On the Formation of Solar Wind and Switchbacks, and Quiet Sun Heating

Vishal Upendran © and Durgesh Tripathi ©
Inter-University Centre for Astronomy and Astrophysics, Post Bag-4, Ganeshkhind, Pune 411007, India; uvishal@iucaa.in
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Abstract
The solar coronal heating in quiet Sun (QS) and coronal holes (CHs), including solar wind formation, are intimately tied by magnetic field dynamics. Thus, a detailed comparative study of these regions is needed to understand the underlying physical processes. CHs are known to have subdued intensity and larger blueshifts in the corona. This work investigates the similarities and differences between CHs and QS in the chromosphere using the Mg II h and k, C II line, and transition region using Si IV line, for regions with identical absolute magnetic flux density (\(|B|\)). We find CHs to have subdued intensity in all of the lines, with the difference increasing with line formation height and \(|B|\). The chromospheric lines show excess upflows and downflows in CH, while Si IV shows excess upflows (downflows) in CHs (QS), where the flows increase with \(|B|\). We further demonstrate that the upflows (downflows) in Si IV are correlated with both upflows and downflows (only downflows) in the chromospheric lines. CHs (QS) show larger Si IV upflows (downflows) for similar flows in the chromosphere, suggesting a common origin to these flows. These observations may be explained due to impulsive heating via interchange (closed-loop) reconnection in CHs (QS), resulting in bidirectional flows at different heights, due to differences in magnetic field topologies. Finally, the kinked field lines from interchange reconnection may be carried away as magnetic field rotations and observed as switchbacks. Thus, our results suggest a unified picture of solar wind emergence, coronal heating, and near-Sun switchback formation.

Unified Astronomy Thesaurus concepts: Solar wind (1534); Quiet solar chromosphere (1986); Solar transition region (1532); Solar magnetic reconnection (1504); Solar magnetic fields (1503); Solar chromosphere heating (1987); Fast solar wind (1872); Slow solar wind (1873); Quiet Sun (1322); Solar coronal holes (1484); Solar coronal heating (1989); Solar magnetic fields (1503)

1. Introduction
The temperature of the solar atmosphere varies from \(\approx5500\) K at the photosphere to \(\geq10^6\) K in the corona. The intervening chromosphere variably lies at around \(\approx10^4\) K, with a steep rise occurring in the transition region (TR). The solar atmosphere further extends outward from the corona, filling the heliosphere with the streaming solar wind. All of these layers of the solar atmosphere interact through a continuous exchange of mass and energy, and are tightly coupled by the highly dynamic magnetic field. Various processes have been proposed, and in some cases, observed to be the drivers of this mass and energy transport. The two primary processes thought to be responsible are dissipation of magnetohydrodynamic (MHD) waves (see, e.g., Alfvén 1947), and of currents produced due to the braiding of magnetic field lines (see, e.g., Parker 1972; Chieue & Zweibel 1987; Parker 1988, and also Klimchuk 2006; Parmell & De Moortel 2012, for comprehensive reviews).

In the solar corona, we usually find three morphologically different regions, viz., coronal holes (CHs), active regions (ARs), and quiet Sun (QS). The CHs are features seen as dark structures in extreme ultraviolet (EUV) and X-ray images of the solar corona, while ARs are seen as localized bright structures. In addition to these dark and bright structures, the omnipresent background over which the CHs and ARs are observed is called the QS. Note that while CHs are clearly distinguishable from QS in the EUV and X-ray images, these two regions appear extremely similar at lower heights, viz., the chromosphere and photosphere (see, e.g., Stucki et al. 2000, 1999; Kayshap et al. 2018; Tripathi et al. 2021; Upendran & Tripathi 2021). However, note that He I 10830 Å (an absorption line) shows excess intensity in CHs (Harvey & Sheeley 1977; Kahler et al. 1983), while the He I 584 Å (an emission line) shows lower intensity (Jordan et al. 2001), and excess blueshift, line width in the CHs, over QS (Peter 1999). However, these differences may be attributed to the sensitivity of these lines to coronal radiation, reflecting conditions in the corona. Furthermore, at 17 GHz in microwave, CHs are found to be brighter than QS (Gopalswamy et al. 1999), while this difference is not observed in radio wavelengths at 1.2 mm (Brajša et al. 2018). Thus, a gross differentiation of a given region in QS or CHs is markedly seen predominantly in the coronal observations.

Observations by Krieger et al. (1973) indicated that the high-velocity streams of the solar wind may be traced back to the CHs on the Sun. The “slow” wind, on the other hand, has been variously traced to the edges of ARs (Brooks et al. 2015) and equatorial CHs (see, e.g., Bale et al. 2019). Similar results have been obtained by various authors (see, e.g., Wang & Sheeley 1990; Schwenn 2006; Janardhan et al. 2008) and more recently through the application of deep-learning-based localization by Upendran et al. (2020). These results demonstrate that CHs are potential source regions of the solar wind and thus provide an opportunity to investigate the physical processes involved in the formation of solar wind. Since CHs and QS hardly differ at the lower atmospheric heights, studying them in tandem may allow us to explore the possibility of a unified explanation of heating in the QS and CHs, including the formation of solar wind (Tripathi et al. 2021).

Hassler et al. (1999) investigated differences between CHs and QS using the Si II and Ne VIII lines, and found a relation between the network regions and blueshifts of Ne VIII, with more blueshifts in CHs. Comprehensive studies of CHs and QS were undertaken by Stucki et al. (1999, 2000) using spectral lines
sensitive to a range of temperatures from \( \approx 8 \times 10^3 \) K to \( \approx 1.4 \times 10^4 \) K. While CHs showed a clear deficit in intensity, excess blueshift and excess line width with respect to QS for spectral lines that form at a temperature higher than \( \approx 4 \times 10^3 \) K, the differences were negligible, and within the measurement errors at chromospheric temperatures. Similarly, Xia et al. (2004) studied the relationship between Doppler shifts of C II, H I Ly\( \beta \), and O VI in CHs, and found a direct relation between the Doppler shifts of O VI with those of C II and H I Ly\( \beta \). These correlated shifts led Xia et al. (2004) to conclude that these shifts are signatures of solar wind in the chromosphere. However, note that the associated uncertainties in the velocity scatter obtained by Xia et al. (2004) were large. Moreover, while the average chromospheric velocities in bins of the O VI velocities were studied, the systematic associations between red- and blueshifted pixels, separately, for these lines, was not performed by Xia et al. (2004).

The correspondence between network region and outflows in the CHs, using Ne VIII line, demonstrated by Hassler et al. (1999) was further investigated by Tu et al. (2005), by mapping the formation heights of Si II, C IV, and Ne VIII in a CH. On further detailed investigation, Tu et al. (2005) showed a clear relation between the Ne VIII blueshifts and the underlying magnetic field configuration, obtained using the potential field extrapolation of photospheric magnetic field. Thus, Tu et al. (2005) suggested a modulation of the solar wind velocities due to the underlying magnetic field configuration.

