Subsurface and Atmospheric Influences on Solar Activity
ASP Conference Series, Vol. 383, ©2008
R. Howe, R. W. Komm, K. S. Balasubramaniam, and G. J. D. Petrie, eds.

Filament Substructures and their Interrelation

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Abstract. The main structural components of solar filaments, their spines, barbs, and legs at the extreme ends of the spine, are illustrated from recent high-resolution observations. The thread-like structures appear to be present in filaments everywhere and at all times. They are the fundamental elements of solar filaments. The interrelation of the spines, barbs and legs are discussed. From observations, we present a conceptual model of the magnetic field of a filament. We suggest that only a single physical model is needed to explain filaments in a continuous spectrum represented by active region filaments at one end and quiescent filaments at the other end.

1. Filament Substructures

A typical solar filament is composed of a spine, barbs, and two extreme ends. The spine defines the upper horizontal part of a filament. Barbs are lateral structures that extend from some of the spine to the chromosphere. The ends, also called "legs," may be a collection of threads that appear to terminate at a single point or at multiple points. These components of filaments differ in appearance and relative importance in filaments in active regions, in quiescent filaments, and in "intermediate" filaments. "Intermediate" filaments are those between active region filaments and quiescent filaments, two categories at the extreme ends of the spectrum of filaments (Martin et al. 2007).

