OBSERVING CASCADES OF SOLAR BULLETS AT HIGH RESOLUTION. II.

E. SCULLION^{1,2}, O. ENGVOLD¹, Y. LIN¹, AND L. ROUPPE VAN DER VOORT¹¹ Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029, Blindern, NO-0315 Oslo, Norway² Trinity College Dublin, College Green, Dublin 2, Ireland; scullie@tcd.ie

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ABSTRACT

High resolution observations from the Swedish 1-m Solar Telescope revealed bright, discrete, blob-like structures (which we refer to as solar bullets) in the $H\alpha$ 656.28 nm line core that appear to propagate laterally across the solar atmosphere as clusters in active regions (ARs). These small-scale structures appear to be field aligned and many bullets become triggered simultaneously and traverse collectively as a cluster. Here, we conduct a follow-up study on these rapidly evolving structures with coincident observations from the *Solar Dynamics Observatory*/Atmospheric Imaging Assembly. With the co-aligned data sets, we reveal (a) an evolving multithermal structure in the bullet cluster ranging from chromospheric to at least transition region temperatures, (b) evidence for cascade-like behavior and corresponding bidirectional motions in bullets within the cluster, which indicate that there is a common source of the initial instability leading to bullet formation, and (c) a direct relationship between co-incident bullet velocities observed in $H\alpha$ and $He\ II\ 30.4\text{ nm}$ and an inverse relationship with respect to bullet intensity in these channels. We find evidence supporting that bullets are typically composed of a cooler, higher density core detectable in $H\alpha$ with a less dense, hotter, and fainter co-moving outer sheath. Bullets unequivocally demonstrate the finely structured nature of the AR corona. We have no clear evidence for bullets being associated with locally heated (or cooled), fast flowing plasma. Fast MHD pulses (such as solitons) could best describe the dynamic properties of bullets whereas the presence of a multithermal structure is new.

Key words: methods: data analysis – methods: observational – Sun: chromosphere – Sun: corona – techniques: image processing – techniques: spectroscopic

Supporting material: animations

1. INTRODUCTION

A recent study of high spatial, spectral, and temporal resolution observations of the solar chromosphere in $H\alpha$ 656.28 nm, revealed the existence of small-scale, highly dynamic clusters of bright blob-like features in solar active regions (ARs; Lin et al. 2012, [Paper I](#)). In [Paper I](#), linearly propagating blobs observed in emission in the $H\alpha$ line core characterized the chromospheric component of multiple clusters (containing a total of 28 blobs), which revealed evidence for propagation along (near-horizontal/lateral motion) magnetic threads with velocities in the range of $45\text{--}111\text{ km s}^{-1}$. [Paper I](#) concluded that the emission and dynamic character of these small-scale features is similar to what one would expect from an MHD fast mode pulse, as a formation mechanism. For discussions of wave-driven mechanisms that might generate such features, we refer to the introduction of [Paper I](#), as well as, Zaqarashvili et al. (2010) and Morton et al. (2011). As deduced in [Paper I](#), observations of any solar phenomenon in only one wavelength channel will reveal limited information on its respective nature and origins. In other words, does the enhanced intensity in $H\alpha$ line core, characteristic of these features, hint at a more diverse temperature structure to at least TR temperature counterparts of blobs, beyond the clearly observed chromospheric component? Here we conduct a follow-up study of one data set described in [Paper I](#), to investigate the nature of these bright blobs, using combined imaging from EUV channels, via the *Solar Dynamic Observatory*/Atmospheric Imaging Assembly (SDO/AIA; Lemen et al. 2012) as well as, co-spatial and co-temporal chromospheric diagnostics via the Swedish Solar Telescope (Scharmer et al. 2003) CRISP Imaging Spectro-

Polarimeter (CRISP; Scharmer et al. 2008). Hereafter, we refer to these bright, discretized blob-like structures that appear to propagate laterally across the lower solar atmosphere (rather than outward) as solar “bullets.” Their observed bullet-like motion appears to best describe the dynamics and interactions of these features. The bullet analogy will be explored in more detail in the next sections, as well as the causes and consequences of such activity in the context of coronal AR fine-scale structure. The new insights into the nature of solar bullets, offered by AIA, is the motivation behind this follow-up study.

The same AR was imaged in the EUV channels of AIA, which was launched approximately four months prior to the CRISP observations investigated here. The co-spatial and co-temporal time series of the $H\alpha$ spectral scan sequences (obtained via imaging spectro-polarimetry) can be very precisely compared with hotter EUV channels, as presented herein. Next, we briefly describe the observations, data processing, and co-alignment methods. Following that section, we present the results of our in-depth study into the thermal properties/temperature structure and nature of solar bullets. In the discussion section, we summarize our findings concerning the observed properties of solar bullets across a broad spectral range. Finally, we draw our discussions to a close with a reflection on possible scenarios that could describe the physical formation of solar bullets.

2. DATA REDUCTIONS

CRISP is an imaging spectro-polarimeter that includes a dual Fabry-Pérot interferometer (FPI) system similar to that described by Scharmer (2006). For $H\alpha$, the pre-filter of CRISP

is 0.49 nm. From 10:58:14–11:30:13 UT on 2010 June 27th, CRISP was set to cycle continuously through 41 line positions (from -0.1713 nm in the $H\alpha$ blue wing through the line center to $+0.1713$ nm in the red wing, in equidistant steps of 0.0085 nm (3.9 km s $^{-1}$). The observations targeted the center AR 11084 close to the solar limb. The resulting cadence of the sequential $H\alpha$ scan sequences is 9 s. By applying the Multi-Object Multi-Frame Blind Deconvolution (MOMFBD: van Noort et al. 2005) image restoration technique, the images in the time series are corrected for high frequency atmospheric distortions (beyond the capability of the adaptive optics system correcting in real-time for low order distortions). We used early versions of a CRISP data reduction pipeline (de la Cruz Rodríguez et al. 2015) to prepare the $H\alpha$ spectral data cubes for this analysis. We explore the fully processed data in the field of view (FOV) with CRISPEX, a versatile code for analysis of multi-dimensional data cubes (Visser & Rouppe van der Voort 2012). Together with CRISP observations, space-based *SDO/AIA* observes the Sun in eight different temperature channels in the (E)UV with an uninterrupted cadence of 12 s. We include in our analysis the following AIA channels: the continuum 170.0 nm channel (for co-alignment of the images with CRISP), the transition region He II 30.4 nm ($\log T = 4.7$) line and the AR low coronal lines of Fe IX 17.1 nm ($\log T = 5.8$), Fe XII 19.3 nm ($\log T = 6.2$) and Fe XIV 21.1 nm ($\log T = 6.3$). These are the only AIA wavelengths under consideration because we only want to sample the transition region and non-flaring active coronal lines with detectability in a range up to a few million degrees to compare with bright structures in $H\alpha$. The standard SolarSoft (SSWIDL) data preparation (*aia_prep.pro*) is applied to raw AIA images to co-align each AIA channel in the continuum and applies hot pixel, plate scale, and limb fitting corrections. A small spatial offset is expected between the internal *SDO/AIA* channels on the order of 0.25–0.5 AIA-pixels (Aschwanden & Boerner 2011). The pixel size of the $H\alpha$ images is $0''.06$, which means ~ 10 times more resolving power than that of *SDO/AIA* images ($0''.6$ per pixel).

