Thermodynamic Properties of the Inverse Evershed Flow at Its Downflow Points

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Abstract

We used spectropolarimetric observations of a sunspot in the active region NOAA 11809 in the Ca II line at 854.2 nm taken with the SpectroPolarimeter for Optical and Infrared Regions at the Dunn Solar Telescope to infer thermodynamic parameters along 100 super-penumbral fibrils that harbor the inverse Evershed flow. The fibrils were identified in line-of-sight (LOS) velocity and line–core intensity maps. The chromospheric LOS velocity abruptly decreases from 3 to 15 km s−1 to zero at the inner footpoints of the fibrils that are located from the mid penumbra to about 1.4 spot radii. The spectra often show multiple absorption components, indicating spatially or vertically unresolved structures. Synthetic spectra with a 100% fill factor of a flow channel in the upper atmosphere yield strongly asymmetric profiles but no multiple separate components. The line–core intensity always peaks slightly closer to the umbra than the LOS velocity. Using the CALcium Inversion using a Spectral ARChive code, we find that the fibrils make an angle of 30°–60° to the local vertical away from the umbra. The temperature near the downflow points is enhanced by 200 K at log τ ∼ −2 and up to 2000 K at log τ ∼ −6 compared to the quiet Sun, without any signature in the low photosphere. Our results are consistent with a critical, i.e., sonic, or supersonic siphon flow along super-penumbral flux tubes in which accelerating plasma abruptly attains subcritical velocity through a standing shock in or near the penumbra.

Key words: line: profiles – Sun: chromosphere – Sun: photosphere

1. Introduction

The mass motions inside and in the vicinity of sunspots are mostly organized as flows along penumbral filaments in the photosphere and along super-penumbral fibrils in the chromosphere. The underlying magnetic field topology consists of a complex mixture of vertical, partially inclined, or horizontal field lines (e.g., Solanki 2003; Beck 2008; Rempel & Schlichenmaier 2011). The direction and strength of the flows along different channels depend on the thermodynamic and magnetic properties of the regions connected by the magnetic field lines. The determination of the flow speed, the flow direction and the temperature of the plasma in these flow channels is critical for understanding the underlying physical mechanisms that are to a large extent governed by the global magnetic structure.

Early spectroscopic observations of sunspots revealed a peculiar flow pattern with a radial, horizontal outflow at photospheric layers, the Evershed effect (Evershed 1909). At high spatial resolution, the Evershed effect was found to be structured into thin, elongated radial flow filaments in which the material flows intermittently at a speed of about 1–6 km s−1 along those elevated flow channels from inside the sunspot to the end of the penumbra and beyond (Bumba 1960; Rezaei et al. 2006; RImmle & Marino 2006; Ichimoto et al. 2007). The flow speed decreases at large radial distances from the sunspot center due to the development of a shock front (Borrero et al. 2005). At chromospheric heights, mass motions with higher speeds were observed along the so-called super-penumbral fibrils. The chromospheric mass propagates in a direction opposite to the photospheric flow ("inverse" Evershed flow (IEF); Evershed 1910; St. John 1911a, 1911b; Maltby 1975; Tsiroupolu 2000). In Hα dopplergrams, flow speeds in the range of 20–50 km s−1 were found (Beckers 1964; Moore 1981). On the other hand, spectroscopic measurements showed lower speeds in the range of 3–7 km s−1 (Haugen 1969; Dialetis et al. 1985; Dere et al. 1990). Dark super-penumbral fibrils exhibited a faster flow velocity than bright ones, with fluctuations on a timescale of about 25 minutes (Georgakilas et al. 2003; Georgakilas & Christopoulou 2003). Most of the older observations were carried out with either a coarse spatial resolution or a coarse wavelength sampling, which might contribute to the large range of reported velocities of 3–50 km s−1. The use of imaging spectroscopy with real-time correction by adaptive optics or spatial deconvolution could help to map the flow channels of the IEF more accurately and to better constrain the range of observed IEF velocities, which in turn could help to better constrain the theoretical models that are proposed to drive the IEF (e.g., Vissers & Rouppe van der Voort 2012; Ahn et al. 2014; Grant et al. 2018). The IEF was found to start with subsonic speeds away from the sunspot, to attain supersonic speeds near the loop top, and to end with subsonic speeds inside the sunspot by Maltby (1975). Wavelength shifts in the core and wing of the Mg I b 518.362 nm line showed a reverse flow at photospheric and chromospheric heights (Bones & Maltby 1978). Simultaneous measurements of Doppler velocities usually show an increase in the flow speed from the photosphere through the chromo- sphere to transition region heights (Alissandrakis et al. 1988; Bethge et al. 2012). The steady flow pattern in dopplergrams of the C IV transition-region line at 154.8 nm observed with the Solar Maximum Mission was seen to be consistent with the IEF (Athay et al. 1982).

