OBSERVATIONAL DETECTION OF DRIFT VELOCITY BETWEEN IONIZED AND NEUTRAL SPECIES IN SOLAR PROMINENCES

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Received 2015 December 23; accepted 2016 April 2; published 2016 May 31

ABSTRACT

We report the detection of differences in the ion and neutral velocities in prominences using high-resolution spectral data obtained in 2012 September at the German Vacuum Tower Telescope (Observatorio del Teide, Tenerife). A time series of scans of a small portion of a solar prominence was obtained simultaneously with high cadence using the lines of two elements with different ionization states, namely, Ca\textsc{ii} 8542 Å and He\textsc{i} 10830 Å. The displacements, widths, and amplitudes of both lines were carefully compared to extract dynamical information about the plasma. Many dynamical features are detected, such as counterstreaming flows, jets, and propagating waves. In all of the cases, we find a very strong correlation between the parameters extracted from the lines of both elements, confirming that both lines trace the same plasma. Nevertheless, we also find short-lived transients where this correlation is lost. These transients are associated with ion-neutral drift velocities of the order of several hundred m s\textsuperscript{−1}. The patches of non-zero drift velocity show coherence in time–distance diagrams.

Key words: magnetohydrodynamics (MHD) – Sun: filaments, prominences

1. INTRODUCTION

It has long been stated that solar atmospheric plasma is not in a neutral state or in a fully ionized state. The effects of partial ionization have been taken into account in many contexts, such as for spectral line formation and inversion techniques. The influence of this plasma state on dynamics has also become the focus of many investigations (Arber et al. 2007; Soler et al. 2010; Leake et al. 2012; Zaqarashvili et al. 2012; Khomenko et al. 2014a; Cally & Khomenko 2015; Khomenko et al. 2015). Many studies of chromospheric and coronal plasma dynamics use the magnetohydrodynamics (MHD) as the main tool to successfully understand the complex structure and dynamical processes of these solar atmospheric layers, but the standard MHD theory does not include partial ionization effects. An extended multi-fluid theory is a conceptually simple form with which to start integrating these effects without invoking mathematically more complex statistical approaches (see Braginskii 1965; Bittencourt 1986; Balescu 1988).

One of the basic assumptions of a multi-fluid theory is that the plasma is composed of different species, each of them behaving like a fluid and interacting with the other species, either directly or under certain conditions, with collisional coupling between the fluids being relatively weak. Hence, the plasma mostly behaves as a single fluid, but in certain processes there might be deviations between the dynamical and thermal properties of the different species, which are then smoothed by interactions on relatively short timescales (typically of the order of minutes).

The general transport equations for a multi-component plasma can be derived from the Boltzmann kinetic equation, taking into account the general properties of the collisional terms (Braginskii 1965; Bittencourt 1986; Balescu 1988). A basic assumption is that the collisional terms can be approximated as $v_{\alpha\beta}^c (v_\alpha - v_\beta)$, where $v_{\alpha\beta}^c$ is the collision frequency between the species labeled $\alpha$ and $\beta$, and $v_\alpha$ is the mean velocity of the species labeled $\alpha$. Using this formalism, an equation for the relative velocity (referred as the “drift” velocity in the rest of the paper) between ions and neutrals, namely, $w = v_i - v_n$, can be written as (Díaz et al. 2014; Khomenko et al. 2014a)

$$w = \xi_n \frac{\mu}{\alpha_n} [J \times B] - \frac{G}{\alpha_n} + m_e v_{en} \frac{J}{e\alpha_n}.$$  \hspace{1cm} (1)

In this equation, $\xi_n$ is the neutral fraction, $\alpha_n$ is the sum of the collisional frequencies between neutrals and other species multiplied by the corresponding mass densities, $v_{en}$ is the electron–neutral collisional frequency, $B$ is the magnetic field vector, $J$ is the current, and $m_e$ and $e$ are the electron mass and charge. The quantity $G = \xi_n \nabla P_n - (1 - \xi_n) \nabla P_e$ is the partial pressure gradient term, where $P_n$ is the electron pressure and $P_e$ is the neutral pressure. Equation (1) comes from combining the momentum equations for the electron, ion, and neutral fluids and neglecting the inertia terms compared to the friction terms. Its derivation is given in details in Section IV B of Khomenko et al. (2014a). By introducing this drift velocity into the combined momentum equation of charged species, the induced electric field and the generalized induction equation can also be obtained (Khomenko et al. 2014a).

