The Association of Filaments, Polarity Inversion Lines, and Coronal Hole Properties with the Sunspot Cycle: An Analysis of the McIntosh Database

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Abstract
Filaments and coronal holes, two principal features observed in the solar corona, are sources of space weather variations. Filament formation is closely associated with polarity inversion lines (PILs) on the solar photosphere which separate positive and negative polarities of the surface magnetic field. The origin of coronal holes is governed by large-scale unipolar magnetic patches on the photosphere from where open magnetic field lines extend to the heliosphere. We study the properties of filaments, PILs, and coronal holes in solar cycles 20, 21, 22, and 23 utilizing the McIntosh archive. We detect a prominent cyclic behavior of filament length, PIL length, and coronal hole area with significant correspondence with the solar magnetic cycle. The spatio-temporal evolution of the geometric centers of filaments shows a butterfly-like structure and distinguishable poleward migration of long filaments during cycle maxima. We identify this rush to the poles of filaments to be co-temporal with the initiation of polar field reversal as gleaned from Mount Wilson and Wilcox Solar Observatory polar field observations, and quantitatively establish their temporal correspondence. We analyze the filament tilt angle distribution to constrain their possible origins. The majority of the filaments exhibit negative and positive tilt angles in the northern and the southern hemispheres, respectively, strongly suggesting that their formation is governed by the overall large-scale magnetic field distribution on the solar photosphere and not by the small-scale intra-active region magnetic field configurations. We also investigate the hemispheric asymmetry in filaments, PILs, and coronal holes. We find that the hemispheric asymmetry in filaments and PILs is positively correlated with sunspot area asymmetry, whereas coronal hole asymmetry is uncorrelated.

Key words: Sun: corona – Sun: filaments, prominences – Sun: magnetic fields – Sun: photosphere – sunspots

1. Introduction

Solar filaments are one of the most common large-scale features observed in the solar corona. Filaments are made of dense chromospheric plasma which is much cooler than the 1 MK hot corona; thus they appear as dark elongated structures against the bright solar disk when observed in the Hα absorption line. The same structures look brighter on the solar limb in the emission line and are known as prominences. Hydrodynamic instabilities can trigger eruptions of filaments, producing solar flares and coronal mass ejections which are hazardous for space weather (Gilbert et al. 2000; Gopalswamy et al. 2003; Jing et al. 2004); therefore observational as well as theoretical studies of filaments have attracted much attention in the context of space weather research. Although filaments are coronal features, their properties depend on the magnetic environment of the solar surface (i.e., the photosphere). They always appear in the vicinity of the polarity inversion lines (PILs) which separate opposite polarities of the photospheric magnetic field (McIntosh 1972; Makarov et al. 1983; Martin 1998). Thus filaments inherit diverse signatures of the temporal and spatial variations of the small- and large-scale surface magnetic fields, establishing them as a crucial component for studying solar variability. Moreover, analysis of filament data spanning over several solar cycles can reveal various aspects of the long-term modulation of the solar magnetic field.

Systematic observations of filaments (in the Hα line) started long ago, in 1915, at Kodaikanal Observatory (India), and in 1919, at the Kislovodsk Mountain Astronomical Station of the Main (Pulkovo) Astronomical Observatory of the Russian Academy of Sciences. Utilizing these multiple databases, researchers (Li et al. 2003, 2008; Hao et al. 2015; Chatterjee et al. 2017) have identified a cyclic time variation in the total filament number (also in their total length; Tlatov et al. 2016), quite similar to the solar cycle. In general, filaments are distributed over all possible latitudes (from the equator to the poles) and longitudes on the solar surface throughout a solar cycle. However, Hao et al. (2015), Tlatov et al. (2016), and Chatterjee et al. (2017) reported that the temporal variation of the latitudinal positions of the filaments’ geometric centers forms a butterfly-like pattern with a spread much larger than the sunspot butterfly diagram (which is usually confined within ±45° latitudes). Their work also includes statistical analysis of the filaments’ tilt angle distribution. Like many other solar activities, filament formation is not uniform in the two solar hemispheres. Li et al. (2003, 2010), Hao et al. (2015), and Kong et al. (2015) investigated north–south asymmetry of filaments during different phases of the solar cycle.