The photospheric Evershed effect could be due to a siphon flow mechanism (Montesinos & Thomas 1997; Sánchez Almeida et al. 2007) or could be a manifestation of magneto-convection in the
Penumbra (Rempel 2012), which has been the subject of considerable debate in recent years. The chromospheric IEF is, however, generally expected to be caused by siphon flows along arched magnetic field lines connecting footpoints with a different magnetic field strength and gas pressure (Meyer & Schmidt 1968; Thomas 1988; Degenhardt et al. 1993; Thomas & Montesinos 1993). Thomas (1988) and the subsequent papers of the series (Montesinos & Thomas 1989, 1993; Thomas & Montesinos 1990, 1991) developed an extensive description of such siphon flows in the solar photosphere. One major distinction they found was related to the question of whether the flow speed was below (subcritical), at (critical) or above (supercritical) the local sound speed. They predicted the generation of a shock front wherever the flow speed reached the supercritical level. Observational evidence for the existence of such shock fronts was found both at photospheric (Degenhardt et al. 1993) and chromospheric heights (Uitenbroek et al. 2006; Beck et al. 2010; Bethe et al. 2012).

For this paper, we acquired spectropolarimetric data in the chromospheric Ca II IR line at 854.2 nm and the photospheric Fe I lines at 1565 nm with the SPectropolarimeter for Infrared and Optical Regions (SPINOR; Socas-Navarro et al. 2006) at the Dunn Solar Telescope (DST; Dunn 1969; Dunn & Smartt 1991) to determine the magnetic and thermodynamic properties of chromospheric fibrils around sunspots that serve as IEF channels. We derive the thermodynamic properties of the solar atmosphere from an analysis of the Ca II IR spectra to determine the thermodynamic properties of the IEF in the lower chromosphere. We focus on the properties near the downflow points to determine which driving mechanism best matches the observed flow pattern and thermal structure. Our analysis provides thermal information from the continuum-forming layers to the chromosphere which allows us to determine the three-dimensional thermal topology of the solar atmosphere in detail. Section 2 describes our set of observations. Section 3 explains the retrieval of atmospheric properties from the data. The results are presented, summarized and discussed in Sections 4–6. Section 7 provides our conclusions.

2. Observations

We observed the leading sunspot of the active region (AR) NOAA 11809 on 2013 August 3 with SPINOR at the DST. The sunspot was located at an heliocentric angle of about 30°. We acquired spectropolarimetric data in the chromospheric Ca II infrared (IR) line at 854.2 nm and the photospheric Fe I lines at 1564.8 and 1565.2 nm. Between UT 15:24 and UT 18:43, nine scans of the sunspot were taken with a cadence of about 30 minutes. For the first map, 400 steps with a step width of 0.22' were recorded while all other scans had 200 steps. The integration time per step was 4 s. The slit width was 30 μm corresponding to about 0.22' on the Sun. The spatial (spectral) sampling along the slit was 0.36 (5.5 pm) at 854 nm and 0.55 (20.6 pm) at 1565 nm. The field of view (FOV) along the slit was about 90' at 854 nm and about 150' at 1565 nm. The full wavelength ranges covered were 852.87–855.70 nm and 1558.05–1568.58 nm, respectively. The spectropolarimetric data were reduced with the standard SPINOR data reduction pipeline.3

Figure 1 shows an overview of the observed FOV in the continuum intensity and the magnetogram from the

3 http://nsos.nso.edu/dst-pipelines

![Figure 1. Overview of the FOV in NOAA 11809 on 2013/08/03 in HMI data. Left: continuum intensity. Right: line-of-sight magnetic flux. The white and red rectangles indicate the areas scanned in the first and all other maps, respectively.](image)

Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) onboard the Solar Dynamics Observatory (Pesnell et al. 2012). The leading sunspot of NOAA 11809 had negative polarity and belonged to a decaying active region. The trailing polarity was located near the upper left corner of the FOV shown, while the several small pores next to the sunspot at x, y ~ 40–60 Mm, 100–130 Mm belonged to newly emerging magnetic flux.

