He I Spectropolarimetry of a Supersonic Coronal Downflow Within a Sunspot Umbra

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Abstract
We report spectropolarimetric observations of a supersonic downflow impacting the lower atmosphere within a large sunspot umbra. This work is an extension of Schad et al. using observations acquired in the He I 10830 Å triplet by the Facility Infrared Spectropolarimeter. Downflowing material accelerating along a cooled coronal loop reaches peak speeds near 200 km s\(^{-1}\) and exhibits both high speed emission and absorption within the umbra, which we determine to be a consequence of the strong height dependence of the radiatively controlled source function above the sunspot umbra. Strong emission profiles close to the rest wavelengths but with long redshifted tails are also observed at the downflow terminus. From the polarized spectra, we infer longitudinal magnetic field strengths of \(\sim 2.4 \text{ kG}\) in the core portion of the He I strong emission, which we believe is the strongest ever reported in this line. Photospheric field strengths along the same line of sight are \(\sim 2.8 \text{ kG}\) as inferred using the Ca I 10839 Å spectral line. The temperatures of the highest speed He I absorption and the near-rest emission are similar (~10 kK), while a differential emission measure analysis using Solar Dynamics Observatory/Atmospheric Imaging Assembly data indicates significant increases in radiative cooling for temperatures between ~0.5 and 1 MK plasma associated with the downflow terminus. Combined we interpret these observations in the context of a strong radiative shock induced by the supersonic downflow impacting the low sunspot atmosphere.

Unified Astronomy Thesaurus concepts: Solar magnetic fields (1503); Solar chromosphere (1479); Solar transition region (1532); Sunspots (1653); Spectropolarimetry (1973)

Supporting material: animations

1. Introduction
Sunspot umbrae, characterized by strong vertical magnetic fields, are intricately structured and vigorously dynamic in their upper layers. In the photosphere, small-scale features include magneto-convective umbral dots and light bridges (Solanki 2003). Photospheric velocity fluctuations (\(\Delta v \sim 0.5 \text{ km s}^{-1}\)) have peak power near 5 minute periods (Khomenko & Collados 2015), while waves propagating upward steepen into shocks (\(\Delta v \sim 15 \text{ km s}^{-1}\)) that drive 3 minute period chromospheric umbral flashes (Beckers & Tallant 1969; Rouppe van der Voort et al. 2003), which exist alongside small-scale brightenings and dynamic fibrils (Henriques et al. 2020). Meanwhile, downward energy deposition from the corona can also generate small brightenings in the umbra transition region (TR) and chromosphere. These complexities, along with the non-LTE formation of chromospheric diagnostics, challenge the modeling of the umbral atmosphere (see, e.g., Iwai et al. 2017; Loukitcheva et al. 2017).

Our focus is on the upper atmospheric drivers of umbral fine structure. In a study of 60 data sets from the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014), Samanta et al. (2018) identified 20 cases of supersonic downflows (SSDs) in the Si IV 1403 Å line located within sunspot umbrae. Kleint et al. (2014) originally reported the association of SSDs with bright dot features in the TR above sunspots. Their primary spectral signatures include a near stationary component and a strongly redshifted (50–200 km s\(^{-1}\)) satellite (Dere 1982; Nicolas et al. 1982; Klejdeseth-Moe et al. 1988; Brynildsen et al. 2004; Kleint et al. 2014; Tian et al. 2014; Nelson et al. 2020a, 2020b). Some SSDs show a chromospheric redshifted counterpart observable in the Mg II h and k and C II lines. Another class of SSD spectral profile exhibits strong red line asymmetries, but without a clear separation between stationary and shifted components (Kjeldseth-Moe et al. 1988; Kleint et al. 2014; Ishikawa et al. 2020).

The origin of these SSDs has been suggested by numerous authors to be coronal rain (Antolin et al. 2012; Ahn et al. 2014) or siphon flows along coronal loops (Cargill & Priest 1980; Orlando et al. 1995). Electron densities in the downflowing component observed by Samanta et al. (2018) \((log n_e \approx 10.17 \pm 0.69)\) are an order of magnitude less dense than the stationary component, supporting a coronal origin. The short-lived bursty behavior of some downflow profiles \((\sim 20 \text{ s})\) in Kleint et al. (2014 over a duration of 2 hr) has been linked to the chunky character of coronal rain (Ishikawa et al. 2020). Meanwhile, the steady nature of the downflows over tens of minutes observed by Straus et al. (2015) and Chitta et al. (2016) require a large mass supply, and may support a siphon flow scenario.

SSDs eventually decelerate and impart their energy into the lower atmosphere, a process important also in solar and stellar flares (Fuhrmeister et al. 2005; Ayres & France 2010; Xu et al. 2016; Graham et al. 2020) and eruption downflows (Gilbert et al. 2013). Few detailed studies of these transitions have been reported (Straus et al. 2015; Chitta et al. 2016), and there are many open questions, including how deep into the atmosphere this energy can penetrate within the umbra.

In this article, we study an umbral SSD with peak speeds near 200 km s\(^{-1}\) observed using spectropolarimetry of the neutral helium 10830 Å triplet, which under equilibrium conditions is formed at temperatures of \(\lesssim 10^{4.5} \text{K}\). SSDs \((\gtrsim 15 \text{ km s}^{-1}\) have previously been observed in He I 10830 Å by Schmidt et al. (2000), Aznar Cuadrado et al. (2007), and Lagg et al. (2007), particularly near pores, but not to our knowledge within sunspot umbrae, and not at the high speeds studied here. Umbral He I typically presents weak absorption.
spectra ($\leq 10\%$) modulated by chromospheric oscillations; though, line shapes can be complex (Lites 1986; Centeno et al. 2005; Anan et al. 2018). With sensitivity to the Zeeman effect and atomic level polarization (Trujillo Bueno & Asensio Ramos 2007), the He I triplet has been used for sunspot magnetic field measurements (Orozco Suarez et al. 2005; Schad et al. 2013, 2015; Joshi et al. 2017). It also is a good diagnostic of coronal rain off-limb (Schad 2018). The observations presented here are associated with cool draining filament material, first studied in Schad et al. (2016), that originates from a highly suspended ($\geq 70$ Mm) coronal cloud filament. Here, we examine closer the response of the lower atmosphere to the impact of this downflow.

2. Observations and Data Reduction

2.1. Dunn Solar Telescope (DST)/FIRS Observations

Spectropolarimetric observations covering the He I 10830 Å triplet were acquired by the Facility Infrared Spectropolarimeter (FIRS; Jaeggli et al. 2010) at the 0.76 m DST on 2011 September 19. The target was the large sunspot near N23W11 ($\mu = 0.92$). While this is the same data set discussed by Schad et al. (2016), we have reprocessed the raw data to better address spectral and spatial scattered light contamination (see Section 2.3).

Figure 1 shows an overview of the single scanned FIRS data set used here and the downflow event of interest. Between 16:29 and 17:01 UTC, FIRS conducted a 218 step slit scan with the slit axis oriented 41.3° clockwise relative to the solar meridian. One second cumulative integration time per step was distributed among two repeated sequences of four polarimetric modulation states. The field of view is $64'' \times 75''$. Sampling along the slit is 0.15'' and the scanning step width is equal to the projected slit width of 0.29''. Spectral sampling is 38.683 mA pixel$^{-1}$ and the spectral range includes −485 to +600 km s$^{-1}$ Doppler velocity coverage of the He I triplet. Numerous spectral lines are observed in this large spectral bandpass (see Table 1 in Schad et al. 2016). Our analysis concentrates primarily on the He I signatures, whose rest components lie at 10829.0911 (Tr1), 10830.2501 (Tr2), and 10830.3398 Å (Tr3)—the latter two transitions are blended, in addition to the shallow Ca I 10838.97 Å line formed in the deep photosphere with a Landé $g_{\text{eff}}$ of 1.5.

Standard reduction methods as per Schad et al. (2016) are applied, including detector nonlinearity correction, dark and flat-field correction, geometric registration, wavelength calibration, and polarization crosstalk correction. We forego removal of any residual interference fringes as flat-field correction is sufficient over the region of interest; though some high frequency detector noise is removed through a combination of Wiener and Fourier filtering. As in our previous work, solar image drift during the slit scan is corrected through careful co-registration with a cooperating $G$-band context imager and linear interpolation of the FIRS data in the spatial domain. The cumulative image drift is 2.55'' and occurred primarily over the latter 15 minutes of the scan. It has a minimal impact on the spatial integrity on scales of a few arcseconds as the linearized slit scanning rate is significantly larger than the average image drift rate.

2.2. Solar Dynamics Observatory (SDO)

To investigate plasma at temperatures above the ionization temperature of neutral helium, as well as the temporal behavior of the observed downflow, we include analysis of EUV observations from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) instrument onboard NASA’s SDO (Pesnell et al. 2012). We use the 12 s cadence level 1 data covering 200 minutes of observations between 15:40 UT and 19:00 UT. We also use continuum intensity data (6173 Å) from the

Figure 1. DST/FIRS spectroscopic observations near He I 10830 Å of an SSD draining into a sunspot umbra near N23W11 on 2011 September 19. Panels (a)–(e) display the full slit-scanned field of view, while panels (f)–(j) zoom in on the umbral region outlined by a white dashed rectangular in the upper row. The left-most column shows the continuum intensity normalized to the local quiet Sun (see contours in panel (f)). The other columns contain normalized monochromatic images at progressively larger redshifts from the rest wavelength of the He I triplet at 10830.3 Å. These data have been spatially deconvolved to treat instrumental stray light. Dashed yellow and solid (black or blue) contours in (g) and (j) surround the region of high speed absorption and the emissive kernel at rest wavelengths, respectively.

