Magnetic Twists of Solar Filaments

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Abstract

Solar filaments are cold and dense materials situated in magnetic dips, which show distinct radiation characteristics compared to the surrounding coronal plasma. They are associated with coronal sheared and twisted magnetic field lines. However, the exact magnetic configuration supporting a filament material is not easy to ascertain because of the absence of routine observations of the magnetic field inside filaments. Since many filaments lie above weak-field regions, it is nearly impossible to extrapolate their coronal magnetic structures by applying the traditional methods to noisy photospheric magnetograms, in particular the horizontal components. In this paper, we construct magnetic structures for some filaments with the regularized Biot–Savart laws and calculate their magnetic twists. Moreover, we make a parameter survey for the flux ropes of the Titov–Démoulin-modified model to explore the factors affecting the twist of a force-free magnetic flux rope. It is found that the twist of a force-free flux rope, $T_{\text{p}}$, is proportional to its ratio of axial length to minor radius, $L/a$, and is basically independent of the overlying background magnetic field strength. Thus, we infer that long quiescent filaments are likely to be supported by more twisted flux ropes than short active-region filaments, which is consistent with observations.

Unified Astronomy Thesaurus concepts: Solar corona (1483); Solar filaments (1495); Solar prominences (1519); Solar magnetic fields (1503)

1. Introduction

Solar filaments are one of the most fascinating structures embedded in the corona. Their temperature ($\sim$7000 K) is much lower and their density ($10^{10}$–$10^{11}$ cm$^{-3}$) is much higher than their surroundings, causing distinct radiative characteristics. They usually appear as dark and extended filamentary structures when viewed against the solar disk, while they are seen as bright cloud-like prominences when seen beyond the solar limb. It has been revealed that the cold and dense plasmas originate from the chromosphere (Spicer et al. 1998; Wang 1999; Berger et al. 2011; Xia & Keppens 2016). Solar filaments are intimately related to solar flares and coronal mass ejections (CMEs; Chen 2011), which are powered by the nonpotential coronal magnetic field. Therefore, solar filaments are the effective tracers of sheared and/or twisted magnetic structures. Generally, the magnetic structure of filaments is described by two typical models: the inverse-polarity magnetic flux rope (MFR) model (Kuperus & Raadu 1974), and the normal-polarity magnetic sheared arcade model (Kippenhahn & Schlüter 1957). Chen et al. (2014) proposed an indirect method to determine the magnetic configuration type of a filament based on the conjugate draining sites upon filament eruption. Applying this method to 571 solar filaments, Ouyang et al. (2015, 2017) found that 89% of solar filaments are supported by MFRs and 11% are supported by magnetic sheared arcades.

Based on different magnetic environments, it is quite general to divide filaments into quiescent and active-region types (Mackay et al. 2010). Many previous works have revealed that these two types of filaments have distinct properties, such as the morphology, dynamics, magnetic configuration, and so on (McCauley et al. 2015; Ouyang et al. 2017; Xing et al. 2018; Zou et al. 2019). Regarding the morphology, quiescent filaments are typically 30 Mm high and 200 Mm long, whereas active-region filaments are usually less than 10 Mm high and typically 50 Mm long (Tandberg-Hanssen & Malville 1974; Tandberg-Hanssen 1995; Filippov & Den 2000; Engvold 2015). Although overall 89% of solar filaments are supported by MFRs, the preference of magnetic configuration of two types of filaments is different: Regarding quiescent filaments, 96% of them are supported by MFRs, while only 4% are supported by sheared arcades. On the contrary, for active-region filaments, 40% of them are supported by sheared arcades (Ouyang et al. 2017). This result seems counterintuitive since, compared to quiet regions, active regions are more nonpotential and more complex, which favors the existence of an MFR (van Ballegooijen & Martens 1989; Mackay et al. 2008; Xia et al. 2014). In this paper, we attempt to provide an explanation for this puzzle from the perspective of magnetic topology.