3. Data Analysis

We derived an extended list of line parameters from the intensity and polarization profiles in both wavelength ranges. In the current study, we only use the continuum intensity I_c, the line–core intensity I_{core} and line–core velocity v_{core} of Ca II IR, and the line–core velocity v_{phot} of one photospheric IR line in the 1565 nm range.

The photospheric spectra at 1565 nm were inverted with the Stokes Inversion based on Response Functions code (Ruiz Cobo & del Toro Iniesta 1992) including eight lines with known transitions inside the observed wavelength range. These results on the photospheric magnetic field will be used in a subsequent study. The intensity profiles of Ca II IR were inverted under the assumption of local thermodynamic equilibrium (LTE) with the CAlcium Inversion using a Spectral ARchive code (CAISAR; Beck et al. 2013b, 2015). We used the non-LTE (NLTE) correction curve for the penumbra from Beck et al. (2015) for the scaling of the LTE temperatures where indicated.

We manually identified chromospheric fibrils in the nine maps using the line–core intensity and velocity of Ca II IR. Each fibril was marked by a set of six spatial positions with a subsequent fit of a second-order polynomial to these points. The first point for each fibril track was chosen to be at about the border between umbra and penumbra along the continuation of the fibril into the sunspot. The fibril tracks were selected to capture the most prominent, fastest and isolated downflow patches near the sunspot in each map and to trace the corresponding flow fibril outwards from the spot as far as possible. The outermost point of the curves was set to
continue the fibril track for about 5" beyond the last clear signature of the fibril itself. We selected 15 fibrils in the 6th and 7th map and 10 fibrils in all others (100 fibrils in total; see Figure 2).

The locations of downflow patches were determined by a threshold in the chromospheric line-of-sight (LOS) velocity in addition. All neighboring spatial positions with a LOS velocity above the threshold were attributed to an individual downflow patch (top row of Figure 2). Most of the manually identified fibrils have an associated patch in these masks, while some patches correspond to fibrils that we did not select. The total number of downflow patches was comparable to that of individual fibrils. The manual selection of fibrils is to some extent arbitrary and incomplete, but the automatic detection of downflow patches through the fixed velocity threshold shows that we selected by eye almost all fibrils that exceeded the velocity threshold at some location (top row of Figure 2).

Given the fibril locations, we extracted the spectra, $I_\text{c}$, $I_{\text{core}}$, $v_{\text{core}}$, $v_{\text{phot}}$ and the temperature stratifications $T(\log \tau)$ from the LTE inversion along each fibril. We determined the location of maximal velocity and maximal line-core intensity along each fibril. For the downflow patches, we determined the average velocities and intensities and the maximal temperature at each optical depth. The area of each downflow patch was derived from all pixels pertaining to it.

Figure 2. Overview of the nine maps taken on 2013 August 03 from UT 15:24–18:13. Bottom to top: continuum intensity, photospheric velocity, line–core intensity, and line–core velocity of Ca II IR at 854.2 nm and mask of fast downflows. Colored lines indicate the locations of fibrils labeled from 0 to 9 (0–14) in each scan. The white pluses in the bottom row indicate the center of the sunspot. The different colored symbols in the second row from the bottom indicate the locations of maximal velocities (diamonds) and maximal line-core intensity (pluses) along each fibril. The maps have not been re-sized to have square pixels. (Magnification will allow for better visibility of small details or labels).
4. Results

Figure 2 shows the SPINOR observations in photospheric and chromospheric quantities. The selected fibril tracks are indicated by colored lines. The sunspot only had a regular penumbra and chromospheric fibrils on the side opposite to both the new flux emergence and the following polarity. A large fraction of the locations of maximal velocities and line–core intensity along each fibril, which are indicated by colored symbols in the second row from the bottom of Figure 2, is inside the penumbra, while the rest are at least close to the sunspot.

