Neutral Helium Triplet Spectroscopy of Quiescent Coronal Rain with Sensitivity Estimates for Spectropolarimetric Magnetic Field Diagnostics

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Abstract

On account of its polarizability and magnetic field sensitivity, as well as the role of neutral helium in partially ionized solar environments, the neutral helium triplet (ortho-helium) system provides important, yet underutilized, diagnostics of solar coronal rain. This work describes off-limb observations of coronal rain in NOAA Active Region 12468 obtained in the HeI 10830 Å triplet using the Massively MultipleXed Imaging Spectrograph experiment at the Dunn Solar Telescope along with cotemporal observations from NASA’s Solar Dynamics Observatory and the Interface Region Imaging Spectrograph (IRIS). We detect rain simultaneously in the IRIS 1400 and 2796 Å channels and in He I 10830 Å. The large degree of spatial coherence present between all channels agrees with previous observations of the multitemperature nature of coronal rain. A statistical analysis of He I spectral profiles for rain identified via automated detection indicates that He I line radiiances are, on average, \(10^4\) erg cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\); the average translational velocity is 70 km s\(^{-1}\), and Doppler widths are distributed around 10 km s\(^{-1}\). Based on these results, forward models of expected He I polarized signals allow us to estimate, using synthetic observables and an inversion algorithm including fits for the scattering angle constraining the material’s location along the line of sight, the magnetic sensitivity of the upcoming National Science Foundation’s Daniel K. Inouye Solar Telescope. We predict that joint observations of the He I 10830 and 5876 Å multiplets using first-light instrumentation will provide inverted magnetic field errors of \(\pm 3.5\) G (2\(\sigma\)) for spatial scales of 0\(\prime\)5 (~360 km), assuming dynamically limited integration times of 5.5 s.

Key words: Sun: corona – Sun: filaments, prominences

Supporting material: animations

1. Introduction

Remote sensing the megakelvin solar corona is difficult, as the corona is primarily optically thin and the responsiveness of available diagnostics, especially for the magnetic field dominating its evolution, is limited. This impedes our ability to answer fundamental questions regarding how stellar coronae are structured and energized. Remarkably, the production of cool material in the otherwise hot corona gives us perhaps our finest probe of its structure. Observations have shown with increasing detail that the >1 MK active corona frequently produces condensed, cool (tens of kK), gravitationally unstable material known as coronal rain (Kawaguchi 1970; Schrijver 2001; Antolin & Rouppe van der Voort 2012). Thought to be caused by a thermal instability (Field 1965; Goldsmith 1971; Antiochos & Klimchuk 1991; Schrijver 2001), it can be formed under multiple scenarios with major categories including quiescent (or noneruptive) and flare-driven, which is typically stronger in terms of mass loading and energy input (Scullion et al. 2016). Its formation is also sometimes associated with prominence/filament dynamics (Liu et al. 2012), for example, in the draining spider “legs” of coronal cloud filaments (Schad et al. 2016). Often, though, it materializes directly from the hot corona. During these fast (~10–150 km s\(^{-1}\)) rain events, coronal material is both localized and bright in cool, radiatively excited chromospheric spectral lines, which in turn provide a valuable probe of local conditions during nonequilibrium.

Helium, as the second most abundant element, generates relatively bright emission from coronal rain. It is chiefly observed using EUV imaging of He II 304 Å (log \(T\) \(\approx\) 4.7 K; de Groof et al. 2004, 2005; Kamio et al. 2011). In comparison, neutral helium coronal rain emission has not been studied in detail. Neutral material observed in coronal rain blobs as they fall, both on- and off-disk, has been best quantified in H\(\alpha\) (Antolin & Rouppe van der Voort 2012; Antolin et al. 2012), which generally exhibits dynamic coupling with the ionized species of He II 304 Å (de Groof et al. 2005), Ca II 8542 Å (Ahn et al. 2014), and Ca II H (Chae 2010). In addition to C II, Si IV, and Mg II, which dominate the Interface Region Imaging Spectrograph (IRIS) 1330, 1400, and 2796 Å imaging filters (Antolin et al. 2015). Sizable fractions of neutrals can potentially affect the plasma dynamics, and models by Zaqarashvili et al. (2011) indicate that the formation of neutral helium in particular can enhance the damping of Alfvén waves in partially ionized plasmas. Transverse oscillations observed within coronal rain have been studied by Antolin & Verwichte (2011).

The resonance lines of neutral helium are formed in the EUV below 584 Å and are not currently observed routinely (Doschek et al. 1974; Peter 1999; Judge & Pietarila 2004); however, for characteristic densities of condensed coronal material, i.e., prominences or coronal rain, photoionization followed by recombination into the triplet system, whose lowest level (2\(s^3S\)) is metastable, overpopulates the triplet in comparison to singlet helium (Heasley et al. 1974; Andretta & Jones 1997; Labrosse & Gouttebroze 2001; Gouttebroze & Labrosse 2009). As a result, the 10830 Å multiplet is the brightest neutral helium feature, therefore making it a promising candidate for studying neutral helium production in coronal rain. A further advantage is that it can be accessed using ground-based facilities.

Due to its brightness and polarizability, the He I triplet may also potentially be used to remote sense the magnetic field of...
coronal condensates. Antolin & Roupe van der Voort (2012) and Scullion et al. (2016) both call attention to the substructure of coronal loops revealed by coronal rain and unseent in hot EUV observations, thereby designating rain an instrument for fine-scaled coronal magnetism studies. The helium triplet is routinely employed to probe chromospheric magnetic fields (Harvey & Hall 1971; Asensio Ramos et al. 2008; Schad et al. 2013), including within prominences (Casini et al. 2003). Its polarized signatures result from the joint action of resonant optical pumping, the Zeeman effect, and the Hanle effect and offers sensitivity for the vector field for a wide range of field strengths. In the case of quiescent coronal rain, short dynamical timescales and weak signals drive the need for large-aperture polarimetry even for the brightest lines to achieve a signal-to-noise sufficient to measure the weak field strengths of the solar corona. The large collecting area of the National Science Foundation’s 4 m aperture Daniel K. Inouye Solar Telescope (DKIST; Rimmmele et al. 2015), currently under construction, is poised to greatly enhance such capabilities.

Owing in large part to the use of novel multiplexed spectroscopic techniques (Schad & Lin 2017), the study presented here performs time-resolved spectroscopy of He I 10830 Å observed in quiescent coronal rain off-limb. This permits analysis of its evolving morphology, as well as statistical quantification of its total integrated line radiance (brightness), spectral line width, and both its apparent and Doppler velocity characteristics. Coordinated IRIS observations are used to compare the neutral helium characteristics with those observed in ionized species of multiple temperatures. Based on the He I results, inversion techniques and an error model are developed to assess the feasibility of using polarized He I measurements of quiescent coronal rain off-limb to infer the coronal magnetic field intensity and orientation, as well as the location of the coronal rain blobs along the line of sight.

2. Observations

High-resolution observations of coronal rain were obtained on 2015 December 9 within the He I 10830 Å spectral lines by the Massively MultipleXed Imaging Spectrograph (MXIS), an experimental infrared imaging spectrograph at the 76 cm aperture Dunn Solar Telescope (DST) in New Mexico, USA. The MXIS field of view was centered on the eastern solar limb and NOAA Active Region 12468. These observations were coordinated with IRIS (De Pontieu et al. 2014) and make use of the high-cadence imaging data provided by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) and Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) instruments on board NASA’s Solar Dynamics Observatory (SDO;Pesnell et al. 2012). Figure 1 presents an overview of the fields of view and relative timing of the coordinated observations.

2.1. MXIS

The MXIS experiment, described in detail by Schad & Lin (2017), provides rapid-cadence, wide-field imaging spectroscopy of He I 10830 Å by taking advantage of multiplexing techniques developed for full-disk spectroheliography (Lin 2014). It consists of two science channels—a grating-based spectrograph and a narrowband imager—simultaneously imaged on separate halves of a single 2048 × 2048 pixel HgCdTe detector. The detector is operated at a frame rate of 9.53 Hz with exposure times of 105 ms.