Coronal magnetic field is essential to fully understand the filament structures. However, the magnetic field in the corona is difficult to measure directly so far. Therefore, several approaches have been proposed to diagnose the coronal magnetic field. One method is coronal seismology, which utilizes coronal loop oscillations or filament oscillations (Tripathi et al. 2009; Zhang et al. 2013). Recently, Yang et al. (2020) mapped the global magnetic field in the corona based on the magnetoseismology. Another extensively used method is nonlinear force-free field (NLFFF) modeling (Yan et al. 2001; Régnier & Amari 2004; Canou et al. 2009; Guo et al. 2010; Jing et al. 2010; Inoue et al. 2012; Jiang et al. 2014; Yang et al. 2015, 2016; Zhong et al. 2019; Qiu et al. 2020). However, when the photospheric magnetic field is weak or the flux rope is high lying, the twisted magnetic structure is hard to obtain by the traditional extrapolation methods. This is because the traditional extrapolation methods strongly rely on the photospheric magnetogram, which is the only constraint. If the horizontal magnetic field is not significantly larger than the noise, the extrapolation frequently leads to a simpler magnetic configuration in the corona, i.e., low-lying sheared arcades. In addition, information is hard to transform correctly from the
bottom to high-lying regions owing to numerical errors. Unfortunately, many filaments are located in decayed active regions or quiet regions, where the horizontal magnetic field is very weak. To construct complicated magnetic structures with a possible MFR, some researchers suggested that coronal observations can be utilized to constrain the magnetic structure. For example, van Ballegooijen (2004) proposed the flux rope insertion method to construct a twisted magnetic structure directly, which has been extensively applied in many events (Bobra et al. 2008; Savcheva & van Ballegooijen 2009; Su et al. 2015; Huang et al. 2019). It is noted that the inserted flux rope deviates from an equilibrium state, which can be achieved by magnetofrictional relaxation. Based on this method, some magnetic structures of quiescent or polar crown filaments have been constructed (Su & van Ballegooijen 2012; Su et al. 2015; Luna et al. 2017; Mackay et al. 2020). Recently, Titov et al. (2018) proposed to use the regularized Biot–Savart laws (RBSLs) to model an approximately force-free flux rope. One of the advantages of this technique is that the flux rope can have any shape in the three-dimensional space. With this technique, Guo et al. (2019) successfully constructed an MFR for a large-scale filament with weak horizontal magnetic field on the solar surface.

In this paper, we construct the twisted magnetic structures for solar filaments and explore what factors affect their twist. Our work has three aims: (1) to construct the twisted magnetic structures for solar filaments with the RBSL method, (2) to understand the factors that affect the twist of an MFR, and (3) to explain the magnetic configuration preference between active-region filaments and quiescent filaments. The paper is organized as follows. In Section 2, we construct magnetic structures for five solar filaments with the RBSL method constrained by observations. In Section 3, we explore the factors affecting the twist of an MFR using the Titov–Démoulin-modified (TDm) model. The summary and discussions are given in Section 4.

2. Magnetic Structures in Observations

2.1. Coronal Magnetic Field Reconstruction

We reconstruct the magnetic structures of five filaments observed by the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) and by the Solar Terrestrial Relations Observatory (STEREO) missions. The Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board SDO provides full-disk coronal images at extreme-ultraviolet (EUV) wave bands. Its pixel size is 0''6, and its temporal cadence is 12 s. Meanwhile, the Extreme Ultraviolet Imager (EUVI; Wuelser et al. 2004) of the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI; Howard et al. 2008) suite on board STEREO supplies other views of the Sun at similar wavelengths, such as 171 and 304 Å. Thus, similar to previous works (Zhou et al. 2017, 2019; Guo et al. 2019; Xu et al. 2020), we can construct the three-dimensional filament geometry by the triangulation technique and take it as the main axis of the MFR. The vector magnetic field is obtained by the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012; Schou et al. 2012; Hoeksema et al. 2014) on board SDO. Similar to Titov et al. (2018) and Guo et al. (2019), we construct the MFR with the RBSL method and embed it in a potential magnetic field, which is extrapolated with the Green’s function method (Chiu & Hilton 1977). Then, the newly combined magnetic field is relaxed to a force-free state by the magnetofrictional code (Guo et al. 2016a, 2016b). The aforementioned reconstructions are performed with the Message Passing Interface Adaptive Mesh Refinement Versatile Advection Code (MPI-AMRVAC; Kepvens et al. 2012; Xia et al. 2018; Keppens et al. 2021). We select five eruptive filaments, which are all observed by SDO and STEREO simultaneously (see Table 1). Taking the first event as an example, the reconstruction process is described in detail in the following two paragraphs.