4.1. Thermodynamic Parameters along Individual Fibrils

Figure 3 shows the thermodynamic properties along all 10 fibrils in the second map. The numbers given in the middle column correspond to those in the second column of the bottom row of Figure 2. Left column: line–core intensity (red lines) and chromospheric velocity (black lines) along the fibrils. Middle column: intensity spectra. Right column: temperature stratifications. Uniform black areas in the spectra or the temperature were beyond the end of the cut along the fibril. The umbra of the sunspot is at the left in the left/right column and at the bottom in each panel in the middle column. The two dashed–dotted vertical lines in the third panel from the top in the left column indicate the locations of maximum velocity and intensity for this fibril. The dashed–dotted vertical lines in the uppermost panel of the right column mark the determination of the width of the fibril.

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the upper photosphere at about $\log \tau \approx -2$ to $-3$. For the majority of the fibrils, we find a tube-like structure of width 1–3 Mm close to the fastest downflow which makes an angle of $0^\circ$–$30^\circ$ to the LOS that corresponds to the $\gamma$-axis in the temperature images. Most fibrils can only be consistently traced for 2–5 Mm from the downflow point in the temperature plots. The majority rises beyond $\log \tau = -6$ out of the formation height of the Ca II IR line. A few fibrils show an intermittent temperature enhancement close to $\log \tau = -6$ far away from the downflow point which could indicate that there is a weak signature of the fibril left at these distances. From the corresponding temperature plots for all of the fibrils in all maps, only about 10% show a structure that returns to the photosphere again as in the bottom (top) right panel of Figure 3 (Figure 4).

The maximal Doppler shifts near the downflow points are rather large so that the spectra (middle columns of Figures 3 and 4) give the impression of having two separate components in some cases. We therefore checked whether our automatic procedure for the derivation of the line–core velocity actually works correctly for such profiles because it determines the location with maximal line depth inside the profile. Figure 5 shows individual spectra of four fibrils around the downflow points. The redshifted flow component is usually the dominant component in the spectra over some range away from the sunspot, but then converts into a weak line satellite of an unshifted, stronger absorption component. Wherever the unshifted component is deeper, the automatic determination yields its Doppler shift instead of that of the flow component.

We therefore manually traced the weak Doppler-shifted component in a subset of fibrils to determine the maximal Doppler shift up to the location where the weak component disappears completely. The velocity values from the automatic derivation for the same profiles usually underestimated the true velocity by a factor of about two. Almost all of the selected downflow patches in the velocity maps and also the flow speeds along the fibril are thus close to or slightly supersonic.
with typical speeds above $8 \text{ km s}^{-1}$. The manual determination also shifted the location of the maximal velocity more toward the sunspot, which gives a better match to the location of maximal line–core intensity. The latter quantity also suffers from the fact that the increasing Doppler shift of the second component raises the line–core intensity—defined as the minimal intensity in the profile—because the absorption profile of the second component moves to the red.

### 4.2. Synthetic Spectra

Given the generic shape of the thermodynamic properties along the fibrils in the observations, we tried to create similar spectra in synthetic data. We used an array of 300 columns by 75 optical depth points similar to the thermal inversion results along the fibrils and filled it with the atmospheric parameters of the modified Harvard Smithsonian Reference Atmosphere model (Gingerich et al. 1971) without a chromospheric temperature rise (Rezaei et al. 2008; Beck et al. 2013b).

The flow fibril was modeled as a perturbation of this initial atmosphere with a Gaussian shape in temperature $T$, velocity $v$, and density, i.e., electron pressure $p$. The center of the Gaussian perturbation was moved upwards in the atmosphere with increasing $x$ (best seen in the rightmost panel of Figure 6), while the temperature and velocity amplitude of the Gaussian were decreased. We added a straight line to the temperature stratifications that increased the temperature toward the upper atmospheric layers to better mimic the observed temperature stratifications (rightmost columns of Figures 3 and 4). The temperature perturbation was set to decrease with $x$ and reached negative values at some point to emulate “dark” fibrils far away from the downstream point. Figure 6 shows examples of the resulting perturbations in $T$, $v$, and $p$. Even if it is not very obvious in $T$ and $v$, the center of the Gaussian perturbation always followed the same path that stands out more clearly in $p$.

