TEMPORAL VARIABILITY OF ACTIVE REGION OUTFLOWS

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ABSTRACT

Recent observations from the Extreme-ultraviolet Imaging Spectrometer (EIS) on board Hinode have shown that low-density areas on the periphery of active regions are characterized by strong blueshifts in the emission of spectral lines formed at 1 MK. These Doppler shifts have been associated with outward propagating disturbances observed with extreme-ultraviolet and soft X-ray imagers. Since these instruments can have broad temperature responses, we investigate these intensity fluctuations using the monochromatic imaging capabilities of the EIS wide slit (slot) and confirm their 1 MK nature. We also look into their spectral temporal variability using narrow slit observations and present the first Doppler movies of the outflow regions. We find that the Fe xii 195.119 Å blueshifted spectral profiles at their footpoints exhibit transient blue wing enhancements on timescales as short as the 5 minute cadence. We have also looked at the fan peripheral loops observed at 0.6 MK in Si vi 275.368 Å in those regions and find no sign of the recurrent outward propagating disturbances with velocities of 40–130 km s\(^{-1}\) seen in Fe xii. We do observe downward trends (15–20 km s\(^{-1}\)) consistent with the characteristic redshifts measured at their footpoints. We, therefore, find no evidence that the structures at these two temperatures and the intensity fluctuations they exhibit are related to one another.

Key words: Sun: atmosphere – Sun: corona – Sun: transition region

Online-only material: animations, color figures

1. INTRODUCTION

Coronal loops are the building blocks of the solar atmosphere. In active regions (ARs), they are structures observable at a wide range of temperatures, from several thousand up to multimillion degrees, although these structures are not necessarily co-spatial and co-temporal.

In the cores of ARs, loops either remain quasi-steady at temperatures beyond approximately 2 MK and show no counterpart but the mott at 1 MK and below (e.g., Antiochos et al. 2003; Brooks & Warren 2009) or experience a continuous and obvious process of heating and cooling across that temperature range (e.g., Winebarger & Warren 2005; Ugarte-Urra et al. 2009).

At the periphery of ARs, rooted in strong flux concentrations (some in sunspots; Foukal 1978), there are cool loops with temperatures of 1 MK (Schrijver et al. 1999) and under, with footpoints that often adopt fan-like geometries: the so-called fan loops. High cadence extreme-ultraviolet (EUV) movies of these loops reveal upward propagating motions with projected velocities of 50–150 km s\(^{-1}\) (Berghmans & Clette 1999; Schrijver et al. 1999; Sakao et al. 2007; McIntosh & De Pontieu 2009) that have been interpreted as flows, but also as waves (De Moortel et al. 2002a, 2002b; Wang et al. 2009; Stenborg et al. 2011). Spectroscopic analyses show that these loops have temperatures of 0.6–1 MK and densities comparable to those of the core loops and emit particularly strongly in the Mg vi, Mg vii, Si vii, and Fe viii lines (Del Zanna 2003; Del Zanna & Mason 2003; Young et al. 2007), which have an ionization equilibrium temperature \(\lesssim10^5\) K. The emission of these lines is consistently redshifted (Winebarger et al. 2002; Marsch et al. 2004; Del Zanna 2008; Warren et al. 2011), which is difficult to reconcile with the upward propagating disturbances, but it is in agreement with the downstreaming plasma that has been observed off-limb in high cadence monochromatic imaging (e.g., Ugarte-Urra et al. 2009). The fans can live for hours and days (Schrijver et al. 1999), but the individual structures evolve on timescales of the order of tens of minutes.

