PROPAGATING WAVES TRANSVERSE TO THE MAGNETIC FIELD IN A SOLAR PROMINENCE

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ABSTRACT

We report an unusual set of observations of waves in a large prominence pillar that consist of pulses propagating perpendicular to the prominence magnetic field. We observe a huge quiescent prominence with the Solar Dynamics Observatory Atmospheric Imaging Assembly in EUV on 2012 October 10 and only a part of it, the pillar, which is a foot or barb of the prominence, with the Hinode Solar Optical Telescope (SOT; in Ca ii and Hα lines), Sac Peak (in Hα, Hβ, and Na-D lines), and THEMIS (“Télescope Héliographique pour l’Etude du Magnétisme et des Instabilités Solaires”) with the MTR (Multí-Raies) spectropolarimeter (in He D\textsubscript{2} line). The THEMIS/MTR data indicates that the magnetic field in the pillar is essentially horizontal and the observations in the optical domain show a large number of horizontally aligned features on a much smaller scale than the pillar as a whole. The data are consistent with a model of cool prominence plasma trapped in the dips of horizontal field lines. The SOT and Sac Peak data over the four hour observing period show vertical oscillations appearing as wave pulses. These pulses, which include a Doppler signature, move vertically, perpendicular to the field direction, along thin quasi-vertical columns in the much broader pillar. The pulses have a velocity of propagation of about 10 km s\(^{-1}\), a period of about 300 s, and a wavelength around 2000 km. We interpret these waves in terms of fast magnetosonic waves and discuss possible wave drivers.

Key words: Sun: corona – Sun: filaments, prominences – Sun: helioseismology – Sun: magnetic fields – Sun: oscillations

Online-only material: color figures

1. INTRODUCTION

In this work we have an unusually complete set of observations with which to analyze oscillations in a large prominence footpoint or barb. These allow us to combine information concerning both three-dimensional motions and magnetic field to analyze these as fast magnetosonic waves moving transverse to the prominence magnetic fields and disturbing the cool material collected in the magnetic dips.

Periodic motions in solar prominences have been routinely observed since the first observations of such oscillations in the 1950s (e.g., Ramsey & Smith 1965). These oscillations are classified as large- or small-amplitude oscillations depending on the velocity of the periodic motions, faster or slower than 20 km \(s^{-1}\), respectively. Large-amplitude oscillations are related to flare activity which causes almost the entire filament to oscillate, shaken by the energetic event. Studies of small-amplitude oscillations have revealed a wide range of periods ranging from seconds to hours (Oliver & Ballester 2002; Arregui et al. 2012). We will concentrate on the literature concerning the small amplitude motions with periods from a few minutes to 10 minutes, called short-period oscillations (see the review of Mackay et al. 2010), that is relevant to our present work.

Prominences at the limb exhibit such short-period oscillations (Oliver 1999). Tsubaki & Takeuchi (1986) and Tsubaki et al. (1987) reported short-period oscillations in Dopplershift observations of limb prominences. Two-dimensional observations of filaments on the disk have revealed oscillations transverse to the direction of fine structures of the filaments with a period around 200 s (Thompson & Schmieder 1991; Yi & Engvold 1991). Recent high spatial resolution observations obtained with the Spitzer Space Telescope show the existence of traveling waves with periods of three to nine minutes in fibril-like structures of filaments. The propagation of the waves are in the same direction as the direction of the mass flows in the prominence fine structures. Okamoto et al. (2007) found that threads in a solar prominence observed with Hinode/Solar Optical Telescope (SOT) underwent vertically oscillating motions with a period of around 250 s. Some threads oscillate all along the filament length. With Hinode/SOT data, Ning et al. (2009) analyzed the oscillations of a quiescent prominence and found a large variety of oscillations both vertical and horizontal with periods of three to six minutes.

The trigger of the small-amplitude, short-period oscillations has not been detected so far. Many authors claimed that the excitation is related with the three and five minute photospheric and chromospheric oscillations. Solar \(p\) modes are generated by turbulent convection beneath the photosphere leaking part of their power to the atmospheric layers: photosphere, chromosphere, and corona (three and five minute oscillations).

