

Observation of intensity oscillations above X-ray bright points from the *Hinode*/XRT: signature of magnetohydrodynamic oscillations in the solar corona

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Accepted 2011 March 24. Received 2011 March 22; in original form 2010 February 1

ABSTRACT

We analyse the temporal image data of the quiet Sun observed by the X-ray Telescope (XRT) onboard the *Hinode* spacecraft and Al-poly filter on 2007 March 31. We choose these temporal image data of ~ 30 s cadence from 11:34:48 UT to 14:19:35 UT to study intensity oscillations above selected X-ray bright points (XBPs) with an exposure time 8.193 s of each XRT image. Using the Fourier filtering method, we reconstruct X-ray light curves for the periods outside the cone-of-influence (COI) of their power spectrum. Using the standard wavelet software, we derive the power spectra of the reconstructed light curves which are generated by filtering the original X-ray time-series at the Fourier scale (54.55 min) outside the COI period (60.18 min) free from the edge effect and inappropriate long-term periodicities. This procedure provides statistically significant and globally distributed multiple periodicities in the intensity and global wavelet power spectra of the X-ray light curves derived from the selected coronal structures. We select seven XBPs to extract their respective X-ray light curves. We find the statistically significant observed periodicities (two or three) for XBP1, XBP2, XBP4, XBP5, XBP6 and XBP7, respectively, to be (28, 15) min, (50, 20) min, (60, 20, 12) min, (51, 23) min, (35, 23, 13) min, (49, 20) min and (35, 19) min. We interpret these observed periodicities in terms of the leakage of various harmonics of magnetoacoustic waves into the higher corona. Some BPs (XBP1, XBP3, XBP5 and XBP7) show the shift in the period ratio either as $(P_1/P_2) < 2.0$ or as $(P_1/P_3) < 3.0$. This period ratio shift provides the first most likely observational signature of the density stratification in these XBPs. Other BPs (XBP2, XBP4 and XBP6) show the shift in the period ratio $(P_1/P_2) > 2.0$, which may serve as evidence for magnetic field divergence with a significant effect on the various harmonics of magnetoacoustic waves.

Key words: MHD – Sun: corona – Sun: oscillations – Sun: X-rays.

1 INTRODUCTION

The major building blocks of the quiet-sun corona, the X-ray bright points (hereinafter XBPs), are small X-ray emitters with a spatial size of less than 60 arcsec and lifetime ranging from a few hours to a few days. These XBPs were first observed during rocket-borne experiments in 1969 (Vaiana et al. 1973) and have been extensively studied during the *Skylab* and *Yohkoh* era (e.g. Harvey et al. 1974; Golub, Krieger & Harvey 1977; Webb 1981; Harvey 1996; Hara & Nakakubo-Morimoto 2003, and references cited therein). The association of these XBPs with small-scale bipolar magnetic polarities

has been explored by Krieger, Vaiana & Van Speybroeck (1971) and Golub et al. (1977), which were resolvable as small-scale loops at high resolution (Sheeley & Golub 1979). The magnetic structures of the XBPs have been modelled by various workers (e.g. Parnell et al. 1994; von Rekowski, Parnell & Priest 2006; Pérez-Suárez et al. 2008). XBPs also show intensity variability in soft X-rays over a wide range of period from a few minutes to a few hours (Strong et al. 1992). The properties of XBPs and their dynamic evolution have also been studied at extreme-ultraviolet (EUV) wavelengths (e.g. Madjarska et al. 2003; Ugarte-Urra et al. 2004; Ugarte-Urra, Doyle & Del Zanna 2005; Pérez-Suárez et al. 2008). Recently, BPs have also been observed from the photosphere to chromosphere as a site of strong magnetic field concentration that can channelize Alfvén waves in the upper corona for its heating locally (Jess et al. 2009). The MHD mode coupling was also recently observed above the small-scale bright point, which may be important in

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energy transport in the lower solar atmosphere (Srivastava & Dwivedi 2010b). Although magnetic reconnection may play a dominant role in the evolution, dynamics, heating, as well as oscillations in various types of BPs, there exists observational evidence of magnetohydrodynamic (MHD) waves and oscillations in these small-scale structures (e.g. Ugarte-Urra et al. 2004; Tian, Xia & Li 2008; Jess et al. 2009; Srivastava & Dwivedi 2010b, and references cited therein).

