ON THE NATURE OF UMBRAL OSCILLATIONS: THEORY AND OBSERVATION BY CDS/SOHO

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ABSTRACT

We will present solutions for magneto-acoustic-gravity (or MAG) waves. The possible wave modes in the 3-5 min range will be discussed. We will then present observations of sunspots performed in the EUV wavelength range with the Coronal Diagnostic Spectrometer (CDS) on SoHO. We examine the time series for the line intensities and relative velocities and calculate their power spectrum using wavelet transforms. We find oscillations in the chromosphere and transition region above the sunspots in the temperature range log T = 4.6 – 5.4. Most of the spectral power above the umbra is contained in the 5-7 mHz frequency range. When the CDS slit crosses the sunspot plume a clear 3 min oscillation is observed. The observations are interpreted in terms of slow magnetoacoustic waves propagating upwards.

1. INTRODUCTION

In the past thirty years, observations of oscillations with periods around 3 minutes have been widely reported in the atmosphere of sunspots (See reviews by Lites, 1992; Bogdan 2000; Fludra 2001; Brynildsen et al. 2002; Maltby et al. 2001; Tziotziou et al. 2002; O'Shea et al. 2002). It is widely believed that these oscillations are the signatures of waves propagating in the sunspot atmosphere. A study of these oscillations can therefore be used to reveal information about the form of the waves and the structure and nature of the sunspot. The aim of the present study is to contribute towards developing a theory of such wave motions and to compare them with observations performed by the Coronal Diagnostic Spectrometer (CDS) on SoHO. In this short contribution we will present a brief outline of our observational campaign and provide a representative result from one of the datasets, s19332r00. The results from several other CDS datasets have been presented in Banerjee et al. (2002). Finally we will compare the observed frequencies with the theoretically calculated ones.

2. OBSERVATIONS AND DATA REDUCTION

For these observations we have used the Coronal Diagnostic Spectrometer (CDS) on board the Solar Heliospheric Observatory (SoHO). The data discussed here were selected from the observing period 14th April and 19-20 April 2000. The observations were performed for two different active regions. Two different CDS sequences were run, one temporal sequence called CHROM_N6 and another raster sequence called CHROM_N5. Temporal series datasets of ~85 mins duration were obtained for the three lines of He i 584 Å (log T=4.6), O iii 559 Å (log T=5.0) and O v 629 Å (log T=5.4) using exposure times of 25 sec and the 2 x 240 arcsec slit. Details on the CDS reduction procedure, plus the wavelet analysis, may be found in O'Shea et al. (2001). The statistical significance of the observed oscillations was estimated by using a Monte Carlo or randomisation method. The details can be found in O'Shea et al. (2001). The probability levels displayed in this paper are the values of (1 - p) x 100, i.e. the percentage probability that periodic components are present in the data. We choose a value of 95% as the lowest acceptable probability level.

3. RESULTS

In Figure 1, using an MDI intensity-gram image, we show a region around the sunspot together with an overlay of a portion of the slit from the temporal series dataset s19932r00 showing its location at the beginning and end times of the observation. The contours for the umbra and penumbra (in Fig 1) are plotted using the average value for the whole MDI intensity-gram as a guide. The penumbra is defined
as the parts of the MDI intensity where the intensity falls below a factor of 1.5 that of the average, i.e. it is the average/1.5. The outer contour around the sunspot shows the contour of the average value, while the inner contour shows the contour of the average/1.5 values. The umbra is then defined as anything that is contained within this average/1.5 contour.

In Figure 2 we show a representative umbral intensity oscillation and the corresponding power spectra analysis for a O V 629Å line at pixel location 67 (marked as a box in Figure 1) in dataset, s19332. In the wavelet spectrum, the dark contour regions show the locations of the highest powers. Only locations that have a probability greater than 95% are regarded as being real, i.e. not due to noise. Cross-hatched regions, on either side of the wavelet spectrum, indicate the 'cone of influence' (COI), where edge effects become important (see Torrence & Compo, 1998). The dashed horizontal line in the global wavelet spectrum indicates the lower frequency cut-off, in this instance 1.5 mHz. The results from the phase plot shows that the intensity shows significant power in the 6.0–7.0 mHz range, for the periods between the 20–30th and 40–65th minutes of the observing sequence. From the overlay of the MDI intensity-gram and the slit location (Figure 1) one can clearly see that this particular pixel was over the sunspot umbra between the time interval 20–65th minute of the observing sequence (for a total of 45 minutes). The global wavelet spectrum (on the right of Figure 2), which is the average of the wavelet power spectrum over the entire observing period, shows the strongest intensity power at 6.2 mHz (~161 seconds). This is printed out in Figure 2 above the global wavelet plots, together with the probability estimate for the global wavelet power spectrum. In the lowest panel we show the variation of the probability level as estimated from the randomization test. Note that the statistical significance is calculated only for the maximum powers in the wavelet spectrum marked by the dotted white line in the dark patches. From these panels we can clearly see that the oscillations were significant in the period between the 20–30 and 40–65 minutes of the time sequence. To save space, we do not show here detailed wavelet plots for other lines, rather we summarize the results in Table 2. The detailed results for the intensity and velocity oscillations will be presented in Banerjee et al. (2002). We also list the duration of the oscillations, estimated as the periods of time different oscillation packets showed significant oscillations above the 95% significance level. This can be easily measured from a comparison of the wavelet phase plots and the variation of the probability level in the wavelet analysis (e.g. in Fig 2).