Oscillations in prominences are usually interpreted as external agents exciting periodic motions on the cool plasma. MHD waves can be propagating or standing. Propagating waves consist of periodic disturbances that propagate through the prominence plasma. In contrast, standing waves are confined in a region of the prominence because they are the normal modes of the system. Several theoretical models of prominence oscillations have been proposed. Joarder & Roberts
considered the whole filament as a vertical plasma slab, ignoring the fine thread structure, with an horizontal straight magnetic field. The influence of the gravity was considered negligible and the slab and corona plasmas were uniform. In this model, the waves are considered trapped along the horizontal direction, and are allowed to propagate in the vertical direction. Oliver et al. (1992, 1993) included gravity in the slab model, which results in the curved field lines of the Kippenhahn–Schlüter equilibrium model. The authors found that the gravity introduces only a small shift on the normal mode frequencies and thus is not relevant in this kind of configuration. Prominence fine structure consists of threads that could influence the global prominence oscillations. Joarder et al. (1997) studied theoretically the oscillatory spectra of an isolated prominence thread. Later, Díaz & Roberts (2006) included this fine structure and studied fast MHD modes of a periodic, Cartesian multi-threaded model. The authors found that the modes behave as propagating modes of an homogeneous prominence with small-scale details due the fibrils.

In this paper, we report the observations of oscillations in a quiescent prominence observed on the limb obtained by several instruments on the ground (Télescope Héliographique pour l’Etude du Magnétisme et des Instabilités Solaires (THEMIS), Sac Peak) and in space (Hinode/SOT). We describe the campaign and instrumentation in Section 2. In Section 3, we discuss the observations and present the results concerning the horizontal magnetic field measured in the prominence and the transverse oscillations. In Section 4, we discuss a possible model to explain the observed oscillations.

2. CAMPAIGN AND INSTRUMENTS

The observations were taken during an international campaign organized around Hinode Observation Plan (HOP) 219. Hinode/SOT observed in Hα and in Ca ii H lines between 14:04 UT and 18:09 UT. Over a similar time period (14:17–19:37 UT), the Dunn Solar Telescope (DST) at Sacramento Peak Observatory (Sac Peak) was used to obtain spectra in the Hα, Hβ, and Na-D lines. THEMIS in the Canary Islands along with the Multi Raies (MTR) spectropolarimeter observed the prominence all day, obtaining four full data sets. The best data were collected from 10:44–15:30 UT. Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA) with the filters of 304 Å and 193 Å and STEREO-A EUVI at 195 Å are used to supply context for the observations.

2.1. THEMIS

The THEMIS/MTR instrument (López Ariste et al. 2000) was used to do spectropolarimetry of the He D3 line in the observed prominences. The spectrograph slit was oriented parallel to the local limb. This direction subsequently defined the sign of the linear polarization: positive Stokes Q means parallel to the slit and, in consequence, parallel to the local limb. The double-beam polarimeter we performed required the use of a grid mask that presented us with three segments 15’:5 wide along the slit, but masked regions of 17” between each slit. The masked regions allowed us to obtain a double image with opposite polarization, but it also meant that in order to get a continuous covering of the prominence along the slit, we also had to scan in this direction by one step of 15’. This extraordinary scan along the slit is the reason for the jumps and dark lines in the data from this instrument presented below. These artifacts are, however, greatly compensated for by the high quality of the polarimetry produced by this observing mode.

In addition to that scan along the slit, a more usual scan perpendicular to the slit was made with steps of 2” from the limb to the top of the prominence. Altogether, typical fields of view of 120” × 40" were covered in about 1 hr with single exposure times of two s per Stokes parameter and scan position. Full polarimetry with beam exchange was done with a modulation cycle of six images, spanning the three Stokes parameters with either positive or negative signs measured in every beam, and the simultaneous double beam measuring the opposite sign. Each Stokes parameter is thus measured in the same camera pixel at two different times and in two different pixels at the same time. This symmetry of measurements results in a reduction in the systematic errors to a fourth order perturbation of the signal and high quality measurements. Each cycle was repeated five times to increase signal-to-noise ratios (S/Ns).

2.2. Hinode/SOT Hα and Ca ii

The Hinode (Kosugi et al. 2007) SOT (Tsuneta et al. 2008; Suematsu et al. 2008) consists of a 50 cm diffraction-limited Gregorian telescope and a Focal Plane Package including the narrowband filtergraph (NFI), the broadband filtergraph (BFI), the Stokes Spectro-Polarimeter, and Correlation Tracker (CT). For this study, images were taken with a 30 s cadence in both the Ca ii H line at 3968.5 Å using the BFI and at line center in the Hα line at 6562.8 Å using the NFI. The Ca ii images have a pixel size of 0.109 with a field of view of 112”×112”, while the Hα images have a pixel size of 0.16 and a field of view 164”×164”.

2.3. Sac Peak Dunn Solar Telescope

At the DST at Sac Peak, we used the Universal Birefringent Filter to observe filtergrams of Hα at line center and line center ±0.5 Å and ±1.0 Å, Hβ at line center and line center ±0.5 Å, and Na-D at line center and line center −0.25 Å. The field of view is about 173 × 173”. In our analysis we focused on the Hα data. A full scan of the five Hα line positions took 10 s and time between images at Hα line center was 22–25.6 s. Pixel size is 0.17 with resolution during our observations near 1’.

