STATISTICAL PROPERTIES OF THE DISK COUNTERPARTS OF TYPE II SPICULES FROM SIMULTANEOUS OBSERVATIONS OF RAPID BLUESHIFTED EXCURSIONS IN Ca α 8542 AND Hα

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ABSTRACT

Spicules were recently found to exist as two different types when a new class of so-called type II spicules was discovered at the solar limb with the Solar Optical Telescope on board the Hinode spacecraft. These type II spicules have been linked with on-disk observations of rapid blueshifted excursions (RBEs) in the Hα and Ca α 8542 lines. Here we analyze observations optimized for the detection of RBEs in both Hα and Ca α 8542 lines simultaneously at a high temporal cadence taken with the Crisp Imaging Spectropolarimeter at the Swedish Solar Telescope on La Palma. In this study, we used a high-quality time sequence for RBEs at different blueshifts and employed an automated detection routine to detect a large number of RBEs in order to expand on the statistics of RBEs. We find that the number of detected RBEs is strongly dependent on the associated Doppler velocity of the images on which the search is performed. Automatic detection of RBEs at lower velocities increases the estimated number of RBEs to the same order of magnitude expected from limb spicules. This shows that RBEs and type II spicules are indeed exponents of the same phenomenon. Furthermore, we provide solid evidence that Ca α 8542 RBEs are connected to Hα RBEs and are located closer to the network regions with the Hα RBEs being a continuation of the Ca α 8542 RBEs. Our results show that RBEs have an average lifetime of 83.9 s when observed in both spectral lines and that the Doppler velocities of RBEs range from 10 to 25 km s\(^{-1}\) in Ca α 8542 and 30 to 50 km s\(^{-1}\) in Hα. In addition, we automatically determine the transverse motion of a much larger sample of RBEs than previous studies, and find that, just like type II spicules, RBEs undergo significant transverse motions of the order of 5–10 km s\(^{-1}\). Finally, we find that the intergranular jets discovered at Big Bear Solar Observatory are a subset of RBEs.

Key words: Sun: atmosphere – Sun: chromosphere – Sun: corona

1. INTRODUCTION

Observing the chromosphere at the solar limb, a great number of thin jet-like features called spicules can be seen protruding outward from the limb. While spicules have been known and studied for a long time (for an extensive overview, see Beckers 1968; Sterling 2000), progress in understanding their nature has been relatively modest. However, interest in this phenomenon has revived considerably in recent years. The seeing-free environment and aperture of sufficient size for high spatial resolution allowed the Hinode satellite to provide an unprecedented view of the solar limb in the form of high temporal resolution, long-duration time series of Ca α H α filtergrams. From these observations, a new class of spicules was discovered (De Pontieu et al. 2007) that is characterized by short lifetimes (typically 10–100 s), vigorous dynamics, and exclusively upward motion (50–150 km s\(^{-1}\)). Their nature is quite different from what are now considered as classical spicules, or type I spicules, which have lifetimes from 5 to 10 minutes and display clear rise and downfall phases at more modest velocities (20–30 km s\(^{-1}\)). The characteristic sideways swaying motion that this newly identified class (or type II spicules) displays has been regarded as a sign that the chromosphere is permeated with Alfvénic waves of sufficient energy to accelerate the solar wind and potentially heat the quiet corona (De Pontieu et al. 2007). Later studies have further strengthened the conjecture that type II spicules have an important role in mass loading and heating of the corona (De Pontieu et al. 2009, 2011).

The driving mechanism behind type I spicules seems to be well understood. Type I spicules have been identified as the off-limb manifestation of what is known as dynamic fibrils in active regions on the disk. The observations and modeling of De Pontieu et al. (2004), Hansteen et al. (2006), and De Pontieu et al. (2007) demonstrated that dynamic fibrils are driven by magnetoacoustic shocks that result from flows and waves that leak along magnetic field lines from the photosphere into the chromosphere. A similar mechanism is responsible for driving part of the quiet Sun mottles (Rouppe van der Voort et al. 2007), which helps explain why type I spicules can be detected in both active regions and the quiet Sun.

In contrast to type I spicules, the formation and driver of type II spicules is not well understood and is still under debate. Martínez-Sykora et al. (2011) describe in detail the formation of what resembles a type II spicule in their three-dimensional radiative magnetohydrodynamics simulation. The simulated jets show similarities to type II spicules in that rapid ejection of cool chromospheric plasma into the corona occurs while it is being heated to temperatures that are high enough to cause apparent fading in typical chromospheric diagnostics. In the simulation, small-scale flux emergence leads to chromospheric plasma being accelerated by a strong, mostly horizontal, Lorentz force into a region of a very strong vertical magnetic field. The subsequent increase in gas pressure induces the ejection of plasma into the low-density corona while being heated to coronal temperatures by heating processes at the footpoint.

While this scenario is tantalizing, further modeling is required in order to firmly establish the physics behind type II spicules. Perhaps more importantly, high-quality observations are essential in order to constrain the models and guide the direction of investigation. A complicating factor here is that due to their narrow spatial extents, short lifetimes, and significant displacement, as well as the superposition of many spicules along the line of sight, spicules are notoriously difficult to properly...
measure at the limb. Finding the disk counterparts of type II spicules makes it possible to separate them spatially and overcome the problem of superposition encountered at the limb.

Langangen et al. (2008) investigated so-called “rapid blueshifted excitations” (RBEs) in on-disk Ca ii 8542 data obtained with the Interferometric Bidimensional Spectrometer at the Dunn Solar Telescope. In their data, events with short-lived blueward asymmetries of the Ca ii 8542 line were tentatively linked to type II spicules. Rouppe van der Voort et al. (2009, Paper I) used high-quality Hα and Ca ii 8542 observations from the Crisp Imaging Spectropolarimeter (CRISP) at the Swedish Solar Telescope (SST) to make a firm connection between these RBEs and type II spicules. They found a large number of RBEs for which properties such as lengths, velocities, and lifetimes were found to agree well with what was measured for type II spicules. In addition, the appearance, including both swaying motions and apparent propagation away from magnetic field concentrations in the photosphere, was considered a clear indication that RBEs are the disk counterpart of type II spicules.

Recently, Judge et al. (2011) challenged the identification of RBEs as type II spicules by arguing that the global occurrence rate of RBEs as inferred from the Paper I measurements is too low. In this work, we further investigate the occurrence rate of RBEs in new high-quality CRISP observations as well as the observations used in Paper I. For the new observations, we employed a dual-line program that provides both spectrally well-sampled Ca ii 8542 and Hα profiles at relatively high temporal cadence. This program allows for a direct comparison between RBEs measured in Ca ii 8542 and Hα, a comparison that could only be done indirectly from the sequentially recorded data sets used in Paper I. Furthermore, we expand on previous results (from Paper I) by extending the automated detection routine for RBEs so that we can automatically determine lifetimes and transversal motion for a much larger statistical sample than in Paper I.

