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INTENSITY OSCILLATIONS IN THE UPPER TRANSITION REGION ABOVE ACTIVE REGION PLAGE

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ABSTRACT

Although there are now many observations showing the presence of oscillations in the corona, almost no observational studies have focused on the bright upper transition region (TR) emission (the so-called moss) above active region plage. Here we report on a wavelet analysis of observations (made with the *Transition Region and Coronal Explorer*) of strong (∼5%–15%) intensity oscillations in the upper TR footpoints of hot coronal loops. They show a range of periods from 200 to 600 s, typically persisting for 4–7 cycles. These oscillations are not associated with sunspots, as they usually occur at the periphery of plage regions. A preliminary comparison to photospheric vertical velocities (using the Michelson Doppler Imager on board the *Solar and Heliospheric Observatory*) reveals that some upper TR oscillations show a correlation with *p*-modes in the photosphere. In addition, a majority of the upper TR oscillations are directly associated with upper chromospheric oscillations observed in Hα, i.e., periodic flows in spicular structures. The presence of such strong oscillations at low heights (of the order of 3000 km) provides an ideal opportunity to study the propagation of oscillations from photosphere and chromosphere into the TR and corona. It can also help us understand the magnetic connectivity in the chromosphere and TR and shed light on the source of chromospheric mass flows such as spicules.

Subject headings: magnetic fields — Sun: chromosphere — Sun: photosphere — Sun: transition region

1. INTRODUCTION

The Sun's outer atmosphere shows a variety of oscillation modes, such as the 3 minute oscillations in the chromosphere or the well-known *p*-modes in the photosphere. In recent years, the advent of high-resolution EUV imagers and spectrographs has led to a remarkable increase in the number of observations of oscillations in the transition region (TR) and corona (see Trimble & Aschwanden 2003 for a review). Most detailed studies of such oscillations have been based on observations made in the *Transition Region and Coronal Explorer* (*TRACE*) 171 Å passband, which is dominated by EUV photons emitted by $Fe^{8+/9+}$ ions (formed at ∼1 MK under ionization equilibrium conditions; Handy et al. 1999). These oscillation studies of the active region (AR) corona so far have focused on either the cool loops or the sunspot fans (partially) visible in the *TRACE* 171 Å passband. These were often found to show longitudinal waves with amplitudes of the order of 5% (De Moortel et al. 2002a, 2002b). We report here on the first extensive exploration of oscillations in moss, which constitutes a large fraction of Fe IX/X 171 Å emission in ARs. Moss is low-lying EUV emission that occurs in a bright reticulated pattern with dark inclusions, structured on spatial scales of 1–3 Mm and highly dynamic on timescales of ∼30 s. It has been conclusively identified as the conductively heated and *classical* upper TR (at ∼1 MK) above AR plage, in the legs of hot (4–6 MK) and high-pressure coronal loops (Berger et al. 1999; Fletcher & De Pontieu 1999; De Pontieu et al. 1999; Martens, Kankelborg, & Berger 2000). The dark inclusions, responsible for much of the dynamics, are caused by chromospheric (∼10^4 K) jets, visible in the wings of Hα, which obscure and interact with the EUV-emitting upper TR plasma (De Pontieu, Tarbell, & Erdélyi 2003).

The source of longitudinal oscillations in the corona is not well understood. Here we study the correlation of the upper TR oscillations with oscillations in the photosphere using the Michelson Doppler Imager (MDI; Scherrer et al. 1995), and in the chromosphere, using ground-based data from the Swedish Vacuum Solar Telescope (SVST) in La Palma (Scharmer et al. 1985). We describe the characteristics of the upper TR oscillations in § 2 and follow with a preliminary study of correlations with oscillations at lower altitudes in § 3. We finish with a discussion and conclusions (§ 4).