Apart from solar filaments, another large-scale coronal feature is coronal holes through which unipolar open magnetic field lines with roots in the solar photosphere extend to the heliosphere. Chromospheric ionized plasma particles gyrate along these lines and propagate in the upper atmosphere quite easily, making coronal holes a potential source of fast solar wind. Geomagnetic storms are primarily caused by this fast solar wind (Gilbert et al. 2000; Gopalswamy et al. 2003; Zhang et al. 2012) and, hence, prediction of the solar wind properties is a key to space weather research applications. The low temperature and density of coronal holes in comparison to their surroundings make them appear as dark patches in X-ray
(Timothy et al. 1975) and EUV (Munro & Withbroe 1972) images. Polar coronal holes have been studied using He II 30.4 nm (Bühl 1977), He I 1083 nm (Sheeley 1980; Webb et al. 1984; Fox et al. 1998; Harvey & Recely 2002), and Fe XIV 530.3 nm (Waldmeier 1981; Maravilla et al. 2001) coronal emission lines, K-coronograph observation (Brau & Stewart 1994), X-ray and EUV observation (Broussard et al. 1978; Webb et al. 1984), and potential field source surface (PFSS) extrapolation modeling utilizing photospheric magnetic field data (Wang et al. 1996; Bravo et al. 1998; Obridko & Shelting 1999). Recently, Lowder et al. (2014, 2017) have used EIT/SOHO and SDO/AIA data to study the signed and unsigned magnetic flux confined in the coronal holes during solar cycles 23 and 24. They have compared these observational results with theoretically calculated magnetic flux associated with those coronal holes by utilizing PFSS modeling on proper surface magnetic maps. They also reported the presence of asymmetry in area evolution of coronal holes in the two hemispheres. In a similar context, Obridko & Shelting (1999), Wang et al. (2009), McIntosh et al. (2015), and Wang (2016) have studied the coronal hole area variation during solar cycles and found a butterfly-like structure in the time–latitude plot of coronal holes’ centroids. In a recent work, Krista et al. (2018) studied the lifetimes and propagation characteristics of low-latitude coronal holes in longitude over several solar rotations using the SDO and STEREO data over a period from 2011 February to 2014 July.

In this paper, we analyze observational data preserved in the McIntosh archive (McA: Gibson et al. 2016; Webb et al. 2017) containing positional information of various observational features such as filaments, PILs, coronal holes, sunspots, and plages during solar cycles 20–23. We mainly focus on the variation of filament length and its hemispheric asymmetry. We further analyze the latitudinal and tilt angle distributions of filaments during this period. We additionally explore various properties of PILs and coronal holes and establish their relationship to solar magnetic activity. The paper is organized as follows: in Section 2, we describe the source of the data; results of our analyses are presented in Section 3; Section 4 contains our conclusions.

2. Data Description

Patrick McIntosh, a scientist at NOAA’s Space Environment Center in Boulder, started creating hand-drawn Carrington maps using both satellite- and ground-based observations from 1967 April to 2009 July. A Carrington map contains positional information of different features observed on the solar photosphere (e.g., sunspots, PILs, and plages) and corona (e.g., filaments and coronal holes). By assembling these maps, he developed a unique database capturing the long-term solar activity during solar cycles 20–23. However, there are three large data gaps: the first from 1974 June to 1978 July, the second from 1991 October to 1994 January, and the third from 1994 April to 1996 May. In the McA project (a Boston College/NOAA/NCAR collaboration, funded by the NSF), all hand-drawn maps were scanned, digitized, and archived at NOAA/NCEI and made available both as images and “fits” format. For our analysis, we have used level 3 fits files from the McA and extracted the data associated with the relevant features present in those Carrington maps.

