WAVELET ANALYSIS OF ACTIVE REGION OSCILLATIONS

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ABSTRACT

Time series arising from SOHO (Solar and Heliospheric Observatory) CDS-NIS (Coronal Diagnostic Spectrometer Normal Incidence Spectrometer) active region observations on 14th-15th November 1996 are used to demonstrate the applicability of wavelet methods. The localised nature of the wavelet transform allows us to study both the duration of any statistically significant oscillations as well as their period. The data consists of observations at approximately 14s cadence in He I 584.33Å (log T[e] = 4.3), O V 629.73Å (log T[e] = 5.3), Mg IX 368.06Å (log T[e] = 6.0), Fe XVI 380.76Å (log T[e] = 6.4). Such data provides detailed intensity information on the active region over a wide range of temperatures. The distribution of statistically significant periods found varies from one to three, as do their duration.

Key words: oscillations, chromosphere, transition region, corona, UV radiation

1. INTRODUCTION

One of the principal objectives of the SoHO mission is to shed more light on how the solar corona is heated. Many mechanisms have been suggested in the literature, as candidates, and many reviews exist outlining them in some detail (for example, Narain and Ulmschneider 1990, Browning 1991, Hollweg 1990 and Zirker 1993). Following Narain and Ulmschneider (1990), heating mechanisms may be divided into two basic classes, AC and DC. AC mechanisms are defined as those mechanisms that can be associated with rapid photospheric footpoint motions. Into this class fall magneto-hydrodynamic wave mechanisms, such as phase mixing (Heyvaerts and Priest 1983, Hood et al. 1997), resonant absorption (Ruderman and Goossens 1993, Wright and Rickard 1995) and magnetoacoustic waves (Porter et al. 1994a, Porter et al. 1994b, Roberts et al. 1984, Leing and Edwin 1995). Conversely, DC mechanisms are associated with slow motions, which lead to magnetic field dissipation. Into this class fall magnetic reconnection mechanisms - for example, nanoflares Parker (1988) and magneto-hydrodynamic turbulence (Heyvaerts and Priest 1992). It is likely that both AC and DC processes are probably at work in the solar corona - SoHO's task is to determine which dominates in which situation. This paper looks for evidence of AC mechanisms via the detection of oscillations in the solar atmosphere. Much effort has gone into creating wave heating mechanisms that can deposit energy in the solar atmosphere, in particular the corona. Clearly, the detection of oscillations is an important step in determining the presence or otherwise of wave heating mechanisms. A wavelet analysis allows one to look at time series in a number of ways that are useful for solar applications. Bocchialini & Baudin (1994) examine some chromospheric velocity oscillations for both frequency and duration of oscillation. Frick et al. (1997) analyse sunspot number for variations in the 11 year period, while Aschwanden et al. (1998) uses a wavelet approach to study power law type behaviour in the timescales present in hard x-ray solar flares. In this study we apply a wavelet approach to active region observations taken with CDS. Section 2 describes a campaign designed to look for oscillations in the solar atmosphere. Section 3 outlines the data processing methods used to find the results described in Section 4, and Section 5 discusses the results of this study.

2. THE ST. ANDREWS/RAL LOOPS CAMPAIGN

The findings described below form part of a series of observations taken with CDS on 12th-15th November, 1996. Two observing sequences were used, EJECT.V3 (version 18) and LOOPS.3 (version 1): CDS sequences are defined by a 6-8 letter acronym, and we note them here for future reference. Each observing sequence can be seen as a self-contained 'unit of observation' that serves a particular purpose. EJECT.V3 was originally designed to look at the onset of coronal mass ejections. This sequence uses the normal incidence part of CDS (see Harrison et al. 1995) with the 4 x 240 arcsec² slit to look at six lines (He I 584.33Å (log T[e] = 4.3), O V 629.73Å (log T[e] = 5.3), Mg IX 368.06Å (log T[e] = 6.0), Fe XVI 360.76Å (log T[e] = 6.4), Si X 347.4Å (log T[e] = 6.0) and Si II 255.6Å (log T[e] = 6.0)) at sixty different solar positions consecutively four arcseconds apart, building up an image in each line of about 240 x 240 arcsec². The first four lines cover a wide spread of formation temperatures (from the chromosphere (He), through the transition region (O) and into the corona (Mg and Fe)) while the last two lines are primarily intended as a density diagnostic at T[e] = 10^7K. EJECT.V3 covers an area of 4 x 4 arcmin² in a short period of time (about 15 minutes) and was used in this campaign to take a snapshot of the region of interest before and after multiple runs of the higher cadence, smaller area LOOPS.3 study. The relation of LOOPS.3 to EJECT.V3 is shown in Figure 1. The narrow rectangles represent the positions of the LOOPS.3