2. OBSERVATIONS AND DATA REDUCTION

The data was obtained from observations at SST (Scharmer et al. 2003a) on La Palma using the CRISP (Scharmer et al. 2008) instrument. CRISP is equipped with a dual Fabry–Pérot interferometer (FPI) system and three high-speed low-noise CCD cameras. These cameras operate at a frame rate of 35 frames per second with an exposure time of 17 ms per frame and are synchronized by an optical chopper. Two of the cameras are positioned behind the FPI and a polarizing beam splitter, while the third camera, which is used as an anchor channel for image processing, is positioned before the FPI but after the CRISP pre-filter and is referred to as the wideband channel. The field of view (FOV) with the CRISP instrument is roughly 61 × 61 arcsec with an image scale of 0′′0592 pixel−1. CRISP allows for fast wavelength tuning (<50 ms) between any two positions within a spectral region given by the spectral width of the pre-filter, which makes it ideal for studies of the dynamic time evolution of the chromosphere through imaging spectroscopy. Here we are interested in the Hα and Ca ii 8542 spectral lines. For Hα, CRISP has a transmission FWHM of 66 mÅ and a pre-filter FWHM of 4.9 Å. For Ca ii 8542, the transmission FWHM is 111 mÅ and pre-filter FWHM is 9.3 Å. High spatial resolution down to the telescope diffraction limit (λ/D = 0′′14 and 0′′18 for Hα and Ca ii 8542, respectively) is accomplished by the use of the SST adaptive optics system (Scharmer et al. 2003b) and the Multi-Object, Multi-Frame Blind Deconvolution image restoration technique (MOMFBD; van Noort et al. 2005).

A 38 minute data set obtained on 2010 June 27 (17:35–18:13 UT) has been analyzed. The target area was a coronal hole with a unipolar magnetic island, at solar coordinates (x, y) ≈ (−70′′, 508′′), (μ = 0.84). Figure 1 gives an overview of the target region.

The observational program was made specifically for the detection of RBEs in Ca ii 8542 and Hα, simultaneously, with a rather high cadence so that the time evolution of RBEs could be resolved properly. The pre-filter wheel limited the amount of dead time to 0.63 s when switching between the two lines. For the Ca ii 8542 line, we ran a program with symmetric sampling at seven positions in each of the two wings, from ±120 to ±1452 with steps of 222 mÅ. In addition, we observed the line core and the blue wing at −600 mÅ with modulation of the liquid crystals with the purpose of obtaining photospheric magnetograms. For Hα we ran a program with dense sampling of 28 positions in the blue wing, from −300 mÅ to −2082 mÅ with steps of 66 mÅ. More detailed information on the sampling positions and their respective Doppler velocities can be seen in Figures 2(d) and (c), respectively. This program was based on our experiences from Paper I and specifically designed to simultaneously detect RBEs in both lines. RBEs are detected in Ca 8542 in Doppler maps constructed from the subtraction of symmetric positions from the line center, and in Hα in maps constructed from the subtraction of the far blue wing image from positions closer to the line center. The program is sufficiently fast (11.8 s cadence) to allow for temporal analysis of RBEs. The symmetric sampling of the Ca 8542 line allows for verification that the detected events are indeed asymmetric in the blue wing, which is the defining characteristic of RBEs.

We acquired 8 exposures per line position, which were used for MOMFBD image restoration (van Noort et al. 2005). Exposures from each spectral line were processed in separate MOMFBD restorations. Precise alignment between the wideband and narrowband cameras is achieved by a separate alignment procedure involving a reference pinhole array target. For the MOMFBD restoration of the sequentially recorded CRISP images, the wideband channel serves as a so-called anchor channel that ensures accurate alignment between the different line positions. For certain seeing conditions, the assumption of the size of the isoplanatic patch used to divide the FOV in subimages (here 128 × 128 pixels, or 7′′6 squared) is not sufficiently accurate and the derived point-spread function (PSF) is not the optimal solution over the whole area of the subimage. This results in remaining rubber sheet deformations between the CRISP line positions in a single restoration. To reduce this effect, we employed an extra step in the processing following an idea from VMJ. Henriques (2011, private communication). The wideband images are used twice in a restoration: (1) all images combined in the normal way resulting in a single restored “anchor” image and (2) separated in sets associated with the corresponding CRISP line positions resulting in one restored wideband image per CRISP line position. Even though individual wideband exposures enter twice in the restoration procedure, they are only used once for the determination of the PSF. For the use of the wideband images separated in sets per CRISP line position, the weight is put to zero for the wavefront sensing. The separately restored wideband images have the same rubber sheet deformations as the corresponding CRISP line positions, which can now be accurately measured by cross-correlation to the anchor wideband images. The deformation grid determined from the wideband images is then applied to the CRISP images, which results in precise alignment between the different line positions.
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Figure 1. Overview of the observed target area. (a) H$\alpha$ line core image. (b) Ca$\text{ii}$ 8542 line core image with overplotted in rainbow color scale a density map of identified RBEs detected at $-20$ km s$^{-1}$ over the whole time series. (c) H$\alpha$ wideband image (FWHM = 4.9 Å CRISP pre-filter) with overdrawn temporally resolved RBEs that are identified in both Ca$\text{ii}$ 8542 and H$\alpha$: the Ca$\text{ii}$ 8542 RBEs are drawn in red, the H$\alpha$ RBEs are green, and the region where they overlap is yellow. (d) Ca$\text{ii}$ 8542 $-600$ mÅ Stokes V image in gray color scale with a density map overplotted of the number of identified RBEs detected in H$\alpha$ at $-45$ km s$^{-1}$ during the whole time series.

The data analyzed in this study benefited significantly from this extra step in the processing.

After the MOMFBD restoration the images from the individual line scans were combined to form a time series and the Ca$\text{ii}$ 8542 images in each scan were aligned with respect to the H$\alpha$ images from the same time step. This alignment between the two lines was done using the wideband images which show photospheric scenes for both spectral lines so that the alignment is done with high accuracy. The images from both lines were then de-rotated to account for diurnal field rotation, aligned and de-stretched to remove warping due to seeing effects by determining local offsets on the wideband images and applying these to the CRISP images.

