Does Nearby Open Flux Affect the Eruptivity of Solar Active Regions?

Marc L. DeRosa* and Graham Barnes†

1 Lockheed Martin Solar and Astrophysics Laboratory, 3251 Hanover Street B/252, Palo Alto, CA 94304, USA
2 NorthWest Research Associates, 3380 Mitchell Lane, Boulder, CO 80301, USA

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Abstract

The most energetic solar flares are typically associated with the ejection of a cloud of coronal material into the heliosphere in the form of a coronal mass ejection (CME). However, large flares exist that are not accompanied by a CME. The existence of these noneruptive flares raises the question of whether such flares suffer from a lack of access to nearby open fields in the vicinity above the flare (reconnection) site. In this study, we use a sample of 56 flares from sunspot Cycles 23 and 24 to test whether active regions that produce eruptive X-class flares are preferentially located near coronal magnetic field domains that are open to the heliosphere, as inferred from a potential field source-surface model. The study shows that X-class flares with access to open fields are eruptive at a higher rate than those for which access is lacking. The significance of this result should be moderated due to the small number of noneruptive X-class flares in the sample, based on the associated Bayes factor.

Key words: Sun: activity – Sun: corona – Sun: coronal mass ejections (CMEs) – Sun: flares – Sun: magnetic fields

1. Introduction

The Sun is an active star that possesses a continually evolving, magnetized corona. The continuous, quasi-steady evolution that is observed to occur most of the time is occasionally interrupted by solar flares, which represent the very rapid conversion of built-up magnetic free energy into light, heat, and kinetic motions on timescales of about a few minutes.

The magnetic energy conversion occurs via magnetic reconnection, which is assumed to take place in a thin layer of the corona where the ohmic resistivity is high enough to facilitate the transfer of energy from the field to the plasma. Understanding the detailed dynamics of both the reconnection region and how flares are triggered are areas of active research (see, e.g., the recent review by Janvier 2017 and references therein).

Theoretical treatments indicate that reconnection is more likely to occur at particular locations in the magnetic field topology, such as null points, separatrix surfaces, and quasi-separatrix layers (as reviewed by, e.g., Pontin 2012). Determining the locations of such topologically important features in the solar corona is challenging, however, owing to the lack of direct measurements of the coronal magnetic field on the spatial scales needed to discern these features. Although the coronal field topology is often more evident from observations off the solar limb (e.g., Lin et al. 2004; Gibson et al. 2017), the complementary photospheric magnetic field observations needed for proper interpretation of the observed limb structures are compromised by foreshortening.

In practice, indirect measurements of coronal magnetic field topology, typically inferred using some combination of coronal imagery and coronal field modeling, are used. Such indirect methods have been used to investigate a broad range of properties, including the persistence of bright loop fans surrounding active regions (ARs) that are otherwise quiescent (Schrijver et al. 2010), how open flux maps down to the photosphere (Antiochos et al. 2011; Platten et al. 2014), cusps in coronal limb observations (Freed et al. 2015), flare ribbon geometries and evolution (Zhao et al. 2014, 2016; Pontin et al. 2016), the temporal concurrence of spatially separated events, including “sympathetic flares” (Schrijver & Title 2011; Jin et al. 2016), how the solar wind may be related to AR upflows in regions of apparently closed fields (Edwards et al. 2016), and why the composition of the solar wind near the boundaries between open and closed fields appears to be a mixture of plasma from both open and closed regions (Pontin & Wyper 2015).

Solar flares are most often characterized by their emission in X-ray wavelengths, as detected by the X-ray spectrometers on board the various Geostationary Orbiting Environmental Satellite (GOES) missions over the years, operated by the U.S. National Oceanic and Atmospheric Administration (NOAA). The GOES flare catalog® categorizes flares in terms of their peak flux in the 1–8 Å wavelength band. The strongest and brightest flares, X-class flares, have a peak flux in the 1–8 Å band of at least $10^{-4}$ W m$^{-2}$ and are often associated with coronal mass ejections (CMEs), in which a cloud of coronal material is observed to be accelerated upward against gravity, away from the Sun, and into the heliosphere. Although there is some correlation between the X-ray emission of GOES flares and the properties and characteristics (e.g., ejection velocities) of the ensuing CMEs, direct proportionality should not be assumed (Emslie et al. 2012). It is thus important to keep in mind that the peak X-ray emission from a flare is not necessarily a good indicator of the total energy involved in the reconnection process.

Indeed, some X-class flares are not followed by any discernible eruption, such as SOL2011-11-03T20:27 from NOAA AR 11339 (Liu et al. 2014) and the cluster of X-class flares from AR 12192 in 2014 October (Sun et al. 2015). An understanding of why most X-class flares are accompanied by CMEs, but some are not, probably depends on detailed knowledge of the forces responsible for the upward acceleration of the coronal material at the core of the flaring AR, how these forces compare to the downward forces that confine this

® At the time of this writing, yearly lists of GOES flares dating back to 1975 September can be downloaded at https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/xrs/.
material in the lower corona, and the partitioning of energy resulting from the reconnection process.