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observations overlaid on top of the EJECT.V3 observations. LOOPS.3 is also a normal incidence observing sequence, using the 4 x 240 arcsec$^2$ slit, that was specifically designed for this campaign to look for rapid variations in active regions. It is designed to provide spectroscopic information (used for Doppler velocity and line broadening studies) in four lines, widely spaced in formation temperature, at high cadence. Only 120 arcseconds of data along the slit is returned in order to reduce the overall cadence time. It covers the first four EJECT.V3 lines, but instead of rastering over a large area of the Sun, LOOPS.3 sits at one particular solar position and takes one image approximately every 14 seconds. Hence the returned data is essentially one dimensional in space (the solar Y direction, north-south along the slit, the first pixel being the northernmost) and has a cadence of about 14 seconds. One complete LOOPS.3 sequence takes 50 of these images, giving a total duration of about 700 seconds. A typical run of the campaign involved running EJECT.V3 initially to provide an overall view of the target active region. Then LOOPS.3 is run three times on one specific point of interest in that region, say at suspected coronal loop footpoints. Since the three LOOPS.3 studies are run consecutively with the same pointing, together they form a time series three times as long as one LOOPS.3 study. To close the campaign, EJECT.V3 is run again to determine if any overall changes in the region of interest have occurred while LOOPS.3 has been running. The time series study presented below looks for oscillations with a sample time of about 14 seconds in time intervals of about 2100 seconds.

3. TIME SERIES ANALYSIS

3.1. Preparation of the data

The data for each block of LOOPS.3 observations was first cleaned for cosmic ray hits on the detectors. The CDS software package VDS.CALIB was run to convert the raw data into photon-events/pixel and then to Multiplying by the exposure time yields the photon-events per pixel. Each block of LOOPS.3 data concatenates to form a time series of about 2100s. We examine total line intensity $I$ only. This is found by fitting

$$F(x) = A \exp \left( -\frac{1}{2} \left( \frac{x - c}{w} \right)^2 \right) + a_0 + a_1 x$$

(1)
i.e., one Gaussian (amplitude $A$, position $c$, line width $w$) plus a linear background ($a_0$, $a_1$) to the sum (in the solar Y direction) of 4 pixels, taking account of the spread of an incoming signal in CDS-NIS (Thompson 1998). Of equal importance is the error in the total line intensity. Thompson (1998) describes a procedure for estimating this error in CDS-NIS data. The error $\sigma_I^2$ in the total line intensity consists of two parts:

$$\sigma_I^2 = \sigma_{\text{renorm}}^2 + (fNS)^2$$  \hspace{1cm} (2)

The first error $\sigma_{\text{renorm}}^2$ is due to the error in fitting the peak amplitude $A$ and line width $w$. Following Thompson (1998), we get

$$\sigma_{\text{renorm}}^2 = \frac{1}{2} \left[ \frac{\sigma_A^2}{A} + \frac{\sigma_w^2}{w} \right]$$  \hspace{1cm} (3)

where $\sigma_A^2$ and $\sigma_w^2$ now refer to the renormalized values of the errors. The second contribution arises from the photon statistics in CDS-NIS, and is due to two effects. The first is the Poisson noise, which for $N$ counts is $\sqrt{N}$. The second is due to the fluctuation in the amplification of the detector system, estimated to be $\sqrt{N}$ and Poisson distributed. These two errors add as the sum of squares, leading to a fractional error $fNS = \sqrt{2}/N$. The quantity $S$ is the fitted signal in the data; hence the term $(fNS)^2$ describes the contribution to error in $I$ due to the photon statistics.

We have already pointed out that the slit is essentially one-dimensional, in the solar Y direction only. In the LOOPS.3 study, a feature is chosen and the slit pointed. Since solar tracking is not present in this study, new material is sliding into the field of view (from the east) as the original material is sliding out (to the west). Hence any time series generated from LOOPS.3 data is a combination of the new material moving in, old material moving out, and the inherent variation of the material in view. One could ask - why not do some sort of solar tracking to combat this problem? One need only move the slit across the surface of the Sun as it rotates, to keep the same material in view. However, it is not possible to do this perfectly with CDS. The solar tracking capabilities of CDS are as follows. Once a feature is chosen, the instrument keeps the same pointing until the feature has moved two arcseconds. The instrument is then repointed to catch up with the rotated material. For the slit we use, this implies that by the time the repointing is done, the slit will be looking at half new and half old material. So even when solar tracking is switched on, the resultant time series still suffers from the same problem of moving material.

