THE EVOLUTION OF DARK CANOPIES AROUND ACTIVE REGIONS

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ABSTRACT

As observed in spectral lines originating from the chromosphere, transition region, and low corona, active regions are surrounded by an extensive “circumfacular” area which is darker than the quiet Sun. We examine the properties of these dark moat- or canopy-like areas using Fe\textsc{i}x 17.1 nm images and line-of-sight magnetograms from the Solar Dynamics Observatory. The 17.1 nm canopies consist of fibrils (horizontal fields containing extreme-ultraviolet-absorbing chromospheric material) clumped into featherlike structures. The dark fibrils initially form a quasiradial or vortical pattern as the low-lying field lines fanning out from the emerging active region connect to surrounding network and intranetwork elements of opposite polarity. The area occupied by the 17.1 nm fibrils expands as supergranular convection causes the active-region flux to spread into the background medium; the outer boundary of the dark canopy stabilizes where the diffusing flux encounters a unipolar region of opposite sign. The dark fibrils tend to accumulate in regions of weak longitudinal field and to become rooted in mixed-polarity flux. To explain the latter observation, we note that the low-lying fibrils are more likely to interact with small loops associated with weak, opposite-polarity flux elements in close proximity, than with high loops anchored inside strong unipolar network flux. As a result, the 17.1 nm fibrils gradually become concentrated around the large-scale polarity inversion lines (PILs), where most of the mixed-polarity flux is located. Systematic flux cancellation, assisted by rotational shearing, removes the field component transverse to the PIL and causes the fibrils to coalesce into long PIL-aligned filaments.

Key words: Sun: activity – Sun: chromosphere – Sun: filaments, prominences – Sun: magnetic topology – Sun: surface magnetism – Sun: UV radiation

1. INTRODUCTION

Active regions are often surrounded by an area whose brightness is reduced even relative to that of the quiet Sun. This phenomenon was first noted in observations of “circumfacular regions” in the Ca\textsc{ii} K-line (Hale & Ellerman 1903; St. John 1911). The dark areas, also prominent in Ca\textsc{ii} 854.2 nm spectroheliograms, were subsequently shown to coincide approximately with the iron-filing or “vortex” pattern of H\textalpha fibrils that rapidly appears around emerging active regions (Howard & Harvey 1964; Bumba & Howard 1965; Veeder & Zirin 1970; Foukal 1971a, 1971b; Harvey 2005, 2006; Rutten 2007; Cauzzi et al. 2008; Reardon et al. 2009). During the first week of development, the major axis of the fibril pattern expands at a rate of \(\sim 0.2 \text{ km s}^{-1}\), corresponding to roughly one supergranular cell radius per day.

With the advent of ultraviolet (UV) and extreme-ultraviolet (EUV) observations, it is now evident that the reduced emission around active regions characterizes a wide range of spectral lines originating in the chromosphere, transition region, and low corona (Moses et al. 1997; Feldman et al. 2000). Indeed, in emission lines formed at temperatures \(T \sim 0.5–1.0 \text{ MK}\) and in He\textsc{ii} 30.4 nm, these large moatlike areas, or “active-region canopies” as we henceforth call them, are sometimes mistaken for coronal holes. Like their H\textalpha counterparts, the EUV canopies consist of dark fibrilar structures, which are generally thought to trace out horizontal magnetic fields in the chromosphere.

Here, we use Fe\textsc{i}x 17.1 nm images and longitudinal magnetograms recorded with the Solar Dynamics Observatory (SDO) to study the properties of dark canopies around active regions. Our main objective is to clarify the relationship between the 17.1 nm fibril structures and the evolving photospheric field, on the assumption that the fibrils are aligned with the chromospheric field. We do not address the question of how the EUV canopies differ from those seen in the visible, or the related and more difficult question of how the spectral lines themselves are formed.