We used four different settings: perturbation in $T$ with a low flow speed ($v \approx 9 \text{ km s}^{-1}$) and a rapid spatial drop-off of the flow speed (configuration 1), the same with a higher flow speed ($v \approx 11 \text{ km s}^{-1}$) and a slower spatial drop-off (configuration 2), the same as configuration (2) with an additional increase in electron pressure $p$ (configuration 3), and, finally, no perturbation in either $T$ or $p$, but only in $v$ (configuration 4). The rightmost column of Figure 7 shows the corresponding temperature stratifications. The synthetic spectra were analyzed with the same methods as the observations to obtain the line–core intensity and velocity. The true flow velocity was determined as the average value over the width of the Gaussian velocity perturbation.

The synthetic spectra (middle column of Figure 7) reproduce the shape of the observed spectra within limits. The
enhancement in the line wing at the downflow points for configurations 1–3 is too strong in comparison with the observations, presumably because the increase in \( T \) was extending too low into the atmosphere. Note that for configuration 4 the apparent increase (decrease) of the intensity in the blue (red) wing is solely caused by the Doppler shift of the absorption core as the temperature stratification was identical for all spectra in that case. No separate absorption components are visible in any of the synthetic spectra and the “crossing” of increased intensity across the full line core that is seen for most observed fibrils is missing.

The parameters derived from the synthetic spectra (left column of Figure 7) match better to the observed pattern than the spectra themselves. The line–core intensity (red lines) peaks slightly to the left of the velocity (black lines). The velocity derived from the line–core position in the synthetic spectra (blue lines) underestimates the true velocity used in the synthesis by a factor of about two in three out of the four configurations. This is similar to the factor between the line–core position and the Doppler shift of the line satellite in the observed spectra that was found when explicitly tracing the location of the latter.

The individual synthetic spectra (Figure 8) show the effect of the flow fibril in the red wing, but never exhibit separate absorption components with a second minimum in the intensity profile. Even arbitrarily increasing the density in the flow fibril in configuration 3 did not produce enough opacity for a clear line satellite. The spectra of the configuration 4 without any temperature increases look very similar to the others in Figures 7 and 8, but have a clear mismatch in the leftmost column of Figure 7 because they completely lack the increase in the line–core intensity at the downflow point.

A more sophisticated method of modifying the temperature stratifications might yield a closer match to the observed spectra, but the simplified modeling already yields a satisfactory match of the general spectral pattern along a flow fibril. Analyzing the synthetic spectra in the same way as the observed spectra yields similar results for the line–core velocity and intensity as in the observations.

4.3. Average Fibril Properties

We then averaged the thermodynamic properties over all of the 100 observed fibrils. We used the location of maximal velocity along each fibril as the common reference point to align the different fibril tracks with each other.

Figure 9 shows the temperature stratifications and the Stokes I and V spectra along the average fibril. The structure has been somewhat smoothed out through the averaging, but the description given for individual fibrils above is still valid. At the location of the fastest downflow at about 3–5 Mm, the average temperature shows a barely inclined, thin (1–2 Mm) tube with a local temperature increase. At an optical depth of about log \( \tau \approx -3 \), this temperature enhancement is no longer apparent. The temperature enhancement rises up to log \( \tau = -6 \) with increasing distance from the sunspot, but can only be tracked there for about 5 Mm from the downflow point.

The average Stokes I spectra do not show the characteristic intensity and Doppler shift pattern very prominently because the full spectral range of the profiles is displayed to cover also the photospheric line blends. The Stokes V spectra are more revealing in this case. The average location of the maximal flow velocity (black horizontal line in the right panel of Figure 9) intersects a clear circular polarization signal in both photospheric and chromospheric lines, but is still not in the region of the strongest polarization signal.