The full reconstructions of the Hα, Hβ profiles have not been done yet because it would require us to cross correlate the non-simultaneous images obtained in the three to five points in the profiles and then fit with a Gaussian. This would allow us to get quantitative estimates of the Dopplershifts, but is out of the scope of the present paper. We use only movies obtained by computing the difference of intensities of two symmetric points in the profiles, a proxy for the Dopplershifts.

3. OBSERVATIONS AND DATA ANALYSIS

Our observations of the prominence oscillations were done from 14:00 UT–18:00 UT on 2012 October 10. The prominence was observed on the western limb of the Sun at a position angle of about 256°.

The prominence was observed as a filament a few days before the main observations. On October 6, only two portions of the Hα filament are visible in a channel between two active regions (Figure 1). The filament is oriented North–South along a meridian. The prominence is well observed on October 9 and 10 in SDO/AIA filters. As seen in AIA 304 Å, it consists of a central pillar with arcades on both sides from which material is flowing horizontally, mostly outward away from the central...
pillar in the plane of the sky (Figure 2). On October 9, the central pillar is already observed in absorption as a dark region over the limb in AIA/193 Å. On October 10, at the time of Hinode observations, bright loops are in front of it and mask the dark area in 193 Å. By this time the prominence was already substantially behind the limb as is shown in the image from STEREO-A’s EUVI imager in Figure 3.

Hinode and the ground-based instruments (Sac Peak and THEMIS) have smaller fields of view and mainly observed the central pillar (Figure 4).

3.1. Wave Observations

Hinode/SOT observed the prominence from 14:04–18:09 UT and the field of view of SOT is centered on the central foot of the prominence. We see mainly a large, broad pillar with bright, relatively narrow (<5") columns consisting of horizontal features and a lateral extension at the top. For our measurements here, we analyzed the Ca II data, although the waves were apparent in the Hα data as well. The Hinode Ca II data were reduced using the standard SOT reduction software (fg-prep) in SolarSoft.

The SOT/CT (Shimizu et al. 2008) allows fixed tracking of regions on the disk, but for regions on the limb there is a slow drift of the target through the field of view. We correct for this drift using manual corrections for large jumps associated with re-pointings and a cross correlation targeted at the limb and the side of the large-scale prominence foot point. The resulting image series is sufficiently stable that remaining jitter and drift do not affect the motions and changes measured for this paper.

The Hinode SOT images show many features that appear to be wave pulses traveling roughly perpendicular to the solar limb in the narrow columns. The analysis of the most clear of these motions is shown in Figures 4–6. We integrated the intensity across a 0.55 (5 pixel) wide area positioned across the oscillating region as shown in Figure 4 at three different locations, with slits labeled (a), (b), and (c). A 50 minute long intensity slice is shown in Figure 5 (top panel (a)), corresponding to the red slit labeled (a). This wave occurs between 1000 and 2000 s, where all times are measured with respect to 14:04:47 UT. In order to remove long-term variations, the intensity data were fitted with a quadratic function which was then subtracted from the intensities. The distance between each intensity peak, measured at a given time, is a measure of the wavelength of the oscillation, and is approximately 2000 km. The slope of the intensity peaks in Figure 5 (top panel (a)), corresponding to the upward velocity of the moving features, is approximately 10 ± 4 km s⁻¹. The velocity corresponds to the phase speed of the wave. Since the phase speed remains approximately constant, the wave can be considered to be non-dispersive. In Figure 5 (bottom panel (a)), we plot the intensity as a function of time at an altitude of 14" above the photosphere. Four peaks and troughs are seen in this time range. A Fourier analysis of this section of the intensity cut, shown in Figure 6 (top panel (a)), gives a wave period of 277 ± 50 s. The wavelet analysis, shown in Figure 6 (bottom
panel (a)), indicates that the period of the wave remains approximately constant for the duration of the wave.

Identical analyses were performed at two other different locations, as shown in Figures 4–6 (panels (b) and (c)). The wave measured by the intensity slice, shown in orange in panel (b) of Figures 5 and 6, shows a similar series of bright moving features between 900 and 2000 s. The speed of the wave is measured to be approximately $5 \pm 3$ km s$^{-1}$ radially outward, and the wavelength is estimated to be roughly 900 km. The intensity cut at an altitude of 5′′ above the solar limb is shown in Figure 5 (bottom panel (b)). The period of this wave is seen from Figure 6 (top panel (b)) to be consistently near 205 ± 54 s.

