Solar Transition Region Features Observed with Hinode/EIS

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Abstract

Two types of solar active region feature prominent at transition region temperatures are identified in Hinode/EIS data of AR 10938 taken on 2007 January 20. The footpoints of 1 MK TRACE loops are shown to emit strongly in emission lines formed at log $T = 5.4$–5.8, allowing the temperature increase along the footpoints to be clearly seen. A density diagnostic of Mg VII yields the density in the footpoints, with one loop showing a decrease from $3 \times 10^9$ cm$^{-3}$ at the base to $1.5 \times 10^9$ cm$^{-3}$ at a projected height of 20 Mm. The second feature is a compact active region transition region brightening which is particularly intense in O V emission (log $T = 5.4$) but also has a signature at temperatures up to log $T = 6.3$. The Mg VII diagnostic gives a density of $4 \times 10^{10}$ cm$^{-3}$, and emission lines of Mg VI and Mg VII show line profiles broadened by 50 km s$^{-1}$ and wings extending beyond $\pm 200$ km s$^{-1}$. Continuum emission in the short wavelength band is also found to be enhanced, and is suggested to be free-bound emission from recombination onto He$^+$. 

Key words: Sun: transition region — Sun: UV radiation

1. Introduction

The Extreme ultraviolet Imaging Spectrometer (EIS) instrument on Hinode (Culhane et al. 2007; Kosugi et al. 2007) covers the two wavelength bands 170–211 and 246–292 Å that are dominated by coronal emission lines mainly from the iron ions. The majority of strong transition region lines in the solar spectrum are found at longer UV wavelengths, and all of the transition region lines found in the EIS bands are weak in normal conditions. Young (2007) however identified two types of active region features that were found from SOHO/CDS observations to yield significantly enhanced transition region emission lines: coronal loop footpoints and active region blinkers. He suggested that in such events the weak EIS lines would become significant, and so yield useful science.

An EIS observation from 2007 January 20 is presented here that displays both types of active region feature identified by Young (2007) and demonstrates the value of including transition region lines in EIS studies.

2. Data

Active region AR 10938 crossed the solar disk during 2007 January 12–24. It was a well-developed active region showing large cool loop structures visible in the TRACE 171 channel (figure 1, left panel), and a more compact high temperature core visible in Hinode/XRT images (figure 1, right panel). During the period January 18–23 the EIS observing study PRY_loopFootpoints was run a number of times at the footpoint regions of the loop system. This study uses the 2″ slit to raster over an area of 100″ × 216″ with 30 s exposure times, giving a total duration of 26 min. The 2″ slit was used to both increase the counts for weak lines, and allow a larger spatial area to be covered more rapidly; the disadvantages are a degradation of the spatial (in the X-direction) and spectral resolution over the 1′ slit. Due to on board data storage restrictions, only a fraction of the total EIS wavelength range could be downloaded, and so 20 wavelength windows were chosen to observe the transition region lines as well as a number of coronal lines. The list of the transition region lines (defined as emission lines whose temperature of maximum ionization, $T_{max}$, is below log $T = 5.8$) is given in table 1. Further discussion of useful transition region emission lines observed with EIS is given in Young et al. (2007).

Raster images for a number of the emission lines are shown in figure 2. The two EIS wavelength bands are imaged onto different CCDs and there is a spatial offset in the Solar-Y direction between the CCDs that varies with wavelength and ranges from 16 to 20 pixels depending on the wavelengths being compared. A fixed offset of 17 pixels has been applied to the images in figure 2. In addition, when comparing raster images from the two CCDs, there is a spatial offset in the solar-X direction of around 2″. The images have also been corrected for this effect.

The data have been calibrated to yield intensities in units of erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ at each pixel in the data-set. The dark current and CCD pedestal were removed by subtracting the median value of the darkest 2% pixels in each wavelength window. Cosmic rays and CCD hot pixels were removed using the IDL routine NEW_SPIKE. The conversions from data numbers
Fig. 1. The left-hand panel shows a TRACE 171 filter image taken at 22:40 UT. The approximate location of the EIS raster is indicated by a black box. The right-hand panel shows an XRT image taken with the Al-Poly filter at 22:36 UT. For both images dark areas are bright in intensity.

Fig. 2. EIS raster images in ten different emission lines for the spatial region indicated in the TRACE image of figure 1. The loop footpoints are most clearly seen in Mg V–VII, Si VII, and Fe VIII. The box on the Si VII image indicates the region shown in figure 3, while the arrow in the O V image points to the location of the active region transition region brightening (ARTRB).
to photons and on to calibrated intensities were performed using data contained in the EIS directory of the Solarsoft IDL distribution.