For the Ca$\text{ii}$ 8542 $-600$ mÅ magnetograms, all 32 exposures of the four different liquid crystal states were included in a single MOMFBD restoration, following the scheme described by van Noort & Rouppe van der Voort (2008) and Schnerr et al. (2011). For the polarimetric response of the telescope at 8542 Å, we used the model derived by de la Cruz Rodríguez (2010; also see de la Cruz Rodríguez & Socas-Navarro 2011). With the 17 ms exposure time, the effective acquisition time for the resulting Stokes V magnetogram is 544 ms. The noise
level is estimated at 0.14% of the continuum. It should be noted that at $-600$ mÅ, the Ca $\alpha$ 8542 magnetogram is dominated by photospheric signals and is not affected by strong Doppler shifts. Strong Doppler shifts make single wavelength magnetograms closer to the line core, which are more photospheric in nature, difficult to interpret. Furthermore, it should be noted that the Ca $\alpha$ 8542 line is less sensitive to polarization than for example more traditional diagnostics, like the Fe $\alpha$ 630 lines. In addition, the wavelength position used here, $-600$ mÅ, is relatively less sensitive to polarization than positions closer to the line core. All these factors combine to a rather limited diagnostic value of the magnetograms used in this study, in particular for the weak magnetic field environment of the coronal hole observed here: the strongest signals barely reach 1% polarization. Despite these limitations, the magnetograms serve as a reliable indicator of the position and polarity of the strongest magnetic field concentrations. These concentrations appear as photospheric bright points in continua and in the far wings of the spectral lines studied here.

We acquired another high-quality data set with the same observing program during the 2010 SST observing campaign: on 2010 July 3, we observed a coronal hole at $(x, y) \approx (19, 862)$ ($\mu = 0.41$) for 45 minutes. In this paper, we present results from the analysis of the 2010 June 27 data set but the 2010 July 3 data set is used as a reference to verify and check our results and conclusions.

3. METHOD

The data set was searched for RBEs in the Ca $\alpha$ 8542 and H$\alpha$ lines separately, where they appear in the spectral wings as roundish or elongated dark absorption features against the photospheric background. An automated algorithm that locates RBEs by isolating the location and time of a long thin feature at high blueshifts was used to find a large number of RBEs in both data sets and both spectral lines in order to get reliable RBE statistics. Apart from some minor refinements, the method is identical to the method used for Paper I.

To make a clean detection of the upper chromospheric RBEs, the background, which often contains linear photospheric features (such as intergranular lanes), has to be reduced or removed from the images. For Ca $\alpha$ 8542 this is done by subtraction of the opposite wing position, thereby constructing a Doppler map, and for H$\alpha$ this is done by subtracting the far blue wing image, at 2 Å, creating a difference image. To minimize the number of false detections, a lower limit for the length of blueshifted structures is set at $\sim 725$ km, 17 pixels, and any thin blueshifted feature with a length below this threshold is not counted. Like in Paper I, we find that this length threshold limits the probability of false detections significantly. A shorter length threshold allows small linear features in intergranular lanes to enter the sample, which upon further scrutiny do not display the typical spectral character of RBEs. The output of the automated algorithm contains every detected event in every time frame, and it also attempts to connect these single events over several time frames by making chains of events, which represents the time evolution of an RBE over several time steps. If an event from one time frame has 30% of its pixels within a 3 pixel distance from any pixel in an event from the next time frame, these two events are considered to be the same RBE observed at different stages in its time evolution. Because the lengths of events may vary greatly from frame to frame, the check has to be done in both temporal directions as the following event, which is supposed to link up with the current event, might be shorter than 30% of the current event’s length. In this case, even if the following event lies completely on top of the current event, it would not be recognized as a valid link, while when performing the check “backward” there is a 100% overlap and the link is approved. This check is performed on all events in a time frame using all the events from the next time frame and also the frame after that, meaning that it allows for a jump in the chain of one time step, thus accounting for occasional moments of bad seeing. This automated method of connecting RBEs in time is an improvement compared to Paper I, where the lifetimes of RBEs were estimated manually by looking at a subset of 35 separate events and following their existence in following time steps.

Having the chains made automatically gives a large sample from which one can study the time evolution and produce accurate statistics of the typical lifetimes of RBEs. The cases where RBEs are connected in chains are also less likely to be false
detections, as it would take errors to occur very close together spatially and temporally. When it comes to the selection threshold for determining the temporal connection in chains, the threshold values were chosen based on trial and error. Allowing for events to be further away from one another introduces a significant number of wrong connections, particularly in the regions where the RBE detections are densest, and by constraining the percentage of pixels that has to be within the selected distance, too many good connections are disallowed. We found that the chosen parameters resulted in the most reliable statistics.

Once the chains are found, these can be used to get a measure of the transverse displacement and velocity. This is achieved by finding the average orientation of all events in a chain and determining its perpendicular direction. The transverse distance is then measured by taking the middle point of each event and projecting it onto the normal, which allows for both a measurement of the distance traversed transversally from one event to the next and also the velocity at which the RBE is moving transversally as we know the time difference between the two events. As explained above, there is an upper limit of 3 pixels on the spatial separation between RBEs in subsequent time frames. Combined with the cadence of 11.8 s, one would expect to have an upper limit for the transverse velocity of 11 km s\(^{-1}\). However, this is not the case since the transversal displacement is measured from the RBE midpoints along the normal to the average direction of the RBE and this can give a larger separation than 3 pixels.

We have made extensive use of CRISPEX (Vissers & Rouppe van der Voort 2012) a widget-based analysis tool programmed in the Interactive Data Language (IDL) that allows for an efficient exploration of multi-dimensional data sets. With CRISPEX, the \(\text{H}_\alpha\) and \(\text{Ca}^{\text{II}}\ 8542\) data sets can be examined at the same time and the tool was particularly useful for the verification of the RBE identifications from the automated detection method.

Figure 2 shows details of one RBE event, clearly identified in both \(\text{H}_\alpha\) and \(\text{Ca}^{\text{II}}\ 8542\). Panels (e) and (f) show the RBE as dark streaks against a background of granulation in \(\text{H}_\alpha\) and inverse granulation in \(\text{Ca}^{\text{II}}\ 8542\). For the spatial locations marked with asterisks, the spectral time evolution is shown in the top panels. This particular RBE displayed little sideways motion so that a single pixel location shows the actual spectral evolution of the RBE. These panels illustrate the defining characteristic of RBEs: a short-lived asymmetry in the blue wings of these strong absorption lines. The bottom panels show the maps used in the automated detection process: in \(\text{H}_\alpha\) the disturbing background is attenuated by subtraction of the corresponding far blue wing image. Through this subtraction, the granulation intensity pattern is inverted so that intergranular lanes, narrow linear features, become bright. Our detection method is based on the negative of this difference images and searches for bright linear structures, removing the risk of intergranular lanes becoming false detection as these are now dark. In \(\text{Ca}^{\text{II}}\ 8542\), a Doppler map is used and RBEs are identified as bright linear structures against a low-contrast background. The detected structures are marked as thin black lines. Panels (c) and (d) show the detailed spectra at the time and location of the asterisks in panels (e) and (f) as solid lines. To separate the RBE spectral profile from the background profile, a reference spectrum constructed from averaging over the whole FOV is subtracted, resulting in the dashed profile. This RBE profile is clearly a blueshifted component separated from the background spectrum, a characteristic that is also apparent from its dynamical evolution, which appears to be unrelated to the chromospheric background seen closer to line center. The RBE profile is used to determine the Doppler velocity and Doppler width, following the method of Paper I. For this location in the RBE, the \(\text{H}_\alpha\) Doppler velocity is 39 km s\(^{-1}\) and width 16 km s\(^{-1}\), the \(\text{Ca}^{\text{II}}\ 8542\) Doppler velocity is 23 km s\(^{-1}\) and width 13 km s\(^{-1}\).

