PROPAGATING SLOW MAGNETOACOUSTIC WAVES IN CORONAL LOOPS OBSERVED BY HINODE/EIS

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ABSTRACT

We present the first Hinode/EUV Imaging Spectrometer observations of 5 minute quasi-periodic oscillations detected in a transition-region line (He ii) and five coronal lines (Fe x, Fe xii, Fe xiii, Fe xiv, and Fe xv) at the footpoint of a coronal loop. The oscillations exist throughout the whole observation, characterized by a series of wave packets with nearly constant period, typically persisting for 4–6 cycles with a lifetime of 20–30 minutes. There is an approximate in-phase relation between Doppler shift and intensity oscillations. This provides evidence for slow magnetoacoustic waves propagating upward from the transition region into the corona. We find that the oscillations detected in the five coronal lines are highly correlated, and the amplitude decreases with increasing temperature. The amplitude of Doppler shift oscillations decrease by a factor of about 3, while that of relative intensity decreases by a factor of about 4 from Fe x to Fe xv. These oscillations may be caused by the leakage of the photospheric p-modes through the chromosphere and transition region into the corona, which has been suggested as the source for intensity oscillations previously observed by Transition Region and Coronal Explorer. The temperature dependence of the oscillation amplitudes can be explained by damping of the waves traveling along the loop with multithread structure near the footpoint. Thus, this property may have potential value for coronal seismology in diagnostic of temperature structure in a coronal loop.

Key words: Sun: corona – Sun: flares – Sun: oscillations – Sun: UV radiation – Sun: X-rays, gamma rays

Online-only material: color figures

1. INTRODUCTION

A variety of propagating and standing MHD waves (e.g., slow mode, Alfvén, and fast mode) have been observed in the Sun’s outer atmosphere. They are mainly in coronal loops, but also in other structures such as coronal plumes and prominences (see reviews by Aschwanden 2004; Wang 2004, 2005; Nakariakov & Verwichte 2005; De Moortel 2005; Banerjee et al. 2007). The detection of MHD waves in the solar corona is crucial for determining the presence and relevance of wave-based heating mechanisms since they are an obvious candidate to transport energy from the solar surface into the solar atmosphere. Such observations may also be used to improve existing estimates of coronal properties, both from direct measurements and indirect methods such as coronal seismology (see, e.g., Roberts et al. 1984; Nakariakov et al. 1999; Nakariakov & Ofman 2001; Roberts & Nakariakov 2003; Nakariakov & Verwichte 2005).

The first detection of propagating slow magnetoacoustic waves was made with Ultraviolet Coronagraph Spectrometer (UVCS) onboard the Solar and Heliospheric Observatory (SOHO) observations of coronal holes, high above the limb by Ofman et al. (1997, 2000b). Similar compressive disturbances, with amplitudes of the order of 10%–20%, and periods of 10–15 minutes, were detected in polar plumes by DeForest & Gurman (1998) with the Extreme-ultraviolet Imaging Telescope (EIT)/SOHO. Ofman et al. (1999, 2000a) identified the observed compressive disturbances as propagating, slow magnetoacoustic waves, damped by compressive viscosity.

Similar intensity disturbances propagating along active-region loops with speeds of 122 ± 44 km s⁻¹ and intensity variations of 4.1% ± 1.5% were observed with Transition Region and Coronal Explorer (TRACE) Fe ix/x 171 Å data (Nightingale et al. 1999; De Moortel et al. 2000; Robbrecht et al. 2001; De Moortel et al. 2002a, 2002b; McEwan & De Moortel 2006) and EIT/SOHO Fe xii 195 Å data (Berghmans & Clette 1999). These disturbances were also interpreted as slow magnetoacoustic waves (Nakariakov et al. 2000). De Moortel et al. (2002a) found a distinct difference in dominant periods of waves in loops situated above sunspots (172 ± 32 s) and those above plage regions (321 ± 74 s). This difference suggests that these waves probably originate from the underlying oscillations, i.e., the 3 minute chromospheric/transition-region oscillations in sunspots and the 5 minute solar global oscillations (p-modes).

Many authors have found evidence for the existence of 3 minute sunspot oscillations propagating through the chromosphere and transition region into the lower corona (e.g., Brynildsen et al. 1999a, 1999b, 2002; Fludra 2001; O’Shea et al. 2002; Rendtel et al. 2003). The amplitude of the oscillations is found to reach a peak in the transition region lines then decrease with increasing temperature. These results are confirmed by a recent study of Marsh & Walsh (2006) who clearly showed that the 3 minute umbral transition region oscillations are directly connected to the 3 minute wave propagation along the TRACE loops.

The p-mode oscillations are normally evanescent because their periods are well above the cutoff period in the upper photosphere and low chromosphere as well as transition region in nonmagnetic solar atmosphere (e.g., Erdélyi et al. 2007). For magnetoacoustic gravity waves; however, Bel & Leroy (1977) predicted that in regions of low-β plasma, the highly inclined magnetic field can channel the low-frequency waves from the photosphere into the overlying coronal atmosphere due to the increase of the cutoff period. Numerical simulations based on this theory have demonstrated the appearance of 5 minute waves in chromospheric spicules and in coronal loops near active regions (De Pontieu et al. 2004,
The presence of this effect in the lower chromosphere was confirmed recently by many authors with the TRACE 1700 and 1600 Å data (McIntosh & Jefferies 2006; Jefferies et al. 2006; Bloomfield et al. 2006; Vecchio et al. 2007). In particular, Fontenla et al. (1993b) and Jefferies et al. (2006) pointed out the importance of the observed low-frequency (less than 5 mHz) waves which may provide a significant source of energy for heating solar chromosphere. Moreover, the detection of these waves propagating from the low atmosphere into the corona is also needed for our understanding of the energy balance in the outer solar atmosphere. Unfortunately, such observations are very few. Only Marsh et al. (2003) reported the observation of 5 minute propagating oscillations simultaneously at chromospheric, transition region, and coronal temperatures.