For case c (Figure 4 green slit) from 4800 to 5900 s the wave is propagating downward rather than upward with a velocity of $-5 \pm 2$ km s$^{-1}$ and a period of 314 ± 125 s (Figures 5(c) and 6(c)) and may be decreasing over time. The uncertainty has been determined by taking a vertical cut through the confidence region of Figures 6 (bottom panels (a), (b), and (c) respectively).

The Dopplershift movies in Hα and Hβ lines obtained from the Sac Peak data show the existence of the same traveling waves at the same locations as the Hinode Ca II intensity observations. These waves can be detected both in intensity and in Dopplershift.

Figure 7 shows a snapshot of the Sac Peak observations of the prominence (Hβ Dopplershift) on 2012 October 10. The maxima of the Dopplershifts moving up in the column of the wave are redshifted compared to the whole prominence.

### 3.2. Magnetic Field Vector

The raw data of the THEMIS/MTR mode were reduced with the DeepStokes procedure (López Ariste et al. 2009). Data reduction included flat-fielding, dark current and bias subtraction, wavelength calibration, and, particularly, a careful handling of the polarization signals. The result of the data reduction are cubes of spectra of the He D$_3$ in intensity, linear polarization (both $Q$ and $U$), and circular polarization for all points along the slit and all positions of the double scan. S/Ns are better than $10^3$ at the core of the He D$_3$ in the central parts of the prominence for all three Stokes parameters. With these S/Ns, we get clear signals of linear polarization as expected (these are a function of height above the limb, but linear polarization is expected at the level of $10^{-2}$ times the intensity and therefore 10 times the noise level) but circular polarization is seldom seen above the noise. Whether this circular polarization is due to Zeeman effect or the alignment-to-orientation transfer mechanism (López Ariste & Casini 2002), those low signals already point to weak magnetic fields, a conclusion that will be confirmed by the inversion codes.

The Stokes profiles are fed to an inversion code based on Principal Component Analysis (López Ariste & Casini 2002; Casini et al. 2003) that efficiently compares the observed profile against those in a database generated with known models of the polarization profiles of the He D$_3$. The comparison is made independently, pixel by pixel. The database used contains 90,000 profiles computed as the emission of a single He atom in its triplet state modeled with the 5 levels of lower energy of the He triplet system. The atom is polarized by the anisotropic radiation of the photosphere below the prominence at different heights (one of the free parameters of the model). Collisions are not taken into account. The atomic polarization of the He atom is modified by a single vector magnetic field with free strength, inclination, and azimuth. The Hamiltonian of the atom includes all terms with its Zeeman sublevels splitting linearly with the magnetic field. We solve the density matrix of the atom in statistical equilibrium; the solution contains all populations and quantum coherences, including atomic alignment and orientation, for all the levels involved in the He triplet atom model. The Hanle effect of every level is thus computed as well as the Zeeman effect. From the resulting populations and coherences we compute the polarization-dependent emission terms in whatever direction we are observing. The scattering angle is thus a free parameter of the model too. Several million profiles thus computed are used to fill the database, keeping just those which are different enough among them and rejecting others so that the database fills as homogeneously as possible the space of possible profiles while keeping at a small size.
Figure 5. (top, (a)–(c)) Intensity maps as a function of time along the three slits shown in Figure 4. Cuts of the intensity were made along the horizontal line (bottom, (a)–(c)). The vertical lines represent the range of times of the data used for the periodogram results in Figure 6. Long term trends were subtracted from the intensities resulting in negative values.

(A color version of this figure is available in the online journal.)
Figure 6. (top, (a)–(c)) Periodograms of the intensity cut shown in Figure 5. The peak power is located respectively at 277 s (± 50 s), 205 s (± 54 s), and 314 s (± 125 s). (bottom, (a)–(c)) Confidence regime for the periodograms, indicating that the period is staying approximately constant for the first two waves but may be changing for the third wave.

(A color version of this figure is available in the online journal.)
After comparison of any observed profile with those in the database, the most similar is kept as the solution and the parameters of the model used in its computation are kept as the inferred vector magnetic field, height above the photosphere, and scattering angle. Error bars are determined for those parameters as well by doing some statistics on all other models sufficiently similar to the observed ones, though not as similar as the one selected as the solution. It is important to stress that although there is always one case in the database that is the most similar one to the observed one, this does not mean that it is a good fit to all of the observed profiles. It is thus important to keep a measure of how similar they are and also to check that all conclusions on the magnetic field strength or orientation are based upon sets of profiles that really correctly represent the observation.

Figure 8 presents three of the four maps of the prominence intensity obtained on October 10 with THEMIS/MTR in the He D₃ line.