The existence of these drifts between species is thus a direct consequence of the partial ionization, and reflects that the coupling between the fluids is not strong enough to behave as a single fluid. However, in the physical conditions of the solar atmosphere, these terms are small, and electric fields and drift velocities rapidly dissipate. The scale depends on the details of the process and the values of the physical parameters, but simulations show that the timescales involved are typically of the order of minutes or even less (Khomenko & Collados 2012; Khomenko et al. 2014b), since the collisions are still efficient enough to prevent large deviations from single fluid theory.

To detect these effects, it is then necessary to measure as accurately as possible the velocity of different species simultaneously and at the same spatial position. Evaluating these drifts does not rely on unknown relations or assumptions,
since measuring the Doppler shifts of different lines is straightforward. In a recent work, we attempted to detect differences between the velocities of the Evershed flow measured co-spinally and simultaneously from spectral lines of neutral and ionized iron atoms (Khomenko et al. 2015). The results reveal a slightly larger velocity of the Evershed flow in neutral lines. However, the drawback of these kinds of measurements is the use of spectral lines with different formation heights in the photosphere of the Sun. On the one hand, there is uncertainty regarding the precise formation height, depending on the model atmosphere adopted for the position on the limb, especially in an inhomogeneous environment such as a sunspot penumbra. On the other hand, the photosphere is dense and collisional effects dominate, which results in lower expected drift velocities according to Equation (1). In the present paper, we try to improve these two aspects. We choose a solar prominence as our target because its plasma can be considered relatively optically thin, so that the formation region of different spectral lines largely occupies the same plasma volume. In addition, the physical conditions in prominences are expected to give rise to significant partial ionization with a considerable amount of neutral and ionized species depending on the height in the prominence where measurements are made. Velocity fields are also non-negligible, and important mass flows (e.g., Schmieder et al. 1991; Zirker et al. 1998; Lin et al. 2003, 2005; Chae et al. 2005, 2008; Chae 2007; Alexander et al. 2013), waves with different periodicities (e.g., Oliver & Ballester 2002; Banerjee et al. 2007; Oliver 2009; Tripathi et al. 2009; Mackay et al. 2010; Arregui et al. 2012; Parenti 2014), as well as instabilities have been observed (Isobe et al. 2005; Berger et al. 2008, 2010, 2011; Heinzel et al. 2008; Ryutova et al. 2010). Instabilities may also lead to mass motions that can have a different impact on neutrals and ions (Soltau et al. 2002; Díaz et al. 2012, 2014; Khomenko et al. 2014b). Our main goal here is to investigate whether or not any measurable drift velocity can be reliably detected in these structures and to discuss the implications of a possible detection in terms of partial ionization effects.

2. OBSERVATIONAL DATA

2.1. Observational Details and Target Background

The data used in this study were taken at the German Vacuum Tower Telescope (VTT, Observatorio del Teide, Tenerife) on 2012 September 11. Several targets were registered during this campaign, but here we focus on one particular series where a prominence near AR11564 at S12W83 was observed continuously for more than half an hour with relatively good seeing conditions for the entire observation. The uncorrected $r_0$ parameter given by the adaptive optics (AO) software of the telescope (Soltau et al. 2002) provided values close to 10 cm during the whole series. The target was an active prominence undergoing evolution during the observation. It had well-developed barbs, and in some parts of the slit there was some contamination from surges arising in the nearby active region that were superimposed with the prominence material. The AO system was working quite well, locked in a nearby pore near the solar limb, and only jumped once in the whole series.

We simultaneously detected spectra of the He I 10830 Å and Ca II 8542 Å lines using the detector of the Tenerife Infrared Polarimeter (TIP II Collados et al. 2007) for the former and a camera optimized for the visible part of the spectrum for the latter. The spatial sampling along the slit was 0.718, which is the same for both detectors. The time cadence was 1.5 s per slit position for both spectral lines. To ensure such a high cadence and an acceptable noise level, we did not use the polarimetric capabilities of TIP II and only detected intensity spectra. The set has 1200 frames organized as follows: 120 scans of the body of the prominence in 10 scanning positions separated by 0.35 in the direction perpendicular to the slit. This means that an area of 3.5 was observed and spectra at a fixed position were taken every 15 s. Additionally, a slit-jaw Hα camera provided full field-of-view images of the prominence in the core of this spectral line. An example Hα image can be seen in the left panel of Figure 1. Note that these data are not used in this study anymore because the camera did not provide spectral information about the Hα line. We only used Hα images to place into context the results from the other lines.