The MXIS spectrograph channel utilizes 17 parallel entrance slits separated by 11°4 over which a 175° × 125° field of view is scanned by a field steering mirror. The great number of slits allows the large field of view to be mapped at high spatial resolution using only 65 discrete steps at a fast cadence (≈8.5 s per full field scan). Each slit has a full width at half maximum spectral bandwidth of 10.5 Å allowing coverage of the Si I photospheric line at 10827 Å and the He I triplet. The He I Doppler coverage is −195 to 85 km s⁻¹. The spectral pixel width is 120.4 mÅ, though the spectral resolution is limited for the data described here by spectral focus aberrations suffered during this campaign, as discussed by Schad & Lin (2017) and carefully calibrated in Section 2.1.1. The slit width is ≈0°19, while the angular sampling along the slit is 0°153.

The MXIS narrowband imaging channel operates using about 1% of the light fed to MXIS, which is reflected by an optical wedge upstream of the spectrograph. With a set of independent reimaging optics, the spatial scale incident on the detector is 0°123 pixel⁻¹. The spectral bandpass is identical to the spectrograph, as the filters are located upstream of both channels. Since that bandwidth is dispersed over ≈90 detector pixels in the spectrograph, the raw signal to noise in the two channels is approximately balanced.

Two data series, spanning 16:34–17:33 and 17:54–18:22 UT, were obtained by MXIS on 2015 December 9 overlapping a portion of the IRIS field of view (see Figure 1). Active tip/tilt correction for MXIS necessitated the spatial offset of the field relative to IRIS, since the DST high-order adaptive-optics (HOAO) system (Rimmmele et al. 2004) requires the limb to be positioned near the field center for active tracking. Data reduction followed the techniques outlined in Schad & Lin (2017), including precise coregistration between the two channels and the post facto correction of residual seeing-induced image motion. However, for these off-limb data, only a scalar correction for tip/tilt variability on a frame-by-frame basis is applied; subfield seeing-induced motion is not corrected.

2.1.1. Line-spread Function Calibration

The MXIS spectrograph data acquired in December 2015 were affected by a suboptimal spectrograph focus limiting the spectral resolution (R) to between 8000 and 18,000, considerably lower than subsequently acquired data (R ≈ 25,000). While these aberrations do not affect the measured integrated line radiiances, to facilitate the fitting of models to the observed profiles and the measurement of true spectral line widths, we have determined a suitable line-spread function (LSF) describing the spectrograph response, which varies across the field of view. Examples of the LSF calibration are shown in Figure 2. Following Schad & Lin (2017), the spectrograph LSF can be approximated by a Lorentzian function; however, to account for the defocus, we instead consider here an LSF modeled by two equal Lorentzian functions separated in wavelength by a small amount. This separation factor approximates the removal of energy from the core of the LSF due to the defocus. Using this functional form, we optimize the parameters of the LSF by fitting, in a least-squares fashion, an LSF-convolved high-resolution solar atlas spectrum of the deep Si I 10827 Å line to the measured spectral profiles obtained during flat-field observations near the disk center. We use the mean disk center Fourier transform spectrograph (FTS) solar atlas of Wallace et al. (1996). The figure shows the resulting LSF and the fits for...
three spatial locations along the center MXIS slit. The corresponding radial locations in the science data described here are noted in the figure. All modeled fits to spectral profiles discussed below include convolution with the field-dependent LSF.

2.1.2. Radiometric Calibration

To convert observed flux from reduced MXIS spectrograph data units to units of absolute spectral radiance, we derive a calibration factor by comparing the center-to-limb flux variation measured in the solar continuum for $0.05 < \mu < 0.3$, where $\mu$ is the cosine of the heliocentric angle, with the well-known center-to-limb variation of the solar continuum spectral intensity at 10830 Å, as available in Allen’s Astrophysical Quantities (Cox 2002). Since we observe a large portion of the solar limb during every scan, this calibration is done on a scan-by-scan basis and thus eliminates any dependencies on temporal sky transmission variability. An example of the converted data units in the continuum and the comparison to the center-to-limb reference curve is given in Figure 3.

2.2. SDO/AIA and SDO/HMI

The SDO level 1.5 data products from AIA and HMI are used to establish the global evolutionary context of the He I 10830 Å MXIS observations, as well as for the image registration steps described in Section 2.4. We focus mainly on the AIA 171, 131, and 304 Å EUV channels and use the 1700 Å UV channel to facilitate alignment with IRIS. For nonflaring conditions, the 171, 131, and 304 Å AIA passbands are dominated by Fe IX, Fe VIII, and He II emission, with respective characteristic temperatures of $T = 5.8$, $5.6$, and $4.7$ K (O’Dwyer et al. 2010). The spatial scale of all level 1.5 data is $0''6$ pixel$^{-1}$, and the cadence is 12 (24) s for EUV (UV) data, while the HMI intensitygrams have a cadence of 45 s. Near the observed region, the field of view of AIA extends to approximately 180 Mm above the limb, i.e., $\gtrsim 1.26$ solar radii.

2.3. IRIS

The IRIS, which consists of both a spectrograph and a slit-jaw imager (SJI), conducted two observation series, spanning 16:12–17:11 and 17:41–18:40 UT, with its pointing centered at $[x, y] = [-1017'', -209'']$. Both series used the OBS 3620259404 program operating both the spectrograph and
and plotted on a consistent but arbitrary scale. Here normalized to the local continuum intensity units relative to the solar radius. The LSF corresponding locations in the near-limb science observations, as indicated in the left panel, were extracted from different positions along the center spectrograph slit, its derived LSF is the separation factor approximating the spectrograph defocus. The effective resolving power is given by the FWHM divided by an absorbed light fraction, as defined in the AIA 1700 Å image nearest in time to each frame of the IRIS 1400 Å channel was remapped into the spatial header coordinates of the first frame in each fixed-pointing IRIS 1400 Å data series. A scalar shift was then determined using cross-correlation, as recommended in IRIS Technical Note 22, that best aligns high-pass-filtered versions of the IRIS 1400 Å image and the AIA 1700 Å image. The spatial offset of each frame of the 2796 Å channel was approximated by that of the nearest 1400 Å frame. For correction, the spatial offsets are applied to the level 2 data.

In the MXIS data, the HOAO active tip/tilt stabilization offered fair correction in the direction perpendicular to the limb, but drifts and seeing-induced jumps in the direction parallel to the limb remain. We correct the pointing perturbations by cross-correlating HMI intensitygrams with each MXIS narrowband context image. A general polynomial warping transformation is first derived between a single HMI intensitygram and a cotemporal MXIS narrowband context image using the SSWIDL routine auto_align_images. The images were selected based on the period of best seeing during the MXIS data series. Using this transformation, an HMI intensitygram is remapped into the MXIS coordinate frame for each time step of the MXIS data series. Then, a scalar shift between the remapped HMI intensitygram and the MXIS context image is derived via cross-correlation and used to correct pointing errors in the MXIS data. This procedure overcomes the difficulty of self-aligning the MXIS time series that arises due to the evolution of the off-limb structures and solar rotation.

3. Temporal Evolution and Rain Formation in NOAA AR 12468

In the AIA 171 Å data (see Figure 1 and its associated animation), NOAA AR 12468 displays bright loops with transequatorial linkage to a distributed plage in the northern hemisphere; the loops exhibit similarities to the rain-producing loops studied by Auchère et al. (2018). The presence of coronal rain is easily discerned using He II 304 Å observations (De Groof et al. 2004; de Groof et al. 2005; Kamio et al. 2011), and the time series of AIA 304 Å observations between 16:00 and 18:40 UT reveal apparent raining downflows in various parts of the active region, including both footpoints of the transequatorial loops. Rain originating from the transequatorial loops, as well as from structures extending to the edge of the field of view directly above the active region, is apparent in the AIA 171 Å data series.

References:

1. Follow these links to reach the HCR-provided IRIS observation details: https://tinyurl.com/iris-rain-series1; https://tinyurl.com/iris-rain-series2.
2. https://www.lmsal.com/iris_science/doc/?cmd=dcurl&proj_num=IS0212&type=pdf
131, 171, and 304 Å channels and the IRIS SJI data (see, e.g., regions A and B in the figure).

At approximately 16:00 UT, a solar surge (see, e.g., Kirshner & Noyes 1971; Roy 1973) erupts from the southwestern edge of the IRIS field of view and extends outward from the solar limb. Components of the surge can be seen in all channels. An apparent downflow similar to the coronal rain material exists in the wake of the surge that persists until approximately 17:10 UT. While this material is observed in the MXIS HeI observations as well, it is not included in our analysis of coronal rain, especially since it is brighter in relation to the rain unassociated with the surge. An active-region prominence can be seen near the limb in all channels. A background portion of the prominence becomes activated around 18:00 UT, while the foreground component remains stable throughout the time period.