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Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) to coalign the observations, via cross-correlation techniques, and to address stray light within the FIRS data. For the latter, we use the point-spread function (PSF) corrected HMI data series denoted “dconS” (Norton et al. 2017, 2018). Each SDO image is derotated and rescaled to a common plate scale of 0.6° pixel⁻¹ using the aiapy package (Barnes et al. 2020). Time series data centered on the region of interest are then coaligned by compensating for the mean synodic solar rotation rate using tools available in the sunpy package (The SunPy Community et al. 2020).

2.3. DST/FIRS Stray-light Treatment

Instrumental stray light negatively impacts the relative spectrophotometry of the FIRS observations, particularly within the sunspot umbra where we concentrate this study. Similar to Borrero et al. (2016), we identify at least two stray-light components: (1) a spectrally dispersed veil component and (2) a spatially scattered component. Following the technique of Borrero et al., we estimate the spectral stray-light fraction using flat-field observations to be 7.5% of the observed spectral intensity while the spectral resolving power is ≈100,000. All FIRS observations are then corrected for this presumed flat spectral stray-light component using Equation (4) of Borrero et al. (2016).

Correction of the spatially scattered light is more difficult as we do not have complete knowledge of the PSF. We make relevant approximations using available calibration data optimized through comparisons with stray-light-corrected HMI data. Figure 2 compares the histograms of the brightness temperature inferred in the continuum across the observed FIRS field of view with that of a coaligned SDO/HMI dconS data product nearest in time, which is a 720 s temporally smoothed image at 19:00 UT, approximately 2 hr after the FIRS scan. The local quiet Sun brightness temperature at 6173 and 10830 Å are both ≈6125 K (Cox 2000), and the sunspot temporal evolution does not play a significant role in the temperature distribution over this time period. Inferred temperatures in the sunspot umbra are approximately 900 K higher in the uncorrected FIRS data compared to HMI.

To facilitate correction of the FIRS data, we adopt and optimize an azimuthally symmetric PSF modeled as the sum of a diffraction-limited Airy function (P) and a Lorentzian function (L), further convolved with a 2D discrete instrument sampling profile (D), given by

$$\text{PSF}(x, y) = D(x, y) \ast [(1 - \alpha)P_{\text{Airy}}(r; \lambda) + \alpha L(r; \gamma)],$$

where $\alpha$ denotes the scattered light fraction and $\gamma$ is the Lorentzian half width at half maximum. The observations were actively corrected during acquisition by the high-order adaptive optics system (Rimmele et al. 2004), which partially justifies the adoption of the diffraction-limited Airy function. Further constraints on the model PSF are provided by narrow FIRS calibration slit scans of an Air Force resolution target placed in an intermediary focal plane, downstream of the main telescope optical tube. Although this excludes the atmospheric and telescopic contributions to the stray light, this calibration provides measurements of the post-focus performance at moderate angular frequencies (as measured in line pairs per arcsec). Figure 3 shows the measured contrast values (i.e., the modulated transfer function or MTF) in the scanning direction ($x$: gold stars) and along the slit ($y$: blue stars). We first point out that the measured MTF is not symmetric, but instead the contrast is comparatively reduced in the scanning direction, which we model by increasing the effective sample width along the scanning direction by a factor of 1.6, i.e., $0.463\alpha$. We speculate incorrect timing between the image scanning and data acquisition is responsible.

Within the MTF plot are two different model PSFs described by Equation (1). These PSFs are optimized solutions determined using an objective function that seeks a match between the HMI brightness temperature histogram and that recovered by FIRS after spatial deconvolution. We use 10 iterations of the Lucy–Richardson procedure for deconvolution (Richardson 1972; Lucy 1974). Figure 3 (bottom panel) shows that a ridge of possible solutions exist for the two free variables of our model ($\alpha$, $\gamma$). The two we select for further comparison are a narrow solution ($\alpha$, $\gamma = 0.34\alpha$, $8\alpha$) and wide solution ($\alpha$, $\gamma = 0.31\alpha$, $20\alpha$), which we use to evaluate the robustness of the results to changes in the modeled PSF. In the top panel, these are the solid and dashed colored curves, respectively. Solutions with a scattered component narrower than $\gamma = 8\alpha$ are unlikely based on the width of the solar limb profiles observed at other FIRS bandpasses by Jaeggli et al. (2012). Both selected PSFs lead to temperature histograms (Figure 2) that compare well with HMI and have an MTF comparable with the measured values at intermediate frequencies (top panel of Figure 3).

Using the two PSF models, we deconvolve the FIRS polarized spectra on an individual wavelength basis and evaluate their differences before detailed analysis below. This approach provides a more pristine view of the observed phenomena otherwise altered by a large fraction of stray light. We introduce the observations in the next section and then go on to show the differences in the corrected profiles when using the different PSF models in Section 3.3. We ultimately find them to be of minor consequence, which is why we concentrate our description on the data corrected using the narrow-PSF model.

We also must recognize the limitations of our approach to the PSF correction. The true PSF is not fully constrained, and we are deconvolving slit-scanned reconstructed images.
acquired over tens of minutes, which is longer than the characteristic dynamical timescales probed by the He I spectral lines. Both may introduce artifacts in the deconvolved signal. Therefore, we pursue below alternate analysis methods to assess the uncertainty in our results introduced by the stray-light contamination (see Section 3.4.7).

3. He I Data Analysis

3.1. Signatures of the SSD and Its Impact

In Figure 1, spatial maps of the deconvolved FIRS intensity data (using the narrow-PSF model) are shown at different wavelengths and for a zoomed in region of the sunspot umbra. The uncorrected data, as presented in Schad et al. (2016), shows qualitatively equivalent features. The field of view includes the area north and east (see cardinal directions in panel (e)) of the dark umbra core where large filament structures are seen in panel (b) near the rest wavelengths of the He I triplet. Distinct from these filaments and at much larger redshifts (67 km s\(^{-1}\)), panel (c) shows multiple channels of absorption left of the sunspot in the image directed toward the sunspots, most notably near X, Y = 15\(^{\circ}\), 65\(^{\circ}\). Schad et al. (2016) traced 23 of these channels, each of which exhibit acceleration of downflowing material converging primarily toward the inner boundary of the photospheric penumbra.

The most prominent downflow channel, which is the subject of the rest of this work, extends from the upper left of the field of view, curves downwards, and traverses (in projection) the darkest part of the sunspot umbra, as seen in panels (d) and (i) at redshifts of 179 km s\(^{-1}\). As it traverses the umbral core, the redshifted feature transitions from absorption to emission and then back into absorption. A high speed emission profile resides within the bounds of a contour line tracing continuum intensities below 0.23 normalized to the quiet Sun. Meanwhile, the downflowing material persists in these monochromatic images up to redshifts of 206 km s\(^{-1}\) (panels (e) and (j)) wherein only a small absorptive feature approximately 1" in size is observed near X, Y = 42\(^{\circ}\), 28\(^{\circ}\), within the sunspot umbra and inside of the 0.28 normalized continuum intensity contour. Coincident with the small patch of highly redshifted absorption in panel (j) is a small kernel of emission, similar in spatial size, and strongest near the rest wavelengths of the He I triplet, as seen in panel (g). We refer to this kernel, which is highlighted by overlapping contours in panels (g) and (j), as the terminus of the downflow within the umbra. We do not find evidence for significantly blueshifted emission within this kernel nor any obvious signature in the photospheric continuum; however, He I emission in this kernel is evident at large redshifts, as shown in panel (h) at a redshift of 67 km s\(^{-1}\), which corresponds to red line wings in the spectra discussed below.

3.2. Image Spectra

The spectrograph slit was fortuitously well aligned with the lower segment of downflow near X \sim 41.1\(^{\circ}\). Figure 4 displays the corresponding observed and narrow-PSF-corrected Stokes I and V image spectra. The high speed He I absorption immediately above the outer umbral edge (Y > 35\(^{\circ}\)) in the lower left panel corresponds to the satellite component centered near 10836.3 Å (~166 km s\(^{-1}\)). It is observed in both Stokes I and V, between photospheric Na I lines near 10834.8 Å and telluric water lines near 10838 Å. The weaker (Tr1) helium transition is not immediately evident. Proceeding downwards (along the slit) into the umbra, this satellite component of He I shows the transition described above from absorption to emission and back to absorption, along with the corresponding change in sign of the Stokes V profile. Its Doppler redshift also continues to increase.

In the area of highly redshifted absorption (X, Y = 41.1\(^{\circ}\), 28.7\(^{\circ}\)), strong signatures of what is presumed to be the blueward Tr1 He I transition appear. Immediately below these signatures (X, Y = 41.1\(^{\circ}\), 27.9\(^{\circ}\)) the high speed absorption weakens and strong emission profiles near the He I rest wavelengths appear with red wings extending to Doppler shifts nearly as high as the proceeding high speed absorption. Note the color scale saturates for intensities 10% larger than the local continuum to enhance the weaker features. In Stokes V, strong Zeeman-like profiles exist near the rest wavelengths with an opposite sign relative to the background He I spectra in the outer umbra. In the extended red wing, though, the emission profiles do not show pronounced Stokes V signals (i.e., between 10832 and 10835 Å).

The primary spectral features of this downflowing event are common to both the uncorrected and deconvolved data; however, the stray-light correction can significantly alter the
line profile shape. The corrected Si I 10827.09 Å line within the umbral core shows reversals in the line core, both in Stokes I and V, within the corrected data. Orozco Suárez et al. (2017) reported the initial discovery of these reversals in stray-light-corrected data from the German GREGOR telescope. In addition, and as expected, the observed unshifted (π) component of the intensity profile in the strongly Zeeman split photospheric lines is largely reduced upon stray-light correction. Less expected, however, are the He I emission signals only found in the stray-light-corrected data near the rest wavelengths (29″ < y < 33″), which also show disrupted complex V profiles. While umbral He I profiles have shown complex profiles in previous observations (see, e.g., Lites 1986 and Centeno et al. 2005), emission profiles are not typically observed. It is possible that these emission signals are real; though, we currently cannot discount that they are artifacts introduced by the stray-light correction.