More recently, Kayshap et al. (2018) investigated the intensity differences between CHs and QS in the Mg II k line, observed by the Interface Region Imaging Spectrometer (IRIS; De Pontieu et al. 2014). They found a clear deficit of intensity in CHs over QS for regions with similar absolute photospheric magnetic flux density (|B|), and with larger differences for larger |B|. A similar analysis for the intensity, velocity, and nonthermal widths for Si IV was performed by Tripathi et al. (2021, henceforth referred to as Paper I). Similar to the results of Kayshap et al. (2018), intensity deficit in CHs over QS for regions with similar |B| was observed. Moreover, CHs (QS) were more blueshifted (redshifted) over QS (CHs) for identical |B|. However, no significant difference was observed in the nonthermal width between CHs and QS. The excess CH blueshifts were interpreted to be signatures of nascent solar wind at Si IV formation height in Paper I. Thus, while a clear signal of solar wind was reported in the hotter Ne VIII line by Tu et al. (2005), the signatures are already present in the TR line Si IV, if the underlying photospheric magnetic flux density distribution is taken into account. Furthermore, since the regions with identical |B| were compared, the deficit in intensity in CHs over QS would mean the energy would be either used to accelerate the solar wind, or heat up the corona. Thus, a unified picture of solar wind formation and coronal heating was presented in Paper I.

In a companion paper (Upendran & Tripathi 2021, hereafter referred to as Paper II), we investigated, similar to Paper I, the C II 1334 Å line. We found intensity deficit and excess blueshifts in CHs over QS for regions with identical |B|, similar to the results from Paper I in Si IV line. However, we also find excess redshifts in CHs over QS for regions with identical |B|, which is the opposite of what is observed in the Si IV line. Finally, we find the total line width to be larger in CHs over QS for regions with similar |B|, while the line skew and kurtosis were found to be similar in both CHs and QS, suggesting that similar physical processes are at work in the two regions, as was also concluded in Paper I.

All of these investigations, taken together, raise several questions: Where does the solar wind actually originate? Can a single height be even ascribed to it? At what height does the differentiation between CHs and QS start? Does the solar wind emergence have any relation to the origin of a million degree Kelvin corona? These questions are critical to diagnose the formation signatures of the solar wind. Furthermore, attempting to answer these questions will also narrow down on the viability and contribution of various heating mechanisms in the solar atmosphere.

Keeping the above questions in mind, we first study the Mg II h and k line dynamics in CHs and QS. We then go ahead and explore the correlations between the Mg II, C II, and Si IV lines in CHs and QS, with the intention to explain the observations. The remainder of the paper is structured as follows: In Section 2, we describe our observations, with feature extraction in Section 2.1. In Section 3, we present results of the Mg II lines, while we recapitulate results for the C II and Si IV lines from Paper II and Paper I in Sections 4 and 5. In Section 6, we summarize and discuss our results. Finally, we provide an interpretation on context of origin of solar wind, switchbacks (Bale et al. 2019), and QS coronal heating Section 8.

2. Data

In this study, we use the observations recorded by IRIS, the Atmospheric Imaging Assembly (AIA; Boerner et al. 2012) and the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012). AIA and HMI are both on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). IRIS observes the Sun in two modes: slit-jaw imaging (SJI) and spectroscopy. In the SJI mode, IRIS provides photometric context images in near-ultraviolet (NUV) and far-ultraviolet (FUV) with a pixel size of \( \approx 0.16'' \), and an approximate cadence of \( \approx 63 \) s. We consider the SJI data centered around 1330 Å and 2796 Å for co-alignment purposes. The spectroscopy is performed in three windows, one in NUV from 2782.7 to 2851.1 Å, and two in the FUV, from 1332 to 1358 Å (FUV 1), and from 1389 to 1407 Å (FUV 2). These have a pixel size of \( \approx 0.16'' \) along the slit, and sample at \( \approx 0.33'' \) across the field of view (FOV). The spectral pixel size in these rasters is \( \approx 25.9 \) mA. Time cadence between successive slit positions is \( \approx 30 \) s. For further details on IRIS, see De Pontieu et al. (2014).

AIA observes the Sun’s atmosphere in UV and EUV using eight different passbands sensitive to plasma at different temperatures (O’Dwyer et al. 2010; Boerner et al. 2012). Here, we use the 193 Å images to distinguish between CHs and QS, and the 1600 Å images to co-align the IRIS, AIA, and HMI observations, as described in Paper II. We obtain the information on the photospheric absolute magnetic flux density (i.e., |B|) from the line-of-sight (LOS) magnetograms obtained with HMI. The AIA images are taken with a pixel size of \( \approx 0.6'' \), with the EUV images a time cadence of \( \approx 12 \) s, while the UV images are taken at \( \approx 24 \) s cadence. HMI obtains the \( B_{\text{LOS}} \) magnetograms at \( \approx 45 \) s cadence with a pixel size of 0.5''.

For our study, we have analyzed five different sets of observations recorded by IRIS in spectroscopic mode. The main criteria used to select these observations are that the raster must include CHs and QS within the same FOV, and that they must be taken within latitude and longitude of \( \pm 60'' \). The IRIS observation details are given in Table 1. Note that the same
data set have been analyzed in Paper II to study the properties of C II lines in CHs and QS. Out of these, three of the observations, DS1, DS2, and DS5 were also studied in Paper I to characterize the similarities and differences in QS and CHs in the TR using the Si IV line. We use corresponding data cubes, with cutouts from the full disk data used from HMI.

The Mg II h and k lines form near 2803.53 Å and 2796.35 Å, respectively, while the C II and Si IV lines form near 1334.53 Å and 1393.755 Å, respectively. The Mg II and C II lines form in an optically thick chromosphere under non-local thermodynamic equilibrium conditions (see, e.g., Leenaarts et al. 2013a; Rathore et al. 2015). Thus, these lines show extremely complex features and have nontrivial associations with local plasma properties. They have been explored in detail in Paper II, Rathore et al. (2015), and Leenaarts et al. (2013a). For all practical purposes, the Si IV line, forming in the QS TR, can be considered to be formed in optically thin conditions (Gontikakis & Vial 2018; Tripathi et al. 2020), and its properties in QS and CHs are studied in detail in Paper I.

### 2.1. Feature Extraction

The Mg II lines offer crucial information on the plasma conditions in the formation region, encoded into the line intensities and Doppler shifts of the line core (k3 and h3) and the peaks (k2v, k2r, h2v, and h2r). For a detailed analysis and discussion of these lines, see Leenaarts et al. (2013b, 2013a) and Pereira et al. (2013).

We first extract the positions and intensities of these different spectral line features. For this purpose, we develop a peak finding algorithm based on Leenaarts et al. (2013a) and Pereira et al. (2013) that locates the zero crossing of dI/dλ within a window of ±40 km s⁻¹ from the reference wavelength (taken to be 2796.350 Å and 2803.529 Å for the k and h lines, respectively; see Pereira et al. 2013).

The line core is identified to be the location with minimum intensity at the zero crossing. If the procedure is unable to locate such a minimum, e.g., in the case of single-peaked or noisy profiles, we assign a default velocity of 5 km s⁻¹ following Leenaarts et al. (2013a), since the remaining procedure rests on the identification of line core. Note, however, that the Mg II spectral profiles in this study, i.e., for QS and CHs, are predominantly double-peaked, as also noted by Leenaarts et al. (2013a).