Also at the periphery, there are low-density areas at 1–2 MK that are hardly noticeable in emission when compared to the core loops. In fact, only recent spectral measurements from the Extreme-ultraviolet Imaging Spectrometer (EIS) on board Hinode have revealed that these areas are very distinct in Doppler maps for their characteristic strong blueshifts and enhanced broadening of Fe xii–Fe xv lines (Doschek et al. 2008; Harra et al. 2008; Del Zanna 2008). The shifts in the spectral line profiles are up to 50 km s\(^{-1}\), but asymmetries in the blue wings expose contributions from plasma at 100–200 km s\(^{-1}\) (McIntosh & De Pontieu 2009; Bryans et al. 2010), indicative of outflows that often persist for many days. These regions lie over or near magnetic flux concentrations of a single polarity (Doschek et al. 2008).

McIntosh & De Pontieu (2009) have argued that the persistent blueshifts in the outskirts of ARs are the spectral signature of the disturbances observed by EUV imagers in the 1 MK loops and suggest that the upflows are related to chromospheric spicule activity. Whether the fan cool loops establish the connectivity between those temperature regimes and become the channels where these disturbances propagate remains unclear. Warren et al. (2011), upon studying the temperature dependence of the outflows, suggest that the fan loops and the outflows form two largely independent populations.

In this paper, we investigate further the relationship between these structures by studying the spectral short-term temporal variability of the fan loops and the low-density areas at the periphery of two ARs. We find short timescale variability in the blue wing enhancements in the Fe xii 195.119 Å line, supportive of the transient nature of the disturbance precursors. We do not, however, find any obvious relationship between the temporal response of the low-density plasma at 1 MK and the evolution of the high-density 0.6 MK loops. We do
observe disturbances propagating out in the Fe\textsubscript{xii} 195.119 Å monochromatic imaging, which is qualitatively consistent with the blueshifts, but no outward disturbances are detected in the Si\textsubscript{vii} 275.368 Å line. Time sequences in this line show downward propagating trends that are consistent with the redshifted emission of the line.

2. OBSERVATIONS

We present results from two AR data sets obtained with the EIS (Culhane et al. 2007) on board Hinode (Kosugi et al. 2007). The EIS instrument is a high spatial (1" or 2" pixel\(^{-1}\)) and spectral (22 mÅ) resolution imaging spectrograph. It observes coronal and transition region spectral lines in two wavelength ranges: 170–210 Å and 245–290 Å. Users can opt between narrow slit spectroscopy (1" and 2" slits) or wide slit imaging (40" and 266" slits).

EIS observed AR 11048 on 2010 February 17. The observing sequence (10:45–15:27 UT) consisted of 480" \(\times\) 488" images made out of 15 consecutive 10 s exposures at adjacent solar positions, resulting in a 3 minute cadence. We will discuss here in more detail images from two spectral lines: Si\textsubscript{vii} 275.368 Å and Fe\textsubscript{xii} \(\lambda\) 195.119 Å. The spectral purity of these images is 0.9 Å. The imaging sequence was preceded and followed by two narrow slit (1") 178" \(\times\) 512" rasters. The rasters are sparsely sampled: the slit takes 3" steps between every exposure (50 s), which allows a faster scanning of the target. The rasters serve as a spectral diagnostics reference, in particular, for the line-of-sight velocity. Top panels in Figure 1 show slot images of the AR for the two lines of interest, plus Fe\textsubscript{xvi} 262.98 Å. The dotted line encloses the field of view of the rasters. They are located over the low-density Fe\textsubscript{xii} regions at the periphery of the AR. Note that in Si\textsubscript{vii} that region also shows bright high-density loops. Some of the spectral properties of this AR were also discussed by Warren et al. (2011).

On 2010 March 8, EIS observed the decaying AR 11045. The observing sequence starts with a context 128" \(\times\) 512" fully sampled raster (1" slit, 60 s exposures), followed by the 3 minute cadence slot imaging (17:23–20:55 UT). To investigate the short-term variability of the spectral signatures, the sequence is followed by a set of sparsely sampled rasters (2" slit, 4" steps) that cover a 58" \(\times\) 368" area in 6 minutes from 21:41 UT until 00:03 UT. The bottom panels of Figure 1 show a view of the AR and the different fields of view. The online version of the journal contains movies of both data sets.