First, we need to construct the 3D path of the MFR axis. In the previous works (Zhou et al. 2017, 2019; Guo et al. 2019; Xu et al. 2020), the triangulation method was adopted to construct the 3D path of the filament axis, which is taken as the MFR axis. However, this method does not work well for the
low-altitude parts of a filament. Moreover, the endpoints of a filament might not correspond to the footpoints of the supporting flux rope (Hao et al. 2016; Chen et al. 2020). Thus, we propose a new method to approximate the 3D path of the MFR axis. According to Chen et al. (2014), the drainage sites upon filament eruption shed light on the MFR footprints. For example, the failed eruption of an active-region filament is observed by SDO/AIA 304 Å on 2012 May 5, as illustrated in Figure 1. At about 17:20 UT, this filament starts to rise and then rotates counterclockwise. Subsequently, some filament material slides down along the field lines as manifested by the new threads, which are pointed to by the black arrows in Figures 1(c) and (e). The material draining forms two conjugate weakly bright spots in the lower atmosphere, as indicated by the green circles in Figures 1(d) and (f). The drainage sites are left-skewed relative to the magnetic polarity inversion line, implying that this filament is dextral and corresponds to left-handed (i.e., with a negative sign) magnetic helicity (Wang et al. 2009; Chen et al. 2014). To see the material draining dynamics clearly, we select two slices along the material draining track, as indicated by the blue dotted lines in Figures 1(d) and (f). The time–distance diagrams of the AIA 304 Å intensity are shown in Figure 2, and one can see that the filament material moves downward. Once the MFR footprints are determined, the projection path of the MFR axis is outlined by blue filled circles in Figure 1(a). We adopt the triangulation method to measure the height of the filament axis, where the apex of the filament is recorded, but the heights of the rest points are fitted by a semicircle arc linking the filament apex and each MFR footpoint. Finally, since the RBSL method requires a closed path, we close it by adding a mirror subphotosphere arc. So far, we have obtained the 3D information of the MFR axis.

Second, we construct the magnetic structure of the filament. It contains two steps, namely, vector magnetic field pretreatment and coronal magnetic field extrapolation. With respect to the vector magnetic field pretreatment, we need to correct the projection effect (Guo et al. 2017a) and to remove the net Lorentz force and torque (Wiegelmann et al. 2006). Regarding the coronal magnetic field extrapolation, we utilize the RBSL method, where we need to set the physical parameters at first, i.e., the minor radius of an MFR (a), the axial magnetic flux (F), and the electric current (I), in addition to the 3D path of the MFR axis we obtained in the previous paragraph. However, the minor radius of the flux rope, a, is hard to measure directly, so we set it as a free parameter, and two values are chosen for each event in Table 1. Accordingly, the magnetic flux \( F_0 = (|F_+| + |F_-|)/2 = 4.13 \times 10^{20} \text{Mx} \) within the minor radius a can be estimated with the vertical component of the field. In this event, we take \( F = 5F_0 \) after a few tests since the MFR is likely to disappear during the ensuing relaxation if the magnetic flux \( F \) is too small. Moreover, the axial flux \( F \) is only an initial parameter for the RBSL method. It has to be added to the background potential field in order to maintain the vertical magnetic field in observations. Then, the current \( I \) is determined by Equation (12) in Titov et al. (2018). Next, we embed the constructed MFR into the background potential field and relax the aforementioned model to a force-free state by the magnetofrictional method (Guo et al. 2016a, 2016b). After relaxation, the force-free metric is \( \sigma_0 = 0.20 \), and the divergence-free metric is \( \langle |F| \rangle = 3.08 \times 10^{-4} \) (see Guo et al. 2016b, for details of the two metrics). Compared to previous studies, the values of these two metrics are basically acceptable (Guo et al. 2016a, 2019; Zhong et al. 2019). The reconstructed 3D magnetic field after relaxation is shown in Figure 3. One can see clearly that the reconstructed MFR shows a similar shape compared to the filament in the 304 Å observation. The reconstruction results of other events are shown in Figure 4.
2.2. Magnetic Topology