The two peaks closest to the line core on either side are considered as the k2 (h2) peaks. Since the line core and peaks form at local extrema of the line profiles (as a function of wavelength), they may be approximated to be a parabola close to the peak value. Thus, we may fit a parabola near the maximum/minimum, and obtain a better estimate of the real extremum. This is called sub-pixel centroiding (similar to Teague & Foreman-Mackey 2018). Thus, the velocities and intensities for the core and peaks are then determined by fitting a parabola to the points near the feature extremum. Profiles that contain missing values of −200 are discarded. This procedure provides us with the intensities and Doppler shifts of the peaks and core of Mg II h and k lines. The line peak Doppler shifts are determined by taking the signed average of shifts of the blue and red peak (Leenaarts et al. 2013a).

Figure 1 displays a spectrum obtained at a random pixel in DS4 centered at the two Mg II lines. The two lines and their associated features are labeled. The core and peaks have been identified using the algorithm presented above. The black vertical line denotes the line core. The red (blue) vertical line corresponds to red (blue) peak of the line. This convention is followed for both the h and the k lines.

Since this paper aims to investigate the dynamics of CHs and QS at different heights in the solar atmosphere, we shall first present the analysis and results obtained from one data set (DS4) for Mg II lines in Section 3.1. In the end, as has been done in Paper I and Paper II, we average the results obtained for all five data sets in Section 3.2. Since the same data set is studied in Paper II, we import the final results for the C II lines from Paper II. For the Si IV line, we present results obtained from the extended data set based on the analysis performed in Paper I.

### 3. Results from the Analysis of the Mg II Lines

#### 3.1. Mg II: Single Data Set

Figure 2(a) displays a portion of the solar disk obtained from AIA 193 Å full disk image. The over-plotted white box represents the IRIS raster FOV. Panels (b) and (c) display the pseudo-rasters of AIA 193 Å and HMI LOS magnetogram. Similar to Paper II, we apply the segmentation algorithm from Upendran et al. (2020) to the AIA 193 Å pseudo-rasters to obtain a demarcation of CHs from QS. In Figures 2(b) and (c), the green contours demarcate CHs from QS. We clearly see that the HMI pseudo-raster does not show any visual difference between CHs and QS, similar to the results obtained by Tripathi et al. (2021) and Kayshap et al. (2018).

We now investigate the dependence of the following features on |B| through scatter plots: (1) core and peak intensities of the two lines, (2) intensity ratios of the two peaks, (3) line core velocities, and (4) average peak velocities. Note that we consider 10 G as the noise floor of |B| (Yeo et al. 2014; Couvidat et al. 2016).

Following the procedure outlined in Paper I and Paper II, to improve the signal-to-noise ratio and statistics, we consider the derived quantities in the bins of |B|, and report the average values in these bins. We use a constant |B| bin size of 0.1 in log-space to account for the fewer pixels at high |B|. Note that

### Table 1

| Data Set Name | Time Range | (Xcen, Ycen) | Raster FOV | μ |
|---------------|------------|--------------|------------|---|
| DS1           | 2014-07-24 11:10:28—14:40:53 | (128°, −180°) | (141°, 174°) | 0.97 |
| DS2           | 2014-07-26 00:10:28—03:40:53 | (469°, −167°) | (141°, 174°) | 0.85 |
| DS3           | 2014-08-02 23:55:28—03:25:53 + 1d | (332°, −152°) | (141°, 174°) | 0.92 |
| DS4           | 2015-04-26 11:39:31—15:00:56 | (−288°, 45°) | (141°, 174°) | 0.95 |
| DS5           | 2015-10-14 11:07:33—14:37:58 | (215°, −165°) | (141°, 174°) | 0.97 |

Note. The data set used is the same analyzed in Paper II, and the average μ is reported for each FOV.

The data sets used from HMI.
the LOS $|B|$ and Doppler shifts are converted to radial field and flows by dividing with $\mu$ (the heliocentric coordinate; see Thompson 2006) of the respective pixel. Furthermore, the errors reported in all of the plots are the standard errors on the mean. The standard error is defined as $\sigma/\sqrt{N}$, where $\sigma$ is the standard deviation for the samples present in the bin, and $N$ is the number of samples. Note that while we are interested in and report the variation of mean value in each bin, we present the distribution of samples in each bin with 1st and 90th percentile bounds in the Appendix.

3.1.1. Intensities

First, we consider the intensities obtained from the two Mg II lines. We have six intensity measurements in total: four from the peaks, and two from the cores of h and k lines. In Figure 3, we display the intensity maps obtained in these features for DS4. The over-plotted blue contours demarcate the QS and CHs. We clearly see no visible difference between CHs and QS in any of the features of Mg II line. However, a clear relation is seen with the photospheric magnetic flux density in Figure 2(c), in line with the results of Kayshap et al. (2018) for Mg II k line.

In Figure 4, we plot the intensities of different Mg II h and k features in bins of $|B|$. In the plots, black (orange) data points represent CHs (QS), with the k (h) line features in the top (bottom) row. We clearly see that the intensity increases with $|B|$ for both CHs and QS for all of the line features. Furthermore, the QS shows excess intensity over CH for $|B| \geq 30$ G. However, there is a mild difference in the intensities already at 10 G for the k line. We further note that the difference in intensities between QS and CHs increases with increasing $|B|$, with an apparent saturation at higher $|B|$. These results are in agreement with those reported by Kayshap et al. (2018).

Figure 1. Mg II spectrum at a random QS location of DS4. The Mg II line features, along with their locations are labeled as k2v or h2v (blue), k3 or h3 (black), and k2r or h2r (red).

Figure 2. AIA 193 Å context image (panel (a)). The over-plotted white box corresponds to the IRIS raster FOV. The pseudo-rasters obtained from 193 Å images and HMI LOS magnetograms corresponding to the IRIS raster for DS4 are shown in panels (b) and (c), respectively. The green contours in panels (b) and (c) demarcate the CHs and QS, obtained from the segmentation algorithm.
Figure 3. Intensity maps obtained in Mg II k (top row) and h (bottom row) line features from DS4. The blue contours represent the CH–QS boundary, as shown in panel Figure 2(b).

Figure 4. Variation of intensities in Mg II k (top row) and h (bottom row) line features with |B|. The orange color indicates QS, and black indicates CHs. Note that the standard errors in |B| have also been plotted in this figure, and all subsequent figures, but they are too small to be seen.
Another key inference from Figure 4 is the larger intensities of the blue peaks \((k_2v\text{ and } h_2v)\) over the red peaks \((k_2r\text{ and } h_2r)\;\text{see panels (b), (c), (e), and (f)}\). Note that the peak ratio \((I_v-I_r)/(I_v+I_r)\) is a proxy for the average chromospheric velocity, as has been suggested by Leenaarts et al. (2013a). Positive peak ratio corresponds to down-flowing plasma in the atmosphere, while a negative ratio corresponds to up-flowing plasma. A preferentially larger blueward or redward peak arises due to increased absorption on the side of the smaller peak (see Leenaarts et al. 2013a, for details). The enhanced intensities in the blue peaks over red peaks suggest that the chromosphere is largely redshifted, resulting in increased redward absorption at the height corresponding to Mg II formation. Note that unless stated otherwise, redshift means plasma moving toward the Sun and blueshift means plasma moving away from the Sun.