We used the *SST* turret pointing information to determine the center of the CRISP FOV, which had an accuracy (prior to the 2013 observing season) of $\pm 5''$ in solar- x and solar- y . To achieve sub-AIA pixel accuracy in the co-alignment of AIA with CRISP narrowband images, we cross-correlate photospheric bright points in near simultaneous CRISP wideband images and the AIA continuum channel of 170.0 nm, thereby achieving an accurate co-alignment between CRISP and the transition region and coronal lines of AIA. Photospheric bright points generally exist as discrete, bright magnetic flux concentrations and they are relatively long lived. They are present in abundance in both CRISP $H\alpha$ near-continuum spectral images and the AIA 170.0 nm images and so an accurate cross-correlation of the bright points between CRISP and all AIA 170.0 nm could be achieved in order to co-align the image sequences from both instruments. Since the other AIA channels were previously aligned with 170.0 nm, by default, we achieve a co-alignment with all AIA channels. A similar approach is demonstrated in Scullion et al. (2014). The cadence of the AIA time series differs from CRISP scans by 3 s. In order to be consistent with the *SST* cadence, we compare the *SDO* images in each channel with the closest CRISP time frame. Since the *SST* is tracking solar rotation in time and the AIA images are now co-aligned and derotate to the first time frame, we only determine the co-alignment correction between

Figure 1. Perspective image of the CRISP FOV with respect to AIA 170.0 nm is presented. The photospheric 170.0 nm image is in the background. The CRISP/ $H\alpha$ FOV is marked as a white box close to the limb sunspot of AR11084. The red and green contours over the $H\alpha$ gray-scale image (bottom) correspond to photospheric bright points of 170.0 nm, which cross-correlate with coincident bright points in the $H\alpha$ far red-wing line position (-0.1032 nm).

CRISP and AIA for the first time frame and apply that correction for the subsequent frames in the observation. Figure 1 presents the pointing of the CRISP FOV (bottom; corrected for solar tilt), with respect to *SDO/AIA* (background) in the 170.0 nm channel, after co-alignment and derotation of the images. The red/green contours of the 170.0 nm photospheric bright points are overlaid onto the $H\alpha$ continuum image to demonstrate the accurate co-alignment of the observations from both instruments. The accuracy of the co-alignment between CRISP and the AIA channels is at the diffraction limit within $H\alpha$, as observed with CRISP, i.e., 0.14 arcsec in solar- x and solar- y . The resulting FOV of the images is $84'' \times 84''$.

3. OBSERVATIONS OF A CLUSTER OF SOLAR BULLETS

In Figure 2, we present the observation FOV in the $H\alpha$ line core (panel A). On the right side, we present image sequences (top to bottom in time) of two solar bullets (#1-2) that are coincident in both the $H\alpha$ line core (upper chromosphere) and He II 30.4 nm images (transition region). The tracks of these bullets (#1-2) are over-plotted in panel-A within the FOV. The bullets in $H\alpha$ have bright cores and faint surroundings and they

Figure 2. CRISP H α 656.28 nm line core full FOV is presented in panel A (left) and a number of (blue solid line) bullet tracks (#1–3) are marked to depict the motion of solar bullets across the image plane. The H α line core spectral position (A) is marked within the 41 point line profile, an inset of panel A. The sub-image sequence (from top to bottom) for coincident bullets (#1–2) in H α (left sub-image) and He II 30.4 nm (right sub-image) describes the evolution of bullets along their respective tracks #1 and #2. Track #3, as presented in panel A, is described further in Figure 3. The tracks (white lines) are overlaid on the sub-images and the red arrows highlight the exact location of the solar bullet in the H α core. The horizontal yellow-dashed lines highlight the co-spatiality between the bullets in H α and He II 30.4 nm. The yellow-dashed lines also represent the times of the sub-image sequences within the X–T diagrams (bottom row) from the start of the event. The X–T diagrams plot the progression of the bullets in time, along the path of the white slits within each sub-image, and the track cross-cut is in units of SST-pixels (1 pixel $\approx$ 43 km). See animation (b) of this figure and the animation associated with Figure 3, which show the bullet cluster propagating across the full FOV in the CRISP H α line core (animation (b), this figure) and AIA 30.4 nm (Figure 3’s animation). See animation (b) of this figure for the 41 position spectral line scan images in H α with CRISP.

(Animations a and b of this figure are available.)

are $0''.3$ – $0''.4$ (~ 300 km) in diameter. Both H α bright core intensities and 30.4 nm bullet intensities vary by 10%–20% across the cluster.

A realistic comparison of bullet brightness in H α and 30.4 nm should take into account the large difference in background brightness at these two wavelengths. Typically, 30.4 nm bullets appear brighter against their background, with bullet intensities 2.2–2.8 times greater than background. Whereas, H α bullets are relatively less bright because they have intensities only 1.3–1.5 times greater than background intensity. The bullets in H α and 30.4 nm are spatially and temporally matched in cases #1 and #2 with a dashed yellow line. The distance–time (X–T) diagrams, shown in Figure 2 (right side, bottom row), corresponds to the motion of the bullets with constant velocity for a lifetime of 180 s, after they first appear in both channels. From the X–T diagrams, we find that the velocities of the H α bullets in the plane of the sky exist in the same velocity range, as reported in Paper I. Importantly, there is an associated 30.4 nm counterpart (for the full duration in bullet #1, but intermittently in bullet #2) that is a notable and important difference in their morphology. In the case of bullet #2, the H α and 30.4 nm X–T diagrams reveal that the bullets do not always appear and disappear (from their respective spectral channel) at exactly the same time.

In Figure 3, we present similar image sequences (evolving in time from panel A–D) for a partially coincident H α and

30.4 nm bullet that represents track #3 (see Figure 2—panel A). By partially coincident, we mean that the bullet is only coincident in H α and 30.4 nm in panel B (matched with a yellow dashed line, also represented in time in panel E). The bullet itself is made identifiable by blue boxes in each sub-image. The spectral evolution in this case is more complicated, such that the bullet initially appears in H α propagating along the white bullet track, as shown in panel A. The 30.4 nm counterpart of the H α bullet first appears after $t = 72$ s. The coincident bullet in 30.4 nm first appears in panel B and increases in intensity along the white track until $t = 202$ s (see panel E). At the same time, a bright bullet in H α continues to propagate along the white track beyond $t = 202$ s. In this case, the bullet’s thermal structure appears to change multiple times as it evolves along the track and the onset of the 30.4 nm component appears coincident with a sharp change in direction of the H α bullet (i.e., within the white-dashed box in panel C). The consecutive nature of hot and cool bullets, and their association with a potential “trigger” event as inferred with the sharp change of direction in the white track, reveals a new characteristic in describing the nature of bullets.

3.1. Coincident He II 30.4 nm and H α Bullets

Despite the large difference in the spatial resolution of the CRISP H α and AIA 30.4 nm, a comparison of the co-temporal and co-spatial time series reveal multiple examples of

Figure 3. Pairs of sub-images ($28'' \times 28''$) in H α (left sub-image) and He II 30.4 nm (right sub-image) show evolving, corresponding bullets in time (increasing from panels A–D) along track #3 (see Figure 2—panel A), as compared with Figure 2. For certain time intervals (yellow-dashed line in sub-images and X–T diagram of panel E), the H α and 30.4 nm bullets are coincident and matched and are identifiable within the overlaid blue boxes. The bullet appears to exist within the blue box in all time frames but only for part of that interval in 30.4 nm. The white dashed box identifies a notable deviation in the trajectory of the bullet motion.