Data were processed using standard EIS software. This involves subtraction of the dark current and correction of artifacts like cosmic rays and warm and hot pixels. Images were co-aligned using standard cross-correlation techniques. This removes both the spacecraft jitter and the displacement of the slot images along the wavelength direction on the detector due to the orbital changes in temperature (Brown et al. 2007).

3. RESULTS

Investigations of apparent motions in AR peripheral loops have been presented before. The novelty of this work is twofold. First, we provide the first look at the motions with relatively

![Figure 1](image-url)
3.1. Morphology

Figure 2 shows the rastered areas of both ARs outlined with dotted lines in Figure 1. The first column is the radiances, followed by Doppler velocities and line widths. These quantities correspond to the Gaussian fit of the spectral profiles, a two-Gaussian fit in the case of the Fe XII 195.119 Å to account for the blend with the Fe XII 195.179 Å line (Young et al. 2009).Contours of the Si VII emission have been put on top of the Fe XII maps for reference. Note that the intensity scaling is the same as in Figure 1.

There are several difficulties with measuring Doppler velocities with EIS and Warren et al. (2011) describe them in some detail. First, we need to correct for the orbital drift of the spectrum on the detector and then we have to assume a reference wavelength as our zero velocity. We use 195.119 Å and 275.368 Å, as suggested by Warren et al. (2011).

The blueshifts and width enhancements are located in regions that are dim compared to the core of the AR. This is now well known from EIS spectra (Doschek et al. 2008; Harra et al. 2008; Del Zanna 2008). The Si VII line is weak outside the clearly defined loops, so the Doppler velocities and widths are only shown for the areas with a high signal-to-noise ratio (~7). As discussed by Warren et al. (2011), these cool loops are consistently redshifted. Width enhancements can also be detected in the March 8 data set. They
mostly correspond to the dim areas in between the bright loop footpoints.

In general, Figure 2 suggests that the bright Si\textsuperscript{vii} loops are co-spatial with the Fe\textsuperscript{xii} blueshifts. There are differences, however, when we look at the details. Extended loop structures in Fe\textsuperscript{xii} have a correspondence in Si\textsuperscript{vii} in the February 17 data set, but not as much on March 8. Some of the Fe\textsuperscript{xii} outward propagating motions, which will be discussed in the next section, occur in areas where no sizable Si\textsuperscript{vii} emission can be seen—for instance, in the southwest corner of the February 17 data set. An explanation could be that at this location only the footpoints of the loops hosting the disturbances have a cooler signature. That is what Movie 1, available in the online version, shows. The March 8 data set, however, shows significant areas of the field of view that have dim Fe\textsuperscript{xii} emission and strong blueshifts with no noticeable signatures in the cooler line, e.g., around [385\textdegree,490\textdegree]. Movie 2 confirms this and rules out the possibility of a time-dependent origin for the discrepancy. What we cannot completely rule out is that the absence of a cooler plasma counterpart in these areas is just due to the instrument’s sensitivity.

### 3.2. Time-dependent Imaging

Movies 1 and 2, both available in the online version of the journal, show the variability of the two ARs' peripheral loops for the two spectral lines, Si\textsuperscript{vii} 275.368 Å and Fe\textsuperscript{xii} 195.119 Å, side by side. The February 17 data set shows Fe\textsuperscript{xii} disturbances propagating radially out from the blueshifted area presented in Figure 2. This also occurs in the March 8 observations. These apparent motions are comparable to the ones observed with Transition Region and Coronal Explorer (TRACE) and XRT/Hinode (McIntosh & De Pontieu 2009; Sakao et al. 2007). Our observations therefore confirm that the phenomenon is observable at 1 MK: the EIS wide slit images isolate a very narrow (0.9 Å) and blend free spectral region around the line (e.g., Ugarte-Urra et al. 2009). TRACE 171 Å and 195 Å passbands can be ambiguous in this respect because both bands have significant contributions from plasma at 0.6 MK, namely the Fe\textsuperscript{viii} and Fe\textsuperscript{ix} lines (Del Zanna & Mason 2003), precisely the lines in which the cool peripheral loops manifest themselves. An analogous argument can be made about the broad temperature response of XRT filters.