One phenomenon indicative of coronal rain produced via thermal instability is the progressive illumination of cooler EUV channels (Kjeldseth-Moe & Brekke 1998; Schrijver 2001; kamio et al. 2011). Light curves displayed in the upper right portion of Figure 1 show spatial averages over the regions labeled A and B versus time. Both of these regions display coronal rain at 16:30 UT in panel (c). The light curves of region B suggest that progressive cooling may be occurring as the hot AIA 171 and 131 Å channels increase and then decrease in brightness prior to increases in brightness of the AIA 304 Å and IRIS 1400 Å channels. The increased brightness of AIA 304 Å and IRIS 1400 Å in region A around 16:30 UT is not preceded by such a brightening in the hotter channels; however, it is likely that the onset of this coronal condensation commences near the transequatorial loop apex outside of the IRIS field of view. Note that no attempt has been made here for background subtraction, and we do not associate the slow rise in the AIA 171 and 131 Å intensities for region A after 17:00 UT with the brightening of the AIA 304 Å and IRIS 1400 Å channels near 18:30 UT.

Figure 4 (and its associated animation) zooms in on the region observed by MXIS in coordination with AIA and IRIS. Here MXIS observes only the lower portion of the extended coronal loops, and thus a majority of the coronal rain observed enters the field of view having already been formed. To describe the observed features, we first concentrate on the narrowband imaging channel of MXIS. An example image averaged over one field scan (i.e., 65 105 ms exposures) is given in panel (c) of the figure with units of percent of \( I_{\text{IRIS}}^{\text{ne}} \), i.e., the total disk center intensity integrated over the imager filter bandwidth. A different scaling is used above the limb to enhance the off-limb features. On the solar disk, the filter’s response is dominated by the limb-darkened photospheric continuum and the SiI absorption at 10827 Å—sunspots and plage are evident. Off-limb, only the He I signal contributes to the prominence becomes activated around 18:00 UT, while the background portion of the prominence becomes activated around 18:00 UT, while the foreground component remains stable throughout the time period.

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For more detailed analysis, a representative sample of 17 raining loops is manually identified and traced using the MXIS narrowband He I imaging data (see loops overplotted in Figure 4(c)). For each traced loop, we extracted a time-slice diagram from each coordinating instrument. Upon inspection of the time-slice diagrams, we found a high level of correspondence between the IRIS channels and He I 10830 Å. For some events, that correspondence is confused by multiple evolving loops near the same location or brief periods of poor seeing at the DST. In other cases, no overlap in time exists for MXIS and IRIS. Below, we closely examine a raining feature representative of the large-scale correspondence and identified by the solid orange line in Figure 4(c).

### 4. Multispectral Properties of Individual Downflows

For more detailed analysis, a representative sample of 17 raining loops is manually identified and traced using the MXIS narrowband He I imaging data (see loops overplotted in Figure 4(c)). For each traced loop, we extracted a time-slice diagram from each coordinating instrument. Upon inspection of the time-slice diagrams, we found a high level of correspondence between the IRIS channels and He I 10830 Å. For some events, that correspondence is confused by multiple evolving loops near the same location or brief periods of poor seeing at the DST. In other cases, no overlap in time exists for MXIS and IRIS. Below, we closely examine a raining feature representative of the large-scale correspondence and identified by the solid orange line in Figure 4(c).

#### 4.1. Morphological Comparison

Figure 5 provides snapshots (extracted from the associated animation) of each cool channel within the 35° × 60° (25 × 44 Mm) blue dot-dashed subregion of Figure 4(c) to illustrate the temporal evolution of the raining feature as a function of characteristic bandpass temperature. This especially serves to put the neutral helium 10830 Å observations in context with the multitemperature fine-scaled substructure of coronal rain discussed by Antolin et al. (2015). The individual images in each row are separated by no more than 10 s in time, whereas each row is progressively separated by \( \approx 165 \) s (2.75 minutes). The translational apparent speeds of the material are between 40 and 95 km s\(^{-1}\) \([0°05’–0°13’ s^{-1}]\) (derived below in Section 4.2), and therefore these images follow the evolution of multiple rain blobs as they fall in what is referred to as a rain shower.

Morphologically, the coronal rain observed in He I 10830 Å shares many of the characteristics shown in the IRIS SJI 1400 and 2796 Å data, including a significant degree of spatial coherence. See, among other examples, the bright kernels in the middle row of Figure 5 near \([X, Y] = [18°, 34°]\). Here we note that under conditions of collisional ionization equilibrium (see, e.g., tables in Chianti v8, Del Zanna et al. 2015), the ionization fraction of Si IV only weakly overlaps with that neutral helium and at fractions less than 3% of the peak ionization fraction.
Therefore, the similarities between IRIS SJI 1400 Å and MXIS He I mostly likely indicate multitemperature plasma cospatial in the plane of the sky. Meanwhile, the equilibrium ionization fraction peak for Mg II directly overlaps neutral helium, although neutral helium can exist more readily at higher temperatures (up to $T \approx 4.7$).

In a minority of cases, rain emission appearing in the IRIS SJI 1400 Å channel is not readily apparent in the He I 10830 Å MXIS observations. See, for example, the material near the bottom of the loop in Figure 5 (i.e., $[X, Y] = [14", 2"]$), especially within the snapshots displayed in the top two rows. The material that shows up very clearly in 1400 Å is also not apparent in the 2796 Å data. While the high-pass filtering applied to the MXIS data does suppress vertically directly (i.e., aligned with the $Y$ axis) features, for many of these cases, the simultaneous lack of emission in the IRIS SJI 2796 Å channel instead suggests a reduced presence of cooler material in these locations.

In agreement with the statistics provided by Antolin et al. (2015), the physical width of individual rain blobs observed in the IRIS SJI 1400 and 2796 Å channels ranges from approximately 0"75 to 1"5. As again evidenced by the close spatial coherence in Figure 5, the physical widths of rain blobs observed in He I 10830 Å appear consistent with those of IRIS; however, we purposefully do not derive statistics for the He I rain widths, since the resolution limit fluctuates due to seeing variability. That said, all evidence points to the He I emission being tightly coupled with the other diagnostics, which suggests either a high degree of neutral-ion coupling within the magnetized rain or possibly rapid ionization of any neutral helium that slips outside of the local rain environment.

### 4.2. Kinematics

The neutral helium emission of coronal rain also appears dynamically coupled, or at least dynamically comparable, with the ionized species as shown by the time-slice diagrams presented in Figure 6. The time slices are extracted along the center of the channel identified by dashed and solid lines in the top row of Figure 5. Prior to extraction, the data are convolved with a square 0"5 wide averaging kernel, and therefore the extracted quantities refer to averages over 0"5 scales. The time slices are also placed on a common temporal axis using nearest-neighbor sampling. Note that, as before, the MXIS He I data presented here are sourced from the narrowband-filter imaging channel and have the high-pass filter applied. For this reason, emission from the active-region prominence is not visible in the bottom portion of panel (d). A rough approximation is made for
Figure 5. Temporal evolution of the individual rain path identified by the solid orange line in Figure 4(c) and for all observed cool channels. The animation shows the full data series between 16:49 and 17:09 UT, while the standard image gives three snapshots in time. For clarity, the orange line has been replaced by minimal dotted and solid outlines in the top row. The MXIS He I data correspond to the narrowband imaging channel data after high-pass filtering as described in the text. Each row is quasi-simultaneous.

(An animation of this figure is available.)
the background structure for each time slice by averaging over the time steps just prior to the appearance of the coronal rain. The resulting diagrams with the background subtracted are in the middle row of Figure 6.

The 34 minute duration time slices, in particular those extracted from the comparatively higher-resolution IRIS and MXIS data, reveal multiple episodes of coronal rain with apparent motion along the selected trajectory. The onset of the rain’s appearance in these channels also corresponds with the onset of enhanced He II 304 Å emission observed by AIA; however, the 304 Å channel has much coarser resolution, and the fine-scale structuring of the multiple raining episodes is only weakly present. In the AIA 171 Å channel, we see relatively weak evidence for extinction of the background EUV emission, which is common in coronal rain observations of hot EUV lines due to the photoionization of neutrals (Gilbert et al. 2011).