The length of an RBE was determined using the same method as Paper I: by first extending the detection skeleton (the thin black line in panels (g) and (h) outlining the detected event) by 20 pixels in both directions and dilation in width and then determining the points where either the Doppler velocity or Doppler width of the RBE profile is 0. This definition is equivalent to measuring the length for which a feature shows enhanced absorption compared to the average spectral profile. Hence, detected events have a possibility of becoming shorter than the minimum length threshold set by the detection routine since the measured Doppler width can become 0 even though there is signal in the detection map.

4. RESULTS

4.1. Number of RBE Detections

We found that the number of RBE detections varies significantly with the Doppler velocity from which the detection maps are constructed. Figure 3 shows histograms for the number of detected events as a function of the Doppler velocity in the detection map. For both spectral lines, we see a significant increase in the number of detected events for lower Doppler velocities. This trend is most pronounced for \(\text{H}_\alpha\), however, revealed a high fraction of false RBEs. For \(\text{Ca}^{\text{II}}\ 8542\) we see a raise in the number of detected events from 346 at 35 km s\(^{-1}\) to 4116 at 12 km s\(^{-1}\). We manually verified a large subsample of the events detected at 30 km s\(^{-1}\) and we confirmed that almost all events are genuine RBEs. For \(\text{Ca}^{\text{II}}\ 8542\) we see a raise in the number of detected events from 346 at 35 km s\(^{-1}\) to 4116 at 12 km s\(^{-1}\). Manual inspection at 12 km s\(^{-1}\), however, revealed a high fraction of false identifications. We conclude that this line position cannot be trusted for the automated detection of RBEs. For the remainder of this paper, we present results from \(\text{Ca}^{\text{II}}\ 8542\) RBEs detected at 20 km s\(^{-1}\), where we find the highest number of detections (2717 events). For \(\text{H}_\alpha\), we present results from RBEs detected at 45 km s\(^{-1}\) (2099 events), which gives a sample of similar size.
as for Ca II 8542. This choice is rather arbitrary since we regard all Doppler velocities reliable for RBE detection. We found it practical to have similar sample sizes for the two lines for the process of linking up the Hα and Ca II 8542 RBEs.

The right axis scaling of Figure 3 gives an estimate of the total number of RBEs at any time on the Sun. This estimate is derived from the average number of detections per time step extrapolated to the whole surface of the Sun.

4.2. Statistical Properties of RBEs

Figure 1(d) shows a density map of the spatial locations of the 2099 Hα RBEs detected at 45 km s$^{-1}$ drawn on a Stokes V magnetogram. Most RBEs are found around the patch of unipolar magnetic field in the upper right part of the FOV, the region that is dominated by fibril structures in the line core images and bright points in the wideband image. There is another notable concentration of RBE detections below the center which is associated with a small concentration of enhanced Stokes V signal, and another smaller concentration to the left edge of the FOV. Besides these RBE concentrations there are a number of isolated RBEs scattered over the FOV that are not obviously associated with patches of Stokes V signal. As explained in Section 2, the diagnostic potential of the Ca II 8542 –600 mÅ magnetograms is rather limited and it is very conceivable that a more sensitive polarization diagnostic would reveal an association of the more isolated RBE signals with areas of enhanced polarization.

Of the 2099 Hα events, 498 were detected only in one time frame, while the rest linked up to other events in nearby time frames to create a total of 453 RBEs existing over several sequential time steps. We will call the events that could not be linked up with events in other time steps “single-frame RBEs,” and the others “multi-frame RBEs.”

The map of Ca II 8542 events (Figure 1(b)) shows a similar distribution of most RBEs being associated with the magnetic field concentrations and a number of events scattered over the FOV. Of the 2717 Ca II 8542 events, 827 were single-frame events, and the rest were linked up as 507 temporally resolved or multi-frame RBEs.

Most of the multi-frame and single-frame RBEs were located in regions with enhanced polarization signal, and of the isolated RBEs that lie scattered over the FOV, the majority are single-frame RBEs, as can be derived from Figures 1(b) and (d).

For each individual detected event the Doppler velocities and Doppler widths were calculated at each pixel in an event. The position of the pixels and time frame in which they were found used for a measure of lengths and lifetimes of the RBEs.

Figures 4 and 5 display histograms of all the important properties of the 1890 and 1601 events that were found to make up 507 and 453 multi-frame RBEs in Ca II 8542 and Hα, respectively. The single-frame events are not included in this statistic as they lack time evolution, and thus cannot contribute to some of the histograms, such as transverse motions.

In panel (a) of Figure 4 the lengths of all events are shown for both Ca II 8542 and Hα. Typically, the Hα RBEs are found to have lengths of 2–6 Mm, with an average of 3.5 Mm, while the Ca II 8542 RBE lengths are seen to lie between 1.5 and 4.5 Mm with an average of 2.9 Mm. A few Ca II 8542 RBEs were found to have lengths shorter than the detection threshold of 725 km,
Figure 5. Histograms for measurements of the transverse motion of RBEs: (a) maximum transverse displacement or distance between the two most extreme positions during the lifetime of an RBE, (c) maximum transverse velocity of all measured velocities during the RBE lifetime, and (d) all measured transverse velocities over all time steps. The scatter plot in panel (b) shows the total transverse distance covered by an RBE during its lifetime against the maximum transverse displacement of (a). The solid line marks the line where the two measures are equal, and the dotted line marks where the total transverse displacement is 50% larger than the maximum transverse displacement.

which is possible since the method of measuring the RBE length is different from the RBE detection (see Section 3). No short Hα RBEs were found and we see a sharp lower cutoff at 2 Mm.

Panel (b) of Figure 4 shows the average Doppler velocity of all RBEs. The average RBE Doppler velocities lie between 10 and 25 km s⁻¹ for Ca ii 8542 and 30 and 50 km s⁻¹ for Hα, with the mean value of the distribution of average Doppler velocities at 17.7 and 36.8 km s⁻¹, respectively. The maximum of all Doppler velocity measurements is as high as 50 km s⁻¹ for Ca ii 8542 and 62 km s⁻¹ for Hα.

Panel (c) of Figure 4 shows the average Doppler width of all RBEs. As for the Doppler velocity, the Doppler widths are noticeably different in Ca ii 8542 and Hα with averages of 10 km s⁻¹ and 15.3 km s⁻¹, respectively, and the range going from 0 to 17 km s⁻¹ in Ca ii 8542, while Hα RBEs display Doppler widths from 7 to 23 km s⁻¹.