### 3.3. Spectral Profiles

Figure 5 displays the observed (solid black) and corrected spectral profiles (solid and dashed blue) sampled key locations along the extent of the channel footprint, as indicated by dashed–dotted lines in Figure 4 and labeled with indices 1–4 (top to bottom in each figure). We select profiles sampling (1) the high speed absorption immediately outside the umbra, (2) the strongest redshifted emission, (3) the largest degree of high speed absorption in the umbra, and (4) the strongest emission at rest wavelengths at the downflow terminus.

To better illustrate the effects of the deconvolution on the spectral line shapes, we compare the deconvolved profiles with the original intensity profiles that are first offset and scaled assuming a spectrally flat stray-light component. This proceeds as follows. First we write the observed Stokes vector \( S = \{ I, Q, U, V \} \) as a linear combination of the true vector and a scattered profile:

\[
S_{\text{obs}} = (1 - f)S_{\text{true}} + fS_{\text{scat}},
\]

where, if the scattered light intensity profile is normalized by its continuum,

\[
f = \frac{I_{C,\text{obs}} - I_{C,\text{true}}}{1 - I_{C,\text{true}}},
\]

with \( I_{C,\text{obs}} \) and \( I_{C,\text{true}} \) being the observed and true continuum intensities. Approximating \( I_{C,\text{true}} \) as that obtained from the PSF-corrected data, \( f \) can be directly determined. Then, in the case of spectrally flat scattered component (\( I_{\text{scat}} = 1 \)), we can use Equation (2) to obtain the offset and scaled profiles as

\[
I_{\text{corr,flat}}(\lambda) = \frac{I_{\text{obs}}(\lambda) - f}{1 - f},
\]

which is plotted in Figure 5 for each selected profile using dashed–dotted black lines.

Also in the figure, we show a version of the \( (\gamma = 8″) \) PSF-corrected intensity profiles for which the contribution of the background absorption signals (i.e., those not associated with the downflow) are estimated and removed. These are the orange curves whose areas relative to the continuum are also filled in orange. As in Section 3.4, the background signals are estimated by first normalizing each profile along the slit by the local continuum and clipping the maximum value to 1, which removes the emissive contribution. We then median filter these continuum-normalized profiles along the slit with a kernel...
width of 25 pixels for wavelengths shorter than 10834 Å and 100 pixels otherwise. The increased kernel width is necessary at higher redshifts as the signal of interest is present along a greater portion of the slit. The filtered and normalized profiles are then removed from the corrected profiles through division.

In Figure 5 this process visually enhances the signatures of the downflow relative to the background spectra. The corrected line shapes in Figure 5 show only minor differences between the two selected model PSFs. We conclude the stray-light correction is not overly sensitive to the slope of the modeled PSF wings. For all further analysis, we adopt only one of the deconvolved data sets, the narrow-PSF version ($\gamma = 8''$).

The profiles of the deconvolved, high speed components of He I (between 10836 and 10837.5 Å) are slightly enhanced and/or narrowed relative to those employing a spectrally flat stray-light profile (i.e., Equation (4)), which is expected given the deconvolution should mitigate the influence of the significant gradients in the Doppler shift of this component along the slit that are smeared by the PSF.

Near the He I rest wavelengths, the point 1 helium profile appears consistently in absorption for the observed and corrected data. For point 2, which is displaced $\sim 2''$ from the loop footpoint, the corrected data display a weak emission profile, and the original Stokes $V$ signal is weakened, leaving a complex profile likely dominated by noise introduced during the deconvolution. Emission above the continuum in point 3, and especially point 4, is evident in the uncorrected data and becomes pronounced in the corrected data. In these locations, the Stokes $V$ profiles are also enhanced, and the sign of the blueward, antisymmetric lobe is opposite of the absorption profile in point 1, consistent with the emission profiles and the

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**Figure 5.** The original uncorrected data (solid black) and the spatially deconvolved Stokes $I$ and $V$ spectra (blue) extracted from the four selected locations in Figure 4. Two versions of the corrected data are shown, one for each selected PSF model. The dashed-dotted black lines show the original intensity profile corrected assuming a spectrally flat stray-light component, while the filled orange curves shows the corrected ($\gamma = 8''$) profiles for which an estimate of the background absorption profiles has been removed. See text for more details.
expectation that the polarity of the magnetic field remains constant across the region.

By comparing the observed and corrected profiles for point 4, especially near the He I rest wavelengths, it is apparent that the observed profile is the additive combination of a symmetric emission profile and a scattered absorptive component (see also Section 3.4.7). The peak of the emission is enhanced by approximately 0.2 in the deconvolved data, in units of the local quiet Sun continuum, when compared to the profile scaled using Equation (4). This is not unexpected given the median He I profile across the field of view exhibits ~30% absorption. Three maxima within the observed emission are transformed into two, which is more compatible with the characteristics of the He I 10830 Å triplet. Furthermore, the anomalous Stokes V reversal near the core of the blended Tr2 +Tr3 component (10830.3 Å) is removed.

3.4. He I Slab Model Fitting

We now perform spectropolarimetric inversions of the observed He I spectra to extract a range of physical parameters. Each selected Stokes spectrum is analyzed with custom multiline models. For the He I triplet, we use forward synthesis modules provided by the HAZEL-2 code (Asensio Ramos et al. 2008), which can treat the full quantum formation of the He I polarized signals including the Hanle, Zeeman, and Paschen–Back effects. HAZEL-2 solves for the radiative transfer in a constant-property slab model using a five term atomic model for triplet state helium taking only radiative transitions into account. The emergent intensity is determined via an analytical solution to the polarized radiative transfer equation given by

\[ I = e^{-K\tau} I_0 + [K^*-1(I - e^{-K\tau})/\beta S]. \tag{5} \]

\( I_0 \) is the Stokes vector incident on the boundary of the constant-property slab, furthest from the observer, and along the same line of sight. \( K^* \) is the propagation matrix normalized by its first element \((\eta_{\nu}) \), \( \tau \) is the optical thickness of the slab, and \( S \) is the source function vector. Each parameter, other than \( \beta \), is wavelength dependent. Values reported below for the slab optical thickness refer to \( \Delta r_{rad} \), the optical thickness at center of the blended red component (Tr2, Tr3).

\( \beta \) is an ad hoc scalar parameter introduced to scale the source function to account for deviations from the radiatively controlled five term model atom. As noted by Asensio Ramos et al. (2008), the five term model does not consistently treat the population mechanism of the helium triplet, which in typical chromospheric conditions is thought to be photoionization of singlet helium by coronal EUV radiation with subsequent recombination into the triplet state (Avrett et al. 1994). Recombination into the triplet state can also occur subsequent to collisional excitation/ionization of singlet helium or through the cooling of ionized coronal plasma. However, the ionization and recombination processes are slow in comparison to the bound–bound radiative transitions within the triplet, and bound–bound transitions via electron collisions are typically negligible at chromospheric densities. Here, though, they likely do play a role in certain cases, for which we adopt \( \beta \) as a free model parameter. In the optically thin case, however, \( \beta \) is ill-constrained and we cannot include it as a free parameter. This can be shown, following Trujillo Bueno & Asensio Ramos (2007), by using an approximated form of Equation (5) and neglecting anomalous dispersion, wherein the optically thin limit yields for Stokes \( I \):

\[ I(\tau) \approx I_0 + \tau (\beta S_0 - I_0), \tag{6} \]

and thus \( \tau \) and \( \beta \) are compensating variables.

3.4.1. Height Estimates

The source function \( S \), in the collision-free case, is governed by the incident radiation field, which is a strong function of location and height relative to the sunspot. Thankfully, stereoscopic imaging analysis in Schad et al. (2016) provides reliable constraints on the geometry of the observed flow, which subsequently allows calculation of the incident radiation field. The flow’s lower portion (\( h \lesssim 20 \text{ Mm} \)) is directed primarily radially and is thus inclined by (arc cos \( \mu \approx 23^\circ \)) relative to the line of sight. As a relative height reference, Figure 4 provides an inset axis that accounts for the projection of the radially oriented downflow, and assumes a zero height at the loop terminus (point 4). We derive estimated heights for use in our models via this scale. However, the absolute height of the loop terminus cannot be precisely inferred from the FIRS observations; although, it is reasonable to assume it is fairly low in the atmosphere. Schad et al. (2016) triangulated heights of \( \approx 3 \pm 3.5 \text{ Mm} \) at the lowest point of the flow; however, the error is likely larger than reported once co-alignment and pointing errors are further taken into account. Our presumption that the height of the helium signals at the loop terminus is in the low atmosphere is partially justified a posteriori based on the inferred field strengths and spectral formation details discussed below, though we also must discuss the influence of these uncertainties on the results.

3.4.2. The Incident Radiation Field

Neglecting any variations in the continuum formation height, we numerically integrate the deconvolved FIRS continuum data (near 10830 Å) to determine the mean intensity along the downflow, quantified as in Asensio Ramos et al. (2008) by the number of photons per mode (\( \bar{n} \)):

\[ \bar{n}(\nu) = \frac{c^2}{2\hbar^3} J_0(\nu) = \frac{c^2}{2\hbar^3} \int d\Omega I(\nu, \mu), \tag{7} \]

where \( J_0^0 \) is the first irreducible spherical tensor component of the radiation field. The spectral irradiance angular dependence, \( I(\mu) \), is sourced from Allen’s astrophysical quantities (Cox 2000), and is scaled according to the fractional contrast of the measured continuum intensity. For locations above the quiet Sun, \( \bar{n}_{QS} \) decreases slowly with increasing height (Figure 6). For a column radially above point 4, however, \( \bar{n}_{\text{loop}} \) increases sharply with height as the radiation cone angle encompasses progressively more of the penumbra and quiet Sun. At a height of 15 Mm, \( \bar{n}_{\text{loop}} \) is \( \approx 90\% \bar{n}_{QS} \). While \( \bar{n}_{\text{loop}} \) relative to the quiet Sun will vary for each transition wavelength of the five term model, we find this effect negligible in our models compared to the overall scale reduction calculated for the 10830 Å transitions, which below is applied to all transitions uniformly.