The EUV Imaging Spectrometer (EIS) onboard Hinode can simultaneously capture many emission lines from the transition region to coronal temperatures, providing us a good opportunity to study the temperature-dependent behavior of the oscillations and the propagation of waves in the solar atmosphere (Mariska et al. 2008) and is highly valuable for coronal seismology (van Doorsselaere et al. 2008; Erdélyi & Taroyan 2008). In this study we report the first Hinode/EIS observation of the 5 minute upwardly propagating slow magnetoacoustic waves simultaneously at the transition region and coronal temperatures in a plage region. The oscillations show up in both Doppler shift and line intensity with an amplitude dependent on the temperature. Section 2 describes the observations. Two examples of oscillation packets are analyzed in Section 3 and the properties of their temperature dependence are presented in Section 4. Interpretation and discussion are given in Section 5, and finally our conclusions in Section 6.

2. OBSERVATIONS

2.1. Data

An overall description of EIS is available in Culhane et al. (2007), and the Hinode mission is described by Kosugi et al. (2007). EIS has both imaging (40” and 266” slots) and spectroscopic (1” and 2” slits) capabilities, in the wavelength range of 170–210 Å and 250–290 Å with high spectral (0.0223 Å) and spatial resolution (1”/pixel). Its spectroscopic mode can operate in a rastering mode (repeated exposures while scanning over the observation target) or a sit-and-stare mode (repeated exposures at the same spatial location).

The observations analyzed in this study cover the central portion of NOAA active region 10940 and were obtained on 2007 February 2, when it was located close to the disk center. An EIS spectroheliogram was taken from 10:42 UT to 11:52 UT with the 1” slit and covering a 256” × 256” region (Warren et al. 2008). The exposure times were 15 s. This data set contained 20 spectral windows.

A sit-and-stare observation within the region began at 12:39 UT and consisted of 1200 exposures with the 1” slit, each with an exposure time of 30 s. Each exposure covered 20 data windows on the EIS detectors. This paper presents results for the lines in ten of those windows. Each window was 24 spectral pixels wide and covered a height of 400” in the north–south direction. Table 1 lists the emission lines included in this study and their temperatures of formation.

The raw data were processed by the standard SolarSoft routine eis_prep to remove detector bias and dark current, hot pixels, and cosmic rays, and calibrated using the prelaunch absolute calibration. The EIS slit tilt and orbital variation in the line centroids were also removed from the data. The emission lines in each spectral window were then fitted with Gaussian profiles, providing the total intensity, the Doppler shift, and the line width. The data in the short-wavelength detector were shifted downward by 18.5 pixels in the y-direction to correct for the offset between the two detectors.

Figure 1 shows the intensity and Doppler shift maps of the active region covered by the EIS spectroheliogram in the Fe xii line. A string of brightenings in a circular shape are dominated...
Data from the GOES X-ray monitors show no flarelike events. The detailed analysis of the oscillation in Sections 3 and 4. Doppler shift and intensity in many emission lines. We will examine the footpoint of this small loop, reveals oscillations in both temperature of 1–2 MK. The sit-and-stare observation, made at about 19:23, 21:02, and 22:40 UT which occurred at about 19:23, 21:02, and 22:40 UT. Since such “dip”-like features were caused by the jitter of several pixels in the y-direction. No high frequency, large amplitude jitter in the y-direction are found in other times. The quasi-periodic Doppler shift oscillation was found to be associated with the small loop at y ~ −60″. The oscillating structure has a width along the slit over more than 10″ and the oscillation is visible over the entire observation. These facts indicate that the detected oscillation could not be caused by jitter in the y-direction.

However, if there is a high gradient in brightness and Doppler shift across the slit, jitter in the x-direction may cause artificial oscillation. To examine if this is the case, we model the sit-and-stare observation based on the EIS spectroheliogram and the drift of the XRT pointing which is obtained using the SolarSoft routine xrt_jitter. The XRT pointing is a good proxy for EIS pointing although not perfect. Since no XRT data are available before about 18:04 UT, we choose to model and analyze the sit-and-stare data set taken after 18:04 UT. The top panel of Figure 3 shows the displacements of the XRT pointing determined from the housekeeping data. Both the x- and y-displacements are mainly orbitally varying, with amplitudes up to 2″–3″. The sit-and-stare observation is modeled by extracting the slit slices from the EIS spectroheliogram taken at 10:42 UT (see Figure 1) with the position of the slit varying with time, whose drifts in the x- and y-directions are taken as the displacements of the XRT pointing. Since the intensity and Doppler shift distributions are assumed not to change with time, the fluctuations shown in the constructed time series (right panels in Figure 2) are only caused by the instrumental jitter. The evident “dip”-like features at about 19:23, 21:02, and 22:40 UT which were caused by large displacements in the y-direction are consistent well with the EIS observation, confirming that the XRT pointing is a good proxy for the EIS. The orbital variations in brightness at y = −20″ were also well reproduced. This feature was caused by the slowly varying, orbit-related displacements in the x-direction which led the EIS slit repeatedly approaching a small brightening in the west.

The middle and bottom panels of Figure 3 show comparisons between the observed and modeled time profiles of the intensity and Doppler shift averaged at the loop of interest over 11 pixels from y = −57″ to −47″ (see the marked positions in Figure 2). Obviously, the variations in Doppler shift caused by the jitter are too small to account for the observed oscillation. Except at the times when the large y-displacements occurred, there is no correlation in intensity variations between the modeled and observed time profiles. Therefore, we can safely exclude the possibility that the detected oscillation was caused by jitter of the EIS pointing. In addition, for the EIS sit-and-stare data to be analyzed in the following sections, the pointing drifts in the y-direction have been removed based on the y-displacements observed in XRT.
3. ANALYSIS OF OSCILLATION PROPERTIES

The quasi-periodic oscillation in Doppler shift detected at the footpoint of the small loop is clearly seen to exist during the whole observation (see middle panel of Figure 3). The average root mean square (rms) amplitude of the time series with the subtracted background trend is about 0.7 km s⁻¹. It is clear that this oscillation was not related to any flares or impulsive energy release events since the GOES X-ray flux was below the B-class level during the observation. We note that the quasi-periodic time series is characterized by a train of oscillations with a nearly constant period on the order of 5 minutes and an amplitude on the order of 1 km s⁻¹, and these oscillations are associated with intensity fluctuations with the same period. For example, two typical oscillation periods are 18:10–19:15 UT and 21:54–22:47 UT.