Recently, MHD waves and oscillations have been observed in various magnetic structures and transient phenomena in the Sun, for example, equatorial corona, spicules, post-flare loops, X-ray jets, prominences, coronal loops, flares, BPs, etc. (e.g. Cirtain et al. 2007; De Pontieu et al. 2007; Okamoto et al. 2007; O'Shea et al. 2007; Tomczyk et al. 2007; Erdélyi & Taroyan 2008; Srivastava et al. 2008a,b; Van Doorselaere, Birtill & Evans 2009; Verwichte et al. 2009; Srivastava & Dwivedi 2010a; Nakariakov et al. 2010, and references cited therein). The most recent and fascinating aspect of MHD seismology is the observation of various wave harmonics and thereby deducing crucial local plasma conditions in different solar structures (e.g. Srivastava et al. 2008b; Andries, et al. 2009; Srivastava & Dwivedi 2010a, and references cited therein). The seismologically derived information of the bounded coronal structures, for example, density contrast, density scale height and clues to hydrostatic/non-hydrostatic plasma conditions, density stratification, magnetic flux divergence/flux tube expansion, spatial MHD seismology, etc., is crucial to understanding local plasma conditions and dynamics of the solar atmosphere (e.g. Aschwanden 2009; Andries et al. 2009, and references cited therein).

In this paper, we use the *Hinode*/X-ray Telescope (XRT) temporal image data to study the intensity oscillations above XBPs. We aim at finding various harmonics of the appropriate MHD mode that excite on selected XBPs and leak into the upper atmosphere. We also derive some information on the local plasma condition of these XBPs where MHD oscillations are dominant. In Section 2, we present observational data and power spectral analyses. We describe results and discussion in Section 3. In the last section, we present the conclusions of this paper.

2 OBSERVATIONAL DATA AND POWER SPECTRAL ANALYSES

A quiet Sun, which contains XBPs and a fully evolved on-disc equatorial coronal hole (ECH), is observed with the XRT onboard the *Hinode* spacecraft (Golub et al. 2007) during three time halves on 2007 March 31. This quiet-Sun region is first observed at 10:52:08 to 11:25:30 UT, then at 11:34:48 UT to 14:19:35 UT and, finally, at 15:16:12 to 18:14:58 UT. These observations have been taken mainly using the Al-poly X-ray filter with a deep exposure of 8.19 s, which is appropriate to capture both faint and small-scale coronal structures in the quiet-Sun corona. We choose the mid-duration of the observation for our analysis as this time is associated with stably evolved XBPs. ($X_{\text{FOV}}, Y_{\text{FOV}}$) was (512 pixels, 512 pixels) with the plate scale of $1.02086 \text{ arcsec pixel}^{-1}$, while ($X_{\text{cen}}, Y_{\text{cen}}$) was (219.089 arcsec, -127.434 arcsec). These soft X-ray images were captured with approximately uniform cadence of ~ 30 s. It is a long-duration time-series data set with 309 data points of a total duration of ~ 165 min. The XRT images of double filters (Al-poly/Ti-poly) were sandwiched at equal time-intervals, that is, every 10th image, in time-series data sets. These were unmatched images compared to the single-filter Al-poly image sequence, which have been removed from the time-series to retain its uniqueness as single-filter (Al-poly) XRT image data for the study of intensity oscillations.

The total number of images is 309 after removing 31 obscured image data of the other filter. In time-series, at every 10th data point, the time-difference with the previous data point is ~ 50 s, while other time-differences are approximately uniform, that is, ~ 30 s. The total span of the time-series is ~ 164.9 min with an effective cadence of ~ 31.9 s. We use standard subroutines to calibrate and clean the *Hinode*/XRT temporal image data. We use `xrt_prep.pro` to remove cosmic-ray hits and streaks, and for the calibration of dark current and normalization of each image for the exposure time. After cleaning and calibrating the *Hinode*/XRT temporal image data, we remove the jitter in the data due to orbital variation using the method given by Shimizu et al. (2007), standard subroutines (e.g. `xrt_jitter.pro` and related routines), and nearest alignment tables and models available in the SSW and SSWDB software libraries. We calculate the shifts in XRT images with respect to the first image and then co-align the time-series data by properly shifting each image as per the estimates of their offsets. Since we want to study the X-ray intensity oscillations above XBPs and their most probable physical reasons, we need to register the time-series precisely up to the subpixel scale. Therefore, we register again the jitter-removed XRT images choosing the first image as a reference and using the Fourier cross-correlation technique up to the subpixel scale. The light curves are extracted from the seven BPs (XBP1, XBP2, XBP3, XBP4, XBP5, XBP6 and XBP7) of different spatial size, covering the whole field of view around the ECH. We have selected these XBPs in the vicinity of a large-scale ECH, which are fully evolved and stable in the entire time-series observations. Although the size varies in selected XBPs, yet we consider the most brightened and fully evolved XBPs over the total span of the temporal length of time-series data. The right-hand panel of Fig. 1 shows the co-aligned *SoHO*/MDI contours overlaid on the XRT image at 12:47 UT. The yellow colour shows the positive-polarity magnetic field regions and the blue colour shows the negative-polarity magnetic field regions. The boxes show the selected XBPs consisting of the pair of small-scale positive- and negative-polarity regions connected probably in the form of small-scale loops near the boundary of the ECH. The base of this ECH is also filled with the distribution of such pairs of positive- and negative-polarity magnetic field regions. We have selected those XBPs near the boundaries of the ECH which show the significant strength of the pair of small-scale magnetic polarities. Therefore, they may be associated with fully evolved, small-scale, closed magnetic flux tube systems suitable for a MHD waveguide. It should be noted that the mean intensity oscillation is estimated over the selected single-pixel locations above XBPs to avoid the effect of background variations, which is the measure of the average normalized flux. Therefore, the consideration of single-pixel locations from inside XBPs is appropriate for measuring this mean flux modulation due to the temporal evolution of the activity without any effect of the background. We have derived the X-ray light curves from all the chosen structures for the power spectral analyses. We do not aim to study the morphological properties and evolution of these XBPs in this paper. Such studies require the automated edge detection of such BPs, which has been carried out by Crockett et al. (2009). However, the mean flux modulations derived from the selected XBPs have been derived from the first principle as already discussed, which is appropriate for our studies. We shall use the robust techniques of the detection of small-scale BPs in our future projects related to the morphological studies of such small-scale structures and their dynamics. However, we have identified the magnetic polarities of the chosen XBPs that provide the information on their magnetic flux tube structuring.