Panel (d) of Figure 4 shows the lifetimes of the RBEs. There is no major difference between the lifetime of Ca ii 8542 and Hα RBEs and they both have lifetimes varying from 24 s up to 2.5 minutes. There were a few detections of very-long-lived RBEs with lifetimes of more than 3 minutes. They were all found in regions with a high density of RBEs and visual inspection exposed these events as falsely connected chains of several separate multi-frame RBEs.

Figure 5 show different measures of the transverse motion of RBEs. Panel (a) shows a histogram of the maximum transverse displacement, which is the distance between the two most extreme transverse positions of an RBE during its lifetime. All RBEs have some transverse displacement and several of the RBEs display transverse displacements of more than 400 km. The scatter plot in panel (b) shows the integrated transverse displacement, or the sum of the absolute values of each displacement during the RBE lifetime, against the maximum transverse displacement. The dotted line marks where the integrated transverse displacement is 50% larger than the maximum transverse displacement. The RBEs that lie above this line display considerable back-and-forth swaying motion during their lifetime. The RBEs that lie close to the solid line are mainly moving in one direction. Panel (c) shows the maximum transverse velocity for each RBE and panel (d) shows all measured transverse velocities. Transverse motions can be at velocities as high as 20 km s⁻¹ although most events' velocities lie below 15 km s⁻¹ with the bulk of the peak velocities around 5 km s⁻¹.

We observe many RBEs displaying back-and-forth sideways swaying motion during their lifetimes. For all of the RBEs that have a duration of more than two time steps, we measured how many times there is a change in direction. We found that for both Hα and Ca ii 8542 RBEs, the change in direction happens an average of 1.7 times during their lifetime.

Figure 6 shows the variation of the Doppler velocity and Doppler width for RBEs along their length as color-coded lines.
Figure 6. Doppler properties of RBEs as a function of their position in the FOV. Hα RBEs at left, Ca ii 8542 RBEs at right. Color-coded Doppler velocities (top panels) and Doppler widths (bottom panels) drawn on background images of (a) Hα line center, (b) Ca ii 8542 line center, (c) Hα wideband, and (d) Ca ii 8542 –20 km s\(^{-1}\) detection map.

drawn at their spatial location in the FOV. All detected RBEs are drawn in successive order, with RBEs detected early in the time series drawn first so that they are covered by later RBEs that occur at the same spatial location. The RBE occurrence in the target area is dominated by the magnetic region, which gives a clear sense of the orientation of the RBEs and where they originate. This representation gives a clear visual impression of many RBEs increasing in both Doppler velocity and Doppler width toward their top. This trend is most clear for the Hα RBEs. It should be noted that despite the visual trend, there is a significant number of RBEs that have a more erratic variation of Doppler properties along their axis and even examples of decreasing trends.

There is a clear correlation between increased Doppler width for increasing Doppler velocity; this is illustrated in Figure 7.

4.3. The RBE Ca ii 8542–Hα Connection

From the initial detection of 2717 and 2099 events in Ca ii 8542 and Hα, respectively, a total of 1890 and 1601 events

Figure 7. Scatter plot of average Doppler width vs. average Doppler velocity of all RBEs, represented as a two-dimensional density function. Darker regions represent the densest areas with data points.
combined to form 507 and 453 multi-frame RBEs. These chains from both spectral lines were then compared to one another in order to see if there is a connection between the Ca ii 8542 and Hα RBEs. The same method that was used for linking separate events to multi-frame RBE chains was employed to link the chains in the two spectral lines. The automated method managed to find about one-third of the multi-frame RBEs in both spectral lines simultaneously, resulting in 169 Ca ii 8542–Hα RBE chains. Figure 1(c) shows the distribution of these 169 chains, drawn on a wideband image. The Hα parts of the chains are drawn as green lines, the Ca ii 8542 parts as red lines, and the region where they overlap as yellow.

Our detection technique finds that a large fraction of the RBEs are detected and matched up in both lines, with a small fraction not matching up. However, from visual inspection of the data set, it becomes clear that for virtually all RBEs detected in one spectral line a corresponding RBE signature is observed in the other spectral line. This is illustrated in Figures 8(a) and (b), where close-ups of one time step are shown for both lines with the detected events in the other spectral line overplotted. The automated detection method managed to link seven RBEs in both spectral lines: four are found in both lines for this time step (marked as 1, 2, 3, and 4), one Ca ii 8542 RBE is linked to an Hα RBE in another time step (marked “a”), and two Hα RBEs are linked to Ca ii 8542 RBEs in another time step (marked “b” and “c”). The other detected RBEs were not flagged as connections (marked with small stars). Visual inspection, however, suggests a much higher connection rate which becomes even more apparent in the composite map in panel (c). Here, Hα and Ca ii 8542 detection maps are combined in a color image where bright Hα features are blue-green, and bright Ca ii 8542 Doppler features are red. Regions where these features overlap (i.e., overlapping RBEs) become white. This map suggests that all RBEs have signal in both Hα and Ca ii 8542.

Panels (d)–(f) of Figure 8 offer a close-up centered on one of the longer RBEs. This long RBE was detected in both Hα and
Ca ii 8542 (see panels (a) and (b)), but the automated method did not connect them. The images (and in particular the composite image) show that there is considerable overlap between the two lines. The other long but thinner RBE to the right is also detected in both lines but not flagged as connections—the composite image leaves no doubt that the two detections are of the same event. And the small RBE in the upper left was only detected for Hα for this time step (marked “b,” connected to a Ca ii 8542 detection in the next time step) but there is indeed RBE signal present also in Ca ii 8542.

Figure 8 demonstrates that Ca ii 8542 RBEs have their lower part closer to the magnetic regions, while Hα RBEs extend to larger distances away from these regions. This trend of Ca ii 8542 RBEs being closer to the magnetic regions is also illustrated in Figure 1(c): most of the red lines (Ca ii 8542) are at the base of the green Hα RBEs. The single RBE in Figure 2 is also found in Ca ii 8542 with the latter feature located closer to the magnetic bright points in the upper right (where the RBE started to appear a few time steps earlier) than in Hα.

When comparing the statistics of RBEs connected in both spectral lines to the ones that are not connected, two properties stand out. The average lifetime of an RBE seen in both spectral lines is 83.9 s, whereas in the RBEs only detected in one of the lines the average lifetime is 45.6 s and 46.1 s for Ca ii 8542 and Hα, respectively. Also, the average length of RBEs seen in both spectral lines, 3.1 Mm and 3.7 Mm for Ca ii 8542 and Hα, respectively, is larger than that of the RBEs only observed in one spectral line, 2.8 Mm and 3.4 Mm for Ca ii 8542 and Hα, respectively. This suggests that a successful connection between the two lines is more likely for RBEs that are longer lived and have a longer spatial extent.

The statistics for Doppler velocities and Doppler widths for the connected RBEs shows the same trend as for RBEs detected in only one line: Hα RBEs have generally larger Doppler velocity and larger width.