Higher order multipoles of the incident radiation field influence the degree of scattering induced polarization, the signatures of which can be found along the coronal downflow at higher heights (see Schad et al. 2016). Here, we ignore the effects of atomic polarization and do not fit the linear polarized spectra. The observational noise in \( Q \) and \( U \) within the dark
umbra typically dominate what signals are apparent (see Appendix). Furthermore, the strength of the Zeeman Stokes V signals, and the estimated low inclination angle of the flow relative to the line of sight, suggest adequate magnetic field inferences can be estimated for He I by fitting only the circularly polarized spectra.

### 3.4.3. Point 1: Single Helium Slab Model in Absorption

The absorptive high speed satellite observed at point 1, centered near 10836.3 Å, can be modeled using a single He I slab model. The PSF-corrected Stokes spectra and optimized fits are shown in Figure 7. In this case, while the blended Tr2, Tr3 component is resolved, the weak Tr1 He I transition of the redshifted satellite is only visually apparent in the Stokes V profile and is otherwise dominated by the blend of three Na I Zeeman-sensitive photospheric lines near 10834.85 Å. We develop a uniform approach to modeling the background photospheric and telluric lines for points 1, 2, and 3. The five strongest Na I and Ca I photospheric lines are modeled using the Unno–Rachkovsky solutions for a Milne–Eddington atmosphere (Landi Degl’Innocenti & Landolfi 2004). This model then enters Equation (5) as \( I_0 \) scaled according to the measured contrast of the background continuum \( I_C/I_{C, QS} = 0.6 \) for point 1) and multiplied by the canonical value of the solar spectral irradiance at 10830 Å. Finally, we use normalized Voigt profiles to model telluric line absorption at 10834, 10837.5, and 10838 Å.

The reduced chi-square statistic, given as the weighted sum of squared deviations per degree of freedom \( \chi^2_w = \chi^2/\nu_{ad} \), is used as the objective function. Measurement variances, relative to the quiet Sun intensity, are estimated from the data as \( \sigma^2(U, Q, U, V) = [0.0036, 0.0009, 0.0009, 0.001]^2 \). Binary fitting weights control which portion of the observed spectra contributes to the fit during the inversion and are shown in each figure.

For point 1, there are 32 free variables in the model fit, but ultimately only four variables directly contribute to the He I slab model. These are the longitudinal magnetic field strength \( B_z \), the slab optical thickness \( \Delta \tau_{\text{red}} \), the Doppler shift \( v_{\text{LOS}} \), and the thermal velocity \( w_T \) governing the line width. The line profile damping and \( \beta \) are held fixed at \( 10^{-4} \) and 1, respectively. The ratio of \( \bar{n} \) relative to the quiet Sun is fixed at 0.89, as determined in Section 3.4.2, using an estimated height of 15.55 Mm.

Our inversion strategy includes pre-optimizing the fits of the photospheric and telluric lines using bounded differential evolution optimization, especially as the helium slab model is computationally more costly. Once initial guesses are adequately determined from this step and manually for the He I lines, a trust region reflective least squares optimization is used to converge to the best-fit solution. Both optimization tools are part of the SciPy package (Virtanen et al. 2020).

We achieve satisfactory fits \( \chi^2 = 2.96 \) to the point 1 spectra using the above described model, and the optimized parameters are reported for it and all subsequent fits in Table 1. In addition to the final fit, Figure 7 plots separately the photospheric portion of the model and the helium slab signal under the approximation that the incidence photospheric illumination is line-free.

### 3.4.4. Point 2: Single Helium Slab Model in Emission

Fitting the satellite emission signal near 10837 Å for point 2 proceeds in the same manner as for point 1, with the results shown in Figure 8. \( I_C/I_{C, QS} \) is 0.18 while the \( \bar{n} \) ratio is fixed to...
Table 1
Retrieved Parameters using Stacked HAZEL-2 Slab Models Fit to the Observed He I Triplet Spectra

| Parameter          | Inversions of Deconvolved Data | Alternate Stray-light Correction |
|--------------------|-------------------------------|----------------------------------|
|                    | Point 1 | Point 2 | Point 3 | Point 4 | Point 4A | Point 4B |
| Estimated height [Mm] | 15.55   | 4.81   | 1.98    | 0.57    | 0.57    | 0.57    |
| \(I_c/I_{CQS}\) (obs) | 0.7     | 0.41   | 0.45    | 0.44    | 0.44    | 0.44    |
| \(I_c/I_{CQS}\) (corr) | 0.6     | 0.18   | 0.25    | 0.24    | 0.24    | 0.24    |
| \(\beta\) ratio     | 0.89    | 0.66   | 0.47    | 0.32    | 0.32    | 0.32    |
| Number of slabs     | 1       | 1      | 2       | 4       | 4       | 4       |
| \(\chi^2\)         | 2.96    | 0.91   | 1.19    | 11.78   | 8.39    | 6.55    |
| \(\beta\) [G]       | −461.29 | −841.180 | −856.113 | −1351.934 | −1347.274 | −1305.238 |
| \(\Delta \tau_{\text{red}}\) | 0.68±0.03 | 0.35±0.05 | 11.88±3.64 | 6.05±3.49 | 6.11±1.94 | 6.32±1.83 |
| \(v_{\text{LOS}}\) [km s\(^{-1}\)] | 165.6±1.3 | 183.6±0.7 | 190.6±0.4 | 195.5±1.9 | 195.2±0.6 | 195.2±0.6 |
| \(w_T\) [km s\(^{-1}\)] | 9.06±0.44 | 8.63±0.91 | 7.27±0.48 | 7.52±1.47 | 7.4±0.74 | 7.65±0.7 |
| \(\beta^3\)         | 1 (fixed) | 1 (fixed) | 1.00±0.01 | 1.59±0.08 | 1.67±0.03 | 1.66±0.02 |
| \(\beta^2\) [G]     | ...     | ...    | ...     | ...     | ...     | ...     |
| \(\Delta \tau_{\text{red}}\) | ...     | ...    | 0.13±0.11 | ...     | ...     | ...     |
| \(v_{\text{LOS}}\) [km s\(^{-1}\)] | ...     | ...    | 153.5±4.3 | ...     | ...     | ...     |
| \(w_T\) [km s\(^{-1}\)] | ...     | ...    | 56.1±2.61 | ...     | ...     | ...     |
| \(\beta^3\)         | ...     | ...    | 0.1±0.01  | ...     | ...     | ...     |
| \(\beta^3\) [G]     | ...     | ...    | ...     | ...     | ...     | ...     |
| \(\Delta \tau_{\text{red}}\) | ...     | ...    | 0.24±0.03 | ...     | ...     | ...     |
| \(v_{\text{LOS}}\) [km s\(^{-1}\)] | ...     | ...    | 38.4±4.1 | ...     | ...     | ...     |
| \(w_T\) [km s\(^{-1}\)] | ...     | ...    | 54.0±3.52 | ...     | ...     | ...     |
| \(\beta^3\)         | ...     | ...    | ...     | ...     | ...     | ...     |
| \(\beta^3\) [G]     | ...     | ...    | ...     | ...     | ...     | ...     |
| \(\Delta \tau_{\text{red}}\) | ...     | ...    | 0.89±0.37 | ...     | ...     | ...     |
| \(v_{\text{LOS}}\) [km s\(^{-1}\)] | ...     | ...    | 8.7±1.4 | ...     | ...     | ...     |
| \(w_T\) [km s\(^{-1}\)] | ...     | ...    | 15.1±2.96 | ...     | ...     | ...     |
| \(\beta^3\)         | ...     | ...    | ...     | ...     | ...     | ...     |
| \(\beta^3\) [G]     | ...     | ...    | ...     | ...     | ...     | ...     |
| \(\Delta \tau_{\text{red}}\) | ...     | ...    | 7.93±0.96 | ...     | ...     | ...     |
| \(v_{\text{LOS}}\) [km s\(^{-1}\)] | ...     | ...    | 6.74±0.39 | ...     | ...     | ...     |
| \(w_T\) [km s\(^{-1}\)] | ...     | ...    | 6.95±0.49 | ...     | ...     | ...     |
| \(\beta^3\)         | ...     | ...    | 3.69±0.09 | ...     | ...     | ...     |

Notes. The top section contains static aspects of the model and the best-fit reduced chi-square statistic. Superscript indices for each model parameter below denote the slab index, which increases with distance from the observer along the line of sight and is further ordered by the Doppler shift of the modeled component. See text for more details.

* The height is estimated from the feature morphology and previous stereoscopic analysis. See text for details.

The contribution of a weak unidentified absorption feature at 10835.8 Å, which is evident in the atlas umbral spectra from Wallace et al. (1999), is weighted out of the fit. A satisfactory fit (\(\chi^2_\text{red} = 0.91\)) is achieved to the emission without any scaling of the source function (\(\beta = 1\)).

