PERIODICITIES IN ACTIVE REGIONS

J. Ireland\textsuperscript{1}, R.W. Walsh\textsuperscript{1}, R.A. Harrison\textsuperscript{2}, E.R. Priest\textsuperscript{1}

\textsuperscript{1} School of Mathematical and Computational Sciences, University of St. Andrews, KY16 9SS, U.K.
\textsuperscript{2} Space Science Department, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, U.K.

ABSTRACT

An active region present on the Sun between 14th-15th November 1996 was studied with the Normal Incidence Spectrometer (NIS), part of the Coronal Diagnostic Spectrometer (CDS) on board SoHO (Solar and Heliospheric Observatory). High cadence observations 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 360.76Å (log $T_e = 6.4$) provide detailed temporal and spectral information on the active region over a wide range of temperatures. It is shown that intensity oscillation periods of about 900 – 1200 seconds may be present in all the lines studied, which may indicate the presence of standing slow magnetooacoustic waves. Oscillations around 300 seconds are also found in He I 584.33Å and O V 629.73Å.

Key words: active regions, waves, EUV Sun.

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 Ulem Schneider 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 falls magnetohydrodynamic wave mechanisms, such as phase mixing (Heyvaerts and Priest 1983, Ireland and Priest 1997), resonant absorption (Ruderman and Goossens 1993, Wright and Rickard 1995) and magnetooacoustic waves (Porter et al. 1994a, Porter et al. 1994b, Roberts et al. 1984, Laing and Edwin 1995). Conversely, DC mechanisms are associated with slow motions, which lead to magnetic field dissipation. Into this class falls magnetic reconnection mechanisms - for example, nanoflares Parker 1988 and magnetohydrodynamic 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.

Much effort has gone into creating wave heating mechanisms that can deposit energy in the solar atmosphere, in particular the corona. Much effort too has gone into detecting both the waves themselves and any consequent heating (Ireland 1996). Pure acoustic waves are unlikely to exist in an atmosphere as strongly magnetised as the solar atmosphere; they are likely to be equivalent to slow mode magnetooacoustic waves. Acoustic waves can be largely dismissed as coronal heating mechanisms. Firstly, any acoustic waves generated at the photosphere will steepen and form shocks at the transition region, and go no further (Narain and Ulmschneider 1990 and references within). Secondly, Edwin 1991 calculates that the upper limit to the acoustic wave flux of $10 W m^{-2}$ compared to the energy flux density of $10^4 W m^{-2}$ renders acoustic wave heating relatively unimportant.

Alfvén waves have received extensive attention in literature in connection with coronal heating. Heyvaerts and Priest 1983 suggest that phase mixing of Alfvén waves may contribute to coronal heating. In this mechanism, an Alfvén velocity structured transverse to the direction of wave propagation generates small length scales that enable the weak coronal damping to remove energy from the wave. The Alfvén wave amplitude is predicted to exhibit an $exp(-ct^2)$ dependence in closed structures such as coronal loops. Ulrich 1996 finds magnetohydrodynamic oscillations in the Na D1 line with a period in the 5 minute band, observed from Mount Wilson. These oscillations are consistent with the properties of outgoing Alfvén waves and carry an estimated energy flux on the order of $3 \times 10^7$ erg cm$^{-2}$s$^{-1}$, sufficient for active region requirements.

The resonant absorption of Alfvén waves in coronal structures (typically loops) has been studied in detail, and seems well established both theoretically (Ions 1975, Kapperman and Tataronis 1977, Ruderman and Goossens 1993) and numerically (Poedts and Kerner 1992, Karpen et al. 1994, Wright and Rickard 1995). However, numerical (Davila 1987) and theoretical (Hollweg 1987) calculations suggest that the main energy deposition region (the resonant layer) maybe either much less than or on the order of 1000 km, which, at best, would place such an obser-

---

(ESA SP-404, September 1997)

© European Space Agency • Provided by the NASA Astrophysics Data System
vation at the limit of CDS (and SUMER (Solar Ultra-
short measurements of Emitted Radiation), Wilhelm
et. al. 1995) spatial resolution. Note, however, that
Koutchmy et al. 1983 presented observational evi-
dence for existence of resonant absorption in loops
but the energy observed was insufficient to account
for the loops radiative losses.