In the following, we analyze these two oscillations with the wavelet method. The details of the procedure are given by Torrence & Compo (1998). For the convolution of the time series the Morlet wavelet is chosen, and to establish whether the oscillations are real, a randomization method is implemented which estimates the confidence level of the peaks in the wavelet spectrum by assuming the background spectrum as white noise (with a flat Fourier spectrum).

3.1. Oscillation 1 (18:10–19:15 UT)

The left panel (a) in Figure 4 shows the evolution of the Doppler shift in the Fe xii line averaged over 11 pixels along the slit between $y = -57^\circ$ and $-47^\circ$. In practice, we first subtract the slowly varying background trend from the time series (left panel (b) in Figure 4). The trend is constructed by using the moving average method with a characteristic smoothing time of 10 minutes. Then the wavelet spectrum and the global wavelet spectrum are constructed for the detrended time series (left panels (c) and (d) in Figure 4). The global wavelet spectrum is the average of the wavelet power over time at each oscillation period. Due to the limited temporal resolution only periods more than 1 minute are considered. The wavelet spectrum shows strong power at the period in a range of 4–6 minutes over a duration of 6 periods. We measure the oscillation period as the value where the global wavelet power is peaked and the uncertainty as the half FWHM. The obtained period, $P_{V1}$, is $5.2 \pm 0.9$ minutes and the amplitude (defined as the square root of the peak global wavelet power), $A_{V1}$, is 1.9 km s⁻¹.

The right panel (a) of Figure 4 shows the evolution of the Fe xii intensity. The intensity time series has been normalized by the mean value. A similar wavelet analysis is applied to the detrended time series (right panel (b) in Figure 4). The wavelet spectrum shows that most of the power is concentrated within two period bands ranging in 4–6 minutes and 10–15 minutes (right panels (c) and (d) in Figure 4). For the short-period band, we measured the oscillation period, $P_{I1} = 5.2 \pm 1.0$ minutes and the relative amplitude, $A_{I1} \approx 5.0\%$. The oscillation period is the same as that for the Doppler shift. The strong power is also seen over a time in agreement with that for the Doppler shift oscillation. The long-period band has an oscillation period of $12.4 \pm 2.2$ minutes and a relative amplitude of $8.7\%$. No significant power is found at this period in the wavelet spectrum of the Doppler shift.

3.2. Oscillation 2 (21:54–22:47 UT)

Oscillation 2 also showed up clearly in both the Doppler shift and intensity oscillations in the Fe xii line (Figure 5). The strong power for the Doppler shift is located at a period range of 3–7 minutes, with a slight shift from shorter to longer period with time (left panel (c) in Figure 5). We measured the oscillation period, $P_{V2} = 4.4 \pm 1.0$ minutes, and the amplitude, $A_{V2} = 2.0$ km s⁻¹, from the global wavelet spectrum using the same method as applied to oscillation 1. The wavelet spectrum for the intensity also shows two strong power bands as oscillation 1, one covering a shorter period range of 4–6 minutes and the other a longer period range of 13–20 minutes (right panel (c) in Figure 5). In contrast to oscillation 1, most of the power for the long-period band of this oscillation is within the cone of the influence where edge effects become important due to the finite length of time series. For the short-period oscillation, the period, $P_{I2}$, is $4.8 \pm 0.9$ minutes, and the relative amplitude, $A_{I2}$, is $5.4\%$. The wavelet analyses for the intensity and the Doppler shift show that the short-period oscillation occurs in the same frequency range and during the same period. For the long-period oscillation in intensity, the period is measured to be $16.1 \pm 3.2$ minutes and the relative amplitude is $6.2\%$. The measured physical parameters for oscillations 1 and 2 are listed in Table 2.

3.3. Phase Relationship

We examine the phase relationship between the Doppler shift and intensity oscillations. For oscillation 1, we reconstruct the
Figure 4. Wavelet analysis for averaged Doppler shift and intensity time series in the Fe XII 195 Å line from 18:10 to 19:15 UT. Left panels: (a) Doppler shift data (solid line) and the background trend (dotted line). (b) The detrended Doppler shift data. (c) The wavelet power spectrum. The dark color represents high power and the dotted contour encloses regions of greater than 99% confidence for a white-noise process. Cross-hatched regions on either end indicate the “cone of influence,” where edge effects become important. (d) The global wavelet spectrum (solid line) and its 99% confidence level (dotted line). Right panels: same as the left panels but for averaged intensity time series.

(A color version of this figure is available in the online journal.)

Figure 5. Wavelet analysis for averaged Doppler shift (left panels) and intensity (right panels) time series in the Fe XII 195 Å line from 21:54 to 22:47 UT. The annotations are the same as in Figure 4.

(A color version of this figure is available in the online journal.)
intensity time series by removing the long-period (12 minutes) power band from the wavelet spectrum since this long-period component has no counterpart in Doppler shift and its origin is not clear. The top panel of Figure 6 shows that the reconstructed intensity time series (dotted curve) is nearly in phase with the original one, and has a phase earlier by about 1/4-period than the Doppler shift oscillation. The cross-correlation gives a phase shift of 53°. The bottom panel of Figure 6 shows a good in-phase relationship between the Doppler shift and intensity oscillations for oscillation 2. The phase analysis gives the phase shift of 18°. Note that for both oscillations the phase of the intensity oscillation is earlier than the Doppler shift oscillation. Examination of other cases show that the approximate in-phase relation is more common.