3.4.5. Point 3: Two Stacked Helium Slabs

At point 3, the redshifted helium signatures are more complex (see Figure 9), showing two strongly absorbing features at 10836 and 10837.1 Å in addition to broad absorption near the Na I lines at 10834.8 Å (see also Figure 5). The former have characteristics indicative of optically thick material. In particular, as the opacity increases, the ratio between the Tr1 and blended Tr2, Tr3 intensities will approach unity; meanwhile, Stokes V of only the blended component will develop a flat segment in its core, like that observed near 10837.2 Å. We, however, found no adequate single slab model and instead adopted a stacked two slab model. In a stacked slab model, the intensity emergent from one (more-distant) slab is fed into a subsequent slab as \(I_0\) in Equation (5). We order the slabs by the redshift of the component such that the most redshifted material is described by the slab closest to the observer. That said, for point 3, the solution is not significantly influenced by the slab order. In total, nine model parameters describe the helium profiles: a single common value for \(B_c\) plus \(\Delta \tau_{\text{red}}, v_{\text{LOS}}, w_T\) and \(\beta\) for each slab. We find that \(\beta\) needs to be a free parameter for both slabs to achieve an adequate fit (\(\chi^2_\text{red} = 1.09\)). In fact, to account for the broad absorption near 10834.8 Å, a value of \(\beta < 1\) is required. Otherwise, we find the opacity will saturate before reaching the degree of observed absorption. Meanwhile, we limit the fit to one value for \(B_c\) because the fit is insensitive to the magnetic field of the broader component. \(I_c/I_{CQS}\) is 0.25 and the \(\eta\) ratio is fixed to 0.45 (\(h \approx 1.98\) Mm).
For point 4, our model seeks to reproduce the strong red-asymmetric emission and the redshifted absorption. The spatial extent of the emission along the slit is only $\sim 1''$, and the redshifted absorption signal is separated from the nearby photospheric lines. This allows us to remove the background lines in Stokes $I$ by dividing the observed profile by the median of the neighboring profiles, which are first normalized and clipped at 1; see Figure 10. By removing the background intensity signals and applying spectrally dependent weights to Stokes $V$, we can model the observed HeI profiles separate from the photospheric and telluric lines.

Four stacked helium slabs are necessary to reproduce the observed profile: three slabs for the red-asymmetric emission and one for the redshifted absorption component. The slab ordering relative to the observer is again according to increasing redshift. The 16 free parameters include $\Delta \tau_{\text{red}}$, $w_T$, and $v_{L\Omega S}$ for each slab, one value of each $B_z$ and $\beta$ that are the same for the three emissive slabs, and also one value of each $B_z$ and $\beta$ for the absorptive slab. In Table 1, the indices for the slabs are (1) for the absorption slab and (3, 4, 5) for the emission. Index 2 is reserved to distinguish the blueward component in point 3 from the point 4 emission.

The assumed height ($h \approx 0.57 \text{ Mm}$) is equal for all components of the signal, as we do not have other constraints. $I_C/I_{\text{LOS}} = 0.24$ and the $\bar{n}$ ratio is fixed to 0.32. The quality of the fit ($\chi^2_{\text{red}} = 11.78$) is not as good here as for the other selected points, though, the signal is also more complex. The use of three slabs to model the emission signal is only an approximation of the real atmosphere that likely has strongly varying properties along the line of sight. Improved fits can be achieved with more slabs; though, the number of possible degenerate solutions also amplifies. In all cases, we have tried to restrict the number of free parameters to those that can be reliably fit.

The inverted model in Figure 10 reproduces the main characteristics of the profile. Recall that Stokes $Q$ and $U$ are not included in the fit. The Stokes $V$ signal provides important constraints on the widths of the three components needed to reproduce the emission signal and its red wing. The location of the second slab (index 4 in the table), whose $T_\text{r2}$, $T_\text{r3}$ component peaks near 10830.4 Å, is essential for reducing the $V$ amplitude in the blended component of the slab ahead of it and for creating the $V$ feature near 10831 Å. The only feature.
the model does not reproduce well is the small offset of the flat portion of Stokes \( V \) near 10830.4 Å, which we suspect is a remnant from the imperfect scattered light correction.

### 3.4.7. Point 4: Fits using Alternative Stray-light Corrections

Finally, although we achieve a satisfactory fit to the deconvolved point 4 spectrum, given the uncertainties in the PSF correction, we further assess its influence on the derived parameters of the four-slab model. Using Equation (2), we first calculate the normalized scattered light intensity profile which has been removed during deconvolution, shown as the red dashed–dotted line in the top panel of Figure 11. In comparison, the blue and green dashed–dotted lines are the first quartile (Q1) and 90th percentile (P90) intensity values by wavelength for all normalized profiles observed across the full FIRS field of view. These represent cautiously wide bounds for the maximum and minimum intensity signal that could be scattered into the observed umbral signal. The shape and width of each are comparable to the profile removed during deconvolution; although, the absorption depth varies substantially. Also, note that the PSF deconvolution will not only remove stray light but also locally sharpen the signal, which is why its scattered absorptive component (red dashed–dotted line) appears deeper in the figure. Using Equation (2), we derive two alternatively corrected profiles, labeled A and B, that make use of the Q1 and P90 profiles as the scattered intensity profile. For Stokes \( V \), the scattered profile is taken as the mean normalized \( V \) profile within the sunspot region (shown in figure multiplied by \( \chi^2 \)), which is small in comparison to the signal in the emission profile. We then carry out the same analysis on these two alternatively corrected Stokes profiles as in the prior section. The fitted profiles are shown in Figure 11 and their parameters given in Table 1. One particular difference is that the inferred magnetic field amplitude decreases when the scattered light profile is assumed to have a great amount of helium absorption. This is expected since the relative degree of circular polarization decreases in that case. Related changes occur for \( \Delta \tau_{\text{red}} \) and \( \beta \) for the most distant slab (index 5 in Table) while \( v_{\text{LOS}} \) and \( w_T \) are not greatly altered, nor the parameters that describe the red line wing or the fast downflowing component.

### 3.4.8. Summary of Helium Model Fits and Error Estimates

Table 1 provides the fitted parameters for each spectral fit that has been discussed. As noted in the caption, the superscript indices for each parameter denote the slab index, which increases with distance from the observer along the line of sight, and is further ordered by the Doppler shift of the modeled component. Slab index 1 is always the most redshifted component of the downflow. Parameters that are coupled across slabs or fixed are as indicated. 95% confidence intervals are explicitly calculated for each parameter using the extra-sum-of-squares F-test (see, e.g., Motulsky & Christopoulos 2004). In short, this method determines the significance level of a nested model under the null hypothesis. Here the nested model is one that reduces the degrees of freedom by one by fixing one parameter to a specific value, which is iteratively changed in both directions from its best-fit value. The significance level is determined for each change using the F-test where the relevant statistic is given by the relative difference in the weighted sum of squared deviations (chi-square) for the best-fit \( \chi^2_{\text{best-fit}} \) and the nested test model \( \chi^2_{\text{test}} \) divided by the relative difference of degrees of freedom. Here,
this reduces to

\[ F(1, n - m) = \left( \frac{\chi^2_{\text{test}}}{\chi^2_{\text{best-fit}}} - 1 \right) (n - m). \]  

(8)

\( n \) is the number of observations, and \( m \) is the number of free parameters for the best-fit case, which is one greater than the model under test. \( F(1, n - m) \) is the \( F \)-distribution with numerator 1 and denominator \((n - m)\). The significance level is calculated using the cumulative distribution of the \( F \)-distribution. This method provides an estimate for the sensitivity of the fits to changes in a given parameter; though, it does not provide information regarding inter-parameter correlations. Our models minimize the number of parameters for the helium slabs to reduce the potential for strongly correlated variables. In the case of point 4, we expect the uncertainties introduced by the stray-light correction to be greater than possible degenerate models.

3.5. Photospheric and Chromospheric Magnetic Field Maps

In Figure 12 we extend our analysis to the photospheric and chromospheric properties of the entire sunspot, in order to place the downflow properties in context to the surrounding area. The vector magnetic field of the photosphere is inferred via inversions of the deconvolved full Stokes data, using the shallow Ca I 10839 Å line formed in the deep photosphere, and the Unno–Rachkovsky solutions for a Milne–Eddington atmosphere (Landi Degl’Innocenti & Landolfi 2004). In the figure, we report the total field amplitude \( (B) \), the inclination along the line-of-sight direction, and the azimuth angle relative to the linear polarization reference direction, which is oriented parallel to the solar equator. For validation, we did a cursory comparison between the retrieved umbral field strengths with that reported in Level 2 Hinode Spectropolarimeter (Kosugi et al. 2007) data on this date for a scan starting at 7:27 UT, which favorably showed values as high as \( \sim 3150 \) G, comparable to those shown in panel (b) of Figure 12.

The He I 10830 Å Stokes spectra across the sunspot are inverted using a single constant-property slab model. Due to the level of noise and weak linear polarization signals (panel (g)), the inclination and azimuth of the field vector are not well recovered across the sunspot. Figure 12 displays instead the absolute value of the longitudinal magnetic field intensity \( (B_L) \). Furthermore, due to the aforementioned presence of complex and emissive He I profiles in the dark umbral core, we do not have high confidence that the magnetic field values returned in the affected areas are reliable. We color these areas black in the \( B_L \) map by masking those areas where an emission signal larger than 4% is observed in the corrected data. We find that these blacked out regions lie along two vertical stripes near \( X = 39'' \) and 42''. Although the fits in these regions are not satisfactory, we do find in the map of Doppler velocity \( (v_{\text{LOS}}) \) evidence that these regions correspond to sharp spatial-temporal transitions, from redshifts to blueshifts, consistent with umbral flashes.

4. EUV Data Analysis

The abrupt termination of supersonic velocities at the location of enhanced subsonic emission in the neutral helium spectra are highly suggestive of the downflowing material undergoing a standing shock transition. To extend our thermal coverage, we investigate time series of SDO/AIA EUV imaging data coaligned with the FIRS data (see Figure 13).