3.2. Wavelet analysis

In section 3.1., it was pointed out that new material moves into the field of view of the LOOPS.3 window, and hence the time series is a combination of new material moving into the field of view and the time variability of the material itself. This implies that later parts of the time series refer to different pieces of material that may or may not be magnetically linked to material earlier in the time series. This introduces the idea that any periods in the time series may be strongly localised in time. Hence the method of analysis should take account of this. Methods such as Fast Fourier Transform and Lomb - Scargle periodogram (Scargle 1982, Horne and Baliunas 1986, Koen 1990) calculate power at particular frequencies by examining the entire time series at the same time and hence, in our dataset, implicitly assume that the material in view remains the same. Hence power detected at any period in a LOOPS.3 may be due to new material moving into the field of view and not due to the inherent time variability of the plasma, which is the quantity we are more interested in. However, the localised nature of time series analysis by wavelets makes them ideal for time series generated from LOOPS.3 data, and any other time series suffering from the same problems. Since wavelets are localised in time, when we analyse using wavelets, we sample the time series locally, removing the effect of looking over the entire observation and hence removing the effect of new material moving into the LOOPS.3 field of view.

Let us assume we have a time series of $N$ observations $x_n$ with sample interval $dt$; then the continuous wavelet transform of the form of the time series $x_n$ is defined as the convolution of $x_n$ with an analysing (or mother) wavelet $\psi(\eta)$. We assume that $\psi$ is normalised, i.e., $\int_{-\infty}^{\infty} \psi^2 d\eta = 1$. For $\eta = (n' - n)dt/s$ we have

$$_N\psi_n(s) = \sum_{n'=-\infty}^{n-1} x_n' \sqrt{s} \psi^*_\eta \left( \frac{(n' - n)dt}{s} \right)$$  \hspace{1cm} (4)

where $s$ is the wavelet scale and $n$ allows us to translate the analysing wavelet in time. By varying $s$ and $n$ we can build up a picture of any features in the time series as a function of the analysing scale $s$ and time, as represented by $n$. In this paper we use the Morlet wavelet

$$\psi(\eta) = \pi^{-1/4} \exp(i\eta) \exp \left( -\frac{\eta^2}{2} \right)$$  \hspace{1cm} (5)

as our analysing wavelet (Farge 1992). This choice reflects both the oscillatory and transitory nature of the motions we are looking for and the way the observations were made. We expect any signal to switch on and off and also be affected by material moving in and out of the observing slit. The wavelet power spectrum is defined as $|W_n(s)|^2$; ranging through $s$ and $n$ allows one to build up a two dimensional transform of the original time series, in scale $s$ and $n$, the time index. The wavelet transform also suffers from edge effects at both ends of the time series. This results in a "cone of influence" in the final transform. Figure 2(d) shows a wavelet transform with the cone of influence indicated as a dashed line. Portions of the transform outside the area formed by the time axis and the cone are subject to edge effects. The choice of model was largely guided by examining the time series. Typically, oscillations are present on top of some linearly varying background. Therefore we choose

$$x_n = a_n + \psi_n + \sum_{n'=1}^{N} \sum_{j=1}^{J} A_{n',j} \psi(\eta_{n,j}) + Z_n$$  \hspace{1cm} (6)

i.e., the sum of a linear trend, a superposition of wavelets and noise $Z_n$, where $\eta_{n,j} = (n' - n)dt/s_j$. In the analysis, we subtract a least squares fitted linear polynomial before calculating the wavelet transform. We determine the significant areas in the wavelet transform by comparing the wavelet transform with that expected by our model for the noise. Any signal significantly greater than
that expected from noise is treated as a candidate wave packet signal (see Section 3.3). The expectation value of a purely noisy CDS time series is

$$|W_n(s)|^2 \equiv \sigma^2_{CDS}$$

(7)

The quantity $\sigma^2_{CDS}$ is found by averaging $\sigma_n$ over the time series. From Torrence & Compo (1998), the local wavelet power spectrum is therefore

$$\frac{|W_n(s)|^2}{\sigma^2_{CDS}} \sim \chi^2_2$$

(8)

at each time $n$ and each scale $s$, where $\chi^2$ is the $\chi^2$ distribution with two degrees of freedom. To determine, say, the 95% confidence level (significant at 5%) one substitutes the value of $\chi^2$ at the 95th percentile. This allows one to calculate 95% confidence contour levels in the wavelet transform $|W_n(s)|^2$ such as those seen in Figure 2(d) (solid line). All the results shown here are based on a 95% confidence level.

3.3. Counting wave packets in the wavelet transform

Figure 2 shows the process of finding wave packets given a time series that rejects the null hypothesis. The original data (Fig. 2(a), a He I intensity time series formed at pixels 28-31 in file s5763) has a linear polynomial subtracted from it and has any spikes removed to form Fig. 2(b). Figure 2(c) presents the wave packets found and their duration (as a multiple of wavelet scale) in the wavelet transform (Fig. 2(d)).