Using the data from the SDO 304 Å channel (right panel of Figure 1), we can see that the target prominence was close to AR11564. The prominence itself can be seen in absorption on the disk during the previous days, and seems to be an active prominence related to the active region. The prominence spine was almost parallel to the limb and the prominence remained quite stable, despite the fact that the active region emitted jets during the observation. This particular active region did not produce any flares during the days before and after the observation.
The raw Ca II and He I spectra were reduced using a standard procedure. First, the data were cleaned of discrepancies between pixel counts from different parts of the CCD cameras by subtracting the averaged dark current images taken before and after the observational sequence. Then, the data were corrected for flat field individually in each spectral region using the corresponding scans in Ca II and He I taken before and after the series at the solar disk center. The continuum of the flat field images was normalized to 10,000 counts. The same normalization factor was applied to the prominence data, and the final amplitudes of the reduced spectra are in the same units of the disk center continuum for both lines. Finally, the only tip-tilt jump in the series was corrected by adequately displacing the spectral images in the slit direction. After these operations, data cubes of the spectra of each of the two lines were obtained in every pixel along the slit and for any temporal position of the series. To perform wavelength calibration, we compared the average flat field spectrum of the lines with the FTS atlas (Neckel & Labs 1984). The spectral sampling was 16.5 mA/pixel for the Ca II spectra and 11.0 mA/pixel for He I, and the spectral range was covered by 668 and 1010 pixels, respectively.

The signal-to-noise level in the reduced spectra was about 11 in the Ca II line and about 400 in the He I line. The signal-to-noise level in the Ca II line was relatively low because the emission is intrinsically lower in this line and because of the low quantum efficiency of the camera used. The Ca II spectra were further filtered using a Principal Component Analysis technique (Rees et al. 2000) which clearly improved the signal-to-noise ratio, as can be seen in Figure 2. For that, each Ca II profile was represented by a linear combination of a set of eigenvectors $e_i(\lambda)$ with appropriate constant coefficients $c_i$:

$$S(\lambda) = \sum_{i=1}^{n} c_i e_i(\lambda).$$

(2)

The system of eigenvectors was obtained from a data set of 4000 randomly chosen Ca II profiles using a singular value decomposition (SVD) method (Rees et al. 2000; Socas-Navarro et al. 2001). In practice, most of the eigenvectors do not carry information about the shape of the profiles, but only about the particular noise pattern of each profile. The truncation of the series therefore allows us to remove information about noise and to improve the signal-to-noise ratio. We truncated the expansion after the first 25 terms. This allowed us to improve the signal-to-noise level in Ca II by a factor of approximately 3.5.

2.2. Data Fitting Procedure

We fit the observed Ca II and He I line profiles to obtain the physical parameters of the plasma necessary for our study. The structure of the Ca II spectra is generally relatively simple and consists of a single emission line profile. Therefore, we fit the Ca II line with a single Gaussian profile (with a base line that accounts for stray light coming from the disk), using the following equation:

$$f(x) = a_0 \exp \left[ -\frac{(x - a_1)^2}{2a_2^2} \right] + a_3$$

(3)

with four degrees of freedom in the fit. Nonlinear least-square fit routines were used to find the best fit for these parameters, and the result is very good in over 80% of the spectra.

However, since the Ca II line counts were relatively low, at some pixels the noise led to problems in the fit. Hence, only those pixels in which the maximum number of counts on at least one spectral position was over five times the noise level were selected and fit. For this reason, we excluded about 39% of pixels where the prominence was not visible in Ca II in the field of view. Such locations appear as black in the upper left and middle panels of Figure 5. Multi-component profiles were also present at some time instants and locations which were produced by surges and jets. The single-component fit failed for the profiles where multi-component signals were clearly present. Such locations were identified and excluded from the analysis of velocities performed below.

Regarding the helium triplet line, we chose as a typical line profile a two-Gaussian mold with fixed spectral separation and the same width, and with a constant base line. The red components of the profile nearly overlap, and so we have used a single Gaussian profile instead of resolving them separately (as in, e.g., Stellmacher et al. 2003; Asensio Ramos et al. 2008). We have not imposed fixed relative amplitudes between the elements of the triplet, and therefore the ratio of the amplitudes of the blue and red components allows us to consider the opacity effects. Those effects are expected to be low for prominence material. The shape of the profile is then given by

$$f(x) = a_0 \exp \left[ -\frac{(x - a_1 + \Delta)}{2a_2} \right] + a_3 \exp \left[ -\frac{(x - a_1)}{2a_2} \right] + a_4,$$

(4)

with five degrees of freedom. The spectral separation ($\Delta = 1.219$ Å) was obtained as the difference between the average positions of the red and blue components, see Stellmacher et al. (2003). As mentioned above, the number of counts is much higher in the He I line than in the Ca II line. Virtually, we could find a significant signal in all areas of the prominence. Nevertheless, the complicated structure of the triplet implied that in those cases where more than one contribution was present, the least-square fit could not distinguish whether the signal had only one contribution or several of them (except in a few selected cases).

