Coordinated Observations of Transition Region Dynamics using TRACE and the SVST

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Abstract. We present coordinated observations from the Transition Region and Coronal Explorer (TRACE) satellite and the Swedish Vacuum Solar Telescope (SVST) on La Palma, Spain. The observations focus on AR 8227 on 30-May-1998 and the analysis of a novel extreme ultraviolet (EUV) emission pattern over plage regions seen in the Fe IX/X 171 Å bandpass of the TRACE instrument. The emission appears as a bright dynamic network with dark inclusions on scales of 2,000–3,000 km, confined to layers approximately 1,000-3,000 km thick at heights between about 2,000–4,000 km above the photosphere. The fact that the emission does not occur over all plage regions implies that it is not a low-temperature contamination of the TRACE bandpass. SVST Hα images establish that the dark inclusions correspond to jets of chromospheric material. Preliminary analyses suggest that we are imaging the upper transition region and its interaction with chromospheric structures for the first time.

1. Introduction

A primary goal of the TRACE mission is to observe the characteristics of the transition region between the $10^4$ K chromosphere and the $10^6$ K corona. Although much theoretical work has been devoted to the transition region (see the book by Mariska, 1992, for an excellent overview), high resolution observations of the solar atmosphere in this temperature regime have for the most part been limited to spectral data (Cook 1991) which do not provide the high temporal cadence images necessary to study the spatial structure of the region. The EIT telescope on SOHO (Delaboudiniere, Artzner, et al. 1995) images the same EUV wavelengths regions as TRACE, but with a full-disk resolution of only 50.2, which is inadequate for studying the interaction of chromospheric structures with the upper atmosphere.

One of the most striking features of TRACE EUV images of solar active regions is the occurrence of a fine-scale, low-lying, network over certain plage regions. Because of its resemblance to the ground-covering plant, this emission pattern has been termed “moss”. It has been previously recognized in lower-
Figure 1. Optical layout of the SVST on 30-May-1998 during coordinated active region observations with TRACE. Courtesy of D. Torgerson, LMSAL.
resolution sounding rocket images (Peres, Reale, & Golub 1994) and correctly deduced as fundamentally distinct from large-scale active region EUV loops. It is also detectable, though not resolved, in EIT 171 Å images. With the improved spatial and temporal resolution of TRACE, we can now study the structure and dynamics of this novel emission for the first time.

On 30-May-1998 we observed AR 8227 in excellent seeing at the SVST over a period of approximately 10 hours. The observations were coordinated with the TRACE observing program, which took Fe IX/X 171 Å images on a roughly 30 second cadence and white-light images of the active region every two minutes. The resulting dataset, along with data from the SXT instrument on Yohkoh, and the MDI instrument on SOHO, has established the basic nature of this newly resolved feature of active regions in the EUV. We report here on the very high resolution data obtained at the SVST and its role in investigating the characteristics of the moss.

2. Observations

2.1. Instruments

TRACE is a Small Explorer (SMEX) satellite in a 600 km Sun-synchronous orbit (Handy et al. 1999). It consists of a 30 cm Cassegrain telescope with a four-quadrant multi-layer coating on the primary and secondary mirrors. Three of the quadrants image the Sun in EUV bandpasses near 171, 195, and 284 Å, respectively. The fourth quadrant acts in combination with a 12.5 cm LiF entrance window and dual focal plane filters to select several bandpasses from the H-Lyα 1216 Å band up to a wide-band visible light bandpass. All quadrants image the Sun onto the same 1024×1024 pixel lumigen-coated CCD, with the wavelengths sequentially recorded in an operator-specified order. The full field-of-view (FOV) in any bandpass is a circle roughly 512 arcseconds in diameter. The EUV spatial resolution is pixel-limited to 0″9986 (J. P. Wülser, TRACE sci-ops email, 1998). Table 1 lists the wavelengths and temperature responses of the various TRACE bandpasses.

The SVST is a 47.5 cm vacuum refractor located at 2400 m ASL on the island of La Palma, Spain (Scharmer, Brown, et al. 1985). On 30-May-1998 we observed AR 8227 using the three camera setup shown in Fig 1. Excellent seeing conditions prevailed for most of the day, with the best seeing occurring during the period from about 12:00-16:00 UT. Post-processing of the SVST data entailed flat-field/dark current correction, rigid alignment of each wavelength set to remove arcsecond-scale jitter and image rotation, and (in the case of the G-band and magnetogram sets only) destretching to remove geometric seeing distortions. In addition, the G-band and magnetogram datasets were spacetime Fourier filtered with a 4 km/sec linear filter to attenuate p-mode brightness variations.