The top row of Figure 10 shows the continuum intensity, the line–core intensity and the line–core velocity after averaging over the fibrils. The continuum intensity (top left panel of Figure 10) confirms that the fastest downflows are on average located inside the penumbra where \( I_c \) drops below unity. The peak in the line–core intensity is roughly symmetric, while the line–core velocity (top right panel of Figure 10) shows a fast increase toward the sunspot with a sharp drop from the peak velocity of 5 km s\(^{-1}\) to about 2 km s\(^{-1}\) on less than 1 Mm. There is a less steep decrease from 2 km s\(^{-1}\) to about zero over the next 3 Mm.

The bottom row of Figure 10 shows the properties of the average temperature stratifications. The temperature (lower left panel) is enhanced at the downflow location from log \( \tau = -6 \)
to about $\log \tau = -3$. At lower atmospheric layers, the temperature is actually lower than further away from the sunspot, reflecting the location in the penumbra. To quantify the temperature enhancement, we averaged the inversion results over a quiet Sun (QS) reference area in the FOV. The middle panel of Figure 10 compares the temperature in the QS (red line) with the maximal value at each layer of optical depth (black line), while the right panel shows their difference. The maximal value of $T_{\text{max}}(\log \tau)$ along the average fibril is not always exactly at the location of the fastest flow (vertical dotted line in the lower left panel of Figure 12), but the difference is usually very small. In the LTE results, the downflows are hotter than the QS stratification by 200 K at $\log \tau = -4$ and by 700 K at $\log \tau = -6$ (bottom right panel of Figure 10). After application of the NLTE correction curve for the penumbra, the difference increases to about 1800 K at $\log \tau = -6$, while the value at $\log \tau = -4$ does not change greatly.

### 4.4. Statistics of Thermodynamic Parameters of Fibrils and Downflow Patches

Figure 11 shows a comparison of the statistics of values taken at the locations of maximal velocity or intensity along the fibrils and the corresponding values inside the downflow patches that were defined through a threshold in the velocity maps. The histograms of chromospheric and photospheric intensities and velocities from the different areas are rather similar. The photospheric velocity shows a small redshift of about 0.4 km s\(^{-1}\), while the chromospheric velocity covers a range from 0 to 15 km s\(^{-1}\) without any correction for the underestimation by the automatic method. The histograms of the line–core intensity are nearly identical, while the continuum intensity is predominantly smaller than unity. Table 1 lists the average values at the downflow points and their 1-$\sigma$ fluctuations.

The temperature stratifications at the different locations i.e., maximal intensity or flow speed or average over a patch, show a similar enhancement over the QS as the stratification for the average fibrils in Figure 10. For the downflow patches, we selected the maximal temperature inside each patch at each layer of optical depth and then averaged these values over all patches. The temperature increase over QS conditions exceeds 2000 K at $\log \tau = -6$. The corresponding standard deviation across all patches is about $\pm 200$ K from $\log \tau = 0$ to $\log \tau = -4$, while it increases to about $\pm 700$ K at $\log \tau = -6$. 

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**Figure 8.** Same as Figure 5 for the synthetic spectra. The numbers at the top of each panel indicate the configuration of the synthesis.

**Figure 9.** Temperature (left panel) and spectra (right panel) averaged over all fibrils. The vertical black line in the left panel indicates the location of maximal velocity while the horizontal dashed line marks $\log \tau = -3$. The horizontal black lines in the Stokes I (bottom right panel) and Stokes V spectra (top right panel) indicate the location of maximal velocity.
4.5. Statistics of Spatial Properties

Figure 12 shows the histograms of the area of downflow patches, the width of the fibrils and the radial distance of the locations of maximal velocity and intensity from the center of the sunspot. The downflow patches (see the top row of Figure 2) are usually thin and somewhat elongated in the radial direction. Typical areas are below 2 $\text{Mm}^2$ (top panel of Figure 12).

The width was determined manually in the temperature plots along individual fibrils (compare with the top right panel of Figure 3), but only for a subset of the fibrils. In some cases, especially for the broader and more diffuse structures, it was not really possible to define an outer border of the flow fibril. There might thus be some slight bias toward lower widths. With this caveat, the typical value for the width of the flow fibrils at the downflow points is $1–2.5 \text{ Mm}$. Some of the variation in the width will also come from the fact that the LOS intersected different fibrils around the sunspot at different azimuth angle.