Recent high-resolution observations obtained with the Swedish 1-m Solar Telescope (SST; Scharmer et al. 2003) show fine detail everywhere within filaments. Figure 1 illustrates the Southern end of a quiescent filament in the Southern hemisphere. In the upper panel, one can see many thin threads in both the spine and the barbs. Most of the threads are inclined with the main axis. The lower panel shows one end of the filament which looks like a "fish-tail". Although, from the Catania Astrophysical Observatory (OACT) full-disk image (upper left corner of the image), the end structure seems to be more perpendicular to the filament main axis, the SST image shows that the fine threads that constitute the end are also aligned with the threads in the spine and the barbs.

Such high-resolution Hα images demonstrate that filament spines, barbs and ends are all composed of thin threads. Seven pieces of observational evidence have been provided that filament threads are field aligned and their magnetic pointing can be deduced unambiguously in almost all cases with the supplementary use of magnetograms (Martin et al. 2007). The Hα movies made from

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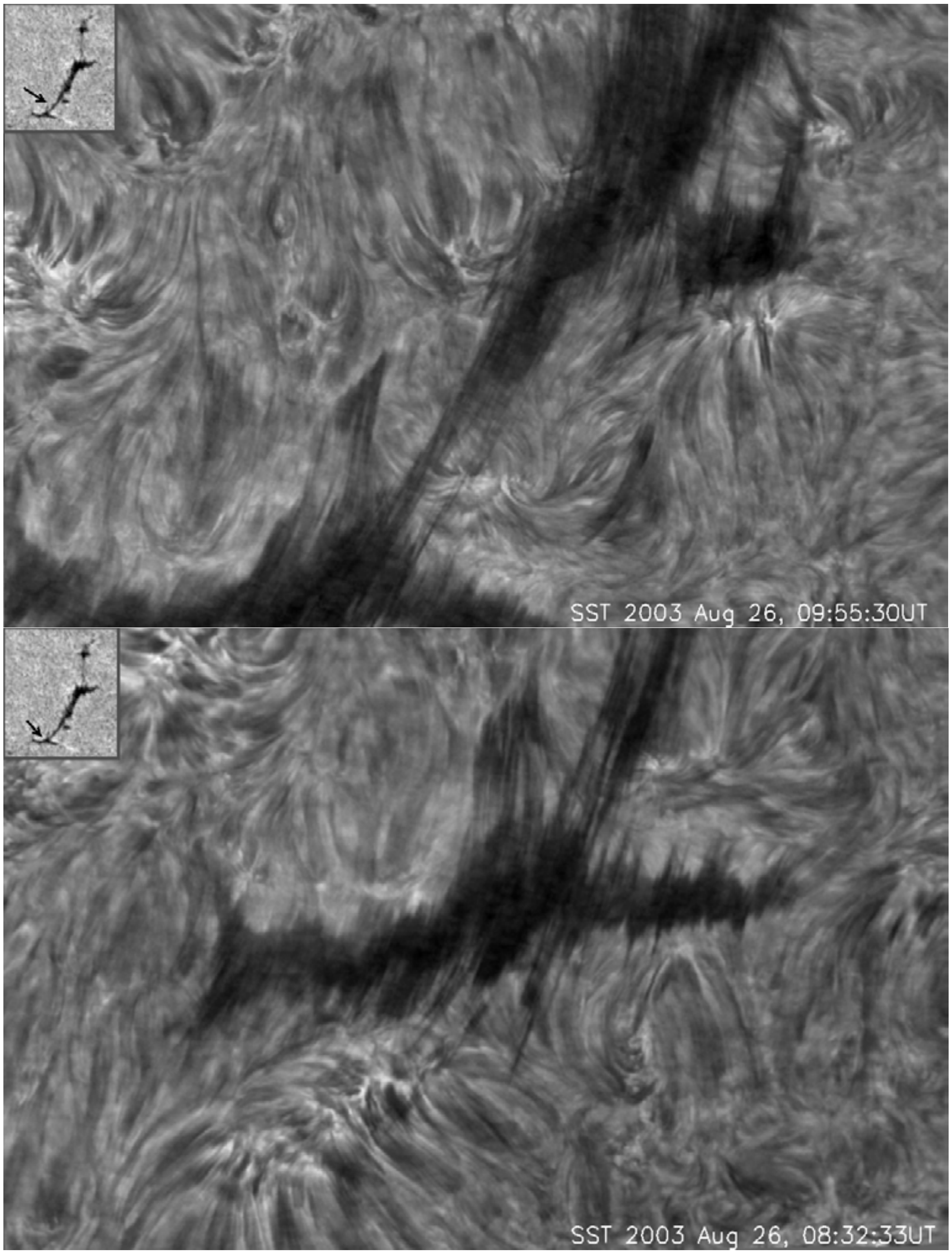

