Critical Magnetic Field Strengths for Unipolar Solar Coronal Plumes In Quiet Regions and Coronal Holes?

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Abstract

Coronal plumes are bright *magnetic funnels* that are found in quiet regions and coronal holes that extend high into the solar corona whose lifetimes can last from hours to days. The heating processes that make plumes bright involve the magnetic field at the base of the plume, but their intricacies remain mysterious. Raouafi et al. (2014) infer from observation that plume heating is a consequence of magnetic reconnection at the base, whereas Wang et al. (2016) infer that plume heating is a result of convergence of the magnetic flux at the plume's base, or base flux. Both papers suggest that the base flux in their plumes is of mixed polarity, but do not quantitatively measure the base flux or consider whether a critical magnetic field strength is required for plume production. To investigate the magnetic origins of plume heating, we track plume luminosity in the 171 Å wavelength as well as the abundance and strength of the base flux over the lifetimes of six unipolar coronal plumes. Of these, three are in coronal holes and three are in quiet regions. For this sample, we find that plume heating is triggered when convergence of the base flux surpasses a field strength of ~300 – 500 Gauss, and that the luminosity of both quiet region and coronal hole plumes respond similarly to the strength of the magnetic field in the base.

Introduction

Coronal plumes are bright, sporadic, fountain-like structures in the solar corona whose lifetimes range from a few hours to several days (Raouafi et al. 2014). Each is a magnetic funnel rooted in a strong patch of dominant-polarity magnetic flux surrounded by a predominantly-unipolar magnetic field, as shown in Figure 1. This funnel is located in either a quiet region or a coronal hole. They are best observed in 171 Å Fe IX emission, but can also be observed in 193 Å Fe XII emission. Multiple observations have been presented regarding how plumes form and disappear, but the processes which govern plume evolution still remain mysterious. To further investigate plume evolution, we track plume luminosity and base magnetic flux over the lifetimes of six coronal plumes.
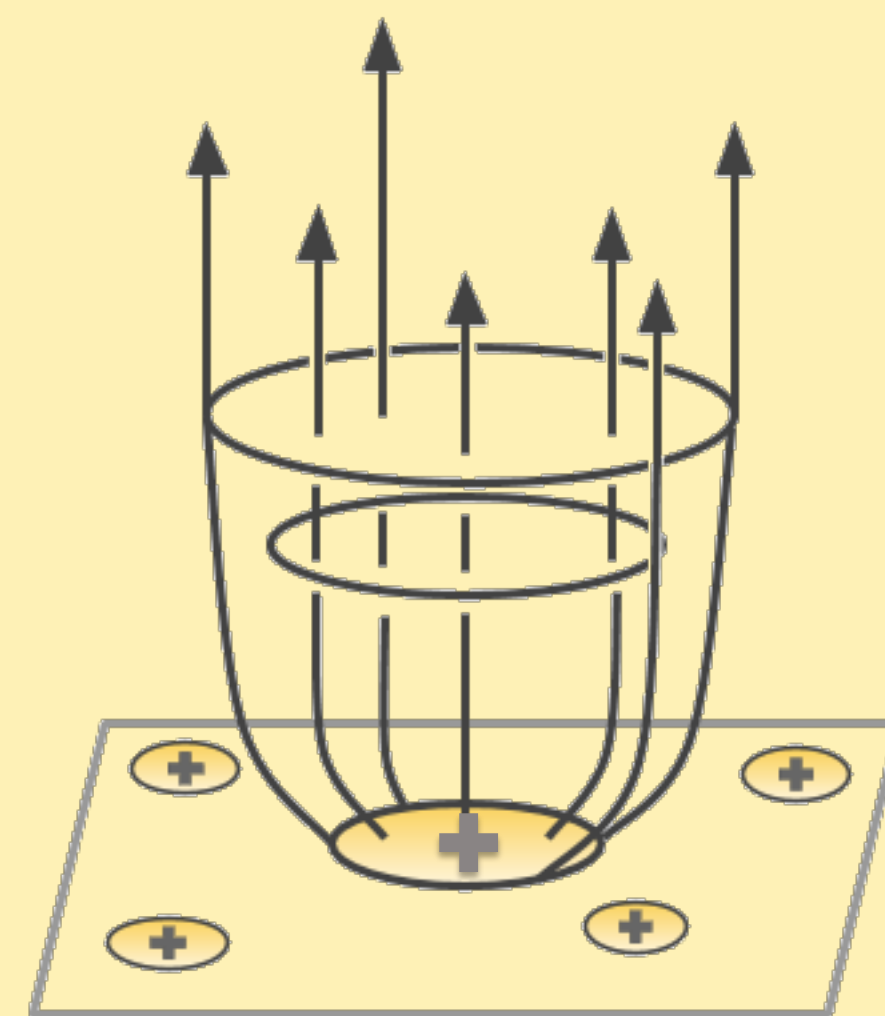