2. INTENSITY OSCILLATIONS IN THE UPPER TR

We use observations of NOAA AR 8558 observed on 1999 June 4 from 8:30 to 11:00 UT at heliocentric coordinates (N15°, W13°) with a heliocentric viewing angle of 20° ($\mu = 0.94$). The data set consisted of *TRACE* 171 Å, Hα (± 700 and ± 350 mÅ) and MDI Dopplergrams, with a spatial resolution of, respectively, 1″, ∼0″.5, and 1″.2 at a cadence of, respectively, 42, 76, and 60 s. Co-alignment of this data set was possible to subarcsecond resolution because of the presence in 171 Å of a stable sunspot light bridge. We rebin the *TRACE* Fe IX/X 171 Å data to 1″ and find that the light curves (intensity vs. time) of many superpixels (each contain 2 × 2 original 0″.5 pixels) show clear oscillations (Fig. 1). Most of these oscillations are not steady harmonic waves but wave trains of finite duration. For this reason we use wavelet analysis, since it allows for localization in time of periodic signals. The mother wavelet we use is the complex valued Morlet wavelet ($k = 6$) that consists of a plane wave modulated by a Gaussian, an appropriate shape for wave trains. To estimate the statistical significance of the wavelet power spectra (95% confidence intervals in Fig. 1), we compare them to theoretical spectra for white noise, following Torrence &

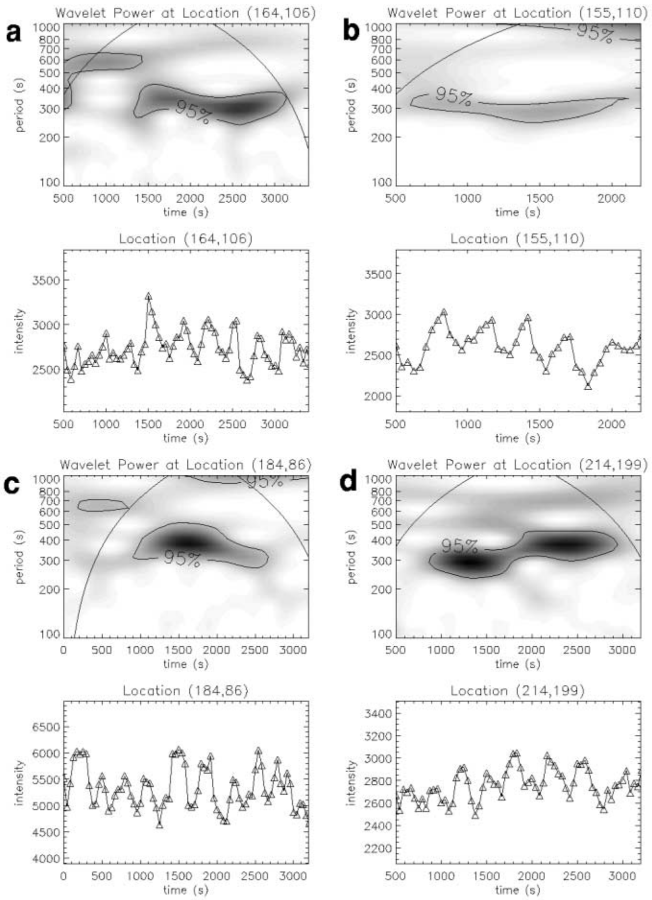

FIG. 1.—Four *TRACE* 171 Å superpixels (1″ × 1″) above AR plage showing oscillations (from 10:06 to 11:06 UT). Coordinates for each location (*a*–*d*) are in arcseconds (see Fig. 2). Top panels show wavelet power spectra as a function of time and wave period. Curved lines show the "cone of influence" (COI), a measure of where edge effects of the finite wavelet transform dominate. Only power spectra in the area between the COI and the horizontal time axis do not suffer from edge effects caused by the discontinuity at the ends of the time series. Bottom panels show intensity vs. time.