Darker regions in (Fig. 2(d)) correspond to regions of higher wavelet power. Also outlined is the 95% confidence contour (solid dark line) and the cone of influence (dashed line). Clearly, the wavelet transform presents us with a lot of information from which we must sift through to get the scales of the wave packets present in the data. Firstly we discard portions of the transform below the chosen confidence level. Secondly, we also disregard all wavelet power outside the cone of influence. The routine then finds all the local maxima in the remaining portions of the transform. Typically, there are one or two wavelet scales at which significant power exists. At each of these scales (indicated by dotted lines), the duration of the wavelet packet (inside the cone of influence and above the significance level) is measured. The duration of this signal must satisfy two criteria. Firstly, the duration must be greater than or equal to the wavelet scale at which it occurs. This ensures that we have at least one complete oscillation in the wave packet. Secondly, the wave packet duration must be greater than 7% of the width of the cone of influence at that wavelet scale. This suppresses the identification of spikes in the data as true wavelet power.

4. RESULTS

The results presented below were obtained from data taken on the 15th November 1996 of an active region present in the south-east quadrant of the Sun. An EJCTE X3 run was taken to start the sequence. This was followed by nine LOOPS.3 runs in three blocks of three. The first block (stored as CDS FITS files labelled s5762r00.01.02) was positioned over a region of positive magnetic flux, as observed with the Michelson Doppler Interferometer (MDI) on board SoHO. Similarly, the third block (CDS FITS s5764r00.01.02) of LOOPS.3 runs was placed over the corresponding negative magnetic flux region. The intermediate block was placed between the flux regions (CDS FITS s5763r00.01.02). Each block of three LOOPS.3 runs forms a long duration, high cadence set of observations over physically different parts of an active region. Figure 1 shows the slit positions over the emerging active region with an instrumental pointing error of $\pm 3$ arcsec. Figures 3(a, c, e) show histograms of wave packet length found in the data for each of the line-wave packets are found in He I, O V, and Mg IX. No statistically significant wave packets are found in the Fe XVI time series. Having identified a wave packet in the data at a particular scale (according to the criteria laid down in Section 3.3.), the duration of the wave packet is measured in units of the scale it occurs at. Hence if the wave packet is 780 seconds long at scale 300 seconds then the wave packet is 2.6 scales long, i.e., between 2 and 3 wavelet scales long, and is binned accordingly in the histogram. Figures 3(b, d, f) show the frequency distribution of the scales found. These figures are formed in a similar manner to Figures 3(a, c, e); instead of binning wave packet lengths into integer bins and noting how many of each we find, we add up all the fractional lengths at a particular scale.

Note the presence of significant numbers of wavelet scales in He I and O V when compared to the higher temperature lines Mg IX and Fe XVI. He I and O V are both bright, well formed lines with total intensities well above that expected from noise. Mg IX and Fe XVI although have total intensities either commensurate with or less than that expected from the noise.

He I has a large number of long wavelet scale (greater than 300 seconds) wave packets between one and 3 wavelet scales long (Figure 3(a)). At shorter scales, longer wave packets are detected, though less frequently. Note there are relatively few observations of significant wavelet power at scales less than 100 seconds. Figure 3(b) has a broad peak with many scales found within one standard deviation of the peak, about 170 to 350 seconds, i.e., 2.8 - 5.8 mHz. This lies in the range found by White and Athay (1979a) Athay & White (1979a), Athay & White (1979b) and White and Athay (1979b) (2.5-9 mHz) and overlaps with the range 2-5 mHz found by Doyle et al. (1997).

O V also shows this same basic wave packet pattern as He I, although it is noticeable that there are some observations of significant scales lasting the maximum possible length for a wave packet at that scale. There are also more wave packets found with scales less than 100 seconds in O V when compared to He I. The transition region line results (Figure 3(b,d)) include evidence of a 300 second oscillation, although the distribution is peaked around 160-250 seconds. Doyle et al. (1998) report on quiet sun oscillations in the upper transition region and note the presence of power at 5 mHz which would correspond approximately to the peak in the distribution Figure 3(d).

5. CONCLUSION

There are several wave packets at a number of scales in He I and O V that lie on the maximum detectable length.
Figure 2. Counting wave packets in the wavelet transform: example data. The original data (a) is a He I intensity time series formed at pixel 28-31 in file s6763. For details of the wavelet scale counting process see Section 3.3.

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Figure 3. Frequency distribution of wave packet length as a function of wavelet scale for (a) He I, (c) O V and (e) Mg IX. Darker rectangles correspond to more frequently found wave packet lengths. The curved dotted line indicates the maximum length possible for a wave packet at a given scale. Corresponding frequency distribution of wavelet scale for (b) He I, (d) O V and (f) Mg IX.