(An animation of this figure is available.)

coincident high speed, small-scale bullets in both channels and with a common apparent lifetime in both channels. Many H α bullets appear to have fairly strong intensity contrasts with the background signal and they are generally rounded, but some are elongated. The 30.4 nm bullets appear larger and possibly more diffuse, i.e., the boundary of the bullet feature is less distinct. In total, there are 13 instances of common 30.4 nm and H α bullets. Table 1 presents the apparent velocity and intensities of these bullets in these channels, comparatively. Eleven examples of these are presented in Figure 4 (top). In the 11 panels, we detect 6 examples of one-time coincident bullet formation in H α together with 30.4 nm (i.e., diagrams #5, #7, #8, #10, #12, and #14). In the remaining 5 bullets (#4, #6, #9, #11, and #13), we detect repetitions of coincident H α and 30.4 nm bullet formation (most notably in diagram #1) along the same track and with variable time intervals between their respective formation. We refer such repetitive activity, associated with bullets along the same path, as a thread of bullets. Coincident bullets are such that the bullet tracks are overlapping or very much adjacent to each other during their lifetime and they must follow the same trajectory for some period of time, such as those displayed in Figure 4. The most extreme example, with respect to the lifetime of coincident bullets observed in H α and 30.4 nm, was where a H α bullet had a lifetime 5.5 times shorter than its 30.4 nm counterpart. A sub-plot [1] within the histogram panel in Figure 5, demonstrates that there is a very linear relationship between these 13 coincident bullets, with respect to their velocity correspondence (outlined in Table 1). However, there is an inverse relationship when considering their respective intensity variations (sub-plot [2]). There is clearly a strong statistical relationship between many bullets formed in H α and those appearing in 30.4 nm. This implies that there is a strong connecting physical process present to explain the dynamic, internal thermal changes in the bullets.

Table 1
Several High Speed Bullets Are Selected from H α and 30.4 nm

Vel. H α (km s $^{-1}$)	Vel. He II 30.4 nm (km s $^{-1}$)	Intensity H α	Intensity He II 30.4 nm
54 $\pm$ 9	62 $\pm$ 2	3300 $\pm$ 130	410 $\pm$ 20
66 $\pm$ 3	...	3280 $\pm$ 170	...
44 $\pm$ 5	...	3280 $\pm$ 80	...
52 $\pm$ 4	62 $\pm$ 8	3350 $\pm$ 70	480 $\pm$ 60
...	65 $\pm$ 2	...	390 $\pm$ 10
...	60 $\pm$ 3	...	380 $\pm$ 20
45 $\pm$ 14	...	2810 $\pm$ 30	...
73 $\pm$ 1	85 $\pm$ 2	3680 $\pm$ 160	280 $\pm$ 20
89 $\pm$ 6	88 $\pm$ 3	3650 $\pm$ 100	320 $\pm$ 20
89 $\pm$ 20	82 $\pm$ 2	3480 $\pm$ 80	270 $\pm$ 10
47 $\pm$ 1	53 $\pm$ 1	3170 $\pm$ 90	380 $\pm$ 100
81 $\pm$ 1	85 $\pm$ 24	3640 $\pm$ 170	320 $\pm$ 20
62 $\pm$ 7	64 $\pm$ 13	3050 $\pm$ 130	530 $\pm$ 20
95 $\pm$ 6	...	3170 $\pm$ 100	...
...	68 $\pm$ 2	...	410 $\pm$ 20
72 $\pm$ 17	68 $\pm$ 11	3530 $\pm$ 120	410 $\pm$ 47
72 $\pm$ 3	79 $\pm$ 2	3490 $\pm$ 70	480 $\pm$ 20
95 $\pm$ 36	99 $\pm$ 2	3390 $\pm$ 40	490 $\pm$ 60
77 $\pm$ 1	82 $\pm$ 13	3410 $\pm$ 140	610 $\pm$ 140
97 $\pm$ 16	107 $\pm$ 15	3440 $\pm$ 130	400 $\pm$ 50
...	89 $\pm$ 11	...	430 $\pm$ 40

Note. Here, 13 bullets are coincident in both wavelengths and 4 bullets are detected only in H α and 4 only in 30.4 nm. The velocities of these bullets in the plane of the sky are in units of km s $^{-1}$ and their mean intensities are in arbitrary units.

3.2. Statistical Analysis of the Bullet Cluster

In order to investigate the thermal structuring and physical characteristics of bullets further, we carried out a statistical analysis of all detectable bullets in the FOV for the full

Figure 4. Top: grayscale distance–time (X – T) diagrams for corresponding and coincident $H\alpha$ and 30.4 nm bullets (#4–14) from bullet tracks. The track data is extracted from splines on the co-aligned CRISP and AIA FOV and individual bullets are marked with orange arrows. Time is positive in the downward direction along the y axis. Hence, as time advances forward the bullets evolve along the slit cross-cut (SST pixels) along the x axis, from left to right, in all panels. Sequential horizontal bands in 30.4 nm are time intervals due to the effect of different cadence in the instruments. Bottom: color-scale X – T diagrams for the trigger event presented in Figure 9, which reveals sequences of relatively hot bullets, emitting across a broad range of temperatures. Time is positive in the upward direction along the y axis. The multithermal properties emanating from a source region are largely concentrated within the boundaries of the green dashed lines.

observation in $H\alpha$, as well as in the hotter channels of AIA. The selection criteria for what one can describe as a bullet is constrained by the intensity of the bullet relative to the

background (deduced from X – T diagrams) and the size of the feature moving across the plane of the sky in the time series. The condition for selection/inclusion of a bullet into the data set, was based on the intensity ratio of the bullet to the background level in each wavelength channel (set to at least 15% above a background level, determined from the X – T data array), as well as, the presence of a propagation along the length of the track, as measured from the bullet track X – T diagrams (for e.g., see Figure 4). In other words, all bullets have a detectable line of propagation within the X – T diagrams. For the observation duration of 1919 s, we detected a total of 78 individual bullet tracks in $H\alpha$, 43 tracks in 30.4 nm, 15 tracks in 17.1 nm, 20 tracks in 19.3 nm, and 15 tracks in 21.1 nm.

The results of this statistical approach are presented in Figure 6. From the first interpretation of this compilation of bullet tracks, we find that not all of the bright bullets in $H\alpha$ (black tracks in panel A) have a coincident signature in the hotter channels (colored tracks). From panel A, it is immediately apparent that the number density of detected bullets is significantly greater in the cool channels (below 100,000 K) compared with hotter channels. The 30.4 nm channel has the closest formation temperature to $H\alpha$ and, as a result, has the closest correspondence with the detected $H\alpha$ bullets. There are significantly fewer detections of bullet activity in the hotter channels ($>100,000$ K). The vast majority of detected bullets propagate from bottom-right to top-middle within the FOV. They propagate roughly parallel to the solar limb as a cluster.

