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Abstract: With modern imaging and spectral instruments observing in the visible light, EUV, X-ray and radio wavelengths the detection of oscillations in the solar outer atmosphere has been a regular feature. These oscillations are the signatures of the presence of a wave phenomenon and are generally interpreted in terms of magnetohydrodynamic (MHD) waves. With multi-wavelength observations from ground and space-based instruments, it has been possible to detect waves in a number of different wavelengths simultaneously and to, consequently, study their propagation properties. Observed MHD waves propagating from the lower solar atmosphere into the higher regions of the magnetized corona have the potential to provide an excellent insight into the physical processes at work at the coupling point between these different regions of the Sun.

High-resolution wave observations combined with forward MHD modelling can give an unprecedented insight into the connectivity of the magnetized solar atmosphere, which further provides us a realistic chance to construct the structure of the magnetic field in the solar atmosphere. This type of solar exploration is also termed as atmospheric magneto-seismology. In this review we summarize some new trends in the observational study of the nature of these waves and oscillations, their origin, and their propagation through the atmosphere.

In particular, we will focus on waves and oscillations in open (e.g. solar plumes) and closed (e.g. loops and prominences) magnetic structures, where there have been a number of observational highlights in the last few years. Furthermore, observations of waves in filament fibrils allied with a better characterization of their propagating and damping properties, the detection of prominence oscillations in UV lines, and the renewed interest in large-amplitude, quickly attenuated prominence oscillations caused by flare or explosive phenomena will be addressed.

*** Response to reviewer's comments**

Comments for the Author:

Reviewer #1: "Present and future observing trends in atmospheric magneto-seismology"

D.Banerjee, R. Erderlyi, R. Oliver and E. O'Shea

This paper presents an overview of some recent examples of observations of waves and oscillations in a variety of coronal structures. The authors have made a significant effort to modify the paper and I now recommend the paper for publication in Solar Physics, if the following (mostly minor) comments are taken into account.

Comments:
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* p1 (l29): add 'with' ('...further provide us with a realistic chance...')
Corrected

* p2: I suggest the authors rephrase the one but last sentence of Section 1 ('...focusing on some new ideas in the observation of waves...') Although I find the manuscript considerably improved, I still did not see much evidence of 'new' ideas. (For example, focusing more on spectroscopic observations has been suggested by many authors previously).

Rephrased, see bold faced p2
* p3 (l39): Correct Finsterleet to Finsterle
Corrected

* p4 (l38 - l41): How does the correlation analysis of De Pontieu (2003b) provide answers to the question of the heating mechanism of the chromosphere and/or corona?

That is NOT what is written. We wrote: "The correlation analysis gives some partial answer to the question of how the heating mechanisms of the chromosphere are related and whether the spatial and temporal variability of moss (and spicules) can be used as a diagnostic tool for coronal heating". With correlation analysis one can find an answer which pixel of images at different height are related with what probability. I.e. tracking photospheric magnetic field changes can (or cannot!) be related to heating activities. This is explained in more details in Berger's moss paper or in De Pontieu's work. Here we wanted to draw attention to this possibility.

* p17 (l43 - l46): The interpretation of EIT waves is still under debate and they can only be used as a seismological tool, if they are actually waves. The authors should comment on this issue at this point in the manuscript (or move this statement to later on in this section, where they actually discuss the various different interpretations of EIT waves). Also, why is the discussion on the nature of EIT waves presented in this review more limited than, e.g. the intro of Ballai et al (2005)?

We have addresses this issue and elaborated on the nature of the EIT waves, see bold faced paragraphs page 18 and 19.

* p19 (l34): I think 'plasma' should be replaced by 'intensity' ('...signatures they leave in the intensity.').
No actually we means plasma only, signatures are recorded in intensity and velocity also

* p20 (l39 - l40): Which 'time delay' is being measured here? (If the 'apex' spectrometer does not observe any line broadening at all as the wave passes, how can the time delay between the 'footpoint' and 'apex' spectrometers be measured?)

the time-delays are measure by phase difference analysis, the intensity and velocity information both can be used. We have added that in page 20 see bold faced

* p20 (l47): replace 'wave' by 'loop' ('If the loop supports the presence...')
Corrected

* p21 (l27): duplication of 'velocity'
Corrected

* p25: In Section 4.2, a table summarizing the various periods observed in prominences would be helpful for future reference and would highlight the wide range of periods associated with prominence oscillations.

We agree and we have included a table. see page 26 (top), accordingly the text has been modified and references has been added.

Present and future observing trends in atmospheric magneto-seismology

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Abstract.
With modern imaging and spectral instruments observing in the visible light, EUV, X-ray and radio wavelengths the detection of oscillations in the solar outer atmosphere has been a regular feature. These oscillations are the signatures of the presence of a wave phenomenon and are generally interpreted in terms of magnetohydrodynamic (MHD) waves. With multi-wavelength observations from ground and space-based instruments, it has been possible to detect waves in a number of different wavelengths simultaneously and to, consequently, study their propagation properties. Observed MHD waves propagating from the lower solar atmosphere into the higher regions of the magnetized corona have the potential to provide an excellent insight into the physical processes at work at the coupling point between these different regions of the Sun. High-resolution wave observations combined with forward MHD modelling can give an unprecedented insight into the connectivity of the magnetized solar atmosphere, which further provides us with a realistic chance to construct the structure of the magnetic field in the solar atmosphere. This type of solar exploration is also termed as atmospheric magneto-seismology. In this review we summarize some new trends in the observational study of the nature of these waves and oscillations, their origin, and their propagation through the atmosphere. In particular, we will focus on waves and oscillations in open (e.g. solar plumes) and closed (e.g. loops and prominences) magnetic structures, where there have been a number of observational highlights in the last few years. Furthermore, observations of waves in filament fibrils allied with a better characterization of their propagating and damping properties, the detection of prominence oscillations in UV lines, and the renewed interest in large-amplitude, quickly attenuated prominence oscillations caused by flare or explosive phenomena will be addressed.

Keywords: Coronal loops, MHD Waves, MHD Oscillations

1. Introduction

From Solar and Heliospheric Observatory (SOHO) and Transition Region And Coronal Explorer (TRACE) data, new results, that shed light onto dynamical events in the outer solar atmosphere, especially short-time scale variability and/or oscillations at EUV wavelengths, have emerged. The detection of waves in the outer solar atmosphere is made possible by observing the effect these waves have on the plasma, that is, by measuring the signatures of these waves. For example, signatures of waves may be detected in the form of variations or oscillations in intensity flux or in the line-of-sight velocities, both measurable from spectral lines. These periodic motions are generally interpreted in terms of magnetohydrodynamic (MHD) waves. They carry information from the emitting regions allowing a diagnosis of the frozen-in magnetic fields as well as the plasma contained in different magnetic structures, e.g., coronal loops. The characteristic sizes of coronal structures are often comparable to the wavelengths of these waves and the time scales are in the range of seconds to minutes which are detectable from space and by ground based instruments, e.g., the detection of EIT (or coronal Moreton) waves (Thompson et al. 1998) or compressible waves in polar plumes (Ofman et al. 1997; DeForest & Gurman 1998). Ground based radio observations have also reported periodic phenomenon in the corona (Aschwanden 1987). Thus, imaging instruments (from space and ground) have uncovered a myriad of wave detections in the corona, which have been reviewed at length in Aschwanden (2003, 2004, 2006), De Moortel (2005, 2006), De Pontieu & Erdélyi 2006, Erdélyi 2006a,b, Nakariakov & Roberts 2003, Nakariakov & Verwichte 2005, Nakariakov 2006, Wang 2004. In this review we will report on current trends in the observational study of MHD waves. Summaries will be provided for imaging observations together with a slightly more detailed description of spectral methods as these have not been dealt with in previous reviews. It is not the purpose and intention of this review to make an exhaustive list of all observations at the likely risk of being repetitive. Instead, we seek to present a complementary view to those mentioned above by focusing **on some recently reported** observation of waves, particularly those related to spectroscopic and not imaging methods. In this paper we will also briefly address the status of prominence oscillations in a separate section, stressing their importance as a natural example and tool for studying wave signatures.

2. MHD waves in the lower solar atmosphere

The solar atmosphere from its visible lower boundary, the photosphere, through a transitional layer with sharp gradients (TR hereafter) up to its open-ended magnetically dominated upper region, the corona, is magnetically coupled. This physical coupling is obvious when one overlays concurrently taken snapshots of the various solar atmospheric layers as a function of height, and, a magnetogram obtained at the same time at photospheric heights. A typical magnetic field concentration, e.g. an active region or an intense flux tube, will show up as a strong brightening at corresponding locations in UV, EUV and X-ray images indicating evidence in support of the coupling of the all pervasive magnetic field.

Recent high-resolution satellite and ground-based technology provides us with unprecedented fine-scale spatial and time resolution data of different magnetic structures in the solar atmosphere (e.g. plumes, coronal loops, arcades, and even dynamic features like spicules) that support periodic motions (propagating waves or oscillations) on wide spatial and time scales. The large concentrated magnetic structures at photospheric to low-TR and coronal heights serve as excellent waveguides for the propagation of perturbations excited at footpoint regions. These observed oscillations *within* the magnetic structures, being intrinsically locked into them (in contrast to the acoustic solar global oscillations that are ubiquitous in the solar interior) provide us with the tools to diagnose the structures themselves.

2.1. WAVE LEAKAGE FROM THE PHOTOSPHERE

As the acoustic wave frequency increases beyond 5.3 mHz, the upper boundary of subsurface cavities becomes increasingly transparent and the acoustic waves are able to propagate into the Sun's chromosphere. The high-frequency waves may therefore convey information about the properties of the chromosphere. Using time-distance analysis of solar acoustic waves with frequencies above the nominal atmospheric acoustic cutoff frequency (5.3 mHz) Jefferies et al (1997) showed that the waves can be partial reflected at both the Sun's photosphere and a layer located higher in the atmosphere. From spectroscopic one dimensional observations Baudin et al. (1996) showed for the first time that upward propagating 5 minute waves emerge from the deep chromospheric network. They suggested that the waves propagating in the open corona are reminiscent of photospheric oscillations transmitted by the magnetic field of the chromospheric network. Using Magneto-Optical filters at Two Heights (MOTH) instrument Finsterle et al. (2004) have recorded simultaneous dopplergrams at a high cadence (10 s sampling intervals) in two Fraunhofer lines formed at different heights in the solar atmosphere. They found evanescent-like waves at frequencies substantially above the acoustic cut-off frequency in regions of intermediate magnetic field. Furthermore, upwardly- and downwardly-propagating waves were detected in areas of strong magnetic field such as sunspots and plage: even at frequencies below the acoustic cut-off frequency. They conjectured that the interaction of the waves with the magnetic field must be a non-linear process depending on field strength and/or inclination.