The apparent downflow speed of individual coronal rain blobs can be well described here by a single velocity. Two such downflows are identified in Figure 6 as events 1A and 1B with respective characteristic apparent speeds of 49 and 96 km s\(^{-1}\). We extract the intensity for each channel along both paths and display the light curves in the bottom row of Figure 6. Recognizing the limitations imposed by the background emission, we see limited evidence in this subsample of events for spatiotemporal correlations in the brightness of individual rain blobs among the various spectral channels. The IRIS 1400 Å and MXIS He I channels show a weak systematic increase in brightness as the blobs fall. The other channels exhibit less systematic behavior, though event 1A shows a sizable increase and then decrease in its IRIS 2796 Å brightness. It is, of course, important to note here that these time slices do not follow the full evolutionary history of the material as it first forms outside of the MXIS field of view.

### 4.3. He I Spectral Analysis

The rapid imaging spectroscopy capability of MXIS allows observation and analysis of the He I 10830 Å spectral

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**Figure 6.** Top: spacetime diagrams of all spectral channels extracted along the solid orange line given in Figure 4(c). Distance along the loop is measured in arcsec from the terminus nearest the solar limb. Middle: same diagrams with an approximation for the background emission subtracted and two separate rain events identified as “1A” and “1B” respectively exhibiting apparent downflow velocities of 49 and 96 km s\(^{-1}\). Bottom: spatiotemporal light curves extracted along the center of paths “1A” and “1B” for each spectral channel. The reference time for the spacetime diagrams is 16:38:22 UT.
signatures within coronal rain. Figure 7 presents a spectral analysis of the radiometrically calibrated profiles extracted for events 1A and 1B identified in Figure 6. As before, the spectral data are first convolved with a square 0.5 wide averaging kernel, and therefore the extracted quantities refer to averages over 0.5 scales. The observations are shown in panels (a1) and (a2) for the two respective events, and example spectral profiles are shown along with model fits (discussed below) in panels (c1), (d1), (c2), and (d2). The data itself readily indicate the presence of the HeI triplet along the majority of event 1A and all of event 1B, though residual instrumental artifacts are also present.

For each spectral profile, we fit an LSF-convolved model spectral profile using least-squares minimization. The model consists of the addition of two Gaussian profiles and a scalar value for the background (scattered-light) intensity. The two Gaussian profiles represent (1) the blue component of the HeI triplet with rest wavelength at 10829.0911 Å and (2) the two blended transitions of the He I red component near 10830.295 Å. The free parameters of the model include the background intensity, peak intensity of the red spectral component, ratio of the blue-to-red component peak intensity, Doppler line width, and Doppler shift. Errors in the fitted parameters are estimated using repeated fits of modeled profiles with different realizations of the measured noise.

Considering the spectral data result from integration times of only 105 ms, it is encouraging that the signal-to-noise of the spectra allows full analysis. Satisfactory model fits are achieved for the majority of the observed profiles; however, we eliminate from further consideration all profiles for which the maximum of the convolved model profile is less than three times the root-sum-square of the fit residuals. Panels (c1), (d1), (c2), and (d2) of Figure 7 demonstrate modeled profile fits with the background subtracted for select spectra along the two rain events. The shapes of the modeled profile prior to and after LSF convolution are both shown. In part, these plots emphasize that the total line radiance is more reliably recovered in these measurements than the peak line brightness due to the influence of the LSF.

For events 1A and 1B, panels (e1) and (e2) of Figure 7 show the radial dependence of the background scattered-light contribution. The total line radiance shown in panels (f1) and (f2) peaks near $8 \times 10^6 \text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, having increased for locations closer to the solar limb in agreement with the trends observed in the narrowband-filter data shown in Figure 6. The inferred ratio of the blue-to-red component intensity is not shown in the figure but is generally small (median value of 0.14) and subject to errors as large as 0.25. The relatively weak signature of the blue component is visible in the modeled profiles show in panels (c1), (d1), (c2), and (d2). The Doppler velocities along each loop, especially 1B,
show blueshifts of \( \approx -10 \text{ km s}^{-1} \) at the top of the traced loop that gradually become redshifts as large as \( \approx 10 \text{ km s}^{-1} \) for locations between 10" and 30" along the loop). Near the lower portion of the loop, the Doppler shifts decline. Such behavior, given the rather steady apparent motion in the plane of the sky (see Figure 6), suggests geometrical changes of the observed loop relative to the line of sight. For event 1B, a 10 km s\(^{-1}\) change in the Doppler shift, assuming a constant 96 km s\(^{-1}\) translational velocity, implies only an (\( \arctan 10/96 \approx 6^\circ \)) change in the loop inclination.

The median Doppler line width for events 1A and 1B is \( \approx 8.5 \pm 2 \text{ km s}^{-1} \), which corresponds to a plasma temperature of \( \approx 17,000 \text{ K} \) (\( \log T \approx 4.23 \)) under the assumption of no unresolved motions. At the lower end of event 1B (\( \leq 4'' \) from the near-limb terminus), the line widths increase to greater than 16 km s\(^{-1}\), which is nonthermal on account of the formation temperatures of He I. This could be the influence of unresolved plasma components in the vicinity of the active-region prominence (see Figure 4).

5. Statistical Properties of He I Coronal Rain

Expanding the above analysis, we now derive the statistical properties of all He I coronal rain produced and observed in our targeted region. We take advantage of the multidimensional rolling Hough transform (MD-RHT) developed by Schad (2017) to detect in an automated fashion coronal rain features in a time-series imaging data set. In the cited work, the MD-RHT technique has already been applied with success to the IRIS SJIR 1400 Å observations described here.

5.1. Application of the MD-RHT

The MD-RHT consists of a computer vision technique that automates tasks traditionally accomplished manually via time-slice analysis and consequently is well suited for the detection and kinematic analysis of coronal rain. We apply this technique on the high-pass-filtered MXIS He I narrowband imaging data by first interpolating the data set to a uniform temporal cadence (\( \delta t = 8.5 \text{ s} \)), as required. The interpolation conservatively uses nearest-neighbor sampling in time. For feature segmentation in the spatial domain, we create binary versions of the data using appropriate thresholds after they have been smoothed temporally with a 168 s wide kernel. In the temporal domain, segmentation is accomplished using the same zero-phase-lag bidirectional difference filter as in Schad (2017) with a difference width of \( \pm 4 \) time steps (\( \pm 33.6 \text{ s} \)) s. We restrict the application to areas in the field of view 10 Mm above the solar limb so as to disregard spiculic motions, and we further disregard a large portion of the prominence body.

The results of the MD-RHT process are shown in Figure 8. Only data points for which the MD-RHT provides statistically significant identifications (see Schad 2017) are included. Furthermore, we only consider data points about which \( >75 \% \) of the neighboring pixels within an \( 0.5'' \times 0.5'' \) area also have good MD-RHT results. This ensures that the identified features have a sufficient width before we extract the spectrum averaged over a \( 0.5'' \times 0.5'' \) area for model fitting. These filters result in \( \approx 3 \times 10^5 \) data points corresponding to material with apparent motion. Eliminating the regions corresponding to the solar surge downflow and where there is line-of-sight confusion near the active-region prominences, there are \( 1.4 \times 10^5 \) data points corresponding to coronal rain.

Apparent translational velocities along each feature in the plane of the sky (\( v_t \)) are derived as part of the MD-RHT and shown for all data points in panel (b) of Figure 8. Errors in \( v_t \) scale with the apparent speed, as shown in Figure 10 of Schad (2017). For each data point corresponding to coronal rain, we extract the He I profile from the MXIS spectrograph data and perform the same model fitting as in Section 4.3. Of the profiles, 85% are successfully fit. In panels (c)-(e) of Figure 8, two-dimensional probability distribution functions (PDFs) are shown for the projected height of the coronal rain as functions of the total line radius, total material speed (\( \sqrt{v_t^2 + v_f^2} \)), and Doppler line width. Below these panels are one-dimensional PDFs of each fitted spectral parameter.