The scenario in which an X-class flare is not followed by any noticeable eruption is intriguing. For the majority of X-class flares, the large amount of energy associated with the X-ray emission is usually accompanied by enough additional energy to overcome the confining forces and accelerate coronal plasma into the heliosphere. The existence of noneruptive X-class flares, however, raises the question of whether such flares suffer from a lack of access to nearby open fields above the flare (reconnection) site in which overlying closed fields effectively block the upward rise of lower-lying flux structures. The observational and numerical studies by Toriumi et al. (2017) and Toriumi & Takasao (2017) show that the ratio between the amount of flux involved in the reconnection process and the total AR flux is smaller for noneruptive flares than for eruptive flares, supporting this possibility. A related study by Wang et al. (2017) also indicates a propensity for the large-scale coronal field associated with noneruptive flaring ARs to be more confining.

If the hypothesis presented above is true, then one would expect a decreased likelihood of eruptivity in cases where the flaring AR is buried more deeply underneath a significant amount of closed magnetic fields. Stated more broadly, identifying whether the presence or absence of particular topological features in the large-scale coronal magnetic field is correlated with whether a flare is confined or eruptive may be a useful diagnostic of the propensity of a flaring AR to foster an eruption.

In the study presented here, we investigate whether the nature of the coronal fields that lie above the locations of strong flares is a contributing factor in determining whether these flares are accompanied by plasma ejected into the heliosphere. More specifically, we test the hypothesis that ARs in which eruptive flares occur are preferentially located near open fields, and conversely that ARs in which confined flares occur are preferentially located underneath closed topological structures. To perform this test, we apply topological analysis software to models of the global coronal magnetic field corresponding to the times of 56 X-class flares in the GOES flare catalog from the past two decades spanning sunspot Cycles 23 and 24. Using statistical methods, we estimate the rate at which flares from ARs with access to open fields are eruptive and compare this estimate to the rate from ARs under closed fields.

2. Methodology

2.1. Obtaining the Flare Sample

According to the GOES database, 176 X-class flares have occurred since the beginning of sunspot Cycle 23 in 1996. The large-scale magnetic environment surrounding each flaring AR may be assessed using models of the global solar coronal magnetic field, including the oft-used potential field source-surface (PFSS) model used in this study.

Determining the magnetic environment associated with each flare location presupposes that the flare location is known. However, some X-class flares in the GOES database from sunspot Cycles 23 and 24 have indeterminate locations, which unfortunately results in their removal from the sample unless the location of the AR can be determined by other means. During sunspot Cycle 23, the absence of H-alpha images contemporaneous with the flares is a significant factor in the lack of locational knowledge. During sunspot Cycle 24 all flares on disk can be determined using the frequent imagery from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) instrument on the Solar Dynamics Observatory (SDO). Flares at the limb suffer from the issue of geometrical foreshortening that makes determinations of precise longitudes difficult.

The PFSS approximation assumes that the coronal volume is current-free, enabling the magnetic field within a spherical shell to be calculated given full-Sun magnetic maps of the photosphere (Schatten et al. 1969). The boundary conditions are completely specified if it is also assumed that the magnetic field is purely radial at the upper boundary. In this study, the lower boundary at \( R_{\text{bot}} = R_e \) in the PFSS models are provided by sampling the evolving flux-transport model of Schrijver & DeRosa (2003), in which magnetograms from either the Michelson Doppler Imager (MDI; Scherrer et al. 1995) on board the Solar and Heliospheric Observatory (SOHO) spacecraft (between 1996 and 2010) or the Helioseismic and Magnetic Imager (HMI; Schou & Scherrer et al. 2012) on board SDO (after 2010) are incorporated into the model. The radius of the upper boundary is chosen to be the canonical value of \( R_{\text{top}} = 2.5 R_e \). Both models used here, namely the evolving surface-flux models of the photospheric magnetic field and the subsequent PFSS models of the coronal magnetic field, are publicly available for download via the PFSS package from the SolarSoftWare (SSW) distribution system.

PFSS models are affected by the additional issue that new flux is only incorporated into the model after it appears in MDI or HMI magnetograms. Occasionally, an AR located at or near the east limb that contains a significant amount of flux and that is not yet incorporated into the model does affect the arrangement of coronal magnetic fields on disk-longitudes (as explored in, e.g., Nitta & DeRosa 2008 or Schrijver & Title 2011). In the more extreme cases, unaccounted east-limb flux may affect the global field situated as far away as 90° to 120° of longitude. We therefore have more confidence in the modeled magnetic fields for locations west of the central meridian (i.e., farther away from possible missing flux on the east limb) than for locations in the eastern hemisphere, and as a result we have screened out all flares with locations east of the central meridian. The final sample comprises 56 flares occurring within 37 ARs, as detailed in Table 1.