Figure 9 presents the maps obtained after inversion of the Stokes parameters recorded in the He D₃ line with THEMIS/MTR: (a) intensity, (b) magnetic field strength, (c) inclination, and (d) azimuth. The angle origin of inclination is the local vertical, the origin of the azimuth is a plan containing the line of sight (LOS) and the local vertical. We see that the brightest parts of the prominence have an inclination of 90°, which means that the magnetic field in these bright columns is horizontal.

Figure 10 presents the variation of magnetic field strength, inclination, and azimuth along the brightest column in Figure 9. The field strength in the bright column is around 7.5 G and horizontal. The azimuth is close to 100°. This means that the magnetic field vector is mainly in the plane of the sky. This confirms previous results (Bommier & Leroy 1998). Observations of prominence footpoints observed on the disk have also shown that the field lines are tangent to the photosphere (López Ariste et al. 2006). Linear force free field extrapolations show that prominence plasma is supported by shallow dips in magnetic field lines like in the Kippenhahn–Schlüter model (Aulanier & Démoulin 1998; Dudík et al. 2008). The feet or footpoint of a prominence would be piles of dips in horizontal field lines. The existence of a dip in magnetic field lines to represent a prominence thread has been discussed accordingly to the value of the β plasma by Heinzel & Anzer (1999). Our observation of prominence fits closely the side view of a footpoint of prominence (or barb) modeled by dips of magnetic field lines in Figure 5 of Dudík et al. (2012). The global shape of the foot is like an anvil and each portion of the field lines is horizontal and roughly in the plane of the sky.

4. FAST MAGNETOSONIC WAVE MODEL

4.1. Theoretical Phase Velocity of Waves

Propagating waves have been detected in three vertical bright columns observed by Hinode/SOT and the DST. In the column with the brightest Ca ii intensity (analyzed with slit a, Figure 4), the observed wave train propagates upward in the prominence with a projected phase speed of around 10 km s⁻¹, a projected wavelength of 2000 km, and a period of 277 s, as described in Section 3.1. These intensity variations in the Ca ii filters are interpreted in terms of plasma compressions and rarefactions. According to the magnetic field measurements, the propagation of the waves is mainly perpendicular to the horizontal local magnetic field. Prominences have a complex fine structure that consists of thin threads (Lin et al. 2005) that extend along the magnetic field. The bright columns consist of many piled-up threads. The wave propagates in a highly non-homogeneous medium; however, the measured phase speed seems independent of the position of the wavefront (see Section 3.2).

As a first approximation, we consider that waves propagate in a uniform medium, and we interpret the observed waves as fast magnetosonic modes. These wave modes propagate perpendicularly to the local magnetic field and the velocity perturbations are longitudinal, along the propagation direction. The restoring force of these waves are the magnetic and gas pressure, and it produces compressions and rarefactions of the plasma and the magnetic field intensity. Based on the observed properties, we explore the different wave modes that could be relevant to the situation by doing a theoretical phase velocity diagram. In Figure 11 we have plotted the sound speed, $c_{\text{sound}}$, the Alfvén speed, $v_{\text{Alfvén}}$, and the magnetosonic speed given by

$$v_{\text{ms}} = \sqrt{v_{\text{Alfvén}}^2 + c_{\text{sound}}^2},$$

as a function of the electron number density, $n_e$, and the averaged magnetic field intensity of our observations of 7.5 G. In the range of typical prominence values of electron number density $n_e \sim 10^9–10^{11}$ cm⁻³ (Labrosse et al. 2010), the plasma β is small and $v_{\text{Alfvén}} > c_{\text{sound}}$. Our observations reveal a projected speed of the order of 10 km s⁻¹ that is much smaller than the magnetosonic speeds. In fact, it is similar to $c_{\text{sound}}$ corresponding to the slow mode. However, the slow modes propagate mainly along the magnetic field in the range of small β, which is perpendicular to the observed direction. The discrepancy between the observed and theoretical values could be explained by the projection effect. The waves form an angle with respect to the LOS, $\alpha_{\text{LOS}}$. In Figure 11, we have plotted the angle $\alpha_{\text{LOS}}$ necessary to have a projected $v_{\text{ms}}$ velocity of
Figure 8. THEMIS/MTR observations of the prominence in He D$_3$ line intensity between (a) 10:44 and 11:52 UT, (b) 12:09 and 13:12 UT, and (c) 14:26 and 15:30 UT. The fields of view are $42'' \times 90''$. The fields of view are not the same. They have been shifted by a few pixels toward the top of the prominence. The images are rotated so that the limb is horizontal. The dark vertical lines are due to the grid mode of the observations.