3. Results and Discussion

3.1. Properties of Filaments

Filament formation is strongly associated with the magnetic field distribution on the solar surface. Thus variation in the appearance of filaments can delineate the magnetic activity of the Sun. In this work, we analyze 442 Carrington map images from 1967 April to 2009 July distributed over approximately 36 years, covering mostly the declining phases of solar cycle 20, cycle 21, a part of cycle 22, the full solar cycle 23, and the beginning of cycle 24. A total of 67,373 filaments are detected from these 442 Carrington maps with their indices varying from 1520 to 2086. In order to calculate the length of an individual filament present in any Carrington map, we first identify the boundary pixels of the filamentary structure and then measure the associated perimeter using the following relation:

\[ L = \sum_n \sqrt{R_n^2 \delta \theta^2 + R_n^2 \cos^2 \theta \delta \phi^2} \]  

where \( L \) is the length of the filament’s perimeter, \( R_n \) is radius of the Sun, \( \theta \) and \( \phi \) represent the latitude and the longitude of a particular pixel, and \( n \) is the total number of pixels associated with the filament’s perimeter. The quantities \( \delta \theta \) and \( \delta \phi \) are latitudinal and longitudinal differences between two adjacent pixels, respectively. We consider the length of any individual filament to be half of its perimeter. In fitting a Gaussian to the filaments’ length distribution, we find the mean and the standard deviation (\( \sigma \)) to be 40 Mm and 24 Mm, respectively, with a very long tail extending up to 1894 Mm. We investigate the different characteristics of these filaments and explore their possible connection to the solar magnetic cycle.

3.1.1. Latitudinal Distribution of Filaments

Filaments are not uniformly distributed over the solar surface. While there is no prominent longitudinal preference for filament formation, we find a discernible pattern in their latitudinal position during a solar cycle. Figures 1(a) and (b) represent the spatio-temporal variation of the filaments’ geometric centers (corresponding to different length scales), showing a wider spread in latitude (−80° to +80°) in comparison to the sunspot butterfly diagram (denoted by red dots within red contour lines). The sunspot data are taken from the Royal Greenwich Observatory (RGO) and US Air Force (USAF) Solar Optical Observing Network database. Figure 1(a) depicts the spatio-temporal distribution of filaments with length varying from 2 Mm (smallest) to 88 Mm (≈mean +2\( \sigma \)) capturing the distribution of the majority (i.e., 76%) of all filaments. When we consider the geometric centers of the very long filaments with length >184 Mm (i.e., mean+6\( \sigma \)), a more apparent butterfly-like structure emerges (see Figure 1(b)), although they form a small subset of all filaments (7.7%).

At higher latitudes, filaments display a poleward migration (see the structures encircled by black ellipses, which are more prominent in Figure 1(b)) during the solar maxima of cycle 20 (year 1971), cycle 21 (1981), cycle 22 (1990), and cycle 23 (2000). This observational characteristic of filaments is known as the “rush to the poles” (Topka et al. 1982; Tlatov et al. 2016; Chatterjee et al. 2017). The presence of similar features was reported in an analysis of the poleward-most filaments using

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* https://www2.hao.ucar.edu/mcintosh-archive/four-cycles-solar-synoptic-maps
In the same figures, we have represented the variation of polar field observed by the Mount Wilson Observatory (north: solid black line; south: dashed black line) and the Wilcox Solar Observatory (north: solid yellow line; south: dashed yellow line). It is clearly visible that the reversal of the polar field begins when the large-scale magnetic structures hosting filaments (see the “tongue-like” features) reach near the polar region in both hemispheres. This result reconfirms earlier reports that the beginning of these “rush to the poles” can be treated as an indicator of the imminent reversal of the polar field (Makarov & Sivaraman 1989; Altrock 1997; Shimojo et al. 2006; Li et al. 2008; Hao et al. 2015; Gopalswamy et al. 2016).
We further compare the timing of filaments reaching the polar caps (regions beyond ±75°) with the reversal of the polar field in both hemispheres and investigate the degree of their temporal conjunction. In Figure 2, the data points denoted by blue stars and red squares (for the northern and southern hemispheres, respectively) represent the relevant timings quantitatively. The overlap of the $y = x$ line over the data points confirms our conjecture that the “rush to the poles” features associated with filaments near the polar cap regions indicates the incoming polar field reversal.