To further understand the physical properties of MFRs, we compute the magnetic topological parameters, including the quasi-separatrix layers (QSLs) and the twists. QSLs can be determined by calculating the squashing factor $Q$ (Priest & Démoulin 1995; Titov et al. 2002). We calculate $Q$ using the method proposed by Scott et al. (2017), but with the code written by Kai E. Yang. QSLs depict the border of an MFR and the favorite places for magnetic reconnection (Guo et al. 2013, 2017b; Liu et al. 2016). So, we measure the minor radius of an MFR by QSLs. The $Q$ distribution in the $x$-$z$ plane at $y = 0$ is shown in Figures 3(c) and 5(a), which clearly shows that the flux rope is surrounded by a quasi-circular QSL, and the minor radius of the MFR is estimated to be about 17 Mm. Then, we calculate the twist number in the following three steps following the formula given by Berger & Prior (2006), which was implemented by Guo et al. (2017b). First, we cut a slice almost perpendicular to the MFR. Second, we select the magnetic field line that is most perpendicular to the slice and take it as the main axis, as denoted by the red line in Figure 5(a). Then, 200 sample magnetic field lines within the MFR are selected to calculate the mean twist, as denoted by the yellow lines in Figure 5(a). Figure 5(b) illustrates the intersections of the MFR axis (red circle) and the sample field lines (purple circles) within the $x$-$z$ plane. We find that the mean twist for this case is about $-1.18$ turns, and the standard deviation is about 0.38. Figure 6(a) displays the twist numbers of the selected magnetic field lines at different distances from the MFR axis. Clearly, the MFR core has a lower twist than the outer shell.

In the same way, we also reconstruct the magnetic structures for the other four filaments. The geometric parameters of the MFRs and their mean twist numbers are listed in Table 1. Apparently the mean twist of an MFR is proportional to the axis length, $L$, and inversely proportional to its minor radius, $a$, defined by the quasi-circular QSL. In Figure 6(b), we plot the mean twist numbers of the five filaments as a function of $L/a$, the aspect ratio of the MFR. Note that for each filament there are two data points since two values of $a$ are assumed for each filament. It is seen that the mean twist almost linearly varies with $L/a$, with a correlation coefficient of 0.991. The inferred least-squares best fit is $T_w = 0.21(L/a) - 0.81$, as shown in Figure 6(b). It seems that, for a flux rope constructed by the RBSL method, the twist amount is highly related to its geometric structure.

3. Theoretical Model

3.1. Construction of Flux Ropes Based on the TDm Model

In Section 2, we constructed MFRs for five filaments and found a quantitative relationship between the twist of an MFR and its geometrical parameter $L/a$. However, it is not easy to perform a large parameter survey through observations. Instead, it would be helpful if we can check the correlation with a theoretical model. It is noticed that the TDm model provides analytical solutions for force-free MFRs, including...
two kinds of electric current profiles (Titov et al. 2014). One is concentrated in a thin layer at the boundary of the MFR, and the other has a parabolic profile, decreasing from the MFR axis to the boundary. In this section, we adopt the parabolic profile for the current density and then construct the TDm model with the RBSL method (Titov et al. 2018). The procedure is as follows.