Very recent observations of the TR, in particular spicules and moss oscillations, detected by TRACE and by SUMER on board SOHO brings us closer to an understanding of the origin of running (propagating) waves in coronal loops. The correlations on arcsecond scales between chromospheric and transition region emission in active regions were studied in De Pontieu et al. (2003b). The discovery of active region moss (Berger et al., 1999), i.e, dynamic and bright upper transition region emission at transition region heights above active region (AR) plage, provides a powerful diagnostic tool to probe the structure, dynamics, energetics and coupling of the magnetized solar chromosphere and transition region. De Pontieu et al. (2003b) studied the possibility of the direct interaction of the chromosphere with the upper TR, by searching for correlations (or lack thereof) between emission at varying temperatures using concurrently taken EUV lines emitted from the low chromosphere (Ca II K-line), the middle and upper chromosphere (Hα), the low transition region (C IV 1550 Å at 0.1 MK), and from the upper transition region (Fe IX/X 171 Å at 1 MK and Fe XII 195 Å at 1.5 MK). The relatively high cadence (24 to 42 seconds) data sets obtained with the Swedish Vacuum Solar Telescope (SSVT, La Palma) and TRACE allowed them to find a relationship between upper transition region oscillations and low-lying photospheric oscillations. Fig. 1 shows a typical example demonstrating the correlation between chromospheric and upper TR oscillations. The wavelet power spectra for TRACE 171 Å (top panel), Hα-350 mÅ (2nd from top), Hα+350 mÅ (3rd panel from top) and light-curves (bottom panel) for TRACE 171 Å (full, with triangles), Hα-350 mÅ (full blue) and Hα+350 mÅ (full red), are quite similar, despite the atmospheric seeing deformations the ground-based data suffer from. While there is generally a good correlation between the TRACE 171 Å signal and the wings of Hα, there is often a delay between the Hα-350 mÅ and Hα+350 mÅ signals, usually of the order 60 to 100 s. A simple estimate using this phase delay and the physical distance between the line formation of TRACE Fe IX/X 171 Å lines has led to the possible conclusion of direct wave leakage.

This correlation analysis gives some partial answers to the question of how the heating mechanisms of the chromosphere are related and whether the spatial and temporal variability of moss (and spicules) can be used as a diagnostic for coronal heating. De Pontieu et al. (2003a) analysed intensity oscillations in the upper TR above AR plage. They suggested the possible role of a direct photospheric driver in TR dynamics, e.g. in the appearance of moss (and spicule) oscillations. Wavelet analysis of the observations (by TRACE) verifies strong ($\sim$ 5 - 15%) intensity oscillations in the upper TR footpoints of hot coronal loops. A range of periods from 200 to 600 seconds, typically persisting for about 4 to 7 cycles was found. A comparison with photospheric vertical velocities (using the Michelson Doppler Imager onboard SOHO) revealed that some upper TR oscillations showed a significant correlation with solar global acoustic p-modes in the photosphere. In addition, the majority of the upper TR oscillations were directly associated with upper chromospheric oscillations observed in Hα, i.e., periodic flows in

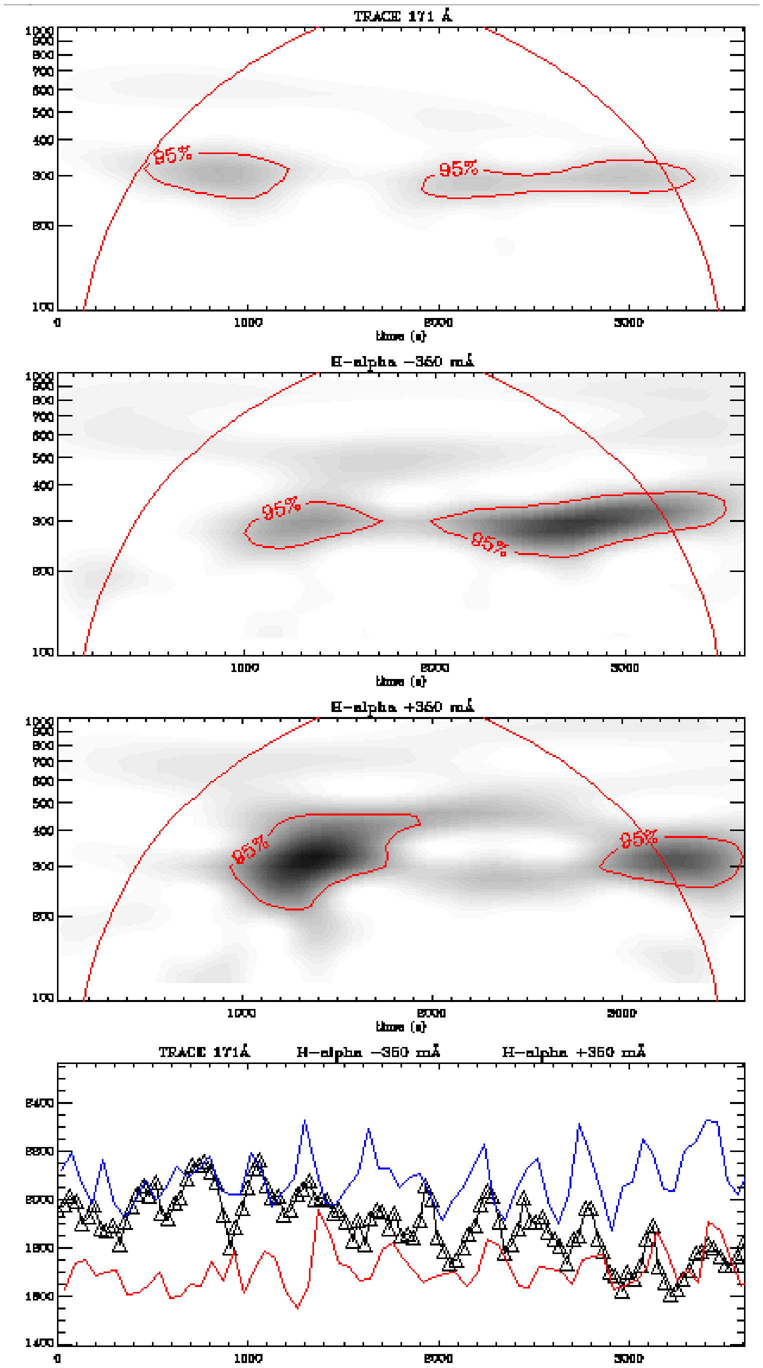

Figure 1. Demonstrating the correlation between chromospheric and upper TR oscillations using wavelet power spectra for TRACE 171 Å, Hα-350 mÅ, Hα+350 mÅ and lightcurves for TRACE 171 Å (full, with triangles), Hα-350 mÅ (full blue) and Hα+350 mÅ (full red). Units of intensity are arbitrary (From De Pontieu 2004).

spicular structures. The presence of such strong oscillations at low heights (of the order of 3,000 km) provides an ideal opportunity to study the direct propagation of oscillations from the photosphere and chromosphere into the TR (De Pontieu et al. 2004) and low magnetic corona (see, for example, De Pontieu et al. 2005). These type of measurements can also help us to (i) understand atmospheric magnetic connectivity that is so crucial for diagnostic reconstruction in the chromosphere/TR, and shed light on the dynamics of the lower solar atmosphere, e.g. the source of chromospheric mass flows such as spicules (e.g. De Pontieu et al. 2004); (ii) explore the dynamic and magnetised lower solar atmosphere using the method of seismology. This latter aspect is discussed in detail in recent review papers by e.g. De Pontieu & Erdélyi (2006) and Erdélyi (2006a).

On the nature of oscillations in sunspots, Bogdan (2000) have summarized the observational and theoretical components of the subject in a coherent, common, and conceptual manner. We will not be covering a detailed review on this subject here but would like to mention some recent development. O'Shea et al. (2002) reported oscillations within the umbra at different temperatures, from the temperature minimum as measured by TRACE 1700 up to the upper corona as measured by CDS Fe xvi 335 (log T=6.4 K). Using the techniques of cross-spectral analysis time delays were found between low and high temperature emission suggesting the possibility of both upward and downward wave propagation. Earlier observations indicated that the waves responsible for these oscillations may not be reaching the corona. Based on a similar observing campaign as O'Shea et al. (2002), and using TRACE and SOHO Brynildsen et al. (2002) found that the oscillation amplitude above the umbra increases with increasing temperature, reaching a maximum for emission lines formed close to 1-2 x 10^5 K, and decreasing for higher temperatures. Furthermore, they report that the 3-min oscillations fill the sunspot umbra in the transition region, while in the corona the oscillations are concentrated in smaller regions that appear to coincide with the endpoints of sunspot coronal loops. This suggests that wave propagation along the magnetic field makes it possible for the oscillations to reach the corona. However, it must be pointed out that Doyle et al. (2003) discussed the possibility that the observed oscillations seen in TRACE 171 Å by Brynildsen et al. (2002) and Mg ix 368 Å (and other coronal lines) by O'Shea et al. (2002) may not actually be coronal in origin due to the effect of non-Maxwellian contributions.