4.1. Light Curves

The FIRS observations indicate the downflow terminus is \( \approx 1'' \) wide. For the AIA analysis we selected a square area \( 2.4 \times 2.4 \) arcsec\(^2\) (4 \times 4 pixels) that overlaps this region (black square in Figure 13). Analogously we selected a quiet nearby umbra region of similar size, shown in green, to act as a quiet-background umbra region. While the selection of the quiet region is arbitrary, analysis of several such nearby regions generally showed similar behavior.

In Figure 14 we show the temporal variation of the integrated signal in the impact and quiet-background umbra. All the filters show a sharp increase in brightness within the signal region (black square in Figure 13) starting \( \approx 15 \) minutes before the FIRS slit position begins to cross the umbra. This may be an indication that downflowing material had already
started impacting the umbra before the FIRS scan started and continued for at least 1 hr after the end of the FIRS scan. The light curves in the signal area also show periodic fluctuations, but only after the initial intensity increase, with a period of ~2.5 minutes, a frequency similar to chromospheric and TR umbral oscillations and suggestive that the EUV increased emission originates below coronal heights.

4.2. Differential EM Inversions

EM analysis is a useful tool for studying changes in the thermal state of the plasma. The column EM is defined as

$$EM(T) = \int_0^\infty n_e^2(T, z)dz \text{ (cm}^{-3}), \quad (9)$$

where $n_e$ is the electron density at temperature $T$ and coordinate $z$ along the line of sight. Using the umbral data from six of the AIA filters (94, 131, 171, 211, 335 Å, and 335 Å), we applied the inversion method described by Cheung et al. (2015) to analyze temporal changes in the EM($T$) and radiative cooling rates. The AIA 304 Å channel, which shows a comparable response to the downflow, is not used for the inversion as it is not adequately modeled as optically thin emission in the coronal approximation.

The AIA temperature response functions were generated using the ch_aia_resp function included in CHIANTI v9.0.1 (Dere et al. 2019) using the default ionization fractions and a constant pressure of $p/k_B = 10^{15}$ K cm$^{-3}$, where $k_B$ is the Boltzmann constant. Variations in the assumed elemental abundances primarily impact the amplitude of the calculated EM($T$) but the shape and temporal variation patterns qualitatively remain the same. The EMs shown here use photospheric abundances from Asplund et al. (2009).

For the inversion we used a logarithmic temperature grid spanning $\log(T[K]) \in [5.5, 7.4]$ with 20 equally spaced bins of width $\Delta \log(T) = 0.1$. The inversion code devised by Cheung et al. (2015) accepts as a starting condition sets of truncated Gaussian basis functions of varying widths centered on each temperature bin (see Figure 15 in Cheung et al. 2015 for a visual representation of one such basis matrix). In searching for a possible solution for EM($T$), the algorithm imposes a sparsity constraint that minimizes the number of basis functions from this starting set that are used to calculate the best-fit solution. Tests done varying the number and widths of input basis functions show small improvements in the $\chi^2$ for the fits are possible, but the resulting qualitative behavior of EM($T$) over time does not change. For the results presented here we settled on using three sets of Gaussian basis functions with varying widths $\sigma = \{0.0, 0.1, 0.2\}$ in log($T$) units.

Figure 15 shows the time series of inverted EMs for the impact and quiet umbra regions. The inversions are calculated for each AIA pixel independently. The results show the average EM($T$) values over the 16 pixels included in the impact and quiet umbra regions selected in the preceding section. While both regions show an increase in the EM($T$) at temperatures below 1 MK, the impact region shows larger absolute and relative increases compared to the time period before the downflow commenced. The signal region also shows brief increases in EM($T$) for temperatures between $10^{6.8}$ and $10^{7.3}$ K.

4.3. Radiative Losses

From the EM($T$) time series it is possible to calculate the total power radiated by the plasma in the inverted temperature range. The radiated power as a function of time $t$ can be written as (see, e.g., Aschwanden 2005)

$$P_{\text{rad}}(t) = \int_{T_i}^{T_f} EM(T, t) \Lambda(T) dT \text{ (erg s}^{-1}), \quad (10)$$

where $A$ is the area of the emitting region (measured in square centimeters) and the radiative loss function $\Lambda(T)$ (measured in
erg cubic centimeters per second) is primarily a function of temperature with a smaller dependence on density. We calculate Λ(T) using CHIANTI and the same elemental abundance as for the EM(T) inversions. For electron densities between 10^6 and 10^12 cm^-3 we find a variation of <10% over the entire temperature range used for the differential emission measure inversion.

Figure 13. A context AIA 171 Å image (top panel) with the FIRS scanned field of view shown by the dashed black line. Also shown in solid white lines are contours of the HMI continuum (not PSF corrected) at 0.4 and 0.8 normalized to the local quiet Sun. The lower panel shows an enlarged region around the active region umbra. The blue plus signs indicate the location of the FIRS pixels discussed in the preceding sections. The black and green boxes indicate the impact and quiet umbral regions selected for emission measure (EM) analysis. The animated version of this figure shows context AIA 171 images covering the full time series analyzed with a label active while the FIRS scanned the umbral part of the active region.

(An animation of this figure is available.)

Figure 14. Time series of the integrated intensity with measurement errors inside the impact signal region and quiet umbral background marked by the black and green boxes in Figure 13. The solid blue lines show synthetic AIA signals computed from the EM(T) inversion (χ^2 in bottom panel) for the impact region. The cyan strip indicates the time range when the FIRS slit crosses the umbra.

Figure 16 shows the excess power radiated in the two selected regions relative to a time before the downflow event begins. The impact region shows significant enhancements in radiated power throughout the downflow event, with periods when the radiative rate is nearly doubled relative to the initial state. This is in contrast to the nearby umbra which only show modest enhancements (<20%) relative to the initial state. The radiative losses also exhibit the temporal oscillations with a period of ∼2.5 minutes.

5. Results and Discussion

We now discuss the main characteristics of the downflow and its impact with the lower atmosphere. We further show how the observed signatures are consistent with a strong
A radiative shock that is uniquely observed to penetrate the lower umbral atmosphere.

5.1. Dynamics

The observed redshifts reach values up to 196 km s$^{-1}$ (see Table 1). In a statistical study, with Doppler coverage up to $\sim$75 km s$^{-1}$, Aznar Cuadrado et al. (2007) found He I SSDs extending to redshifts of 60 km s$^{-1}$ and always observed in absorption. SSDs observed at TR temperatures by IRIS show emission components, well separated from the line core intensity, with redshifts up to $\sim$200 km s$^{-1}$ (Kleint et al. 2014; Samanta et al. 2018). High speed ($\sim$180 km s$^{-1}$) transverse motion of raining material has been observed off-limb with IRIS observations and in He I (Schad 2017, 2018). Using the stereoscopic determined loop inclination of 23° (relative to the line of sight), the equivalent radial-directed speeds observed here peak near 212 km s$^{-1}$. If we assume freefall motion starting at rest, the estimated initial height of the material is $(v^2/2g_e) \approx 82$ Mm, similar to the location of the highly suspended filament material associated with the source of this drainage in our earlier work (see Figure 4 of Schad et al. 2016).

A closer look at the kinematics show a nonuniform acceleration in the lower portion of the downflow. In Figure 4, below $y = 31^\circ$, the rate of Doppler velocity change
along the slit for the redshifted component increases. We recognize the estimated heights naively assume a radial loop even at the lower heights that are not well imaged with stereoscopic methods. Using these estimates, however, the linearized acceleration of the redshifted material between points 1 and 2, assuming a continuous flow and using the fitted values in Table 1, is \(0.5(v_2^2 - v_1^2)/(\beta_2 - \beta_1)\) \(= -292 \pm 17\) m s\(^{-2}\), roughly in agreement with gravitational acceleration \((g_\odot = 274\) m s\(^{-2}\)). However, the estimated acceleration increases to \(-536 \pm 116\) m s\(^{-2}\) between points 2 and 4, whose estimated height difference is \(\sim 4.2\) Mm. Only if the height difference is grossly underestimated by \(>4\) Mm would the inferred acceleration be consistent with solar gravitational acceleration. We note that if we repeat the height estimate of the source location under the freefall assumption, using the velocities at point 1 at an estimated height of 15 Mm where the acceleration is consistent with freefall, then we revise our earlier estimate to 74 Mm, which remains roughly compatible with the highly suspended filament material described in our earlier work.

Increases in the flow acceleration near the footpoint are not commonly reported for TR SSDs. Kleint et al. (2014) did observe peak velocities faster than expected for freefall acceleration along a curved loop, which would require a nonzero initial velocity for the freefall scenario. Meanwhile, the majority of coronal rain events show acceleration less than freefall (see, e.g., Antolin & Rouppe van der Voort 2012). Müller et al. (2005) suggested high speeds could be created when material flows along a pre-evacuated loop, though their simulations suggest the material will still be decelerated near the flow footpoint.

In this case, the footpoint is embedded in the sunspot and the flow persists for more than an hour based on the AIA observations. If we approximate it as continuous, compressible field-aligned flow, increases in the velocity can be expected when the cross-sectional area \((A)\) reduces and the magnetic field intensifies. Estimates of the density using the He I profiles are not possible when the signal is optically thin (see Section 5.3); however, using the continuity equation \((nAV = \text{constant})\), where \(n\) is the total number density and magnetic flux conservation \((BA = \text{constant})\), we can infer relative changes in the flow properties using the fitted values (Table 1), where \(v_{\text{LOS}} \approx v, B_1 \approx B,\) and \(T\) is inferred from \(w_T,\) i.e., \(T = M \sqrt{w_T^2 - \xi^2/2k_0},\) where \(M\) is the mass of helium and \(\xi\) is the instrumental broadening. Assuming an ideal gas, the relative pressure change is equivalent to the relative density change multiplied by the relative temperature change. Based on this approach, Table 2 provides the flow properties inferred from the redshifted material and expressed as a fraction relative to point 1. There is only modest evolution of the highly redshifted material—a factor of 2 change in temperature and density, while the pressure remains fairly constant (within the error bounds).

