

# PERIODIC VARIATIONS IN X-RAY EMISSION INTENSITY OF CORONAL LOOPS

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## ABSTRACT

The analysis of light curves generated from *Yohkoh* Soft X-ray Telescope observations of coronal loops, described by McKenzie (1997) and McKenzie and Mullan (1997), revealed apparently periodic variations in the brightness of X-ray emission. The amplitudes of the variations were on the order of one percent of the total brightness, and the periods were between 9 s and 60 s. The oscillations have been interpreted as due to waves in the magnetic coronal loops, possibly indicating sufficient energy to contribute significantly to coronal heating.

The X-ray data have recently been revisited in light of two developments: First, an improved calibration of the SXT data is now available, allowing more confidence in the separation of instrumental artifacts from the measurements. Second, the broad availability of wavelet analysis tools provides an alternative to the Fourier-based programs used in the original analysis. The results of a new analysis of the coronal X-ray light curves will be presented.

Key words: waves; oscillations; coronal heating; coronal seismology.

## 1. INTRODUCTION

The analysis of light curves generated from *Yohkoh* Soft X-ray Telescope (SXT) observations of coronal loops, described by McKenzie (1997) and McKenzie & Mullan (1997), revealed apparently periodic variations in the brightness of X-ray emission. The amplitudes of the variations were on the order of one percent of the total brightness, and the periods were between 9 s and 60 s. Interestingly, visible light observations made during solar eclipses (*e.g.*, Pasachoff (1991), Singh *et al.* (1997), and recently Williams *et al.* (2001, 2002)) indicate brightness oscillations with similar periods and amplitudes. The oscillations have been interpreted as due to waves in the magnetic coronal loops. In the case of the X-ray modulations, McKenzie (1997) and McKenzie & Mullan (1997) considered the oscillations to be a signature of a global mode resonance of the coronal loops. The periods of the oscillations and the apparent lengths of the coronal loops were taken to indicate wave speeds between approximately 1800 and 14,000 km s<sup>-1</sup>, inconsistent with acoustic speeds.

The X-ray data have been re-analyzed in light of two developments: First, an improved calibration of the SXT data is now available, allowing more confidence in the

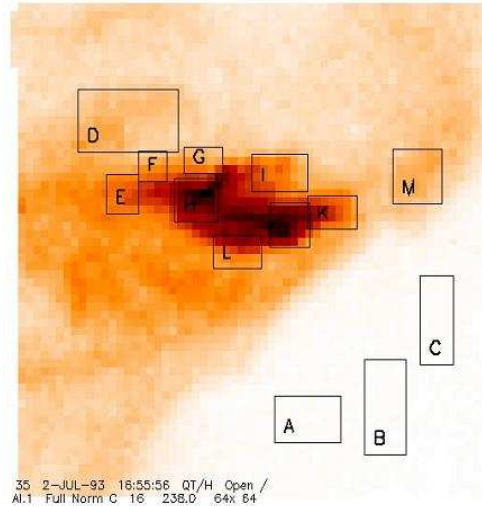


Figure 1. Subimages for Movie #58. Pixels at different positions along a number of magnetic loops are selected for creation of X-ray light curves.

separation of instrumental artifacts from the measurements. Second, the broad availability of wavelet analysis tools provides an alternative to the Fourier-based programs used in the original analysis. We present the results of a new analysis of the coronal X-ray light curves.

## 2. DATA

The X-ray data differ from the eclipse data used by the authors mentioned above in a few regards. First, there is simply more of the X-ray data, owing to *Yohkoh*'s mission span of slightly more than 10 years. The data include cases in which a given active region was observed over the course of several days, an option not available to eclipse studies. Possibly of more importance is that the SXT data permit observations of coronal features on the disk, rather than at the limb. There is thus less potential for viewing multiple coronal loops along the line of sight. On the other hand, the eclipse data often sample higher frequencies than are available to SXT. The eclipse data described by Williams *et al.* (2001, 2002), for example, have a significantly higher sampling frequency than the SXT data. However, the cadence of SXT data is well suited for detecting oscillations with frequencies in the range of our interest. Periods between approximately 4 seconds and 9 minutes are testable with the data we analyzed. For comparison, global mode resonance in a 10<sup>4</sup> km loop with an Alfvén speed of 1000 km s<sup>-1</sup> implies an oscillation period of 20 seconds.