2.2. The source of propagating waves

In order to answer the question of what is the source of propagating coronal waves, and, inspired by the observational findings of similarities between photospheric and TR oscillations, De Pontieu, Erdélyi and James (2004)

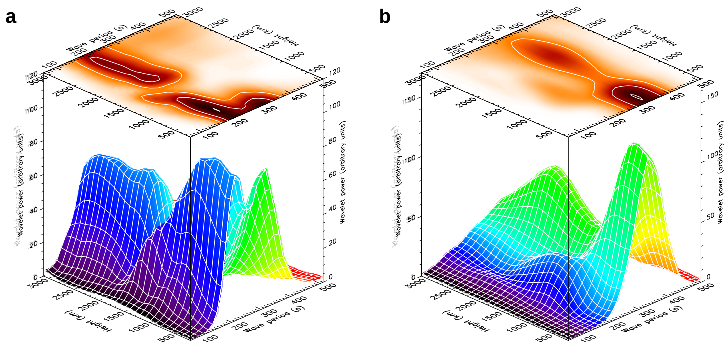

Figure 2. Leakage of evanescent photospheric p-mode power into the chromosphere. Distribution of wavelet power (for cases a and b, resp. $\theta = 0°$and $50°$), in arbitrary units, independent for each height as a function of wave period for different heights above the photosphere. Vertical flux tubes (a) allow minimal leakage of p-modes with periods of 300 s ($> P_c \sim 220$ s), so that only oscillations with lower periods (< 250 s) can propagate and grow with height to dominate chromospheric dynamics. Inclined flux tubes (b) show an increased acoustic cut-off period P_c, allowing enhanced leakage and propagation of normally evanescent p-modes. Adapted from De Pontieu, Erdélyi and James (2004).

developed the general framework of how photospheric oscillations can leak into the atmosphere along inclined magnetic flux tubes. In a non-magnetic atmosphere p-modes are evanescent and cannot propagate upwards through the temperature minimum barrier since their period P ($\sim 200 - 450$ s) is above the local acoustic cut-off period $P_c \approx 200$ s. However, in a magnetically structured atmosphere, where the field lines have some natural inclination θ, where θ is measured between the magnetic guide channelling the oscillations and the vertical, the acoustic cut-off period takes the form $P_c \sim \sqrt{T}/\cos\theta$ with the temperature T. This inclination will allow some non-propagating evanescent wave energy to tunnel through the temperature minimum into the hot chromosphere of the waveguide, where propagation is once again possible because of higher temperatures ($P_c > 300$ s). The authors have shown that inclination of magnetic flux tubes (applicable e.g. to plage regions) can dramatically increase tunnelling, and may even lead to direct propagation of p-modes along inclined field lines, as plotted in Fig. 2. McIntosh et al. (2006) have demonstrated observationally that the acoustic cutoff frequency in the lower solar chromosphere can be modified by changing the inclination of the magnetic field in the lower solar chromosphere. Though they have demonstrated this effect from a study of sunspot with TRACE, they expect a similar modification of cutoff frequency to occur when plasma conditions permit (low-beta, high-inclination magnetic fields) elsewhere on the Sun, particularly for magnetically intense network bright points anchored in super-granular boundaries.

A perfectly natural generalisation of the above idea was put forward by De Pontieu, Erdélyi and De Moortel (2005) who proposed that a natural consequence of the leakage of photospheric oscillations is that spicule driven quasi-periodic shocks propagate into the low corona, where they may lead to density and thus intensity oscillations with properties similar to those observed by TRACE in 1 MK coronal loops. In other words, the origin of the *propagating slow MHD waves* detected in coronal loops (see a recent review on their properties by, e.g., De Moortel 2006) was linked to wave energy leakage of solar global standing oscillations. De Pontieu et al. 2005 highlighted that oscillations along coronal loops associated with AR plage have many properties that are similar to those of moss oscillations: (i) the range of periods is from 200 to 600 seconds, with an average of 350 ± 60 s and 321 ± 74 s, for moss and coronal oscillations, respectively; (ii) the spatial extent for coherent moss oscillations is about 1-2″, whereas for coronal waves, the spatial coherence is limited to $\sim 2''$ in the direction perpendicular to that of wave propagation. They also point out that, although the oscillations in moss and corona have similar origins, they are results of different physical mechanisms: moss oscillations occur because of periodic obscuration by spicules, and coronal oscillations arise from density changes associated with the propagating magneto-acoustic shocks that drive the periodic spicules. A typical example of a comparison of the observed properties of coronal intensity oscillations with synthesized observations is shown in Fig. 3.

3. Propagating waves into the corona

In the pre-SOHO/TRACE era, the first observations of MHD waves in the corona were reported by Chapman et al. (1972) with a GSFC extreme-ultraviolet spectroheliograph on OSO-7 (the spatial resolution was a few arcsec, the cadence time was 5.14s). In Mg VII, Mg IX and He II emission intensity periodicity of about 262s was detected. The importance of this early work is that within the range of low-frequencies an analogy to photospheric and chromospheric oscillations was found, and, it was further speculated that the photospheric and chromospheric evanescent waves become vertically propagating, gravity-modified acoustic waves at that height in the chromosphere where a temperature rise admits propagation again. Antonucci, and Patchett (1984) using the Harvard College Observatory EUV spectroheliometer on Skylab detected oscillations in the C II, O IV, and Mg X emission intensity with periods of 117s and 141s. They suggested that the intensity fluctuation of the EUV lines was caused by small amplitude waves, propagating in the plasma confined in the magnetic loop, and that the size of the loop might be important in determining its preferential heating in the active region. A final example from that era, though at much shorter

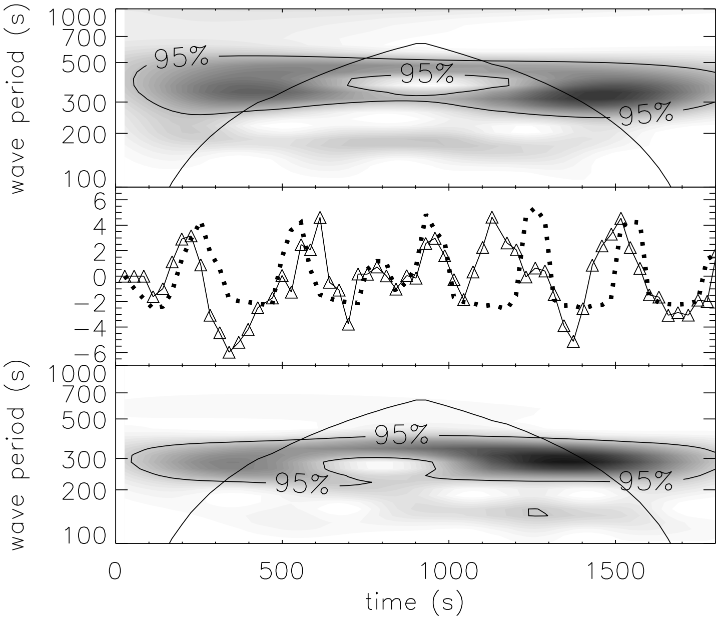

Figure 3. Wavelet power of loop intensity oscillations as a function of time and wave period, as observed with TRACE (top panel, case 16a of De Moortel et al. (2002) and for simulations (bottom panel) driven by MDI velocities at the loop footpoint region. Middle panel shows the running difference (δI) of loop intensity at one location (relative to total intensity I) as a function of time for observations (full line, diamonds) and simulations (dashed). The area contained between the horizontal axis and cone of influence is free of edge effects introduced by the wavelet analysis. Adapted from De Pontieu, Erdélyi and De Moortel (2005).

wavelengths, is the observation by Harrison (1987), who detected, with the Hard X-ray Imaging Spectrometer on-board SMM, soft X-ray (3.5-5.5 keV) pulsations of 24 min period lasting for six hours. The periodicity was thought to be produced by a standing wave or a travelling wave packet which exists within the observed loop. It was concluded that the candidates for the wave were either fast or Alfvén MHD modes of Alfvénic surface waves.

Since the launches of SOHO and TRACE, and the abundant evidence that has emerged for MHD phenomena and, in particular, propagating waves, our views have changed considerably. However, the source of propagating waves still remain a puzzle.

3.1. Waves in open structures

Propagating waves may propagate in open (e.g. plumes) and closed (e.g. loops) coronal magnetic structures. The first undoubted detection of propagating slow MHD waves was made by the Ultraviolet Coronagraph Spectrometer (UVCS/SOHO). Detection of slow waves in an open magnetic structure high above the limb of coronal holes was reported by Ofman et al. (1997, 2000*a*). DeForest & Gurman (1998), analysing Extreme-ultraviolet Imaging Telescope (EIT/SOHO) data of polar plumes, detected similar compressive disturbances with linear amplitudes of the order of 10-20% and periods of 10-15 minutes. Ofman et al. (1999, 2000*b*) identified the observed compressive longitudinal disturbances as propagating slow MHD waves. We have summarized the main features of the observed oscillations following De Moortel (2006) in TableI. A number of studies using the CDS and SUMER spectrographs on SOHO have reported oscillations in plumes, interplumes and coronal holes in the polar regions of the Sun (Banerjee et al. 2000; 2001a,b). All of these studies point to the presence of compressional waves, thought to be slow magnetoacoustic waves as found by DeForest & Gurman (1998). The detected damping of slow propagating waves was attributed to compressive viscosity. Up to now evidence for the fast magnetoacoustic wave modes in these same regions has been absent, even though recent results by

Table I. Overview of the periodicities and propagation speeds of propagating slow MHD waves detected in coronal structures.

Authors	**Period (s)**	**Speed (km/s)**	**Wavelength**
Berghmans & Clette (1999)	∼600	75–200	195
Nightingale et al. (1999)	–	130–190	171 & 195
Schrijver et al. (1999)	300	70–100	195
Banerjee et al. (2000)	600 − −1200 (plume)	-	629
Banerjee et al. (2001a)	1200–1800 (inter-plume)	-	629
Banerjee et al. (2001b)	600–1200 (coronal hole)	-	629
De Moortel et al. (2000)	180–420	70–165	171
Robbrecht et al. (2001)	-	65–150	171 & 195
Berghmans et al. (2001)	-	∼300	SXT
De Moortel et al. (2002*a*)	(282 ± 93)	122 ± 43	171
De Moortel et al. (2002*b*)	172 ± 32 (sunspot)	-	171
	321 ± 74 (plage)	-	171
Sakurai et al. (2002)	180-600	100-200	5303
King et al. (2003)	120–180 & 300–480	25–40	171 & 195
Popescu et al. (2005)	600–5400 & 10200 (off-limb)	–	SUMER
O'Shea et al. (2006)	300–1000(off-limb)	150–170	CDS
O'Shea et al. (2007)	300-1000(coronal hole)	50-70	CDS

Verwichte et al. (2005) have shown that propagating fast magnetoacoustic waves can be present in open magnetic field structures, albeit in this instance, in a post-flare supra-arcade. For the fast mode the wavelengths of the propagating wave should be much shorter than the size of the structure guiding the wave. Shorter wavelength implies shorter periodicity, thus it demands high cadence observations. TRACE can work on 20-30 second cadence, allowing us to detect a wave with a 40-60 s periodicity at best. Thus it is difficult to detect smaller periodicity with the present space based instruments, whereas ground based coronagraphs and radioheliographs have much better time resolution and have been used for the detection of the fast waves.