2.2. Dataset Alignment

Major effort was required to align and scale the various SVST and TRACE wavelength datasets to a common coordinate system since each camera at the SVST has its own plate scale and field-of-view (FOV), each of which is entirely differ-
Table 1. TRACE Bandpass Characteristics

Inter-wavelength alignment was accomplished in the following sequence: common features in the TRACE white light image nearest in time to the initial G-band image were used to determine the G-band/TRACE white-light alignment. The TRACE EUV dataset was then aligned to the G-band dataset using calibrated TRACE white-light/EUV offset values (R. Shine, TRACE sci-ops email, 1998). The Ca II K-line images were aligned to the G-band using common bright points associated with magnetic elements. The magnetograms were aligned to the G-band dataset using the RCP pre-magnetogram image set which also shows magnetic element bright points; the LCP images were subsequently “stretched” onto the RCP set before magnetogram creation. The Hα datasets were aligned to the G-band dataset by using magnetic element bright points visible in the Hα-700 mÅ filtergrams and then assuming that all other Hα wavelength offset images possessed the same relative alignment to the G-band images. Residual seeing distortions and alignment drifts in the SVST datasets limit the random frame-to-frame image alignment accuracy to about 1–2", although subframes can be manually adjusted to align with better than 1" accuracy across most of the FOV.

The final images in all datasets were formatted to 2028×2044 pixel 16-bit arrays; in those datasets with smaller FOVs (such as the Hα and magnetogram sets), the images were imbedded in the arrays with zero-valued borders in the blank areas. We used the G-band dataset as a temporal reference as well, creating nearest-neighbor interpolated symbolic links in the other datasets where necessary to arrive at a uniform number of files covering the period from 7:50
<table>
<thead>
<tr>
<th>Dataset</th>
<th>Wavelength (Å)</th>
<th>Atmospheric Region</th>
<th>Cadence (sec)</th>
<th>FOV (arcmin)</th>
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</thead>
<tbody>
<tr>
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<td>PS</td>
<td>20</td>
<td>2.82×2.82</td>
</tr>
<tr>
<td>Ca II K-line</td>
<td>3933</td>
<td>Low CS</td>
<td>15</td>
<td>2.76×2.14</td>
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<tr>
<td></td>
<td>-700 mÅ</td>
<td>Low CS</td>
<td>120</td>
<td></td>
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<tr>
<td></td>
<td>-350 mÅ</td>
<td>Mid CS</td>
<td>120</td>
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<tr>
<td>Hα</td>
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<td>CS</td>
<td>120</td>
<td>2.87×1.88</td>
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<td></td>
<td>+350 mÅ</td>
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<td>6302</td>
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<td>30</td>
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<td>TRACE White Light</td>
<td>5000</td>
<td>PS</td>
<td>120</td>
<td></td>
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Table 2. Coordinated dataset list for AR 8227 on 30-May-1998. PS = photosphere, CS = chromosphere, TR = transition region. All datasets cover the period from 7:50 to 16:50 UT. FOV values are original values; final datasets are clipped or imbedded into G-band FOV.

This resulted in 1540 images in all datasets with a total storage requirement of approximately 22 Gbytes. Table 2 lists the coordinated datasets and their properties.

3. Image Analysis

Fig.2 shows AR 8227 on 30-May-1998 14:40 UT (heliographic coordinates N26°7 E10°4) as seen in the TRACE Fe IX/X 171 Å 171 Å bandpass. The dotted box outlines the FOV of the aligned and scaled dataset used in all subsequent analyses. Moss regions are prominent throughout the central area of the image. In particular, Boxes A and C outline regions of strong moss emission. In contrast, Box B shows very low-level Fe IX/X 171 Å emission.

Fig.a–d show representative SVST images of AR 8227 corresponding to the dotted outline shown in Fig.2 The locations of Boxes B and C are outlined in
Figure 2. TRACE Fe IX/X 171 Å image of AR 8227 on 30-May-1998 14:40 UT. Heliographic position is N26°7 E10°4. The dotted box outlines the maximum field-of-view achieved in coordinated observations at the SVST. The active region consists of a unipolar spot group (just to the north of Box B) and a large trailing plage complex.

Comparison of TRACE images with SVST Fe I 6302 Å magnetograms and Ca II 3933 Å K-line images shows that moss regions in the SVST FOV occur exclusively over plage magnetic field regions. On 10,000–20,000 km scales, outlines of the moss regions follow the magnetic network patterns closely. However there are conspicuous areas of plage that lack moss: Box B in Figure 2 for example. This indicates that moss is not a ubiquitous feature of the magnetic network in active regions; the presence plage is a necessary but not sufficient condition for the occurrence of moss. This finding implies that the moss emission in the TRACE 171 Å bandpass is not from a low temperature contamination line such as the O VI 173 Å line formed at a temperature of about 300,000 K. Since all plage regions are visible in spectroheliograms in lines with formation
temperatures up to about 400,000 K, a low-temperature contamination source for the moss would result in moss occurring over all plage regions.