Next, we consider pixels with only positive and negative ratios separately and study the variation of the ratio with \(|B|\). This would amount to considering only pixels that have downflows (or upflows), as a function of \(|B|\). Figure 5 plots positive (panels (a) and (c)) and negative ratios (panels (b) and (d)) for \(k_2\) and \(h_2\) line features. From the plots, we find that the peak ratios vary between 0.1 and 0.2, which is in a sufficiently linear regime of the scatter between peak ratio and average \(v_z\) (as may be seen in Figures 8(e) and (f) of Leenaarts et al. 2013a). Thus, we may consider the peak ratio as a proxy for the average chromospheric velocities in CHs and QS. The plots further show that the peak ratio becomes increasingly positive or negative with rising \(|B|\) until 50 G and saturates thereafter. Also note that the positive as well as negative peak ratios are larger in CHs than in QS for identical \(|B|\). This intriguing finding is indicative of larger downflows as well as upflows in CHs over QS for the regions with identical \(|B|\).

3.1.2. Doppler Shifts

To explore and understand the chromospheric velocities further, we now consider the velocities derived from Doppler shifts, which have a tight correlation with local plasma velocity at the height of formation (Leenaarts et al. 2013a). Figure 6 displays the velocity maps obtained for \(k_3\) (panel (a)), \(k_2\) (panel (b)), \(h_3\) (panel (c)), and \(h_2\) (panel (d)). Note that while the core velocities...
are the straightforward shifts from the reference wavelength, the peak velocities are a signed addition of the peak shifts from the reference wavelength. The red contours demarcate CHs from QS. The velocity maps for both k and h lines reveal that on average the chromosphere is redshifted in both QS and CHs, as observed in Mg II lines. Moreover, there are no conspicuous differences between CHs and QS in the Doppler maps obtained in k3/h3 as well as k2/h2.

In Figure 7, we plot the variation of velocities obtained in k3 (top row) and h3 (bottom row) with |B|. Following Paper I and Paper II, we analyze this data in two ways. On the one hand, we consider the signed average velocities in every |B| bin and plot the variation with |B| (panels (a) and (d)). On the other hand, for each bin of |B|, we consider the redshifted and blueshifted pixels separately and plot the variation of velocities with |B| (panels (b) and (e) for upflows, and panels (c) and (f) for downflows). While the former provides us the average velocities, the latter gives us a systematic variation of downflows and upflows with increasing |B|. This is akin to the systematic variations seen in Figure 5. Such an exercise can tell us if the dynamics of the magnetic field causes any preferential effect on the redshifts and blueshifts.

Figures 7(a) and (d) clearly show that, on average, the chromosphere is redshifted in both QS and CHs, similar to what is inferred from the maps shown in Figure 6. This result is consistent with the known observations (see, e.g., Stucki et al. 2000, 1999; Avrett et al. 2013, and references therein). Moreover, CHs show larger redshift than QS for |B| \(\leq 30\) G, beyond which there are no differences in the velocities. At |B| \(\geq 80\) G, there is some hint of the CHs showing larger redshift. However, note that the average velocities are quite small in both the regions.

When we consider the blue/redshifted pixels separately, both in CHs and QS we find a definite increase in the upflows (see Figures 7(b) and (e)) and downflows (see Figures 7(c) and (f)) with increasing |B|. Moreover, the magnitudes of upflows and downflows are larger in CHs than in QS for the regions with identical |B|. Such a trend is consistent with the inference made using the ratios of the two peaks shown in Figure 5. Note that the magnitude of the downflows in QS and CHs is much larger than that of the upflows, explaining the predominant downflows. Finally, the velocity differences between CHs and QS increase with increasing |B|, with an apparent saturation of velocities for |B| \(\geq 60\) G.

Figure 6. Velocity maps obtained in Mg II k3 ((a)), k2 ((b)), h3 ((c)), and h2 ((d)) from DS4. The red contour shows the CH–QS boundary.
To investigate if these variations are also seen at the average formation height of $k_2$ and $h_2$, we perform the same analysis with the average velocity obtained from the $k_2$ and $h_2$ peaks, and display the results in Figure 8. The plots reveal that the average velocities obtained at $k_2/h_2$ peaks are much smaller than the core velocities. The CHs show larger redshifts than QS for regions with $|B| \leq 30$ G, beyond which the difference in velocities cease to exist. Moreover, the velocities in both CHs and QS increase with $|B|$ until 30 G and saturate thereafter.

Figure 7. Mg II $k_3$ and $h_3$ velocity variation with $|B|$. Panels (a) and (d) show the variation of signed average velocities in $k_3$ and $h_3$ binned in $|B|$. Similarly, panels (b) and (e) show the variation of only blueshifted pixels, while panels (c) and (f) show the variation of only redshifted pixels. The black (orange) scatter corresponds to CHs (QS).

Figure 8. Same as Figure 7, but for $k_2$ and $h_2$. 

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We further note that CHs show excess upflows ((b) and (e)) as well as downflows ((c) and (f) of Figure 8) over QS for regions with identical $|B|$. Both upflows and downflows in CHs show a monotonic increase with increasing $|B|$ until about 60 G and saturate thereafter. For QS, however, variation in upflows is very tiny, while downflows do show an increase with increasing $|B|$ that also saturates beyond $\approx 60$ G. The velocities obtained from the peaks largely follow the velocities obtained using the core of the line, with the former being smaller than the latter.

3.2. Mg II: Combined Data Set

Having demonstrated the analysis and results obtained for a single data set, we now consider all five data sets listed in Table 1 to increase the statistical significance of our results. We emphasize that the results for each data set are similar to the results reported for DS4 in the previous section. For this purpose, we average the obtained parameters from all five sets of observations, and study the dependence of intensities and velocities on $|B|$. Note that combining all of the data sets is possible because the observations are taken at similar values of $\mu$.

We further note that we present the results only for the Mg II k line features for brevity, as the results for both k and h lines are extremely similar.

In Figure 9, we plot the variation of averaged intensities obtained in k3 (panel (a)), k2v (panel (b)), and k2r (panel (c)) as a function of $|B|$. For all three features of Mg II k line, we find that the intensity increases with increasing $|B|$, albeit some sign of saturation at higher $|B|$. We also find that QS regions show excess intensity over CHs for the regions with identical $|B|$ and that the difference in intensities increases with increasing $|B|$.

We study the behavior of Doppler shifts as a function of $|B|$ in Figure 10. We plot the signed average of the Doppler shifts of k3 (k2) in Figure 10(a) (Figure 10(d)). The plots clearly show that both QS and CHs are redshifted on an average, and that the redshift increases with increasing $|B|$. Moreover, for $|B| \lessgtr 30$ G, the CHs show marginally excess redshifts, which disappear at higher $|B|$. We plot the velocity variation of pixels showing upflows in panels (b) and (e), and of downflows in panels (c) and

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**Figure 9.** Same as the top row of Figure 4, but for the combined data set.

**Figure 10.** Same as the top rows of Figures 7 and 8, but for the combined data set.
There is clear signature of monotonic increase of upflows and downflows in CHs with increasing $|B|$. However such a clear monotonicity is not seen for QS regions. In fact, while the flows do increase for QS until about 30 G, they get saturated thereafter. Moreover, the CHs show larger excess upflows as well as downflows over QS for larger $|B|$. Finally, the magnitudes of the flows in k3 are larger than those in k2.