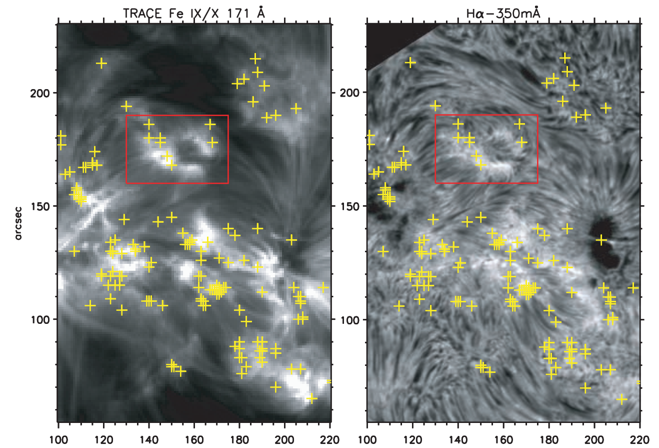

FIG. 2.—*Left*: *TRACE* 171 Å image of NOAA AR 8558 constructed by replacing each superpixel with the median of intensity during a time series from 8:35 to 9:50 UT on 1999 June 4. *Right*: Same as left panel, but for Hα −350 mÅ taken at 9:28 UT. Yellow crosses mark locations that show oscillations with significant (95%) wavelet power for longer than 4 cycles. The red box shows a patch of moss. The coordinate system used is compatible with the locations in Figs. 1 and 3.

Compo (1998) and De Moortel & Hood (2000). To calculate cross wavelet power spectra and wavelet-based coherence phase differences between two signals, we follow § 6 of Torrence & Compo (1998).

The four examples in Figure 1 were chosen because they show typical characteristics of many of the oscillating superpixels in moss. Most oscillations are wave trains of finite duration with typically 4–7 cycles of oscillations with periods between 250 and 600 s. Figure 1*a* illustrates that the oscillations usually suddenly start (in this case) or stop and rarely continue for longer than 40 minutes. Typically, neighboring superpixels show some periodicity as well, with similar periods, though frequently not as clear or sustained. Such neighboring superpixels have the same phase, which indicates that transverse oscillations of, e.g., swaying flux tubes (bright in EUV) are not causing these oscillations. There is a range of wave forms, with many oscillations not sinusoidal in wave form but rather more steepened (see Fig. 1*b* for a consistently steepened wave form). The amplitude of the oscillations is sometimes not constant and in some cases can vary considerably from one cycle to the next (see Fig. 1*c* and to a lesser extent Fig. 1*a*). This is somewhat different from oscillations seen in fans associated with sunspots, which typically show either relative constant amplitude or slowly decreasing amplitude (De Moortel et al. 2002b). Not only the wave amplitude but also the wave frequency often changes with time. This is nicely illustrated by Figure 1*d*, which starts out with 3 cycles at a period of about 300 s and then seemingly abruptly switches to 3–4 cycles at a longer period of 400 s. While such abrupt changes in wave period are rarer, a gradual change in wave period occurs frequently, as can be seen in several of the examples in Figure 1.

The oscillations in moss are not rare, as illustrated by Figure 2 (*left*), which depicts a *TRACE* Fe IX/X 171 Å image of AR 8558 overlaid with small yellow crosses for superpixels showing significant (95%) wavelet power for at least 4 cycles from 8:35 to 9:50 UT. We consider only locations that show a median brightness (during the 75 minutes) larger than the average brightness of the image. We find 148 oscillating superpixels, about 1.5% of the total number considered. The average oscillation period for these superpixels is 349 ± 60 s or 5.8 ± 1 minutes, with an average lifetime of 32 ± 7 minutes (4.8 ± 0.8 cycles) and an average rms amplitude $\delta I/I$ of 10% ± 3%. Some of the oscillations are located close to sunspots and in loops visible in *TRACE* 171 Å. However, the majority is found in the vicinity of AR moss, i.e., above AR plage at the footpoints of loops that are too hot to be seen in *TRACE* 171 Å but that are visible in images taken with the soft X-ray telescope of *Yohkoh*. Interestingly, many of the locations with significant oscillatory power are found not at the center but more at the periphery of moss patches, such as the one in the red box around (155″, 175″) in Figure 2.