Figure 1: Diagram showing the structure of a positive-polarity coronal plume. The large patch at the base of the plume represents the base flux, while the smaller patches represent the external magnetic field.

Methods

To perform our measurements, we used Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA) extreme ultraviolet (EUV) images and SDO/Helioseismic and Magnetic Imager (HMI) line-of-sight magnetograms. SDO AIA provides high-resolution full-disk images in seven EUV wavelengths with a spatial resolution of 1.5 arcsec (Lemen et al. 2012), and HMI provides full-disk magnetograms with a spatial resolution of 0.5 arcsec per pixel (Scherrer et al. 2012). We selected six isolated unipolar plumes using JHelioviewer software (Mueller et al. 2017). AIA 171 Å channel, which detects plasma at temperatures at around 600,000 K, was used to find plumes, whereas AIA 211 Å channel, which detects plasma at temperatures around 2,000,000 K, was used to confirm each plume was located in a quiet region or a coronal hole. AIA 211 Å images of two plumes, one in a coronal hole and one in a quiet region, are shown in Figure 2. AIA 171 Å data and HMI magnetogram data were then acquired using the Joint Science Operations Center (JSOC), and downloaded at a three minute cadence over the lifetime of each plume. Data was derotated, normalized by exposure time, and converted into maps using routines in SolarSoft IDL. These maps were then imported into python to take all measurements including luminosity in 171 Å and base flux over each plume's lifetime.
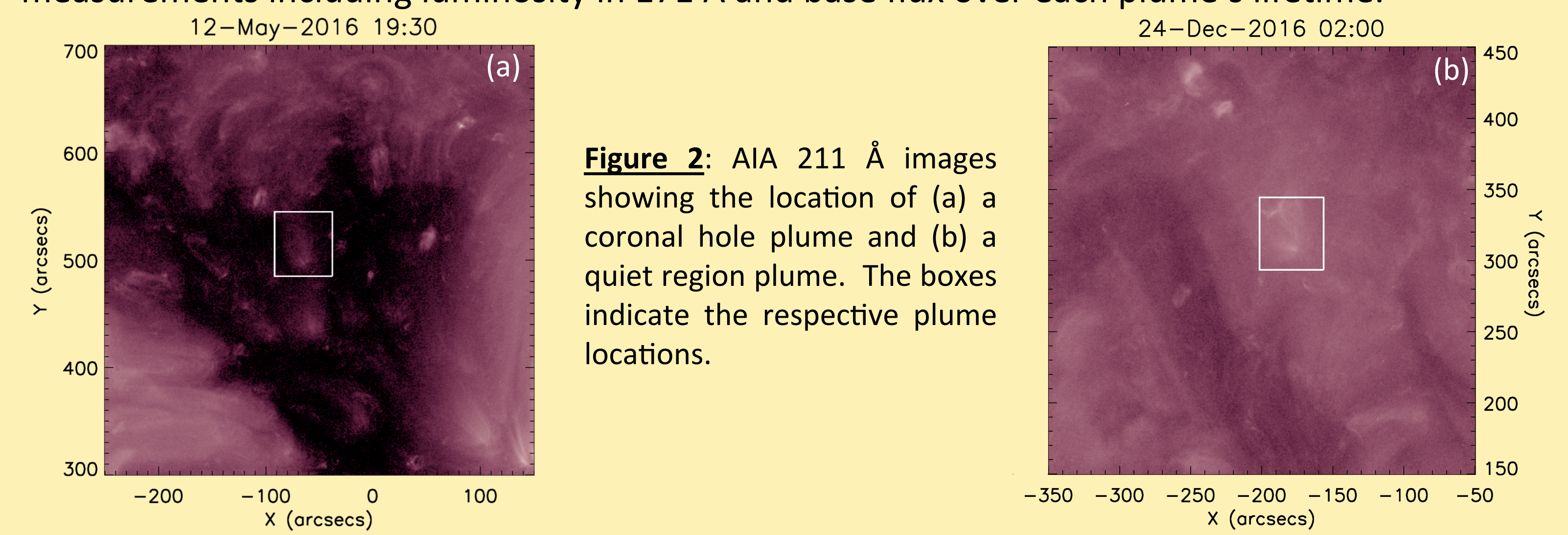