2. OBSERVATIONS

The Atmospheric Imaging Assembly (AIA) on SDO records full-disk images in seven EUV, two UV, and one white-light channel, with 0.6 pixels and 10 s cadence.\(^5\) The Helioseismic and Magnetic Imager (HMI) provides longitudinal magnetograms with similar spatial resolution, taken every 45 s in Fe\textsc{i} 617.3 nm.\(^6\) The AIA and HMI images were coaligned using the disk centers as the common reference point, after correcting for the factor of 0.844 plate-scale difference, determined from the ratio of AIA 170.0 nm and HMI disk diameters in pixels. The data employed here are all from the period 2010 August–September, early during the rising phase of solar cycle 24.

As an illustrative example, Figure 1 shows a large, decaying active region (NOAA 11100) in the southern hemisphere, as it appeared at 23:01 UT on 2010 August 20. On the left are AIA images recorded in Fe\textsc{i}x 17.1 nm (characteristic temperature \(T \sim 0.7 \text{ MK}\)), He\textsc{ii} 30.4 nm, and Fe\textsc{xiv} 21.1 nm \((T \sim 2.0 \text{ MK})\). On the right are three versions of a simultaneous HMI magnetogram, saturated, respectively, at \(\pm 100 \text{ G}, \pm 30 \text{ G}\)

\(^5\) Daily full-resolution images may be viewed at http://sdowww.lmsal.com/suntoday.
\(^6\) See http://hmi.stanford.edu.
Figure 1. AIA and HMI images showing a “dark canopy” surrounding an active region in the southern hemisphere, 2010 August 20 at 23:01 UT. (a) FeXV 17.1 nm. (b) HeII 30.4 nm. (c) FeXV 21.1 nm. (d) Simultaneous line-of-sight magnetogram saturated at ±100 G. (e) The same magnetogram saturated at ±30 G after 2″ × 2″ smoothing. (f) Polarity distribution after smoothing the magnetogram with a 60″ × 60″ running window. Boxes highlight areas containing dark fibrilar material and relatively weak longitudinal field, where the spreading active-region flux encounters background network of the opposite polarity. Arrows point to a large filament aligned with the internal PIL of the active region.
structures that fan out more or less radially from the active region. 

Reduced-resolution HMI and AIA movies can be viewed at http://sdo.gsfc.nasa.gov/data/aiahmi/browse.php.

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The boxed areas labeled “A” and “B” in Figure 2 enclose newly formed (or newly darkened) fibril structures located next to opposite-polarity flux elements in close contact, which in turn appear as compact 17.1 nm bright points. By constructing time-lapse movies at 30 minute cadence, we have verified that these flux elements are in the process of converging and canceling. The box labeled “C” encloses a string of small emerging bipolar fields; note, however, that most of the mixed-polarity flux in these magnetograms represents pre-existing network and intranetwork elements that are undergoing random encounters in the supergranular flow field, rather than ephemeral regions (for a discussion of network, intranetwork, and ephemeral region fields and their interactions, see Martin 1988).

During the first three weeks of 2010 August, a dark canopy that stretched across ~180° of longitude, extended from below the equator to above $L \sim +40°$, and contained a number of new-cycle active regions, was observed rotating across the solar disk. The left column of Figure 3 displays this giant northern-hemisphere canopy as it appeared on August 11 in a Hz filtergram taken at the Big Bear Solar Observatory (BBSO), in a 17.1 nm image from AIA, and in an HMI magnetogram saturated at ±30 G (after $2′$ $\times$ $2′$ smoothing) and at ±0.1 G (after $60′$ $\times$ $60′$ smoothing). The right column of Figure 3 shows the same area one rotation later on September 8, after the active-region fields have undergone further weakening and dispersal. It is evident that the 17.1 nm fibrils are now more concentrated around the large-scale polarity inversions, forming structures that more closely resemble PIL-aligned filaments. In particular, the northern section of the canopy has evolved into a U-shaped filament channel (see the boxed area) enclosing the sheared, negative-polarity remnant of the large active region on the southwest side of the canopy. Correspondingly, the Hz image shows filament material extending along the northern edge of the canopy, which was not present on August 11.