4. C II: Results from the Combined Data Set

The properties of C II lines as a function of $|B|$ in CHs and QS using exactly the same five data set have been studied in great detail in Paper II. Here we summarize the salient conclusions from Paper II, which are relevant to this paper. The relevant results are graphically summarized in Figure 11, which shows the variation of intensity (panel (a)) and signed average velocity (panel (b)), and average velocity in up-flowing (panel (c)) and down-flowing pixels (panel (d)) as a function of $|B|$. These variations are by and large similar to the results obtained from the analysis of Mg II lines in Section 3.

There are a few notable differences between the properties in C II and Mg II lines, though. The QS shows excess average redshifts for $|B| \leq 30$ G, while the CHs show excess average redshifts for larger $|B|$ in the C II line (see Figure 11(b)). Such a relation is not observed for the Mg II line (see Figure 10). This arises due to consistent redshifts in both CHs and QS for $|B| \leq 35$ G from Figure 11(d). Note furthermore that the upflow−$|B|$ relation in C II is weaker than in Mg II features.

5. Si IV: Results from the Combined Data Set

We now present the results from the intensity and Doppler shift of the Si IV line for all of the data sets. The only difference between results presented here and those from Paper I is the inclusion of two additional observations in this work, thereby increasing the statistical significance of the results. We obtain the Si IV line parameters by fitting the spectra with a single Gaussian and constant continuum. The relevant results are graphically summarized in Figure 12. These results are in complete agreement with those obtained in Paper I. Moreover, the results obtained for Si IV bear some similarities with those obtained for C II and Mg II lines.

The intensity (Figure 12(a)) and blueshift (Figure 12(c)) differences between CHs and QS, and their relations with $|B|$ are consistent across all three lines, though more enhanced for Si IV line. However, the signed average velocities clearly indicate reduced average redshifts in CHs over QS (Figure 12(b)). These average redshifts increase with $|B|$, and saturate at $\approx 40$ G. The CHs show excess blueshifts over QS (Figure 20(c)), with the variation similar to those exhibited by the C II line (Figure 11(c)). The redshifted pixels alone also show a direct relation to $|B|$, but the QS is more redshifted than CHs (Figure 12(d)). Note also that the upflow and downflow
velocities obtained for Si IV are much larger than those inferred from the Mg II (Figure 10) or C II lines (Paper II).

6. Correlations between Doppler Shifts of Mg II, C II and Si IV

The velocities and intensities show a highly nontrivial relation as a function of the formation height of different spectral lines. Therefore, to investigate if there is any correlation between Doppler signatures observed in the three different spectral lines, viz., Mg II, C II, and Si IV, we consider the approximate formation height of these lines obtained from numerical simulations. It has been suggested that on average C II lines form slightly higher in the atmosphere than the Mg II lines. Between the Mg II lines, the k line forms higher than the h line. Moreover, it has also been found that the line cores of both k and h lines form higher than their respective peaks (Leenaarts et al. 2013a; Rathore et al. 2015). The Si IV line forms in optically thin conditions, so ascribing an exact formation height is not possible. However, it forms at a higher temperature in the TR. We may, therefore, ascribe a greater height to Si IV than the Mg II and C II lines. With this prior, we may assume that the formation height (ascending order) is approximately Mg II h2 ≲ Mg II k2 < Mg II h3 ≲ Mg II k3 ≈ C II < Si IV.

The obtained velocities in different line features of Mg II (Figures 10 (b), (c), (e), and (f)), C II (Figures 11 (c) and (d)), and Si IV (Figures 12 (c) and (d)) clearly show that the velocity magnitude increases with increasing formation height. Considering mass flux conserving flows (Avrett et al. 2013), and that the density decreases as a function of height in the solar atmosphere, it is plausible to hypothesize that the upflows (downflows) at lower (greater) heights are enhanced (reduced) while traveling toward greater (lower) heights.

To check this hypothesis, we investigate the correlations between Mg II, C II, and Si IV velocities. Since Mg II and C II form at approximately the same height, we expect these two lines to have similar properties as the Si IV line. In Paper I, it is suggested that the increase in Si IV blueshift with increasing |B| may indicate the signatures of the solar wind emergence. This motivates us to explore if the observed flows in chromosphere detected in the Mg II and C II lines are in any way related to those obtained from Si IV. For this analysis, we use the results obtained from the combined data set. Note that we only consider the Mg II h follow the results from the k feature and hence are not shown for brevity.

We split the velocities observed in Mg II, C II, and Si IV into sets of pixels containing upflows and downflows. Then, we consider scatter plots between flows in the intersection of these sets, e.g., relation between pixels showing upflows in Mg II k3 and upflows in Si IV, upflows in Mg II k3 and downflows in Si IV, and so on. These scatter plots are obtained for Si IV velocities, in Mg II and C II velocity bins to improve statistics.
Note that the bins here are selected in deciles, i.e., every 10% of the data for each Mg II or C II feature is considered to be in one bin.

In Figure 13, we plot the correlations between downflows (top row) and upflows (bottom row) observed in Si IV with those observed in Mg II k2 (panels (a) and (d)), Mg II k3 (panels (b) and (e)), and C II (panels (c) and (f)). Panels (a), (b), and (c) demonstrate that the downflows observed in Si IV are strongly correlated with those observed in Mg II k2, k3, and C II. For a given value of downflow in Si IV, the downflows are stronger in k3 and C II than those in k2. Note though, that the downflows in k3 and C II are very similar. Moreover, Si IV displays excess downflows in QS with respect to CH for similar C II and Mg II downflows. These differences in QS–CH Si IV downflows are also observed to increase with increasing Mg II and C II downflows. Similarly, panels (d), (e), and (f) suggest that the upflows in Si IV have a slightly better correlation with upflows in Mg II k3 and C II than those in Mg II k2. Moreover, like downflows, we find that for similar upflows in Mg II and C II, the CHs exhibit larger upflows than QS in Si IV. We further note that there is a slight hint of increase in the difference of upflows observed in CHs and QS in Mg II and C II lines.

In Figure 14, we study the correlations between the upflows in Si IV with downflows in Mg II and C II and vice versa, as shown in the top and bottom rows, respectively. We find that the upflows in Si IV have a monotonic relation with the downflows in Mg II and C II (top row). In addition, we note that for similar downflows observed in Mg II and C II, Si IV shows stronger upflows in CHs and than in QS. On the other hand, the Si IV downflows do not show any particular correlation with Mg II and C II upflows. Furthermore, the Si IV downflows in CHs and QS remain consistent for similar upflows in Mg II and C II. Thus, we do not find any relation between the downflows in Si IV with the upflows in Mg II and C II.

