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Sunspot Umbral Oscillations: Results from SOHO JOP097

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Abstract. We present results of an ongoing analysis of time series data, which were obtained in the context of the Joint Observing Program (JOP) 97 of the year 2000. This JOP included the Coronal Diagnostic Spectrometer (CDS) and the Michelson Doppler Imager (MDI) instrument, both part of SOHO, the TRACE satellite and various ground based observatories. We show evidence for apparently upwardly propagating in a sunspot umbra which we suggest are due to magnetoacoustic waves. These waves manifest themselves as oscillations in lines ranging in temperature from the upper photosphere/chromosphere to the corona. To our knowledge this is the first time umbral oscillations have been conclusively seen in coronal lines. This research is part of the European Solar Magnetometry Network (ESMN) supported by the EU through the TMR programme.

1. Observations

The CDS time series observations presented here were obtained on the 23rd September 2000 in a sunspot umbra associated with AR 9169, using the 4×240 arcsec^2 slit. Time series in the lines of He I (log T=4.3), O III (log T=5.0), O V (log T=5.4), Mg IX (log T=6.0), Mg X (log T=6.1) and Fe XVI (log T=6.4) were obtained with a cadence of 20s. 240×240 arcsec^2 raster images were also obtained in the sunspot region. These were used for coalignment of CDS with TRACE to ensure that oscillations measured from both instruments originated from the same umbral location.

TRACE observed high cadence time series of the same active region with three of its UV filters (centered at 1550 Å, 1600 Å and 1700 Å). The 1550 and 1600 filters contain emission from the low chromosphere, while the 1700 filter contains emission from the upper photosphere.

MDI magnetograms were also obtained in the same active region with the instrument being operated in its high resolution mode. These magnetograms were later used to confirm the location of the sunspot and its umbra in the CDS and TRACE images.

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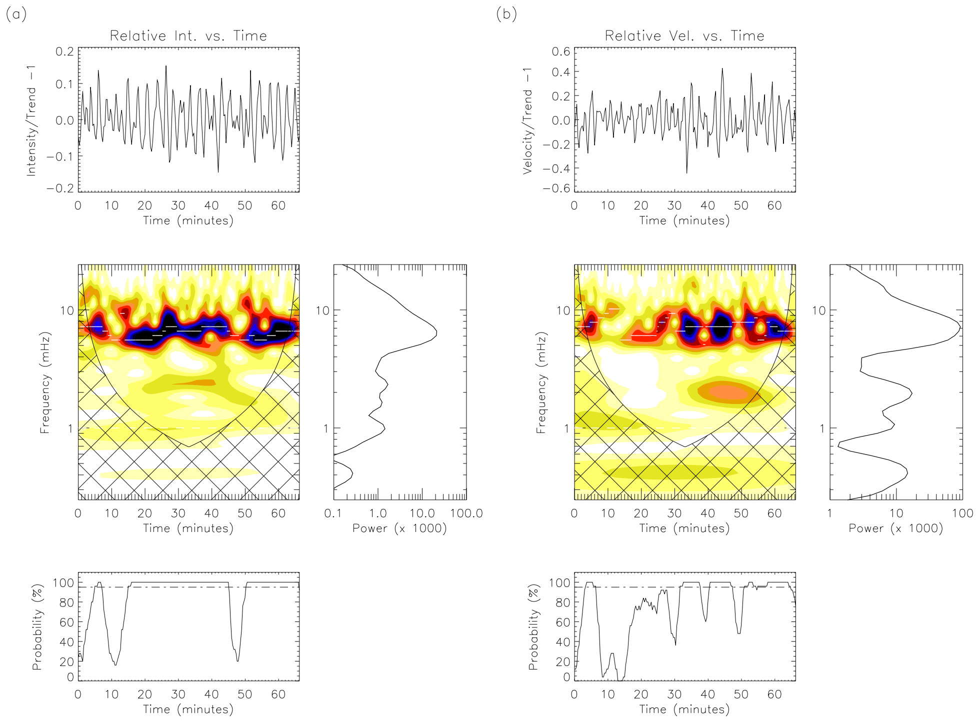

Figure 1. O V line intensity and velocity wavelet power plots

2. Results

For this analysis we shall concentrate on the intensity measurements obtained from a single pixel position in the sunspot umbra. To investigate the frequencies of oscillation in our measurements we use the method of wavelets.