According to linear MHD wave theory, intensity and Doppler shift oscillations are usually associated with a slow magnetoacoustic longitudinal wave in coronal loops. From the EIS spectroheliogram the oscillation is detected near the footpoint of a small loop so that longitudinal motions should have a line-of-sight (LOS) component resulting in the observed Doppler shift.
shift. The phase relation of oscillation 1 may indicate the presence of a standing wave or two oppositely propagating waves at that time. While the approximate in-phase relation for oscillation 2 may indicate that the oscillations are dominated by an upwardly propagating wave, but probably overlaid with a weak downwardly propagating wave, which caused the small phase shift observed between intensity and Doppler shift oscillations. In addition, the long-period component of intensity oscillations has no counterpart (for oscillation 1) or only weak corresponding power in Doppler shift (for oscillation 2). This may occur if the long-period oscillations are present in a coronal loop perpendicular or nearly perpendicular to the LOS.

The propagation direction of the wave is determined based on the following linear wave theory. Given the axis of $z$ is orientated toward the observer (i.e., the Doppler blueshift (upward motion) takes positive values), the velocity perturbation of an upwardly propagating linear wave can be described in the form

$$v(z, t) = V' \sin(kc_z t - kz),$$

while for a downwardly propagating wave the velocity perturbation is

$$v(z, t) = V' \sin(kc_z t + kz),$$

where $V'$ is the amplitude, $k$ is the wavenumber and $c_z$ is the sound speed. In the above we assumed $\omega = kc_z$ with positive $\omega$, $k$, and $c_z$. The linearized continuity equation is

$$\frac{\partial \rho'}{\partial t} + \rho_0 \frac{\partial v}{\partial z} = 0,$$

where $\rho_0$ is the background density (a constant) and $\rho'$ the density perturbation. From Equations (1)–(3) it follows that for an upwardly propagating wave

$$\rho'(z, t) = \left(\frac{V'}{c_z}\right) \rho_0 \sin(kc_z t - kz),$$

and for a downwardly propagating wave

$$\rho'(z, t) = -\left(\frac{V'}{c_z}\right) \rho_0 \sin(kc_z t + kz).$$

The above equations indicate that the velocity and density perturbations are in phase for the upwardly propagating wave, while in the opposite phase for the downwardly propagating wave. Clearly, the in-phase relation for oscillation 2 is consistent with the upwardly propagating wave.

In contrast, the standing acoustic wave shows a quarter-period phase relation, and such examples have been observed by the Solar Ultraviolet Measurement of Emitted Radiation (SUMER) spectrometer on SOHO (Wang et al. 2003a, 2003b). In addition, we can exclude the possibility that the observed oscillations are caused by a fast sausage-mode wave, because the fast sausage mode is characterized by short periods on the order of several to tens seconds in coronal loops (Aschwanden 2004, p 306), which are not consistent with the dominant period (5 minutes) of the observed oscillations.

The fast kink mode is nearly incompressible, i.e., with negligible density perturbation; however, Cooper et al. (2003) demonstrate that intensity variations can be produced by the kink modes, depending on the viewing angle. Since the intensity of the emission is proportional to the column depth of the loop, the variation of the LOS column depth due to the effect of projection causes the variation of the intensity. They find that the observed amplitude increases with the decreasing wave length and the increasing displacement amplitude of kink perturbations, and also depends on the angle between the LOS and the axis of the structure. However, the condition in our case is not in favor of such an effect because of the very long wavelength (inferred from the period of 5 minutes), the small displacement amplitude (inferred from the Doppler shift amplitude), and the high inclination of the loop. Provided the LOS is coplanar with the plane of the kink oscillation and has an angle of $45^\circ$ to the axis of the loop, we estimate that the intensity amplitude produced by the kink oscillation should be less than 1% with the measured parameters and the theory of Cooper et al. (2003), which cannot account for the intensity amplitudes observed in our study.

### 4. Dependence of Oscillations on the Temperature

#### 4.1. Oscillations in Fe $x$–Fe $xv$

We examine the temperature dependence of the oscillation in six coronal emission lines with formation temperatures ranging from 1.0 to 2.7 MK (see Table 1). Figure 7 shows the evolution of intensity and Doppler shift for the oscillating loop in a part of time series. The background trend for Doppler shift time series has been subtracted at each position along the slit in order to show the oscillation more clearly. The loop is visible in all the six emission lines, but most clearly seen in the Fe $x$–Fe $xv$ lines. The intensity oscillation is weak and not easily discerned, while the Doppler shift oscillation can be clearly seen in all lines except for Fe $xvi$. The quasi-periodic oscillation actually existed over the whole observation. At the time of oscillations 1 and 2, the oscillation appears to be more coherent along the slit (or across the loop) and more periodic compared to most of the other time.

The top panels of Figure 8 show comparisons of the averaged Doppler shift profiles over 11 pixels along the slit between $y = -57''$ and $-47''$ in the Fe $x$–Fe $xv$ lines for oscillations 1 and 2. Strikingly, the plots clearly reveal a dependence of the oscillation amplitude on the plasma temperature, i.e., the amplitude decreases with increasing temperature. For oscillations 1 and 2, the maximum amplitudes in the Fe $x$ line are about $2.5$ and $3.1$ km s$^{-1}$, while those in the Fe $xv$ line are $0.8$ and $1.1$ km s$^{-1}$, respectively, indicating that the amplitude decreases by a factor of about $3$. The oscillations seen at different temperatures are nearly in phase. Although the cross-correlation shows that the phase of the oscillations in Fe $x$ is slightly earlier than in Fe $xv$, the shift is measured to be within a half exposure time. The bottom panels of Figure 8 show the evolution of the corresponding intensity profiles. For an easier comparison between the different emission lines, we have normalized the intensity for each line by the mean value of the time profile and shifted the light curve by a certain value along the $y$-axis. Although the intensity oscillation is weak compared to the Doppler shift oscillation, the behavior of the temperature dependence of the amplitude is the same as for the Doppler shift oscillation. For oscillation 1 three peaks can be seen in the Fe $x$ and Fe $xii$ lines, but are hardly discerned in the Fe $xiv$ and Fe $xv$ lines. For oscillation 2 the decreasing trend of the amplitude from Fe $x$ to Fe $xv$ is most evident for three peaks during 22:22–22:34 UT.