Figure 4 focuses on the far western edge of the same northern-hemisphere canopy, as it appeared at 12:01 UT on August 8. The dark fibrils originating from the negative-polarity plage along the sunspot (located in the bottom left corner of the images) are seen to fan out more or less radially into the nearby network; the outer endpoints can be presumed to have positive polarity, even though they are sometimes located where both polarities are in close proximity or where the flux is very weak. Somewhat farther to the west, where the dominant polarity changes from negative to positive, the fibril structures become oriented more or less parallel to the large-scale PIL. Considering the small active region on the right-hand side of these images, we observe a fountain pattern of dark fibrils that occupy a corridor of weak line-of-sight field and connect the negative-polarity plage to the positive-polarity background network lying to the west. Viewed from the positive-polarity background side of the PIL, the field lines point to the right, consistent with the “dextral” handedness characterizing the majority of northern-hemisphere filaments (Martin et al. 1994; Martin 1998). The fibrils and “proto-filaments” surrounding the large active region on the left-hand side of the images likewise exhibit dextral handedness.

The sequence of 17.1 nm images and magnetograms in Figure 5 shows how the northern edge of the giant canopy evolves during August 10–13 (the field of view lies within the boxed area in Figures 3(a)–(d)). Here, we see a collection of dark, featherlike structures lying between the predominantly positive-polarity area to the north and the sheared band of negative-polarity flux originating from the active region to the west. Early on August 10 (Figures 5(a) and (b)), the fibrils inside the white box are oriented almost perpendicular to the large-scale PIL, which is clearly defined by the line of strong negative-polarity network elements stretching from northeast to southwest. Over the next two days, the negative-polarity flux spreads northward into the positive-polarity background region, and the two polarities intermingle; at the same time, the fibrils begin to bend in the direction of the PIL. In time-lapse movies, separate clumps of 17.1 nm fibrils oriented at different angles to each other are seen merging into longer structures with intermediate orientations (as in Figures 2 and 3 of

\[7\] Reduced-resolution HMI and AIA movies can be viewed at http://sdo.gsfc.nasa.gov/data/aiahmi/browse.php.
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Figure 2. Close-up of the northern edge of the active-region canopy in Figure 1. Field of view has dimensions $530'' \times 424''$; north is up and west is to the right. (a) Fe IX 17.1 nm image recorded at 17:01 UT on August 20. (b) Simultaneous line-of-sight magnetogram, smoothed to a resolution of 2'' and saturated at $\pm 30$ G. (c) Fe IX 17.1 nm image recorded at 23:01 UT on August 20. (d) Simultaneous line-of-sight magnetogram. Arrows indicate the presumed local direction of the horizontal fibril fields, with the arrowheads pointing toward the negative-polarity footpoints. Boxes labeled "A" and "B" highlight canceling magnetic flux elements; box "C" encloses newly emerged ephemeral regions.

Wang & Muglach 2007). Movies made from the HMI magnetograms show rapid flux cancellation occurring at the PIL, as well as rotational shearing, with the positive-polarity flux elements drifting eastward relative to the negative-polarity region to the south. By August 13, the fibrils have coalesced into long, filament-like structures that are more or less aligned with the PIL. It should be emphasized that the observed change in orientation of the fibrils relative to the PIL cannot be due to the photospheric differential rotation alone, which would cause a north–south aligned fibril with endpoints at latitudes 36° and 42° to tilt only $\sim 14^\circ$ over a four-day period.

The characteristic height or vertical extent $h_{171}$ of a 17.1 nm fibril above the photosphere can be estimated by comparing the corrugated texture of the limb in 17.1 nm with AIA images taken at 450.0 nm. From the fact that the fibril structures typically protrude $\sim 6''$–$8''$ beyond the white-light limb, we deduce that $h_{171} \sim 4000$–$6000$ km, well above the nominal height of the chromospheric–coronal transition region.