Histograms of the measured velocities, lifetimes and track lengths of all bullets in all spectral channels, are presented in panels D–F. A Gaussian profile has been fitted to the $H\alpha$ distribution for panels D and E. The bullet velocity distribution in the cluster peaks at 52 km s^{-1} with an FWHM of $\pm 33 \text{ km s}^{-1}$. The tail of the velocity distribution extends out to a maximum of 145 km s^{-1} , i.e., corresponding to the fastest propagating $H\alpha$ bullet. This outer limit is marked with a vertical dashed line in panel A and labelled b . There exists a set of bullets outside of the fitted distribution with higher velocities beyond b , which features only bullets from the hottest AIA channels, i.e., 19.3 and 21.1 nm. The fastest bullet detected was in the coronal 19.3 nm channel with an apparent velocity of 200 km s^{-1} . The significance of these bullets will be explored in the cascade trigger events sub-section.

Statistical analysis of the bullet lifetimes within the main cluster, is presented in Figure 6 panel E. A fitted Gaussian profile has shown that most $H\alpha$ bullets survive for 75 s with HWHM of lifetimes of ± 135 s. The hottest (19.3 and 21.1 nm) detected bullet lifetimes are also most commonly occurring in the 35–95 s time interval (with peaks at 65 s in 21.1 nm and 70 s in 19.3 nm), whereas, the relatively cooler 17.1 and 30.4 nm bullets have a peak lifetime in the 155–215 s time interval. Another notable feature of the total cluster of tracks (panel A) in the FOV is the preferential/predominant direction of motion (indicated by the large black arrow). We can reveal from the velocity distribution map (panel B and C) that there are two distinct threads/flows within the main cluster of bullets, i.e., a relatively high velocity, long length thread (light blue tracks) on the left side of the cluster, and a low velocity, short length thread (dark blue) on the right side of the cluster. This indicates that most bullets propagate with a constant velocity throughout the observation. This is not surprising since the X – T diagrams of all tracks describe bullet profiles, which is

Figure 5. Examples of coincident $H\alpha$ bullet tracks (black) and 30.4 nm bullet tracks (red). The velocity distributions of these $H\alpha$ bullets (light blue) and 30.4 nm bullets (dark blue) are presented in the histogram (top right). The sub-plot [1] within the histogram represents the linear relationship (fitted dashed line) between coincident bullets with respect to bullet velocity. Sub-plot [2] describes an inverse relationship between respective $H\alpha$ and 30.4 nm coincident bullets with line fits over plotted.

suggestive of propagation with constant velocity. As a result, a larger bullet velocity with a similar lifetime will result in a greater track length. The bullet with the largest lifetime and length appeared in 30.4 nm with values of 725 s and 27.5 Mm, respectively. The shortest track length bullet is 2.7 Mm ($=3''7$) and exists within the 17.1 nm channel. The peak in the distribution (1) for $H\alpha$ bullet track lengths occurs at a length of 6.2 Mm, which is in close agreement with 17.1, 21.1, and 19.3 nm distributions, which peak at the 8–1 Mm range. However, a second Gaussian distribution (2) was fitted to the 30.4 nm track length distribution, which appears to constitute the tail end of (1). The peak of distribution (2) occurs at 12.3 Mm for 30.4 nm. It may be that there is a bi-modal distribution in the lengths of $H\alpha$ bullets since there is indeed a fairly large density of bullets at 11.8 Mm, which is in close agreement with the peak of distribution (2). The average track length, considering the mean of both distributions (1) and (2), is 9.3 Mm with a FWHM of ± 7.3 Mm. There appears to be a stronger correlation between bullets in $H\alpha$ (light blue bars in the histogram) and 30.4 nm (dark blue bars in the histogram) with respect to apparent velocity, but less so with respect to lifetime and track length distributions.

In the next section, we will discuss the evolution of a number of bullet cascades which could be identified within the main cluster. Within the main cluster, we can identify three distinct cascades of bullets, namely cascades A, B, and C. Cascade C is composed of the initial high speed, long length bullets of the

main cluster (i.e., left-side of Figure 6 panels B and C). Cascade A is composed of the right-side (relatively slower and short length) bullets that appear later in time and further along toward to top half of the FOV. Likewise, cascade B occurs later in the evolution and is relatively small-scale, compact cascade formed within the top half of the cluster.

3.3. Cascades A and B

In Figure 7, we present a sequence of images (left to right) describing evolving bullet tracks for cascades A (top row) and B (bottom row). Cascade A has a limited thermal structure (only bullets for $H\alpha$ and 30.4 nm are present) compared with cascade B, which contains bullets from 17.1, 21.1, and 193 nm. For both cascades, all bullets propagate diagonally upward and tend to fan outward (avalanche effect) from the boxed source regions, labelled source A and source B.

Cascade A evolves over an interval of 585 s and the formation of two near-parallel threads (#1 and #2, see 11:10:10 UT panel) clearly generate from source A. The cascade starts in source A as 3 bullets, 2 $H\alpha$ and 1 30.4 nm bullet, at 11:00:25 UT (t_0). At this time, the 30.4 nm bullet appears to be coincident with one $H\alpha$ bullet constituting the start of cascade thread #1. The third bullet in $H\alpha$ constitutes the onset of cascade thread #2. Within 3 minutes the $H\alpha$ bullet in thread #2 can be seen to evolve into a 30.4 nm bullet, i.e., the black track connects with the start of a 30.4 nm red track (Figure 7, top row of panel 2). In the same time interval, the

Figure 6. Statistics on all detected bullet tracks identified within the FOV (panel A—color-scale denotes spectral channel) are presented in panels (D—apparent velocity (km s^{-1}), E—lifetime (s), and F—track length (Mm). Panel B describes the spatial distribution of bullet tracks in a blue color scale, whereby light blue denotes relatively faster bullets and darker bullets denote relatively slower bullets. Likewise, panel C describes the spatial distribution of bullet lengths with light blue depicting the longest lived bullets and progressively darker tracks representing shorter bullet tracks. The faint solid line (panels A–C) marks the solar limb in AIA 170.0 nm and the outline of the CRISP FOV. Panels (D–F) show histograms of the properties of all of the bullets of panel A. A different color scale is used to distinguish the different spectral channels, as shown in the legend of panel E. The fitted Gaussian profile in panel F marked as (2) is fitted to the 30.4 nm distribution. The vertical dashed line (labelled *b*) in panel D, represents the upper limit of bullet velocities within the relatively cool bullets of $\text{H}\alpha$ and 30.4 nm. See the animation associated with this figure for the formation of bullet tracks in $\text{H}\alpha$ and 30.4 nm, collectively, as presented in panel A.

(An animation of this figure is available.)

coincident $\text{H}\alpha$ and 30.4 nm bullets of thread #1 extend further across the FOV and then appear to split into another pair of coincident $\text{H}\alpha$ and 30.4 nm bullets. Extending from this new pair of bullets, an independent $\text{H}\alpha$ bullet is triggered that propagates in the direction of thread #2, at $\sim 70^\circ$ to thread #1. At 11:04:55 UT ($t_0 + 270$ s) the new pair of bullets in thread #1 appears to trigger a new $\text{H}\alpha$ bullet which then continues to extend further along thread #1 (between panels 3 and 4). The total length of thread #1 is estimated to be 15.0 Mm from source A. After 90 s, the newly formed 30.4 nm bullet in thread #2 appears coincident with a chain of two short-lived $\text{H}\alpha$ bullets. In the same time interval, the 30.4 nm bullet formed in thread #2, extends a great distance along thread #2. The estimated total length of thread #2 is 16.2 Mm.