Figure 1. Adjoining parts of the Southern end of a filament observed in the Southern solar hemisphere with the Swedish 1-m Solar Telescope on 26 August 2003. The upper panel shows the filament spine and the barbs. The lower panel shows the extreme Southern end of the filament. The two small images (upper left corners of the two frames) are cut from the Catania Astrophysical Observatory (OACT) full-disk image (26 Aug 2003, 08:16:44UT) and show the approximate position of the filament sections.

high-resolution images further reveal that thin threads are present at any time and everywhere in filaments. We conclude that thin threads are the fundamental structures of solar filaments.

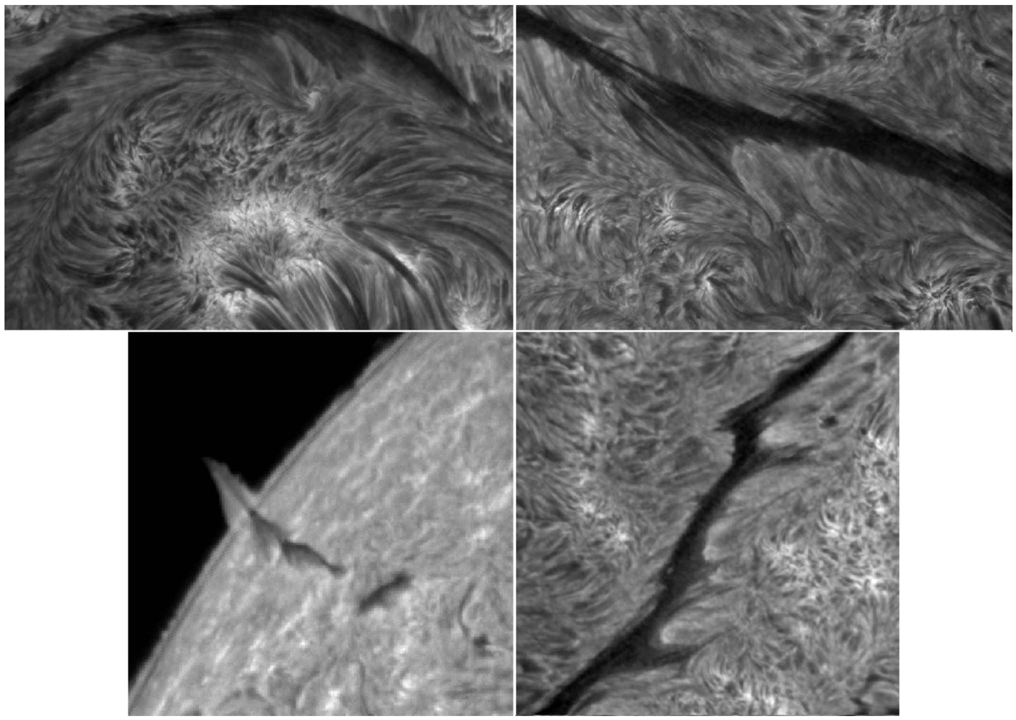

Figure 2. Four filaments seen from different perspectives. These images were chosen and oriented to closely correspond to the standard views in the 3-dimensional schematic drawing of a filament in Figure 3. *Upper left*: An active region filament seen from the side (27 Aug 2003). *Upper right*: An intermediate filament seen from above (27 Aug 2003). Lower left: An East limb filament seen from its West end (14 Jan 2002). Lower right: A quiescent filament seen partly from the side and partly above (6 May 2000). The upper two images are from the Swedish 1-m Solar Telescope. The lower left is from a full disk image from Big Bear Solar Observatory. The lower right image is from National Solar Observatory at Sacramento Peak.

2. Filament Topology Inferred From Observations

Figure 2 shows some examples of four different filaments seen from four perspectives chosen and oriented or flipped East–West to be similar to the views in the 3-dimensional schematic drawing of a dextral filament in Figure 3. The upper left panel shows the side view of an active region filament, where one again sees the threads in the spine and the barbs. The upper right panel illustrates the view of an intermediate filament with two independent barbs on either side of the spine. Many threads are stacked along the spine. Some depart smoothly from the spine with small inclinations down towards the chromosphere and form the barbs. The lower left panel shows an end view of a filament crossing the

East limb, which clearly shows several barbs extending from both sides of the spine to the chromosphere. This view reveals the narrowness of the spine and shows it in absorption above the limb because it has high optical thickness due to many threads in the line-of-sight. In contrast, the barbs, as usual, are seen in emission above the limb and in absorption against the disk. In the lower right panel, a quiescent filament with several barbs is viewed partly from the side and partly from above. This view favors the barbs on the west (right) side of the filament and therefore the barbs on this side appear to be longer than on the East (left side). Although some threads of barbs on the west side can appear to be aligned with threads on the East side, the barbs are independent structures on each side of filaments. The proof of this independence has required analyses of the same filament from different perspectives as made possible in the past only from observing them over long intervals as the Sun rotates as well as from observing many similar filaments at different locations on the Sun (Martin & Echols 1994; Martin, Bilimoria, & Tracadas 1994).