These outward propagating disturbances are not observed in the Si\textsuperscript{vii} images. Figures 3 and 4 show examples of time–distance plots for various representative locations in both ARs. Each figure compares the time-dependent intensity fluctuations of Fe\textsuperscript{xii} and Si\textsuperscript{vii} along four loop segments. The time–distance plots were constructed in the following manner. Following Warren et al. (2010), we first manually selected the points along the segment. The points were used as spline knots to define a loop coordinate system (s, t), where s goes along the loop’s axis and t perpendicular to it. From this interpolated straightened loop segment, we extracted the intensity along the

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**Figure 3.** Sample loops in the February 17 data set. Each six panel display at each corner of the figure is a comparison of the Fe\textsuperscript{xii} 195.119 Å and Si\textsuperscript{vii} 275.368 Å intensity fluctuations along a loop structure outlined in red. The leftmost panels show the context slot image. The middle panel is the time–distance plot, namely the radiance changes as a function of time and position along the loop. The rightmost panel is the running difference of the time–distance plot.

(A color version of this figure is available in the online journal.)
axis (1" across) and plotted it as a function of time. This is shown in the logarithmic scale in the middle panel. To its right, we also show the running difference, i.e., the difference between two consecutive intensity values at a particular location. The running difference time–distance plots have been smoothed (boxcar of three pixels) to increase the signal-to-noise ratio.

The loops are shown as a solid red line. The top two loops were selected based on the propagating lanes followed by the disturbances. The bottom two outline clearly defined loops in the Si\textsuperscript{vii} images. The time–distance plots in Fe\textsuperscript{xii} show features very similar to ones seen by TRACE and XRT: recurrent inclined ridges that represent intensity fluctuations propagating along the loops as a function of time. The velocity of propagation ranges between 40 and 130 km s\textsuperscript{−1}, as the reference solid blue lines show. These are propagation velocities on the plane of the sky and therefore only lower limits. Therefore, for Fe\textsuperscript{xii}, we find qualitative consistency between the spectral blueshifts and the upward apparent motions in the imaging.

The Si\textsuperscript{vii} time–distance plots of the top two loops do not exhibit any distinct variability. In particular, most of the emission of this line at the southwest corner of the image’s field of view is noise. The bottom loops do experience some variability. We observe downward propagating intensity changes at lower speeds 15–20 km s\textsuperscript{−1}, qualitatively consistent with the spectral redshifts measured in the rasters. Similar downflows in Si\textsuperscript{vii} loops have also been observed off-limb (Ugarte-Urra et al. 2009). If this is a manifestation of cooling loops, we do not see any evidence of them in the hotter line. The picture, however, can be more complicated than just downflows, as the last panel in Figure 3 shows, where the ridges show oppositely directed trends. Schrijver et al. (1999) already pointed out the rather complex evolution of these fan loops comparing them to “rippling curtains.” Ultimately, what seems clear from the comparison of the time–distance plots is that there is no evidence that the structures and the intensity fluctuations they exhibit in Fe\textsuperscript{xii} (1.3 MK) and Si\textsuperscript{vii} (0.6 MK) are related to one another.

As stated before, sensitivity can be an issue in the case of the cooler and weaker line, however, it does not explain why we do not see the Si\textsuperscript{vii} downward trends in Fe\textsuperscript{xii}.

The time–distance plots of the March 8 data set may appear less compelling due to the data gaps. Movies 1 and 2 show, however, that both examples portray the same phenomenon. This is important because the March 8 data set allows us to look into the time-dependent spectroscopic properties.