7. Inferences from Intensity and Velocity Diagnostics

The problems of coronal heating in QS and CHs, and the formation and acceleration of solar wind are intimately tied to the structure and dynamics of the magnetic field in the respective regions. Therefore, comparative studies between CHs and QS become important in understanding the plasma dynamics, and the underlying processes. The Mg II, C II, and Si IV lines observed by IRIS probe different layers in the chromosphere and TR, and have provided us with a unique opportunity to understand the dynamics of these regions as a dynamically coupled system. In this paper, we characterize, in detail, the dynamics of the Mg II line by combining the information related to the plasma dynamics with that of the magnetic field. In addition, we also probe the correlations between the Doppler shift obtained for Mg II lines, and those obtained for the Si IV line from Paper I and the C II line from Paper II, to investigate if a common origin may be ascribed to the observed dynamics in the different lines. Below we summarize and discuss our results followed by an interpretation in Section 8.

7.1. Intensity Differences

The intensities in the Mg II h, k lines (both in the core and peaks) and C II line, which form in the chromosphere, and those of the Si IV line, which form in the TR, increase with |B| (see Figures 9, Figures 11(a), and 12(a)). For all three lines, CHs show reduced intensity over QS for the regions with identical |B|. Moreover, the difference in the intensities increases with increasing |B|. The observed differences in the chromospheric intensities in CHs and QS suggest that CHs have lower source function values over QS for regions with identical |B| (Rathore et al. 2015).
Our results further show that the differences between CH and QS intensities exist already at the chromospheric level for a given magnetic flux region (see also Kayshap et al. 2018, and Paper II). We note that the ratios of QS to CH intensities in the largest |B| (∼80 G) bins are smallest in Mg II k2, and increase through the C II, Mg II k3, and Si IV lines as 1.18, 1.22, 1.26, and 1.32, respectively, suggesting an increasing differentiation between CHs and QS from low chromosphere to TR.

The intensity differences in the CHs and QS in the corona are well known (see, e.g., Krieger et al. 1973). However, such differences are not seen in either the chromosphere or TR above noise level (Stucki et al. 1999; Xia et al. 2004). These observations led Wiegelmann & Solanki (2004) to attribute the CH–QS intensity differences to loop statistics in these regions. Based on potential field extrapolations, Wiegelmann & Solanki (2004) found that the QS have excess numbers of longer closed loops over CHs, while similar numbers of shorter closed loops are present in both the regions. Using the scaling laws, valid for optically thin plasma, they proposed that the reduction in CH intensity over QS naturally comes out as a function of a deficit of longer loops in CHs.

While the scenario proposed by Wiegelmann & Solanki (2004) is used to explain the intensity difference in Si IV in Paper I, it may not be directly applicable to the chromosphere, as also argued by Kayshap et al. (2018). However, since the loop statistics of Wiegelmann & Solanki (2004) is derived from the extrapolations of photospheric magnetograms, it may be plausible to suggest that the statistics itself (and not the scaling relation for plasma emission) is also valid for the chromosphere. Therefore, we may conclude that at a relatively higher |B|, a deficit of shorter loops in the CHs with respect to the QS is observed already in the low chromosphere. The source function of the chromospheric lines may be partially influenced by this loop statistics at chromospheric heights and may explain the marginal deficit of intensities in CHs over QS.

7.2. Doppler Shift: Variations and Correlations

Doppler measurements in all three lines demonstrate that on average both the chromosphere and TR are redshifted (see Figures 10(a) and (d), 11(b), and 12(b)). The average redshifts are found to increase with |B|, and increase from Mg II k2 to Si IV for similar |B|. By studying the redshifted and blueshifted pixels separately, we find that in the chromospheric lines, CHs have larger (excess) upflows as well as downflows compared to QS for identical |B| and that the excess increases with increasing |B| (see Figures 10, and 11(c) and (d)). However, in the TR, CHs have excess (reduced) upflows (downflows) over QS for the regions with identical |B| (see Figures 12 (c) and (d)). With uncertainties, the magnitudes of upflows and downflows are in an approximate descending order of Si IV, Mg II cores, C II, and Mg II k3. We further note that, while Mg II k3 and C II lines show similar downflows, the upflows are larger in Mg II k2.

To assess any (or otherwise) association between the flows observed in the chromosphere and TR, we perform a correlation study in the intersection of sets of pixels that show flows in different lines. That is, we study the mean variation of upflows in the TR pixels that also show upflows in the chromosphere, and so on for different combinations of flows. This analysis gives us the variation of mean TR flows with chromospheric flows, and provides information on the persistence of flows in different lines. We find that the flows in chromosphere and TR are tightly correlated, i.e., the downflows in chromosphere with both upflows and downflows in TR, upflows in chromosphere with those in TR. However, we did not find any correlation between chromospheric upflows.
with downflows in TR. Moreover, for the similar downflows (upflows) in the chromosphere, the CHs showed reduced TR downflows (excess upflows) over QS. Additionally, for similar downflows in the chromosphere, the CHs show excess upflows over QS in the TR.

The observations reported here lead to two questions. First, what physical mechanism(s) give rise to these flows? Second, is it possible to explain the observed differences between the flows observed in CHs and QS in the chromosphere and TR, including the difference in the intensities discussed in Section 7.1? While we deal with the former here, the latter is taken up in Section 8.

The tight correlations between TR downflows measured using Si IV and those observed in the chromosphere measured using Mg II and C II may either be explained by field-aligned downflows due to condensations from the corona to TR to chromosphere (see, e.g., Klimchuk 2006; Tripathi et al. 2009, 2010, 2012) or due to return flows of type II spicules (Klimchuk 2012; Ghosh et al. 2019, 2021; Bose et al. 2021). However, we note that the observed magnitude of the TR downflows is much larger than those predicted using 1D hydrodynamic simulations of coronal impulsive heating followed by evaporation and condensation. Therefore, for the reasons elaborated in Ghosh et al. (2019, 2021), it is more likely that the observed downflows are due to the return flows of type II spicules. Our finding that the speeds of chromospheric downflows are lower than those in TR is very likely due to the plasma flowing from lower density to higher density. Note, however, that the net deceleration of the plasma is dependent on the interplay of deceleration due to atmospheric stratification and magnetic pressure, and acceleration due to gravity and plasma compression.

Our observations further show that the upflows in chromosphere and TR are also correlated. Moreover, these upflows show an increase in magnitude with increasing $|B|$ as well as atmospheric height. This may be possible if the upflows are moving through an expanding flux tube, under the assumption of constant mass flux. The upflows themselves, however, may have been caused by the launch of events like type II spicules (De Pontieu et al. 2007a; Tian et al. 2008a, 2014; Samanta et al. 2019). However, note that such upflows may also be generated due to upward propagating waves (e.g., Cranmer & Van Ballegooijen 2005). Since Alfvén waves are known to be ubiquitous in the chromosphere (De Pontieu et al. 2007b), disentangling the exact effects of Alfvén waves versus spicule-like propagation upward is difficult (see, however, Ghosh et al. 2019, 2021).

Finally, the chromospheric downflows also bear a direct relationship with the upflows in TR. Such correlations suggest a common origin of these flows and hint towards the existence of bidirectional flows. Bidirectional flows have been observed in QS and CH (predominantly occurring in the CH) network regions by Aiouaz (2008), and in active regions by Barczynski et al. (2021) as redshifts in TR and blueshifts in the low corona (see also, Gupta et al. 2018, for bidirectional flows in transient events). We propose that such bidirectional flows occurring between the chromosphere and the TR can suitably explain our observations.