Figure 9. THEMIS/MTR observations of the prominence in the He D$_3$ line. (a) Intensity between 10:44 and 11:52 UT, (b) magnetic field strength, (c) inclination, and (d) azimuth. The color chart refers from $0^\circ$ to $+180^\circ$ (left to right). Orange means around $90^\circ$. The inclination is measured from the vertical. All the orange pixels in the inclination map (on the left) show that the field direction is mainly horizontal. The azimuth is mainly around $110^\circ$, so that the field direction is directed approximately (within about $30^\circ$) parallel to the plane of the sky.

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

Figure 10. From left to right, plots of the inferred magnetic field strength ($G$), inclination (degrees, $90^\circ$ being horizontal), and azimuth (degrees, $90^\circ$ being in the plane of the sky). They are plotted along a cut through the brightest prominence column (similar to the column indicated by slit (a) in Figure 4, right panel). The diamonds are the actual data, while the shaded region is the $3\sigma$ smoothed confidence region of the results. The azimuth is subject to a $180^\circ$ ambiguity that has been solved ad-hoc but that invalidates the computation of the confidence limits.

10 km s$^{-1}$ defined as $\alpha_{\text{LOS}} = \arcsin(10/v_{\text{m}})$. This indicates that for the range of typical prominence densities the wave moves in a direction forming a small angle with respect to the LOS of $\alpha_{\text{LOS}} < 15^\circ$ (or $\alpha_{\text{LOS}} > 165^\circ$). These angles are very extreme, indicating that for typical prominence values the propagation is mainly along the LOS. Another possibility is that the prominence electron density is larger than $10^{11}$ cm$^{-3}$ and the projection angle is small. For example, with $n_e = 5 \times 10^{11}$ cm$^{-3}$
the magnetosonic speed is of around 22 km s\(^{-1}\) and \(\alpha_{\text{LOS}} = 27^\circ\). Thus, a combination of a relatively small \(\alpha_{\text{LOS}}\) and relatively large prominence density can explain the small phase speed of the observed magnetosonic waves.

4.2. Model of Waves

The propagating waves seem to be confined in the cool prominence column. This could be because we only observe the cool plasma in our observations, and the visibility of the waves is difficult to observe outside the cool prominence. However, theoretical models predict that the waves are truly confined in the prominence, as described by Joarder & Roberts (1992a, 1992b, 1993) and Oliver et al. (1992, 1993). These authors modeled the prominence as a slab of cool plasma using different configurations of the magnetic field. These systems exhibit many normal modes that are confined or trapped in the horizontal direction but propagate vertically. These works concentrated on the large wavelength limit, \(k_zL \ll 1\), where \(k_z\) is the vertical wavenumber and \(L\) is the length of the prominence field lines. In that situation, the whole prominence oscillates in phase in the vertical direction. However, in the waves described in this work, the wavelength is short compared with the length of the prominence magnetic field so that \(k_zL \gg 1\). A detailed normal mode analysis of the system is out of the scope of this paper; it will be a subject of a future work.

For the present work, we have modeled the prominence as a uniform plasma slab with a uniform horizontal magnetic field (see Figures 12(a) and (b)). The average magnetic field intensity is set to 7.5 G. We have made a time-dependent simulation of the system described by Joarder & Roberts (1992b). The model consists of a vertical prominence slab with a horizontal magnetic field transverse to the prominence slab. Gravity is neglected because it has little influence on the waves (Oliver et al. 1992). In this simulation, we try to understand how the waves propagate in the prominence structure and not how the waves are produced and reach the prominence. For this reason, we considered the prominence slab with an infinite vertical extension and we did not model the photosphere, chromosphere, and transition region. The model atmosphere is uniform, the top of the photosphere is placed at \(z = 0\). The driver perturbs the \(v_z\) component of the velocity and consists in a planar pulse located at \(z = -10\) Mm with a Gaussian shape, \(v_z = e^{-(x+10)^2/2}\). The width of the Gaussian is 3 Mm. We have checked several driver shapes and all produce similar results. The driver oscillates three times with a period of 300 s that is similar to the observed one. The prominence slab is placed between \(x = -5\) Mm and \(x = 5\) Mm, with a total width of 10 Mm. The electron density of the prominence is set to \(n_e = 5 \times 10^{11} \text{ cm}^{-3}\), 100 times larger than that of the surrounding corona. The temperature of the prominence plasma is 8000 K and the corona is \(10^6\) K. We fulfill the pressure imbalance condition \(\rho_p T_p = \rho_c T_c\), where the \(p\) and \(c\) subscripts refer to prominence and coronal medium, respectively. The equilibrium magnetic field is uniform and horizontal, \(\mathbf{B} = B_0 \hat{\mathbf{x}}\), with \(B_0 = 7.5\) G. The length of the field lines are 100 Mm, which is in agreement with most of the theoretical modeling.