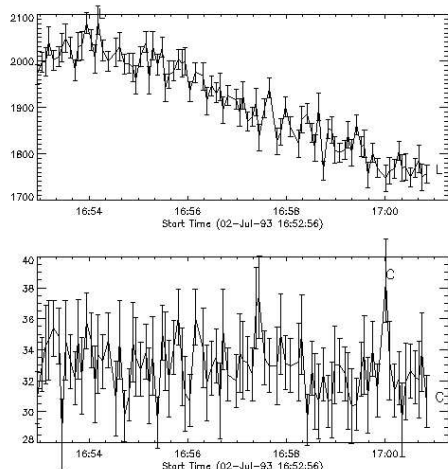


Figure 2. X-ray light curves from subimages L and C (boxes in Fig. 1).

For this investigation, image sequences were specifically chosen so as to avoid observations of flares. The data were prepared using the SXT\_PREP tools in SolarSoft (Freeland & Handy, 1998), to compensate for dark current, stray visible light in the camera, and to align all the images. Since the end of *Yohkoh* operations, the databases for dark current and stray light have been improved, allowing for slightly better separation of instrumental effects from the images. This fact was one of the motivations for performing this study.

As in the original study by McKenzie (1997), groups of pixels were selected and binned together to generate light curves from various positions along each coronal loop. Also as in the earlier study, light curves were generated from apparently empty regions of the field of view, in order to check for any instrumentally induced periodicity. The images above (Fig. 1 & 2) demonstrate the concept, and show two example light curves.

### 3. ANALYSIS

Secular trends and very low frequency (VLF) modulations were removed from the light curves via fitting with a running mean. The residual (*i.e.*, high-pass filtered) light curves were then analyzed by means of wavelet transforms (Torrence & Compo, 1998). The mother wavelet used in the analysis was a Morlet. The significance of features in the wavelet spectra was judged by comparison with a white noise spectrum. Example residual light curves, and the resulting wavelet power spectra, are shown in Fig. 3.

Many of the light curves show sudden increases in X-ray brightness. These result in large peaks in the wavelet spectra, though they are not truly periodic. The running-mean fit is not always able to match these sudden brightness changes, and sometimes makes the situation worse by amplifying the departure from the running mean brightness. This often results in a “false positive” detec-

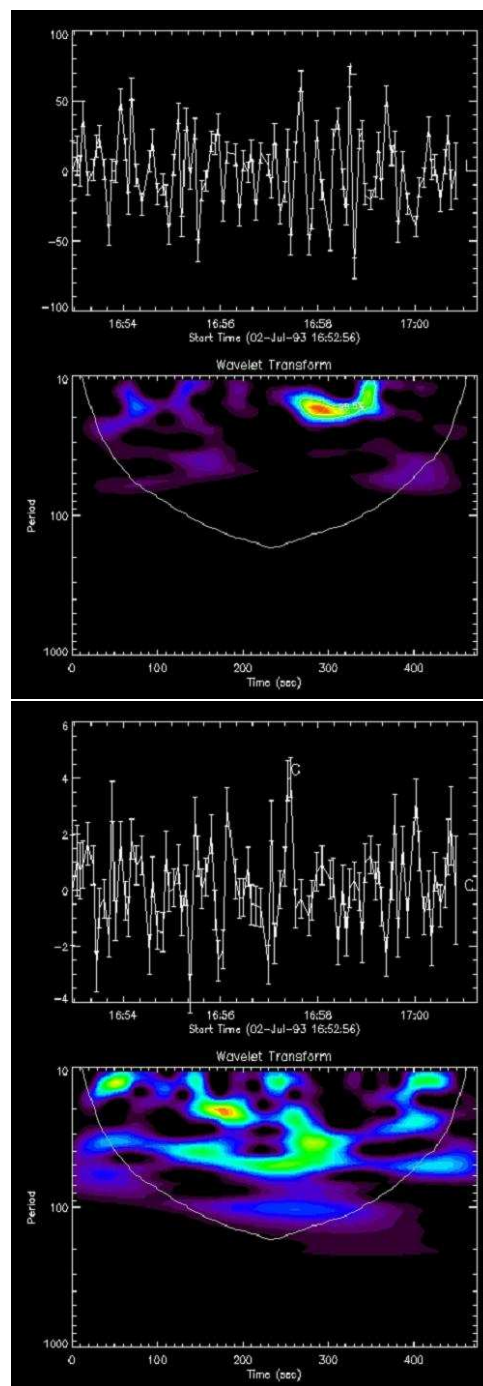


Figure 3. Analysis of light curves 58\_L (upper pair of frames) and 58\_C (lower pair). In each pair of frames, the top panel shows the light curve from the respective subimages seen in Fig. 2, after high-pass filtering. The bottom panel shows the wavelet power spectrum of the filtered light curve. The color scale is not identical for each plot; only the large feature in 58\_L reaches 99.5% confidence.

Table 1. Summary of detections with at least 99.5% confidence and at least 5 complete cycles of oscillation.