### 5.2. He I Line Formation of the High Speed Material

The redshifted He I component is in absorption away from the sunspot, while near the highest speeds, and when projected over the darkest parts of the sunspot umbra, the He I lines appear in emission. We can explain the emission profiles as the consequence of the relative increase of the mean intensity of the radiation field exciting the material at higher heights above the sunspot compared to the intensity of the background continuum along the line of sight. This is best shown in Figure 17, where the line signal along the slit (from Figure 4) is compared to the background continuum intensity \((I_0, \text{solid blue line})\), the line source function (black line) determined using Equation (9,14) of Landi Degl’Innocenti & Landolfi (2004) and the level populations calculated by HAZEL-2, and the mean intensity from Figure 6 (dashed blue line). All are given in units of temperature. Recall that to fit the emission spectra for both points 1 and 2, no ad hoc scaling of the line source function was necessary \((\beta = 1)\). In the optically thin case, Equation (6) shows the relative amplitude of the source function and the background intensity dictate whether the line is in emission or absorption. Indeed, we find the line source function is slightly larger than the background intensity within the umbra, which explains the point 2 emission. For point 3, the modeled profile

### Table 2

| Parameter  | Point 1       | Point 2       | Point 3       | Point 4       |
|------------|---------------|---------------|---------------|---------------|
| \(T\) [KK] | 17.6\(_{+1.5}^{-+0.4}\) | 15.8\(_{+1.6}^{-+0.1}\) | 10.6\(_{+1.6}^{-+0.1}\) | 11.5\(_{+1.6}^{-+0.1}\) |
| Temp (\(T\)) | ...          | 0.90\(_{+0.26}^{-+0.27}\) | 0.64\(_{+0.18}^{-+0.14}\) | 0.65\(_{+0.04}^{-+0.01}\) |
| Area (\(A\)) | ...          | 0.54\(_{+0.28}^{-+0.24}\) | 0.54\(_{+0.13}^{-+0.16}\) | 0.34\(_{+0.16}^{-+0.16}\) |
| Dens (\(n\)) | ...          | 1.65\(_{+0.39}^{-+0.37}\) | 1.61\(_{+0.29}^{-+0.29}\) | 2.48\(_{+0.24}^{-+0.32}\) |
| Pres (\(P\)) | ...          | 1.47\(_{+0.24}^{-+0.24}\) | 0.97\(_{+0.16}^{-+0.16}\) | 1.62\(_{+0.61}^{-+0.61}\) |

- **Figure 17.** (Top) Peak line signal normalized to the local continuum for the redshifted satellite component of He I observed between 10835.38 and 10837.7 Å and as a function of the y-axis coordinate along the slit at \(x = 41.08\) Å (see Figure 4). (Bottom) Comparison between the background continuum (in temperature units) and the calculated source function, for the collision-free radiative-equilibrium case \((\beta = 1)\), where the mean intensity of the exciting radiation field at 10830 Å is derived from the observations.

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is optically thick and required a marginal scaling of the line source function ($\beta = 1.18$). However, the line remains in absorption, which is consistent with the figure wherein the continuum brightness temperature exceeds the mean intensity at low heights. This level of agreement provides us some confidence that our height estimates are credible to within 1 or 2 Mm.

One consequence of this finding is that the detection of SSDs within sunspot umbras in He I 10830 Å lines may be more complicated, especially for large dark sunspots, as the line will not remain in absorption and could become weak and harder to detect, especially in the presence of telluric and photospheric line absorption.

### 5.3. He I Density Estimates of the High Speed Material

Similar to point 3, the highly redshifted component of point 4 requires scaling of the modeled source function ($\beta = 1.59$ in Table 1); however, this scaling is especially sensitive to the estimated height on account of the mean intensity of the photoexcitation rapidly increasing between heights of 0 and 5 Mm. That said, an enhanced source function could also be a sign of electron collisions at higher densities. In Figure 18, we evaluate the expected enhancement of the source function as a function of electron density using CHIANTI v9 calculations under the coronal approximation (Dere et al. 2019). Similar to HAZEL-2, these calculations do not incorporate all the necessary mechanisms to understand the helium triplet population; however, they do provide an initial estimate on the role of collisions on the source function, which is not included in HAZEL-2. Our calculations assume the same degree of photoexcitation as used to model the point 4 spectra ($\bar{n}/n_{eq} = 0.2$), which in the formulation of CHIANTI corresponds to excitation by a radiation field of 3864 K at zero height. The CHIANTI and HAZEL source functions for $\beta = 1$ agree at low density. For an electron temperature $T_e = 10$ K, $\beta = 1.59$ for point 3 implies an electron density of $(\log n_e \approx) 12.1$. This is on the higher end of what could be expected and is likely an upper estimate. Samanta et al. (2018) reported $(10.17 \pm 0.69 \text{dex})$ for IRIS observed SSDs at TR temperatures. Antolin et al. (2015) estimated core coronal rain densities, inferred using EUV absorption due to hydrogen and helium, to be $10.3–11.4 \text{dex}$. Scullion et al. (2016) estimated $11.9–12 \text{dex}$ for flare-driven coronal rain.

To gain a better understanding of how the estimated heights affects the inferred $\beta$ values for point 4, we repeated the above analysis, including the model fitting, by assuming the height is 1 Mm higher than our nominal estimates. In this case, the height is taken to be $1.57 \text{Mm}$ and $\bar{n}/n_{eq} = 0.43$ and the inferred values of $\beta^e$ (corresponding to the high speed absorption) and $\beta^f$ (corresponding to the emission) change to 1.17 and 2.73, respectively. The former would imply an electron density of $\sim 11.3 \text{dex} \left[ \text{cm}^{-3} \right]$ in the high speed component, which is more in line with previous observations.

Oddly, the second, less-redshifted, component in the point 3 profile required a very small source function, $\beta \approx 0.1$, to be fit. We do not have a good explanation for this small value; though, we discuss below that nonequilibrium effects may be important. It is also possible that it is an artifact of our fitting methodology. In order to preserve the relative shape that the optically thick faster component imparts on the profile, the broad blue component is forced to take on a small optical thickness, which then drives the reduction in the source function in order to account for the total absorption. Alternative models might be considered; however, the photospheric line blends pose a severe challenge to achieving a robust fit for a more complex model.

### 5.4. He I Line Formation of the Near-rest Emission

Finally, we focus on the formation of the large emission component and its red tail in point 4. Three model slabs adequately reproduce the profile shape, with components at 1, 8.7 and 38.4 km s$^{-1}$. Respectively, the optical thickness declines from a thick near-rest component ($\Delta \tau_{red} = 7.92$) to two thin components. We expect the redward tail to be generated by large gradients in the atmosphere along the line of sight, which is further corroborated by the lack of a defined Stokes V redshifted component in the line wing. In other words, there are no distinct velocity components within the tail. Note that the large line width of the fastest emissive slab (54.03 km s$^{-1}$) represents unphysical temperatures for neutral helium (i.e., 700 K). Meanwhile, the inferred value of $\beta$ is 3.69, which is reduced to 3.05 in the event the spectral stray light has an absorption signal at the lower bound of what is expected (profile B in Figure 11). In Figure 18, the corresponding electron densities are in the range of 12.8–13 dex. As above, the height estimates will have an influence on the density estimate; however, this uncertainty is unlikely to lower the estimated density more than 0.5 dex given the strength of the emission. This is also corroborated by our calculations that increase the height by 1 Mm from the nominal estimates.

### 5.5. Comparison to an Isothermal Radiative Shock Model

The characteristics of the terminus of the observed SSD are consistent with a nearly isothermal radiative shock, wherein the shocked gas downstream of an initial normal shock radiatively cools rapidly. First consider that in the limit of a very strong shock, the Rankine–Hugoniot jump conditions (see, e.g., Shu 1992) permit at maximum a factor of 4 enhancement in...
the gas density, and a likewise factor of 4 reduction in the velocity immediately behind the shock. For the observed flow, assuming the local sound speed is between 10 and 20 km s$^{-1}$ at the shock, the upstream Mach number ($M_1$) is $\sim$20–10. The expected downstream flow velocity is then $\sim$50 km s$^{-1}$, and the downstream temperature would increase by a factor between 30 and 125, assuming a perfect gas. For an upstream temperature of 10–20 kK, as inferred from the measurements, the gas temperature would rise to between 0.3 and 2.5 MK, or 5.5–6.4 dex [K].

In an optically thin radiative shock that efficiently cools downstream of the initial shock layer (see, e.g., Shu 1992), the density and pressure can continue to be enhanced beyond the strong shock factor of 4 as the flow continues to decelerate. In the limit where the final temperature ($T_2$) is equal to the original upstream temperature ($T_1$), which is approximately the case in our observations, the isothermal shock conditions give $\rho_2/\rho_1 = u_0/\nu_0 = M_2^3$, or between 400 and 100 assuming a constant local sound speed between 10 and 20 km s$^{-1}$. Although the density estimates we can glean from the He I are approximate, this two order of magnitude density increase is in line with the estimates given above for the upstream and downstream gas. Furthermore, the Doppler extent of the helium line profile at point 4 can be explained by the isothermal shock conditions where the ratio of the upstream and radiatively cooled gas velocity is $\sim$200/1.