The periods and the amplitudes for the Doppler shift and intensity oscillations in the five emission lines are quantitatively measured from the global wavelet spectrum by applying the
same method as used in Section 3.1, and are listed in Table 2. The periods measured in the different lines are nearly same. For oscillation 1 the mean value of the periods for the Doppler shift in the five lines is 5.2 ± 0.1 minutes, and for oscillation 2 the mean value of the periods is 4.6 ± 0.2 minutes. The oscillation amplitude measured for the Doppler shift from Fe x to Fe xv decreases by a factor of about 3. This result obtained with the wavelet method is consistent with that by directly measuring the maximum amplitudes mentioned above. For the intensity oscillations the measurement shows that the amplitude decreases by a factor of about 4. Note that the intensity oscillations in Fe xiii—Fe xv for oscillation 1 and that in Fe xiii for oscillation 2 are so weak that the peak measured in the global wavelet spectrum is below the 99% confidence level.

In addition, we can also examine the temperature dependence of the oscillation amplitude by measuring the average rms amplitudes. For the averaged time series of intensity and Doppler shift during 18:10–23:10 UT, we first exclude bad data points at about 20:10 UT and 21:45 UT which were caused by cosmic rays (see Figure 7), and then subtract the background
trend which is taken as the 20 pixel smoothing average. Finally, the rms amplitudes are calculated as the standard deviation for the mean of the detrended time series in five coronal lines and are listed in Table 2. We find that the oscillation amplitudes in Doppler shift and intensity decrease by a factor of 2.7 and 3.5, respectively, from Fe x to Fe xv. This result is in good agreement with that measured from oscillations 1 and 2 with the wavelet method.

4.2. Oscillations in He ii

The 5 minute quasi-periodic oscillations are also clearly detected in the transition-region line, He ii 256.32 Å, in both intensity and Doppler shift time series over the whole observation (see bottom panels in Figure 7). Interestingly, we did not find any correlation between the oscillations observed in the Fe x–Fe xv lines (e.g., oscillations 1 and 2) and those in the He ii line, even considering the possible time delays. Figure 9 shows comparisons in the detrended relative intensity and Doppler shift between the Fe xii and He ii lines. We have removed the contribution of a main blended line, Si x (256.37 Å), from the He ii line intensity by measuring the line intensity of Si x 261.04 Å. Indeed, the blended emission from Si x can be safely ignored for the purpose of the oscillation study because it only contributes about 7% of the total emission of He ii in the data analyzed. Assuming that the Si x line has the same relative amplitude in intensity variation as the Fe xii line, we estimate that its contribution to the intensity variation in He ii is below 0.4%. The lack of correlation between the oscillations measured in Fe xii and He ii can be clearly seen from Figure 9 and the calculated correlation coefficients (see Table 3). The correlation coefficients between Fe xii and He ii are about 10% in both intensity and Doppler shift, while those between Fe xii and Fe x are more than 50% in contrast. The

![Figure 9. Comparison between the Fe xii (195.12 Å) and He ii (256.32 Å) time series in intensity (upper panel) and Doppler shift (bottom panel) from 22:05 to 23:08 UT.](image_url)

(A color version of this figure is available in the online journal.)

Table 3

| Lines            | 22:05–23:08 | 18:10–23:13 |
|------------------|-------------|-------------|
|                  | ρI          | ρV          | ρI          | ρV          |
| Fe x/Fe x       | 0.52        | 0.12        | 0.57        | 0.16        |
| Fe x/He ii      | 0.61        | 0.16        | 0.53        | 0.16        |

Note. Oscillations in Fe xii and Fe x lines and those in Fe x and He ii lines for intensity (ρI) and Doppler shift (ρV) over a 1 hr and a 5 hr time series.

A similar result is obtained for a 5 hr period of data set. The above analysis indicates that the He ii line detected the oscillation in the transition region but not in the corona due to the blended emission.

We analyze the oscillations seen in the He ii line from about 19:30 to 20:30 UT with the wavelet analysis. Figure 10 shows that two trains of oscillations can be identified in the wavelet spectrum and their power distributions in Doppler shift and intensity are similar (panels (c)). Each oscillation contains about three periods. We measure the oscillation period and amplitude from the global wavelet spectrum using the same method mentioned above and list them in Table 2. We find that the period is in the range of 4–6 minutes, and the Doppler shift and relative intensity amplitudes are comparable to those measured in the Fe x line. Figure 11 shows that the Doppler shift and intensity oscillations are approximately in phase. Their phase shift measured with the cross-correlation is 28°. Interestingly, the phase of the intensity oscillation is also slightly earlier than that of the Doppler shift oscillation as found in Fe xii. The approximate in-phase relation between intensity and Doppler shift oscillations indicates the presence of an upward-propagating slow magnetoacoustic waves in the transition region. The small phase shift may imply that it is overlaid with a weak downwardly propagating wave as suggested for oscillations seen in the coronal lines in Section 3.3.