2.2. PFSS Model Sanity Checks

PFSS models assume a current-free magnetic field solution, and thus these models are not physically appropriate in the low corona in the cores of ARs, where significant currents are known to exist. However, farther away from ARs, PFSS models often possess field geometries that resemble many larger-scale features observed in the solar coronal magnetic field, suggesting that much of the coronal volume is largely current-free. Because this investigation considers only coronal magnetic fields on larger spatial scales, PFSS models are
fan-shaped open-structure that may accelerate upward, even though the

There is a significant volume of closed field above the flare site that likely blocks access to open fields for any flux structure that may accelerate upward, even though the flare location is laterally adjacent to open flux. An example of this phenomenon is shown in Figure 2.

The flare is sited near a (small, often) region of open field that significantly expands with height, creating a funnel- or fan-shaped open-flux domain that overlies any upwardly mobile flux structure located at the flare site. An example of this phenomenon is shown in Figure 6.

The location of the flare is underneath a separatrix dome associated with a null point located in the coronal volume, according to the PFSS model.

### Table 1

| Event       | SOL (Flare Peak Time) | Flare Class | NOAA AR | Location | Eruptive? | Access? | Notes |
|-------------|-----------------------|-------------|---------|----------|-----------|---------|-------|
| SOL1996-07-09T09:12 | X2.6 | 7978 | S10W30 | Yes | No |
| SOL1997-11-04T05:58 | X2.1 | 8100 | S14W33 | Yes | Yes |
| SOL1998-05-02T13:42 | X1.1 | 8210 | S15W15 | Yes | Yes |
| SOL1999-08-27T18:05 | X1.1 | 8674 | S26W14 | Yes | No |
| SOL1999-11-27T12:12 | X1.4 | 8771 | S15W68 | No | No |
| SOL2000-11-24T15:13 | X2.3 | 9526 | N22W7 | Yes | Yes |
| SOL2000-11-25T18:44 | X1.9 | ☐ | N20W23 | Yes | Yes |
| SOL2001-03-20T16:48 | X4.0 | ☐ | N18W38 | Yes | Yes |
| SOL2001-06-15T06:15 | X1.7 | 9402 | N20W19 | Yes | Yes |
| SOL2001-05-10T08:26 | X2.3 | 9415 | S23W9 | Yes | Yes |
| SOL2001-03-T19:05 | X1.4 | ☐ | S20W85 | Yes | Yes |
| SOL2001-10-09T16:30 | X1.6 | 9661 | N15W29 | Yes | No |
| SOL2001-10-25T02:05 | X1.3 | 9672 | S16W21 | Yes | No |
| SOL2001-11-04T09:20 | X1.0 | 9684 | N6W18 | No | No |
| SOL2002-07-15T02:40 | X1.8 | 10030 | N19W30 | Yes | Yes |
| SOL2002-08-21T05:34 | X1.0 | 10069 | S12W51 | Yes | Yes |
| SOL2003-03-17T19:05 | X1.5 | 10514 | S14W39 | Yes | No |
| SOL2003-03-18T12:08 | X1.5 | ☐ | S15W46 | Yes | No |
| SOL2003-05-27T23:07 | X1.3 | 10365 | S7W17 | Yes | No |
| SOL2003-05-01T01:05 | X1.2 | ☐ | S6W37 | Yes | No |
| SOL2003-10-26T18:19 | X1.2 | 10484 | N2W38 | Yes | Yes |
| SOL2003-10-29T20:49 | X1.0 | 10486 | S15W2 | Yes | Yes |
| SOL2003-11-02T21:25 | X8.3 | ☐ | S14W56 | Yes | Yes |
| SOL2003-11-03T01:30 | X2.7 | 10488 | N10W83 | No | No |
| SOL2003-11-03T09:55 | X3.9 | ☐ | N8W77 | Yes | No |
| SOL2003-11-04T19:50 | X28. | 10386 | S19W83 | Yes | Yes |
| SOL2004-02-26T02:03 | X1.1 | 10564 | N14W15 | No | No |
| SOL2004-08-13T18:12 | X1.0 | 10656 | S13W24 | Yes | Yes |
| SOL2004-08-18T17:40 | X1.8 | ☐ | S14W90 | Yes | Yes |
| SOL2004-03-30T14:46 | X1.2 | 10691 | N13W25 | Yes | Yes |
| SOL2004-11-07T16:06 | X2.0 | 10696 | N9W17 | No | No |
| SOL2004-11-10T02:13 | X2.5 | ☐ | N9W49 | No | No |
| SOL2005-01-15T23:02 | X2.6 | 10720 | N14W8 | Yes | No |
| SOL2005-01-17T09:52 | X3.8 | ☐ | N15W25 | Yes | Yes |
| SOL2005-01-19T08:22 | X1.3 | ☐ | N15W51 | Yes | Yes |
| SOL2005-01-20T07:01 | X7.1 | ☐ | N14W61 | Yes | Yes |
| SOL2005-07-14T10:55 | X1.2 | 10786 | N11W90 | Yes | No |
| SOL2005-09-15T08:38 | X1.1 | 10808 | S12W14 | No | No |
| SOL2006-12-17T00:40 | X3.4 | 10930 | S6W23 | Yes | Yes |
| SOL2006-12-14T22:15 | X1.5 | ☐ | S6W46 | Yes | Yes |
| SOL2011-02-15T01:56 | X2.2 | 11158 | S20W10 | Yes | No |
| SOL2011-03-02T23:23 | X1.5 | 11166 | N8W11 | No | No |
| SOL2011-08-09T08:05 | X6.9 | 11263 | N14W69 | No | No |
| SOL2011-09-07T22:20 | X2.1 | 11283 | N14W18 | Yes | Yes |
| SOL2011-09-07T22:38 | X1.8 | ☐ | N14W31 | Yes | Yes |
| SOL2012-07-12T16:49 | X1.4 | 11520 | S13W3 | Yes | No |
| SOL2013-10-20T02:03 | X1.0 | 11675 | N4W66 | Yes | Yes |
| SOL2013-11-10T03:14 | X1.1 | 11890 | S14W13 | Yes | No |
| SOL2014-03-27T17:48 | X1.0 | 12017 | S10W32 | Yes | Yes |
| SOL2014-10-27T10:56 | X2.0 | 12192 | S14W37 | No | No |
| SOL2014-10-27T14:47 | X2.0 | ☐ | S16W56 | No | No |
| SOL2014-12-07T00:28 | X1.8 | 12242 | S21W24 | Yes | Yes |
| SOL2017-09-09T09:10 | X2.2 | 12673 | S8W32 | Yes | Yes |
| SOL2017-09-06T12:02 | X9.3 | ☐ | S8W34 | Yes | Yes |
| SOL2017-09-07T14:36 | X1.3 | ☐ | S8W48 | Yes | Yes |
| SOL2017-09-10T16:06 | X8.2 | ☐ | S8W88 | Yes | Yes |