3. Loop Footpoints

Figure 3 shows a number of “clumps” of loop footpoints that can be readily identified with the loops in the TRACE 171 image (figure 1). The spectroscopic properties of such loops have been studied previously by Del Zanna (2003) and Del Zanna and Mason (2003) using SOHO/CDS spectra. In particular, there is a steep temperature increase at the loop base, leading to transition region lines being formed in a small spatial area at the footpoint of the loop. The main body of the loop is at temperatures of around 1 MK and thus strongly emits in the Mg V, Mg VI, and Si VII lines clearly demonstrates that the TRACE 171 passband. The Mg VII λ319.0/λ367.7 density diagnostic yielded densities of \( \approx 2 \times 10^9 \text{ cm}^{-3} \).

Although EIS lacks the strong transition region lines (such as Ne VI λ562.8, O V λ629.7) observed by SOHO/CDS, the images in figure 2 clearly demonstrate that the footpoints of the 1 MK loops can be identified in the EIS data. In particular, enhanced emission at the base of the loops can be seen in Mg V, Mg VI and, to a lesser extent, O V. A comparison from flux outside of the footpoint regions is shown in figure 4, demonstrating the strong enhancement of the cool lines. Generally the cool Mg emission can be identified to extend for a significant length along the loops (10–50”). We demonstrate below how the EIS spectra can be used to derive temperature, density, and filling factor information about these loops.

3.1. Temperature Analysis

A simple visual inspection of the loop footpoint images in figure 2 shows that the Fe VIII λ185.21 structures look very similar to Si VII λ275.35 structures. This is at odds with the temperatures of maximum ionization given in table 1 that are derived from the Mazzotta et al. (1998) ion balance calculations. The ionization and recombination rates are expected to be considerably more uncertain for Fe 7+ than those for Si 6+ given its more complex atomic structure. A conclusion from the EIS images is thus that Fe VIII is actually principally formed at a temperature of \( \log T = 5.8 \). This will have a knock-on effect for Fe IX which also must be formed at a higher temperature than given by Mazzotta et al. (1998).

The different appearance of the loop footpoint regions in the Mg V, Mg VI, and Si VII lines clearly demonstrates that the loops are not isothermal in the lowest \( \approx 10 \text{ Mm} \) of the loop. We defer to a later paper a discussion of whether the loops are not isothermal in the lowest \( \approx 10 \text{ Mm} \) of the loop. Del Zanna (2003) inferred the latter from his analysis of SOHO/CDS spectra.

Two weak footpoints are highlighted by two arrows in the Mg VII image of figure 3. They show a different character...
Fig. 4. Comparison of spectra at the two pixels identified in figure 3. The spectrum from within the footpoint (white cross in figure 3) is identified with a solid line. The shaded spectrum is from a pixel outside of the footpoint (black cross in figure 3). The $Y$-axis shows the strength of the lines in data numbers (DN) per second.

Fig. 5. Theoretical variation of the Mg VII $\lambda$280.75/\(\lambda\)278.39 ratio with density. Produced using v.5.2 of the CHIANTI atomic database (Landi et al. 2006).

to the other more extended footpoints in the image, being significantly more compact in Mg V–VII. Comparing the different images in figure 2 and also the TRACE image (figure 1) shows that these loops are hotter, emitting principally in Fe XII $\lambda$195.1 rather than Fe IX and Fe X.

3.2. Density Analysis

The EIS long wavelength channel contains the Mg VII $\lambda$280.75/$\lambda$278.39 density diagnostic which is directly comparable to the $\lambda$319.0/$\lambda$367.7 diagnostic that was observed with SOHO/CDS (Young & Mason 1997; Del Zanna 2003). The diagnostic is sensitive to densities in the range $10^8$–$10^{11}$ cm$^{-3}$ (figure 5), but analysis is complicated by a blend of the $\lambda$278.39 line with Si VII $\lambda$278.44. A simultaneous two Gaussian fit to the feature is, however, able to resolve the two components if both are assumed to have the same width (this is a reasonable assumption since the two ions are formed at very similar temperatures). Tests of the validity of the two Gaussian fits have been confirmed with the current data-set by comparing the derived intensities with the Si VII $\lambda$275.35 and Mg VII $\lambda$276.14 lines. The Si VII $\lambda$278.44/$\lambda$275.35 and Mg VII $\lambda$276.14/$\lambda$278.39 ratios are branching ratios with fixed theoretical ratios of 0.32 and 0.20, respectively.