First, we construct the bipolar-type background magnetic field \( B_0 \). We set two subphotosphere magnetic charges of strength \( q \) at a depth of \( d_q \), which lie on the \( y \)-axis at \( y = \pm L_q \). Second, we set physical parameters for the RBSL method. Different from that in Section 2, the axis path of an MFR in the TDm model has a semicircular shape, which follows a contour line of the potential magnetic field \( B_\perp \) on the \( y = 0 \) plane. The axis also needs to be closed by adding a subphotosphere semicircle. Hence, the flux rope axis is a circular arc with a major radius \( R_c \). According to the force balance conditions, the electric current \( I \) is determined by Equation (7) in Titov et al. (2014), and the axial flux of the MFR is calculated by Equation (12) in Titov et al. (2018). Third, we embed the flux rope constructed by the RBSL method with the aforementioned parameters into the potential magnetic field. Finally, we relax the combined magnetic field to a quasi-force-free state by the magnetofrictional code (Guo et al. 2016a, 2016b). As the benchmark, we set \( q = 100 \) T Mm\(^2\), \( L_q = 50 \) Mm, \( d_q = 50 \) Mm, \( R_c = 94.2 \) Mm, and \( a = 20 \) Mm, which is labeled as case RF, standing for “reference.” After the relaxation, the force-free metric is \( \sigma_f = 0.086 \), and the divergence-free metric is \( \langle |f_\parallel| \rangle = 1.47 \times 10^{-5} \), indicating that the flux rope model is almost force-free and divergence-free. Then, we measure the minor radius of the resulting MFR and calculate its twist number similar to those in Section 2. It is found that the mean twist is about 2.27 \pm 0.98 turns.

### 3.2. Parameter Survey

We explore how the twist of an MFR depends on its geometric and magnetic parameters, including the MFR length \( L \), the MFR minor radius \( a \), and the background magnetic field strength \( B_q \). To explore the effect of \( L \), we construct six magnetic field models with different \( R_c \) as listed in Table 2, and the other input parameters remain the same as those in case RF. Similarly, to investigate the effect of the MFR minor radius, we choose eight values of \( a \) as listed in Table 2, with the other input parameters being the same as those in case RF. Besides, we also study the influence of the background magnetic field strength on the twist of the resulting MFR. Keeping the other input parameters the same as those in case RF, we set the magnetic charges with different strengths. Table 2 lists the input parameters \((R_c, L, a, L/a, q, d_q, L_q)\) and the output quantities \((|T_\parallel|, \sigma_f, \langle |f_\parallel| \rangle)\) of the MFRs, where all the cases are categorized into three groups, with \( R_c, a, \) and \( q \) being the control parameters individually. Figure 7 depicts the QSLs and selected magnetic field lines in cases A7 and R5. It shows clearly that the MFRs are wrapped by closed QSLs.
Figure 4. AIA 304 Å images (left column) and the extrapolated coronal magnetic field lines superposed on longitudinal magnetograms (right column) of other events.
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Figure 5. (a) Distribution of the squashing factor $Q$ (color scale) and sample magnetic field lines (yellow lines) superposed on the longitudinal magnetogram (gray scale). The red line denotes the MFR axis. (b) Zoom-in view of the $Q$-map in the $x$-$z$ plane at $y = 0$. The red circle indicates the intersection of the MFR axis with the $x$-$z$ plane, and the purple circles indicate the intersections of the sample field lines of the MFR with the $x$-$z$ plane.

Figure 6. (a) Variation of the twists of selected magnetic field lines with the distance from the MFR axis in F1-2. (b) Mean twist of MFRs as a function of their aspect ratio $L/a$ of the five filaments as listed in Table 1. The data points of an individual filament are denoted by the same color. The dashed line is the linear fitting to the data points.