The histogram in Figure 3(a) reveals that the latitudinal distribution of the geometric centers of the filaments exhibits a bimodal nature, with two peaks between 10° and 30° in both hemispheres. The high concentration at low latitudes indicates that filaments are closely associated with the magnetic activity occurring around the active region (AR) belts in both hemispheres. These results are consistent with the earlier findings by Hao et al. (2015) and Tlatov et al. (2016), who used different data sources. We further show that the longitudinal positions of the filaments’ centroids are evenly distributed over 360° (Figure 3(b)).

3.1.2. Variation of Filament Length

We consider total filament length a better indicator of the solar magnetic activity as compared to the total number of filaments present in any individual Carrington map because the same number of filaments, but with greater total length, indicates the presence of higher magnetic flux content on the solar surface. We measure a quantity, $L_{\text{total}}$, the total filament length corresponding to a certain Carrington map by summing the length of all filaments present in that particular map, which shows a cyclic variation in phase with the 11 yr solar cycle. To examine the different origins of filament formation, we further sub-categorize the filaments into two classes depending on the association of their geometric center with the sunspot activity belts where the positions of sunspots are determined from the RGO-USAF/NOAA database. We define filaments with their geometric center falling within the pair of black lines (see Figure 4) in both hemispheres as activity-belt associated filaments (AA-filaments hereafter) and their cumulative length as $L_{\text{AA}}$. Filament centers situated outside of these black lines are considered to be activity-belt unassociated filaments (UN-filaments), and their cumulative length is $L_{\text{UN}}$. The AA-filaments and UN-filaments are represented in Figure 4 by green and blue asterisks, respectively. The emergence of sunspots along the activity belt can naturally influence the formation of AA-filaments on a smaller scale; whereas the UN-filaments can be considered to be predominantly governed by the large-scale structures of the magnetic field.

Figure 5 depicts the variation of $L_{\text{total}}$ (black curve), $L_{\text{AA}}$ (green curve), and $L_{\text{UN}}$ (red curve) during cycles 20–23 in comparison to the AR area variation (denoted by the orange curve). It is evident that the AA-filaments are the primary contributors to the total filament length and they display a prominent solar-cycle-like modulation. The complex magnetic field distribution throughout the activity belt creates a favorable environment for AA-filament formation. However, during cycle 20, 21, 22, and 23 minima (around the years 1974, 1986, 1995, and 2008, respectively), $L_{\text{UN}}$ exceeds or becomes comparable with $L_{\text{AA}}$, which demonstrates that during the solar minimum filaments mostly originate from the large-scale structures. In general, the filament length increases quite steeply during the rising phase of solar cycles compared to their descending phase. We speculate that the distinct slow decay rate of filament length throughout the descending phase of cycle 23 is coupled with the elongated minimum of that cycle. We cannot comment on this aspect regarding the other cycle minima due to the limited availability (or discontinuity) of data. In case of UN-filaments, the cyclic modulation is less noticeable.

To quantify the inter-dependency between filament length and solar activity, we perform a correlation analysis. The Spearman rank correlation coefficient between $L_{\text{total}}$ and AR area is 0.63 with a p-value of 0, whereas the degree of correlation increases in the case of AA-filaments; the rank correlation coefficient is 0.75 with a p-value of 0. However, the high-latitude UN-filaments do not correlate with the AR area.