5.2. Average He I Properties

Changes in the total line radiance and/or Doppler width as a function of height can indicate that the material evolves as it falls and/or becomes radiatively excited in different ways. Antolin et al. (2015), for example, discovered decreases in the average height of material observed in progressively cooler spectral bands, spanning chromospheric to coronal temperatures, which was interpreted to be a signature of runaway cooling ongoing as the material falls. Furthermore, spectral lines radiatively excited by nonflat portions of the solar spectrum—for example, resonance lines such as He I 584 and 537 Å—are subject to Doppler dimming and brightening effects; however, these effects are expected to be very small for the He I triplet lines (Labrosse et al. 2007a, 2007b).

The 2D PDFs in Figure 8 do not show evidence that the average He I 10830 Å properties are changing over the restricted range of heights studied here. This may very well be a consequence of the rain being fairly mature in its formation before entering the MXIS field of view, or, it is possible that the loops do not have coherent evolution across the observed region. Either way, for heights up to 50 Mm—and especially between 30 and 50 Mm, where the majority of the rain is detected—the properties are fairly uniform, albeit with broad distributions in the 1D PDFs shown on the bottom of the figure. We note that the shape of the 2D PDF for the total speed of the He I rain is different from that of IRIS 1400 Å presented in Schad (2017), primarily because the selection of data points differs greatly. The earlier study includes the solar surge and covers a slightly different time period.

Regarding average properties, we learn from these data that approximately half of the observed material has He I 10830 Å line radiance greater than \( 10^5 \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \). The total speeds are dominated by the apparent translation velocities with a median of \( \approx 70 \text{ km s}^{-1} \). The distribution of Doppler line widths has a median value of \( 10 \text{ km s}^{-1} \) and is largely consistent with thermal widths in the absence of unresolved motions; however, no constraint for potential nonthermal line broadening is available here.

6. Error Estimates for He I Triplet Spectropolarimetric Diagnostics of Coronal Rain

The observed constraints for He I triplet coronal rain emission allow us to assess the sensitivity of future spectropolarimetric diagnostics of coronal rain that include the
The magnetic field vector. Coronal rain, as shown, occurs on small scales and evolves quickly; therefore, the most important consideration is what role photon noise has in the sensitivity at dynamically limited integration times. We use forward modeling of the He I polarization and a Monte Carlo inversion experiment that take into account realistic photon-dominated measurement errors. Other technical complications are ignored.

Since observations of different multiplets differently in fluence and/or reduce errors when observed alone or together (Casini et al. 2009), we consider synthetic observations of both of the two brightest orthohelium multiplets, i.e., 10830 and 5876 Å (D3). In addition to the normal reduction of errors provided by multiple measurements with uncorrelated noise, the increased diversity of the individual multiplet’s polarizability provides additional physical constraints for inverted solutions.

6.1. HAZEL Forward Modeling

Forward calculations performed here use the HAZEL (an acronym for HAnle and ZEeman Light) computer program (Asensio Ramos et al. 2008). HAZEL rigorously solves the statistical equilibrium equations for the atomic density matrix of the He I triplet system under the multiterm atom formalism (see Landi Degl’Innocenti & Landolfi 2004). This self-consistently includes atomic-level polarization induced by radiative anisotropies, the modification of quantum coherences by the Hanle effect, and the Zeeman and Paschen–Back effects. It also includes coherences between different J levels for the same term, which are important for magnetic strengths for which different J levels experience crossings and repulsions.

We consider magnetic field strengths in the range of 0–100 G consistent with coronal loops hosting raining material...
\[ h_{\text{proj}} \geq 10 \text{ Mm} \] above strong active regions. This range encompasses the Hanle-sensitive regime for both multiplets and the level crossings between 10 and 100 G for D\(_3\). It represents the most limiting case for error estimation: the linearly polarized component of the Zeeman effect becomes measurable for \( B \gtrsim 350 \text{ G} \). While the D\(_3\) multiplet is less bright than 10830 Å, its transitions have larger critical field strengths \( B_{\text{crit}}^{\text{He}} \) for the operation of the Hanle effect than 10830 Å (Asensio Ramos et al. 2008). As a result, the D\(_3\) Hanle-sensitive regime extends up to \( \approx 70 \text{ G} \), while 10830 Å is fully saturated for fields greater than \( \approx 8 \text{ G} \), making D\(_3\) a valuable constraint for weak coronal rain magnetic fields.

All synthesized profiles are calculated in the optically thin limit assuming plasma with constant emissive properties localized to a single point in space. The optically thin assumption is justified by the weak blue component observed in the He I 10830 Å rain spectra, which is roughly consistent with the small blue-to-red brightness ratio (~0.12) for optically thin plasmas (Centeno et al. 2008). The HAZEL modeling approach does not specify the mechanism by which the He I triplet levels are populated. As described by Asensio Ramos et al. (2008) and Centeno et al. (2008), for realistic models of the solar atmosphere, the number of bound–bound transitions for the triplet dominates the number of photoionizations from the triplet level, thereby concluding that the triplet system atomic density matrix elements are governed by the radiative transitions within the triplet system itself without significant influence from singlet helium.

The He I model parameters included in HAZEL are the magnetic field intensity \( B \), its inclination \( \theta_B \) with respect to the reference axis (i.e., \( \hat{x} \), the solar vertical), and its azimuth \( \Phi_B \) about \( \hat{x} \); the Doppler (thermal) line width \( \nu_T \); the Doppler velocity \( \nu_T \); and a line-damping parameter \( a \). It is further constrained by the height of the material above the solar surface \( h \), which in turn governs the anisotropy factor of the presumed cylindrically symmetric pumping photospheric radiation field.

The angles, \( \chi_{\text{obs}} \) and \( \Theta_{\text{obs}} \), shown in Figure 1 of Asensio Ramos et al. (2008), designate the observational geometry by specifying the direction of the line of sight with respect to the reference axes, while the angle \( \gamma_{\text{obs}} \) designates the observation direction for the positive Stokes \( Q \). In this work, \( \chi_{\text{obs}} \) and \( \gamma_{\text{obs}} \) are both taken to be 0. The choice of \( \chi_{\text{obs}} = 0 \) establishes the reference direction for \( \gamma_{\text{obs}} \) as the plane containing the solar vertical and the line of sight. The resulting geometry is schematically illustrated in Figure 9 (discussed further below), showing two different magnetic field vectors \( \mathbf{B}_1 \) and \( \mathbf{B}_2 \). Here \( \Theta_B \) and \( \Phi_B \) respectively refer to the inclination and azimuth of the magnetic field vector with respect to the line-of-sight direction.

### 6.2. Inverted Parameters and Degeneracies

Typically, He I spectropolarimetric inversions fit the model line parameters \( (B, \Theta_B, \Phi_B, \nu_T, \nu_{\text{max}}, a) \) using a fixed observational geometry; \( \Theta_{\text{obs}} \) and \( h \) are held constant, with \( \theta_{\text{obs}} \) usually constrained by the projected location of the material on the solar disk or in the plane of the sky. However, for material at large heights and/or projected above the solar limb, \( \Theta_{\text{obs}} \) and the height \( h \) are not well determined by observations; only the projected height of the material \( h_{\text{proj}} \) may be directly measured off-limb. For low-lying material near the limb, e.g., active-region prominences, it may suffice to assume the material lies near the plane of the sky \( (85^\circ \lesssim \Theta_{\text{obs}} \lesssim 95^\circ) \), as done in Casini et al. (2009). However, this is not the case for coronal rain that may form at heights up to and greater than \( \sim 100 \text{ Mm} \). Here we show that with a known projected height \( h_{\text{proj}} \), the scattering angle \( \Theta_{\text{obs}} \) and true material height \( h \) may be directly inverted along with the He I line parameters, thereby determining the raining material’s location in 3D space.

Figure 9 helps to illustrate how the observational geometry influences the polarized signatures for the He I triplet and gives insight into how this allows it to be fit via inversion when the projected height is known. The magnetic field vectors \( \mathbf{B}_1 \) and \( \mathbf{B}_2 \) have identical inclination \( \Theta_B \) and azimuth \( \Phi_B \) angles relative to the line of sight and the same height \( h \), but each vector denotes material located on opposite sides of the Sun relative to the observer. For spectral lines polarized only via the Zeeman effect, two such vectors are indistinguishable on account of the polarization amplitude and direction being only sensitive to the orientation of the magnetic field vector relative to the line of sight. In contrast, the two vectors are distinguishable for the He I triplet because the atomic-level polarization and the Hanle effect introduce an additional dependency of the polarized

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\(3\) The subscript “obs” has been added here for clarification.
amplitude and direction on the orientation of the magnetic field relative to the local solar vertical.