For both the Ca II and He I lines, the fits were weighted to provide more relevance to spectral points with higher counts, since we are more interested in the peak position for velocity determination.

In Figure 2, we have plotted some spectra for the He I and Ca II lines taken at the same position and time. We have overplotted the result of the best fit in red lines. The first pair (panels (a)) corresponds to a regular point where the single-component fit was very accurate; in this particular example, we can also check that both spectral lines are blueshifted. However, there are other spectra which show significant extra components in the red wing (panels (b) and (d)) or the blue wing (panels (e) and (f)) of Ca II. In cases such as those shown in panels (b) and (d), the velocity shift between the components is relatively mild, while in cases (e) and (f) it becomes more pronounced. In some rare instances, there are components that only appear in one of the lines, such as in panel (f), where there is a discernible contribution in the Ca II blue wing, but no
Figure 2. Pairs of spectra of the He I (left panels) and Ca II (right panels) lines for the six temporal and spatial locations along the slit shown in the panels. The red lines are the result of the single-component fit. The profiles correspond to the middle of the scan (position 5) for both spectral lines. Horizontal dashed lines mark the positions of the average line centers.
significant contribution in the HeI triplet, although the secondary peak is slightly higher. This is related to the fact that the HeI line is much wider than the CaII one and multiple components can be more easily distinguished in the latter case. There is also a prominent example of the contrary behavior, shown in panel (c) where the HeI line shows a clear multiple component structure, while the CaII signal is of low amplitude and asymmetric with a discernible low-amplitude red component in its wing. Nevertheless, in most of the cases, both lines show the same features, and thus we can conclude that the plasma emitting these lines has very similar dynamical properties. Even if secondary components are present, their amplitudes in the majority of the cases are very close to the noise level. The single-component fit is accurate enough in over 80% of the points.

While a single-component fit is acceptable in the cases shown in panels (a), (b), and (d) (with a somewhat larger width in cases (b) and (d)), profiles such as those shown in panels (c), (e), and (f) cannot be reliably handled with such a fit. Their spacetime location is related to a plasma ejection from the nearby active region which happens to overlap with the prominence.

2.3. Selection Criteria

Since in this work we are interested in reliably establishing the difference between the velocities of neutral and ionized atoms, we proceeded by discarding those spacetime locations where the velocities cannot be reliably measured. Besides disregarding those points where the amplitude of the signal was too low, we used the following additional criteria to identify such locations.

1. Locations where the width obtained after the fit is above 6 km s\(^{-1}\) in CaII line or above 12 km s\(^{-1}\) in HeI line. The line width above these values reveals the presence of multiple components separated in velocity but not spectrally resolved. We excluded 2% of the pixels due to this criterion.

2. Locations where the width obtained after the fit is below 1 km s\(^{-1}\) in the CaII line, since an extremely low line width indicates errors in the fit. We also used this criterion to select locations where the signal in both the CaII and HeI lines is reliably measured. This criterion coincides with the one based on the number of counts to identify the locations where the signal is above the noise in the CaII line. About 39% of pixels were excluded.

3. Locations where the amplitude of the blue-wing or red-wing signal in HeI is above a certain level. We choose as a reference wavelengths of 1.4 Å and −1.96 Å to the red and blue from the average line center position of the red component. The presence of a significant signal at these locations can be indicative of the existence of several components with large differences in velocities overlapping at the line of sight.

4. Locations where the ratio of the amplitudes of the blue and red components of HeI is above 0.24 or below 0.12. In optically thin plasma, this ratio should be exactly equal to 1/8 = 0.125. Larger values indicate that the plasma is not completely optically thin and lower values are not physically feasible. Since our aim is to measure the CaII and HeI velocities originating from the same plasma, we discarded the locations where the plasma becomes thicker than a certain threshold, which would introduce uncertainty concerning the location at which the signal in both lines originates. About 5.5% of points suffer from this kind of problem in our data. Most of them are coincident with the criterion based on the amplitude of the blue-wing or red-wing signal in HeI above.

Since in some of the pixels various items from the list above are present simultaneously, all in all we excluded about 44% of pixels. The last criterion is the most important in our analysis. Figure 3 shows the map of the ratio between the blue and red components of HeI, \(a_0/a_3\), see Equation (4). This image shows that the amplitude ratio varies around a mean value of about 0.18 for most of the prominence locations. The spatial variation of the ratio is in a narrow range, essentially remaining between 0.16 and 0.20. It indicates that the plasma in the observed prominence is very close to being optically thin with a very small spatial variation in opacity. One may also distinguish some isolated locations where the ratio is above 0.24 or below 0.12. Those locations are marked by red contours and are excluded from the analysis. The middle and right panels of Figure 3 show the map of the HeI signal in the red and blue wings, respectively. It can be seen that the locations with \(a_0/a_3 > 0.24\) coincide with those of the strong blueshifted signal (right panel) and those with \(a_0/a_3 < 0.12\) coincide with the redshifted signal (middle panel). This causes the last two criteria in the above list to be the same.
Figure 4. Correlation coefficient between the time-slit map of the Ca II velocities from the fifth scan position, and the corresponding time-slit maps of the He I velocities. The scan position of the He I velocities is given at the horizontal axis of the plot.