![Figure 11](image-url)  
Figure 11. Plot of the theoretical phase velocity of the magnetosonic mode (solid line), the slow mode (dashed line), and the Alfvén mode (dotted line) as a function of the electron number density of the prominence plasma. The magnetic field intensity used is 7.5 G and the prominence plasma temperature is 8000 K. The typical prominence values of the electron number densities are \(n_e \sim 10^9\)–\(10^{11} \text{ cm}^{-3}\) (see Labrosse et al. 2010). The dark area corresponds to larger values of \(n_e\) and we have plotted these values in order to have values of the theoretical magnetosonic speed comparable to the observed velocities. We have also plotted (dot-dashed line) the \(\alpha_{\text{LOS}} = \arcsin(10/v_{\text{LOS}})\) defined as the angle should form the propagation direction of a magnetosonic wave with respect to the LOS in order to have a projected velocity of 10 km s\(^{-1}\) (the observed value).

![Figure 12](image-url)  
Figure 12. Time-dependent simulation results of a wave train traveling along the prominence. The prominence slab is placed between \(x = -5\) Mm and \(x = 5\) Mm with a uniform electron density of \(10^{11} \text{ cm}^{-3}\). The magnetic field is horizontal and uniform \(\mathbf{B} = 7.5\) G. In (a) the wavefront appears from below and in (b) the full wave train has appeared, traveling upward. The gas pressure (color) shows almost planar wavefronts confined in the prominence column. Similarly, the velocity field (vectors) is almost vertical inside the prominence with the largest values, whereas it is almost horizontal outside with smaller values.

(A color version of this figure is available in the online journal.)
We impose that the magnetic field perturbations are zero at both ends of the field lines representing the photospheric line-tying effect. The top and bottom boundaries of the simulation box are opened in order to mimic the infinite extension of the prominence in the vertical direction. We refer to Joarder & Roberts (1992b) for the equilibrium configuration and the equations describing the evolution.

The simulation shows that a train of waves traveling upward is confined in the prominence (see Figures 12(a) and (b)). In Figure 12(a), the wave appears from the bottom. The gas pressure shows that this wave produces compressions and rarefactions of the prominence plasma. The velocity field oscillates vertically in the prominence plasma and horizontally in the corona, with the velocity in the prominence larger than that outside. The wave propagates vertically confined in the prominence body with a wave front almost planar. The motion of the plasma of the corona can be understood as follows: the coronal plasma reacts to the pressure changes of the prominence plasma. An increase of the plasma pressure in one selected position forces the coronal plasma to move away from this region along the magnetic field lines. Similarly, a decrease of the prominence plasma pressure forces the coronal plasma to move toward that region. In Figure 12(b), a three-wavelength-long wave train has appeared and travels upward. In the rear of the train, a small perturbation appears with a short wavelength. These are associated with an overtone also excited by the driver. The amplitude of these small perturbation is small in comparison with the upward-propagating waves. The phase speed of the magnetosonic waves, as seen in Figure 11, is 80\,km\,s\(^{-1}\), which coincides with the speed of the magnetosonic waves, as seen in Figure 11. We performed several numerical experiments with different configurations and in all the cases the propagation speed coincided with the magnetosonic velocity. In Joarder & Roberts (1992b, 1993), the authors found that the short-period oscillations are essentially trapped magnetosonic waves reflecting off the boundaries of the prominence slab and propagating along it. The normal mode excited in the simulations can be identified by the so-called string mode fIF. This mode is classified as internal mode by Joarder & Roberts (1992b) where the velocity of the perturbation is mainly located inside the prominence. Oliver et al. (1993) more accurately classified the normal modes of a prominence and found that the fIF modes are hybrid. This means that removing the coronal or prominence medium the mode remains, but with a different frequency and shape.