5. DISCUSSIONS

In this paper, we have reported the simultaneous detections of 5 minute quasi-periodic oscillations in the transition region and coronal lines by Hinode/EIS in a corona loop rooted at plage. The oscillations show up in both Doppler shift and intensity throughout the whole observation, characterized by a series of trains with a nearly constant period lasting for 3–6 periods. These oscillation trains are more evident in Doppler shift than in intensity. The oscillations detected in five coronal lines in the range Fe x–Fe xv show a high correlation and exhibit a temperature dependence of the amplitude in both Doppler shift and intensity. The wavelet analyses show that the oscillation power is concentrated at the period in a range of 4–6 minutes. Both measurements with the wavelet analysis and the average rms method show that the oscillation amplitude decreases by a factor of about 3 in Doppler shift while decreasing by a factor of about 4 in intensity from Fe x to Fe xv. The oscillations measured in the transition region line, He ii, also have the dominant power at the period band of 4–6 minutes, and the amplitudes are comparable to those measured in the Fe x line. No correlation between the oscillations in Fe x–Fe xv and He ii is found. The cross-correlation shows that the phase of intensity oscillation is slightly earlier (by about 20°–30°) than the Doppler shift oscillation in Fe x–Fe xv and He ii. The approximate in-phase relation indicates the presence of upwardly propagating slow magnetoacoustic waves in both the transition region and the corona near the footpoint of a loop.
5.1. The Source of Waves

From Equation (4) we obtain $\rho'/\rho_0 = V'/c_s$. We examine this relation for oscillations 1 and 2 in Fe xii with the measurement obtained by the wavelet analysis, which gives the Doppler shift amplitude, $V' \approx 2.0 \text{ km s}^{-1}$ and the relative intensity variation, $I'/I_0 \approx 5.2\%$ (see Table 2), where $I_0$ is the undisturbed intensity of the loop. Considering $I'/I_0 \approx 2\rho'/\rho_0$ and taking $c_s = 170 \text{ km s}^{-1}$ for the formation temperature of Fe xii, we deduce the expected value of the velocity amplitude, $V' \approx 4.5 \text{ km s}^{-1}$. The result of $V'_1 = 0.43V'$ is consistent with the fact that the coronal loop, along which the slow-mode waves propagate, is highly inclined as seen in Fe xii (see Figure 1(a)). Assuming that $V'_1$ is the LOS component of $V'$, we estimate that the inclination angle of the magnetic field to the vertical is about $65^\circ$. By applying the measured average rms amplitudes, almost the same value for the inclination angle is obtained. The high inclination of coronal fields in the loop may explain the absence of correlation between the oscillations detected in Fe x–Fe xv and He ii lines supposing the waves travel from the transition region to the corona along the loop, because the waves detected in the coronal lines and the transition region line should come from the different sources due to the inclination of the coronal fields.

The oscillations we present here show many properties which are very similar to those of upward-propagating waves observed in coronal loops associated with plages using the TRACE 171 and 195 Å bandpasses (e.g., De Moortel et al. 2002a, 2002b;
First, these oscillations both have the dominant period of about 5 minutes and the amplitude of intensity variations of about 4%–5% (in the Fe x and Fe xii lines for EIS). Second, they are both long-term existing and clearly nonflare excited. Third, they both appear in the footpoints of the highly inclined coronal structures and are detected simultaneously at the transition region and coronal temperatures. These similarities indicate that the source of these waves is same, i.e., the leakage of the $p$-modes through the chromosphere and transition region into the corona. In our case the oscillations typically containing wave trains of 4–6 cycles with no apparent temporal damping are also consistent with the property of the photospheric $p$-modes. De Pontieu et al. (2004) have shown that the inclination of magnetic flux tubes can dramatically increase tunneling and may even lead to direct propagation of the $p$-modes along inclined field lines.

### 5.2. Interpretation for the Temperature Dependence

Using the EIS data, we have detected the upwardly propagating slow magnetoacoustic waves simultaneously in five coronal lines with the formation temperature in the range about 1–2 MK. The waves in different lines show highly correlation (almost in phase). Particularly, the temperature dependence of the oscillation amplitude is revealed for the first time. The feature that the amplitude decreases with the increasing temperature is in good agreement with the observations of 3 minute sunspot oscillations which show that the amplitude peaks in the transition-region lines then decreases with increasing temperature (Fludra 2001; Brynildsen et al. 2002; O’Shea et al. 2002; Marsh & Walsh 2006). The local maximum amplitude of waves at the transition region can be explained by strong stratification growth (Érdélyi et al. 2007), while the decreasing of the amplitude at increasing temperatures may be relevant to dissipation of slow magnetoacoustic waves in the corona. The propagating disturbances observed in the TRACE EUV images were found to be damped very quickly and typically only detected in the first 3–23 Mm along the loop (De Moortel et al. 2002b). Numerical simulations of slow MHD waves by De Moortel & Hood (2003, 2004) showed that a combination of thermal conduction and area divergence yielded detection lengths that are in good agreement with observed values. Klimchuk et al. (2004) further developed the model considering a nonisothermal loop, and found again that thermal conduction plays an important role in quickly damping of the waves. Here three possibilities are proposed to account for the temperature dependence of the amplitude for the observed propagating waves.

1. Assuming that the slow mode waves propagate upwardly in a nonisothermal coronal loop, then the smaller amplitude detected at higher temperature lines is because the lower temperature line forms at a height lower than the higher temperature line and the waves undergo a quick damping during the propagation from the low level to the high level. With this interpretation time delays are expected to exist between the oscillations detected in the lines of different temperatures. Cross-correlation analyses for oscillations 1 and 2 show that the phase of Doppler shift time series for Fe xv is slightly later than that for Fe x, but the time delay is less than 1 exposure (i.e., $<30$ s). By using the results of the sunspot model of Obridko & Staude (1988), we estimate the height difference of $\sim 6400$ km in the vertical direction for the Fe x and Fe xv lines. This value is on the same order as estimated from observed heights of EUV lines and the coronal model for the active Sun (Simon & Noyes 1972; Simon et al. 1974). Taking the sound speed of 200 km s$^{-1}$ and an inclination angle of $\sim 60^\circ$ of the magnetic field to the vertical, we estimate the expected time delay to be about 60 s, which is inconsistent with the observed. On the other hand, the inclination of $\sim 60^\circ$ implies a projected distance of more than 15” on the disk for the part of the loop with a vertical height of 6400 km. Since the slit appears to sit across the loop (see Figure 1(a)), this means that the emissions detected with the 1” slit in Fe x and Fe xv lines should not come from the same loop. Thus, this scenario should predict no correlation between oscillations detected in the lines of different temperatures (at different heights), which contradicts to the observation. In the following we propose the other two alternative scenarios based on the loop with multiple threads of different temperatures.