3.2. Waves in closed structures

Koutchmy et al. (1983) devoted an experiment to the search of short period coronal waves using the green coronal line 5303 A of Fe XIV. Their power spectra showed evidence of Doppler velocity oscillations with periods near 300 sec, 80 sec, and especially 43 sec. However no prominent intensity fluctuations were reported. Though Koutchmy considered their oscillations were due to resonant Alfvén oscillations viewed at a low level through several legs of coronal arches, later on these data were re-interpreted as standing kink waves by Roberts et al. (1984). The first detection of microwave quasi periodic pulsations, with a periodicity of 6.6 s, which could be associated with the fast kink mode was performed by Asai et al. (2001) with Nobeyama radioheliograph. Four bursts were observed with the hard X-ray telescope onboard Yohkoh and the Nobeyama Radioheliograph during the impulsive phase of the flare.

Williams et al. (2001, 2002) and Katsiyannis et al (2003) reported the presence of high-frequency MHD waves in coronal loops observed during a total solar eclipse with the SECIS instrument. The detections lie in the frequency range 0.15-0.25 Hz (7-4 s), last for at least 3 periods at a confidence level of more than 99% and arise just outside known coronal loops. This led them to suggest that they occur in low emission-measure or different temperature loops associated with active regions.

Madjarska et al. (2003), using a number of different transition region and coronal lines from SUMER on SoHO, was the first to report oscillations in coronal bright points, finding a periodicity of 6 min. Ugarte-Urra et al. (2004), using data from CDS on SoHO, found evidence of oscillations ocurring with period between 420-650s in a number of TR lines (O V and O III) but none in the coronal line of Mg IX. They also report on a separate measurement of an oscillation of 491s period observed in a bright point observed with the transition region line of S IV of SUMER.

In closed loop structures, using EIT/SOHO, Berghmans & Clette (1999) reported first on slow modes. Following the success of SOHO, observers using TRACE also searched successfully for quasi-periodic disturbances in coronal loops (e.g. Schrijver et al. 1999; Nightingale et al. 1999; De Moortel et al. 2000). A detailed overview of the observed properties of these propagating intensity perturbations is given by De Moortel et al. (2002*a*, *b*).

From a ground based coronagraphic observation at the Norikura Solar Observatory, Sakurai et al. (2002) have reported on the detection of coronal waves from Doppler velocity data. The propagation speed of the waves was estimated by correlation analysis. The line intensity and line width did not show clear oscillations, but their phase relationship with the Doppler velocity indicates propagating waves rather than standing waves.

In all the reported cases the phase speed is of the order of the coronal sound speed. In TRACE observations the propagating waves are observed as intensity oscillations, hence they are likely to be candidates for compressive disturbances. No significant acceleration or deceleration was observed. The combination of all these facts leads to the most plausible conclusion that the observed propagating waves are indeed slow MHD waves.

3.3. DETECTION OF WAVES THROUGH STATISTICAL METHODS

Most of the aforementioned detection was restricted to a few specific case studies. A new approach has been taken up by O'Shea et al. (2001), where wavelets were used to measure oscillations in a statistical manner. A novel randomisation method was used to test their significance. This form of statistical testing is useful as it provides a more accurate picture of the processes at work in the atmosphere than a smaller number of discrete observations can. Recently McEwan & DeMoortel (2006a) have studied a number of examples of observed longitudinal oscillations in coronal loops to find evidence of the small temporal and spatial scales of these loop oscillations. Increasing the number of observed longitudinal oscillations allowed an improvement in the statistics of the measured parameters, providing more accurate values for numerical and theoretical models.

O'Shea et al. (2001) studied several active regions using data from the the Coronal Diagnostic Spectrometer (CDS) (Harrison et al., 1995). Three different lines were used, a transition region line of O V and two coronal lines of Mg IX and Fe XVI. For this work three different active regions were studied in a statistical way, using 17 individual datasets in total to build up histograms of the typical oscillation frequencies present in all of the active regions. In Fig. 4, the combined histogram (of primary and secondary) frequencies measured in the intensity (flux) (top row) and the combined histogram of the frequencies measured in the velocities (bottom row) is shown. Comparing these plots, it is clear that the coronal lines of Mg IX

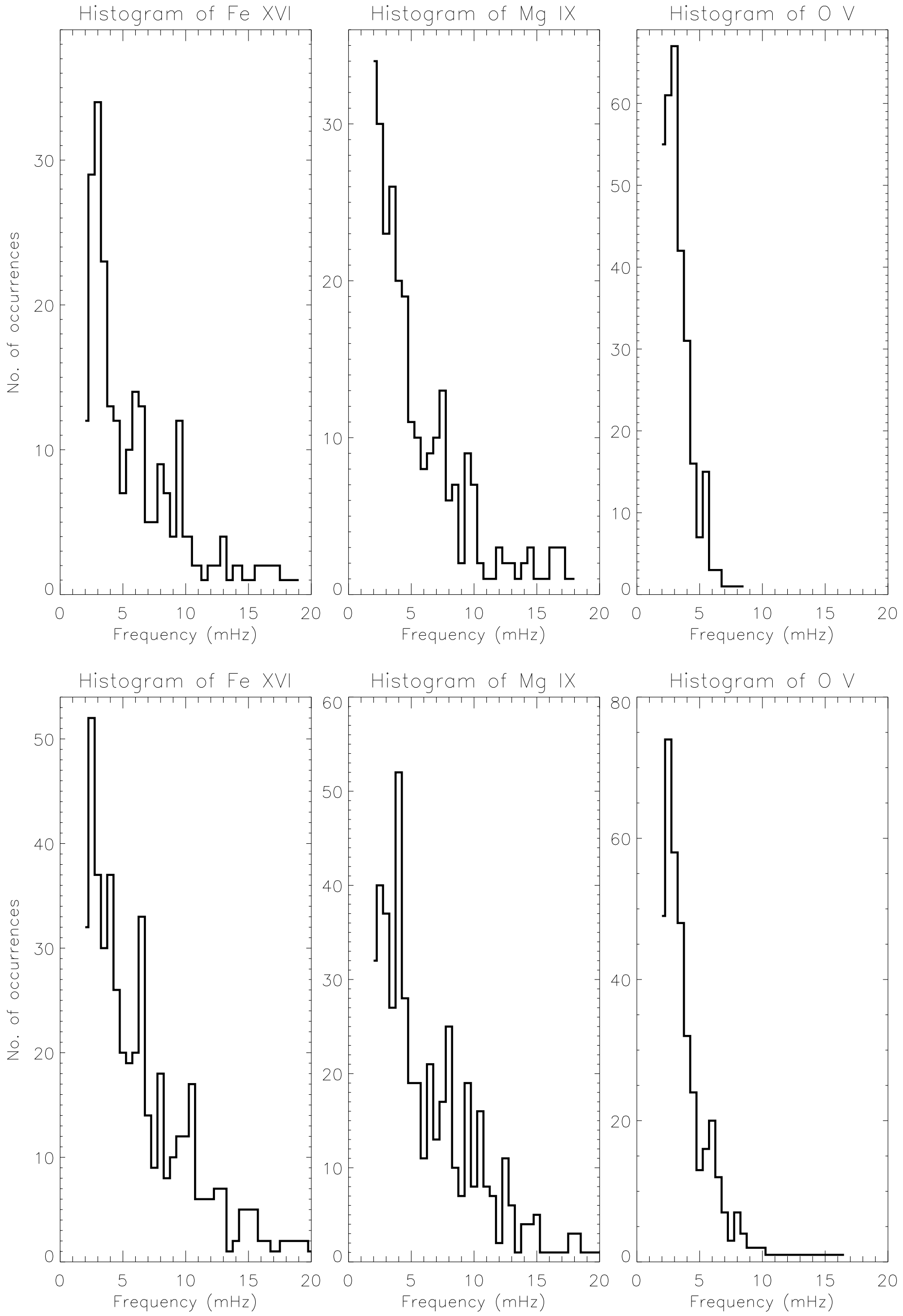

Figure 4. Histograms of the combined oscillation frequencies, from the primary and secondary oscillations, obtained from the intensity (top row) and velocity (bottom row) time series of Fe XVI 333Å (left panel), Mg IX 368Å (middle panel) and O V 629Å (right panel) (From O'Shea et al. 2001).