To quantify the dependency of the polarization on the field orientation relative to both the line of sight and the local solar vertical directions, in part to understand what limits exist on constraining the scattering angle via inversion, it is useful to introduce simplified expressions for the frequency-dependent emission coefficients along the line-of-sight direction ($\Omega_0$). Here we present the more simplified two-level atom approximation in the saturated regime of the Hanle effect (assuming a weak-field Zeeman effect), which offers a suitable approximation to the more complicated behavior of the multiterm He I system. The following have been derived for magnetic-dipole transitions by Casini & Judge (1999) and Landi Degl’Innocenti & Landolfi (2004), and the transformation for electric-dipole (E1) transitions like the He I triplet is straightforward. Adopting notation from Landi Degl’Innocenti & Landolfi (2004; Section 13.5) and using the reduced statistical tensor representation for the atomic density matrix, we can write for E1 transitions

$$
eqi(\nu, \Omega_0)_{E1} = C_{L/l} \left[ 1 + \frac{\omega_{L/l}^2}{4\sqrt{2}} (3 \cos^2 \Theta_B - 1) \right] \times (3 \cos^2 \theta_B - 1) [\sigma_0^2(\alpha_a J_a)] \phi(\nu),$$

$$\epsilon_q(\nu, \Omega_0)_{E1} = \frac{3C_{L/l} \omega_{L/l}^2 [\sigma_0^2(\alpha_a J_a)]_v}{4\sqrt{2}} [(1 - 3 \cos^2 \theta_B) \sin^2 \Theta_B \cos 2\Phi_B] \phi(\nu),$$

$$\epsilon_q(\nu, \Omega_0)_{E1} = \frac{3C_{L/l} \omega_{L/l}^2 [\sigma_0^2(\alpha_a J_a)]_v}{4\sqrt{2}} [(1 - 3 \cos^2 \theta_B) \sin^2 \Theta_B \cos 2\Phi_B] \phi(\nu),$$

$$\epsilon_q(\nu, \Omega_0)_{E1} = \frac{3C_{L/l} \omega_{L/l}^2 [\sigma_0^2(\alpha_a J_a)]_v}{4\sqrt{2}} [(1 - 3 \cos^2 \theta_B) \sin^2 \Theta_B \cos 2\Phi_B] \phi(\nu),$$

where $[\sigma_0^2(\alpha_a J_a)]_v$ is the “reduced” fractional atomic alignment in the vertical frame aligned with the solar vertical, and

$$C_{L/l} = \frac{\ell \nu}{4\pi N \sqrt{2J_a + 1}} A(\alpha_a J_a \rightarrow \alpha_l J_l) \rho_0^2(\alpha_a J_a),$$

where $\omega_{L/l}$ is a scalar coefficient depending on the atomic parameters, $\nu_l$ is the Larmor frequency (dependent on the field intensity $B$), $\tilde{g}$ is the effective Landé factor, $\Delta$ is a factor that depends on atomic parameters and the Landé factors of the levels, and $\phi(\nu)$ is the frequency dependence of the line profile shape. These expressions encode the geometrical dependencies of the polarized line emission on $\theta_B, \Theta_B$, and $\Phi_B$, which are related via the scattering angle and the spherical law of cosines by

$$\cos \theta_B = \cos \theta_{obs} \cos \Theta_B - \sin \theta_{obs} \sin \Theta_B \cos \Phi_B.$$

As before, the reference direction of the linear polarization is the plane containing the solar vertical and the line of sight. Note that Equations (20)–(22) of Asensio Ramos et al. (2008) are consistent with Equations 1(b) and (c). Finally, the projected and true height are related by

$$h_{proj} = \cos \left( \frac{\pi}{2} - \theta_{obs} \right) (R_{Sun} + h) - R_{Sun}. \quad (4)$$

Returning to the illustration of Figure 9, we observe that the inclination $\theta_B$ (relative to the vertical) of $B_1$ is substantially greater than that of $B_2$. As drawn, $\theta_B = 30^\circ$ and $\theta_B = 90^\circ$. Due to the $(1 - 3 \cos^2 \theta_B)$ dependence of Equations (1b) and (c), this implies that $B_1$ and $B_2$ will have opposite signs (directions) of linear polarization. This is known as the Van Vleck effect, with the “magic” Van Vleck angle being $54.7^\circ$. It is this $\theta_B$ dependence of $\epsilon_q$ and $\epsilon_u$ that discriminates $B_1$ from $B_2$. It is worth pointing out that $\epsilon_q$ also has a weak dependence on $(1 - 3 \cos^2 \theta_B)$, meaning that the Stokes V amplitude is slightly different for $B_1$ and $B_2$ despite having the same longitudinal magnetic field strength.

We now ask what conditions give the same (or approximately the same) values for the Stokes vectors to discuss the degeneracies and/or limited constraints present in Equation (1) when the projected height is known. In principle, the combination of the angular dependencies and the height dependence of $[\sigma_0^2]$, limits the presence of true degeneracies; however, the height dependence of $[\sigma_0^2]$, is weak, and noise in any measurement may make it unfeasible to distinguish between similar solutions. Also, note that $\epsilon_q$ and $\epsilon_u$ have no dependence on the field intensity, and $\epsilon_v$ (in the limit of weak $[\sigma_0^2]$) constrains only the longitudinal component of the field intensity ($B \cos \Theta_B$). However, this does not inherently limit our ability to infer the true field intensity $B$. Any scaling of the field intensity used to match an observed Stokes V amplitude requires a change in $\Theta_B$, and, as seen in Equation (3), there is no way to preserve $\theta_B$, which sets the linear polarization amplitude, under a perturbation in $\Theta_B$ by using the scattering angle $\theta_{obs}$ to compensate.

One approximately degenerate solution is immediately apparent given the transformation of $\Phi_B$ to $\Phi'_B = \Phi_B + \pi$ when $\Theta_B = \Theta_B$ is held fixed. Here $\epsilon_q$ and $\epsilon_u$ are preserved if the scattering angle switches from $\theta$ to $\theta' = \pi - \theta$, which implies $\theta_B = \pi - \theta_B$. This “180° ambiguity” is an approximate degeneracy, since the change in $\theta_B$ does have a weak effect on $\epsilon_v$ that would be difficult to observe due to the presence of measurement noise.

Remaining potential ambiguities may be determined by solving for the combinations of $(\theta_{obs}, \Phi_B)$ that give equivalent values for $\epsilon_q$ and $\epsilon_u$, assuming fixed values of the field intensity in the saturated Hanle regime and constant $\Theta_B$ and neglecting the height dependence of $[\sigma_0^2]$. Then, $\epsilon_q$ and $\epsilon_u$ have two terms that can vary to compensate for the signs of each other. The potential ambiguities are given for $\Phi'_B = \{ \Phi_B, \Phi_B + \pi, \Phi_B - \pi/2, \Phi_B + \pi/2 \}$. For the first two potential $\Phi'_B$ values, we can solve for $\theta'$ subject to the constraint $(1 - 3 \cos^2 \theta'_B) = (1 - 3 \cos^2 \theta_B)$, while for the latter two potential $\Phi'_B$ values, the constraint is $(1 - 3 \cos^2 \theta'_B) = (1 - 3 \cos^2 \theta_B)$. Using Equation (3) and tangent half-angle substitution, the solutions are given by the roots of the quadratic equation

$$at^2 + bt + c = 0. \quad (5)$$
where

\[ a = (\mathcal{K} - \cos \Theta_B), \]
\[ b = (-2 \sin \Theta_B \cos \Phi_B), \]
\[ c = (\mathcal{K} + \cos \Theta_B), \]
\[ \mathcal{K} = \begin{cases} \cos \Phi_B & \text{if } \Phi_B' = \{\Phi_B, \Phi_B + \pi\}, \\ \frac{1}{\sqrt{3}} - \cos^2 \Theta_B & \text{if } \Phi_B' = \{\Phi_B \pm \pi/2\}, \end{cases} \]
\[ t = \tan \frac{\theta_{\text{obs}}}{2}. \]

In some cases, the degenerate solutions give values of \( \theta_{\text{obs}} \) that may imply an unphysical, large height of the observed material (especially in the case of coronal rain). Here we restrict the solutions to \( 60^\circ < \theta_{\text{obs}} < 120^\circ \). Furthermore, no solutions exist for the \( \phi_B = \pi/2 \) degenerate angles when \( \theta_B < 35^\circ \) or \( \theta_B > 145^\circ \); however, there may still be local minima caused by this potential degeneracy.