Only 63 s before the end of cascade A (11:09:07 UT) do we detect the beginning of cascade B (Figure 7, bottom rows in panels 1–4). Notably, the origin of this cascade (source B) is situated ahead of source A within cascade A and between threads #1 and #2. The total duration of cascade B is 271 s, which is approximately half the lifetime of cascade A. Cascade B is composed of bullets in all wavelengths discussed here and there is only one dominate thread (#3). Thread #3 is in fact situated between threads #1 and #2 of cascade A, so the

formation of cascade B is not entirely disconnected from cascade A. Just as with thread #1, thread #3 also appears to originate as a coincident pair of $\text{H}\alpha$ and 30.4 nm bullets and in its progression it also triggers bullet tracks in directions near-orthogonal to the predominant direction of the cluster. Cascade B contains a bullet network that is more compact and contains a higher number density of short-lived bullets, compared to cascade A. Thread #3 has a total length of 9.8 Mm and contains a total of 14 individual bullets. Just as with thread #2, the initial pair of bullets within thread #3 evolves up the temperature spectrum within 91 s, to apparently trigger even hotter 17.1 and 21.1 nm bullets. Then, 90 s after this, the hot bullet cluster appears to trigger a burst of very-short-lived cool $\text{H}\alpha$ bullets, as seen in Figure 7 (bottom rows of panels 3 and 4). Just as with cascade A, the evolution of bullet tracks in cascade B appears to fan out across the FOV, away from the source region. Cascade B ends at 11:13:38 UT, less than two minutes prior to the start of the largest cascade in the cluster, i.e., cascade C.

3.4. Cascade C

Figure 8 presents the largest detected cascade within the cluster. Cascade C is also composed of two threads (#1 and

Figure 7. Within the cluster, we identify two distinct examples of cascades of bullets, namely, cascade A (top) and cascade B (bottom). The image frames are zoomed in regions of the full CRISP FOV (faint dashed line). The color scheme for the bullet tracks depicts the different different spectral channels ($H\alpha$: black, 30.4 nm: red, 17.1 nm: light yellow, 19.3 nm: light brown, 21.1 nm: green). The solid and dashed black boxes mark the origins of the respective cascades and their sub-structure threads #1, #2 (cascade A), and #3 (cascade B). See the animations associated with this figure for movies of cascades-A and B.

(Animations a and b of this figure are available.)

#2), the second of which contains the highest number density of bullets (28) in all wavelengths. Thread #1 (*top row*) appears later in time than thread #2 (*bottom row*) and contains 16 bullets. The larger spatial extent of bullets in thread #1 allows us to investigate the dynamic interactions between bullets in the cascade progresses.³ Thread #2 has a range of 67.1 Mm, which is more than double that of thread #1 with a range of 31.2 Mm. Within the range of the cascade, there are several interesting source regions where the apparent coronal line bullets appear in the FOV, labelled A1–A2 followed by B1–B2 then C1–C2 (corresponding to their order of appearance). The order of appearance for all bullets is presented in Figure 8 panel 2 for both threads (rows), and again there is a clear evolution from bottom right (light blue) to top left (progressively darker blue). Despite thread #2 having >50% range of motion compared with thread #1, its duration is only ~9% greater. There is an indication of a higher average group velocity in the bullets of thread #2 compared to thread #1. Thread #2 appears before thread #1 and has a higher than average group velocity of 66 km s^{-1} .

Source regions here are identified as regions of interaction/formation of the hottest bullets. Given that they occur sequentially within the progression of the cluster (from the order of appearance of the bullets for threads #1 and #2) this implies that they may not be independent events. The sources

coincide with the formation of cooler bullets, which extend and expand the cluster across the FOV. For confirmation of the correspondence between hot and cool bullets, we present the X – T diagrams for source B2 trigger event in Figure 4 (*bottom row*). Through aligning the flows within the green-dashed line, in each X – T diagram, it can be shown that the initially hot motion of the bullet (in AIA 17.1, 19.3, 21.1 nm) are followed later in time by an increased intensity and formation of the $H\alpha$ counterpart, within the 225 s total lifetime of the bullets’ trigger event. This direction of evolution of sources is indicated with green arrows in panel 2 of thread #2 (Figure 8). The separation angle between the global progression of the cluster of all bullets (black arrow) and the signal inferred from the evolution of the trigger events is 35° .

3.5. Cascade Trigger Events

A set of the highest velocity bullets (in the range of 85 – 200 km s^{-1}) exist in Figure 6 outside (or at least on the tail-end) of the Gaussian distribution fitted for $H\alpha$ bullets. We can confirm that these high velocity bullets correspond to the location of the trigger events of cascade C threads #1 and #2. The trigger events contain only the apparent coronal line bullets and precede cooler bullet formation (in $H\alpha$ and 30.4 nm) in thread #2 (as mentioned previously). The bullet tracks for trigger events are distributed across the FOV, as shown within the sub-plots of Figure 9. In the left sub-plot, there is a direct connection between hot bullets (in 30.4, 17.1 and 19.3 nm)

³ See the animations associated with Figures 6–8 for the evolving bullet tracks in all cascades presented.

Figure 8. Sub-structural properties of the main cluster of bullets, namely cascade C, is presented for its threads #1 (*top row*) and #2 (*bottom row*). Top row, first panel: we present the tracks of the detected bullets, color coded for different spectral channels. The dark boxed regions, labelled A1 and C2 are the locations of sources of only coronal line bullets. The labelling convention of the source regions is increasing alphabetically with respect to the order of appearance (numbered) to compare with other source regions of bullets in thread #2. Top and bottom rows, second panel: we describe the order of appearance of bullets in each thread such that the darker blue tracks occur later in time relative to light blue tracks. Bottom row, second panel: green arrows reveal an overall diagonal component to the cascade thread #2 order of progression, away from a predominant direction of the main cluster (containing all cascades: black arrow). Top and bottom row third panel: the velocity distribution of bullets in each thread of the cascade in comparison with the Gaussian distribution for all bullets. See this figure’s animation of cascade-C.

(An animation of this figure is available.)

from the initial source A2 of thread #1 in cascade C and source B2 bullets. In the right sub-plot, the order of appearance also depicts the sequential evolution of the trigger bullets, i.e., numbered from 1–10 (light blue to dark blue) in thread #1. The bullet tracks have the same direction so there is no direct association between hot bullets of source B2 and source C1. The hot bullets corresponding to source C1 occur in sequence after A2 then B2. Cooler bullet tracks are shown to evolve out of all of the source regions, which have lower velocities on average compared to the hot high velocity trigger bullets. These connecting bullets linking sources C1 with B1, as well as C2 with B2 and A1 (of thread #1), can be more easily seen in Figure 8 (panel one, bottom row), via the tracks from the cooler channels of 30.4 nm and $H\alpha$. This gradual progression of cooler bullet tracks appearing out of the hottest source regions, as also shown in Figure 10. The green dashed line in Figure 10 marks the interaction region between the relatively hot red (30.4 nm) and relatively cooler black ($H\alpha$) tracks. These tracks correspond to the longest lifetime bullets detected here, which are greater than 400 s.