Figure 2: AIA 211 Å images showing the location of (a) a coronal hole plume and (b) a quiet region plume. The boxes indicate the respective plume locations.

Results

In order to find the critical magnetic field strength for each plume, we select potential minimum pixel values, or thresholds, for computing magnetic flux, and only measure the pixels above each threshold. We then use those thresholds to compare the profile of the measured base flux through that plume's lifetime to the profile of the luminosity in 171 Å and find which threshold field strength generates the flux plot that most closely correlates to the luminosity plot. The critical magnetic field strength for each plume is the threshold value of the best-fitting flux plot for that plume. We compare critical magnetic field strengths and peak luminosities for plumes in quiet regions and coronal holes to look for any differences in behavior for plumes in the two regions. To present these results, we give two examples, one plume in a coronal hole and one plume in a quiet region. Figures 3 and 4 show the evolution of the coronal hole plume and the quiet region plume, respectively, in both AIA 171 Å images and HMI magnetograms. The images and magnetograms show that the formation/disappearance of each plume in 171 Å images coincides with base flux convergence/divergence in the magnetograms. Flux measurements of the coronal hole plume over its lifetime yield a best-fitting flux plot with a critical magnetic field strength of 300 Gauss (Figure 5), while the quiet region plume yields a critical magnetic field strength of 500 Gauss (Figure 6). Critical field strengths for all six plumes can be found in Table 1.
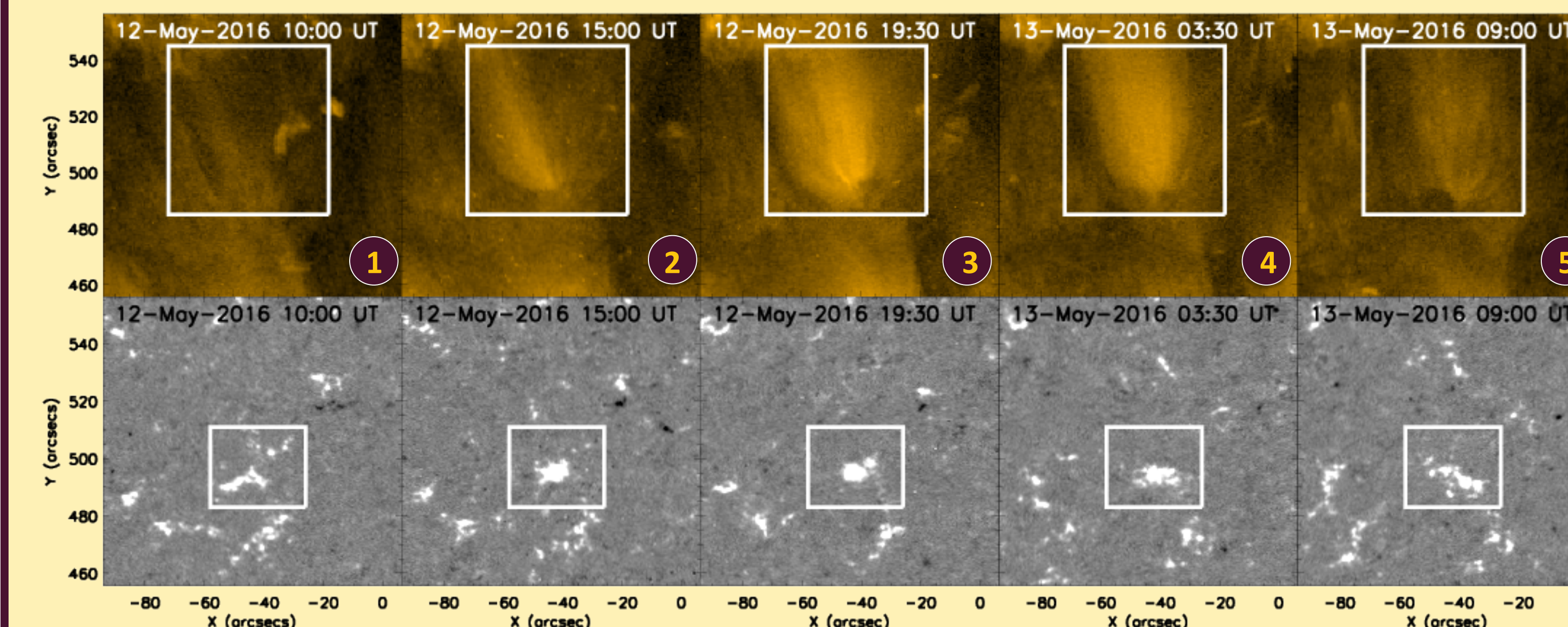