As was mentioned above, magnetoacoustic waves
are likely to exist in the corona. Švestka 1994 attributes
quasi-periodic X-ray brightenings of about 20 min-
tures to slow standing magnetoacoustic waves, de-
scribed theoretically Roberts et al. 1984. Porter
et al. 1994a suggests that slow mode waves with
periods less than 300s/100s could damp sufficiently
quickly enough to balance radiative energy losses in
quiet/active solar regions. Chapman et al. 1972 pro-
vides evidence for a 262s intensity oscillations in the
EUV (T ≤ 10⁷K) from OSO-7. Also, Tsubaki 1977
demonstrates line of sight Doppler velocity, and to
a lesser extent, line width, oscillations with periods
around 300s in Fe XVI 5303Å Sacramento Peak Ob-
servatory data.

2. THE ST. ANDREWS/RAL LOOPS
CAMPAIGN

The findings described below form part of a series of
observations taken with CDS on 12th-15th Novem-
ber, 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 on-
set of coronal mass ejections. This sequence uses
the normal incidence part of CDS (see Harrison et al.
1995) with the 4 × 240arcsec² 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 347.44Å (log T_e = 6.0) and Si X
356.04Å (log T_e = 6.0)) at sixty different solar po-

tions consecutively four arcseconds apart, building
up an image in each line of about 240 × 240arcsec².

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 = 10⁹K. EJECT.V3 cov-
ers an area of 4 × 4arcmin² 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 af-
after multiple runs of the higher cadence, smaller area
LOOPS.3 study.

LOOPS.3 is also a normal incidence observing se-
quence, using the 4 × 240arcsec² slit, that was specif-
cally designed for this campaign to look for rapid
variations in active regions. It is designed to provide
spectroscopic information (used for Doppler veloc-
ity 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 ra-
tering over a large area of the Sun, LOOPS.3 sits
at one particular solar position and takes one image
approximately every 14 seconds. Therefore, this is
the temporal resolution for our time series analysis.
One complete LOOPS.3 sequence takes 50 of these
images, giving a total duration of about 700 seconds.
A summary description of LOOPS.3 and EJECT.V3
are given in Table 1 and Table 2.

<table>
<thead>
<tr>
<th>Table 1. EJECT.V3 observing sequence.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Instrument</strong></td>
</tr>
<tr>
<td><strong>Locations</strong></td>
</tr>
<tr>
<td><strong>Duration</strong></td>
</tr>
<tr>
<td><strong>Lines</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2. LOOPS.3 observing sequence.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Instrument</strong></td>
</tr>
<tr>
<td><strong>Locations</strong></td>
</tr>
<tr>
<td><strong>Duration</strong></td>
</tr>
<tr>
<td><strong>Lines</strong></td>
</tr>
</tbody>
</table>

A typical run of the campaign would involved run-
ning EJECT.V3 initially to provide some density di-
agnostics and an image of the region of interest. Then
LOOPS.3 is run, perhaps a few times, on one of sev-
eral specific points of interest in that region, say at
suspected coronal loop footpoints. To close the cam-
paign, EJECT.V3 is run again to determine if any
overall changes in the region of interest have occurred
while LOOPS.3 has been running.

3. 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
EJECT.V3 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 Michels-
on Doppler Interferometer (MDI) on board SoHO.
Similarly, the third block (CDS FITS s5764r00.01.02)
of LOOPS.3 runs was placed over the correspond-
ning negative magnetic flux region. The interim-
ate 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 ob-
servations over physically different parts of an active
region. Figure 1 shows the slit positions over the
emerging active region (in a reverse colour table).
The instrumental pointing error is ±5 arcsecs. The
high cadence (of the LOOPS.3 observing sequence
makes it ideal for time series analysis. The data for
each block of LOOPS.3 observations was first cleaned
<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Data Type</th>
<th>Period(s) $\tau_+^{\circ}$ ( % FAP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$&lt; 1.0%$</td>
</tr>
<tr>
<td>He I $\lambda 1083$</td>
<td>$I$</td>
<td>10171299 (8.10 -19), 631988 (4.10 -13)</td>
</tr>
<tr>
<td>He I $\delta$</td>
<td>$\lambda 1083$</td>
<td>-</td>
</tr>
<tr>
<td>He I $\delta$</td>
<td>$\lambda 1083$</td>
<td>911992 (0.02)</td>
</tr>
<tr>
<td>He I $\lambda 1083$</td>
<td>$\varpi D$</td>
<td>7205826 (6.10 -6)</td>
</tr>
<tr>
<td>O V $\lambda I$</td>
<td>$I$</td>
<td>10631294 (4.10 -12)</td>
</tr>
<tr>
<td>O V $\varpi D$</td>
<td>$I$</td>
<td>7542124 (1.10 -3)</td>
</tr>
<tr>
<td>O V $\delta$</td>
<td>$\lambda 1083$</td>
<td>74972 (1.0)</td>
</tr>
<tr>
<td>O V $\lambda 1083$</td>
<td>$I$</td>
<td>111844 (2.10 -10)</td>
</tr>
<tr>
<td>O V $\varpi D$</td>
<td>$I$</td>
<td>778888 (6.10 -6)</td>
</tr>
</tbody>
</table>