Finally, the histogram of the radial distance in the bottom panel of Figure 12 confirms that the majority of the downflow points are located inside of or close to the outer boundary of the penumbra. The radial distance in fractions of the sunspot radius is from 0.6 to 1.4. We note that the smallest radius values are still outside of the umbra. There is no obvious case of similar fast chromospheric downflows ending inside the umbra while several are clearly located outside of the sunspot (see Figure 2).

5. Summary

We observed a sunspot in the active region NOAA 11809 at a heliocentric angle of $30^\circ$ with SPINOR at the DST. We acquired nine maps of spectra of the Ca II IR line at 854.2 nm under good seeing conditions. We manually identified and traced 10–15 chromospheric fibrils per map in or near the undisturbed segment of the sunspot that showed a penumbra. Those chromospheric velocity and intensity fibrils originated from the mid-penumbra up to locations outside the sunspot and extended further outward into the super-penumbral canopy while showing the inverse Evershed effect.

The patches of maximum flow velocities were primarily found near the outer penumbral boundary from 0.6 to 1.4 spot radii, with a peak of the distribution inside the sunspot at 0.9
radii. The chromospheric velocities of 3–15 km s\(^{-1}\) were about one order of magnitude higher than the photospheric velocities. An explicit tracking of the absorption components in individual spectra and a comparison to synthetic spectra revealed that the LOS velocity derived from the line–core position tends to underestimate the true LOS velocity by a factor of about 2 in most cases. The projection effects of the flow vector onto the inclined LOS increase the true flow velocity by another about 15% (1/\(\cos 30^\circ\) = 1.15).

The thermal inversion results showed that the flow channels are inclined by 0°–30° to the LOS near the downflow points, tilting away from the umbra, while the LOS itself makes an angle of 30° with the local vertical. The majority of the fibrils tracked were on the center-side of the sunspot. Taken together, this means that the fibrils are not horizontal at the downflow points but are instead inclined to the local vertical by 30°–60° (see Figure 13). The end points of the flow channels were found to show an abrupt drop in velocity and an enhancement of intensity that is characteristic of the presence of a shock front. On average, the shock front was located at about 5 Mm from the outer umbral boundary and occurred at heights from \(\log \tau \sim -2.7\) to \(-6\). The temperature in the shock was increased relative to the QS by about 200 and 2000 K at these two optical depths. The shock locations cannot be identified in the maps of the continuum intensity and the temperature of layers below \(\log \tau \sim -2.7\). The lateral width of the fibrils in spatial maps and their extent in the temperature stratifications were from below 1 to up to 2.5 Mm, while the area of the downflow patches was from almost zero to 4 Mm\(^2\).

### Table 1

| \(I_c / I_l\) | \(I_c / I_l\) | \(v_{\text{chrom}}\) (km s\(^{-1}\)) | \(v_{\text{phot}}\) (km s\(^{-1}\)) | \(\sigma T\) (K) |
|---|---|---|---|---|
| 0.93 ± 0.05 | 0.32 ± 0.03 | 5.2 ± 2.9 | 0.0 ± 0.4 | ±200–350 |

6. Discussion

The mass motions along the fibrils, which are assumed to trace the magnetic field lines in the super-penumbra of the sunspot, could result from a variety of different phenomena that are illustrated in Figure 13. Configuration “A” represents a siphon flow (e.g., Meyer & Schmidt 1968; Cargill & Priest 1980; Thomas 1988; Degenhardt 1989; Uitenbroek et al. 2006) that originates in a magnetized region in the super-penumbra, either a moving magnetic feature in the sunspot moat or the network at its boundary, and ends near or in the penumbra. The flow in this case is maintained by the pressure difference at the two photospheric end points that are connected by the fibrils. It is characterized by an upflow at the end point of lower field strength and a downflow at the one with higher field strength (e.g., Bethge et al. 2012). In case “B,” a rising flux bundle drains plasma along its length. That causes downflows at both ends and upward velocities at the middle of the fibril (e.g., Gömöry et al. 2010). Configuration “C” represents the scenario of coronal rain (see, e.g., Antolin & Rouppe van der Voort 2012, and references therein), in which cool, dense coronal condensations slide down along guiding magnetic field lines. Such flows commonly show very high speeds of up to 80 km s\(^{-1}\) and are often intermittent in time (Vissers & Rouppe van der Voort 2012; Ahn et al. 2014). At the temporal cadence of the current observations of a few tens of minutes, we cannot comment on any temporal evolution. The majority of the fibrils in Figure 2 show a smooth radial variation without a patchy or blotchy pattern in the radial direction and thus do not resemble the flocculent flows seen in H\(\alpha\) by Vissers & Rouppe van der Voort (2012). Our flow pattern with rather steady, uniform downflows of about sound speed over a connected segment of the sunspot therefore matches best to the siphon flow scenario, as upflows, multiple times supersonic speeds, or any patchy substructure are absent.