4.4. Scattered Events

Figures 1 and 6 show that apart from the dense concentrations of RBEs associated with regions of enhanced polarization, there are a significant number of events scattered over the FOV. Here we present statistical properties of these isolated events by masking out the three regions with densest RBE concentrations.

Figure 9 shows histograms for length, Doppler velocity, and Doppler width. The histogram for RBE length peaks just below 3 Mm, just like for the multi-frame RBEs in Figure 4(a), but there is no extended tail toward longer lengths (note that some of the scattered RBEs show temporal evolution and are part of both Figures 4 and 9). The histograms for Doppler velocity and width are similar as for multi-frame RBEs.

Figure 10 shows sample images of two scattered Hα RBEs. The top panels are from an event that appeared one time step earlier in the far blue wing in the middle of a granule. The RBE could be followed for four time steps so it has a lifetime of more than 36 s. In the left panel, the RBE appears to cross a granule, while in the images closer to the line core (for example the middle panel), it seems to be part of a structure that is rooted in the intergranular lane to the right of the granule. No photospheric bright point or enhanced polarization signal that is obviously associated with this event is present in this area.

The bottom panels show an RBE that was visible for eight time steps, and like the previous example seems to cross granules and is not obviously connected to magnetic regions in the vicinity. The line core image however suggests that the RBE is associated with the dense fibrils that are rooted in the extended magnetic region to the upper right, which dominated the FOV in Figure 1. The closest photospheric bright points along the direction of the RBE main axis are more than 10′′ away.

5. DISCUSSION

We studied the disk-counterparts of type II spicules that are observed as short-lived, elongated features in the blue wings of strong absorption lines like the Hα and Ca ii 8542 spectral lines. These features are also known as rapid blueshifted excursions due to their asymmetric, blueward spectral profile. The work presented here is in many ways a continuation and elaboration of the work of Paper I. We observed a similar target, a coronal hole, and employed a program of simultaneous Hα and Ca ii 8542 spectral scans. The observation program was specifically tailored for the observation of RBEs with reasonably high temporal cadence and sufficient resolution for robust spectral analysis. This allowed us to more directly compare the two spectral diagnostics, a comparison which could only be done indirectly from the data employed in Paper I, where RBEs were studied in two separate but sequentially recorded single-line time series in Hα and Ca ii 8542. Furthermore, we have extended the method of automated detection of RBEs to allow for a...
temporal connection between RBE detections so that properties such as lifetimes and transversal motion could be studied more rigorously on an extended statistical sample. In Paper I, these properties were measured manually on a limited subsample of the RBE detections.

5.1. Statistical Properties of RBEs

We present histograms on RBE lengths, and Doppler velocities and Doppler widths for 1890 Ca\textit{II} 8542 and 1601 H\textalpha RBEs in Figure 4. These measurements agree very well with those presented in Paper I. We confirm that a larger number of longer RBEs (≥3.5 Mm) can be observed in H\textalpha, while the shortest RBEs (≤2 Mm) are observed in Ca\textit{II} 8542. We confirm that in H\textalpha, one observes larger Doppler velocities and larger Doppler widths than for Ca\textit{II} 8542 RBEs.

These RBEs were connected in temporal chains and combined to form 507 Ca\textit{II} 8542 and 453 H\textalpha multi-frame RBEs for which we could determine the lifetime and transversal motion. This is an increase in statistical sample size of more than an order of magnitude for this type of measurements.

T. Pereira et al. (2011, private communication) measure statistical properties of 111 type II spicules from two \textit{Hinode} Ca\textit{II} H limb time series. Their results allow for a more detailed comparison between RBE properties and spicule type II properties than was possible for Paper I. They find lifetimes ranging between 20 and 160 s, with the peak of the distribution around 1 minute and an average of about 80 s. For our sample of RBEs, we find a similar range in lifetimes but mostly lower values for the peak transverse velocity, RBEs display a comparable range but mostly lower values for the peak transverse velocity to the higher cadence of the 2008 Ca\textit{II} 8542 data set. For the 2010 July 3 data set, we find an average of 4.4 km s\textsuperscript{−1} for 94 RBEs. For the 2010 July 3 data set, we find average transverse velocities that are very similar as for 2010 June 27.

De Pontieu et al. (2007) discovered Alfvénic waves in the chromosphere using type II spicules as tracers for oscillatory motions. The velocity amplitude was measured for 94 spicules, which can be compared to the distribution of the peak transverse velocity in Figure 5(c). They found a range between 0 and 30 km s\textsuperscript{−1}, with the peak of the distribution around 15 km s\textsuperscript{−1}. As for the average transverse velocity, RBEs display a comparable range but mostly lower values for the peak transverse velocity as compared to type II spicules at the limb. Continuing on the arguments of the previous paragraph, we note that the measurements of the RBE transverse velocities seem to be limited by the cadence of the time series. Faster cadence observations are needed to properly resolve the distribution of transverse velocities of RBEs.

For the transverse displacement, Pereira et al. find values ranging between 0 and 1.4 Mm, with most values between 0.1 and 0.5 Mm, in close agreement with the De Pontieu et al. (2007) measurements. We find a total transverse displacement of less than 1 Mm for RBEs, with most RBEs covering a distance of less than 0.2 Mm during their lifetime.

Even though the shapes of the statistical distributions of properties of RBEs and type II spicules observed at the limb differ in detail, the similarities between the distributions provide
a sufficient basis for the interpretation of RBEs being the disk counterparts of type II spicules, as already put forward in Paper I. In addition to similarity in statistics, we observe that RBEs rapidly disappear or fade, and that RBEs show both swaying motion and apparent motion away from magnetic regions, which can be interpreted as an upward motion. There are no signs of flows returning to the surface associated with RBEs. This kind of dynamical behavior is one of the defining characteristics of type II spicules observed in Ca \( \Pi \) at the limb.

The most striking difference between RBEs and type II spicules is the distribution of lengths. Pereira et al. measure a range between 1.5 and 11.5 Mm, with the average length around 6 Mm. We find for RBEs an average length around 3 Mm and only few H\( \alpha \) RBEs measure up to 6 Mm. This difference can be attributed to the fact that above the limb, faint signals toward the top of spicules can still be reliably detected against the dark background. Against the disk, however, these top parts of spicules are likely to have too little opacity to be detected as an integral part of RBEs. So there is likely an intrinsic bias for shorter lengths measured for RBEs. For length measurements of type II spicules at the limb, there is arguably also a selection effect for detecting longer spicules that stick out above the dense forest of spicules encountered in limb observations. The same projection effect could possibly explain the trend of higher transverse and transverse displacement measured for spicules at the limb: tall spicules that extend to greater heights move in a lower density environment, so for equal wave energy flux they can be expected to display higher velocities and thus cover greater transverse distances.