Table 3. Time series analysis: periods (upper and lower errors and % FAP) found from data CDS FITS s5762r00.01.02 (150 observations in 2117.0468s; slit position 62 (see Figure 1)). $\varpi D$ = average Doppler velocity over indicated solar $Y$ range, $I$ = average intensity over indicated solar $Y$ range, $\delta$ = average line broadening over indicated solar $Y$ range.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Data Type</th>
<th>Period(s) $\tau_+^{\circ}$ ( % FAP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$&lt; 1.0%$</td>
</tr>
<tr>
<td>*He I $\lambda 1083$</td>
<td>$I$</td>
<td>1185315 (0.0001), 498548 (0.001)</td>
</tr>
<tr>
<td>He I $\delta$</td>
<td>$\lambda 1083$</td>
<td>-</td>
</tr>
<tr>
<td>He I $\lambda 1083$</td>
<td>$I$</td>
<td>291310 (3.10 -5)</td>
</tr>
<tr>
<td>*He I $\delta$</td>
<td>$\lambda 1083$</td>
<td>882101 (0.003)</td>
</tr>
<tr>
<td>*He I $\lambda 1083$</td>
<td>$I$</td>
<td>1315186 (0.003)</td>
</tr>
<tr>
<td>O V $\lambda I$</td>
<td>$I$</td>
<td>118715 (4.10 -8), 52221 (1.10 -5)</td>
</tr>
<tr>
<td>O V $\lambda 1083$</td>
<td>$I$</td>
<td>1051326 (0.003)</td>
</tr>
<tr>
<td>O V $\varpi D$</td>
<td>$I$</td>
<td>1472398 (7.10 -10), 852195 (1.10 -7), 552993 (0.002)</td>
</tr>
<tr>
<td>O V $\lambda 1083$</td>
<td>$I$</td>
<td>9511303 (0.4)</td>
</tr>
<tr>
<td>*O V $\lambda 1083$</td>
<td>$I$</td>
<td>9685398 (1.0)</td>
</tr>
<tr>
<td>*O V $\lambda 1083$</td>
<td>$I$</td>
<td>699292 (0.0001), 29393 (0.0002)</td>
</tr>
<tr>
<td>O V $\lambda 1083$</td>
<td>$I$</td>
<td>1031132 (3.10 -5)</td>
</tr>
<tr>
<td>O V $\varpi D$</td>
<td>$I$</td>
<td>1150312 (1.5.10 -5)</td>
</tr>
<tr>
<td>Mg IX $\lambda I$</td>
<td>$I$</td>
<td>1227767 (3.10 -8)</td>
</tr>
<tr>
<td>Mg IX $\lambda 1083$</td>
<td>$I$</td>
<td>-</td>
</tr>
<tr>
<td>Mg IX $\varpi D$</td>
<td>$I$</td>
<td>-</td>
</tr>
<tr>
<td>Fe XVI $\lambda I$</td>
<td>$I$</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4. Time series analysis: periods found from data CDS FITS s5763r00.01.02 (150 observations in 2117.6638s; slit position 63 (see Figure 1)). * indicates that a linearly increasing background was subtracted from the data before period analysis.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Data Type</th>
<th>Period(s) $\tau_+^{\circ}$ ( % FAP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$&lt; 1.0%$</td>
</tr>
<tr>
<td>*He I $\lambda 1083$</td>
<td>$I$</td>
<td>6202128 (7.10 -13), 603430 (0.09)</td>
</tr>
<tr>
<td>*He I $\delta$</td>
<td>$\lambda 1083$</td>
<td>897929 (0.008)</td>
</tr>
<tr>
<td>*He I $\lambda 1083$</td>
<td>$I$</td>
<td>6202128 (7.10 -13)</td>
</tr>
<tr>
<td>He I $\varpi D$</td>
<td>$I$</td>
<td>609292 (0.02)</td>
</tr>
<tr>
<td>*O V $\lambda 1083$</td>
<td>$I$</td>
<td>799292 (3.10 -5)</td>
</tr>
<tr>
<td>O V $\delta$</td>
<td>$\lambda 1083$</td>
<td>-</td>
</tr>
<tr>
<td>*O V $\varpi D$</td>
<td>$I$</td>
<td>1000109 (0.19), 477457 (5.6)</td>
</tr>
<tr>
<td>O V $\lambda 1083$</td>
<td>$I$</td>
<td>409948 (2.10 -14), 554309 (0.013)</td>
</tr>
<tr>
<td>O V $\delta$</td>
<td>$\lambda 1083$</td>
<td>-</td>
</tr>
<tr>
<td>O V $\varpi D$</td>
<td>$I$</td>
<td>116315 (1.10 -7), 42621 (0.05)</td>
</tr>
<tr>
<td>+Fe XVI $\lambda 1083$</td>
<td>$I$</td>
<td>1210138 (0.11)</td>
</tr>
<tr>
<td>+*Fe XVI $\lambda 1083$</td>
<td>$I$</td>
<td>762531 (0.55)</td>
</tr>
<tr>
<td>+Fe XVI $\lambda 1083$</td>
<td>$I$</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5. Time series analysis: periods found from data CDS FITS s5764r01.01.02 (150 observations in 2128.3905s; slit position 64 (see Figure 1)). Near integral period ratios denoted by $\alpha, \beta, \gamma, \delta, \mu, \nu$. * indicates that the Gaussian data was fitted without also finding a background behaviour.
Figure 1. Position of the observing slit for the three LOOPS.3 runs s5762, 63 and 64 respectively (darkest region has highest intensity) overlaying EJECT.V3 data. Solar north is at top of page, south at bottom.