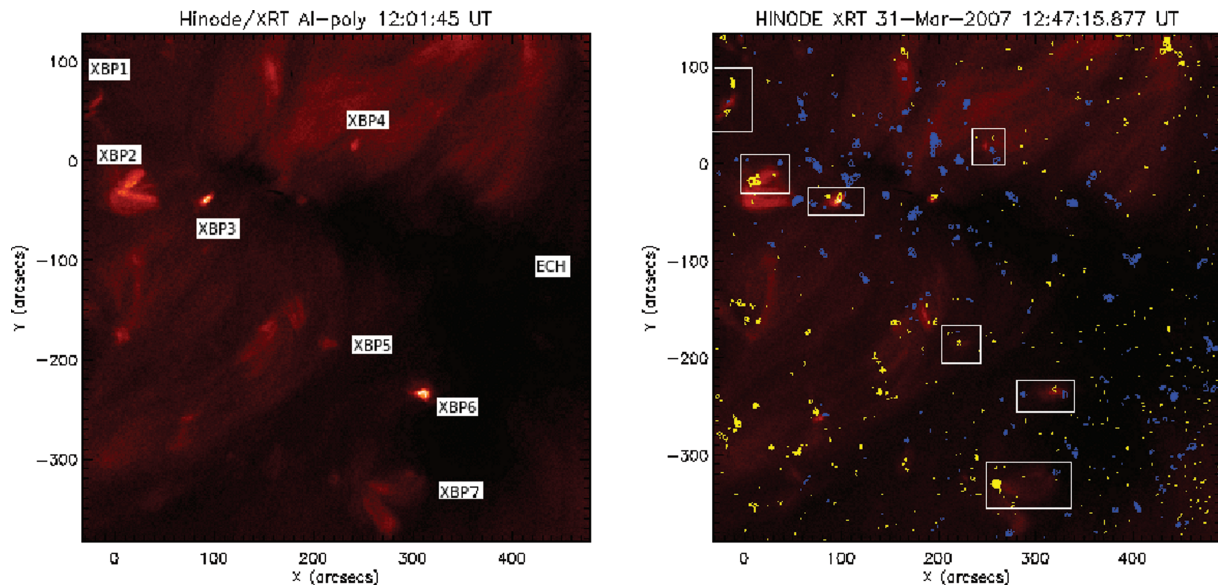


Figure 1. Left-hand panel: *Hinode*/XRT, Al-poly image slice at 12:01:45 UT on 2007 March 31, which shows the XBPs and on-disc ECH. The pointing position is ($X_{\text{CEN}} \approx 219.089$ arcsec, $Y_{\text{CEN}} \approx -127.434$ arcsec) and the full field of view is ($X_{\text{FOV}} = 512$ pixels, $Y_{\text{FOV}} = 512$ pixels) with the plate scale of 1.02086 arcsec pixel $^{-1}$. Right-hand panel: the co-aligned *SoHO*/MDI contours overlaid on the XRT image of 2007 March 31 at 12:47 UT. The yellow colour shows the positive-polarity magnetic field regions, while the blue colour gives the negative-polarity field regions. The boxes show that the selected XBPs consist of a pair of small-scale positive- and negative-polarity regions connected in the form of small-scale loops. (Courtesy: *Hinode*/XRT, *SoHO*/MDI).