Notes:

a Solar Object Locator (SOL) of time of peak flare emission from the GOES flare catalog.

b Flare class from the GOES flare catalog.

c Active region number assigned by NOAA.

d Flare location from the GOES flare catalog.

e Is there an eruption in LASCO C2 and/or C3 data following the time of the flare peak?

f Does the PFSS model imply access to open fields from an upward-directed eruption centered on the flare location?

g Access to open fields is provided via a narrow channel located between separatrix surfaces. This channel extends either into or through the AR and encompasses the flare site, as in the example shown in Figure 5.

h There is a significant volume of closed field above the flare site that likely blocks access to open fields for any flux structure that may accelerate upward, even though the flare location is laterally adjacent to open flux. An example of this phenomenon is shown in Figure 2.

i The flare is sited near a (small, often) region of open field that significantly expands with height, creating a funnel- or fan-shaped open-flux domain that overlies any upwardly mobile flux structure located at the flare site. An example of this phenomenon is shown in Figure 6.

j The location of the flare is underneath a separatrix dome associated with a null point located in the coronal volume, according to the PFSS model.
assumed appropriate; it nonetheless seems prudent to evaluate the resemblance between observations and the PFSS models for the specific times considered here to see whether there are any significant discrepancies, as a sanity check.

To this end, we employ two qualitative tests: (1) comparisons between the topological structures found in PFSS models with the locations of streamers and pseudostreamers evident in white-light coronagraph images, and (2) comparisons between the locations of coronal holes visible in extreme ultraviolet (EUV) images with the open-flux regions determined from the PFSS models. For all events, these tests either support the idea that the coronal magnetic field is current-free on large scales, or were inconclusive. The online materials associated with this article (http://www.lmsal.com/forecast/DB2018.html) provide images and topological renderings for each of the 56 events used for this investigation. These images allow the reader to assess the applicability of the PFSS model in the manner described in this section.

Although more rigorous comparison schemes are possible, these involve more physically realistic modeling of the coronal magnetic field. These more rigorous tests are not considered here, as such modeling requires knowledge of (at least) photospheric currents, plasma densities and temperatures, and/or coronal heating mechanisms—quantities that are generally not readily available for a large enough sample of ARs and for a large enough area on the Sun. Additionally, these models are more computationally intensive and are not as readily applied to a large sample of regions.

### 2.2.1. Comparisons with (Pseudo-)Streamers

The first sanity check is based on the fact that the cusp-shaped streamers evident in white-light coronagraph images from, e.g., the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995) on SOHO result from the increased density associated with tall, high-arching closed fields that underlie the heliospheric current sheet (HCS). If a PFSS model successfully captures the largest spatial scales in the actual coronal field, then the position angles of the LASCO streamers are expected to correspond with the highest-arching closed field structures in the PFSS model. The persistence of coronal streamers over several rotation periods (an observational fact that was first realized approximately 50 years ago, e.g., Bohlin 1970) lends credence that streamers are a robust feature of the large-scale corona. The magnetic null points associated with these streamers located lower down in the corona have also been found to persist (Freed et al. 2015).