Figure 3: Evolution of a coronal hole plume shown in AIA 171 Å and HMI magnetogram snapshots. The circled numbers on the snapshots mark the times of the corresponding images/magnetograms on the plots in Figure 5. The boxes on the snapshots are the regions used to make measurements of luminosity in AIA 171 Å and flux.
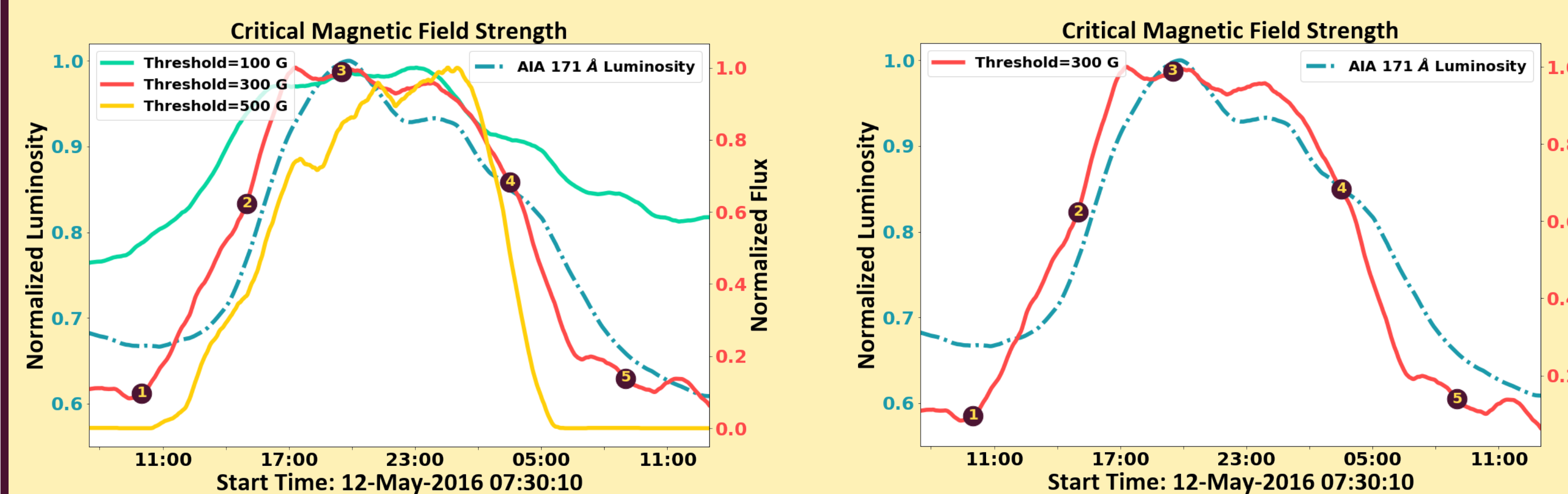

Figure 4: Evolution of a quiet region plume shown in AIA 171 Å and HMI magnetogram snapshots. The numbers on the snapshots mark the times of the corresponding images/magnetograms on the plots in Figure 6. The boxes on the snapshots are the regions used to make measurements of luminosity in AIA 171 Å and flux.