In Fig. 1 we show the results of our wavelet analysis carried out on both intensity and velocity time series of the CDS O V 629 Å line. In these wavelet plots the stronger powers are shown as darker colours (i.e. the colour table is reversed).

In Fig. 1(a) it can be seen from the wavelet phase plot that, between the times of ∼15 and 40 minutes in the intensity time series (shown in the top panel), there are strong oscillations present at ∼6–8 mHz. In the lower panel we show the variation of the probability estimated from the randomisation significance test (see O'Shea et al. 2001 for details). Only probabilities greater than 95% are considered significant, and from the plot it can be seen that the oscillations between ∼15–40 minutes are clearly significant. These probabilities correspond to the local maxima in the wavelet phase plots that are marked with white lines.

In Fig. 1(b) we show similar results for the velocities. However, we will not further discuss the velocity results here.

In Fig. 2 we plot together the oscillations obtained from the three TRACE filters and all the CDS lines. The amplitudes of oscillation of all the lines have been plotted relative to the amplitude of the weakest oscillation, TRACE 1700. That is, the time series for each line have been divided by the factors shown in

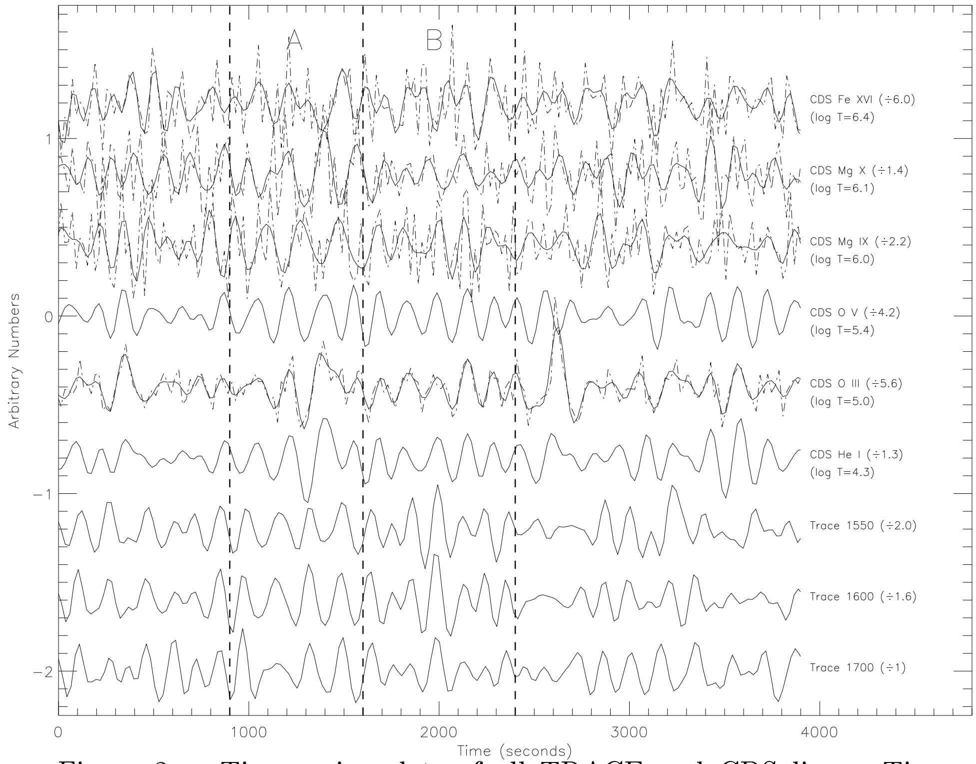

Figure 2. Time series plots of all TRACE and CDS lines. Time periods A and B are marked by the dashed lines.

the brackets, e.g. Fe XVI by 6.0 etc., so that its amplitude matches that of the TRACE 1700 oscillation.

We can see from these factors that the amplitudes of oscillation are at their smallest at the lower temperatures of the upper photosphere/chromosphere, i.e. the temperature of the TRACE 1700 filter. If we ignore the He I line, which has a complicated formation history, we can see that the amplitudes of oscillation increase from the temperature of the TRACE 1700 filter up to the temperature of O III, where they reach a maximum. The amplitudes of oscillation then decrease steadily up to the coronal temperature of Mg X before finally increasing dramatically again at the temperature of Fe XVI. It is possible that the reason for the decrease in oscillation amplitudes, from the temperature of O III to Mg X, is due to some form of heating by which the oscillation energy is dissipated. The subsequent increase in the oscillation amplitude again at the temperature of Fe XVI may be due to its much higher temperature and hence height in the atmosphere. At these greater temperatures(heights) the densities are lower and hence we might expect the oscillation amplitudes to increase again.