3.1.3. Statistics of Filament Tilt Angles

We determine the tilt of a particular filament by identifying the angle its axis forms with the local latitude. Each filament is fitted with a suitable straight line to deduce its axis and associated tilt angle. We presume that a thorough investigation of tilt angle distribution can shed light on the origin of filament formation. Figure 6 consists of a series of histograms representing frequency distribution of filament tilt angles in the two hemispheres with different latitude and length criteria. In our study, filaments with length varying from 0 to 28 Mm (i.e., mean–σ/2) are regarded as short, and those with length greater than 52 Mm (i.e., mean+σ/2) are considered to be long. In general, the filaments form along the PILs on the solar surface. Since the PIL associated with a bipolar AR separates positive and negative polarities, it is expected to be oriented perpendicular to the line joining the centers of the two spots of that particular AR. According to Hale’s polarity law (Hale et al. 1919), the sunspot should have negative and positive tilt angles in the northern and southern hemispheres, respectively. Therefore the tilt angles of the filaments linked with ARs (those following Joy’s law) should be positive in the northern.
hemisphere and negative in the southern hemisphere. The first three panels of Figure 6 (images (a) to (i)) represent the frequency distributions of tilt angles in the northern hemisphere. Figure 6(b) shows that longer filaments are prevalent. In plotting the histograms of tilt angle distribution of AA-filaments under different classes, (i.e., long and short), we find that they are predominantly long with negative tilts (see Figure 6(d)–(f)); hence they are not closely associated with the ARs. This result leads us to consider that long filaments form along the PILs which originate from the large-scale magnetic structure on the solar surface. Surprisingly, the short AA-filaments (see Figure 6(f)) also have primarily negative tilt angles, which is contrary to our expectation of typical intra-AR filament orientation. There might be two possible explanations: first, a filament can form between two different ARs in which case tilt angle alignment is precisely opposite to an intra-AR filament, as described in Martens & Zwaan (2001); second, these small AA-filaments are generated from the same large-scale structures hosting long filaments. Since the McIntosh database lacks detailed magnetic field information, we cannot conclusively determine the origin of these short AA-filaments. Evidently, UN-filaments mostly have negative tilt angles (Figures 6(g)–(i)) as they are bound to originate from the large-scale structures. The last three panels (images: (j) to (r)) of Figure 6 consist of histograms depicting the tilt angle distribution in the southern hemisphere. Irrespective of the length or positional classification, the tilt angles of the southern hemispheric filaments are predominantly positive. These observations confirm that large-scale magnetic structures primarily govern filament formation. The rest of the filaments with their length varying in the range of mean $\pm \sigma/2$ also show dominant negative (positive) tilt angle in northern (southern) hemisphere regardless of their latitudinal positions concerning the sunspot activity belt. Utilizing the positional information of sunspots present in the Carrington maps, we have simultaneously identified filaments with their geometric centers falling within ten degrees radii of any sunspot, and characterized them as sunspot-associated filaments. In the northern and southern hemispheres, the percentages of short sunspot-associated filaments with negative and positive tilt are 62% and 58%, respectively, consistent with the results obtained in case of short AA-filaments. Since the McIntosh database only provides positional information, investigating the chirality of filaments (Martin 1998; Yeates et al. 2007, 2008; Yeates & Mackay 2009) is beyond our scope. The above analyses corroborate that distribution of tilt angles over latitude is not random (Tlatov et al. 2016) but follows systematic rules.

We further perform a Rayleigh test of uniformity on the tilt angle data of filaments belonging to the northern and southern hemispheres separately. The Rayleigh test evaluates whether the tilt angles are equally scattered over the full range of $-90^\circ$ to $90^\circ$ based on circular statistical data analysis. In case of the northern hemispheric filaments’ tilt angles, the Rayleigh Z statistic value is 0.5 with a p-value of zero, whereas the test statistic value is 0.49 with a p-value of zero for those present in the southern hemisphere. The test results reject the null hypothesis of uniformity, thus indicating that the tilt angles of the filaments are not evenly distributed over $-90^\circ$ to $90^\circ$. In Figure 7, we study the variation of average tilt angle (denoted by the blue curve), which is primarily negative in the northern and positive in the southern hemisphere, validating our earlier findings in the analyses of tilt angle distribution. In the same figure, the modulations of average positive (red curve) and negative (green curve) tilt angle with latitudes are depicted. We notice that the average signed tilt angle is maximum near the equator and decreases as we move to higher latitudes. This occurs because, with increasing latitude, the PILs hosting the filaments become more parallel to the equator.