Figure 6 shows the densities derived from the Mg VII diagnostic for a number of positions along the loop structure highlighted by an arrow in the Mg VII image of figure 3. Four to five pixels across the loop width (i.e., in the solar-$Y$ direction) were averaged to derive the line intensities. An estimate of the background was made by summing a number of pixels in a low intensity region just to the north of the loop. There is a clear trend of decreasing density along the structure. The density estimates are in excellent agreement with those obtained by Del Zanna (2003) and Del Zanna and
Mason (2003) demonstrating that such values are typical for 1 MK loops. The improved spatial resolution of EIS over CDS now means that the spatial variation of density in the footpoint regions can be accurately measured giving additional constraints on theoretical loop models.

By assuming an isothermal plasma whose temperature is $T_{\text{max}}$ of Mg VII, it is possible to use the density measurements to estimate the column depth of the plasma in the loop. The atomic data from v5.2 of CHIANTI (Landi et al. 2006; Dere et al. 1997) were used together with the coronal abundances of Feldman et al. (1992) to derive column depths of 1.6–5.4 Mm ($2.48\times10^3–7.01\times10^3$). These values are comparable to the observed diameter of the loop (around $5\times10^3$–$10\times10^3$) and thus suggest a filling factor of around unity.

4. Transition Region Brightening

The small intense brightening (heretoafter referred to as an ARTRB — active region transition region brightening) seen in the raster images (figure 2) was only present in one of the sequence of EIS rasters. However, the evolution of the event can be seen from TRACE images (figure 7) that demonstrate that it began at 22:42 UT and had faded completely by 23:49 UT. No TRACE data were available between 22:55 UT and 23:42 UT. The peak intensity occurred at 22:55 UT, corresponding closely to the time at which EIS scanned the region (22:57 UT). The brightening was very bright in the transition region at the temperature of O V ($\log T = 5.4$) and the brightness decreased to higher temperatures, until it was barely discernible in Fe XV ($\log T = 6.3$). The brightening was not apparent in co-temporal XRT images.

The density and temperature properties (discussed below) appear to be similar to those of impulsive events identified in EUV Skylab spectra by Widing (1982), and to an active region brightening seen in EUV spectra from SOHO/CDS by Young and Mason (1997), later termed active region blinkers and discussed further by Young (2004). There are also similarities in terms of intensity enhancement and line broadening to the bidirectional jet observed by Doyle et al. (2004) in TRACE and SOHO/SUMER data.

4.1. Oxygen Emission Lines

A number of $n = 3$ to 2 transitions of O IV–VI are found in the EIS wavebands (Young et al. 2007). They are mostly very weak but can be detected with the high spectral resolution and sensitivity of EIS. The O V $2s2p^3P_2^0–2s3d^3D_J$ transitions are of particular interest as they lie close to Ca XVII 192.82 — an EIS core line that is observed in every EIS study. (This line is actually blended with Fe XI $\lambda192.83$ which dominates in most solar conditions.) The left-hand panel of figure 8 compares spectra of the ARTRB with a region outside of the ARTRB. The dashed line shows the normally dominant Fe XI line, while the solid line demonstrates the strong enhancement of O V $\lambda192.89$. The contribution of O V is complicated as there are actually five significant O V components, and the CHIANTI prediction for the relative strengths is shown in the right panel of figure 8. It is thus seen that O V makes up around one half of the emission seen at 192.8 Å.

4.2. Line Broadening

The brightening displayed significantly broadened line profiles in the transition region, as demonstrated for Mg VI $\lambda268.99$ and Mg VII $\lambda280.75$ in figure 9. The cores of the lines were seen to be broadened by around 50 km s$^{-1}$ while the
Fig. 8. Left panel: Comparison of spectra in the vicinity of the Fe XI–Ca XVII–O V blend at 192.8–192.9 Å. The solid line is a spectrum from the ARTRB, while the dashed line is from a region to the north of the brightening showing the more typical appearance of the spectrum. Right panel: Synthetic spectrum generated with CHIANTI showing the five O V components (vertical lines) and the resulting spectral distribution (assuming Gaussian line profiles).

wings extended out beyond \( \pm 200 \text{ km s}^{-1} \). Given the strongly dynamic behaviour of the ARTRB in the TRACE movie, these features are most likely to be due to a superposition of high speed up- and down-flows in the structure.