Two periods A and B between the times of 900 and 2400 seconds (i.e. 15–40 minutes) have been marked in Fig. 2. This is the time interval that was shown in the wavelet plot of Fig. 1 to have strong oscillations. During the periods A and B we find that the higher temperature CDS lines are delayed in time relative to the TRACE filter emission. By using a method of cross-spectral analysis we

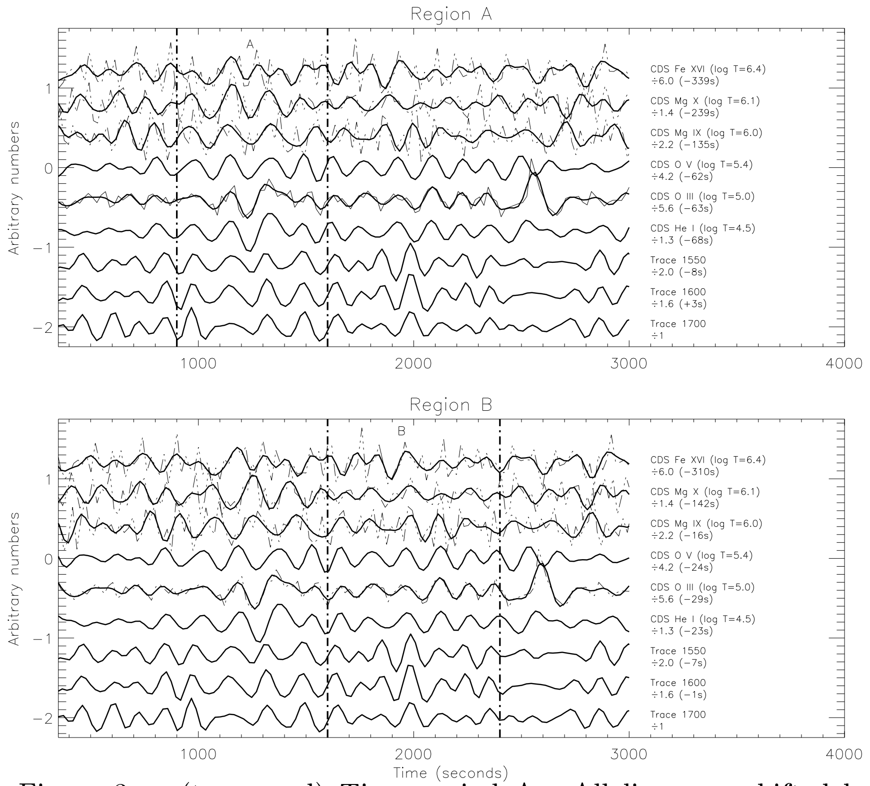

Figure 3. (top panel) Time period A - All lines are shifted back, relative to the TRACE 1700 filter, by amounts in seconds shown in the brackets (bottom panel) Time period B - All lines are similarly shifted back relative to TRACE 1700.

determined the time delays between each line/filter and the lowest temperature TRACE 1700 filter.

In Fig. 3 we again plot the oscillations from the periods A and B. However, now all the lines in each period interval have been shifted back in time relative to the TRACE 1700 filter, by the amounts indicated in the brackets. For example, for region A in Fig. 3 O V was shifted back by 62 seconds as TRACE 1700 leads O V by this amount in time. As can be seen there is a reasonable correspondence now between all the lines in period interval A and also in interval B. Typically the squared coherency between the different lines, as measured, from the cross-spectral analysis, is better than a value of 0.7.

Note that in period A, between the temperatures of the TRACE filters and the coronal lines of Mg X and Fe XVI, the time delays increase, from a value of 8s at TRACE 1550 to a value of 339s at Fe XVI. A simple explanation of this is that in this region the disturbances causing the oscillations are propagating upwards. However we note that between the temperatures of He I and O V there is a slight decrease in time delay with temperature, i.e. from 68s at He I to 62 seconds at O V. However, it is not clear if this decrease is real as it falls within the errors calculated for these time delays (typically $\sim$5s).

Note that in period B, between the temperatures of TRACE 1700 and O III, the time delays also increase, again suggesting upwardly propagating waves.