3. CORRELATION WITH LOWER ATMOSPHERE OSCILLATIONS

To study the correlations between upper TR oscillations and (quasi) periodic signals in the lower atmosphere, we use simultaneous Hα filtergrams of the chromosphere (taken at the SVST) and photospheric Dopplergrams taken by the *Solar and Heliospheric Observatory*/MDI. The *TRACE*, SVST, and MDI data were very carefully aligned to subarcsecond levels using the wavelet techniques described by De Pontieu et al. (1999). More than half of the 148 oscillating moss locations show a clear correlation between upper TR oscillations (in *TRACE* 171 Å) and upper chromospheric oscillations as observed in the wings of Hα (+350 and

−350 mÅ). This is demonstrated in the example of Figure 3, which shows that the wavelet power spectra for *TRACE* 171 Å (Fig. 3*b*) and Hα −350 mÅ (Fig. 3*a*) and Hα +350 mÅ (Fig. 3*c*) are quite similar, despite the atmospheric seeing deformations that the ground-based data suffer from. Cross wavelet power spectra between *TRACE* 171 Å and Hα −350 mÅ (Fig. 3*e*) and between *TRACE* 171 Å and Hα +350 mÅ (Fig. 3*g*) confirm that the correlation between the upper TR and upper chromospheric light curves (see also Fig. 3*i*) is significant. Generally, there is a better correlation between *TRACE* 171 Å and Hα −350 mÅ, but the best correlation is usually between *TRACE* 171 Å and the sum of Hα −350 mÅ and Hα +350 mÅ. The upper TR and upper chromospheric oscillatory signals typically do not show any significant delay times within the temporal resolution of the data (42 s for *TRACE* 171 Å and 76 s for Hα). Our data analysis thus shows that the upper TR/low coronal oscillations are clearly correlated with oscillations in the upper chromosphere.

The relationship of upper TR oscillations with oscillations in the photosphere is less clear. MDI Dopplergrams, which show the (roughly) vertical velocity in the photosphere, are dominated by oscillations such as the *p*-modes, with most of the power at 5 minutes. A preliminary study of correlations between upper TR oscillations and a $3'' \times 3''$ area in the MDI Dopplergrams around the upper TR location reveals several examples of a nice correlation. Figure 3 shows such an example in which the wavelet power spectra of *TRACE* 171 Å and MDI, as well as the cross wavelet power spectra between the two signals, indicate a significant correlation for many "cycles" between the photospheric velocity and upper TR intensity. The average phase difference between MDI and *TRACE* 171 Å is $160° \pm 25°$, signifying a delay of the order of 150 s, with the peaks in photospheric (upward) velocity usually occurring at the troughs of the upper TR (and thus upper chromospheric) intensity. Given the periodic nature of the photospheric signal, this phase difference suffers from a 360° ambiguity. However, such a nice correlation with photospheric oscillations is generally much rarer (6 out of 148) than the correlations between chromospheric and upper TR oscillations. Often the photospheric signal directly below the upper TR oscillation does not correlate well with the upper TR, and frequently a good correlation occurs only with a photospheric location that is horizontally offset by a few arcseconds (as in the example of Fig. 3). Also, oscillations in MDI and *TRACE* 171 Å often do occur at the same location but with different periods or variable phase shifts. This could be indicative of a lack of relationship or perhaps some kind of nonlinear relationship between photospheric and upper chromospheric/TR oscillations.

Irrespective of detailed one-to-one correlations between MDI and *TRACE* 171 Å, a preliminary comparison in location between upper TR oscillations and MDI Doppler oscillations with significant fast Fourier transform power between 250 and 350 s shows that upper TR oscillations almost never occur above or around photospheric locations where *p*-modes are strongly suppressed (not shown). In addition, the upper TR oscillations typically consist of wave trains of 3–7 cycles long, which is very similar to the appearance of oscillations at one location in the photosphere, where superposition of *p*-modes usually leads to wave trains containing 4 or 5 (and up to 9) cycles (Priest 1982, p. 175).