Figure 2. Typical time series and corresponding Lomb-Scargle periodogram for 500 evenly spaced angular frequencies in the range shown. This particular dataset corresponds to the first entry in Table 5.
for cosmic ray hits on the detectors. These are easily identified as pixel enhancements or tracks. The data were further cleaned using a CDS software command to fill in any data dropouts (of which there were relatively few in the data) with averages generated from the surrounding values. Finally, data calibration was applied to take account of instrument generated uncertainties. With the data in this form, it is now ready for time series analysis. By concatenating the data in each block of observations, we form a time series about 2100 seconds long. Gaussian profiles were fitted to the spectral information at every solar Y position for every time and for every wavelength (solar Y is taken as the north-south direction along the slit, the first pixel being the northernmost). This allows us to look at line intensity, line broadening and Doppler velocity in an active region in a number of different temperatures simultaneously.

To generate time series, the physical quantity we wish to analyse is summed over a specified range of solar Y, usually some interesting bright feature like the increased emission feature in He I 584.33Å, position 63 in Figure 1. The resulting time series is then analysed using a periodogram technique (Scargle 1982, Horne and Baliunas 1986) which allows a false alarm probability (FAP) to be assigned to any periods found in the data (Koen 1990). Figure 2 shows a typical time series and its corresponding Lomb-Scargle periodogram. Periods are then tabulated into those having percentage false alarm probability less than a certain level - here we have chosen 4 levels to aid tabulation, 0.1%, 1.0%, 10.0% and 50.0%. A percentage FAP of < 1.0% implies that particular period has a less than 1% chance of occurring randomly. The periods found, and at what level of percentage FAP are shown in Tables 3, 4 and 5. Period errors are assessed by noting where the wings of the periodogram peak crosses the next nearest false alarm probability level.

A number of different periods are found in the data, occurring at various false alarm probabilities. These are summarised in Figure 3. Firstly, many more periods are found in He I He I 584.33Å and O V 629.73Å than in Mg IX 368.06Å and Fe XVI 360.76Å. Secondly, there appear to be two distinct populations arising from the analysis. The first set, appear to have long periods (1000 seconds), very low false alarm probability, but very large errors. The very low false alarm probability may be caused by the fact that we have commonly only fitted approximately two periods in the observation time of 2100 seconds. We simply do not have a long enough observation time to say if the apparent oscillation is truly real or not. To properly confirm such a period, a longer observation time is needed.

The second population of periods are commonly less than 1000 seconds, and have good to high false alarm probability and smaller errors. In this set, we can fit more oscillations into the observation time. Note in particular the He I 584.33Å 291s, 434s, and O V 629.73Å 293s intensity oscillations and the O V 629.73Å 426s Doppler velocity oscillation. All these periods are well resolved in the dataset and in particular, appear to have detected a 5 minute oscillation in O V 629.73Å intensity. The remaining periods have relatively high false alarm probabilities, implying again that a longer observation time is required in order to adequately decide their veracity.