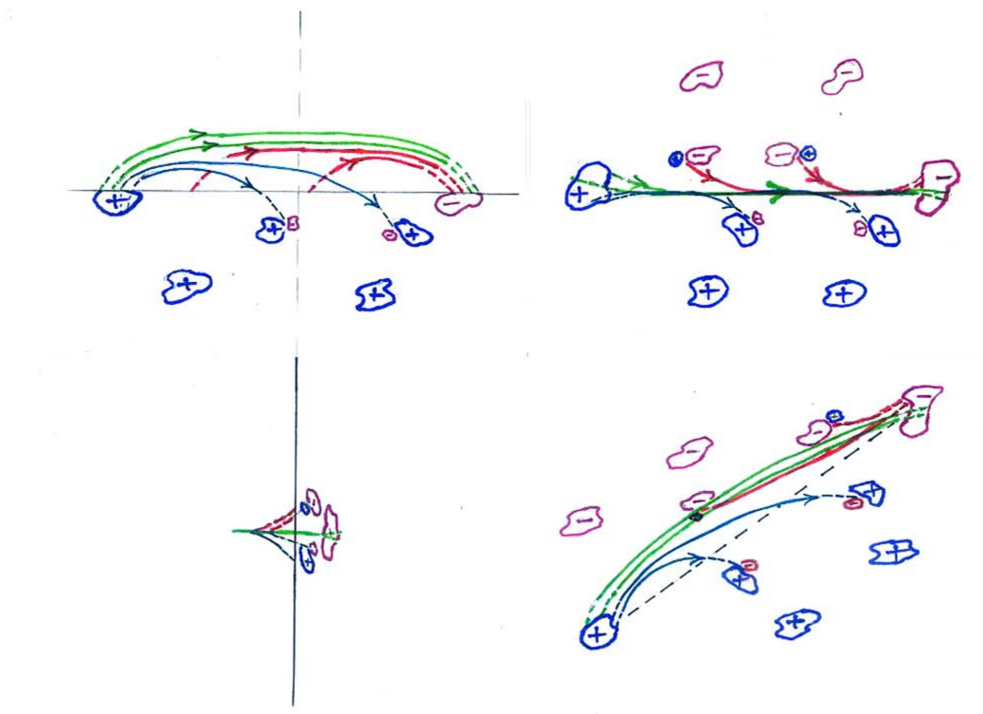

Figure 3. Topology of a dextral filament inferred from observations and schematically depicted as a three-dimensional object with six key field lines. The two longest field lines represent the part of the spine without barbs. Two field lines on each side extend from opposite ends of the filament and splay sideways to form the barbs. The upper left panel shows the view from the side, the upper right, the view from above, the lower left, the view from the end. The lower right panel shows the filament magnetic field in a "perspective" view that allows one to see the structure partly from all of the other three views.

Based on the above works and our conclusion that all filaments are composed of field-aligned threads, we present a conceptual 3-dimensional model of the magnetic field of a filament in Figure 3. The model is intended to illustrate the key features known from observations and also those that still need to be answered. Figure 3 includes four drawings of a schematic representation of the magnetic field of a single filament, with four views like those in Figures 2. In Figures 2 and 3, the four perspectives were selected to correspond to those most commonly shown in the standard drafting of three-dimensional objects. From left to right, top to bottom these are front, top, end, and "perspective" views. In Figure 3, the lines represent six conceptual magnetic field lines that are keys to understanding the magnetic fields of filaments.

2.1. Spines

In our conceptual magnetic model of a filament in Figure 3, part of the spine (green lines, in the on-line version of this paper) runs the full length of a filament. The spine is common to all filaments whether active region, intermediate or quiescent. Spines are long narrow ribbons with horizontal, parallel threads stacked vertically. Other parts of the spine smoothly lead outward from the polarity reversal boundary to become barb field lines. In our conceptual model, threads, that become parts of the barbs, were initially part of the spine magnetic field; by magnetic reconnection with nearby photospheric magnetic flux, their field lines have been shortened and "reconnected" to adjacent locations in the chromosphere/photosphere. The barbs are therefore regarded as secondary to the magnetic field of the spine without barbs.

Given knowledge of the polarity of the network magnetic field on only one side of a filament, the direction of the magnetic field along the purely spinal field lines can be found from the one-to-one chiral (handedness) relationships among solar features. For example, if the chirality of a filament is known to be sinistral from observing its barbs, the fibrils in the associated filament channel will also be sinistral (Foukal 1971; Martin et al. 1994), the overlying coronal loops will be right-skewed (Martin & McAllister 1996) and an X-ray sigmoid if present above the filament will be right-handed (Pevtsov 2002).

2.2. Barbs and Ends

The general direction of the magnetic field lines of the barbs (blue lines/red lines, in the on-line version) can be determined in the same way as for the purely spinal field lines. Their exact field direction is then known from the well-founded assumption that filament threads are everywhere parallel with the local magnetic field. In Figure 3 we depict field lines as having a "spinal" end and a "lateral" apparent end in the chromosphere at one side of the spine. The spinal end appears to terminate at the chromosphere and is associated with network magnetic field consistent in polarity with the purely spinal field lines. The lateral barb end is therefore deduced to be in the opposite polarity. Indeed, small pockets of opposite polarity magnetic fields are embedded among the network magnetic fields at or close to the end points of barbs as schematically represented in Figure 3. In magnetograms of sufficient spatial resolution, these pockets of opposite polarity field originate from ephemeral region bipoles or intranetwork magnetic fields opposite in polarity to the network. Such small pockets are known as the "minority" polarity (Martin 1998).