Examples of this first test are demonstrated in Figures 1 and 2, corresponding to the times of Events 11 and 48 in Table 1. In both figures, the topological skeleton associated with the PFSS model nearest to the time of the event is shown in panel (a) and a corresponding LASCO C2 image in panel (b). The topological skeleton renderings shown here are largely similar to those shown in Platten et al. (2014), and illustrate the separatrix surfaces, null points, and spine lines in the PFSS models. These features are depicted in the figures as semitransparent surfaces, small red dots, and cyan lines, respectively. We note as an aside that the same topological elements of interest found in the PFSS models, such as the location of null points and the boundaries between magnetic field connectivity domains, are likely to also be present in nonpotential fields (Régnier 2012). The algorithms by which the topological features were calculated are the null-point finding method of Haynes & Parnell (2007) and the separatrix-surface mapping scheme described in Haynes & Parnell (2010), after adapting for spherical geometries.

In the comparison with LASCO images, the most relevant topological features in the PFSS models are the separatrix surfaces that intersect $R_{\text{top}}$. The largest and most noticeable separatrix surfaces of this kind are the surfaces that extend downward from the polarity-inversion line at $R_{\text{top}}$, and serve to separate field lines that are considered open to the heliosphere.

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**Figure 1.** SOL2001-04-15T13:50 (Event 11 in Table 1) comparison: (a) topological skeleton for the PFSS model of 2001 April 15 at 12:04 UT and (b) the corresponding LASCO C2 image. The topological skeleton comprises the separatrix surfaces (semi-transparent surfaces), null points (small red dots), and spine lines (cyan lines) present in the PFSS model. The dark blue line is the polarity-inversion line at the upper boundary of the model at $R_{\text{top}} = 2.5 R_\odot$. Red lines are drawn where the separatrix curtains intersect $R_{\text{bot}}$ and $R_{\text{top}}$. The arrows in both images indicate the positions of the brightest LASCO streamers, which correspond to the largest separatrix surfaces in the topology skeleton. The conical cyan pointer indicates the location of the X-class flare at 20W85.
(i.e., field lines that have one endpoint at $R_{\text{bot}}$ and another at $R_{\text{top}}$) from closed field lines (i.e., field lines having both endpoints at $R_{\text{bot}}$). These HCS curtains (as termed by Platten et al. 2014) are yellow in Figures 1(a) and 2(a), and the polarity-inversion line at $R_{\text{top}}$ at the apexes of these surfaces is dark blue. HCS curtains are conceptualized to continue upward to form the HCS (as in Figure 1 of their paper) and to be at the same position angles in the PFSS models, when viewed from along the Earth–Sun line, as the white-light coronal streamers seen in LASCO images (Wang et al. 2007a).

Additionally, each null point located inside PFSS coronal volume has a separatrix surface associated with it. While these surfaces often take the shape of domes that wall off self-contained domains of field lines covering sections of the photosphere, in some cases the fan plane extending away from a null point is found to be oriented vertically, such that the associated separatrix surface extends upward and intersects $R_{\text{top}}$. These separatrix curtains (as termed by Platten et al. 2014) divide open field lines having the same polarity, and are often associated with coronal pseudostreamers observed in the LASCO images (Wang et al. 2007b). In Figures 1(a) and 2(a), all separatrix surfaces associated with coronal nulls (including the separatrix curtains) are rendered in various pastel colors. The intersection of these separatrix surfaces with either the upper or lower boundary are colored red.

Because the HCS curtains and separatrix curtains are both associated with LASCO streamers and pseudostreamers, comparisons between the renderings of the topological skeletons of the PFSS models (centered on the solar central meridian longitude and latitude for the time of interest) and the LASCO images provide a way to validate the PFSS models. In Figure 1, corresponding to Event 11, the position angles of the three brightest streamers in LASCO (marked by arrows) match well with the HCS curtains and one of the upward-extending separatrix curtains. As a result, the PFSS model for Event 11 is considered plausible.

In Figure 2, corresponding to Event 48, the comparison is less conclusive. The LASCO image contains a multitude of streamers and pseudostreamers. The PFSS model topology is also more complex, with an undulating and warped HCS curtain surrounded by many smaller separatrix curtains. In this case, it is more difficult to predict where streamers might occur by looking only at the topological rendering, and it is correspondingly difficult to choose features in the topological rendering that match the LASCO streamers. Streamers and pseudostreamers are only evident when there is a significant amount of plasma density along the line of sight, and this suggests that the orientation of the HCS curtains may affect the presence or absence of streamers, especially if the HCS curtains are more face-on than edge-on. Figure 2(a) indicates that the HCS curtains for Event 48 are more folded and undulated, with portions being oriented face-on. As a consequence, for this particular case, the comparison is deemed inconclusive.

2.2.2. Comparisons with Coronal Holes

The second sanity check relies on the association of dark regions in EUV images with open fields. The plasma along open field lines is too cool and too rarefied to emit in EUV wavelengths, and much of it is instead streaming upward to become the solar wind. Therefore, comparisons between the open-flux domains predicted by the PFSS model and the dark regions in EUV and X-ray imagery can be used to gauge how well the large-scale coronal magnetic field is represented by the PFSS models.