Movie ID (catalog number and subimage)	Date, Time (beginning of obs.)	Duration of movie (seconds)	Number of images in movie	Period detected (seconds)	Duration of oscillation (seconds)
49s, subimage D	28-Jun-1993 19:23:08	1304	288	31	233
50s, subimage H	28-Jun-1993 20:26:02	1050	230	25	141
55, subimage K	29-Jun-1993 19:07:08	620	113	44	457
58, subimage L	02-Jul-1993 16:52:56	474	89	16	85
61, subimage K	02-Jul-1993 18:56:26	1834	354	44	237
61, subimage P	02-Jul-1993 18:56:26	1834	354	55	319
61s, subimage I	02-Jul-1993 18:56:24	1828	354	40	412
63, subimage H	01-Feb-1993 06:54:22	314	157	18	135
49s, subimage A ("empty" box)	28-Jun-1993 19:23:08	1304	288	30	176

tion in the wavelet power spectrum. Each light curve and each spectrum was examined, and light curves suffering from this kind of artifact were rejected and not considered further. This "VLF and transient" filtering leaves 22 SXT movies in our sample, with 224 light curves.

#### 4. RESULTS

A large number of the spectra show transient oscillatory power with greater than 99.5% confidence; but often the oscillations appear to die out after only 1-2 cycles. In our analysis, we consider only those oscillations which persist for more than 5 cycles (determined from the wavelet power spectrum), and which are detected with at least 99.5% confidence. In light curves from coronal loops, eight detected oscillations meet these criteria (7.8 sigma more than expected by chance). In light curves from apparently empty pixels (no loops visible), only one detection meets the criteria (1.4 sigma). The greatest number of cycles observed in any one case is 10.4 cycles. Table 1 summarizes the detected oscillations. (An additional 5 oscillations were detected, with periods between 14 and 48 seconds, that persisted for more than 4 but fewer than 5 complete cycles.)

#### 5. DISCUSSION

In this study we have used wavelet transforms to search for periodic modulations in X-ray brightness. We specifically chose sequences of images that do not record solar flares, and so the emphasis is on quiescent active regions. The wavelet technique provides some advantages

over Fourier analysis, particularly information about the temporal extent of evanescent oscillations (*i.e.*, the start and end-times of transient periodicities). Tests of the wavelet software were performed with synthetic data, including light curves with irregular sampling. The tests will be more fully described in a future publication; we found that the wavelet software satisfactorily handled small gaps in the data stream and successfully detected brightness oscillations in the low signal-to-noise regime.

Our findings are similar to those of McKenzie (1997) and McKenzie & Mullan (1997), although a one-to-one correspondence to their detections is not found. The reasons for this are being investigated. Nine of 224 light curves were found to have oscillations with (*i*) at least 99.5% confidence and (*ii*) durations of at least 5 complete cycles. The detected periods are in the same range as those found by McKenzie (1997) and McKenzie & Mullan (1997). As the periods were detected in the same loops as were analyzed by those authors, the associated speeds are assumed to be similar, in excess of  $1000 \text{ km s}^{-1}$ . For comparison, McKenzie (1997) measured temperatures in the coronal loops on the order of 3 million kelvins, implying acoustic speeds of approximately  $220 \text{ km s}^{-1}$ .

One can use the findings above to estimate the ubiquity of intensity oscillations. All but one of the SXT movies in Table 1 monitor the same active region, NOAA 7530, and thus the same coronal loops were observed repeatedly. The loop recorded in Movie #61, subimage "K", for example, was observed for a total of 3024 seconds. Oscillations were detected during 412 seconds of that period, indicating an oscillation duty cycle of approximately 14

percent. On the other hand, the loop seen in Movie #49s, subimage “D”, oscillated for only 374 seconds of its 6916 seconds in the spotlight, indicating a duty cycle of 5 percent.

One interpretation obviously is that although magnetic waves in a coronal loop may die out within 5-10 cycles, a given coronal loop harbors the resonances during as much as 5-15 percent of its life, even in the absence of flares. The low quality of the resonances (*i.e.*, short durations) may indicate that the energy carried by the waves is lost, possibly to heating. Amplitudes of the oscillations have not been measured at the present time. If the change in emission is due to variations in plasma density, then brightness changes of one percent (*e.g.*, McKenzie & Mullan 1997) suggest density variations of about one-half of one percent. This leads us to believe that sufficient energy is carried by these waves, and (by extrapolation from the low quality of the resonances) deposited by the waves, to make a significant contribution to the heating of the corona. At the same time, the low duty cycle (5-15 percent) suggests that—unless there are waves below the threshold of detectability, which is entirely possible—some mechanism other than resonant absorption of magnetic waves must also be providing energy for coronal heating.

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