It is interesting to note that for some time series where two or more periods are listed for the same solar Y region and physical variable (whether it be intensity, Doppler velocity or line broadening), the ratio of the extracted periods is often nearly integral. A good example of this is found in Table 5 for an O V average Doppler velocity time series, summed over solar Y pixels 26 → 40. The 573s period is almost exactly one half the longest (marked by μ in Table 5). Note also that subtraction of any of the three periods from this dataset leaves the remaining two virtually unaffected. This is strong evidence that these oscillations are present in the data. Similar near-half period ratios are indicated in Tables 3, 4 and 5. If a wave interpretation is used then the occurrence of these near-half periods suggests that the first harmonic of

Figure 3. Time series analysis: summary of the periodogram analysis of Tables 3, 4 and 5. A diamond indicates that the period was extracted from an intensity time series, a triangle indicates a Doppler velocity time series and a square indicates a line width time series.
4. CONCLUSIONS

It can be seen from Figure 3 that oscillations are most clearly established in He I and O V, the most popular periods those around 300 and 1000 seconds. Periods in these ranges are also distinguished in the hotter Mg IX and Fe XVI lines, but since less of these are found, and are almost exclusively seen only in intensity, the existence of these periods is less well established. It would seem that the 300 second oscillations have been identified in He I 584.33\AA and O V 629.73\AA.

Tables 5 suggests the existence of oscillations having period ratios of almost exactly one half. In very simple terms, this could be interpreted as the detection of the first harmonic of a fundamental period. Once again, this interpretation is stymied by the lack of obvious oscillating structure in the EJECT.V3 data.

Harrison 1987 detected soft X-ray pulsations with a period of 1440s over 6 hours and ascribed this to a travelling Alfvén wave packet or standing Alfvén wave in a large coronal loop. These periods are concomitant with those found in this analysis, with the caveat that these periods are found at much lower temperatures than those commonly associated with soft X-rays. Also, with a total sample time of about 2100s in this analysis, at most only two periods can commonly fit into the data.

Such long periods are not without precedent (see Section 1.). Švestka 1994 analyses data from the Hard X-ray Imaging Spectrometer on the Solar Maximum Mission and GOES-2 in terms of the slow standing magnetoacoustic waves of Roberts et al. 1984. The period of these waves is given by $\tau = 12L/\sqrt{T}$, for a loop of length $L$ (measured in kilometres) and temperature $T$. If, in our analysis, we assume that these waves are present in the LOOPS3 data then we require coronal inhomogeneities on the order of 12Mm (17°), 37Mm (53°), 83Mm (120°) and 130Mm (190°) for $\tau = 1000$s in He I, O V, Mg IX and Fe XVI respectively. Although these are not unreasonable length-scales for the size of region we are looking at, it is very difficult to establish unambiguously the presence of such structures in the EJECT.V3 data.

ACKNOWLEDGEMENTS

All would like to acknowledge the encouragement and friendliness of all those present at the Experimental Operations and Analysis Facilities at the Goddard Space Flight Centre, Greenbelt, Maryland, USA.

REFERENCES

Browning, P.K. Plasma Physics and controlled nuclear fusion, 33, 6, 539
Edwin, P. M., Ann. Geophysicae, 9, 188
Harrison, R.A., A.A.A., 182, 337
Heyvaerts, J., Priest, E.R., A.A.A., 117, 220
Hollweg, J.V., Computer Physics Reports, 12, 205
Ireland, J., Ann. Geophysicae, 14, 485
Koutchmy, S., Žugžda, Y.D., Łoëns V., A.A.A., 120, 185
Laing, G.B., Edwin, P.M., Sol. Phys., 157, 103
Poedts, S., Kerner, W., J. Plasma Phys., 47(1), 139
Qin, Z., Li, C., Fu, Q., Gao, Z., Sol. Phys., 163, 383
Rušin, V., Minarovjech, M., IAU Colloquium 144 “Solar Coronal Structures” eds. Rušin, V. Heinzel, P., Vial, J.-C., 487
Ruderman, M.S., Goossens, M., Sol. Phys., 143, 69
Švestka, Z., Sol. Phys., 152, 505
Tsubaki, T., Sol. Phys., 51, 121
Zirker, J.B., Coronal heating, Sol. Phys., 148, 43