5.2. RBE Detection Rate

In Paper I, in the 40 minute Ca \( \Pi \) 8542 time sequence with a cadence of 11 s, 413 RBEs were detected from Doppler maps at 30 km s\(^{-1}\). With the 215 time steps, this corresponds to a detection rate of 1.9 RBEs per time step. In the 24 minute H\( \alpha \) time sequence with a cadence of 6.7 s, 608 RBEs were detected from difference maps at 60 km s\(^{-1}\). With the 245 time steps, this corresponds to a detection rate of 2.5 H\( \alpha \) RBEs per time step. We note that detection velocities of 30 km s\(^{-1}\) for Ca \( \Pi \) 8542 and 60 km s\(^{-1}\) for H\( \alpha \) are on the extreme end of the average Doppler velocities found for RBEs; see Figure 4 (or Figure 10 in Paper I). Given the typical values for the Doppler width and velocity it is likely that at these extreme detection velocities, a significant fraction of RBEs have absorption signals that are too faint to be detected by the automated method. In this work we investigated the detection rate as a function of the detection velocity used in the automated method. We find similar detection rates to Paper I at the detection velocities used in Paper I: 3.4 RBEs per time step for Ca \( \Pi \) 8542 and 1.8 RBEs per time step for H\( \alpha \). Running the automated detection method on maps constructed at lower Doppler velocity, we find a significant increase in the detection rate; see Figure 3. At 30 km s\(^{-1}\) we had a detection rate of 48 H\( \alpha \) RBEs per time step, an increase in the number of detected events of more than a factor 25. For Ca \( \Pi \) 8542 we see a similar increase in the detection rate toward lower Doppler velocity, but we found that at the lowest Doppler velocity possible in our data set, 12 km s\(^{-1}\), the fraction of false detections was too large and the detections are not reliable. For the detection velocity for which we present RBE statistics, 20 and 45 km s\(^{-1}\) for Ca \( \Pi \) 8542 and H\( \alpha \), we see an increase in the detection rate with a factor of about 6, to 14.2 and 11.1 RBEs per time step, as compared to the Paper I detection velocity. This resulted in a significant increase of the RBE sample used for detailed analysis in this work.

We find similar trends of increased RBE detections at lower Doppler velocity for the 2010 July 3 data set and the 2008 June 15 data sets used in Paper I.

We also note that the automated detection method does not identify all RBEs present in the data. We estimate that for the 45 km s\(^{-1}\) H\( \alpha \) detection maps, only about half of the events that are visually identified as genuine RBEs are registered by the automated detection. Running the detection routine on lower Doppler velocity maps results in a lower relative number of undetected RBEs (about a quarter remains undetected), but we must underline that we considerably underestimate the abundance of RBEs in our data.

Judge et al. (2011) proposed that type II spicules correspond to warps in two-dimensional sheet structures as an alternative to the main-stream interpretation of spicules being tube-like structures. One of their arguments in favor of sheet-like structures is that RBEs (which are hard to interpret as “sheets”) are not the disk counterparts of type II spicules because the occurrence rate of RBEs is at least an order of magnitude lower than type II spicules observed at the limb. From the number of detected RBEs in Paper I, they extrapolate to an estimate of \( 10^5 \) RBEs on the Sun at any given time. This is then orders of magnitude lower than estimates for type II spicules, e.g., \( 2 \times 10^7 \) (Judge & Carlsson 2010), and Beckers’s (1968) estimate of \( 10^6 \) for what are now considered as classical spicules.

The detection rate of RBEs at lower Doppler velocity we find here agrees with the estimate of a total number of \( \sim 10^5 \) RBEs (see Figure 3). However, as argued above, the RBE detection rate we find here is an absolute lower limit that significantly underestimates the actual number of spicules for several reasons.

First, the automated detection method rejects a significant fraction of real RBEs to avoid false positives.

Second, there are clear indications that many spicules lack opacity to show a disk counterpart signal. Detecting an RBE-like feature against the disk requires observations of excellent quality, and most importantly requires that the RBE has a certain degree of enhanced opacity. Our disk observations indicate that the opacity of RBEs varies strongly between the Ca \( \Pi \) 8542 and H\( \alpha \) lines, with the former showing significantly fewer and shorter features (concentrated toward the bottom of the H\( \alpha \) features). This is compatible with an ever decreasing opacity in chromospheric lines as one moves away from the footpoints. This is not surprising because limb spicules also show a very strong decrease in intensity (with scale height of the order of 2000 km) over their full length. It is thus highly likely that there is a significant number of faint RBEs that cannot be detected even in H\( \alpha \). We note that RBEs are very difficult to observe: detecting RBEs was impossible before the advent of subarcsecond, high-cadence, high signal-to-noise imaging spectroscopy with Fabry–Perot interferometers. It is quite possible that even higher quality observations would increase the detection rate significantly.

Third, RBE detection is subject to strong “velocity filtering”: due to the unknown angle between the velocity vector and line-of-sight vector, our method always misses features that are significantly inclined from the line of sight. This is especially the case because we cannot distinguish RBEs from other chromospheric features at velocities closer to the core. The increase of the number of RBE detections for lower Doppler velocity as illustrated in Figure 3 indicates that there might be a significant number of RBEs at even lower Doppler velocity that
are not detected by our method. Detection of type II spicules at the limb suffer much less from these latter two effects: it is relatively easy to detect faint signals against the off-limb dark background (with space-based instruments like Hinode that do not suffer from seeing effects introduced by Earth’s atmosphere) and velocity filtering is much less an issue for the relatively wide passband of the Hinode/SOT Ca H filter.

In the discussion of Paper I, it was argued that the detection rate of RBEs on the disk corresponds to a detection of 1.9 RBEs per linear arcsec if they were observed at the limb. This was considered to be in reasonable agreement with an order of magnitude estimate of the number of type II spicules per linear arcsec from the De Pontieu et al. (2007) observations. In this study, we confirm the results from Paper I and find that the detection rate extrapolates to \( \sim 1 - 2 \times 10^5 \) RBEs over the whole Sun. We caution that all of these occurrence rate estimates, including those of Beckers (1968) and Judge & Carlsson (2010) are based on incomplete data sets, limiting assumptions, and observational limitations, and should thus be taken with a grain of salt. For example, it is not clear from Judge & Carlsson (2010) how deterministic their occurrence rate of \( 10^7 \) type II spicules really is. The visual comparison in their paper is unconvincing with their simulations showing many more spicules than observations do: \( \sim 10^5 \) type II spicules would correspond to more than 100 spicules per linear arcsec at the limb or more than 5 spicules per Hinode/SOT pixel, in contradiction to observations. This implies that the \( 10^7 \) type II spicules estimated by Judge & Carlsson (2010), is likely a significant overestimation of the number of type II spicules at the limb. In any case, their argumentation for that number is based on a series of assumptions and models whose effect on the estimated number of spicules has not been studied or estimated. This sheds doubt on the robustness of their determined detection rate.

We conclude that the rejection of Judge et al. (2011) of RBEs being the disk counterparts of type II spicules on the basis of too low an occurrence rate is unjustified. There may well be sheet-like features in the atmosphere, but challenging the “tube hypothesis” based on rejection of the RBEs as disk counterparts of spicules is not convincing for the reasons outlined above.