Aside from evidence of coincident $H\alpha$ and 30.4 nm bullets in cascade A, there is clearly evidence of greater temporal thermal evolution in the detected progressive cooling of

consecutive bullets in cascade B and C. Another characteristic of bullet evolution is with respect to their direction of propagation discussed next.

3.6. Bi-directional Bullets

One particularly interesting finding in this analysis may be the discovery of bi-directional bullets in $H\alpha$ and 30.4 nm channels. Six examples were found and four are presented in Figure 11. In all but one case, the 30.4 nm bullet travels in the upward direction following the cascade, with an associated $H\alpha$ bullet motion in almost exactly the opposite direction, and both are initiated from a common origin. The other important difference in each example is the delay interval between the bi-directional bullet formation in $H\alpha$ and 30.4 nm. The longest delay corresponds to ~ 108 s with respect to the start time of the bullet in $H\alpha$ versus 30.4 nm. However, there is one instance where the bi-directional bullets occur within the same time frame so the delay is less than 9 s (the CRISP cadence) making this very much co-temporal. The source region corresponding to each example, reveals that the spatial offset between the start of oppositely directed bullets is always within the range of $2''$ – $7''$ on average. The origins of the bi-directional motion appear

Figure 9. Highest velocity and hottest bullets from cascade C trigger events (A2–C2) are: (a) reproduced as color-coded tracks in the sub-plots (Left: spectral distribution, Right: numbered order of appearance) and (b) displayed on the color-coded bullet velocity histogram, which is over plotted with the $H\alpha$ bullet Gaussian-fit (black curve). See the animation associated with Figure 11, which shows one example of a strong association between a bullet formation and an explosive trigger event.

Figure 10. Lower velocity, cooler bullet tracks of cascade C are presented. $H\alpha$ (black) and 30.4 nm (red) bullet tracks of thread #2 are compared. The bullets appear to propagate consecutively from the bottom right to the top left almost entirely across the CRISP FOV (outlined). The green dashed line indicates the interaction region marking the transition from relatively warm to cool bullets.

within the boxed regions, which lie close to the sources of trigger events driving the cluster cascade-C. Although at the time of their occurrence there is no clear explosive activity within that might suggest a hot “trigger” origin to the outward propagating bullets. This behavior may provide valuable information on the nature of the formation of bullets.

4. DISCUSSION

This paper represents a more in-depth, statistical analysis of a cluster of small-scale, bright blobs (now referred to as bullets), as initially described in Paper I. A new analysis of the cluster here has provided new insights into the dynamics of bullets, as well as their thermal structure. This was achieved through the incorporation of new information from EUV channels via *SDO/AIA* observations sampling at least TR temperature plasma in bullets. Co-spatial and co-temporal activity from AIA, together with $H\alpha$ bullets in CRISP provide valuable new spectral information.

4.1. New Observable Characteristics of Bullets

Bullets appear as small-scale, bright, laterally propagating projectiles that follow magnetic field topology, tend to appear in cascade, and are self-contained thermally evolving structures. The foremost result in this research is the one-to-one correspondences of bullets observed in a broad range of

Figure 11. Bi-directional motion of bullets are evident in six examples, four of which are presented here, for bullets observed in $H\alpha$ and 30.4 nm. The solid line tracks correspond to bullet motion only in the upward direction in the FOV, i.e., in agreement with the general cascade direction. The dashed-line tracks correspond to bullet motion only in the downward direction in the FOV. The boxed regions indicated the sources of each bullet pair in these examples. The delay intervals printed in each panel correspond to the offset in the start time of the bullets in their respective channels.

(An animation of this figure is available.)

spectral channels. Bullets can evolve in a number of ways throughout their lifetime. Some of the defining characteristics of bullets are as follows.

Size and Brightness: It is important to consider the reduced spatial resolution of the AIA instrument when observing 30.4 nm in comparison with the more resolved $H\alpha$ bullet components from CRISP. We tracked a total of 171 bullets within a dynamic, propagating cluster. More than half of these were observed in $H\alpha$. The features appear close to the diffraction limit within the CRISP observations. We measured typical bullet widths, using boundaries at the 10%–20% intensity level (relative to the background), to be in the range of $0''.3$ – $0''.4$, corresponding to 215–290 km, which is in agreement with Paper I. Alexander et al. (2013) presented observations of numerous small-scale anti-parallel flows within coronal loop threads in the 19.3 nm coronal channel at a resolution limit close to that of Hi-C (Cirtain et al. 2013). It was concluded that such fine scale million degree structures would have gone undetected in AIA. Therefore, it may be that the 30.4 nm bullets observed in AIA here could also exist at scales more comparable with the $H\alpha$ bullets. Zacharias et al. (2011) simulated the formation of a small-scale (1–2 Mm) hydrodynamic blob-like feature numerically, which was seemingly pumped from a loop foot-point in the solar transition into the corona along a trajectory defined by the coronal magnetic field. The observed bullets described here differ, such that they are almost one order of magnitude smaller, they fragment into a cluster, are faster, and have a more complicated thermal structure. We discovered that some bright bullets in $H\alpha$ are co-spatial and co-temporal (coincident) with similar features in emission in 30.4 nm; however, the 30.4 nm bullet, on average,

has a larger diameter of $1''$.5 or 720–1080 km. The size ratio of coincident bullets can vary quite a lot. Bullet 3 of Figure 3 panel C has a 30.4 nm counterpart that is ~ 15 times larger in cross-sectional area. One assumes that the $H\alpha$ bullet represents the cool, compact core being surrounded by a slightly larger 30.4 nm emitting TR. The true size of the 30.4 nm bullet cannot be determined from the current data, given the instrumental limitations.

The relative brightness ratio (with respect to the spectral background level) was a factor of ~ 2 greater in the 30.4 nm bullet than in the coincident $H\alpha$ bullet. The relative intensity of $H\alpha$ bullets appears within a 10%–20% intensity range while the coincident 30.4 nm bullets have a 50%–60% intensity range throughout the cluster (as depicted in Figure 2 sub-plot [2]). The intensity ratios determined here are measured with respect to the background level of the respective passbands of 30.4 nm and $H\alpha$. However, the brightness ratios in these lines are widely different in terms of radiated energy per unit area and time. The background continuum around $H\alpha$ is about 300 times brighter than the observed background of 30.4 nm (Lean 1991; Woods 2002). Given that the $H\alpha$ line center is close to 20% of the nearby continuum level suggests that the $H\alpha$ reference background could be 60 times that of the 30.4 nm background. Taking into account the factor of two difference in the relative intensity ratios of the bullets deduced here, on an absolute scale, it should correspond to $H\alpha$ bullets being around 30 times brighter than the 30.4 nm. As an approximation, the 30.4 nm bullets may indeed be at least a factor of 10 brighter relative to the background than actually observed at the resolution of AIA. Therefore, taking this factor of 10 into consideration for the bullet case, the best estimate is that the typical absolute brightness of the $H\alpha$ bullets is 3–10 times brighter than the corresponding 30.4 nm bullet. Hall & Hinteregger (1970) and Ahmad & Withbroe (1977) indicate a relative difference of several orders of magnitude in considering $H\alpha$ compared with 30.4 nm. This estimate seems reasonable since the 30.4 nm component is possibly emitted from a thinner, surrounding transition layer. The picture being presented here is of a bullet with a highly rounded 3D structure, a relatively dense and cooler core (in $H\alpha$ forming at ~ 7000 – $10,000$ K), which has an outer envelope of transition region of less dense and hotter plasma at $\sim 80,000$ K.