2. With simultaneous TRACE observations in 171 and 195 Å bandpasses, King et al. (2003) have revealed that the slow mode waves propagate outward along coronal loops of multiple-temperature structure. They show that the correlation between time series of disturbances observed in the different bandpasses has a tendency to decrease with the distance along the structure. They suggest that the initially high correlation may infer the same mechanism for generation of the disturbances observed at different temperatures, while the decreasing correlation along the loop may be due to phase mixing of the waves. We may explain the temperature dependence of the oscillation amplitude with a similar picture, since the footpoint of the loop analyzed in this study is clearly not isothermal as revealed by the EM loci curves for Fe x–Fe xvi (not shown). Provided the waves have the same amplitudes at the base of the corona and propagate along parallel threads of different temperatures, we expect the wave of smaller amplitudes detected in higher temperature lines because the dissipation of slow MHD waves is higher at the hotter plasmas by thermal conduction and compressive viscosity, which have been interpreted as the dominate damping mechanism in coronal loops by many theoretical studies (e.g., Nakariakov et al. 2000; Ofman & Wang 2002; De Moortel & Hood 2004; Klimchuk et al. 2004). The interpretation in this picture, however, still needs to explain the high correlation between the oscillations detected in the different coronal lines, because time delays are expected if the waves travel at different speeds in different threads of the loop having different temperatures. One explanation could be that the time delay is too short to resolve with the 30 s cadence. For example, if assuming that the waves travel over a distance of 7000 km (about half size of the footpoint brightening) in two threads with the temperature equal to the formation temperatures of Fe x and Fe xv, respectively, the expected time delay is only 15 s, less than the exposure time.

3. The third picture is proposed specifically to interpret the high correlation between the oscillations observed in coronal lines of different formation temperatures supposing that the absence of time delays is not due to the limited temporal resolution of the observation. We assume that the propagating waves are only present in an isothermal coronal loop with the plasma temperature of $\sim 1$ MK, which is overlaid by the hotter (more than 1 MK) loops with no waves propagating inside. The overlying relatively hotter loops are shown in the spectroheliogram in the
Fe\textsubscript{xv} line (not shown). Then the high correlation may be explained by the effect of the line response function (emissivity as a function of the temperature) since the modulated emissions of the different lines come from the same plasma disturbed by the waves. For the lines with higher formation temperatures, the emission contributed from the 1 MK oscillatory plasma becomes less while those from the relatively hotter nonoscillatory plasmas become more dominant, therefore, the amplitude of the detected oscillations in both intensity and Doppler shift tend to decrease with increasing temperature of the emission lines. However, since both the Fe\textsubscript{x} and Fe\textsubscript{xv} lines form in a narrow temperature range, more exactly, the contribution of the emission to the Fe\textsubscript{xv} line from a plasma at 1 MK is more than 3 orders of magnitude lower than its peak emission, the presence of waves only in the 1 MK plasma hardly explains the oscillation amplitude of 1\%–2\% measured for Fe\textsubscript{xv}.

In addition, this picture is lack of the theoretical basis for the assumption that the slow mode waves are only allowed to propagate in the 1 MK cool loops.

Therefore, the second scenario provides the best interpretation of the temperature dependence of the oscillation amplitude based on the present observations. Higher cadence (less than 15 s) observations are suggested in the future to check the reliability and accuracy of time delays between the oscillations detected in coronal lines of different temperatures, which will help us confirm this scenario. Based on linear wave theory, we can explain why the amplitude of relative intensity decreases faster than the amplitude of Doppler shift with increasing temperature for the oscillations we observed. From the relation of $I'/2I_0 \approx V'/c_s$ it follows that 

$$\frac{I'}{I_0} = \frac{V'}{V_0} \propto T^{-1/2},$$

where $T$ is the plasma temperature of the loop. If assuming $T_1 = 1$ MK and $T_2 = 2$ MK, respectively, as the temperature of the Fe\textsubscript{x} and Fe\textsubscript{xv} lines, we estimate the following ratio theoretically:

$$R_{\text{theo}} = \frac{(I'/I_0)_{T_1}/(I'/I_0)_{T_2}}{V'_{T_1}/V'_{T_2}} = \left(\frac{T_1}{T_2}\right)^{-1/2} \approx 1.4.$$  

This estimate is independent on scenarios proposed for explaining the temperature dependence of the oscillation since Equation (7) is derived from the continuity equation. If assuming that the inclination angle of the field line for oscillations detected at $T_1$ and at $T_2$ is same, we estimate this ratio

$$R_{\text{obs}} = \frac{(I'/I_0)_{T_1}/(I'/I_0)_{T_2}}{V'_{T_1}/V'_{T_2}} = \left(\frac{V'_{T_1}}{V'_{T_2}}\right)^{-1/2} \approx 1.3, \tag{8}$$

with the observational measurements of $(I'/I_0)_{T_1}/(I'/I_0)_{T_2} \approx 4$ and $(V'_{T_1}/V'_{T_2}) \approx 3$. A good agreement between $R_{\text{obs}}$ and $R_{\text{theo}}$ provides further support to our interpretation of the observed 5 minutes oscillations in terms of a slow magnetoacoustic wave.