Moss elements move and vary in brightness on time scales of one minute or less. The motions are random displacements of the bright EUV elements on scales of 1000 km. We see no systematic drifts or flows of the bright elements, nor do we detect any intrinsic “spinning” or vortex motions within these structures. In the large majority of TRACE active region observations to date, moss patterns appear relatively static on scales of plage regions (10^4 km). As with the Ca II K-line plage pattern, the large-scale moss pattern usually evolves slowly on time scales of 10–20 hours.

The rapid brightness variations seen in the moss are due to two independent mechanisms: intrinsic variability of the EUV irradiance in the bright elements and extinction of the line-of-sight EUV irradiance by relatively cool spicule-like “jets.” Extinction by dark jets is most clearly visible in limb images. Intrinsic variability of the EUV emission is difficult to quantify with the existing datasets.
due to temporal resolution limitations. However it is clear that the moss is a highly dynamic phenomenon.

On the disk, TRACE Fe IX/X 171 Å movies show clear cases of dark material both projecting horizontally over bright moss elements to obscure the emission as well as “pushing” the bright elements laterally. The dark material corresponds nearly exactly to dark absorbing features seen in simultaneous SVST images taken in the wings of the Hα 6563 Å line. Specifically, the dark inclusions in the moss correlate most closely to dark absorbing features in “summed images” created by adding nearly co-temporal Hα ±350 mÅ filtergrams. Fig.4 exhibits this in a single snapshot: the bright moss contours defined in Panel A are complementary to the double contours that delineate dark features in the summed Hα image in Panel B.

Such red/blue shifts in Hα are consistent with upward-directed jets accompanied by backfalling material, as in classical spicules. However we note that these “jets” are on average somewhat smaller than classical spicules and are found over plage regions. Whatever the details of these chromospheric events, comparisons of TRACE and SVST Hα ±350 mÅ movies show that moss temporal variations are closely tied to their dynamics. However the occurrence of chromospheric jets is apparently not linked to moss regions since we see similar jets over all magnetic network in SVST movies, and particularly in the moss-less plage region of Box B of Figure 2.

4. Conclusions

Given the high-temperature and low altitude of the moss emission, we hypothesize that it is due to thermal conduction from overlying hot coronal loops. Such a mechanism was successfully modelled by Peres, Reale, & Golub (1994) as-
suming hydostatic loop models. Although the hydrostatic assumption is clearly dubious given the dynamic nature of the moss (and presumably any connected loops), thermal conduction is clearly a factor in upper transition region heating (Mariska 1992). We thus delineate between the bright moss EUV emission caused by thermal conduction and the dark inclusions caused by chromospheric jet extinction of the moss EUV emission.

If we associate the bright moss elements with the locations of coronal field lines along which thermal conduction heats the transition region, the misalignment with chromospheric flux elements magnetic field is intriguing. One interpretation is that large-scale coronal loops are formed from the interaction of many separate field-lines originating from a myriad of small-scale magnetic elements lower in the atmosphere. In this picture, coronal loops are not simple extensions of magnetic field lines rising from the photosphere into the corona, but are instead formed from a complex merging or tangling of the field lines caused by the constant relative motions of magnetic elements in response to convective flows in the photosphere. Downward thermal conduction leading to the EUV emission would then occur along coronal field lines that are not necessarily vertically aligned with the photospheric flux elements. A similar relationship of coronal field lines to photospheric flux tubes has been proposed in previous theoretical work (Spruit & Roberts 1983) and empirically modelled in recent G-band bright point work (Van Ballegooijen et al. 1998).

In summary, our data indicate that the TRACE Fe IX/X 171 Å “moss” emission is due to $10^5$ K plasma in the plage footpoint regions of coronal loops. The emission is localized in relatively thin bright elements on 2–3×10$^3$ km scales typically about 3000 km above the photosphere. The characteristic appearance in high resolution EUV images is that of a dynamic low-lying network of bright elements interspersed with dark inclusions. The dark inclusions often correspond to jets of chromospheric plasma visible in simultaneous Hα images. Neither the bright EUV elements nor the dark jets align well with the locations of magnetic elements in the photosphere and lower chromosphere. These characteristics suggest that we are for the first time at least partially resolving the structure and dynamics of the upper transition region in the solar atmosphere.

Group Discussion

Zirker: The moss-less region seems to have stronger magnetic fields and yet has no 3-5 MK loops, which are necessary for moss. Can you explain?

Berger: The mossy and moss-less regions do have comparable magnetic fields. The 3-5 MK loops are those main loops connecting the leader sunspot group to the trailing plage.

Bala: Could these structures be hot, low-lying loops brimming off the transition region surface?

Berger: If this were the case, one would expect the moss to be a ubiquitous feature of the magnetic network. Instead we see many regions of strong field network without moss. This fact argues against a "generic" source for the heating of the moss.