3.3. Time-dependent Spectroscopy

We have confirmed that there are outward propagating disturbances at 1 MK that originate in blueshifted areas at the periphery of ARs. The time–distance plots clearly show that the perturbations are discrete in nature, but spectroscopically we only know that they can persist for days (Bryans et al. 2010).

We investigate the variability of the Doppler shifts in short timescales to determine whether that transient nature is also reflected in the line profiles. Figure 5 shows a sequence of radiances and Doppler shifts for the two spectral lines in the March 8 data set. The field of view corresponds to the dashed line in Figure 1. The rasters, consisting of fifteen 20 s exposures
with 4′ steps in between, result in a 5 minute cadence. We only show one-third of that cadence in the figure. The movie is available in the online version of the journal. It confirms that Fe xii and Si vii are consistently blueshifted and redshifted.

Figure 6 (also check the movie version) shows in its left panel the Doppler shift and width variations of the Fe xii line at one particular location. While the changes observed in the main component of the line are small, within the standard deviation (dashed lines), we do detect asymmetric wing enhancements in the blue side of the line profiles, on timescales as short as the 5 minute cadence (see the right panels in Figure 6). The enhancements occur at velocities of ≈150 km s\(^{-1}\). This result confirms the suspicion that the reported asymmetric profiles discussed by Bryans et al. (2010) and McIntosh & De Pontieu (2009) can have a short-term nature, which favors an association with the discrete outward propagating intensity disturbances. The spectral line, however, is dominated by emission that exhibits a rather constant line-of-sight velocity of ≈20 km s\(^{-1}\).

4. DISCUSSION AND CONCLUSIONS

We have investigated the time-dependent spectral properties of areas at the periphery of AR cores. In Fe xii 195.119 Å (1.3 MK), we find recurrent intensity disturbances originating in low-density regions that propagate outward along loop structures at projected velocities of 40–130 km s\(^{-1}\). This is consistent with the characteristic blueshifted emission measured along the line of sight at their footpoints. We confirm the existence of asymmetrical line profiles (McIntosh & De Pontieu 2009; Bryans et al. 2010) at those footpoints and reveal for the first time that the intensity enhancements in the blue wing at velocities of ≈150 km s\(^{-1}\) are transient on timescales as short as the available cadence: 5 minutes. This supports of the interpretation of the fluctuations as a result of transient events (McIntosh & De Pontieu 2009). However, it remains to be proven that transients are the dominant contributors in these areas. The spectral profiles are dominated by small blueshifts (≈20 km s\(^{-1}\)) in the main component of the spectral line, and these shifts remain constant not only generally over hours and days (Bryans et al. 2010), but, as we show here, also in short timescales at one single location. Whether this dominant constant flow is the added result of multiple unresolved transient events remains to be tested.

Given that TRACE 195 Å images can be contaminated by the emission of 0.6 MK cool lines (Del Zanna & Mason 2003), this is the first confirmation that the outward propagating disturbances take place at 1 MK temperatures. Outward propagating perturbations have also been observed by TRACE in its 171 Å filter images, which are mostly dominated by emission from Fe ix–x lines. We do not observe those perturbations in the Si vii fan loops, which suggests either that the EIS instrument is not...
sensitive enough to detect them or that the perturbations observed on the 171 Å fan loops are coronal in nature and a result of the broader temperature response.

In Si VII 275.368 Å (0.6 MK), the areas in the periphery of the AR alternate apparent voids with high-density bright loops characterized by emission which is consistently redshifted. No sign of the recurrent outward propagating disturbances is detected; instead, when trends are present they are generally downward at velocities of ≈15–20 km s\(^{-1}\), qualitatively consistent with the spectral measurements at the footpoints. We therefore find no evidence that the structures and the intensity fluctuations visible at 1 MK and 0.6 MK are related.