4.3 Density

The Mg VII ratio used in the previous section yields a density of \( \log N_e = 10.63^{+0.10}_{-0.09} \) for the ARTRB. Note that, because of the non-Gaussian profiles, it was necessary to use the Si VII \( \lambda 275.35 \) line to estimate the Si VII contribution to Mg VII \( \lambda 278.39 \). This high density is consistent with the high densities measured by Widing (1982), Young and Mason (1997), and Young (2004) for the transition region events studied using Skylab and SOHO/CDS spectra, respectively.

4.4 Continuum Emission

Another feature demonstrated by this small brightening is enhanced continuum emission in the short wavelength band (figure 10). The continuum level has been estimated from regions apparently free of emission lines, however figure 10 suggests that some of the regions chosen are affected by emission lines. The continuum is probably due to recombination onto H-like helium. The photoionization edge of He\(^+\) is at 227.8 Å, thus explaining why there is little continuum enhancement in the long wavelength band.

Note that the continuum level appears to rise at the longest wavelengths in the 246–292 Å band. This is probably the short wavelength wing of He\(\Pi \lambda 304\), given the significant broadening of other cool lines in the EIS spectrum (figure 9).

4.5 Time Evolution

The short lifetime of this ARTRB (as judged from the TRACE data) means that high cadence (at most a few minutes between rasters) EIS rasters are required to study such events in detail. EIS has the capability of automatically switching to a new study if a threshold intensity is reached in a specified emission line, and this will be a valuable tool for studying such short-lived features. EIS slot movies are also an alternative as the small spatial scale of the events should limit any spatial–spectral ambiguity introduced by using a wide slit. XRT data would appear to be of limited value due to the low temperature of the events, but SOT data will be extremely important for relating the ARTRBs to the magnetic field and photospheric/chromospheric plasma. A cursory glance of Ca II images revealed that the ARTRB here was located at the edge of a plage region and was bright in Ca II.

5. Conclusions

The EIS active region data-set shown here shows two types of structure that yield strongly enhanced transition region emission lines. Footpoints of large active region loops that are most characteristically seen in TRACE 171 filter images can clearly be seen in emission lines of Mg v–vii, Si v–vii, and Fe VIII—ions formed at temperatures \( \log T = 5.4–5.8 \). The density in these footpoint regions can be accurately measured using the Mg VII \( \lambda 280.75/\lambda 278.39 \) ratio, and a fall-off in density from \( 3 \times 10^9 \) to \( 1.5 \times 10^9 \text{ cm}^{-3} \) from the base of a loop to a (projected) height of 20 Mm is found here.
A strong active region transition region brightening (ARTRB) was also seen in the data-set and demonstrates very strong emission in \( \text{O V} \lambda 192.9 \). The ARTRB shows broadened emission line profiles and extended wings. The \( \text{Mg VII} \lambda 280.75/\lambda 278.39 \) yields a density of \( 4 \times 10^{10} \text{ cm}^{-3} \). The brightening was short-lived, but co-spatial TRACE images demonstrate a highly dynamic, small loop-like feature with a lifetime of around 60 min.

The value of including transition region lines in EIS studies has been demonstrated here, and observers are recommended to include one or more of the emission lines listed in table 1 when designing EIS studies.

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References

Culhane, J. L., et al. 2007, Solar Phys., 243, 19
Del Zanna, G. 2003, A&A, 406, L5
Del Zanna, G., & Mason, H. E. 2003, A&A, 406, 1089
Dere, K. P., Landi, E., Mason, H. E., Monsignori Fossi, B. C., & Young, P. R. 1997, A&AS, 125, 149
Doyle, J. G., Madjarska, M. S., Dzifčáková, E., & Dammasch, I. E. 2004, Sol. Phys., 221, 51
Feldman, U., Mandelbaum, P., Seely, J. F., Doschek, G. A., & Gursky, H. 1992, ApJS, 81, 387
Kosugi, T., et al. 2007, Solar Phys., 243, 3
Landi, E., Del Zanna, G., Young, P. R., Dere, K. P., Mason, H. E., & Landini, M. 2006, ApJS, 162, 261
Mazzotta, P., Mazzitelli, G., Colafrancesco, S., & Vittorio, N. 1998, A&AS, 133, 403
Widing, K. G. 1982, ApJ, 258, 835
Young, P. R. 2004, in Proc. 13th SOHO Workshop, ESA SP-547, 257
Young, P. R. 2007, in ASP Conf. Ser., 369, New Solar Physics with the Solar-B Mission, ed. K. Shibata, S. Nagata, & T. Sakurai (San Francisco: ASP), 307
Young, P. R., et al. 2007, PASJ, 59, S857
Young, P. R., & Mason, H. E. 1997, Solar Phys., 175, 523