### 3.2. Properties of PILs

The PILs are the lines separating two opposite magnetic polarities on the solar surface. We measure the length of every PIL using the relation described in Equation (1), and finally calculate the total length of PILs for each of the 442 Carrington maps (1967 April–2009 July) by adding their individual lengths.

#### 3.2.1. Variation of PIL Length

The time variation of the total length of the PILs (represented by the solid black line in Figure 8) shows a strong correlation with the cycle of sunspot area orange line). The Pearson linear
correlation coefficient is 0.61 with a p-value of $6.37 \times 10^{-46}$. The total length is primarily influenced by the AA-PILs (solid green line), which we measure by adding the length of PILs within the region enclosed by the pair of black lines in Figure 4. We believe that the complex distribution of PILs around ARs amplifies the overall length in lower latitudes. As the number of ARs drops significantly during cycle minima, we observe a decrease in AA-PIL length during those periods. We notice a general growth in the length of activity-belt unassociated PILs during solar minima (through the years 1974–1975, 1984–1987, 1994–1995, and 2005–2008), reasonably similar to the variation of filament length. However, we encounter an unexpected rise in the PIL length from 2008, which cannot be explained by our current understanding of PIL formation. Since a filament always forms over the PILs, a strong correlation exists between PIL and filament length with a Pearson linear correlation coefficient of 0.74 with a p-value of $2.25 \times 10^{-77}$.

3.3. Properties of the Coronal Hole

Apart from filaments and PILs, the Carrington maps in the McA also store information on the coronal holes appearing on the solar disk. Our primary objective is to investigate the time evolution of the coronal hole area over the solar cycle. A total of 442 Carrington maps from the McA are used to acquire coronal hole area information. Apart from the three aforementioned significant data gaps in this database (see Section 2), coronal holes are absent from all Carrington maps from 1967 April to 1973 November. We compute the coronal hole area using

$$ A = \sum_n R_n^2 \cos \theta \, d\theta \, d\phi $$

where $A$ is the coronal hole area, $n$ is the total number of pixels associated with the coronal hole with each pixel having
latitudinal and longitudinal coverage of $\delta \theta$ and $\delta \phi$, respectively. $R$, $\theta$, and $\phi$ are defined as below Equation (1).

### 3.3.1. Coronal Hole Area Variation

In Figure 9, the time variation of total coronal hole area associated with individual Carrington maps along with the sunspot area is depicted. We define coronal holes present above $40^\circ$ latitudes as high-latitude coronal holes. The time evolution of the area associated with these high-latitude coronal holes is shown by a green curve. It is quite apparent that coronal holes primarily appear at higher latitudes throughout the major period of solar cycles. The high-latitude coronal hole area reaches its peak value during solar minima (e.g., cycle 21 minimum: year 1985; cycle 22 minimum: 1995; cycle 23: 2004), and decreases as the sunspot cycle approaches its maximum activity. In

**Figure 6.** Frequency distribution of tilt angles of filaments plotted for different length and latitude criteria in the two hemispheres. Sub-figures (a) to (i) depict distributions of filament tilt angles in the northern hemisphere, whereas sub-figures in the last three panels (j) to (r) represent the same in the southern hemisphere. Sub-figure (a) corresponds to the distribution of all filaments in the northern hemisphere. Sub-figures (b) and (c) show the tilt angle distribution in the northern hemisphere for long (>52 Mm) and short (<28 Mm) filaments, respectively. Sub-figure (d) represents the distribution of AA-filaments in the northern hemisphere, which is further sub-categorized in long and short filaments, as shown in (e) and (f). Tilt angle distribution associated with UN-filaments are represented in sub-figures (g) to (i) with similar long-short length segregation. Sub-figures (j) to (r) outline the tilt angle frequency distribution under the same length and latitudinal classification for filaments present in the southern hemisphere. From these series of figures it is apparent that majority of the northern hemispheric filaments have negative tilt angles and southern hemispheric filaments exhibit a dominance of positive tilt.

**Figure 7.** Average tilt angle variation of filaments with latitude. Red and green curves depict the variation of average positive and negative tilt angle of filaments with latitude, respectively. The blue curve shows the modulation of the averaged cumulative tilt angle (signed) with latitude.