3. PHYSICAL INTERPRETATION

We proceed from the basic premise that the dark features seen in Fe IX 17.1 nm represent horizontal flux tubes that contain chromospheric material and connect photospheric flux elements of opposite polarity. (The cool material may consist of neutral hydrogen and helium which absorb the EUV radiation impinging from below: see, e.g., Chiuderi Drago et al. 2001; Rutten 2007.) Such horizontal fields form low-lying canopies that fan out from the edges of magnetic flux concentrations, whether they be active regions, sunspots, or network boundaries/vertices (Harvey 2005, 2006). In emerging active regions, the flux balloons outward in a dipole-like configuration and the surface-skimming field lines become connected to background network and intranetwork elements, forming a pattern of dark fibrils diverging from the area occupied by strong plage (as sketched in Figure 10 of Wang & Muglach 2007).
Figure 3. Giant northern-hemisphere canopy observed on 2010 August 11 (left panels) and one rotation later on September 8 (right panels). Field of view has dimensions 1268′′ × 845′′. (a) BBSO Hα filtergram taken at 16:03 UT on August 11 (line-center observations with 0.025 nm bandpass). (b) AIA Fe IX 17.1 nm image recorded at 23:01 UT on August 11. (c) HMI longitudinal magnetogram (23:01 UT), saturated at ±30 G after 2′′ × 2′′ smoothing. (d) Corresponding polarity distribution after 60′′ × 60′′ smoothing. (e) BBSO Hα filtergram taken at 16:07 UT on September 8. (f) 17.1 nm image recorded at 05:01 UT on September 8. (g) Longitudinal magnetogram recorded at 05:01 UT. (h) Corresponding polarity distribution. The boxed area evolves into a U-shaped filament channel as the active-region fields decay and the dark 17.1 nm fibrils become increasingly concentrated around the large-scale PILs.
We expect the fibril pattern to continue to expand outward even after the active region has fully emerged, because of the diffusive effect of the nonsteady supergranular convection, which causes the plage to disintegrate and spread into the weaker-field background. The flux is swept to the boundaries of the randomly distributed supergranular cells, which have a characteristic diameter of \( \sim 30,000 \) km and lifetime of 1–2 days. As the cells decay and re-form at other locations, the fibril patterns continually change in response, in such a way that the fibrils remain centered above areas of relatively weak photospheric field, while their endpoints remain anchored in network or intranetwork elements of opposite polarity. Flux cancellation will act to weaken the network fields, with the fibrils rooted in the canceling flux (see Figure 6). Small, low-lying loops are in turn associated with mixed-polarity flux, whether in the form of canceling network elements, intranetwork fields, or small ephemeral regions. The net effect is to concentrate the fibrils around the large-scale background PILs surrounding the active region, where the bulk of the mixed-polarity flux is located. Systematic flux cancellation in this region then expedites the conversion of the fibrils into PIL-aligned filaments.

In his seminal studies of \( \text{H}\alpha \) fine structure, Foukal (1971a, 1971b) came to the conclusion that \( \text{H}\alpha \) fibrils cannot connect across supergranule cells, but must be open-ended absorbing features that bend upward and link to remote areas where the network has opposite polarity. This conclusion was based on inspection of a then-available magnetogram showing that the opposite sides of a supergranule are usually of the same polarity. However, it has since become clear from higher-resolution observations that so-called unipolar regions contain large amounts of minority-polarity flux; indeed, Schrijver & Title (2003) assert that, in the quiet Sun, as much as one-half of the network flux connects down into the immediately surrounding intranetwork areas. We also note that, because the magnetic network becomes increasingly fragmented toward the peripheries of active regions, horizontal field lines that are not “captured” by nearby loops are as likely to be channeled through gaps in the network as to be deflected sharply upward into the corona, as in Foukal’s picture.