4. DISCUSSION AND CONCLUSIONS

Our *TRACE* 171 Å observations reveal strong (∼5%–15%) intensity oscillations in the upper TR or low coronal footpoints

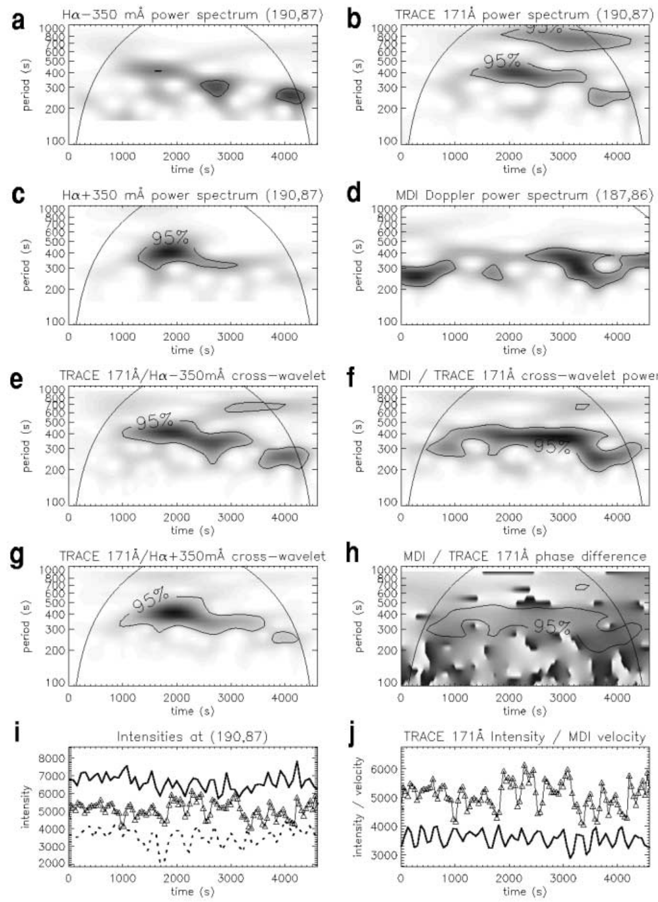

FIG. 3.—Example of correlated photospheric, chromospheric, and upper TR oscillations: wavelet power spectra for (*a*) Hα −350 mÅ, (*b*) *TRACE* 171 Å, (*c*) Hα +350 mÅ, and (*d*) MDI velocity; cross wavelet power spectra for (*e*) *TRACE* 171 Å/Hα −350 mÅ, (*f*) MDI velocity/*TRACE* 171 Å, and (*g*) *TRACE* 171 Å/Hα +350 mÅ; (*h*) phase difference between MDI and *TRACE* 171 Å (with contours from panel *f*); (*i*) light curve of Hα −350 mÅ (*solid line*), *TRACE* 171 Å (*solid line with triangles*), and Hα +350 mÅ (*dotted line*); (*j*) light curve of *TRACE* 171 Å and MDI velocity. Units of velocity/intensity are arbitrary.