Earlier measurements of the IEF using a coarse wavelength sampling in the H\(\alpha\) line showed large spatio-temporal variations in the flow speed (Georgakilas et al. 2003). This
could result from the fact that the flow often only shows up as a weak line satellite (Figure 5) that would be impossible to isolate at low spectral resolution. The fibril tracks in the observations were laid along the central axes of the fibrils in the 2D temperature plots along the fibrils (compare with the upper rightmost panel of Figure 3). The different siphon flow solutions in Bethge et al. (1993, middle panel of their Figure 3). The formation height of the Ca II IR line at 854.2 nm samples the solar atmosphere from continuum-forming layers to where the chromospheric plasma turns from high to low plasma-$\beta$ (Pietarila et al. 2007). The different siphon flow solutions in Thomas (1988) or Montesinos & Thomas (1993) that attain supersonic speeds predict the occurrence of a shock front when the supersonic chromospheric or upper-photospheric flow encounters the denser lower atmosphere. Such shock fronts are clearly indicated by the brightenings in the line–core intensity of the Ca II line at 854.2 nm, while the inversion of the spectra allowed us to also localize their extent through a more detailed three-dimensional modeling containing a complete flow channel with lateral boundaries and the spectral synthesis over an extended spatial region instead of a single cut. A vertical atmospheric structure with multiple components in motion or at rest seems, however, more probable at this point.

The flow speeds reported here are consistent with the flow pattern observed in H$\alpha$ and C IV with a sharp decrease in the downflow velocity a few arcseconds outside the penumbra (Alissandrakis et al. 1988; Georgakilas et al. 2003). The location of maximal downflow should vary with the heliocentric angle of the observations. A study of the center-to-limb variation of the IEF should be able to reveal this effect. The velocity profiles along the fibrils or their average in our observations with a deceleration to nearly zero over less than 1 Mm match the shape of the flow speed shown in Bethge et al. (2012, their Figure 3) for a siphon flow in He I at 1083 nm that shows significantly larger speeds of up to 40 km s$^{-1}$. The average flow profile also matches well the values predicted by Montesinos & Thomas (1993, middle panel of their Figure 3) for a photospheric siphon flow of critical speed.

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response because of their longer wavelength, but at least show a strongly raised line core in such cases (Cauzzi et al. 2009; de la Cruz Rodríguez et al. 2013). Cauzzi et al. (2009) found that the line width of Ca II IR at 854 nm is no good tracer of temperature, opposite to the case of the Hinston line. The inversion of the Ca II IR spectra in the current analysis attempts to match the observed profile shape both in the line width and the intensity throughout the line profile. A visual inspection of several individual profiles showed that the complex, multi-component shape of the Ca II IR profiles inside the flow fibrils could not be fully matched in the inversion, but the increase of the line-core intensity at the downflow points could always only be generated by an increased temperature. The raised line core was also found to be missing in a spectral synthesis of an emulated temperature. The raised line core was also found to be missing in a spectral synthesis of an emulated temperature.

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7. Conclusions

We have studied the thermodynamic structure and properties of the solar atmosphere along chromospheric intensity and velocity fibrils in the super-penumbra of a sunspot that harbor the inverse Evershed effect. We focused on the thermodynamic properties near the downflow points at the end of the fibrils. We find that the properties match best to a siphon flow that attains supersonic speed and ends in a shock front inside the penumbra of the sunspot. The flows are inclined by 30°–60° to the local vertical near the downflow points.

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