy from the photospheric cancellation provides a sufficient amount to coronal heating. The free energy budget in the coronal hole is not only sufficient for coronal heating but also capable of accelerating solar wind.

4. The EUV spicules (visible in AIA 171 Å) are found in seven out of 88 Hα spicules. They have a close connection with the small-scale reconnection and associated brightening in the base of the eruptions. The direction of the ejecta is the same as that of Hα spicules.

5. 61 of 88 enhanced spicules are rooted near the network field cluster. Interactions between network and IN fields are closely associated with the spicule/jet-like eruptions.

The accuracy of these results is subject to the sensitivity of the magnetograms, i.e., the minimum detectable flux ($3 \times 10^{15} \text{ Mx}$) due to the spatial resolution limit and the noise in the magnetograms. Comparing with radiative loss in the chromosphere ($\sim 0.1 \text{ erg cm}^{-3} \text{ s}^{-1}$, Vernazza et al. 1981), energy release via cancellation in the CH has an energy excess, while in the QS the energy release of cancellation barely compensates for the radiative loss. This result suggests that the energy dissipation in the CH is sufficient to support coronal heating and solar wind via the small-scale magnetic...
Outside the CH, other mechanisms such as wave dissipation would play a significant role in heating the corona.

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