The scenario we propose is illustrated in Figure 15. The vertical color bars changing from deep yellow in the photosphere to white in the corona indicate reducing density with increasing height in the atmosphere. The approximate formation heights (or rather, a proxy for temperature) of different ions corresponding to the spectral lines studied here are labeled with horizontal lines. The “asterisks” indicate the location of an impulsive event, while the arrows mark the direction of expected flows. The blue (red) arrows indicate upflows (downflows).

We present four different scenarios, based on the same physical mechanism, to explain the three sets of observation. As evidenced by similar skew and kurtosis in C II 1334 Å line (see Paper II) and nonthermal widths in Si IV (see Paper I), it is plausible to conclude that similar physical mechanisms give rise to the observed spectral profiles in CHs and QS. This mechanism, in our interpretation, is an impulsive dumping of energy in CHs and QS. For an impulsive event occurring between the formation height of Si IV and C II or Mg II, bidirectional flows will be produced in the form of upflows in Si IV and downflows in C II and Mg II. Since the chromosphere is denser than the TR, the chromospheric radiative cooling timescales are smaller. Hence, the downflows would cool down faster, and be visible in cooler lines like Mg II and C II, while the upflows persist in relatively hotter lines like Si IV. Some of the upflows observed in Si IV may persist until greater heights and then fall back, similar to type II spicule return flows (Figure 15(b)). The returning flows will be observed as persistent downflows in all three lines, with successively reducing speeds. We note, however, that the persistent downflows may also be caused by the impulsive event occurring above or about the formation height of Si IV (Figure 15(c)), and may have similar signatures of descending speeds as in the previous case. Finally, the impulsive events may also occur either below or at the height of formation of Mg II peaks (Figure 15(d)) resulting in the launching of chromospheric jets that may show persistent upflows in the chromosphere and TR, followed by the downflows at later times.

Bidirectional flows in an expanding, cylindrically symmetric flux tube have been observed in field-aligned 1D simulations by He et al. (2008). In these simulations, impulsive events deposit energy at the height of $\approx 5$ Mm, which is also the location where expansion of the flux tube starts. The results demonstrate that at the onset of the impulsive event, the plasma moves outward from the location of the impulse, showing bidirectional flows. He et al. (2008) show that the velocities in Si II, C IV, and Ne VIII obtained from their setup match those observed by Tu et al. (2005). He et al. (2008) further show that the downflows at 10$^4$ K are $\approx 2$ km s$^{-1}$ The magnitude of these downflows increases with height, reaching up to 4 km s$^{-1}$ near the energy dumping heights. These velocities were obtained with a $|B|$ of 56.5 G in the simulation. The velocities obtained in this simulation are consistent with the downflow speeds observed in Mg II k2 (see Figure 10(i)) at $\approx 56$ G, but are much lower than the downflow speeds observed in Mg II k3 and C II.$\$

Hansteen et al. (2010) performed a 3D simulation of a QS region for different average $|B|$, spanning from the convection zone to the corona. It is found that impulsive events due to reconnection occurring at various heights give rise to bidirectional flows, seen as co-spatial blueshifts (redshifts) in the corona (TR) concentrated at loop footpoints.

Such events occurring across a range of heights can give rise to correlated flows similar to the results reported here. Hansteen et al. (2010), in the their B1 model setup, were able to reproduce velocities consistent with blueshifts observed in the corona (see Figure 11 of Hansteen et al. 2010). Note however, that the downflow speeds near the formation temperature of
Mg II and C II inferred from these simulations were between 2–4 km s\(^{-1}\), which are lesser than those reported in this work. Nevertheless, we note that the scenario presented by Hansteen et al. (2010) may potentially explain the correlated bidirectional flows reported in this paper.

Finally, while the above-described scenario based on impulsive events may explain the observed downflows, it is important to highlight that spicule-like flows may also be obtained due to “squeezing” of flux tubes near the chromosphere (see, e.g., De Pontieu et al. 2007a; Martínez-Sykora et al. 2011, 2017, 2019, and also Isobe et al. 2007). The rising plasma from the ’squeeze’ has been observed to be heated up and detected in various IRIS lines such as Mg II and Si IV (Martínez-Sykora et al. 2017). Thus, the persistent upflows may also be explained through such spicule-like flows, while the downflows may then be explained by the return of such spicule-like flows. Note that, throughout the paper, we assume that the type II spicules are produced due to impulsive events (Moore et al. 2011, 2013; Martínez-Sykora et al. 2011; Samanta et al. 2019).

8. **A Unified Scenario: The Origin of Solar Wind, Switchbacks, and QS Heating**

While the occurrence of impulsive events at the interface between chromosphere and corona may explain the observed flow variations with |B| in different lines and their interrelations, the question remains as to what leads to the observed differences between the intensities as well as flows in CHs and QS. To explain the differences in the intensities, in Section 7.1, we invoked the loop statistics in CHs and QS derived by Wiegelmann & Solanki (2004). The predominant velocity differences between CHs and QS are: (i) reduced Si IV downflows in CHs over QS for similar downflows in the chromospheric lines, and (ii) excess Si IV upflows in CHs over QS for similar upflows and downflows in the chromospheric lines. These results indicate excess acceleration of upflows in CHs and excess deceleration of downflows in QS. Furthermore, while the QS shows enhanced intensity over CHs for regions with similar |B|, the CHs show larger flow speeds (except Si IV downflows) over QS. Such an observation thus hints toward a unified scenario of heating of the corona in QS and CHs as well as the emergence of the solar wind. Therefore, we then ask if it is possible to combine the loop statistics and the occurrence of flows due to impulsive events illustrated in Figure 15, to explain the observed differences in intensities as well as the Doppler shifts in CHs and QS, similar to those discussed in Tripathi et al. (2021) for Si IV.

A graphic depicting the scenario we propose is shown in Figure 16. The left panel depicts the predominant topology in CHs while the right panel is for QS regions, based on the loop statistics of Wiegelmann & Solanki (2004), according to which both CHs and QS have equal numbers of short closed loops. However, QS has predominantly large closed loops, and CHs have open field lines. In CH regions, the interchange reconnection (e.g., Fisk 2005; Janardhan et al. 2008), leading to impulsive events, may occur between closed and open field lines, while in QS, the impulsive events will be due to reconnection among closed–closed loops, similar to those observed in the core of active regions during transient formation of loops (see Tripathi 2021). The excess open and expanding flux tubes in CHs may cause preferential acceleration of upflows in CHs over QS. In principle, the scenario proposed here is similar to those employed by Tian et al. (2008b, 2008a) and He et al. (2007) to explain the Doppler shifts observed in QS–CH in coronal and TR lines, and similar to Figure 5 of He et al. (2010). Note that the concept of

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**Figure 15.** A schematic depicting a unified picture of flow generation, including observed correlations between flows. The vertical bar denotes density reducing with height from dark yellow to white. The red asterisk depicts an impulsive event, which gives rise to flows (arrows). Blue upward arrows depict upflows, and red downward arrows depict downflows. Panel (a) shows the basic bidirectional flow generation, which eventually gives rise to the return flow in panel (b). Impulsive events occurring much higher than Si IV formation height, giving rise to downflows, is shown in panel (c). Upflows generated due to impulsive events, low in the atmosphere are depicted in panel (d). See the text for details.