Brightness evolution: The predicted existence of a temperature evolution of the $H\alpha$ bullets from Paper I, is confirmed in this study. The majority of bullets tracked appear as bright $H\alpha$ features with one-quarter of all tracks observed in 30.4 nm, and about one-eighth were equally distributed across the hotter channels. A very interesting finding in comparing coincident $H\alpha$ and 30.4 nm bullets is the inverse relationship in the brightness of these two lines as shown in the sub-plot [2] of Figure 5, with a fitted gradient of -2.18 despite the linear correlation between corresponding/coincident bullets with respect to velocity. Assuming that the $H\alpha$ line emission is controlled by recombination in a partially ionized hydrogen gas and thereby scaled as N_e^2 (cf Engvold 1976), the observed variations in $H\alpha$ emission should imply fairly modest changes in density of about 3%–5%. A momentary increased emission in $H\alpha$ will result from an electron density increase, which subsequently leads to increased recombination and enhanced Balmer line emissions. The effect on the 30.4 nm intensity resulting from a density increase will be different, as shown in non-LTE prominence model calculations (Labrosse &

Gouttebroze 2001; Labrosse et al. 2010). A density increase will lead to a decrease in singly ionized He, which very likely also may result in a decrease in 30.4 nm emission. The sub-plot [2] of Figure 5 is in agreement with this interpretation since increased brightening in H α (implying electron density increase) corresponds with reduced intensity in 30.4 nm matched bullets. Since the 30.4 nm line is also influenced by incident radiation from the surrounding atmosphere, further discussion of the observed inverse relation should be based on more detailed radiative transfer modeling. Bullet formation could be interpreted as a response of an AR corona being in a near-continuous state of thermal non-equilibrium, leading to recycling of thermal energy transferred in the form of bullets. Evidence for the effects of thermal non-equilibrium in the form of small-scale coronal loop sub-structures is clearly demonstrated in recent advanced 3D radiation MHD simulations (Olluri et al. 2013; Froment et al. 2014). The detectability of the bullets in the hotter EUV channels, such as 19.3 and 21.1 nm, is more challenging given the reduced signal-to-noise and apparently more diffuse appearance of the bullets, within the respective X - T diagrams. As a consequence of the intensity ratio thresholding, as a criteria for bullet selection, we may be under-sampling the bullet number densities detected in these channels. The response of various emission lines in the EUV to the bullet triggering mechanism, will inevitably depend on the radiative origin and nature of these different lines, which is further complicated by the broadness of the passbands and thereby sensitive to line blending. We have already indicated that H α of neutral hydrogen responds very differently compared with He II 30.4 nm of ionized helium. It is a very important issue for future follow-up studies to understand the significance of the relative brightness variations in all other EUV channels presented here, with regard to the multithermal nature of bullets.

Velocity properties: Bullets propagate with relatively constant velocities in time. From Figure 6, we find that the bullet velocity distribution in the cluster peaks at 52 km s^{-1} with an FWHM of $\pm 33 \text{ km s}^{-1}$. This distribution is again in agreement with the velocity properties of Paper I; however, now we can demonstrate an equally close agreement with the hotter bullets in the cluster, as observed with AIA. Within the H α bullet velocity distribution of Figure 5, we find a striking linear correlation with coincident 30.4 nm bullet velocities, as presented in sub-plot [1], with a fitted line with 0.87 gradient indicating an almost 1:1 linear correlation between the bullets. The tail-end of the velocity distribution in H α extends out to a maximum of 145 km s^{-1} , which corresponds to the fastest detected H α bullet. However, an interesting feature from the velocity distribution was the presence of very-high-velocity bullets, which exist outside of the Gaussian fit to the more abundant cooler bullets. When considering only the AIA channels, the fastest bullet detected was in the apparent coronal 19.3 nm channel, with an apparent velocity of 200 km s^{-1} . Higher velocity bullets appear early on in the evolution of the cluster with progressively cooler bullets following. This trend was in agreement with the order of appearance of cascade C (Figure 8). Within the cluster, we identified a number of sources of concentrated bullet tracks from the apparent coronal channels, named as trigger events. These trigger bullets propagate in the range of $85\text{--}200 \text{ km s}^{-1}$. Within the main cluster 5 trigger source regions could be identified and they spread sequentially across the main cluster. Note that there is

no observational evidence for Doppler shifts of the bullets in H α , where we have highly sampled line scans.

Cascading trajectories: As the cascade evolves, the bullets appear to fan outward into multiple threads in what could be described as an avalanche-effect. 63 s before the end of cascade A (11:09:07 UT), we detect the beginning of cascade B. Additionally, thread #3 is situated between threads #1 and #2 of cascade A, so the formation of cascade B is most likely related to cascade A. The vast majority of the detected bullets propagating along the same direction within the FOV (represented by the large black arrow in Figure 6) and throughout the evolution of the cascades. Within individual bullets there are slight deviations away from the straight-line direction, as is evident from the threads of cascade A in Figure 7. Bullets do not necessarily propagate in one given direction over their lifetime. H α Bullet #3 of Figure 3 (panel C) displayed a significant deviation to the left (in the plane of sky) by $\sim 70^\circ\text{--}80^\circ$ and then to the right by $\sim 70^\circ\text{--}80^\circ$ (within the white dashed box) to bring it back on course with the cluster flow direction. Nano-flare storms are considered to be one such impulsive heating mechanism that can spontaneously occur in coronal loop systems, driven by multiple small-scale magnetic reconnections and with resulting small-scale projectiles that are thought to exhibit cascade-like behavior (Warren et al. 2002, 2003; Winebarger & Warren 2005; Klimchuk 2006; Testa et al. 2014). In the case of bullets, we see parallels with nano-flare storms since the cascading and bi-directional bullets are sourced to a common origin in the cluster and therefore may have a common triggering mechanism. Individual nano-flares in coronal loops have been shown to exhibit bursty behavior in *SDO* channels lasting 500 s and with lengths of 150 Mm (Viall & Klimchuk 2012). When we combine the information from the track lengths of cascade C, we estimate, similarly, a total propagation distance of the cluster to be 98.3 Mm over a lifetime of approx. 900–1000 s. Viall & Klimchuk (2012). Likewise, Archontis & Hansteen (2014) used radiation MHD simulations of interacting magnetic bipoles in a coronal environment, which resulted in clusters of small-scale flares 1–2 Mm in scale. This activity formed naturally via patchy reconnection, leading to small-scale plasmoid ejections with energetics characteristic of nano-flare behavior. These flares were short-lived (30 s to 3 minutes) and on a similar spatial and temporal scale, as hot components of bullets observed here. However, those simulated plasmoids exhibit similar characteristics from previous studies of larger flare-driven plasmoid eruptions (Tsuneta 1997; Archontis et al. 2006), such as, having associated jets and cusp-like structures and we do not detect such flaring behavior associated with bullets here. Furthermore, the cluster of bullets tend to laterally propagate and cascade across the FOV, rather than erupt upward or downward. Since there is no evidence for Doppler motions in bullets, we do detect evidence of internally heated mass flows in bullets and so they cannot be similar to nano-flare behavior.