For the oscillation in He \textit{i}, we find that the amplitudes of relative intensity and Doppler shift measured with both the wavelet method and the average rms method are inconsistent with the relation of $I'/2I_0 \sim \rho/v_0$. For example, taking $c_s = 43$ km s\textsuperscript{-1} we derive the perturbed velocities are 1.5 and 1.0 km s\textsuperscript{-1} for oscillations 1 and 2, respectively, from the measured relative intensities (see Table 2), which are evidently smaller than the measured LOS velocity amplitudes (2.4 and 3.1 km s\textsuperscript{-1}). This inconsistency may imply that the measurements of relative intensity amplitudes are underestimated, which could be relevant to the complexity of the He \textit{i} line formation (e.g., Fontenla et al. 1993a). Instead, we may estimate the lower limit of the true amplitude for relative intensity from the measurements of Doppler shift amplitudes. From $I'/I_0 \sim 2V'/c_s$, we obtain $I'/I_0 \geq 11\%$ and 14\% for oscillations 1 and 2, respectively. The estimated amplitudes are in good agreement with that measured by Marsh et al. (2003) for the 5 minute oscillation at the footpoint of fanlike TR
c loops. They find amplitudes of 12.4 ± 2.1\% for the transition region line, O \textit{v}, observed with \textit{SOHO}/SUMER observations above a sunspot region and find intensity amplitudes of 11\% and Doppler velocity amplitudes of 2.7 km s\textsuperscript{-1} for O \textit{v}. Therefore, our measurements of Doppler shift amplitudes and the derived intensity amplitudes for He \textit{i} are consistent with the amplitudes for O \textit{v} found by other studies. Thus, our observations show that the relative intensity amplitude of 5 minute oscillations decreases from the transition region to the corona. This agrees with the observations of Fludra (2001), Brynildsen et al. (2002), O’Shea et al. (2002), and Marsh & Walsh (2006) who find that the oscillation amplitude above the umbra reaches a maximum for emission lines formed close to (1–2)×10\textsuperscript{5} K and decreases for higher temperatures.

5.3. Estimates of Wave Energy Flux

We can estimate the energy flux for the propagating waves measured in Fe\textsubscript{x}–Fe\textsubscript{xv} and He \textit{i} lines in the coronal loop by

$$F = \frac{1}{2}\rho_0(V')^2c_s,$$  

where the sound speed is taken as $c_s = 152T^{1/2}$ km s\textsuperscript{-1} with the plasma temperature, $T$, in units of MK, and $V' = (1/2)c_s(I'/I_0)$. For the oscillations observed in Fe\textsubscript{x}–Fe\textsubscript{xv}, we estimate $V'$ from the relative intensity amplitudes measured with the wavelet method, while for the oscillations in He \textit{i}, we directly take the measured Doppler shift amplitudes as the low limit of $V'$ for the reason discussed above. We use Si\textsubscript{x} λ258.37/261.04 and Fe\textsubscript{xiv} λ264.79/274.20 density sensitive ratios to diagnose the loop density, where the line ratio data are calculated with SSW/CHANTI version 5.2.1. For the data observed from 18:10 to 23:10 UT, we obtain the mean electron density as $(2.0 \pm 0.4) \times 10^{10}$ cm\textsuperscript{-3} with the Si\textsubscript{x} line ratio, and $(1.7 \pm 0.2) \times 10^{10}$ cm\textsuperscript{-3} with the Fe\textsubscript{xiv} line ratio. We find that the values estimated from Si\textsubscript{x} and Fe\textsubscript{xiv} agree well. Note that in measurements of the Fe\textsubscript{xiv} λ274.20 intensity, the emission of a blended line Si\textsubscript{vii} λ274.18 has been removed by considering the density-insensitive line ratio, λ274.18/λ275.35. We find that the blended emission from the Si\textsubscript{vii} λ274.18 indeed can be ignored in this study because it only contributes about 3\% to the Fe\textsubscript{xiv} λ274.20. Using $\rho_0 = 1.2m_pN_e = (4 \pm 0.8) \times 10^{15}$ g cm\textsuperscript{-3} (where $N_e$ is taken as the electron number density measured with Si\textsubscript{x} line ratio, $m_p$ the mass of proton, and a constant of 1.2 due to consideration of coronal He abundance), we estimate the energy flux for oscillations 1 and 2 in five coronal lines and list the values in Table 4. In estimates of the wave energy flux for He \textit{i}, a typical value of mass density for the transition region, $\rho_0 = 5 \times 10^{-14}$ g cm\textsuperscript{-3}, is taken. We find that the energy flux of waves for He \textit{i} and Fe\textsubscript{x} is on the order of 10\textsuperscript{6} erg s\textsuperscript{-1} cm\textsuperscript{-2}, which decreases to the order of 10\textsuperscript{3} erg s\textsuperscript{-1} cm\textsuperscript{-2} for Fe\textsubscript{xv}. Since
the coronal radiative energy losses are typically on an order of $10^6$ to $10^7$ erg s$^{-1}$ cm$^{-2}$ for active regions (Aschwanden 2004, p 357), the energy carried by the observed waves is too small to heat coronal loops.

6. CONCLUSION

In conclusion, the upwardly propagating slow magnetoacoustic waves with periods of about 5 minutes have been detected in the transition region and coronal emission lines by Hinode/EIS at the footpoint of a coronal loop rooted at plage. The amplitude of the oscillations decreases with increasing temperatures. The temperature dependence of the amplitude observed in coronal lines can be explained by the waves traveling along a loop with multithermal temperature structure near the footpoint, and thus this feature may be valuable for coronal seismology to diagnose the property of multithreads in the loop. Many similarities between the waves observed by EIS in this study and the waves observed by TRACE in large fanlike loops suggest that the source of the waves is the same, i.e., a leakage of $p$-modes through the temperature-minimum region into the chromosphere and transition region reaching the corona. Although the energy carried by these waves is not enough to heat the corona, they may be important for the heating of the chromosphere, which have been found to be the source for generation of the periodic spicules in active regions (De Pontieu et al. 2004).

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