### 5.3. Acceleration along RBEs

Paper I reported a systematic variation of the Doppler velocities and widths: many RBEs were found to show an increase of Doppler shifts and widths from the footpoint to the top. We confirm this trend in the 2010 data, which is visually evident from Figure 6, which shows the Doppler measurements as a function of their position in the FOV. In this representation, the orientation of (most of) the RBEs can be comprehended with respect to their footpoints which appear to be rooted in the magnetic field concentrations. The trend of increasing Doppler velocity and width for many RBEs is particularly striking for the \( \text{H}_\alpha \) RBEs. We note that there is also a significant number of RBEs displaying a more erratic variation of their Doppler properties.

Irrespective of the variation along the RBE main axis, we report a more general trend of increasing Doppler width for Doppler velocity in Figure 7. This trend illustrates the characteristic spectral profile at the location of RBEs, which consists of a wide blueward asymmetry (from which the RBE profile is then extracted by subtraction of a background profile). This is different from profiles with a narrow, isolated absorption component which can for example sometimes be observed for on-disk coronal rain (Antolin & Rouppe van der Voort 2012; Antolin et al. 2011). Sometimes coronal rain condensations appear as separated absorption profiles in the far wings of \( \text{H}_\alpha \). This is unusual for RBEs, even for RBEs that are oriented along the line of sight and appear as small, roundish features with strong absorption in the blue wing (dubbed “black beads” in Paper I); the spectral profile displays enhanced absorption throughout the blue extending to large Doppler offset.

In any case, the correlation between Doppler velocity and widths and tendency toward increased values for both parameters toward the top of the RBEs may suggest a link between the acceleration and heating mechanism involved in RBEs, if we speculate that the Doppler widths are related to temperature. Whatever the cause of this intriguing correlation, it provides strict constraints for any theoretical model for spicules.

### 5.4. Comparing \( \text{H}_\alpha \) and \( \text{Ca} \ ii \ 8542 \) RBEs

From the sequentially recorded \( \text{H}_\alpha \) and \( \text{Ca} \ ii \ 8542 \) data sets of Paper I, it was observed that \( \text{Ca} \ ii \ 8542 \) RBEs are located closer to magnetic regions and it was inferred that the \( \text{Ca} \ ii \ 8542 \) line samples the lower part of spicules. In our data sets with co-temporal \( \text{H}_\alpha \) and \( \text{Ca} \ ii \ 8542 \) observations, we can directly confirm that the two lines sample different parts of RBEs, with the \( \text{Ca} \ ii \ 8542 \) line sampling the bottom part of the spicule, and \( \text{H}_\alpha \) sampling the upper part, and both lines sampling an overlapping region in the middle (see Figure 8). Even though the automated detection method does not nearly identify all RBEs in both lines, we find from visual inspection that virtually all RBEs display signal in both lines.

This observation strengthens the explanation for the differences in Doppler velocity measured in \( \text{H}_\alpha \) and \( \text{Ca} \ ii \ 8542 \) (see Figure 4) as put forward in Paper I: \( \text{H}_\alpha \) is sampling the top part of spicules where lower density plasma is propelled to higher velocities.

The observation of the \( \text{Ca} \ ii \ 8542 \) and \( \text{H}_\alpha \) lines sampling different parts of RBEs also removes some of the discrepancy between length measurements of RBEs and type II spicules at the limb: we can infer that the actual length of the RBEs is longer than measured in the two lines separately. In addition, of course, it remains the case that we cannot expect to completely remove the length discrepancy between RBEs and type II spicules. This is because off-limb measurements allow for more reliable measurements of faint signals.

### 5.5. Scattered RBEs

We find most RBEs to be concentrated near regions with enhanced magnetic fields. In addition to these dense concentrations, we find a number of more isolated RBEs that are scattered around the FOV. When comparing statistical properties of length, Doppler velocity, and Doppler width, we find that these isolated events are not particularly different from the RBEs in denser regions, except that we do not find a population of longer RBEs. For these isolated RBEs, it is often unclear if they have any association with regions of enhanced magnetic fields, although we note that our diagnostic, \( \text{Ca} \ ii \ 8542–600 \) mÅ Stokes V maps, is not a particularly sensitive measure for magnetic fields. One might speculate that a more sensitive diagnostic might reveal a connection to weaker and possibly more extended, magnetic fields.

From fixed wavelength, \( -1300 \) mÅ \( \text{H}_\alpha \) observations from the 1.6 m New Solar Telescope (NST) at Big Bear Solar Observatory, Goode et al. (2010) report the observation of small jet-like features that appear to originate from intergranular lanes. The authors claim that these features are different from...
RBEs, as they are not unequivocally tied to strong magnetic field concentrations.

Figure 10 shows blue-wing Hα images of two examples of scattered RBEs. The left panels show far blue wing images of these events. In these images, these events seem to match the description of the jet-like features described by Goode et al. (2010): narrow features that cross granules and are not obviously connected to magnetic regions in the vicinity. The spectro-temporal information that we have for this data, however, reveals that these events are RBEs. Even though the bottom example of Figure 10 is not directly associated with photospheric bright points, it seems plausible that this feature is related to the extended magnetic region in the upper-right part of the FOV.

Goode et al. (2010) report a typical length of 1 Mm and a typical width of 0.2 Mm for the jet-like features in their blue-wing Hα data. The width agrees well with what we find for RBEs; the length is compatible but on the short side. It should be noted that the length in Goode et al. (2010) is measured at a fixed wavelength position at 60 km s⁻¹ Doppler offset, while we measure RBE lengths taking the spectral profile into account. This naturally leads to a trend of measuring longer lengths. We confirmed visually that RBE lengths at fixed wavelength filtergrams have a trend of becoming shorter at a higher Doppler offset.

Given the striking similarities, we interpret the jet-like features reported by Goode et al. (2010) as similar features to what we observe as isolated RBEs scattered over the FOV.

6. CONCLUDING REMARKS

The statistical properties resulting from this data set, along with better estimated occurrence rates, further strengthen the interpretation of RBEs as the disk counterpart of type II spicules as first proposed by Langangen et al. (2008) and further established in Paper I. Given their important role in understanding the outer solar atmosphere, either as seemingly passive tracers for the pervasive presence of Alfvénic waves (De Pontieu et al. 2007) or more directly as a potential source for mass loading and heating of the corona (De Pontieu et al. 2011), further observational study of type II spicules is highly desired in order to advance knowledge of their physical nature. An essential property that is not part of this work but can readily be addressed from the analysis method employed on this time series is the spectral evolution of RBEs during their lifetime. Such detailed study of the temporal evolution of RBEs is currently under way and will be the subject of a forthcoming paper. We further note that observations from the Solar Dynamics Observatory of this target provide the possibility of investigating the response of the transition region and coronal diagnostics to RBEs.

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