**Figure 8.** Total PIL length (denoted by the black curve) variation during a solar cycle showing a positive correlation with the sunspot area, the evolution of which is represented by the orange curve. The green and red curves show the length variation of AA-PILs and UN-PILs, respectively, during the last four solar cycles. For consistency, we apply a 13 month running mean on every variable presented in this figure.
contrast, the low-latitude coronal holes (depicted by the red curve) appear predominantly during the solar cycle and generally disappear during a sunspot minimum. The correlation analysis between high-latitude coronal hole area and sunspot area shows a negative correlation; the Pearson linear coefficient is $-0.58$ with a p-value of $6.8 \times 10^{-34}$. However, the low-latitude coronal holes do not possess any correlation with sunspot area, resulting in overall decrease in the correlation value between the total coronal hole area and sunspot area, such that the Pearson correlation coefficient is $-0.43$ with a p-value of $1.3 \times 10^{-17}$. Coronal holes always appear over the open magnetic field lines which are extended from the photosphere to the solar corona and mostly populated beyond 40° latitudes in both hemispheres. The high-latitude open field lines near the polar regions are governed by the global dipolar magnetic configuration of the Sun. The amplitude of this dipole becomes minimum during a sunspot cycle maximum. Therefore, the prominent negative correlation between high-latitude coronal hole area and sunspot area is quite apparent in this context.

3.4. Hemispheric Asymmetry in Filament Length, PIL Length, and Coronal Hole Area

The solar magnetic activity is observed to be somewhat asymmetric in the two hemispheres, which inherently introduces north–south asymmetry in different magnetic features appearing on the solar photosphere and corona. We define the asymmetry in the sunspot area, which reasonably represents the magnetic flux input on the solar surface, by

$$A_s = \frac{N_s - S_s}{N_s + S_s},$$  

where $N_s$ and $S_s$ are the total area of the sunspots that emerged during each year of the observational period in the northern and southern hemisphere, respectively. The time variation of $A_s$ during solar cycles 20–23 is depicted by the orange curve in panel (d) of Figure 10, showing a surplus of magnetic activity in the southern hemisphere. In the following sections, we explore the hemispheric asymmetry of different observables in the McIntosh database and their degree of correlation with the asymmetry present in the sunspot area.

3.4.1. North–South Asymmetry of Filaments

Earlier studies (Li et al. 2003, 2010; Hao et al. 2015; Kong et al. 2015) reported that the filament number possesses hemispheric asymmetry, and changes with time. We define asymmetry in filament length by a quantity $A_f$,

$$A_f = \frac{N_f - S_f}{N_f + S_f},$$  

where $N_f$ and $S_f$ are the total filament length in the northern and southern hemisphere, respectively. Naturally, if $A_f > 0$, the total filament length in the northern hemisphere dominates that in the south. We find that $A_f$ fluctuates over the time of observation with a prominent inclination toward the southern hemisphere (see panel (a) of Figure 10). Only during a few short periods (for example, the years 1968, 1971, 1980, 1995, and 1999) we observe filaments belonging to the northern hemisphere dominating those in the south. The hemispheric asymmetries in total filament length show a weak correlation with the sunspot area with a linear correlation coefficient of 0.32 with a p-value of 0.0493.

3.4.2. North–South Asymmetry of PILs

The development of PILs is entirely regulated by the magnetic activity on the solar surface, which usually exhibits hemispheric asymmetry. Therefore, PILs are bound to show hemispheric preferences. We define a normalized north–south asymmetry index for PIL ($A_p$) using the following formula:

$$A_p = \frac{N_p - S_p}{N_p + S_p},$$  

where $N_p$ and $S_p$ are the total length of PILs in the northern and southern hemisphere, respectively. If $A_p > 0$, the northern hemisphere shows dominance over the south regarding the total length of PILs. Figure 10(b) depicts the variation of the yearly averaged north–south asymmetry index of the PILs. Similar to the hemispheric asymmetry existing in filament length, we observe a southern hemispheric dominance in the PIL length over the whole period of the available data. The hemispheric asymmetries in total PIL length show a weak correlation with
the sunspot area with a Spearman rank correlation coefficient of 0.30 with a p-value of 0.0719. A correlation analysis between the hemispheric asymmetry found in filaments and PILs confirms that their origins are physically interconnected. We find the Spearman rank correlation coefficient to be as high as 0.69 with a p value of $2.92 \times 10^{-6}$.