4. MAGNETO-AcouSTIC-GrAvITY WAVES

We assume a cartesian geometry where z, the vertical co-ordinate, is measured positive upwards. The gravity acts in the z direction, which is chosen to point away from the Sun. For simplicity, let us assume that the equilibrium atmosphere is isothermal. In order to obtain a physical picture of the solution, we consider a cavity of thickness d, which permits a
Table 1. Summary of the oscillation frequencies (mHz) observed, with the probability level estimates and the durations corresponding to the dataset, s19332r00.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Lines</th>
<th>Pixel</th>
<th>Intensity results</th>
<th>Velocity results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Freq.</td>
<td>Probability</td>
</tr>
<tr>
<td>s19332r00</td>
<td>He I</td>
<td>67</td>
<td>6.2</td>
<td>99-100%</td>
</tr>
<tr>
<td></td>
<td>O III</td>
<td>67-68</td>
<td>5.6</td>
<td>99.2%</td>
</tr>
<tr>
<td></td>
<td>O V</td>
<td>67</td>
<td>6.7</td>
<td>99-100%</td>
</tr>
</tbody>
</table>

Standing wave solution. The asymptotic properties of the waves and the normal modes of a stratified atmosphere with a weak magnetic field was extensively studied by Hasan & Christensen-Dalsgaard (1992) and Banerjee et al. (1995). The existence and the nature of the different elementary wave modes were studied for different sets of boundary conditions. In this paper we will apply zero gradient boundary conditions to both ends of the cavity i.e.,

\[ \frac{d^2 \xi}{dz^2} = \frac{d \xi}{dz} = 0 \text{ at } z = 0 \text{ and } z = d. \]

(1)

Studying the asymptotic properties of the modes in the vicinity of the avoided crossings it was predicted by Banerjee et al. (1995) that the eigenmodes become complex. We consider an isothermal atmosphere extending over several scale heights \((D = d/H)\). There are two families of solutions (for \(K \rightarrow 0\)), which correspond to slow magnetoacoustic modes or \(p\)–like modes with frequencies given by (see Banerjee et al. 1995)

\[ \Omega_{p,n} = \sqrt{\frac{n^2 \pi^2}{D^2} + \frac{1}{4}}, \]

(2)

and fast magnetoacoustic modes or \(m\)–modes with frequencies approximately given by (Scheuer & Thomas 1981)

\[ \Omega_{m,l} = \sqrt{\frac{\epsilon^2}{4} j_{2K,l}^2 + K^2}, \]

(3)

where \(j_{2K,l}\) denotes the \(l\)-th zero of \(J_{2K}\). Equations (2) and (3) are used to classify the modes close to \(K = 0\) in the diagnostic diagram. Note that, the \(p\)–mode frequencies are essentially independent of \(K\). For zero-gradient boundary conditions we find another branch, which we call as magneto gravity Lamb, the MgL–mode given by,

\[ \Omega^4 - (\epsilon^2 + 1)K^2\Omega^2 + \Omega_{BV}^2K^2 = 0. \]

(4)

The behaviour of the different wave modes is reflected in their properties in the \(K - \Omega\) diagram. Figure 3a,b show respectively the variation of the real and imaginary part of the complex frequency with horizontal wave number \(K\) for \(D = 10, \epsilon = 0.5\) (\(B = 1.2 \text{ kG}\)). In contrast to the earlier work of Banerjee et al. (1995) we do not assume the frequencies to be real everywhere. The solutions were obtained by solving the Eqs. (3) and (4) numerically using a complex version of the Newton-Raphson-Kantorovich scheme (Cash & Moore, 1980). The

Figure 3. Diagnostic diagram with \(D = 10\) and \(\epsilon = 0.5\). Panel (a) shows the variation of real part of the frequency and panel (b) shows the variation of imaginary part of the frequency with \(K\).
Table 2. Eigenfrequencies of different modes corresponding to a sunspot with $D = 20, B = 3$ kG and radius $= 5000$ km.

<table>
<thead>
<tr>
<th>Mode type</th>
<th>$\Omega$</th>
<th>$P$(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$MgL$</td>
<td>0.2969</td>
<td>325</td>
</tr>
<tr>
<td>$p_1$</td>
<td>0.5341</td>
<td>184</td>
</tr>
<tr>
<td>$p_2$</td>
<td>0.5905</td>
<td>164</td>
</tr>
<tr>
<td>$p_3$</td>
<td>0.6870</td>
<td>140</td>
</tr>
<tr>
<td>$p_4$</td>
<td>0.8029</td>
<td>120</td>
</tr>
</tbody>
</table>

The salient feature of our observation is that we have detected both intensity and velocity oscillations in chromospheric and transition region lines as observed by CDS. We should point out that the velocity resolution of CDS is, at best, $5$ km s$^{-1}$, and generally it is quite difficult to detect velocity oscillations with any confidence from noisy data. But with the inclusion of a reliable probability test and the use of wavelet techniques we were able to extract velocity information in most of the cases with a 95% confidence level or higher. Most of the earlier work on sunspot oscillations with CDS (Fludra et al. 2001; Brynjaldsen et al. 2002; O'Shea et al. 2002) presented only intensity results. Our results clearly show that the 3 minute intensity and velocity oscillations are a property of the umbra, and not just the sunspot plume. We also detect $3$ mHz oscillations corresponding to the penumbra, which supports the recent observation by Themis, Tziotziou et al. (2002). We have computed the frequencies of the modes from the full MAG equation (see Table 2) and found that for our model atmosphere they correspond to the slow magneto-acoustic modes. The $p_1$ and $p_2$ mode frequencies fall well within the observed range (compare Tables 1 & 2). Our observational results very much complement earlier results and provide additional input for the study of the characteristics of the wave modes.

REFERENCES

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Scheuer, M.D. & Thomas, J.H. 1981, Sol Phys, 71, 21