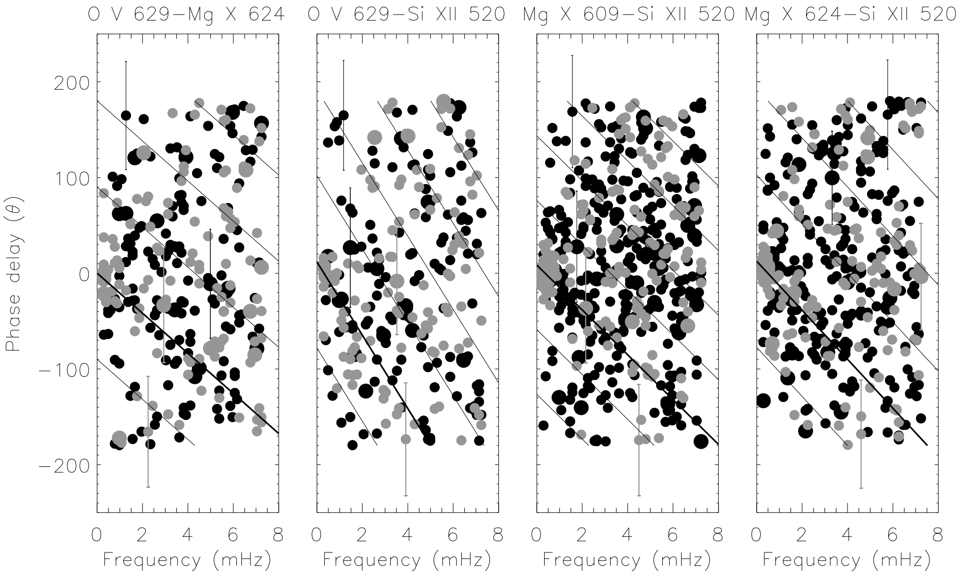

Figure 5. Phase delays measured between the oscillations in the different line pairs, as labeled, e.g., between O v and Mg x 624 (left panel). Phase delays from radiant flux oscillations are shown as the black circle symbols, while phase delays from L.O.S. velocity oscillations are shown as the grey circle symbols. Phase delays were measured at the 95% and 99% significance levels. Phase delays at the 99% significance level are indicated by the slightly larger symbols. Average uncertainties in the 95% and 99% phase delay estimates are shown by the representative error bars in each plot. Over-plotted on this plot are lines corresponding to fixed time delays (From O'Shea et al. 2006).

and Fe xvi contain more significant oscillations in the velocity than in the intensity, which suggests that in the velocity additional non-compressive modes are being measured. This suggests that these non-compressive modes are perhaps being produced in and confined to the corona. This effect is not seen in the transition region line of O v suggesting a change between the different temperature regimes of the transition region and corona.

Recently, O'Shea et al. (2006, 2007), have used measurements of spectral lines obtained from CDS to perform a statistical study of the presence of oscillations in off-limb polar regions and in coronal holes. Phase delays were measured using the technique of Athay & White (1979), in which phase delays are plotted over the full –180° to +180° range and as a function of frequency. An example of the results of this are shown in Fig. 5 from O'Shea et al. (2006). In this figure the combined phase delays measured between different line pairs, e.g., between O v and Mg x, are shown. The results shown here are from a number of observations in the northern off-limb polar region, combined to obtain a more statistical view of the processes at work in the Sun's atmosphere. From Fig. 5, it can be seen that the measured oscillations are present over the frequency range of ≈0–8 mHz and that the phases line up along roughly straight lines (there is a large scatter in the points around these 'straight' lines). This distribution of phases along straight lines indicates the presence of outwardly propagating waves. Measuring the slope of these lines allows one to obtain the time delays between the different lines, based on the phase equation;

$$\Delta\phi = 2\pi f T \tag{1}$$

where, f is the frequency and T the time delay in seconds. From this equation it can be seen that the phase difference will vary linearly with f, and will change by 360° over frequency intervals of $\Delta f = 1/T$. In the case of Fig. 5, the time delay measured between the O V 629 line and Mg X 624 line (the first plot on the left) was found to be 58±7 s (17 mHz). Using the measured time delays, in conjunction with height differences measured between the different lines using limb brightening measurements, O'Shea et al. (2006) calculated propagation speeds of 154±18 kms^{-1} between the O V 629 and Mg X 624 lines, 218±28 kms^{-1} between the O V 629 and Si XII 520 lines, and 236±19 and 201±17 kms^{-1} between Mg X 609 and Si XII 520 and Mg X 624 and Si XII 520, respectively. These speeds suggest the presence of slow magnetoacoustic waves in these off-limb locations and as being the waves responsible for the observed oscillations.

From a study of flux-velocity (I-V) phase plots, O'Shea et al. (2006) found evidence for more transverse-like waves to be present at coronal temperatures while at transition region temperatures more longitudinal-like waves were present. They attributed the presence of these more transverse-like waves to be due to fast magnetoacoustic waves, while the more transverse-like were due to slow magnetoacoustic waves. It is not clear how fast magnetoacoustic waves are present.In this context, we would also like to point out the possibility of spicules, in the form of obscuration, having an effect on the measurement of intensity-velocity phase measurements. The concern is that this obscuration could be causing a false periodicity and obscuring the actual periodicity. But one should note that the spicules do not project more than 10" above the limb on average (see Xia et al., 2005) essentially ruling them out as affecting substantially the off-limb results of O'Shea et al. (2006). This is due to the fact that the O V line used (the line that could be directly affected by spicules) is measured out to a height of 50" above the limb where spicules cannot affect its periodicity, while the coronal lines are being measured out to something like 200" above the limb. Even if we assume that spicules are affecting the results at lower altitudes, the fact that the results as presented in O'Shea et al. (2006) are a combination of seven datasets and contain results from all heights, up to 50" above the limb (for O V) and up to 200" for the coronal lines, will tend to reduce the possible effects of these obscuration on the overall results. Any effects from obscuration will essentially be 'drowned out' in the large amount of 'real' data. In O'Shea et al. (2006), I-V phase measurements found a 180 degree phase difference between I and V for the transition region O V line, but typically a 0 degree phase difference for the coronal lines. From Xia et al. (2005), there is no mention of the velocities measured from the spicules being in any way correlated with the radiance measurements. The fact that O'Shea et al. (2006) see strong correlations between I-V in their statistical results would suggest that the essential nature of what they have reported is not due to spicules but to propagating waves.

In a similar work, O'Shea et al. (2007), using the same technique, found evidence for similar slow magnetoacoustic waves in equatorial and polar coronal holes. In that work, however, the propagation speeds found were substantially lower than those found off-limb, perhaps related to the presence of a more complicated magnetic geometry in the coronal holes. Again, by examining the I-V phase delays, they found that there was a difference in the distribution of these I-V phases between transition and coronal lines; the transition region line of O V showing phases at –180 and +180° not present in the coronal lines. This again suggests a change in the majority of the waves between the transition region and the corona. They also claim to see an indication of the presence of standing waves at coronal temperatures of Mg X and Si XII, due to the presence of significant peaks at –90 and +90° in their phase histograms. The presence of standing waves fits nicely with their discovery that the measured phase delays between line pairs occur at fixed phase intervals of 90 and 135° which, like in O'Shea et al. (2006), were linked with some form of resonant cavity effect on the waves.

In this type of off-limb studies another big concern is that how do projection effects affect the comparison between propagation speeds observed off-limb and in coronal holes? This is essentially unquantifiable as the angle of the magnetic fields in which one measures the propagating waves is unknown in both regions. However, one can note that waves that one measures at the poles are essentially propagating at 90 degrees to our line-of-sight, but being compressional longitudinal (slow) waves are still completely measurable in intensity at this angle. From these measured intensities in lines at different temperatures one can obtain the propagation speeds (like, O'Shea et al., 2006). One can assume that the speeds off-limb are essentially 'true' speeds unaffected by projection effects, propagating as they are at almost 90 degrees. Those waves measured on-disk in coronal holes, however, are propagating at angles between 0 and 90 degrees, and therefore, will have a propagation speed reduced by the effect of this projection effect relative to the line-of-sight (LOS). For example, an angle of 60 degrees relative to the LOS would result in the propagation speed being reduced by a factor of 2 relative to its ‘true’ speed. So one should keep these facts in mind when interpreting the quoted wave speeds.

3.4. EIT WAVES

One of the earliest observations of global waves known, is that of the chromospheric Moreton waves (Moreton & Ramsey 1960). It was seen in the wings of H-α, propagating in the hot chromosphere with speeds of 400–2000 km s^{-1}. Based on their propagation characteristics, Moreton waves are interpreted as fast shock waves. Further unambiguous evidence for large-scale coronal propagating disturbances initiated during the early stages of a flare and/or CME has been provided by recent EUV Imaging Telescope (EIT) observations on board SOHO in the 195Å bandpass. Thompson et al. (1999) reported first on these phenomena based on their SOHO EIT observations. Although this instrument has a relatively poor temporal and spatial resolution, there are already more than 200 wavelike events found (Klassen et al. 2000; Biesecker et al. 2002). Since these global waves were first seen by the SOHO EIT instrument, they were labeled as ”EIT waves”. EIT waves have circular or arc-shaped fronts of enhanced emissions and are generated in or near an active region.

An interesing event was observed on November 4, 1997 (Eto et al. 2002), at the time of an intense flare (X2.1 in the NOAA/GOES standard). A Moreton wave was observed in H-$\alpha + 0.8$ Å , and H-$\alpha - 0.8$ Å with the Flare-Monitoring Telescope (FMT) at the Hida Observatory. At the same time an EIT wave was observed in EUV with the Extreme ultraviolet Imaging Telescope (EIT) on board SOHO. There is an ongoing debate about whether the EIT waves are a coronal counterpart of Moreton waves or not. On the nature of these global waves opinions are divided between different interpretations (e.g., fast magnetohydrodynamic waves, shock waves, non-wave feature, etc.). These global waves originate from impulsive and/or eruptive sources such as flares or coronal mass ejections (CMEs) and are able to travel over very long distances, sometimes these distances being comparable to the solar radius. It has been proposed that (1) EIT waves are different entities from Moreton waves, and that (2) X-ray waves as detected by Yohkoh SXT, instead, are a coronal counterpart of Moreton waves, therefore signifying fast mode MHD waves as predicted by Uchida et al. (1973). There are also many events in which a sharp EUV wave front is seen to be co-spatial with a soft X-ray (SXR) wave front, the latter exhibiting the characteristics of coronal fast-mode waves (Khan & Aurass 2002). These results tend to favor the coronal fast-mode wave model for EIT waves. Observations show that an EIT wave has two stages: first, there is an early (driven) stage where the wave is correlated to a radio II type burst. This correlation can be attributed to the fact that in the initial stage the propagating wave can excite plasma radiation accelerating electrons and creating an energized population which serves as the source of the radio emission. The second stage consists of a freely propagating wavefront. Harra & Sterling (2003) investigated an EIT wave jointly seen by TRACE and CDS/SOHO (JOP70). They concluded that EIT waves consist of a faster propagating, piston-driven portion and a more slowly propagating portion due to the opening of the field lines associated with an erupting filament. They found that these slowly propagating waves later interact with coronal loops forcing them to oscillate.