3.4.3. North–South Asymmetry in the Coronal Hole Area

We define the normalized asymmetry index of the coronal hole area by

$$A_c = \frac{N_{c,\text{north}} - N_{c,\text{south}}}{N_{c,\text{north}} + N_{c,\text{south}}}$$

(6)

where $N_{c,\text{north}}$ and $N_{c,\text{south}}$ are the total area of coronal holes in the northern and southern hemisphere, respectively. The index $A_c > 0$ implies that the total area of coronal holes in the northern hemisphere exceeds those in the south. The modulation of $A_c$ is shown in Figure 10(c), which mostly varies between $+/-0.1$ except for a few years. Unlike the asymmetry in filament or PIL length, $A_c$ fluctuates between positive and negative values throughout the time span of observation, indicating no consistent hemispheric dominance. Furthermore, asymmetry in coronal holes is almost uncorrelated with the sunspot area asymmetry.

4. Conclusions

We have explored different properties of filaments, PILs, and coronal holes over the past four solar cycles, starting from the maximum of solar cycle 20 (1967 April) to the beginning of cycle 24 (2009 July) using the McIntosh database. Despite the presence of data gaps, our analysis of 442 Carrington maps spread over 36 years establishes some important trends. We find a cyclic behavior of total filament length with time that is consistent with earlier reports (Hao et al. 2015; Tlatov et al. 2016). The variation of the total PIL length with time shows a cyclic behavior similar to the solar cycle. Analyzing the PIL length in the backdrop of their association with the sunspot activity belt reveals that AA-PILs contribute more toward the cumulative trend. We find a negative correlation between high-latitude coronal hole area and sunspot area. The high-latitude (>40°) coronal holes are the main contributors to their total area. This modulation of coronal hole area with time is understood in the context of the evolution of open magnetic field lines through different phases of a solar cycle. We further find that hemispheric asymmetry in the filaments and PILs is weakly correlated with asymmetry in sunspot areas. However, the asymmetry in the coronal hole area is found to be uncorrelated with sunspot area asymmetry, suggesting processes other than (asymmetric) flux emergence may govern the former.

Additionally, we classify filaments based on the latitudinal positions of their geometric centers to explore their connection with the photospheric magnetic environment. The AA-filaments contribute more toward the overall cyclic variation compared to the UN-filaments, thus implicating complex magnetic field distribution and flux emergence and cancellation within the sunspot activity belt. The latitudinal distribution of filaments is bimodal with peaks between $10^\circ$ and $30^\circ$ in both hemispheres, which is consistent with the overall latitudinal profile of magnetic flux emergence.

The butterfly-like spatio-temporal distribution of long filaments reveals a distinguishable feature: the poleward migration of high-latitude filaments during solar maxima. Through quantitative analysis we find this to be co-temporal with the initiation of global, solar polar field reversal. We propose that high-latitude filament migration could be a tracer of flux cancellation at the high latitudes, leading to the reversal of the old cycle polarity.

Average tilt angles of filaments decrease from the equator toward the poles, consistent with earlier findings by Tlatov et al. (2016), Chatterjee et al. (2017), and Hao et al. (2015). The tilt angle statistics show an unexpected dominance of negative tilt angle in the northern hemisphere and positive tilt angle dominance in the southern hemisphere. This trend remains even when we segregate the filaments depending on their association with the sunspot activity belt. Based on this we conclude that filament tilt angle distribution is governed by the large-scale magnetic structures on the solar surface and not the orientation of small-scale intra- or inter-AR magnetic fields. In summary, our work has established a substantial dependency of filament formation on large-scale surface magnetic field distribution through detailed analyses.

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