Figure 10 gives a graphical representation of the candidate degenerate solutions for two magnetic field vectors. The geometric dependencies of \( Q \) and \( U \) under the approximate solution (i.e., the angular-dependent terms of Equations 1(b) and (c)) are shown. Using the global optimization approach described in the next section, we find that, given expected noise amplitudes for a large-aperture solar telescope, typically only the “180° ambiguity” applies.
6.3. Inversion Approach

Given synthetic Stokes profiles with known parameters and noise applied, we numerically optimize the set of inverted parameters that provide the best reduced \( \chi^2 \) fit (i.e., Equation (23) of Asensio Ramos et al. 2008) to the synthetic profiles under test. The free parameters include all of the HAZEL He I optically thin line parameters \((B, \theta_B, \phi_B, v_T, \text{ and } \nu_{\text{mac}})\) except the line-damping parameter \(a\), which is held fixed throughout. In addition, the fitted parameters include the total line radiance and the scattering angle \( \theta_{\text{obs}} \), but the projected height is assumed to be known.

While HAZEL has a built-in inversion module for singly observed He I multiplets, here we use only its forward-modeling engine and instead use optimization modules from the SciPy Python library (Jones et al. 2001), including the differential evolution (DE) algorithm (Storm & Price 1997) and the wrapper for the Levenberg–Marquardt (LM) method implemented in MINPACK (Moré 1978). This allows simultaneous inversions of the 10830 \( \AA \) and 53 multiplets and the ability to fit the scattering angle constrained by a constant projected height. The DE is a metaheuristic optimization routine with features and performance similar to the PIKAIA algorithm (Charbonneau 1995), which has previously been used for solar inversion problems. Unlike LM, it evolves stochastically without knowledge of the gradient of the objective function. It can locate degenerate solutions using repeated applications, as done using PIKAIA in Schad et al. (2016) and used here to test for potential ambiguities (see Figure 10). Below, we use a minimal number of DE iterations to provide the initialization for the LM fit so that our results are not dependent on initial guesses.

6.4. Monte Carlo Error Simulation

Our Monte Carlo simulation estimates errors for inverted coronal rain parameters by generating and inverting a database of synthetic observables with realistic measurement noise applied. Multiple scenarios are studied, including those consistent with currently existing 1.5 m class facilities, e.g., the 150 cm GREGOR solar telescope (Schmidt et al. 2012) and the 160 cm Goode Solar Telescope (Goode et al. 2010), and the upcoming 4 m aperture DKIST (Rimmele et al. 2015). The database includes 4000 models (2000 for \( B < 10 \) G and 2000 for \( B > 10 \) G) selected via Latin hypercube sampling (LHS) of parameters defined in Table 1, and thus our results represent an average over the respective domains. For the He I 10830 \( \AA \) line radiance and Doppler width, median values derived from our observations for angular sizes of \( 0.5 \) are used. The He I D\(_3\) line radiance is set by a fixed energy ratio \( E_{10830}/E_{5876} = 6 \) (\( \approx 11 \) in units of photons), consistent with the optically thin prominence models of Labrosse & Gouttebroze (2004).

The additive photon noise applied to the modeled profiles assumes uncorrelated normally distributed values with a standard deviation of \( \sqrt{J(\lambda)} \) for Stokes I and \( \sqrt{J(\lambda)/\xi} \) for the polarized spectra. Here \( \xi \) denotes polarimetric modulation efficiency (del Toro Iniesta & Collados 2000) and is set to \( \xi = 1/\sqrt{3} \) for all polarized states. The maximum integration time of 5.5 s is motivated by the angular sample (\( 0.5 \approx 360 \) km) crossing time for material with median translational velocities of \( \sim 70 \) km \( s^{-1} \). The measured signal amplitude depends on the line brightness and effective aperture of the telescope, which include the transmission of post-focus instrumentation. Before considering specific instrumentation, we model separate cases of 1.5 and 4 m telescopes with effective apertures set by the respective collecting area and a total transmission of 10%.

The inversions sequentially invoke the DE and LM algorithms. Four generations of the DE algorithm are first carried out with specific bounds enforced on the candidate solution, including a field intensity within \( \pm 20 \) G of the known model parameters and all angles within \( \pm 12 \) of the modeled values. This step provides a stochastically sourced initial guess for the LM-based inversion step. The parameter bounds are only used in the DE step in order to limit the parameter space searched to that where the known global minimum exists. The LM step proceeds until convergence criteria are met. The inverted profiles must achieve a reduced \( \chi^2 \) of less than 1.05 to be considered a valid solution. The results are discussed in Section 6.6.

6.5. Estimates for DKIST First-light Instrumentation

First-light instrumentation under fabrication for DKIST has been designed to support a broad scientific mission.
Elmore et al. 2014). Using performance predictions for the visible spectropolarimeter (VISP; de Wijn et al. 2012) and the diffraction-limited near-infrared spectropolarimeter (DL-NIRSP), we further refine our DKIST error predictions for coronal rain observations by performing the same simulation described above but with parameters representative of particular instruments. Here we assume the use of VISP for observations of D₃ and DL-NIRSP for 10830 Å.

Using the provided instrument performance calculator, we expect VISP to reach an end-to-end transmission of ~1.2% at the D₃ multiplet. Meanwhile, the spatial sample for VISP, which is a single slit scanning spectropolarimeter capable of simultaneous observations in three spectral windows, is controlled by its slit width and spatial sampling along the slit. The widest available slit (0′′.213) is assumed to be used here so as to achieve the highest observable flux for the rain observations, and we further assume coaddition of 0′′.5 along the slit. The spectral resolution is $R \sim 65,000$.

The DL-NIRSP is a fiber-optic-based integral field spectropolarimeter with three different spatial sampling modes of varying instantaneous fields of view. Prioritizing field coverage, we assume the use of the wide-field mode with an effective spatial sample size of ~0′′.5 and an instantaneous field of view of $\sim 28'' \times 19''$. Some uncertainty exists in the total end-to-end transmission of DL-NIRSP using the wide-field fiber, but here it is estimated to be 4.1% for observations at 10830 Å. The spectral resolution is expected to be similar to the wide-slit VISP case.

### 6.6. Results of the Monte Carlo Error Model

Error estimates for the three cases described above are given in Table 2. We report the 68% ($\pm 1\sigma$) and 95% ($\pm 2\sigma$) confidence intervals defined as the width of the error distribution containing 68% and 95% of the inverted models; however, note that the 95% confidence interval can be influenced by a small sample of modeled field vectors with large errors. Once again, these errors represent an average over the modeled domain. The true errors will vary depending primarily on the field intensity and orientation. Since the error in the total radiance, Doppler width, and Doppler velocity are insignificant here, only the magnetic field parameters and scattering-angle errors are included in the table. For each case, the results are given for inversions for each multiplet separately and when combined.

For weaker magnetic fields ($0 \leq B < 10$ G), the D₃ multiplet, despite its lower total radiance, exhibits a smaller inverted $1\sigma$ error in the magnetic field intensity compared to 10830 Å when the effective aperture is the same at both wavelengths. This can likely be attributed to its extended range in Hanle sensitivity, which at these field strengths exhibits a significant response to the field intensity. Meanwhile, its angular errors are greater than those of the brighter 10830 Å multiplet, which is expected due to its lower signal-to-noise ratio. In contrast, at larger field strengths ($10 < B < 100$ G), 10830 Å exhibits smaller errors for all parameters compared to D₃. When both multiplets are observed simultaneously, the errors in all parameters are reduced further.

In the case of DKIST with its first-light instrumentation, the different transmissions and spatial samples of VISP and DL-NIRSP have a noticeable effect on the resulting error estimates, especially in comparison to the idealized 10% transmission examples. However, the combination of VISP and DL-NIRSP observations of D₃ and 10830 Å proves to be a powerful diagnostic of coronal rain magnetism. Based on the half width of the 68% confidence intervals, we predict an average $\pm 1\sigma$ magnetic field error of $\pm 0.4$ and $\pm 0.8$ G, respectively, for weak and intermediate magnetic field intensities. The errors in the angular parameters are $1''$ to a few degrees. At the $2\sigma$ level (i.e., the 95% confidence intervals), errors increase significantly for the weak fields, suggesting a fraction of poorly constrained models. Alternatively, if we calculate the 90% confidence interval width, its width is 6 G, which is narrower than the 95% confidence interval for models with $B > 10$ G, which is 7 G.
These values may be marginally refined using more models in the synthetic database at the cost of longer computing time; however, here the upper bound of the 2σ error, based on the half width of the confidence intervals, is taken to be ±3.5 G.