High-cadence movies made from the full-resolution 17.1 nm images suggest that the fibril material streams continually from one footpoint to the other. These flows may be triggered by reconnection between the small loops and the fibril fields, generating chromospheric jets that inject new material into the corona, as in Foukal’s picture. We have earlier remarked that areas of weak, “salt-and-pepper” fields far from active regions (such as that in the upper right corner of the images in Figure 1) are brighter than the canopy regions in \( \text{Fe}\text{IX} \) 17.1 nm, whereas the opposite is the case in higher-temperature coronal lines. The darkness of the 17.1 nm canopy is due to the presence of the organized, large-scale horizontal fields originating from the active region; in the quiet Sun, the fibrils are smaller and oriented more randomly, except around large-scale PILs, where systematic flux cancellation takes place. In contrast, the emission from coronal loops is correlated with their footpoint field strengths, so the
Figure 5. Sequence of 17.1 nm images (left) and corresponding longitudinal magnetograms (right), showing the evolution of the northern edge of the giant canopy of Figure 3 during August 10–13. Note the change in the orientation of the fibril structures inside the 158″ × 158″ boxed area (centered at L = +37°), from nearly perpendicular to nearly parallel to the large-scale PIL, as the negative-polarity flux from the sheared active-region remnant diffuses into the positive-polarity background region to the north. Arrows indicate the presumed local direction of the horizontal fibril fields. The line-of-sight magnetograms are again saturated at ±30 G after 2″ × 2″ smoothing.
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quiet Sun generally appears darker than the areas immediately surrounding active regions when observed in lines such as Fe xii 19.3 nm and Fe xiv 21.1 nm.

4. CONCLUSIONS

We have used high-resolution Fe x 17.1 nm images and longitudinal magnetograms from SDO to explore the relationship between the circumfocal areas or “dark canopies” surrounding active regions and the evolving photospheric field. Our main conclusions may be summarized as follows:

1. As has long been recognized, the canopies consist of dark fibril-like structures that appear as soon as the active regions emerge; the low-lying horizontal field lines balloon out over the surrounding area and reconnect with the background network to form a quasiradial or vortical pattern. The 17.1 nm fibrils overlap areas of relatively weak photospheric field.

2. The nonsteady supergranular convection causes the fibril fields to spread outward from the active region, with the outer boundary of the dark canopy stabilizing where the diffusing flux encounters a unipolar region of opposite sign.

3. The 17.1 nm fibrils are often rooted in mixed-polarity regions, because of the tendency for the horizontal flux tubes to reconnect with small, low-lying loops.

4. As a result of this attraction toward mixed-polarity flux, the diffusing 17.1 nm fibrils gradually accumulate around large-scale PILs.

5. Systematic flux cancellation at the PIL removes the component of the field transverse to the PIL and progressively converts the fibrils into PIL-aligned structures.

6. In the absence of new flux emergence, active-region canopies thus evolve toward a state where the dark material becomes concentrated around the surrounding background PILs, forming proto-filaments and filaments.

This study, like that of Wang & Muguac (2007) where Hα observations were employed, points to the primary role of photospheric flux cancellation and fieldline reconnection in the evolution of fibrils into filaments. By making full use of the high temporal resolution of the SDO observations, which we have not properly exploited here, it should be possible to track the evolution of individual fibril structures, to characterize their mass flows, to pinpoint their footpoint locations, to clarify the relationship between fibrils and chromospheric jets, and to determine more precisely how flux cancellation leads to the coalescence of fibrils and their transformation into PIL-aligned filament channels and filaments.

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Figure 6. Low-lying, horizontal field lines have a natural tendency to become linked to weak, mixed-polarity network and intranetwork flux. (a) A long fibril (dashed) anchored in active-region plage and extending out into the background network reconnects with a pair of small bipoles and splits into two pieces. (b) A fibril that initially links two strong, opposite-polarity network elements reconnects with the surrounding small bipoles and becomes rooted in weak, mixed-polarity flux. (c) Reconnection with small bipoles may also give rise to fibrils whose endpoints are located near strong network elements of the same polarity. In all of these cases, reconnection occurs at low heights and may trigger chromospheric jets that supply mass to the fibrils.