Such comparisons are imperfect, and a one-to-one correspondence between EUV-dark regions in the images and open-flux domains from the model is not expected (see Lowder et al. 2014, 2017 for recent comparisons). Several reasons probably account for these discrepancies: (1) coronal holes may not indicate open flux; instead, this plasma may be located on long, closed field lines that connect faraway regions of opposite polarities. The plasma found on such long field lines is often
not at the proper density or temperature to emit in EUV wavelengths, and thus remains dark. (2) The corona is optically thin, and as a result lines of sight passing through both closed and open fields will almost always appear bright. Such bright coronal structures may obscure open-field channels, especially away from disk center, and as a result open-flux regions will not appear dark in the EUV if there is not a direct line of sight into the channel. (3) The static upper boundary of the PFSS model only crudely approximates the dynamic environment present at the boundary between the magnetism-dominated corona and the plasma-dominated heliosphere. One consequence of this situation is that measurements of the in situ open flux at 1 au do not match that predicted by the PFSS model (Linker et al. 2017). (4) The PFSS open-flux domains are large-scale features that span the full height of the model, and as a result may be affected by the lack of up-to-date surface magnetic fields at east-limb longitudes (as in the case discussed in Pevtsov et al. 2016). Structures in the eastern hemisphere may be adversely affected when there is a significant amount of flux at or past the east limb that has not yet been assimilated into the surface-flux model that comprises the lower-boundary condition of the PFSS extrapolation.

Figure 3 illustrates the comparison between the modeled open flux and coronal holes for Event 11 (the same event shown in Figure 1). The image in Figure 3(a) shows a magnetogram for 2001 April 15 at about 0 UT, on which are overplotted the outlines of the photospheric footpoints of field lines that intersect $R_{\text{top}}$. Open field lines fan out from these contours, sometimes with significant expansion factors. The colors of the open field contours in the figure indicate the polarity of the open flux. These open field contours may be qualitatively compared with the darker regions of the full-Sun image from the 284 Å channel observed by the Extreme ultraviolet Imaging Telescope (EIT; Delaboudinière et al. 1995) on SOHO, shown in Figure 3(b).

In the case shown in Figure 3, there is a fair amount of correspondence between many of the open-flux contours and the coronal holes, with the shapes of the darker features in the EIT image bearing resemblance to several of the shapes of the open-flux contours. In particular, the coronal hole and the PFSS open-flux domain at the north pole have similar outlines. Similarly, the curved shape of the open-flux region near the central meridian that spans the near-equatorial latitudes resembles the corresponding darker channels in the EUV image, though the degree to which they match is not as good for this equatorial coronal hole as in the polar coronal hole described earlier. This region of open flux is narrow, and brighter plasma associated with neighboring closed fields may be obscuring the full coronal hole. The same effect may be why the modeled open-flux extension in the southeast quadrant of Figure 3(a) has no noticeable coronal hole in the EUV image of Figure 3(b); though, east-limb open-flux contours may also be affected by inaccuracies in the photospheric boundary condition.

Figure 4 shows the same comparison for Event 52. On this date, a PFSS open-flux region extends northward from the south polar region. At the top of this extension there is a ring of open flux that surrounds a closed field domain. The comparison image from the 193 Å channel of AIA also contains a dark coronal hole extending in the same direction as in the model, as well as some evidence that a circular channel of open flux might be present. Additionally, the coronal hole in the northeastern quadrant of the AIA image that appears to extend behind the limb matches well with the location of an open-flux region evident in the same location in the PFSS model.

### 3. Results and Discussion

The final sample of events comprises 56 flares occurring within 37 ARs, as listed in Table 1 and in the online materials associated with this article (http://www.lmsal.com/forecast/DB2018.html). Each flare in the sample is classified as either eruptive or noneruptive, based on whether a CME is observed...
in LASCO data. We made use of the LASCO CME catalog\(^5\) to determine whether the flares have an associated CME. Examining LASCO C2 and C3 running difference movies is particularly helpful for this purpose, and the LASCO CME catalog has conveniently provided a useful movie-making tool that synchronizes LASCO C2 and C3 running difference movies with \textit{GOES} X-ray light curves. In the online materials, clickable links to such synchronized movies are provided for all 56 events.

We also characterize each event based on whether there is access to open fields from the location of the flare. More specifically, we consider in a qualitative manner how likely it is that a rising flux structure located at the flare site would encounter open fields as it moves radially outward through the PFSS model. In some cases, this is easily judged as, for example, when the source AR is permeated by open fields, or when the source AR is centered underneath the helmet surface (and is thus obviously buried beneath a significant amount of closed field). Many cases are more ambiguous, and thus making the determination is more subjective.

Narrow channels of open flux are a common feature in PFSS coronal field models, and are usually nestled either between separatrix surfaces that divide different topological domains of the magnetic field or between tight folds in the HCS curtain. The fields emanating from these channels often have high expansion factors, especially in the direction perpendicular to the channel orientation, and are believed to play a key role in the formation of the slow solar wind (Antiochos et al. 2007, 2011; Titov et al. 2011; Higginson et al. 2017). In the context of this study, narrow channels that pass in or through a flaring AR provide a pathway by which plasma and fields may be readily ejected into interplanetary space, even though the flare site may not be located precisely above the photospheric open field footprint. Because of their small photospheric area, such open field channels are sometimes difficult to identify in EUV imagery.