### 5.6. Energetics

The above scenario is also consistent with the increased EM inferred from the EM inversions of the SDO/AIA data. Enhanced emission below $10^7$ K in Figure 15, peaking toward the lower temperatures of the thermal bandpass of the EM distribution, is consistent with the increased radiative cooling of the shocked material, with the radiative loss rate $\Lambda(T)$ being the highest in the range of $(0.9–3) \times 10^5$ K as calculated using CHIANTI. The EM distributions also show in the top panel of Figure 15 brief heating episodes up to temperatures of $10^7$ K, particularly in the time period 60–115 minutes after 15:40 UT, and a weak decrease of the EM between 6.3 and 6.6 dex K compared to the reference time period. The latter is likely influenced by the evolution of the region as a whole along the line of sight.

We have derived the total radiative loss rate associated with the downflow in Figure 16, which shows values in the range of $(0.5–2.5) \times 10^{22}$ erg s$^{-1}$. We can compare this to the total power in the downflow. Assuming a continuous flow, the total power can be written as

$$\text{power} = \frac{1}{2} \rho v^2 A \approx \frac{1}{2} m_p n_e \left( \frac{1}{1 + 2 \left( f_{\text{He/H}} \right)} \right) v^3 A,$$

where $A$ is the cross-sectional area of the flow and $f_{\text{He/H}}$ is the fractional abundance of helium relative to hydrogen, assuming a H–He gas mixture. Adopting $f_{\text{He/H}} \sim 0.08$, and taking $n_e \sim 10^{13} \text{ cm}^{-3}$, $v = 195 \text{ km s}^{-1}$, and $A$ of 1 arcsec$^2$ as representative of the observed flow, the estimated downflow power is $\sim3.5 \times 10^{24}$ erg s$^{-1}$. And so the downflow power is sufficient for driving the observed radiative losses.

The inferred AIA emission measure distribution also provides some additional constraints for the electron density in the shock-heated and radiatively cooling gas. Taking the peak columnar EM near $10^{5.8}$ K to be $\sim1-4 \times 10^{27}$ cm$^{-5}$ from Figure 15 and attributing it to the cooling post-shocked gas radiatively over some column length, we can estimate the electron density using Equation (9) further assuming it is constant. The length of the radiating layer, however, is not well known and the density is expected to strongly increase as the material cools. For a large range of possible radiating lengths between 100 km and 2 Mm, we calculate densities of 11.8–10.8 dex cm$^{-3}$, which are compatible with the densities inferred using the helium profiles.

### 5.7. Mass Supply

Similar to Straus et al. (2015) and Chitta et al. (2016), the observed duration of the downflow is long compared to the estimated timescale to drain the coronal loop’s volume without addition mass supply. The primary drainage channel, shown in panel (c) of Figure 1, persists long enough for FIRS to resolve material along its entire length during the associated 23 minutes scan time between the beginning of the scan to when the slit reaches the location of the downflow terminus in the umbra. The SDO/AIA light curves in Figure 14 indicate the increased radiative losses in the umbra near this downflow’s footpoint begin just prior to the beginning of the FIRS scan and continue for $\sim$100 minutes. Following Chitta et al. (2016), the drainage timescale can be estimated as $\tau_{\text{drainage}} \approx 0.1 L/v$. Assuming a semicircular coronal loop with constant cross-sectional area and a height of $h = 80 \text{ Mm}$, and $v = 200 \text{ km s}^{-1}$, $\tau_{\text{drainage}} \approx 10$ minutes. This suggests the observed downflow needs an additional mass supply. However, given its association with the filament material that resides above the active region complex, as described in Schad et al. (2016), and its near freefall acceleration at heights of $\sim15 \text{ Mm}$, interpreting this flow as a siphon flow does not seem justified.

### 5.8. Interpreting the He I Emission Profile Tails

The presence of the long redward emissive tail for point 4 can be explained as a natural consequence of post-shock cooling during deceleration provided there is sufficient opacity in the neutral triplet. In the simplified radiative shock picture above, assuming a strong shock, the velocity immediately behind the shock front is $\sim200/4 = 50 \text{ km s}^{-1}$; though, the observations show emission up to $\sim140 \text{ km s}^{-1}$. This may imply that sufficient neutral helium remains present through the viscous layer of the shock in order to have emission at high velocities. Furthermore, there is the odd enhanced absorption feature for point 3 that is not easily explained. Golding et al. (2014) modeled the helium triplet lines for a weaker shock, not in umbral conditions, but including the effects of nonequilibrium ionization, concluding that nonequilibrium relaxation timescales can be long compared to the dynamics and are thus important to consider. Brief enhancements in He I 10830 Å absorption followed by strong emission has been observed during solar flares (Xu et al. 2016) and has been found in numerical calculations that include electron beam heating by Ding et al. (2005), Huang et al. (2020), and Kerr et al. (2021). We suspect a similar scenario may be possible for enhanced collisions at the shock front of a strong downflow, as in the event studied here, but further investigations are necessary to confirm this possibility.
5.9. Magnetic Fields: How Deep Does the Flow Penetrate?

Finally, we consider more closely the inferred magnetic field values. The longitudinal magnetic field \( B_z \) inferred from the redshifted component increases from \(-461 \) G at a height of \( \approx 15.5 \) Mm, to \(-1351 \) G at or directly above the shock. In the strong post-shock emission, \( B_z \sim 2381 \) G within the deconvolved data set, or between \(-2207 \) and \(-2607 \) G using alternative stray-light correction (Section 3.4.7). The photospheric Ca I magnetic field strength along the line of sight is \(-\approx 2800 \) G. Meanwhile, the inferred longitudinal field strengths in the He I line outside of point 4, shown in Figure 12, give values of \(-\approx 2000 \) in the outer umbra and suggest field strengths in the nominal chromosphere are above this within the region probed by the downflow; however, unfortunately, it this region, the complex profiles in the PSF-corrected data do not permit suitable estimates.

The magnetic field strength of 2.4 kG, or even the less likely lower estimate of 2.2 kG, inferred in the bright He I 10830 Å emission may be the largest reported to date for this line. Schad et al. (2015) and Joshi et al. (2017) reported peak He I umbral field strengths ranging between 1.5 and 1.8 kG. For the same data set, using the nearby Si I and Ca I lines, Joshi et al. inferred photospheric umbral field strengths between 2.5 and 2.8 kG. In a C class flare, Anan et al. (2018) inferred a value of 1400 G in He I 10830 Å. Meanwhile, in the He D3 5876 Å line, Libbrecht et al. (2019) reported values as high as 2.5 kG for a C flare above a pore, although, they remark their observed spectra can also be fit using substantially larger values (up to 5 kG).

The uncertainties involved in measuring the magnetic field in the umbral chromosphere makes it challenging to relate the post-shock downflow field strength to the nominal (yet dynamic) chromosphere. From our work, we have learned that correcting for stray light is essential and may effect previous analyses. Where the neutral helium is formed in the umbra is ill-determined and will influence measurements of the height gradient of the sunspot magnetic field, which is still an open question as discussed by Balthasar (2018). The post-shock helium emission field strength of \(-\sim 2.4 \) kG is only 400 G weaker than the underlying photosphere (2.8 kG). Likely the difference is even less as the former value refers to only the longitudinal component whereas the latter is the total field strength. It should also be noted that the He I material is optically thick where this field is measured, and so the flow likely penetrates further than what we can estimate using this line. If we adopt a shallow estimate for the height gradient of \(-0.5 \) G km\(^{-1}\) as reviewed in Balthasar (2018), then the post-shock material would be at heights less than 800 km, in the low chromosphere for most umbral models (see, e.g., Loubkitchev et al. 2017). We have not found any signatures of the downflow in the photosphere. Ordinarily, the population of triplet state helium in the photosphere and low chromosphere is minute (Centeno et al. 2008); however, in a nonequilibrium state, longer relaxation timescales for recombinations from He II (Golding et al. 2014), together with fast downflow speeds, might populate the triplet state in the lower atmosphere.

We also infer a kilogauss difference in the pre-shock (1.3 kG) and post-shock field (2.4kG) for point 4. The shock normal is expected to be parallel with the magnetic field direction, in which case we do not expect the shock itself to change the field intensity. Increases in the gas pressure downstream of the shock would presumably lead to a field reduction. We suspect the difference may be related to the height difference between the pre-shock and post-shock material, which is not well constrained by our observations as already implied by the density analysis above for the upstream density. A height difference of at least 1 Mm between the upstream high speed material and the post-shock (lowest speed) material could be possible.

6. Summary

We have reported He I spectropolarimetric observations of an SSD into a sunspot umbra that exhibits signatures consistent with a strong isothermal radiative shock impacting the lower atmosphere. Recent studies, i.e., Samanta et al. (2018) and Nelson et al. (2020b), have begun to quantify the extent of the role of SSDs in sunspot umbral atmospheres and their evolution; though, more studies are necessary. Our observations are unique in that measurements of the magnetic field strength in the optically thick post-shocked helium have values only a few hundred Gauss less than the underlying photosphere. This suggests that penetration of the flow well into the chromosphere, and perhaps the upper photosphere, might be possible for such strong flows. These observations have also provided a detailed spectral and polarimetric view of the signatures of neutral helium through each phase of the shock, which are important to consider further with nonequilibrium models for strong downflow events like that observed here or during solar flares.

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Appendix

Linear Polarized Spectra

Figure 19 shows the Stokes \( Q \) and \( U \) image spectra along the observed SSD. We do not analyze these signals in the main paper but instead show them here to be complete. Small traces of the \( Q \) and \( U \) scattering polarized signals in the downflow, which were analyzed by Schad et al. (2016), can be seen near 10836.3 Å for \( 34^\circ < y < 36^\circ \). Within the umbra, residual interference fringes and increases in observational noise dominate; although, helium signals in the near-rest emissive component are observed near \( y = 28.1^\circ \).
Figure 19. Same as Figure 4 but showing Stokes Q and U scaled between $-1\%$ and $+1\%$.

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