2.4. Errors of the Fit and Zero Velocity Reference

In order to evaluate the velocity errors associated with the fit, we proceed in the following manner. The proper nonlinear fitting routines provide a formal error for the fit of each of the free parameters in Equations (3) and (4). However, those errors are very small and do not provide a true evaluation of the uncertainty but a measure of the inaccuracy of the fitting procedure. We therefore assumed that the uncertainties of the velocity measurements are limited by the wavelength resolution of the observations. We adopted an upper estimate for such errors of half a pixel in wavelength. This gives us an uncertainty of ±0.29 km s$^{-1}$ in Ca II and ±0.15 km s$^{-1}$ in He I.

The wavelength calibration of the zero velocity position was achieved by comparing the averaged spectra of each of the lines to the FTS atlas and correcting for the velocity of solar rotation at the latitude of the observed prominence, as in Snodgrass (1984).

2.5. Differential Refraction

To be able to compare as accurately as possible the signal from the two lines, we need to take into account the differential refraction from Earth’s atmosphere. The setup of the campaign ensured that the data from the two spectral regions were taken simultaneously and with the telescopes pointing at the same place, but since both infrared lines have different wavelengths, they have a different refraction angle, and so the light entering the optical system of the telescope does not originate from the same position on the Sun. Because of the orientation of the slit during the observation, this effect was almost in the direction of the scan.

A direct calculation (using the time of day and the relative position of the Sun to the horizon) gives us a value of 0°3. Additionally, we have compared the images from the different scanning positions in order to find the best correlation between them. In Figure 4, we plot the correlation between the time-slit maps of velocities for different scanning positions. The best correlation is obtained when the He I map is taken at the previous scanning position (which is shifted 1.5 s in time), but the correlation is almost as good with the same position. This means that the differential refraction is present, but is below the size of the scanning step (0°3.5). Since both positions provide very similar results, for the rest of the paper we compare the results for the Ca II and He I lines at the same scanning positions because this implies no temporal shift.

3. RESULTS OF THE GAUSSIAN FIT

3.1. Plasma Parameters

We proceed to analyze the parameters resulting from the Gaussian fit. Figure 5 shows the time-slit maps of the amplitudes, widths, and displacements for the first scan position for both the Ca II (top) and He I (bottom) lines. Similar results are obtained for the rest of the scan positions. The contour lines (same in all panels) underline the locations selected under the criteria listed in Section 2.3. One can observe that the Gaussian amplitude, which can be used as a proxy of the density of the plasma, is quite uniform in the emitting regions, with some higher values in specific knots. The Doppler velocities show spatial and temporal correlations, with plasma flowing toward and away from us at a fixed slit position depending on the time instant.

The comparison between the time-slit maps shows that both lines originate from plasma with very similar dynamical conditions. The amplitudes of the lines (left panels) are coherent and show the same features, taking into account that the signal in the Ca II line was much lower, meaning that we could not fit it confidently in those points with lower counts. Regarding the line widths (middle panels), we also verify that there is good agreement between the lines, taking into account that the thermal width (assuming LTE emission) is related to the atomic number, so that the width of the Ca II line is related to the width of the He I line by a factor of $(m_{\text{Ca}}/m_{\text{He}})^{1/2} \approx 3.16$. However, the most striking similarity appears in the Doppler velocity (right panels) where the same features can be identified in both lines.

3.2. Dynamics of the Prominence and Nearby Plasma

There are several dynamical processes that were taking place during the observations of the prominence. The slit was crossing the body of the prominence, while at some moments the jets from the nearby active region were contaminating the line of sight.

3.2.1. Waves

One can see in Figure 5 that there is strong evidence of wave behavior in the observed signal. Since information about the magnetic field vector is not available, it is hard to infer the type of wave. Nevertheless, the wave parameters can be inferred rather reliably.