Wills-Davey & Thompson (1999) examined observations that show the first evidence of a coronal wave event seen by TRACE. They concluded that the observed disturbance behaves more like a fast-mode magnetoacoustic wave. Their observations support Uchida's (1968) model of the propagation of an Alfvénic wave in a medium of non-uniform magnetic field. Wills-Davey (2006) have recently developed mapping algorithms which allows automated tracking of a propagating coronal wave, enabling the finding of reproducible fronts and propagation trajectories. On the nature of EIT waves the debate seems to have widened now. While studying the same event simultaneously with different EUV instruments, Wills-Davey et al. (2007) have concluded that fast MHD compressional waves do not properly describe dynamics of many EIT wave events. The physical properties of EIT waves, their single-pulse, stable morphology, the non-linearity of their density perturbations and the lack of a single representative velocity instead suggests that they may be best explained as a soliton-like phenomena. **Given their propagation characteristics and ability to convey information about the medium in which they propagate, global EIT waves if their mode physics is identified properly could be used as an excellent tool for global coronal seismology.**

Ballai, Erdélyi and Pintér (2005) studied TRACE EUV data to show that these global coronal disturbances are indeed waves with a well-defined period. They showed that EIT waves interact with the coronal loops, and as a result coronal loops begin to oscillate. These induced oscillations are considered to be fast standing kink modes, in good agreement with the theory developed by Roberts et al. (1984). Ballai et al (2005) further conjectured that one possible explanation of the different behavior of the same event seen in two wavelengths is that the waves seen in 195 Å (EIT) are just some ruffles of a rapid wave propagating in a much denser plasma (probably propagating at the chromospheric level in form of shock waves), very similar to the wave produced by a ship's bow. The more energetic the wave propagating in the chromosphere is, the larger the amplitude the EIT waves generate. It is possible that small events do not produce large enough waves in the chromosphere to be detected in the low corona. This would explain the relatively small number of EIT waves seen compared to the flaring frequency.

EIT and Moreton waves are sufficiently different and some have theorized that they are two entirely different populations, which originate from different sources (Eto et al. 2002). Moreton waves are strongly-defined, narrow, semi-circular fronts, while EIT waves are broad ($\sim$ 100 Mm), extremely diffuse, and usually produce circular wave fronts. Moreton waves have relatively short lifetimes (usually $<$ 10 minutes), and have shown cospatial observational signatures between the chromosphere and the soft x-ray corona (Khan & Aurass 2002). EIT waves are primarily visible in the lower corona (at 1-2 MK), but typically have lifetimes of over an hour and can travel the entire diameter of the Sun while remaining coherent. It appears that there should be two types of wave phenomena in the corona during an eruption, a fast-moving wave which is the coronal counterpart of the H-α Moreton wave (or the coronal Moreton wave), and a slower moving one which is the EIT wave, with diffuse fronts. SOHOs EIT may catch several EIT wave fronts and at most one front of the coronal Moreton wave in one event if the coronal Moreton wave is moving very fast. **We should also point out that though Moreton waves are always viewed in conjunction with EIT waves, the converse is not true, even in high-cadence data. So on the nature of EIT waves the subject is still very much open and debatable.**

3.5. Detection of waves from variation of line width study

So far, it has been mentioned that waves may be detected using the oscillatory signatures they leave in the plasma. Another method of detecting waves is to examine the variation of line widths measured from spectral lines. Propagating waves may be detected through spectral line broadenings, if concurrently more than one spectral slits are pointing at the same magnetic waveguide, e.g., a coronal loop, and are sampling distinct regions of the waveguide. The measured broadening of the optically thin spectral lines of ions is due to two effects, thermal broadening and non-thermal broadening associated with Doppler shifts due to unresolved line-of-sight motions

$$T_{eff} = T_i + \alpha \frac{m_i}{2k} < v_{LOS}^2 >$$

where T_i is the ion temperature, k is the Boltzmann constant, v_{LOS} is the line-of-sight component of the velocity, and, $2/3 \leq \alpha \leq 1$. Let us suppose, there is a coronal loop at about the center of the solar disk and one spectrographs samples the footpoint, while another the apex of the same loop. Let us suppose there is, e.g., a longitudinal wave excited casually at the footpoint of the waveguide that will propagate along the magnetic structure. Since the motion is longitudinal, and the first spectrograph points exactly in the direction of propagation, it will detect line broadening as long as the

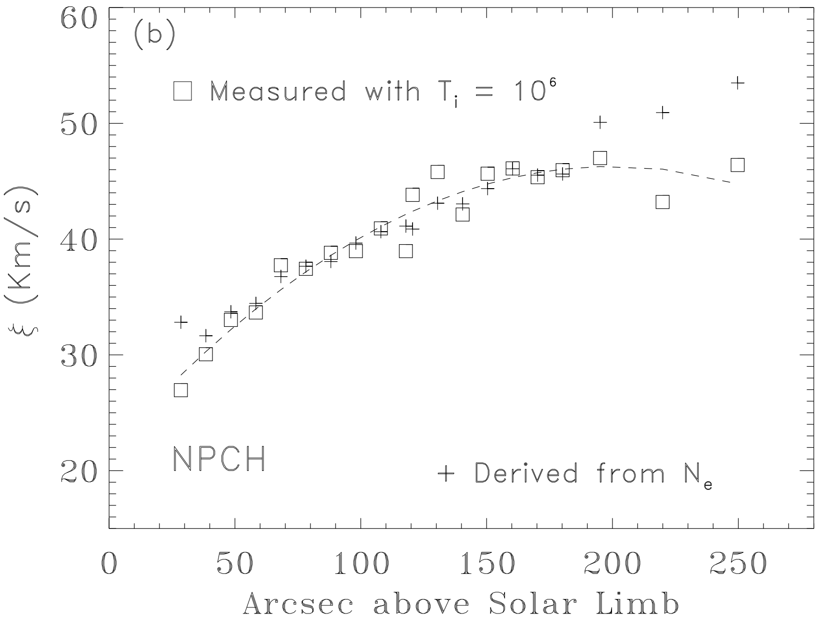

Figure 6. The non-thermal velocity as derived from Si VIII SUMER observations, using $T_i = 1\ 10^6$ K. The dashed line is a second order polynomial fits, while the (+) symbols correspond to theoretical values (From Banerjee et al. 1998).

wave passes through the slit, in spite of it not being able to actually resolve the wave. However, the second spectrograph that samples the apex will not observe any line broadening at all due to the passing travelling wave, since the wave perturbation will be perpendicular to the LOS. Measuring the time delay **(by studyting phase differences)** could give information about the average longitudinal wave speed. Unfortunately we are not aware of any experiment that has explored the above described opportunity offered by line-broadening, perhaps due to the practical difficulty involved in arranging for two independent and complementary (spectrally) spectrographs to point at the same solar structure at the same time. Instead, a popular observational sequence is to point the slit, e.g., at the apex of the loop, and let the Sun rotate the loop so that the slit scans from apex to footpoint. If the loop supports the presence of e.g. longitudinal waves, one would find a systematic line broadening from apex to limb. On the other hand, if the loop supported the presence of transversal (e.g. kink) motion, one would find line narrowing. Although this technique, often referred to as centre-to-limb variation in the literature, does not allow one to deduce the propagation velocity of the observed wave, it may give information about the polarisation of the wave,

Table II. (a) Skylab; (b) SOHO.

Source	Instrument	LOS (km/s)	Location
Mariska et al. (1979)	SO82-B^a	33	white limb+12"
Hassler et al. (1990)	Sounding Rocket	20-25	1-1.2 $R_\odot$
Ofman & Davila (1997)	UVCS^b	~300	1.7$R_\odot$
Erdélyi et al. (1998)	SUMER^b	1-100	limb
Doyle et al. (1997)	HRTS	19-27	quiet sun
Doyle et al. (1998)	SUMER^b	24-28	limb to 25Mm
Banerjee et al. (1998)	SUMER^b	27-46	limb+20-180 Mm
Chae et al. (1998)	SUMER^b	20-30	disc
Esser et al. (1999)	UVCS^b	20-23	1.35-2.1 $R_\odot$
Moran (2003)	SUMER^b	40-60	1.02-1.3 $R_\odot$

and, of course, about the rms velocity amplitude. Two studies of this type are Erdélyi et al. (1998) and Doyle et al. (2000). We should also point out here that at this moment it is still very difficult if not impossible to resolve individual loops spectroscopically, but perhaps using the high resolution EIS on Hinode together with CDS or instruments on the upcoming Solar Orbiter individual loops will in future be able to be resolved and of these ideas tested.

Table II. summarizes some results and indicates that either slow MHD waves (i.e. mainly longitudinal wave propagation) or Alfvén waves (waves that travel along the field lines but are perpendicularly polarised to them) are detected. Harrison et al. (2002) examined the Mg X 625 Å line ($\sim 1\times10^6$ K) in the equatorial quiet region using the CDS instrument on SoHO. Their most significant result was the discovery of emission line narrowing as a function of altitude and intensity above 50,000 km. All earlier observations of emission line broadening with increasing altitude are consistent with the propagation of linear undamped Alfvén waves in open field regions with decreasing density. Harrison et al. (2002) attributed the narrowing as being due to the dissipation of Alfvén waves in the corona. One should remember that there is a fundamental difference in the properties of wave propagation in the equatorial corona (closed field regions) when compared to coronal holes (open field regions). Thus it is important to see if one can also observe this narrowing of coronal lines in the coronal hole regions. Both Banerjee et al. (1998) and Doyle et al. (1999) studied Si VIII line profiles with SUMER in the off-limb northern polar hole regions. They recorded line broadening up to 110,000 km (150 arcsec off-limb) and then a levelling off in the line widths up