Figure 5: Plots used to choose the critical magnetic field strength for the formation of a coronal hole plume. Flux and luminosity are both normalized to easily compare profiles. We find that a threshold of 300 Gauss produces the best fitting curve for this plume. For reference, we show flux plots with thresholds of 100 Gauss and 500 Gauss, which produce poorer fits (left), and show the best fitting plot alone (right).
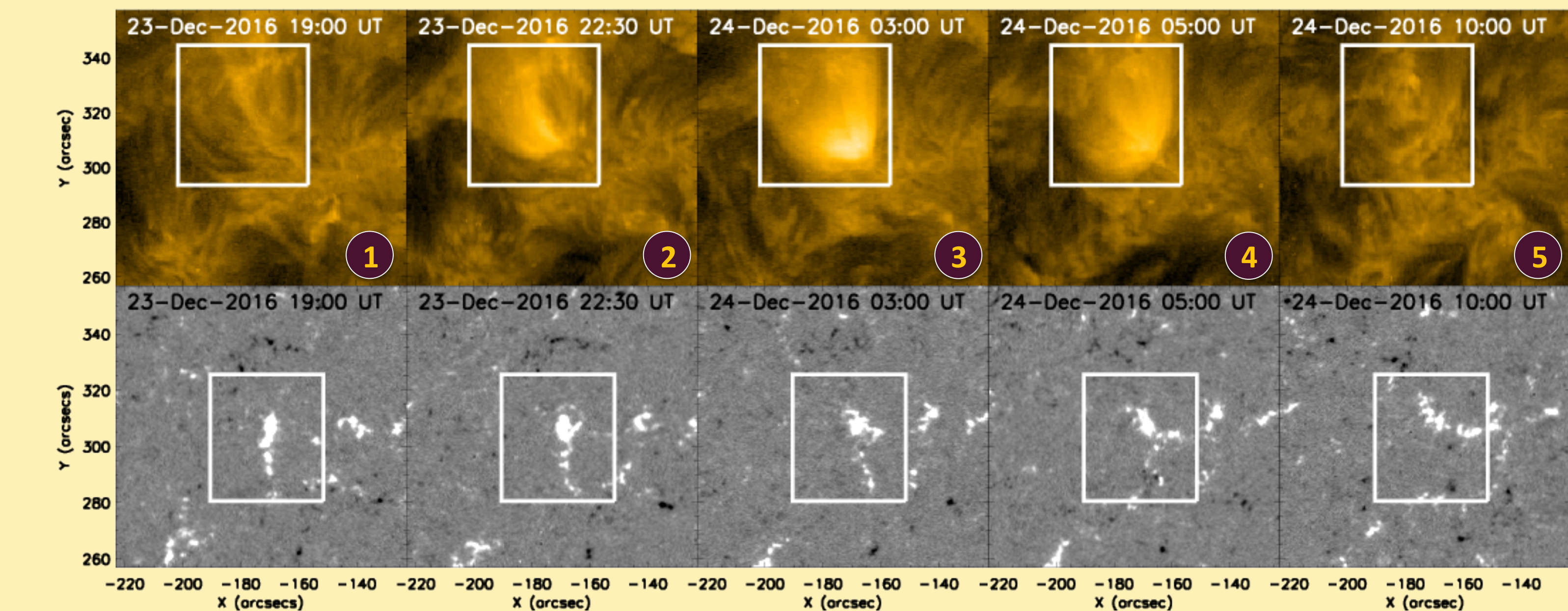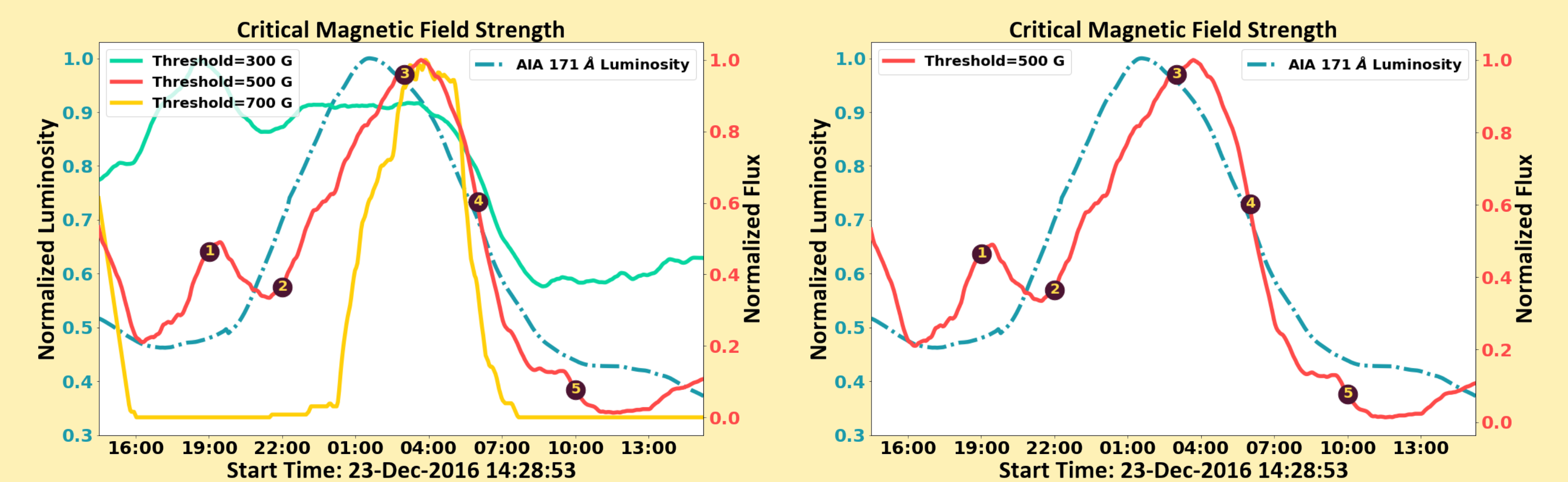