The wave main period of the waves is around 3 minutes. The 3 minute oscillations are present during almost all of the observations at all of the slit positions covering the prominence. The wavelength of the oscillations appears to be larger than the whole observed prominence (more than 60″), i.e., the whole body of the prominence is oscillating, although not necessarily in phase at all parts. The amplitude of oscillations reaches 3 km s$^{-1}$ and the oscillations appear to be slightly nonlinear. The oscillations continue without apparent damping during the entire observation, that is, for more than half an hour.
3.2.2. Active Region Jets

The active region close to the observed prominence showed some activity with jets and plumes sometimes coming from it and crossing the slit. Most of this activity was located in the other part of the slit which is not shown in Figure 5. However, in one instance, we found evidence of one of these jets in the spectral information where the prominence signal was also recorded. An example of such spectra is pair (c) from Figure 2. The spacetime evolution of the jet can be followed in Figure 5 at around 12 minutes and between 60″ and 70″. It can also be seen in the Hα slit-jaw images. The line-of-sight velocity component is almost zero at the onset of the jet, but it becomes much higher at later stages, reaching over 50 km s\(^{-1}\). The jet is clearly seen in the red wing, and it accelerates as time passes until its amplitude vanishes without slowing down or reversing the velocity sign.

4. DETECTION OF DRIFT VELOCITY

In this section, we compare in detail the velocities obtained from the He I and Ca II lines shown in Figure 5. We assumed that the Ca II line serves as a proxy of the movement of ionized species, while the He I line is related to neutral species. The drift velocity is defined as the difference between the velocity of both lines, \(w = v_{\text{Ca II}} - v_{\text{He I}}\).

Figure 6 provides examples of time and space cuts through the velocity maps from Figure 5 for both spectral lines. The upper panels of this Figure show that the match between the velocities of the lines is extremely good. Both lines follow each other closely and show the same displacements, with very little differences between them. Nevertheless, at the instants of extreme velocities (maxima and minima), there is some difference in the behavior of both lines, with the Ca II velocities being slightly larger. We could not find evidence that the difference between the Ca II and He I velocities follows the 3 minutes oscillations, as individual velocities do. The phase shift between the velocities of both lines is found to be around zero.

Similar behavior is also found when considering spatial variations at a fixed time (bottom panels of Figure 6). There, one may observe similar patterns for both lines with some hints that spatial variations of He I velocities are slightly smoother. This is particularly evident in the bottom right panel of Figure 6 where the gradients of the Ca II velocity are slightly more pronounced.

The left panel of Figure 7 shows the time-slit map of the drift velocity \(w = v_{\text{Ca II}} - v_{\text{He I}}\) for the same scan position as in Figure 5, which is obtained by directly subtracting the velocity maps from that figure. We set \(w\) artificially to zero at locations that do not satisfy the selection criteria outlined in Section 2.3.

Inspection of this figure confirms the conclusion already apparent from Figure 5, namely, that the difference between the Ca II and He I velocities is small in most of the locations, taking into account the error bars. However, patches of blue and red are distinct, showing regions where the drift velocities are nonzero. Typical values at those locations are in the range of \(±1\) km s\(^{-1}\). There are also patches where \(w\) is positive and above 2 km s\(^{-1}\) at the left border of the structure visible in the image. The inspection of the line profiles of both lines at these locations reveal that they have some asymmetry. The latter may be a consequence of the line-of-sight velocity gradient at these locations, affecting the velocity measurements by the method adopted in this paper.

The middle panel of Figure 7 shows the histogram of \(w\) over all of the selected locations of the time-slit map and all scans (solid line). The dotted line in the same figure is the histogram...
of the same quantity but with the opposite sign, shown for the purposes of highlighting the asymmetry of the distribution. It can be seen that the distribution of the relative velocity is slightly asymmetric, with its most probable value being slightly negative (i.e., He I velocity larger than Ca II velocity), but with a more extended tail toward the larger positive values (i.e., more locations where the Ca II velocity is significantly larger than He I velocity). This histogram confirms the impression from Figure 6 where we have observed that Ca II shows larger extreme values of the velocity compared to He I. The average value of $w$ over all locations is very close to zero.

We have verified whether or not the values of $w$ are affected by the opacity of the prominence material, i.e., if the difference in the Ca II and He I velocity originates because the lines are not formed at exactly the same location. The right panel of Figure 7 shows the bi-dimensional histogram of $w$ as a function of the ratio between the blue to red amplitudes of the He I profile, as an indicator of the opacity of the prominence. It reveals no dependence between both quantities. Therefore, we conclude that to first order, the presence of non-zero $w$ is not due to line formation effects.

We also checked whether there is a dependence between $w$ and any other line parameters, such as the Doppler width, amplitude, or displacement. The bi-dimensional histograms of the kind shown in Figure 7 reveal no such dependence for any of the quantities. Nevertheless, the locations with non-zero $V_{\text{Ca II}} - V_{\text{He I}}$ are not randomly distributed over time and space, but there is temporal and spatial coherence. The areas with non-zero $w$ cover about 2″ in space and have typical lifetimes around 1 minute.