Warren et al. (2011) suggest that the fan cool loops and the outflows form two largely independent populations. The disturbances would propagate out from the low-density outflow regions, possibly connected to the heliosphere by open field lines, while the 0.6 MK loops reveal closed connections subject to the usual AR heating and cooling processes (e.g., Ugarte-Urra et al. 2009). Our results support this scenario, which is still compatible with a transient chromospheric origin for the disturbances, just one in which the fan loops are not necessarily the channels. New coordinated observations combining the spectral purity of EIS and the high sensitivity and fast cadence of the Atmospheric Imaging Assembly/Solar Dynamics Observatory should shed some light on this issue.

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REFERENCES

Antiochos, S. K., Karpen, J. T., DeLuca, E. E., Golub, L., & Hamilton, P. 2003, ApJ, 590, 547
Berghmans, D., & Clette, F. 1999, Sol. Phys., 186, 207
Brooks, D. H., & Warren, H. P. 2009, ApJ, 703, L10
Brown, C. M., et al. 2007, PASJ, 59, 365
Bryans, P., Young, P. R., & Doschek, G. 2010, ApJ, 715, 1012
Culhane, J. L., et al. 2007, Sol. Phys., 243, 19
Del Zanna, G. 2003, A&A, 406, 5
Del Zanna, G. 2008, A&A, 481, 49
Del Zanna, G., & Mason, H. 2003, A&A, 406, 1089
De Moortel, I., Hood, A., Ireland, J., & Walsh, R. 2002a, Sol. Phys., 209, 89
De Moortel, I., Ireland, J., Walsh, R., & Hood, A. 2002b, Sol. Phys., 209, 61
Doschek, G., Warren, H., Mariska, J. T., & Muglach, K. 2008, ApJ, 686, 1362
Foukal, P. 1978, ApJ, 223, 1046
Harra, L. K., Sakao, T., Mandrini, C. H., Hara, H., Imada, S., Young, P. R., Van Driel-Gesztelyi, L., & Baker, D. 2008, ApJ, 676, L147
Kosugi, T., et al. 2007, Sol. Phys., 243, 3
Marsch, E., Wieleman, T., & Xia, L. 2004, A&A, 428, 629
McIntosh, S. W., & De Pontieu, B. 2009, ApJ, 706, L80
Sakao, T., et al. 2007, Science, 318, 1585
Schrijver, C. J., et al. 1999, Sol. Phys., 187, 261
Stenborg, G., Marsch, E., Vourlidas, A., Howard, R., & Baldwin, K. 2011, A&A, 526, A58
Ugarte-Urra, I., Warren, H. P., & Brooks, D. H. 2009, ApJ, 695, 642
Wang, T. J., Ofman, L., Davila, J. M., & Mariska, J. T. 2009, A&A, 503, L25
Warren, H. P., Kim, D. M., DeGiorgi, A. M., & Ugarte-Urra, I. 2010, ApJ, 713, 1095
Warren, H. P., Ugarte-Urra, I., Young, P. R., & Stenborg, G. 2011, ApJ, 727, 58
Winebarger, A. R., & Warren, H. P. 2005, ApJ, 626, 543
Winebarger, A. R., Warren, H. P., van Ballegooijen, A., Deluca, E. E., & Golub, L. 2002, ApJ, 567, L89
Young, P. R., Del Zanna, G., Mason, H. E., Doschek, G. A., Culhane, L., & Hara, H. 2007, PASJ, 59, 727
Young, P. R., Watanabe, T., Hara, H., & Mariska, J. T. 2009, A&A, 606, 887

Figure 6. Left: Doppler velocity and width of the Fe xii 195.119 Å line as a function of time for a representative location in the fast scans (cross symbol in Figure 5). The average value and the standard deviation from it are represented by the horizontal solid and dotted lines. Right: spectral line profiles for six different times (vertical dotted lines) in blue. In black is shown a reference profile for a location outside of the blueshifted region (plus symbol in Figure 5).

(An animation and a color version of this figure are available in the online journal.)