As an example of this phenomenon, Figure 5 illustrates a narrow channel encroaching upon the trailing polarity of AR 12673, which produced the series of recent X-class flares in 2017 September. Although the closest region of photospheric open flux is not directly underneath the flare site, we consider this region to have access to open fields because of how quickly with height this nearby open flux splay s out. A variant of this effect involves open-flux domains with even smaller photospheric areas that map down to strong flux, such as for SOL2002-08-21T05:34 shown in Figure 6. As with AR 12673, the open fields above AR 10069 map down to a small, isolated region on the photosphere in the trailing polarity of the flaring AR.

Determining whether open flux can be associated with a flare is often more ambiguous. In the online materials for SOL2005-07-14T10:55 (Event 37 in Table 1), it is evident that the flare location occurs near the southern extent of an open-flux region that stretches southward from the north pole. Although the photospheric location of open flux extends very close to the latitude and longitude of the flare site, the topological domain of connectivity above the flare site contains a large volume of closed field that bows outward above the AR. Because eruptions are directed outward and upward, we judge in this case that the significant amount of overlying closed field would serve to confine any upward motion. As a result, this case and others like it are listed in Table 1 as not having access to open fields due to the particular geometry of the closed field domain located above the flare site. The series of X-class flares originating from AR 12192 also possess this property.

Table 2 is a contingency table that summarizes the number of events that fall into each of the defined categories. The tabulation shows that of the 50 X-class flares associated with a CME, 30 of these (60\%) occurred in locations judged as having access to open flux. There are only 6 noneruptive X-class flares in the sample, and 5 of these were located in places with

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\(^5\) At the time of this writing, the LASCO CME catalog can be found at https://cdaw.gsfc.nasa.gov/CME_list/index.html.
significant overlying closed fields. We estimate the rate at which X-class flares with access to open flux are eruptive as 0.97 (30/31) compared with 0.80 (20/25) for X-class flares without access to open flux. These estimates are, however, based on a small number (6) of noneruptive flares.

To test how robust the results are, we computed the Bayes factor $K$ (e.g., Kass & Raftery 1995) comparing a model in which the rate at which X-class flares are eruptive is independent of access to open fields with a model in which access to open field results in a different rate of eruptions (see the Appendix). Depending on the choice of priors, the Bayes factor is in the range of $0.12 \leq K \leq 0.74$, which indicates that there is weak to moderate evidence to support that access to open field influences whether an X-flare is eruptive.

4. Conclusions

We conclude that X-class flares are more likely to be eruptive when they occur in locations with access to open flux. The evidence to support this, however, is statistically sensitive to the small number of noneruptive X-class flares in the sample. Of the 31 X-class flares that were judged to originate in locations with access to open fields, all except one (SOL2005-09-15T08:38) were eruptive. The sample also contains 25 X-class flares located far away from open fields, of which 20 were eruptive and 5 were noneruptive. Access to open field is therefore neither a necessary nor a sufficient condition for a flare to result in an eruption.

The fact that proximity to open fields is not a more clear-cut discriminator is an indication that other properties of the source AR also contribute to whether an X-class flare is associated with an eruption. For eruptive ARs, features such as the reconnection flux and the decay index have been demonstrated to be correlated with CME speeds (e.g., Liu 2008; Deng & Welsch 2017; Kazachenko et al. 2017). Even though non-eruptive flares are not considered in these studies, we speculate that these aforementioned trends extend into the realm of noneruptive flares, i.e., we suspect that flaring ARs without discernable eruptions involve less reconnected flux and a lower decay index than eruptive ARs; though, we acknowledge that these trends should be established more rigorously using samples that include both eruptive and noneruptive flares.
Other source-region properties, such as the distance between the center of the AR and the flare site, may also be important (Wang & Zhang 2007).

The topology of the magnetic field overlying a flare site is also thought to affect the chances of an eruption. For instance, the presence of a null point in the magnetic field may be necessary for an eruption to proceed or may otherwise facilitate an eruption (e.g., Démoulin et al. 1994; Antiochos et al. 1999; Reid et al. 2012; Joshi et al. 2017), as in a pseudostreamer configuration (Török et al. 2011). Even models possessing the same topology may yield different results depending on the geometry and shape of the magnetic field lines (e.g., Sterling & Moore 2001; Masson et al. 2013). Discriminating between the characteristics of these various scenarios and understanding how the details of the topologies affect the evolution of an eruption requires a larger ensemble of events than we were able to include in the work presented here.