We have used the wavelet analysis IDL code ‘RANDOMLET’ developed by Dr E. O’Shea. This program executes non-parametric randomization tests (Linnell-Nemec & Nemec 1985; O’Shea et al. 2001), which is an additional feature along the standard wavelet analysis procedure (Torrence & Compo 1998) to examine the statistically significant real periodicities in the time-series data. We use Fourier filtering at a certain Fourier period ($F_c = 54.55$ min) outside the cone-of-influence (COI) (60.18 min) to avoid the edge effect and inappropriate long periodicities to reconstruct the time-series for further power spectral analyses to find statistically significant real oscillation periods in the X-ray light curves. The reconstructed time-series is the sum of the wavelet transform over all scales below the selected Fourier period for filtering (F_c).

In our time-series at each 10th data point, the difference in time from the previous data point is ~ 50 s, while other time-differences are uniform, ~ 30 s. The total span of time-series is ~ 164.9 min with an effective cadence of ~ 31.9 s. The Fourier period difference over the time-series is ~ 60 s, which is the minimum period that we can resolve in the intensity wavelet. Only at each 10th Fourier period, the data point is scaled at ~ 1.66 min. Since we observe the statistically significant periods of the order of a few tens of minutes, this minimum resolvable Fourier scale lies within the Gaussian width of the power spectrum peak in the intensity wavelets. The problem may arise if one tries to find the signature of the periods near the Nyquist frequency related to high-frequency oscillations. However, this mild variation in the Fourier scale at symmetric locations of time-series will not affect the detection. There is uniform variation in the wavelet scale or Fourier period at each data point of the time-series. Therefore, it is an approximately uniformly sampled time-series that is suitable for the power spectral analyses using the wavelet technique. Because of the long duration of the data set, this cadence and the Fourier scale shift at a few places in the time-series is obvious. Accordingly, the time-series data are treated as approximately uniformly sampled data.

The wavelet transform and periodogram analyses (Scargle 1982) are performed on the X-ray light curves of all the seven selected

XBPs. We report only those periodicities as real ones that are statistically significant using both methods. It should be noted that the X-ray light curves possess the closely associated and diffused power peaks outside the COI. Therefore, our choice of the cut-off period (54.55 min) for the Fourier filtering and wavelet reconstruction is the best possible one which distinguishes the COI region and isolates the first two or three well-distinguished power peaks outside the COI that are associated with statistically significant and globally distributed periodicities.

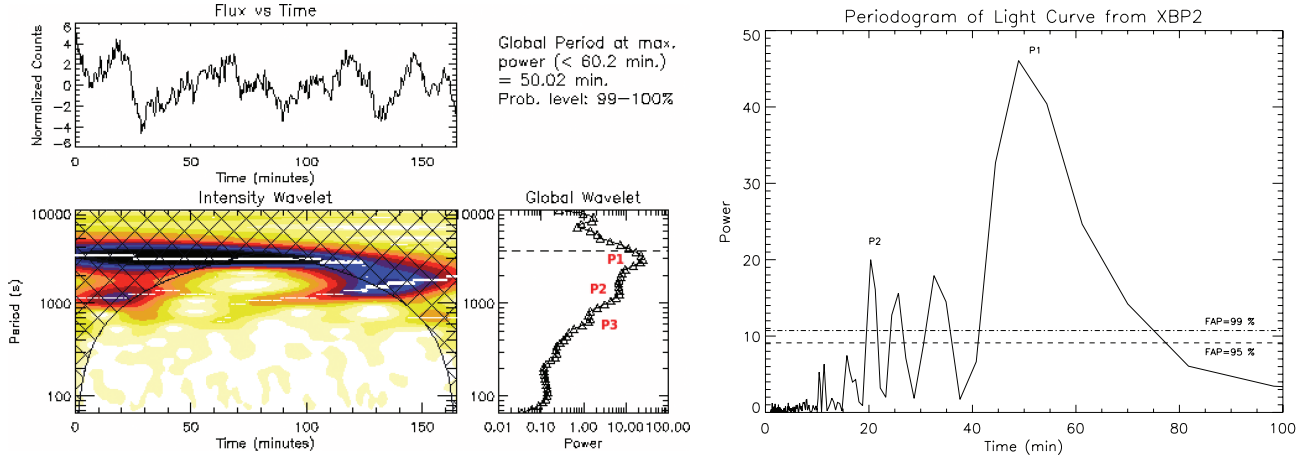
We summarize the detected long periodicities of XBPs in Table 1, which are significant in both the wavelet and the periodogram. However, we only present the wavelet and periodogram results of XBP2 and XBP7 in detail, which have clearly resolved small-scale bipolar loop-like structures. These periodicities observed over various XBPs may be the most likely signature of various harmonics of magnetoacoustic waves. We choose two XBPs (XBP2 and XBP7) to represent our results as given in Table 1 because the period ratio (P_1/P_2) of XBP2 falls in the category >2.0 , while that of XBP7 falls in the category <2.0 , which have different physical aspects (see Table 1). The results summarized in Table 1 for other XBPs fall in one of these two categories.