Some of those areas may correspond to locations where jets contaminated the signal from the prominence in the field of view. Although we have tried to avoid those areas with multi-component profiles, it is still possible that the selection criteria...
used do not completely eliminate such locations. Nevertheless, at other locations, the one-component fit is reliable but $w$ is still non-zero. This is the case in most of the time-slit map.

We analyzed in more detail one of the regions in Figure 8 with a reliable one-component fit. The spectra in this area have no significant second components, and so the fits are quite reliable and the effect cannot be attributed to problems in the fit. The plots show that there is part of the prominence with patches of non-zero drift velocity distributed coherently both across the slit (with a typical size of about $2''-3''$) and in time (with lifetimes of about 1–2 minutes). The structures coherently evolve from one slit location to another. The fact that coherence is maintained only for short periods of time below one minute reinforces the necessity of high time and spatial resolution observations in order to reliably detect those drift velocities.

5. DISCUSSION AND CONCLUSIONS

In this paper, we have analyzed high temporal and spatial resolution observations of a prominence obtain simultaneously in an ionized Ca II line and a neutral He I line. Our analysis reveals that the structures observed with both lines are very similar, indicating that they both form in essentially the same plasma volume. The velocities obtained from both lines are also very similar. At the same time, we determined that there are small-scale and small-life-time transients where the balance between both velocities is broken and drift velocity is observed. The balance is usually lost at locations with large individual velocities or large spatial or temporal gradients. The magnitude of this drift velocity is below 1 km s$^{-1}$ in most of the locations where it is detected, and both positive and negative values of $w$ are measured, apparently unrelated to the dynamical processes (such as wave motions) that the prominence was undergoing during the time of observation. The patches with non-zero drift velocity are distributed coherently in time and space when carefully considering only cases with reliable one-component fit to the profiles. Large drift velocities are also detected at locations where some jet from the nearby active region overlaps the observed field of view. However, at those locations, multi-component profiles are typical for one or both spectral lines, and the one-component fit becomes less reliable. Those locations are nevertheless interesting and require further detailed investigation.

There are several effects that may be responsible for the appearance of the mismatch between the velocities of both spectral lines. As mentioned in the Introduction, in a partially ionized atmosphere, as collisions weaken, the ionized and neutral plasma components become partially decoupled. The drift velocity given by Equation (1) depends on currents, magnetic field, and partial pressure gradients of the species. Our finding from Figure 6 that the mismatch between the Ca II and He I velocities becomes more pronounced at locations with larger individual velocities and larger gradients may serve as confirmation that the detected drift velocities are due to physical decoupling of the components by partial ionization effects. The facts that the patches are coherent over space and time, are short-lived, and only occupy small areas also provide confirmation that the observed effects are due to some physical process rather than observational drawbacks. Numerical simulations of prominence instabilities by Khomenko et al. (2014b) show that similar amplitudes of the drift velocities are expected in the prominence-corona transition region.

Other explanations for the mismatch between the Ca II and He I velocities are also possible. One of the possible drawbacks of our approach is the uncertainty about the formation region of both spectral lines. The prominence material is frequently assumed to be optically thin. The ratio between the amplitudes of the blue and red components of the He I profile shows that the observed prominence plasma was indeed very close to being optically thin, with some slight variations of the opacity in space in time. However, we have found no correlation between the amplitude ratio of the He I components and the magnitude of the drift, see Figure 7. Figure 5 demonstrates that the amplitudes and widths of both lines are well correlated, taking into account the fewer counts in the Ca II line. Therefore, it can be concluded that the velocity signal measured by both lines originates at essentially the same locations over most of the observed prominence.

We were able to detect drift velocities due to the very high temporal resolution of our observations. If the signal were
integrated over larger intervals, then the effect apparent in Figures 6–8 would probably be lost or become much smaller. It is therefore expected that, if the resolution increases, the amplitudes of the ion-neutral velocity difference would become larger. In future work, it would be desirable to include more ionized and neutral spectral lines for the analysis in order to confirm the physical origin of the non-zero drift velocities measured in this work.

This work is partially supported by the Spanish Ministry of Science through projects AYA2010-18029, AYA2011-24808, and AYA2014-55078-P. This work contributes to the deliverables identified in FP7 European Research Council grant agreement 277829, “Magnetic connectivity through the Solar Partially Ionized Atmosphere.” The authors also thank Drs. M. Luna, R. Oliver, and M. Zapior for discussions.