Lifetime: The peak in the lifetime distribution for the cluster (Figure 6) revealed that most bullets exist for 75 s with an HWHM extending the typical lifetimes of bullets to 135 s. The hottest (19.3 and 21.1 nm) detected bullet lifetimes are in the range of 35–95 s (with peaks at 65 s in 21.1 nm and 70 s in 19.3 nm), whereas, the relatively cooler 17.1 and 30.4 nm bullets have a peak lifetime in the 155–215 s interval. Given that the left-side tail of the lifetime Gaussian distribution is not

present in Figure 6 (panel E), implies that there may be shorter-lived bullets that have gone undetected. With a detection criteria of at least six frames used to construct bullet tracks (i.e., making them identifiable within X - T diagrams), the shortest-lived detectable bullets will therefore have a lifetime of ~ 54 s, so our observations are not very sensitive to short-lived bullets of less than 1 minute. Faster bullets with shorter lifetimes (than the minimum lifetime detected of 69 s) should be detected within our detection criteria of six frames. If they exist, they are presumed to have been too faint to confidently detect for this study. One notable feature concerning 30.4 nm and $H\alpha$ bullets is the difference in the observed lifetimes and lengths with 30.4 nm being on average longer lived by ~ 100 s resulting in their longer lengths on average (as revealed in distributions (1) and (2) of panels E and F of Figure 6). This could be a result of differing rates of compression of the plasma, assuming an MHD fast mode pulse explanation, for the same reason as discussed in the brightness evolution section. As the MHD pulse amplitude may gradually be dampened and weaken and thereby decrease the induced plasma density, it will lead to some reduction in the $H\alpha$ bullet emission. The consequences for the corresponding 30.4 nm bullet may be different for reasons discussed under the subsection of brightness evolution, which ultimately may give rise to slightly different bullet lifetimes in these two spectral lines.

Multithermal structure: Co-moving, multithermal associations of bullets most likely imply that bullets are wrapped in a temperature transition layer. Such properties have been observed previously in the outer solar atmosphere, e.g., in the envelope that appears around large-scale filaments, commonly referred to as the prominence-corona-transition-region (PCTR: Chiuderi & Chiuderi Drago 1991; Heinzel et al. 2001; Heinzel & Anzer 2001; Labrosse et al. 2010). In the PCTR models, the temperature of plasma in prominences exhibits a similar rise from about 7000 K up to 1 million K. Given the relative proximity of the formation of the $H\alpha$ line core (Leenaarts et al. 2012) and the 30.4 nm line, with respect to height in the solar atmosphere, it is expected that there should be a lot of correspondence between the behavior of detectable features in both spectral channels. The AIA instrument has a broad temperature coverage in the 30.4 nm channel compared with the narrower thermal range of the $H\alpha$ line core with CRISP. Assuming an environment where there is a local pressure and thermal equilibrium, as an initial condition, a change in density will be accompanied by a local change in pressure and emission and so detectability in cooler spectral channels. This imbalance of thermal equilibrium, with respect to temperature and density fluctuations, may be evident in the examples of bullet threads in cascades A and B (see Figure 7), which appear to fluctuate between the 30.4 nm and $H\alpha$ passbands. The important point here is that in describing the multithermal structure, the bullet itself may not have necessarily ended at the apparent end-point along its track but rather simply evolved out of detection in that respective passband, as a result of local internal enhancements in pressure/density which explains the observed brightness variations, rather than by heating or cooling processes.

5. CONCLUSIONS

This study highlights the fact that the outer atmosphere of the Sun is riddled with small-scale, dynamic and rapidly evolving structures that frequently appear out of

thermodynamic equilibrium. The most notable new result in this analysis is the discovery of multiple, connected bullet cascades and bi-directional motions in the activity of a laterally propagating cluster of bullets, previously studied as part of Paper I. The observations of cascades of bullets at high resolution, across a broad temperature spectrum is a very new and exciting insight into the fine-scale structure of the solar corona and transition region. Given that many of the bullets appear close to the diffraction limit in CRISP $H\alpha$ spectral scans and that we have set a fixed intensity contrast criteria for selection in the X - T diagrams, we conclude that the number densities of bullets detected in each of the wavelength channels must be considered as a lower limit. The nature of solar bullets remains open to debate and in our conclusions, we will outline the pros and cons concerning their association with other detections of equally small-scale structures in solar corona AR.

5.1. Formation of Bullets: Internally Heated Mass Flows or MHD-Type Pulses Affecting Plasma Emission?

We arrive at two main scenarios depicting their formation. The timescale of multithermal bullet evolution (over hundreds of seconds) is comparable to other similar thermal instabilities, driving small-scale cooling processes with origins near coronal loop-tops, such as coronal rain (see Antolin & Rouppe van der Voort 2012, and references therein). Such dynamic multithermal behavior in small-scale features near coronal loop-tops of AR, including the short-term presence of chromospheric plasma sub-structures is also attributed to flare-driven coronal rain clumps undergoing catastrophic cooling processes (Scullion et al. 2014). Although, gravity driven acceleration is thought to explain coronal rain flows along magnetic strands, this is not likely in the case of faster moving bullets, which do not appear to fall into the Sun but rather traverse laterally across its surface. Additionally, this picture does not fit because internal heating should evidently cause an observable tail of radiative cooling of the plasma, as detected in coronal rain flows. However, bullets appear as rather distinct, bright slightly elongated structures that do not exhibit tail-like structures.

In Paper I, the MHD wave pulse mechanism was suggested to explain the formation of the bullets. An acoustic (sound pulse) such as the MHD slow-mode could not explain the high speeds of bullets observed. A pure Alfvén wave pulse would not lead to compression of the plasma to account for internal density and temperature variations leading to enhanced emission in the $H\alpha$. Zaqarashvili et al. (2010) observed an upward propagating intensity blob at the solar limb with similar morphology to bullets described here and proposed that it could be explained as a slow sausage soliton (see Roberts & Manganey 1982; Ballai et al. 2003). This remains as one of the most plausible formation mechanisms behinds these features, since nonlinear sausage waves can propagate faster than the sound speed in the magnetically structured solar atmosphere. It is generally assumed that fast MHD pulses are resulting from local magnetic flux emergence and reconnection at the photospheric roots of the magnetic fields.

The bi-directional and cascading nature of the bullets is a very essential new finding of this paper, which suggests that the roots of the involved magnetic field structures are occasionally located sufficiently close such that several bullets may be triggered by the same disturbance. Bi-directional jets are commonly associated with magnetic reconnection events (Innes et al. 1997). Bullets can indeed exhibit bi-directionality,

but do not behave as jet-like events and an absence of a Doppler velocity component in the H α line scans of bullets is indicative that the internally heated mass flow argument is not well supported within the best available observations. The propagating MHD pulse model should best describes the overall multithermal structure, evolution, and observational properties of bullets.

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