Figs 2 and 3, respectively, present the wavelet transforms and periodograms of the X-ray light curve from XBP2 and XBP7. The intensity wavelet transforms and global power spectra of the respective reconstructed X-ray light curves (top panel) are shown, respectively, in the lower left-hand and lower right-hand panels of each wavelet figure. The periodograms of the same light curve and significant periodicities are shown in the rightmost panel of each figure. The main results from these XBPs are presented as under.

In XBP2 (cf. Fig. 2 and Table 1), we obtain three periodicities of ~ 50.00 , ~ 21.00 and ~ 10.00 min in the wavelet, in which the first periodicity is measured as the global periodicity with the probability of 99–100 per cent in the time-series of soft X-ray. However, we obtain only two periodicities at ~ 50.00 and ~ 20.00 min, statistically significant in the corresponding periodogram, which are almost close to ~ 50.00 and ~ 21.00 min, respectively. The third periodicity

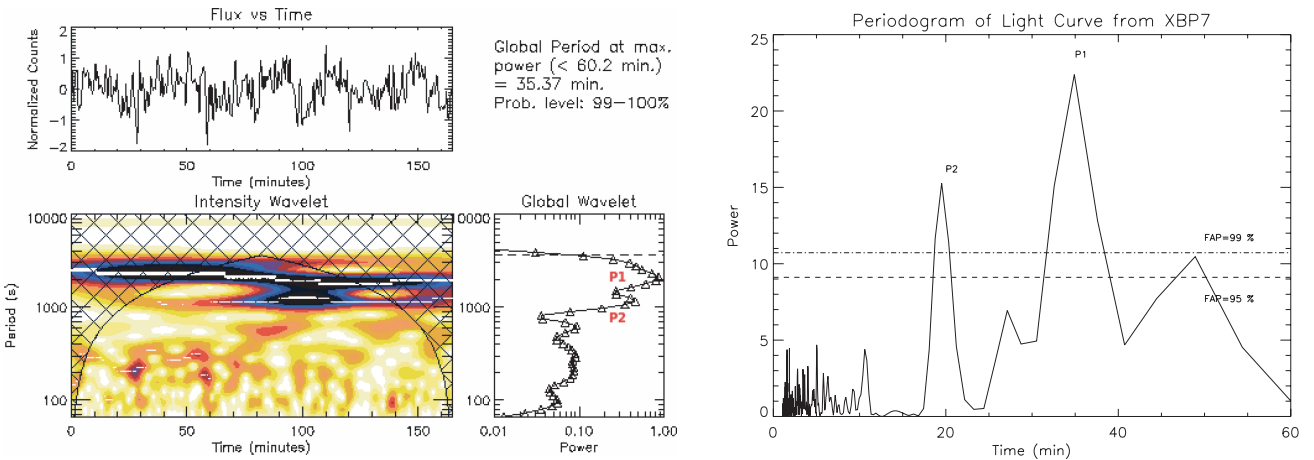
Table 1. Periodicities detected in XBPs from periodograms close to corresponding wavelets and their consequences.

Coronal structures	Pixel location (x, y)	First period (min)	Second period (min)	Third period (min)	Probability (per cent)	P_1/P_2	P_1/P_3	Seismological information from the wave period ratio
XBP1	(16, 444)	~28	~15	–	>99	1.86	–	Density stratification
XBP2	(51, 364)	~50	~20	–	>99	2.50	–	Magnetic field divergence
XBP3	(127, 346)	~60	~20	~12	>99	–	3.00	No density stratification, higher order periodicities
XBP4	(274, 399)	~51	~24	–	>99	2.12	–	Magnetic field divergence
XBP5	(248, 198)	~35	~23	~13	>99	1.52	2.69	Density stratification
XBP6	(343, 147)	~49	~20	–	>99	2.45	–	Magnetic field divergence
XBP7	(312, 51)	~35	~19	–	>99	1.84	–	Density stratification

**Figure 2.** Wavelet results for the second XBP (XBP2): in the wavelet figure, the upper left-hand panel shows the X-ray flux versus time profile, the lower left-hand panel shows the intensity wavelet and the lower right-hand panel shows global power spectra. The periodogram of the same light curve and significant periodicities in minutes are shown in the right-hand panel for comparison. The light curve is derived from single-pixel locations inside the BP at (51th pixel, 364th pixel).

is not significant in both power spectral analyses. Therefore, we do not consider it. Since the resolution between the power peaks is better in the periodogram than in the global power spectra of the wavelet, we consider only two periodicities, namely ~50.00 and ~20.00 min, as statistically significant periodicities (>99 per cent).