REFERENCES

Alexander, C. E., Walsh, R. W., Régnier, S., et al. 2013, ApJL, 775, L32
Arber, T. D., Haynes, M., & Leake, J. E. 2007, ApJ, 666, 541
Arregui, I., Oliver, R., & Ballester, J. L. 2012, LRSP, 9, 2
Asensio Ramos, A., Trujillo Bueno, J., & Landi Degl’Innocenti, E. 2008, ApJ, 683, 542
Balescu, R. 1988, Transport Processes in a Plasma (Amsterdam: North-Holland)
Banerjee, D., Erdélyi, R., Oliver, R., & O’Shea, E. 2007, SoPh, 246, 3
Berger, T., Testa, P., Hillier, A., et al. 2011, Natur, 472, 197
Berger, T. E., Shine, R. A., Slater, G. L., et al. 2008, ApJL, 676, L89
Berger, T. E., Slater, G., Hurbury, N., et al. 2010, ApJ, 716, 1288
Bittencourt, J. A. 1986, Fundamentals of Plasma Physics (Oxford: Pergamon) Braginskii, S. I. 1965, in Transport Processes in Plasma, ed. M. A. Leontovich (New York, USA: Consultants Bureau)
Cally, P. S., & Khomenko, E. 2015, ApJ, 814, 106
Chae, J. 2007, AdSpR, 39, 1700
Khomenko, Collados, & Díaz

Chae, J., Ahn, K., Lim, E.-K., Choe, G. S., & Sakurai, T. 2008, ApJL, 689, L73
Chae, J., Moon, Y.-J., & Park, Y.-D. 2005, ApJ, 626, 574
Collados, M., Lagg, A., Díaz García, A. J., et al. 2007, in ASP Conf. Ser. 368, The Physics of Chromospheric Plasmas, ed. P. Heinzel, I. Dorotović, & R. J. Rutten (San Francisco, CA: ASP), 611
Díaz, A. J., Khomenko, E., & Collados, M. 2014, A&A, 564, A97
Díaz, A. J., Soler, R., & Ballester, J. L. 2012, ApJ, 754, 41
Heinzel, P., Schmieder, B., Färnik, F., et al. 2008, ApJL, 686, 1383
Isobe, H., Miyagoshi, T., Shibata, K., & Yokoyama, T. 2005, Natur, 434, 478
Khomenko, E., & Collados, M. 2012, ApJL, 747, 87
Khomenko, E., Collados, M., Díaz, A., & Vitas, N. 2014a, PhP, 21, 092901
Khomenko, E., Collados, M., Shchukina, N., & Díaz, A. 2015, A&A, 584, A66
Khomenko, E., Díaz, A., de Vicente, A., Collados, M., & Luna, M. 2014b, A&A, 565, A45
Leake, J. E., Lukin, V. S., Linton, M. G., & Meier, E. T. 2012, ApJL, 760, 109
Lin, Y., Engvold, O., Roupe van der Voort, L., Wiik, J. E., & Berger, T. E. 2005, SoPh, 226, 239
Lin, Y., Engvold, O. R., & Wiik, J. E. 2003, SoPh, 216, 109
Mackay, D. H., Karpen, J. T., Ballester, J. L., Schmieder, B., & Aulanier, G. 2010, SSRv, 151, 333
Neckel, H., & Labs, D. 1984, SoPh, 90, 205
Oliver, R. 2009, SSRv, 149, 175
Oliver, R., & Ballester, J. L. 2002, SoPh, 206, 45
Parenti, S. 2014, LRSP, 11, 1
Rees, D. E., López Ariste, A., Thatcher, J., & Semel, M. 2000, A&A, 355, 759
Ryutova, M., Berger, T., Frank, Z., Tarbell, T., & Title, A. 2010, SoPh, 267, 75
Schmieder, B., Raadu, M. A., & Wiik, J. E. 1991, A&A, 252, 353
Snodgrass, H. B. 1984, SoPh, 94, 13
Socas-Navarro, H., López Ariste, A., & Lites, B. W. 2001, ApJ, 553, 949
Soler, R., Díaz, A. J., Ballester, J. L., & Goossens, M. 2012, ApJ, 749, 163
Soler, R., Oliver, R., & Ballester, J. L. 2010, A&A, 512, A28
Soltau, D., Berkefeld, T., von der Lühe, O., Wöger, F., & Schelenz, T. 2002, AN, 323, 236
Stellmach, G., Wiehr, E., & Dammusch, I. E. 2003, SoPh, 217, 133
Tripathi, D., Isobe, H., & Jain, R. 2009, SSRv, 149, 283
Zaqarashvili, T. V., Carbonell, M., Ballester, J. L., & Khodachenko, M. L. 2012, A&A, 544, A143
Zirker, J. B., Engvold, O., & Martin, S. F. 1998, Natur, 396, 440