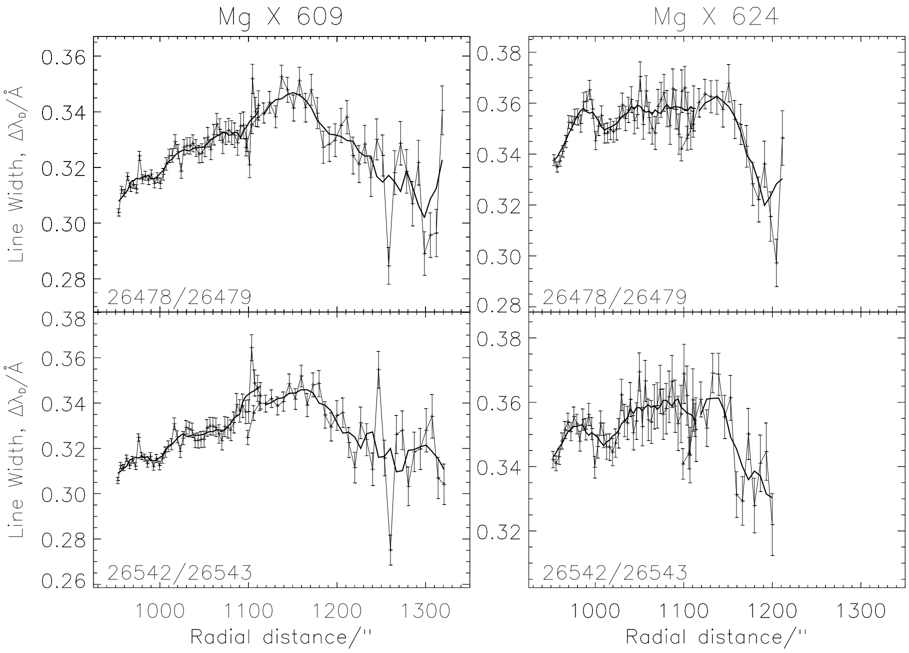

Figure 7. Variation of the Doppler width (uncorrected for instrumental width contributions) versus radial distance for the 26478/26479 and 26542/26543 datasets, as indicated by the numbers shown in each plot. The thick black lines show the result of a box-car averaging. Radial distance locations where the radiance fell below a critical S/N value do not show the results of the line width measurements (From O'Shea et al. 2005).

to 220,000 km (see Fig. 6), after which there was a faint hint of a fall-off in the widths, although this last observation was inconclusive due to uncertainties in the data. O'Shea et al. (2003) measured the variation of Mg X 624 line widths (from CDS) above the north polar limb and found that there was an initial linear increase with altitude, supporting the interpretation of linear undamped Alfvén waves propagating outward in open field regions. Also noted in these results was a turnover point, at a particular altitude, where the line widths suddenly decreased or levelled off. This decrease in the line widths at a particular height is consistent with a dissipation of the Alfvén wave energy. In a follow up paper, O'Shea et al. (2005), measuring the line widths of the Mg X 609 and 624 lines from CDS, again found evidence for a decrease in the line widths above a certain height off-limb (cf. Fig. 7). This was again attributed to damping of upwardly propagating MHD waves. In addition, O'Shea et al. (2005) measured the ratio of the two Mg X lines as a function of radial distance above the limb. They found that this ratio changed from values expected for a collisionally dominated plasma to one expected from a radiatively dominant plasma as the same approximate height that the decrease in line width occurred. This suggest that the decrease in the line widths, the damping of the waves, may be linked to this change in the dominant excitation, perhaps due to decreases in the electron density. We note in passing that Doyle et al. (2005) have found evidence for some broadening above the limb to be due to spicules. Areas where spicules were absent were found to have lower line widths suggesting that spicules have some part to play in line broadening at least close to the limb.

It is very important to understand the mechanism of line width decrease as it may trigger the acceleration of plasma particles in these regions. In polar coronal holes, where the magnetic field is open and predominantly vertical, Alfvén waves mainly contribute to the off-limb line broadening due to their transverse velocity polarisation. Acoustic waves propagating along the magnetic field are unlikely to contribute to the line broadening because their velocity polarisation is predominantly perpendicular to the line of sight. The decrease of the line width in polar coronal holes can then be explained either by the Alfvén wave damping or due to the conversion into acoustic waves. Recently Zaqarashvili et al. (2006) have shown that the resonant energy conversion from Alfvén to sound waves near the region where the plasma β approaches unity (or more precisely, where the ratio of sound to Alfvén speeds approaches unity) may explain the observed sudden decrease of the spectral line width in the solar corona.

4. Observations of waves and oscillations in prominences

The solar corona is populated by peculiar dense clouds of cold plasma inexplicably floating tens of thousands of kilometres above the photosphere. Such features are routinely seen during solar eclipses, when they can be easily distinguished by their red glow, but they can also be unveiled with the help of filters, such as Hα, devised to observe the chromosphere. These features (usually called prominences or filaments) are essentially like chunks of chromospheric gas defying the downward pull of gravity and staying in a place higher than the one that apparently corresponds to their large density. This is not the only enigma surrounding solar prominences. For example, in contrast with the MK temperature of the surrounding corona, prominences remain at a comparatively cool 10,000 K, which prompts one to ask what prevents the mechanisms that heat the corona from also raising the temperature of prominences and consequently dispersing them. Other pieces of the prominence puzzle concern their beginning and end: first, one may wonder not just how prominences form but also why they are born in an adverse environment. Secondly, despite their internal dynamics, prominences that have been stable for weeks suddenly disappear in a spectacular eruption. The processes shaping the lifetime of prominences are largely unknown. Nevertheless, the intervention of a decisive element is quite clear: the magnetic field, that is central to all the mentioned processes.

The reason for our limited insight into the nature of prominences probably has three causes (Vial, 1998): there is no such thing as a canonical prominence, but a wide range of parameters is observed in different objects; no prominence has a uniform structure, but they are made of thin threads (or fibrils) and, in addition, different parameter values can be detected in different parts of a prominence; and no structure is really isolated, so it is necessary to understand the physics of the prominence-corona interface, the effect of the coronal radiation field (e.g. Anzer & Heinzel, 2005) and to trace the magnetic fields permeating the prominence to their origin at the Sun's surface (e.g. Lin et al., 2005b). Our knowledge about prominences has been well reviewed by Tandberg-Hanssen (1995), Martin (1998) and Patsourakos & Vial (2002), where most information on the topic can be found.

Where does the study of waves and oscillations in prominences stand in the middle of this panorama? It constitutes a discipline that may complement the direct determination of prominence parameters by providing independent values based on the comparison between observations and theory. However, this is more a promise than a reality because of the large gap between observation and theory. Such a gap arises because of the few restrictions imposed by observational works (which are sometimes reduced to reporting the period of the detected oscillations) and the simplicity of theoretical studies (which neglect the intricate nature of prominences and substitute it by a very simplified physical model). Nevertheless, these two sides are coming together as the complexity of works increases. Previous advances, both observational and theoretical, have been examined by Oliver & Ballester (2002), Engvold (2004), Wiehr (2004) and Ballester (2006), so it is our purpose here to review the observational facts of prominence oscillations with special emphasis on the last few years. Erdélyi et al. (2007) should also be considered for a review of the theory.

4.1. INSTRUMENTAL SETUP AND DATA ANALYSIS

Most observational works on prominence oscillations are based on Doppler velocity data acquired with a spectrograph slit. This, in principle, allows one to determine wave properties along the slit (as in Molowny-Horas et al., 1997), but nothing can be said about the propagation properties perpendicular to the slit. Such as we describe in Sects. 4.5 and 4.6, only in a few occasions has this simple setup been substituted by a two-dimensional one, which obviously results in a much deeper insight into the features of waves and oscillations.

On the other hand, the data analysis has usually been restricted to the computation of the power spectra, while other techniques have been rarely used. The advantages of wavelet analysis, for example, have been exploited by Molowny-Horas et al. (1997), Bocchialini et al. (2001) or Foullon et al. (2004); however, more complex tools have never been used in this subject.

4.2. Spectral Indicators

Apart from the Doppler velocity, some other spectral indicators have also been used in the search for periodic variations in prominences and sometimes a periodic signal has been recognised in more than one of these indicators. Landman et al. (1977) observed periodic fluctuations in the line intensity and width with a period around 22 min, but not in the Doppler shift. In addition, Yi et al. (1991) detected periods of 5 and 12 min in the power spectra of the line-of-sight velocity and the line intensity. Also, Suematsu et al. (1990) found signs of a $\sim$60 min periodic variation in the Doppler velocity, line intensity and line width. Nevertheless, the Doppler signal also displayed shorter period variations (with periods around 4 and 14 min) which were not present in the other two data sets. We here encounter a perhaps perplexing feature of other investigations, namely that the temporal behaviour of various indicators corresponding to the same time series of spectra do not agree, either because they show different periods in their power spectra (as in Tsubaki et al., 1987) or because one indicator presents a clear periodicity while the others do not (Wiehr et al., 1984; Tsubaki & Takeuchi, 1986; Balthasar et al., 1986; Tsubaki et al., 1988; Sütterlin et al., 1997).

Special mention must be made of the study performed by Balthasar & Wiehr (1994), who simultaneously observed the spectral lines He 3888 Å, H_8 3889 Å and Ca^+IR_3 8498 Å. From this information they analysed the temporal variations of the thermal and non-thermal line broadenings, the total H_8 line intensity, the He 3888 Å to H_8 emission ratio and the Doppler shift of the three spectral lines, which correlated well and thus reduced to a single data set. The power spectra of all these parameters yielded a large number of power maxima, but only two of them (with periods of 29 and 78 min) are present in more than one indicator.

The interpretation of the results just summarised appears difficult. First, the theoretical models predict the temporal behaviour of the plasma velocity, and sometimes the density and other physical parameters, in a prominence. The observations, however, yield information on quantities such as the line intensity or the line width. Hence, a clear identification of spectral parameters with physical variables (density, pressure, temperature, etc.) is required before any progress can be achieved. Then, the presence of a certain period in one or a few signals could be used to infer the properties of the MHD mode involved.

Table III. *Summary of observations of small amplitude prominence oscillations: reported periods and structures in which observations were carried out.*

Reference	Period (min)	Structure
Harvey (1969)	1–17	Prominence
Bashkirtsev & Mashnich (1984)	42–82	Prominence
Tsubaki & Takeuchi (1986)	2.7, 3.5	Prominence
Yi et al. (1991)	5, 9, 16	Thread
Balthasar et al. (1993)	0.5, 12, 20	Prominence
Bashkirtsev & Mashnich (1993)	5–90	Prominence/Filament
Sütterlin et al. (1997)	3–10, 20, 60	Prominence
Terradas et al. (2002)	30–40, 75	Prominence
Foullon et al. (2004)	720	Filament
Lin (2004)	4–20, 26, 42, 78	Thread
Lin et al. (2007)	3–9	Thread

4.3. PERIODS

Periodic variations have been detected in a variety of configurations (in prominences, in filaments, in threads) in a range spanning from less than a minute to about 90 minutes, and there is even a reported value around 12 hours. Some of these results are summarised in Table III, which by no means is exhaustive (see also Oliver & Ballester, 2002). Unfortunately, on its own a period reveals very little about the conditions in the prominence since it may correspond to infinite combinations of density, temperature, magnetic field strength, etc. Such as discussed before, more restrictions can be imposed by the temporal variation of the physical variables, which can help ascertain the wave mode responsible for the oscillations, which in turn can lead to restrictions on the physical conditions of the plasma. This is yet a pending subject. The spatial distribution of oscillations (see Sect. 4.5) is another essential source of supplementary information that may lead to the identification of the wave mode nature.