In XBP7 (cf. Fig. 3 and Table 1), we obtain two periodicities of ~35.36 and ~19.28 min in the wavelet in which the first periodicity is measured as the global periodicity (probability of 99–100 per cent). The second periodicity shows 99–100 per cent probability from 50 to 164 min period of the observations, while the

**Figure 3.** Wavelet results for the seventh XBP (XBP7): in the wavelet figure, the upper left-hand panel shows the X-ray flux versus time profile, the lower left-hand panel shows the intensity wavelet and the lower right-hand panel shows global power spectra. The periodogram of the same light curve and significant periodicities in minutes are shown in the right-hand panel for comparison. The light curve is derived from single-pixel locations inside the BP at (312th pixel, 51th pixel).

first periodicity shows 99–100 per cent probability over the full span of the observation duration. Here, too, we obtain only two periodicities at ~ 35.00 and ~ 19.00 min, statistically significant in the corresponding periodogram, almost close to ~ 35.36 and ~ 19.28 min, respectively, as detected in the wavelet. Therefore, we consider two clearly resolved periodicities ~ 35.00 and ~ 19.00 min as statistically significant periodicities (>99 per cent).

These XBPs show the multiple periodicities in the X-ray intensity oscillations, which may be the signature of various harmonics of magnetoacoustic oscillations that may have origin in the lower solar atmosphere or due to recurrent small-scale magnetic reconnection. Recently, Srivastava & Dwivedi (2010b) have reported the leakage of 5.0-min acoustic oscillations above the BP using *Hinode*/EIS data and reported a most possible signature of wave mode coupling there. However, this study reveals the long-period MHD oscillations. Possibly, they are magnetoacoustic waves that excite in the lower solar atmosphere and leak through the magnetic flux tube system associated with XBPs. The observations of various harmonics provide the crucial seismological information about the local plasma conditions of the observed XBPs that may be significant in understanding their dynamics and heating.

3 RESULTS AND DISCUSSION

The acoustic oscillations can excite in small/large-scale solar structures, for example, BP loops, small-scale magnetic cavities, magnetic networks and their BPs, foot-points of coronal loops, etc. (e.g. De Moortel et al. 2002; McAteer et al. 2003; De Pontieu, Erdélyi & James 2004; Ugarte-Urra et al. 2004; Srivastava et al. 2008; Tian et al. 2008; Srivastava et al. 2010a,b, and references cited therein) either *in situ* or due to the leakage of photospheric powers. It is also found that acoustic oscillations, which leak through the magnetic field lines of the solar atmosphere, are converted into magnetoacoustic waves in the region where the plasma beta tends to unity and reach the upper solar atmosphere (e.g. Bogdan et al. 2003; Kuridze et al. 2007; Srivastava et al. 2010b; Erdélyi & Fedun 2010). In time-series imaging observations of coronal structures, these waves cause density fluctuations and therefore intensity oscillations. However, in spectroscopic time-series observations, they cause periodic perturbations in density (thus intensity) as well as Doppler shift oscillations (e.g. Wang et al. 2002). Moreover, in the case of XBPs, the intensity oscillations may also be generated due to recurrent magnetic reconnection (e.g. Ugarte-Urra et al. 2004; Doyle, Popescu & Taroyan 2006; Tian et al. 2008, and references cited therein).

Using power spectral analyses of the X-ray light curves derived from various XBPs, we find the signature of multiple (two or three) long periodicities above these structures. All periods are statistically significant and globally distributed. These periodicities carry the most likely signature of the acoustic MHD oscillation modes, and thus their leakage above the XBPs. Unfortunately, the co-spatial and co-temporal high-cadence *Hinode*/SOT magnetograms are not available to study the magnetic flux oscillations associated with these XBPs. Such observations may shed new light on the magnetic behaviour of longitudinal waves which propagate above the observed XBPs. However, the right-hand panel of Fig. 1 shows the co-aligned *SoHO*/MDI contours overlaid on the XRT image of 2007 March 31 at 12:47 UT. This shows that the selected XBPs consist of small-scale positive- and negative-polarity regions, probably connected in the form of small-scale loops near the boundary of the ECH, serving as a waveguide for MHD activity. To the best of our knowledge, we have attempted for the first time to derive some cru-

cial seismological information of XBPs based on MHD seismology theory and the observational signature of wave harmonics. Assuming the typical temperature of XBPs to be ~ 2.0 MK, we calculate the typical sound speed as ~ 207 km s $^{-1}$. Therefore, the acoustic cut-off period above the XBPs is ~ 48 min.