Figure 8 displays the twist distribution from the MFR axis to its boundary in four cases with different $a$ and $R_C$. It is seen that the twist of an MFR increases with its axial length but decreases with its minor radius. Interestingly, it is found that when $a$ is large or $R_C$ is small, the twist becomes nearly uniformly distributed from the MFR axis to the boundary. Otherwise, the TDm flux ropes with the parabolic current density profile have a weakly twisted core and a highly twisted shell. Figure 9 shows the relationship between the mean twist of an MFR and its minor radius in panel (a) and the axial length in panel (b). It is found in panel (a) that the mean twist of an MFR is inversely proportional to its minor radius with a Pearson correlation coefficient of $-0.920$, where $a$ is in units of Mm. On the other hand, as shown in Figure 9(b), the mean twist of an MFR increases linearly with its axial length, and the fitting function is $|\tau_w| = 0.014L - 0.48$ with a Pearson correlation coefficient of $0.996$, where $L$ is in units of Mm. It is further found that the twist of an MFR is independent of the background potential field even though the magnetic flux $F$ of the MFR is different in those cases. The reason is explained as follows. For MFRs of the TDr model with the parabolic current profile, unlike the TD99 model (Titov & Démoulin 1999), the magnetic flux $F$ is a linear function of current $I$ governed by Equation (12) in Titov et al. (2018), so the twist of an MFR derived by the TDr model mainly depends on its geometry.

Since the mean twist of an MFR is roughly proportional to both $1/a$ and $L$, it is straightforward to think that $|\tau_w|$ is proportional to the aspect ratio $L/a$ of the flux rope in the TDr model. We plot the variation of $|\tau_w|$ with $L/a$ as the red asterisks in Figure 10, where the data points are fit with the red dashed line. It is found that the variation can be fit with a linear function, i.e., $|\tau_w| = 0.26(L/a) - 0.15$, with a correlation coefficient of $0.995$. In order to compare the $|\tau_w|-L/a$ relationships between observations and theoretical model, we overplot the observational results (i.e., Figure 6(b)) in Figure 10, as indicated by the blue asterisks along with the fitted line, i.e., the blue dashed line. It is found that, with the same aspect ratio $L/a$, the twist in observations is systematically smaller than that of TDr flux ropes by $\sim 1$ turn, although their tendency is almost identical. This is explained as follows. The theoretical TDr flux ropes are closer to a force-free and divergence-free state, so generally only a few hundred iterations are needed in the magnetofrictional relaxation. However, to derive an MFR in a force-free state from observations, the magnetofrictional method is performed with many more iteration steps (according to our experience, about 60,000 steps), during which the electric current density distribution inside the MFR keeps changing, reducing its twist.
For example, the twist of an MFR decreases from 4.3 turns to 3.9 turns after relaxation in Guo et al. (2019).

### 4. Summary and Discussions

Twist is an important topological parameter of MFRs, and it is closely related to its stability and dynamics. Studies showed that a flux rope is likely to become kink unstable when its twist exceeds a threshold. Additionally, assuming that the magnetic helicity is conserved, some of the twist might be converted to writhe by an untwisting motion, which leads to the rotation of helicity is conserved, some of the twist might be converted to writhe by an untwisting motion, which leads to the rotation of the helical threads and material motions in an MFR (Green et al. 2007). Another more widely used method is the NLFFF model. Then, the twist can be calculated (e.g., Wang et al. 2019). In contrast, in the cases of the TDm models, the twist is related to the aspect ratio by \( T \sim \frac{r}{a} \). In the cases of the TDm models, we have \( T \sim \frac{r}{a} \). On the one hand, these two quantitative relationships can help us estimate the mean twist of a force-free MFR. On the other hand, these results can deepen our understanding on the magnetic structures of solar filaments, coronal MFRs, and interplanetary magnetic clouds (MCs).

#### 4.1. Difference of the Magnetic Configuration between Two Types of Filaments

Statistics shows that only 60% of the active-region filaments are supported by flux ropes, whereas 96% of the quiescent filaments are supported by flux ropes (Ouyang et al., 2017). In this subsection, we try to provide an explanation for this observational result by investigating the factors affecting the twist of an MFR.
Our parameter survey indicates that the twist of an MFR is proportional to its axial length, inversely proportional to its minor radius, and basically independent of the background magnetic field strength. As mentioned before, there is much difference between active-region and quiescent filaments. For example, compared to active-region filaments, quiescent filaments are usually longer and lie along the weaker and dipole regions (Tandberg-Hanssen & Malville 1974; Tandberg-Hanssen 1995; Filippov & Den 2000; Kuckein et al. 2009; Mackay et al. 2010; Engvold 2015), implying that quiescent filaments might have much longer magnetic field lines. Unfortunately, the minor radius of an MFR is difficult to measure directly in observations. However, it is expected that active-region filaments with high magnetic twists and small minor radius are more prone to becoming kink unstable compared to quiescent filaments for two reasons. First, the resulting high magnetic pressure leads to a small plasma $\beta$ (the ratio of the gas pressure to magnetic pressure) and hence a smaller threshold of kink instability according to Hood & Priest (1979). Second, small minor radius means a small volume of
Figure 9. Variation of the absolute value of the mean twist of an MFR, $|\bar{T}_w|$, as a function of its minor radius $a$ (panel (a)) and its axial length $L$ (panel (b)), as listed in Table 2. The red lines display the fitting curves.