The ends of all field lines are shown in Figure 3 as dashed lines to indicate that the true rooting of the ends of filament threads is not yet established. However, it is known that the barbs terminate close to negative, minority polarity fields on the positive network side and close to positive minority magnetic fields on the negative field side of the filament.

By inference, the ends of the filament spine are originating at the boundaries of positive network fields and terminating at the edges of negative network fields. Because the field direction in the barbs is consistent with the field direction in the spine, it is then implied in the model (although not proven from observations) that the barbs terminate in the minority polarity. Some high quality images show the barbs terminating between the majority polarity and minority polarity features and sometimes joining small-scale filaments between positive and negative field interfaces.

3. General Comments on Filament Threads

Thin filament threads with typical width of 0.3 arc sec (Lin et al. 2005), close to the limit of the spatial resolution of the SST images, are assumed to be aligned with the local magnetic field. Images of time series show dynamic aspects of filament threads that are consistent with this assumption: First of all, the plasma is seen to move along the threads in both directions with typical speeds of 10–20 $\mathrm{km\,s^{-1}}$. This is usually referred to as counterstreamings (e.g., Zirker, Engvold, & Martin 1998; Lin, Engvold, & Wiik 2003). Secondly, individual threads or a group of threads oscillate up and down with periods from less than one minute to several hours (cf. Engvold 2004). These observed characteristics of filament threads reflect the dynamic nature of small-scale magnetic structures in filaments. Because of these effects and possible varying temperatures, the dark Hα plasma is generally inhomogenous along the threads. Some observed dark threads therefore appear detached from the main body of the filament. Thus, the true length of a magnetic field associated with a thread is very likely much longer than the apparent length of the dark Hα thread.

The direction of the threads in barbs in all of the high resolution SST images enable one to determine unambiguously whether a filament is sinistral or dextral. For example in Figure 1, the high-resolution SST image reveals that all the threads of the barb have nearly the same orientation relative to the threads in the spine. However, in some barbs such as the one in the upper right in the upper panel of Figure 1, only a few threads appear to connect the barb to the spine and there is an apparent gap between most of the barb and the spine due to a lack of cool, absorbing Hα plasma. Nevertheless, the barb can still be identified as belonging to a sinistral filament; according to the definition of sinistral, if one looks away and along the spine, and the barbs threads on the left side veer left and away from the spine to their apparent endpoints in the chromosphere, the filament is sinistral. Exchanging right for left in the above sentences, provides the definition of a dextral (right-handed) filament.

4. Concluding Remarks and Remaining Questions

High resolution images shown in this paper reveal small-scale thread-like structures in solar filaments. These long, thin, magnetic threads are the building blocks of all filaments. From the properties of these threads, we conclude that filaments have their own magnetic field separate from coronal magnetic fields that form a tunnel overlying them.

Quiescent filaments are tall with many barbs whereas active region filaments are low with few barbs but their fundamental structures are similar. All threads in barbs appear to emerge from threads of the spine. The magnetic nature of thin threads can be inferred from high resolution studies of the observed flows (counterstreaming) and filament oscillations. It is noticed that not all parts of the entire magnetic structure of filaments necessarily contain observable material in Hα at a given time.

Observations suggest that there is a continuous spectrum of filaments from active region filaments, intermediate filaments to quiescent filaments (Martin et al. 2007). From observations, we have presented a conceptual magnetic model, which seems to fit the whole spectrum of filaments. However, some key questions about filaments still need to be addressed. Some of these are: How is mass brought into the magnetic structure of a filament? How does the filament magnetic field interact with its magnetic environment? What processes are involved in the destabilization of filament magnetic fields?

Acknowledgments. The contribution of S. F. M. is supported by NSF grant ATM-0519249. Y.L. acknowledges the Norwegian Research Council grant FRINAT171012. The authors appreciate stimulating discussions with Terry Forbes, Yuri Litvinenko, K .S. Balasubramaniam, Alexei Pevtsov, Jonchul Chae, Nandita Srivastava, Vic Gaizauskas, and Duncan Mackay. Y. L. and O. E. thank the staff of the SST for their invaluable support with the observations. The Swedish 1-m Solar Telescope is operated on the island of La Palma by the Institute for Solar Physics of the Royal Swedish Academy of Sciences in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

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