We summarize in Table 1 the observed long periodicities above XBPs, most likely signature of acoustic wave harmonics, crucial seismological information. In the case of the second BP (XBP2), the first two observed periods ($P_1 = 50.00$ min and $P_2 = 20.00$ min) are the most likely signatures of the first two harmonics (first and second) of magnetoacoustic oscillations that excite in it. These harmonics of acoustic oscillations leak upwards along the small-scale loop system/expanding magnetic flux tube system associated with this XBP in the form of magnetoacoustic waves. However, the observations of 50 min periodicity associated with the leakage of magnetoacoustic oscillations above this XBP are difficult to explain because this period lies above the acoustic cut-off period. The wave can propagate only in the elevated cut-off environment, if the magnetic field lines are inclined in the BP (see De Pontieu et al. 2004; Tian et al. 2008). Although we do not find any clue of the tilted flux tube system in this BP, yet the possibility of its existence cannot be ruled out. Therefore, the radiative cooling and thus the generation of finite radiative relaxation time may also be an efficient mechanism to produce the reduced cut-off frequency environment (i.e. elevated cut-off period) in which these waves can propagate upwards above this BP. This phenomenon is well studied in theory and for the EUV BPs (e.g. Roberts 1983; McAteer et al. 2003; Khomenko et al. 2008; Srivastava & Dwivedi 2010b). It is therefore most likely that we observe the leakage of the first and second harmonics of acoustic oscillations in the higher corona in the form of magnetoacoustic wave modes, which cause the modulations in the X-ray intensity above XBP2. The period ratio $P_1/P_2 = 2.50$ is clearly shifted ahead of 2.0, which probably indicates the occurrence of magnetic field divergence in the associated flux tube serving as a waveguide for the fast magnetoacoustic wave (e.g. Andries et al. 2009 and references cited therein). However, theory is not yet well established except for kink wave harmonics.

In the case of the seventh BP (XBP7), the first two observed periods ($P_1 = 35.00$ min and $P_2 = 19.00$ min) are the most likely signature of the first two harmonics (first and second) of magnetoacoustic oscillations that excite in XBP7. These harmonics of the acoustic oscillations leak upwards along the small-scale loop system/expanding magnetic flux tube system associated with this BP in the form of magnetoacoustic waves as these periods lie below the acoustic cut-off period. Therefore, we most likely observe the leakage of the first and second harmonics of acoustic oscillations in the higher corona in the form of magnetoacoustic wave modes, which cause the modulations in the X-ray intensity above BP7. The period ratio $P_1/P_2 = 1.84$ is clearly shifted from 2.0, which probably indicates the occurrence of density stratification in the plasma environment associated with this BP. The period ratio shift (P_1/P_2) of acoustic oscillations as a tracer of density stratification in the large-scale coronal loops is well established in both theory and observations (e.g. McEwan, De Moortel & Roberts 2006; Srivastava et al. 2008b; Andries et al. 2009; Macnamara & Roberts 2010, 2011; Srivastava & Dwivedi 2010a, and references cited therein). However, it is probably the first observational signature of the density stratification in the small-scale loop system associated with XBPs from the observed harmonics of acoustic oscillations.

It is clear from Table 1 that we observe the first period $P_1 \sim 60$ min which may be the most likely signature of the first acoustic harmonics that leak in the form of magnetoacoustic waves above

XBP3. However, ~ 20 and ~ 12 min are higher order observed periodicities. Therefore, we most likely observe the leakage of the first (~ 60 min) and third (~ 19.33 min) harmonics of acoustic oscillations in the higher corona in the form of magnetoacoustic wave modes, which cause the modulations in the X-ray intensity above XBP3. The period ratio $P_1/P_3 \sim 3.00$ is absolute and does not show any significant shift from this value as recently obtained in the observed kink overtones of coronal loops (Van Doorsselaere et al. 2009). Therefore, we do not find a clear indication of the occurrence of density stratification in the plasma environment associated with XBP3. Another period of ~ 11.99 min is probably associated with the higher order fourth harmonic of acoustic oscillations. This may also leak into the higher corona in the form of a magnetoacoustic wave. Another possibility of this periodicity being generated independently by the recurrent small-scale magnetic reconnection events in and around this BP cannot be ruled out (Tian et al. 2008). Although we interpret the observed periodicities in XBP3 also in terms of magnetoacoustic wave modes, the absence of second harmonics casts doubt. Consequently, these periodicities may be generated independently by recurrent small-scale magnetic reconnection. However, the signature of small-scale reconnection is indirect in our case study. Signatures of various acoustic wave harmonics as observed above the other XBPs and summarized in Table 1 either lie in the category of the observations of XBP2 or lie in the category of XBP7. Our main goal is to study the possible role of the excitation of various MHD wave harmonics in XBPs and diagnose some crucial plasma conditions using MHD seismology techniques. Moreover, the simultaneous presence of the ECH in the observations provides an opportunity to compare the intensity oscillations and thus MHD activity of small-scale coronal (XBPs) structures with a large-scale (coronal hole) structure. Accordingly, we derive X-ray light curve choosing a box of $100 \text{ pixels} \times 100 \text{ pixels}$ size over the ECH which is centred at (411th pixel, 209th pixel). Using wavelet and periodogram analyses, we obtain a periodicity of ~ 26.26 min with the probability of 99–100 per cent. This may be the most likely signature of the leakage and propagation of acoustic oscillations in the form of magnetoacoustic waves along open field lines of the ECH. However, we could not convincingly detect the other harmonics as observed in XBPs.