The detection of oscillations with a period near 12 hours in the intensity of the 195 Å line by Foullon et al. (2004) is remarkable. These authors exploited the long-term stability provided by a space telescope (in this case EIT on SOHO) to obtain an almost uninterrupted data series lasting 260 hours. Although this is not the first time that a telescope onboard SOHO has been used in connection with prominence oscillations (see Bocchialini et al., 2001; Régnier et al., 2001), it is the only study to uncover such very long period perturbations. Foullon et al. (2004), however, discarded an important part of the information in their data by spatially averaging the line intensity and so notably reducing the possibilities of their analysis. It is fair mentioning that many other authors have followed a similar path.

4.4. Wave damping

While it has been clear for a long time that prominence disturbances last only a few periods (Oliver & Ballester, 2002), this phenomenon has been seldom quantified. We must emphasise the importance of characterising the wave damping because this is a place where theory and observations can meet (see Erdélyi et al., 2007 for a discussion of the theory of this topic).

Terradas et al. (2002) studied wave motions in a two-dimensional field of view and detected a propagating perturbation which is damped both in space and time. The temporal damping is such that it can be well fitted by an exponential function and, depending on the position in the prominence, varies between two and three times the period. Even though these results are not too restrictive from the theoretical point of view, they are unique in their kind and so similar efforts should be undertaken in the future.

4.5. Wave propagation

Terradas et al. (2002) also provide us with a solid investigation of wave propagation in a prominence. The damped oscillations just described originate in a narrow strip of 3000 km × 10,000 km and then spread out away from this region, which is near the prominence edge and parallel to it. Waves propagate over an area of some 54,000 × 40,000 km. These authors found that wave propagation is quite anisotropic and mostly in the directions parallel and perpendicular to the prominence edge. Terradas et al. (2002) determined the two-dimensional distribution of the phase velocity and obtained values between 10 and 20 km s^{-1}, where the highest and lowest values take place in the parallel and perpendicular directions, respectively. Once more this is a singular work since it is the only one in which the two-dimensional distribution of oscillations is sudied (except for the papers described in the next section) so these results must also be confirmed in the future.

4.6. Fibril structure

Solar prominences are formed by many thin, parallel magnetic threads filled with cold plasma, and as a consequence the dynamics of these components can be easier to understand than that of the whole object. Early works (Yi et al., 1991; Yi & Engvold, 1991) already noted the possible link between prominence oscillations and the fibril structure. Unfortunately, the spatial resolution of the data analysed by Terradas et al. (2002) is not good enough to distinguish the prominence threads. It was necessary, hence, to wait until the advent of telescopes with much better spatial resolution to have observations in which the prominence fine structure is well resolved (Lin et al., 2003; Lin, 2004).

In the analysis of the Doppler velocity in two threads belonging to the same filament, Lin (2004) finds a clear sign of propagating waves and determines their period, wavelength and phase speed. This study is followed by a much more profound one in which the two-dimensional motions and Doppler shifts of 328 features (or "blobs") of different threads are examined. These features are observed to flow along the filament axis while oscillating at the same time. To simplify the evaluation of oscillations, Lin (2004) computed average Doppler signals for each fibril and found that groups of adjacent threads oscillate in phase with the same period. This has two consequences: first, since the periodicity is outstanding in the averaged signal for each thread, the wavelength of oscillations is larger than the length of the thread. Second, fibrils have a tendency to vibrate bodily, in groups, rather than independently, an issue that has been investigated theoretically (Díaz et al., 2005). Hα observations conducted with the Swedish 1-m Solar Telescope by Lin et al. (2007) lead to similar results concerning the collective dynamics of fibrils, although propagating Doppler velocity signals with various periods and wavelengths in other threads of the same filament are also detected. All these observations seem to indicate that prominence fibrils sometimes support collective oscillations and sometimes oscillate on their own. This topic deserves a more detailed observational study and, given the simplicity of fibrils compared to the full filament structure, a theoretical investigation can give rise to a fruitful comparison with observations.

4.7. LARGE AMPLITUDE PROMINENCE OSCILLATIONS

All the results described above correspond to waves and oscillations with comparatively small amplitudes, i.e. with Doppler velocity peaks typically below 1–2 km s^{-1}. Nevertheless, prominence oscillations of much larger amplitudes (with oscillatory velocities up to 90 km s^{-1}) have also been observed. These large amplitude oscillations normally occur after an energetic, explosive event disturbs the whole prominence (see the movie in Jing et al., 2003 for an illustrative example). The topic of large amplitude prominence oscillations has remained practically dormant for more than thirty years until its recent revival (see Oliver & Ballester, 2002 for a review of older results).

Because of the great velocities involved, large amplitude oscillations sometimes substantially modify the absorption/emission wavelength of the prominence material. For example, Eto et al. (2002) and Okamoto et al. (2004) observed two filaments as they underwent one of these episodes and could detect their absorption in Hα ± 0.8 Å filters. This indicates that the velocity of the plasma is in excess of 20 km s^{-1}. During the event studied by Eto et al. (2002) the filament disappeared from the Hα line centre image during the time when the velocity was at its maximum. Such behaviour can periodically repeat in time if the oscillation lasts for a few periods with sufficiently high amplitude, such as observed by Ramsey & Smith (1966).

The periods of these oscillations exceed the most common values of small-amplitude oscillations and range from 30 minutes to almost 3 hours (Isobe & Tripathi, 2006; Jing et al., 2006). In addition, these oscillations are commonly damped with damping times which (as in the case of small-amplitude oscillations) are 2–3 times the corresponding period (for a few examples see Jing et al., 2006). This prompts us to question whether the mechanisms involved in the attenuation of the two types of prominence oscillations are the same.

4.8. FUTURE DIRECTIONS

Some hints for the future development of prominence seismology have been given here. It is particularly important to carry out observations with high spatial and temporal resolution, such as those in Lin et al. (2005a); Lin et al. (2007) using the Swedish Solar Telescope in La Palma. The purpose of this kind of investigation is to characterise the temporal properties of thread oscillations (with a particular emphasis on their excitation and damping) as well as their spatial properties (with a particular emphasis on their collective or individual behaviour). Prominence threads are promising research objects because their dynamics can be treated theoretically or numerically using simple models. A second topic that requires some development is the translation of detected variations of the line intensity and line width into variations of physical variables. This probably requires some multilevel non-LTE transfer modelling (e.g. Heinzel et al., 2005). Finally, observations of prominences from space have the advantage of very good stability and long time series duration, but they have been seldom used for the study of prominence oscillations. Space instruments do not enjoy the spatial resolution of the best terrestrial telescopes but they should nevertheless be exploited in the future.

5. Concluding Remarks

Systematic detection of waves in a wide range of magnetic structures in the corona is possible with modern day space and ground based instruments with sufficient spatial and temporal resolution, although with some limitation as outlined in this review. With future observing facility the field of solar atmospheric seismology will yield better and more accurate diagnostic results.

Comparing data from the multi-wavelength observation and MHD wave theory and numerical simulations makes this field of atmospheric seismology very exciting and interesting. In this review we have summarized the current trends in the observational study of these waves in open (coronal holes) and closed (loops and prominences) solar atmospheric magnetic structures with a little more emphasis on the different spectral signatures for the detection of waves.

With strong evidence of fast and slow magnetoacoustic modes arising in the solar atmosphere there is scope for an improvement in determining coronal parameters through atmospheric magneto-seismology. For example the ratio $P_1/2P_2$, in an homogeneous medium is unity, where P_1 is the fundamental mode and P_2 is the first harmonic of the standing transverse kink mode. But in a more complex configuration it can be shifted to lower values. Andries et al. (2005), Goossens et al. (2006) and Erdélyi & Verth (2007) have pointed out that the identification of harmonics could provide important diagnostic information for the coronal seismology of a loop. McEwan et al. (2006b) have studied how the ratio $P_1/2P_2$ deviates from unity for fast and slow MHD modes in response to such effects as structuring in the longitudinal or transversal directions or gravity. They concluded that longitudinal structuring is the most important effect and this can be used in coronal seismology to estimate properties such as the density stratification scale.

The future of atmospheric seismology looks bright. The recent launch of the Hinode satellite, containing the X-Ray Telescope (XRT) and the EUV Imaging Spectrometer (EIS), and the upcoming launch (in 2008) of the Solar Dynamics Observatory (SDO), containing the Atmospheric Imaging Assembly (AIA), means that it will soon be possible to obtain slit and image data at a much increased spectral resolution with excellent time resolution. For example, the Atmospheric Imaging Assembly (AIA), offers a replacement for the TRACE instrument, will allow the Sun to be imaged at ten different wavelengths simultaneously with a time resolution of $\approx$10s. The time resolution of EIS, in comparison, can go down to 1s depending on the lines chosen, allowing for the measurement of very high frequency oscillations. The good spectral resolution of EIS will, in addition, allow the accurate measurement of non-thermal velocities and allow other studies that are based on the detailed measurement of line widths, e.g., the variation of line widths off-limb due to wave dissipation, etc. EIS, moreover, has the advantage over previous instruments and observations, e.g., with TRACE, in that it will allow for the observation of time series images (with it wide slits) together with the simultaneous measurement of electron density in the different solar structures observed through the presence of a number of excellent density-sensitive line ratios, at coronal temperatures, within its spectral range. Together then, XRT, EIS and AIA will allow an unprecedented opportunity to observe waves in many solar structures and together they offer the solar community a great opportunity to significantly progress the still nascent field of coronal seismology.

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