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**Figure 16.** The left panel depicts the predominant topology in CHs and QS regions, based on the loop statistics of Wiegelmann & Solanki (2004), according to which both CHs and QS have equal numbers of short closed loops. However, QS has predominantly large closed loops, and CHs have open field lines. In CH regions, the interchange reconnection (e.g., Fisk 2005; Janardhan et al. 2008), leading to impulsive events, may occur between closed and open field lines, while in QS, the impulsive events will be due to reconnection among closed–closed loops, similar to those observed in the core of active regions during transient formation of loops (see Tripathi 2021). The excess open and expanding flux tubes in CHs may cause preferential acceleration of upflows in CHs over QS. In principle, the scenario proposed here is similar to those employed by Tian et al. (2008b, 2008a) and He et al. (2007) to explain the Doppler shifts observed in QS–CH in coronal and TR lines, and similar to Figure 5 of He et al. (2010). Note that the concept of
interchange reconnection has been invoked to explain active region outflows by Del Zanna et al. (2021) and Barczynski et al. (2021), solar wind disappearance events by Janardhan et al. (2008), active region jets and X-ray and cool jets in polar coronal holes (Moore et al. 2011, 2013, 2015), and type III radio bursts (e.g., Mulay et al. 2016).

Under the scenario presented in Figure 16, the impulsive events may occur across a range of heights via magnetic reconnection among open fields and closed loops of various heights in the CHs. Thus, if the energy dumping events were to occur below the formation height of Mg II, the up-flowing plasma may be accelerated preferentially in CHs, and reach Si IV heights, where a strong correlation is obtained. Similarly, if the event were to occur at much greater heights, or if plasma launched from the lower heights (e.g., type II spicule-like events) was returning to the low solar atmosphere, the down-flowing plasma may be falling from the Si IV formation height, which will show deceleration due to increasing density toward the lower atmosphere mapped by Mg II. Assuming a mass flux conserving flow, we have \( \rho V = \text{const} \), where \( \rho \) is the mass density, and \( V \) is the velocity. For a given downflow in Si IV, the downflows in chromospheric lines are smaller in QS over CHs (Figures 13(a)–(c)). Hence, the density increase from Si IV formation heights to Mg II formation heights is larger in QS over CH, resulting in a larger velocity reduction in QS. Note that the excess acceleration of upflows in CHs and excess deceleration of downflows in QS may also be explained by a difference in the coronal pressure in CHs (lesser pressure) and QS (more pressure), as seen in simulations by Suematsu et al. (1982) and Shibata & Suematsu (1982). However, note that since the mass flux is typically different for CHs and QS, a quantitative comparison is beyond the scope of this work.

For bidirectional flows due to reconnection events between Mg II and Si IV formation heights, the counterpart upflows will be preferentially accelerated into Si IV formation height in CHs over QS due to excess open expanding flux tubes in CHs over QS. Since the QS has predominantly closed loops, the closed-loop reconnection only serves to fill the loop with plasma, raising its intensity. Thus, impulsive events occurring across a range of heights combined with loop statistics in CHs and QS elegantly tie together all of our observations, and provide a unified scenario for QS heating and solar wind emergence.

Finally, the scenario we present in Figure 16 is also appealing to explain the switchbacks observed in the near-Sun solar wind (Balogh et al. 1999; Bale et al. 2019) using Parker Solar Probe. One of the competing scenarios for the formation of these switchbacks is through interchange reconnection events occurring in the TR and lower corona (Fisk & Kasper 2020; Sterling & Moore 2020; Sterling et al. 2020; Zank et al. 2020; Bale et al. 2021; Fargette et al. 2021; Mozer et al. 2021; Tripathi et al. 2021; see also Liang et al. 2021 for an assessment of viability of switchbacks from the linear theory of Zank et al. 2020). The kinked field lines as a result of reconnection between the close loop and open field in the coronal holes, as shown by the black arrow in Figure 16, may be transported outwards into the solar wind, which are then observed as rotations in the magnetic field. In such a scenario, the flows reported in this paper serve as constraints and modeling inputs for solar wind switchback simulations.

A straightforward association between the scenario we present, and polar CH jets is clearly seen. Interchange reconnection seems to play the predominant role in generation of mass flux and plasma heating in these events. However, note that the jets observed by Moore et al. (2015) have velocities almost two orders of magnitude higher than the velocities we report, and show morphological differences arising due to twist and shear in the ambient magnetic field (see also Moore et al. 2013). Since we are averaging over multiple pixels for boosting signal, checking for such morphological signatures is beyond the scope of this work. However, newly emerged bipolar may interact with the ambient vertical field similar to the scenario proposed by Moore et al. (2011), giving rise to spicule-like events. The interaction height and the amount of magnetic flux converted into thermal energy would then determine the lines that show correlated flow.

The observational results and the scenario presented in this paper explain the solar wind formation including switchbacks and the dynamics observed in the QS. We, however, stress that disentangling the absolute effects of wave propagation versus impulsive upflows is needed. Furthermore, disentangling the effect of the return of spicule-like events versus downflows due to impulsive events occurring higher up in the TR is also difficult. Disentangling these different effects requires further...
high-resolution spectroscopic observations simultaneously taken at different heights, combined with numerical simulations incorporating radiative transfer and evolution of the solar corona into the solar wind. Such observations may be provided with the EUV High-Throughput Spectroscopic Telescope on the upcoming Solar-C mission (Shimizu et al. 2020).

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Software: Numpy (Harris et al. 2020), Astropy (Price-Whelan et al. 2018), Sunpy (Mumford et al. 2018), Scipy (Virtanen et al. 2020), Scikit-image (van der Walt et al. 2014), Matplotlib (Hunter 2007), Multiprocessing (McKerns et al. 2012), OpenCV (Bradski 2000), Jupyter (Kluyver et al. 2016).

Appendix

Distribution of Various Properties as a Function of $|B|$.

We present here the distribution of intensity and velocity from Mg II, C II, and Si IV lines as a function of $|B|$. The plots shown from Figures 17–20 are the same as those from Figures 9–12, except that the error bars reported correspond to the 1st and 90th percentiles of the samples in each bin. Since the overall distribution of the various quantities looks very similar in CHs and QS, the distribution within bins of $|B|$ reflects how systematically differences arise in the ensemble of

Figure 17. Same as Figure 9, but the errors now represent the 1st and 90th percentile bounds of the distribution of samples present in the bin of $|B|$.

Figure 18. Same as Figure 10, but the errors now represent the 1st and 90th percentile bounds of the distribution of samples present in the bin of $|B|$.
Figure 19. Same as Figure 11, but the errors now represent the 1st and 90th percentile bounds of the distribution of samples present in the bin of $|B|$.
The distributions of samples between CHs and QS slowly drift apart in their mean values, depicting the transition from statistical signatures in the lower atmosphere to very clear signatures in the corona. Thus, the distribution of samples in each bin provides further constraints to expected results from simulations.

Figure 20. Same as Figure 12, but the errors now represent the 1st and 90th percentile bounds of the distribution of samples present in the bin of $|B|$.

ORCID iDs
Vishal Upendran @ https://orcid.org/0000-0002-9253-6093
Durgesh Tripathi @ https://orcid.org/0000-0003-1689-6254

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