The magnetic field structuring of the quiet-Sun coronal hole contains both closed loop and open field regions. Coronal holes are the source of fast solar wind (e.g. Tu et al. 2005; Marsch et al. 2006). Tian et al. (2009) have also reported the Doppler flow structures in such quiet-Sun regions which are associated with various types of loops (e.g. BP loops, small-scale loops showing siphon flows, large-scale coronal loops, loops at the boundaries of open field lines), and also the flow structures of the open field region. We also find a mixed polarity distribution in the observed ECH and nearby the quiet Sun as seen in the bottom panel of Fig. 1. Therefore, it may likely hint at the presence of low-lying small-scale loops at the base of the coronal hole. The multiple acoustic wave harmonics may possibly excite in the small-scale XBPs, which leak in the upper atmosphere along their tilted magnetic flux tube system (De Pontieu et al. 2004) or in the reduced plasma cut-off environment (Srivastava et al. 2010b). However, the observations of only a single periodicity of ~ 27 min above the ECH may have several explanations. This long-period intensity oscillation may be the signature of propagating magnetoacoustic waves, which may be excited and leak in the low atmospheric magnetic network cavities at the base of the coronal hole (e.g. Srivastava et al. 2008a; Kuridze et al. 2009). The observations of only a single periodicity, which may be related to the fundamental mode cavity acoustic oscillations, indicate this

fact as higher order harmonics are unlikely in the upper atmosphere (e.g. Kuridze et al. 2007). The long-period Alfvén waves that drive and heat the solar wind originating from the coronal hole are well established in theory (Hollweg 2006; Suzuki 2008, and references cited therein). Another reason behind the excitation of acoustic oscillations in the coronal hole may be due to a ponderomotive force of double period Alfvén waves that can resonantly transfer the energy to longitudinal oscillations in the lower solar atmosphere where the plasma beta probably tends to unity and generates magnetoacoustic waves (Zaqarashvili, Oliver & Ballester 2006). However, the atmospheric conditions should be known precisely to arrive at a definite conclusion on the resonant energy transfer. In conclusion, the observed wave signature above the coronal hole may have different periodicity and origin from the observed XBPs. The future multiwavelength observations of the coronal holes should be carried out through space-borne experiments to address this problem appropriately.

4 CONCLUSIONS

The main conclusions from this investigation of XBPs are as follows:

- (1) We report the observational signature of the leakage of various harmonics of acoustic oscillations above XBPs in the form of magnetoacoustic waves which generate intensity oscillations in the X-rays. In the case of XBP1 and XBP7, we observe the first two harmonics of magnetoacoustic waves. The observed period ratio shifts ($P_1/P_2 < 2.0$) in these BPs provide the first seismological clue to density stratification. In the case of XBP5, we observe the first three periodicities which are related to magnetoacoustic wave harmonics. The observed period ratio shifts ($P_1/P_2 < 2.0$ and $P_1/P_3 < 3.0$) in this BP also provide the seismological clue to density stratification.
- (2) In XBP2, XBP4 and XBP6, we clearly observe the first two harmonics of magnetoacoustic waves and the period ratio shift ($P_1/P_2 > 2.0$) which provides clues to magnetic field divergence of the flux tube in which the magnetoacoustic wave excites.
- (3) In XBP3, we observe the higher order periodicities (first, third and fourth) also in terms of the X-ray intensity oscillations and may be associated with the periodic modulation of density mainly due to magnetoacoustic waves. The third periodicity may be the fourth harmonics of acoustic oscillations. Although we interpret the observed periodicities in XBP3 in terms of magnetoacoustic wave modes, yet the absence of the second harmonics provides a ground for debate.

ACKNOWLEDGMENTS

We wish to express our gratitude to the referee for his valuable suggestions which substantially improved this work. We thank Prof. L. Golub for his valuable suggestions on XRT data. We also thank the scientific editors of the MNRAS for their encouragement during the revision of this paper. We thank Dr E. O'Shea for kindly providing 'RANDOMLET'. The wavelet software was kindly provided by C. Torrence and G. Compo, and is available at <http://paos.colorado.edu/research/wavelets/>. *Hinode* is a Japanese mission developed and launched by the ISAS/JAXA, with the NAOJ as the domestic partner, and the NASA and STFC (UK) as international partners. It is operated by these agencies in cooperation with the ESA and NSC (Norway). AKS acknowledges the support of DST-RFB(INT/RFB/P-38).

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