7. Discussion

7.1. He I Triplet Rain Characteristics

The MXIS imaging observations of He I 10830 Å coronal rain indicate that neutral helium bears a resemblance to both IRIS SII transition region diagnostics of the Si IV 1393.78 and 1402.77 Å spectral lines (log T ≈ 4.8) and those of Mg II k at 2796.35 Å (log T ≈ 4). Generally, we have not seen evidence suggesting that neutral helium is present at the same time that the IRIS diagnostics are absent. This is consistent with the multitemperature nature of coronal rain discussed by Antolin et al. (2015). However, the MXIS observations only cover the lower 50 Mm (in projected height) of very tall coronal structures (≥100 Mm). We do not resolve where the onset of neutral helium formation occurs in relation to the IRIS diagnostics; that is an interesting question going further, considering the height dependence of different thermal diagnostics shown in Antolin et al. (2015). The wide distribution in the observed He I line widths, without any perceivable average height dependence, may suggest the various blobs of coronal rain transversing the MXIS field of view have inhomogeneous thermal structure; however, the line widths measured here have wide errors due to observational noise.

Unlike the IRIS diagnostics, He I is a neutral species and thus feels no Lorentz force due to the presence of the magnetic field. And yet, as already shown by Antolin & Rouple van der Voort (2012), AHN et al. (2014), and Schad et al. (2016), cool coronal downflows observed in neutral species seem to follow the same trajectories of the ionized species, seemingly tracing out magnetic field lines, and suggestive of a high degree of ion-neutral coupling. This seems to also be the case for these observations. As pointed out in the earlier studies, the expected cross-field diffusion speeds, calculated using the formalism of Gilbert et al. (2002), are typically small in comparison to the bulk velocities of the material. Moreover, simplified numerical models of falling partially ionized coronal rain by Oliver et al. (2016) indicate that a relatively small drift speed between ions and neutral is sufficient to dynamically couple the two species. Observational studies of the decoupling of ionic and neutral species for prominences have been studied, with differing results, by Khomenko et al. (2016) and Anan et al. (2017). A very detailed spectroscopic study would be required to understand how well coupled the various species are in coronal rain.

7.2. Relation to Prominence Models

The formation of neutral helium emission in coronal rain has not yet been investigated using realistic numerical models of gravitationally unstable rain material; however, many of the complications involved are well known due to the detailed nonlocal thermodynamic equilibrium modeling efforts for prominence material (see review by Labrosse et al. 2010). In general, the total line radiance is not only a function of the column mass density and state variables but also the external radiative environment, dynamics, and composition (see Gouttebroze & Labrosse 2009 and references therein).

Multiline observations, like those for singlet and triplet helium by Ramelli et al. (2012), provide useful constraints on these effects. Multispectral helium observations of coronal rain are not yet available; here we only have observations of the He I 10830 Å multiplet and can only make broad comparisons.

The cylindrical thread model of Gouttebroze & Labrosse (2009) is useful to compare to our observations. Gouttebroze & Labrosse modeled the emission of principal lines of helium for cylindrical threads with diameters of 1000 km and for a range of temperature, pressure, and helium abundance. Such sizes are comparable with the physical widths of coronal rain observed here. Therefore, we directly compare the modeled emergent intensities for He I 10830 Å with those we observed. For models with a constant pressure of 0.1 dyn cm−2, an (He/H) abundance of 0.1, and temperatures ranging between 6000 and 50,000 K, Gouttebroze & Labrosse inferred line radiiances in the range of (0.5−2) × 10⁴ erg cm−2 s−1 sr−1, much in line with the values observed here. A similar agreement is seen with the models including a radially dependent temperature for a wide range of pressure and helium abundance.

7.3. Coronal Rain He I Spectropolarimetric Sensitivity

The confirmed brightness of He I 10830 Å in coronal rain, especially of the quiescent type not associated with flares or other phenomena, has important implications for its use to study the structure of the coronal magnetic field, specifically under nonequilibrium conditions. Only a few previous studies have demonstrated measurements of the coronal field in general, including very long integration measurements of the Fe XIII 10747 Å coronal emission line by Lin et al. (2004) and measurements of thermal bremsstrahlung and gyroresonant radio emission by Briosius & White (2006). In the case of Lin et al., only the longitudinal component of the field intensity was measured, and it had an amplitude of about 4 G at projected heights of ~100″ (~70 Mm) off-limb. Schad et al. (2016) inferred the height dependence of the vector coronal magnetic field using the He I 10830 Å multiplet observed in absorption on the disk. In that study, the total magnetic field strength for heights of 30–70 Mm above an active region were in the range of 10–150 G.

Measuring the solar coronal magnetic field more routinely using forbidden coronal emission lines formed in megakelvin plasma is an essential part of DKIST’s mission (Rimmele et al. 2015). Its sizable jump in collecting area (a factor of 29 greater than the DST) allows for a significant reduction in the integration times needed to measure the megakelvin magnetic field. Still, as implied by Penn et al. (2004), the integration times may need to be long, depending on the application. Using the same methodology as that work, we can estimate the time required for Fe XIII observations at DKIST under ideal background-free conditions to achieve a magnetic field sensitivity equivalent to the cool He I lines estimated above. Assuming a 1″ × 1″ angular sample, a Fe XIII line brightness of 40 millonths of the disk intensity (width of 2 Å), and a 1σ error of 0.8 G, the exposure time required is ~460 s (7.6 minutes). As evidenced by this, the presence of neutral helium in coronal rain, with brightnesses two orders of magnitude larger than the hot forbidden lines and response to the Hanle-sensitive regime, offers a huge advantage in measuring the coronal magnetic field under nonequilibrium conditions. Of course, one limitation is that coronal rain is not ubiquitous in the corona.
8. Summary

Leveraging massively multiplexed spectroscopic techniques, this work has provided new measurements and a statistical analysis of the strength and character of the neutral helium triplet formed in coronal rain. Using coordinated IRIS measurements, we have found that the fine-scaled nature present in the ionized species correlates well, both morphologically and dynamically, with the structure in the neutral helium observations, at least within the limits of these observations. At present, we have only found weak correlations between the brightness of the IRIS diagnostics and the neutral helium, and this is a subject for further work. Meanwhile, our He I spectral analysis has shown distributed Doppler line widths largely consistent with the formation temperatures of the neutral helium, and the small ratio between the triplet spectral components suggests that the light is optically thin at these wavelengths.

Importantly, we have solidified the potential of using the He I triplet within coronal rain for coronal magnetic field measurements. Our analysis of coronal rain brightnesses in He I 10830 Å has indicated a substantial portion of material with radiances greater than 10^4 erg cm^{-2} s^{-1} sr^{-1} for angular scales of 0.5. Large-aperture spectropolarimetry should be capable of making great advances in fine-scaled coronal field measurements using these diagnostics. The techniques that we have pursued even indicate that He I triplet spectropolarimetry may constrain the location of rain blobs in 3D space. As coronal rain is now known to be a common phenomenon in active regions, continued observations of the He I offer a valuable probe of localized plasma in the otherwise diffuse solar corona.

Special thanks to Haosheng Lin and Doug Gilliam for their support and assistance in conducting these measurements and Sarah Jaeggli for a careful reading of the manuscript. Great appreciation is also extended to Andres Asensio Ramos for developing very user-friendly tools for the modeling of the helium triplet polarization. The National Solar Observatory (NSO) is operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under cooperative agreement with the National Science Foundation. IRIS is a NASA small explorer mission developed and operated by LMSAL with mission operations executed at NASA Ames Research Center. Special thanks to Haosheng Lin and Doug Gilliam for their support and assistance in conducting these measurements and Sarah Jaeggli for a careful reading of the manuscript. Great appreciation is also extended to Andres Asensio Ramos for developing very user-friendly tools for the modeling of the helium triplet polarization.

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