Figure 6: Plots used to choose the critical magnetic field strength for the formation of a quiet region plume. Flux and luminosity are both normalized to easily compare profiles. We find that a threshold of 500 Gauss produces the best fitting curve for this plume. For reference, we show flux plots with thresholds of 300 Gauss and 700 Gauss, which produce poorer fits (left), and show the best fitting plot alone (right).

Location, Polarity	Peak Location (arcsec)	Start Time	Duration (hours)	Critical B Field Strength	Peak Luminosity (DN/s)	Peak Flux (Maxwell)
Coronal Hole, +	(43, 258)	5-Jul-2011 18:30	25.5	400 G	2.3×10^6	5.4×10^{19}
Coronal Hole, -	(-302,223)	5-Oct-2013 15:00	16	300 G	6.2×10^5	3.4×10^{19}
Coronal Hole, +	(-64,496)	12-May-2016 12:30	19.5	300 G	7.2×10^5	3.2×10^{19}
Quiet Region, -	(185,-391)	4-Dec-2015 07:00	14.5	300 G	1.7×10^6	2.5×10^{19}
Quiet Region, +	(-178,302)	23-Dec-2016 20:00	14	500 G	1.2×10^6	1.4×10^{19}
Quiet Region, -	(305,236)	12-May-2017 13:00	13	300 G	1.6×10^6	1.5×10^{19}

Table 1: Location, duration, critical magnetic field strength, peak luminosity, and peak value of the above-threshold flux for all six plumes. We can see that there is no significant difference between coronal hole plumes and quiet region plumes with respect to the response of the luminosity in the corona to the behavior of the magnetic field at the base.

Conclusions

Based on AIA and HMI observations of a sample of six unipolar plumes, we find that plume formation requires enough convergence of magnetic flux at the plume's base to surpass a base line-of-sight magnetic field strength of approximately 300 – 500 Gauss. Dimming and disappearance of plumes can be directly linked to flux divergence. We also find that plumes in quiet regions and coronal holes have similar durations and have similar peak luminosities. We find, through random sampling of plumes, that plumes with obvious mixed polarity are rare. Our observations suggest that the EUV visibility of apparently-unipolar coronal plumes depends on the amount and strength of magnetic field at their base for plumes of a single polarity, however we cannot rule out the possibility that there is hidden mixed polarity unresolved by HMI. Future generation solar telescopes e.g., DKIST and Solar-C, and advanced MHD simulations, should clarify this issue.

References

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