To more definitively conclude that access to open field influences whether an X-class flare is likely to be eruptive, a larger sample of noneruptive flares is needed. This sample might be accomplished, for example, by relaxing the requirement used here that the flare be located west of central meridian, though by doing this there is a concern that the open field regions on the Sun may not be accurately determined by the PFSS model. This would probably increase the risk of a flare location being classified as having access (or nonaccess) to open flux in a way that is difficult to quantify.

Alternatively, the sample might be expanded to include flares of smaller magnitude. While including such smaller magnitude events would result in better statistics, it would also raise the question of whether noneruptive flares are such because they lack the energy to fully propel a CME or whether they are noneruptive due to a lack of access to open field. In reality, these two factors (energy deposited versus access to open field) are likely linked, given that a very energetic event may be able to push through a small amount of closed field to access open field that would otherwise be inaccessible for less energetic cases.

In this investigation, we focused on whether an X-class flare was positioned in a location with access to open fields. However, the topology of the coronal magnetic field is complex, and contains narrow channels of open flux wedged between closed domains of connectivity. Closed fields may lie underneath separatrix domes associated with coronal null point, or they may be found under the large helmet surface(s) that often wrap around the Sun. With a larger sample size, the specific topologies associated with both eruptive and noneruptive flares may become more apparent.

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Appendix

Statistical Considerations

To quantitatively evaluate whether access to open field influences whether an X-flare is eruptive, consider the following two models. In the first model, $M_1$, access to open fields does not play a role in determining whether an X-flare is eruptive. In the second model, $M_2$, X-class flares are eruptive at a different rate when there is access to open fields compared to when there are no nearby open fields. To determine which of these models is more likely, we compute the Bayes factor (odds ratio), which is a statistic that compares the likelihood of getting the observed data from each of the models. More explicitly, the two models for the observations are:

- $M_1$: the probability that an X-flare will produce an eruption, $p_e$, is independent of the proximity to open field.
- $M_2$: the probability that an X-flare will produce an eruption depends on whether there is access to open fields at the flare site, where $p_o$ is the probability that the site of the X-class flare is located near access to open fields, and where $p_c$ is the probability that an X-flare occurs in a location without any nearby open fields.

The data used to evaluate the likelihood of each of these models is summarized in a contingency table $D$ (i.e., as shown in Table 2), whose elements are:

- $n_{oe}$: the number of eruptive X-class flares with access to open field.
- $n_{no}$: the number of noneruptive X-class flares with access to open field.
- $n_{ec}$: the number of eruptive X-class flares under closed field.
- $n_{nc}$: the number of noneruptive X-class flares under closed field.

The probability of the observed contingency table $D$ resulting from each of the models $M_i$ assuming binomial random variables, can now be calculated. For $M_1$, the probability of getting $D$, for a given eruption probability $p_e$, is

$$Pr(D|p_e, M_1) = \frac{n_o! n_e!}{n_{oe}! n_{no}! n_{ec}! n_{nc}!} p_o^{n_o} (1 - p_o)^{n_{no}} (1 - p_e)^n_e,$$

where $n_e$ is the number of eruptive X-class flares, $n_o$ is the number of noneruptive X-class flares, $n_o$ is the number of X-class flares from ARs with access to open fields, and $n_c$ is the number of X-class flares from ARs under closed fields. Marginalizing over $p_e$ results in the following probability of the data, assuming a uniform prior on $p_e$ given model $M_1$ ($Pr(p_e| M_1) = 1$ for $0 \leq p_e \leq 1$):

$$Pr(D|M_1) = \int_0^1 dp_e Pr(p_e| M_1) Pr(D|p_e, M_1) = \int_0^1 dp_e \cdot \frac{n_o! n_e!}{n_{oe}! n_{no}! n_{ec}! n_{nc}!} \frac{n_o! n_e!}{n_{oe}! n_{no}! n_{ec}! n_{nc}!} (n_e + n_o + 1)!$$

For $M_2$, the probability of getting $D$, given probabilities $p_o$ and $p_c$ is

$$Pr(D|p_o, p_c, M_2) = \left[ \frac{n_o!}{n_{oe}! n_{no}!} p_o^{n_o} (1 - p_o)^{n_{no}} \right] \times \left[ \frac{n_e!}{n_{ec}! n_{nc}!} p_c^{n_e} (1 - p_c)^{n_{nc}} \right].$$

Marginalizing over $p_o$ and $p_c$ results in the probability of the data, assuming uniform priors on $p_o$ and $p_c$ given model $M_2$: $Pr(p_o| M_2) = 1$ for $0 \leq p_o \leq 1, Pr(p_c| M_2) = 1$ for...
Thus, the Bayes factor for these priors is given by

$$K = \frac{Pr(D|M_1)}{Pr(D|M_2)}$$

$$= \frac{n_e n_c n_o n_e}{(n_e + n_o)(n_c + n_e)(n_c + n_o + n_c + n_o)}.$$  

which has a value $K = 0.12$ for the values given in Table 2. This value indicates that model $M_2$ is much more likely.

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The conclusion clearly depends on the choice of priors, in part because of the extremely small number of noneruptive flares. The two sets of priors chosen represent the extremes, and thus the real Bayes factor should lie between these two.