Our simulations demonstrate that the vertically propagating waves transverse to the magnetic field are magnetosonic waves ducted along the prominence column and the treatment of waves in a homogeneous medium is applicable. The observed prominence is quiescent and seems quite static in the observed time. This indicates that the plasma \(\beta\) is small and then \(v_{\text{Alfvén}} > c_{\text{sound}}\) and the observed waves are fast magnetosonic modes. In order to have a projected magnetosonic speed comparable to the observed velocity, the projection angle \(\alpha_{\text{LOS}}\) should be small. In fact, assuming that the prominence density has a typical \(n_1\), \(\alpha_{\text{LOS}} < 15^\circ\). As the wave is ducted in the prominence, this indicates that the column of cool plasma forms small angle with respect to the LOS. This could be associated with the column not being placed exactly at the solar limb at the moment of the observations. In Figure 3, we see that the dark pillar is considerably behind the limb. It is almost 150 arcseconds behind, almost 10° with respect to the Sun’s center. This means that the local vertical to the solar surface at the pillar position is 80° instead of 90° with respect to the LOS. Additionally, the bright column forms part of the prominence foot or barb, and such structures are often very elongated when seen on the disk but are not very tall when seen at the limb, indicating large inclinations of those structures with respect to the solar surface. In Figure 3, we can see that the horizontal extension of the pillar is of the order of 50 arcseconds, and the vertical extension is less than 50 arcseconds from Figure 4. This means that the pillar is inclined more than 45° with respect to the vertical direction. Numerical simulations indicate that the prominence foot consists of many horizontal threads pilled to form inclined structures with respect to the solar vertical (see Figure 7 by Dudík et al. 2012). In Figure 13, we have included a sketch of the configuration of the pillar in the observation. The prominence foot consists of a pillar of threads that are placed in the dips of the magnetic field lines. The pillar is behind the limb (red line), as the observations reveal (see Figure 3). The pillar has also an inclination with respect to the local vertical. Thus, it is plausible and consistent with our model that the oscillating columns form a small angle with respect to the LOS (\(\approx 30^\circ\)) and have a relatively large density (a few times \(10^{11}\) \,cm\(^{-3}\)).

The DST observations reveals Doppler velocities (see Section 2.3). These velocities are non-zero projections of the oscillation velocity along the LOS. This can also be explained by the inclination of the propagation of the waves with respect to the LOS. In the magnetosonic waves, the oscillation and propagation directions are the same. Thus, in the case of \(\alpha_{\text{LOS}} \neq 90^\circ\), the velocity of oscillation has a projection along the LOS.

Along the third slit we analyzed (slit c), we observed downward motion, and visually it appears that some waves move upward and then reflect back downward. These motions can be attributed to the propagation of the waves in a non-homogeneous medium. The study of the propagation of the waves in such a complicated medium will be a subject of a future work.

5. CONCLUSION

A quiescent prominence has been observed with Hinode (Ca II H, He I), Sac Peak (Hα and He II) over a time period of four hours, THEMIS/MTR (vector magnetograms in He D\(_2\)), SDO/AIA (193 Å, 304 Å), and STEREO-A/EUVI (195 Å) on 2012 October 10. The small field of view of the later instruments is centered on one large foot of the prominence. This foot appears in 304 Å as a large quasi-vertical pillar with material flowing on each side along horizontal field lines. The polarimetry in the He D\(_2\) line obtained by the observations of THEMIS in the MTR mode allows us to derive the magnetic field strength, the inclination,
and the azimuth in the region of the prominence observed. The magnetic field is mainly horizontal with a field strength around 5–10 G.

The observed waves propagate perpendicular to the magnetic field according to the measurements of the magnetic field by THEMIS. The observed phase speeds are below 10 km s⁻¹, the periods are around 300 s, and the wavelengths are about 2000 km. Our simulations reveals that fast magnetosonic waves are ducted along the prominence foot moving upward and probably away from the observer. These waves produce compressions and rarefactions of the plasma as seen in the observations. The direction of the propagation is perpendicular to the magnetic field as expected. We can explain the small projected observed phase speed as a combination of a relatively small α_LOS and relatively large prominence density.

In some cases it seems that the wavefronts propagate downward after a reflection at some height. This could be associated with non-homogeneities of the plasma and magnetic field. However, the waves are observed emanating from the direction of the solar surface. We cannot identify the driver of these waves. We speculate that they could be associated with rapid spicule jets, magnetic reconnection in or just above the photosphere, due to the emerging of small flux close to the prominence, or jets, magnetic reconnection in or just above the photosphere, whose PI is E. Khomenko.

In the next future we will investigate the propagation of the waves to the chromosphere. This fact could be important for the coronal heating problem because these waves contribute to the AC heating. In a future work we will investigate the propagation of the waves in non-homogeneous plasmas and how different triggers can excite these waves in prominences.

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ERRATUM: “PROPAGATING WAVES TRANSVERSE TO THE MAGNETIC FIELD IN A SOLAR PROMINENCE” (2013, ApJ, 777, 108)

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In the published version of this paper, “SST” was incorrectly expanded as “Spitzer Space Telescope” in the Introduction. The correct full form should have been “Swedish Solar Telescope.”

IOP Publishing sincerely regrets this error.