Figure 10. Variation of the absolute value of the mean twist of the flux ropes vs. their aspect ratio $L/a$. The red and blue asterisks represent the MFRs in the TDm theoretical models and observations, respectively, which are fit with the red and blue dashed lines, respectively.

filament material. The resulting small weight of the filament cannot play the role to suppress kink instability as heavy filaments do (Fan 2018). Thus, we infer that the magnetic structures of quiescent filaments are likely to be more twisted than those of active-region filaments. This naturally accounts for why almost half of the active-region filaments, e.g., quiescent filaments located in weaker magnetic regions have a larger plasma parameter related to the MFR structure. Thus, an MFR with a large aspect ratio might have a large critical twist for the kink instability. Besides, according to Hood & Priest (1979), the critical twist increases with the plasma $\beta$. Compared to active-region filaments, quiescent filaments located in weaker magnetic regions have a larger plasma $\beta$, implying that the gas pressure contributes to make quiescent filaments stabler. Moreover, observations and numerical simulations also indicated that the gravity of a filament can suppress the onset of eruption, and the drainage can promote the eruption earlier (Seaton et al. 2011; Bi et al. 2014; Fan 2018; Jenkins et al. 2018; Fan 2020). Therefore, the gravity of filaments should not be neglected when studying the stability of large quiescent filaments. In a word, with our results, we tend to believe that it is not impossible for some quiescent filaments to be stably supported by highly twisted MFRs with 3–5 turns even before eruption, as recently modeled by Mackay et al. (2020).

On the other hand, in many cases, a long quiescent filament is supported by several flux ropes or an arcade of weakly twisted (say, $\sim$1.5 turns) MFRs as illustrated by the schematic Figure 6 in Chen (2011), rather than a single highly twisted flux rope. For example, Zheng et al. (2017) reported an eruption event after the interaction between two filaments inside a filament channel. Luna et al. (2017) reconstructed the coronal magnetic field for this event by using the flux rope insertion method. It shows that the filament channel corresponds to two weakly twisted flux ropes or sheared arcades, as illustrated by Figure 13(d) in Luna et al. (2017).

Indeed, while some authors showed that large filaments can be supported by low-twist MFRs or sheared arcades (Jibben et al. 2016; Luna et al. 2017), others showed that large filaments can also be supported by a single highly twisted MFR (Su & van Ballegooijen 2012; Su et al. 2015; Mackay et al.
Because of the intrinsic difficulty of coronal magnetic field extrapolation and the unreliable magnetic field measurement of the quiet region, the magnetic field and topological properties of quiescent filaments are still elusive. The specific magnetic structure supporting a quiescent filament might depend on the photospheric flows and their magnetic field evolution. We expect that future data-driven simulations can provide more hints.

4.3. Origin of Twists in Interplanetary Magnetic Clouds

Observations have revealed that large-scale interplanetary MCs detected by in situ instruments usually have highly twisted magnetic structures. For example, Hu et al. (2014) investigated 18 MCs with the Grad–Shafranov reconstruction method. They found that the mean twist of the MCs varies from 1.7 to 7.7 turns per astronomical unit, with an extreme case reaching 14.6 turns per astronomical unit. Case studies of highly twisted MCs originating from active regions, magnetic reconnection during eruption. We expect that future data-driven simulations can provide more hints.

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