(moss) of hot coronal loops. These oscillations seem to be caused by intensity oscillations in the wings of Hα (at ±350 mÅ) roughly in phase with those in *TRACE* 171 Å. The Hα oscillations are caused by the (quasi) period occurrence of Doppler-shifted dark features in the wings of Hα. These features form a subset of "fibrils," the AR equivalent of quiet Sun mottles or spicules. Above mossy plage, fibrils are on average shorter and more vertical than typical fibrils. Despite unresolved issues regarding the relationship among fibrils, mottles, and spicules, there is agreement that all of them are exponents of short-lived chromospheric jetlike features that bring cold (∼10^4 K) dense plasma up to greater heights than expected from hydrostatic equilibrium models (see, e.g., Suematsu, Wang, & Zirin 1995). The correlation between oscillations in EUV and Hα is perhaps not surprising, given our recent study of moss dynamics (De Pontieu et al. 2003), which shows that much of the upper TR dynamics are caused by spicular jets obscuring and interacting with EUV-emitting upper TR plasma. More surprising is the presence of *(quasi) periodic* chromospheric features that interact with the upper TR. Periodicities of the order of 5 minutes in spicular properties, such as radial velocity, half-width, and line intensity, have been suggested based on older observations at the limb (not on the disk, to our knowledge), but their interpretation has been difficult because of the complicated line formation of Hα and line-of-sight superposition (Beckers 1968; Platov & Shilova 1971; Kulidzanishvili & Zugzhda 1983). The presence *on the disk* of correlated oscillations in Hα *and* the EUV provides strong evidence of (quasi) periodic mass flows in the chromosphere.

What causes these periodic flows? Our preliminary analysis shows that there is a general correspondence between *p*-modes and upper TR oscillations, in duration, periods, and locations of oscillatory power, as well as a few tantalizing one-to-one correlations between upper chromospheric/TR oscillations and photospheric *p*-modes. However, the detailed picture is unclear. Many upper TR oscillations do not show a direct linear correlation with photospheric oscillations. In fact, many upper TR oscillations seem to have a nonlinear relationship with *p*-modes, with, e.g., a different (usually lower) period for the *p*-modes or a time-dependent phase difference between MDI and *TRACE* 171 Å. Such a nonlinear relationship between driver and chromospheric flows is expected in some theoretical models of spicules and fibrils, such as the rebound shock model, which is based on a photospheric driver (single velocity pulse) nonlinearly developing into a series of interacting shocks as the perturbation travels upward (Hollweg 1982; Sterling & Hollweg 1989). While a periodic photospheric driver and more dimensions should be included to allow detailed comparisons with observations, it is interesting to note that the spicular development in the 1.5-dimensional rebound shock model is highly dependent on the geometry of the spicular flux tube. Perhaps this dependency is behind our finding that most upper TR oscillations occur in the periphery of plage areas, where the magnetic field is typically more inclined (visible in Fig. 2*b* as canopy-like structures). It is evident that if spicules are (sometimes) driven by *p*-modes (or other photospheric velocities), crucial details about their formation are still missing. Clearly, not all spicular flows in plage are periodic, whereas most photospheric velocities are. In addition, the horizontal scale for amplitude coherence of *p*-modes (~8000 km) is well beyond the width of fibrils.

Whether these 5 minute intensity oscillations in the upper chromosphere/TR couple into propagating waves in the corona is not clear. There are many observations of such propagating waves in the corona. De Moortel et al. (2002a) find wave periods of 172 ± 32 s for coronal loops associated with sunspots. For "nonsunspot" loops associated with plage or network, they find longer periods of the order of 321 ± 74 s, which is similar to the 5 minute periods that we find in the upper chromosphere/TR, as well as the periods of low chromospheric oscillations in network or plage (e.g., Muglach 2003). Despite these similarities in period and wave train duration, it is possible that our upper TR oscillations are not a sign of propagating waves but occur only because dense chromospheric jets periodically reach high enough altitudes to obscure the EUV emission. However, numerical models of spicules show that it is difficult to avoid propagation of compressive disturbances into the corona when strong flows of dense chromospheric matter periodically slam into the thin TR and overlying low-density corona. In addition, observations show that chromospheric jets not only obscure but also *interact* with upper TR plasma (De Pontieu et al. 1999). To resolve these issues, further observational analysis will be necessary, e.g., of oscillations in both intensity and velocity of upper TR emission lines (e.g., from SUMER, the Solar Ultraviolet Measurement of Emitted Radiation), as well as higher quality ground-based data at higher cadence than currently available.

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