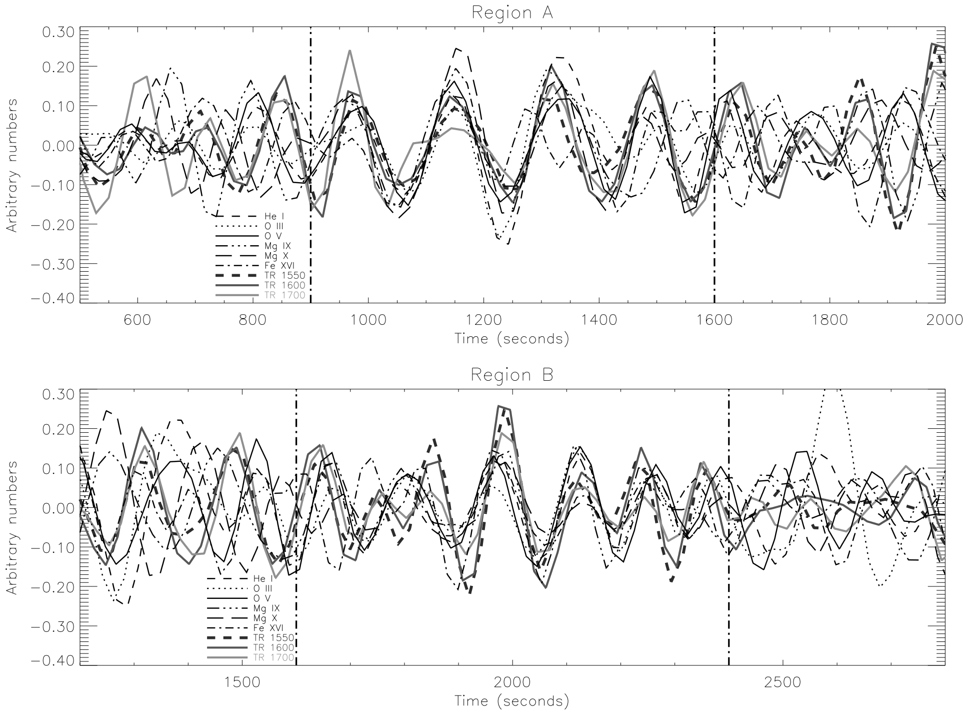

Figure 4. (top panel) Overplot of all oscillations in time period A (bottom panel) Overplot of all oscillations in time period B.

However, for temperatures between He I and Mg IX, there is no increase in the time delays between the lines, even though He I and Mg IX are formed at very different heights. In fact, from the temperature of O III to the temperature of Mg IX the time delays decrease from 29 to 16s. If this decrease is real then this would suggest that in the transition region there is also evidence of downwardly propagating waves. Between Mg IX and Fe XVI the time delays increase again, suggesting a renewed upward wave propagation at these higher coronal temperatures.

In Fig. 4 we again plot the two periods, A and B but this time we overplot all the lines in the one plot. Within the regions marked by the vertical dot-dashed lines the coherence of the oscillations is obvious for both regions, whereas outside these dot-dashed lines there is little coherence and all the oscillations appear to interfere with each other. The fact that there are oscillations present in all lines (e.g. see Fig. 3) but that these are only coherent in the time periods A and B suggests that over the full time of the observations the structure of the sunspot changes in some way. For example, if at one time our field-of-view was directly along the magnetic flux elements in the sunspot then we might expect to see coherent oscillations propagating all the way from low to high temperatures along the magnetic fields, while if at other times our field-of-view was not directly along the magnetic flux elements but at some angle to them, then we might still expect to see oscillations at different temperatures but not for them to be coherent due to the fact they might be originating in different structures and locations.

3. Conclusions

Below we summarise the main results found in this work:

We have found umbral oscillations in all lines ranging in temperature from the upper photosphere/low chromosphere to the corona. To our knowledge this is the first time that umbral oscillations have been found in coronal spectral lines.

We find that the amplitude of the oscillations are smallest at the lower temperatures of the photosphere and chromosphere and become larger at the temperatures of O III and O V (factor of ~ 3 increase), where sunspot plumes are normally visible. From the temperature of O III to the temperature of Mg X the amplitudes decrease again to reach a minimum at the coronal temperature of Mg X. The amplitudes increase dramatically again at the temperature of Fe XVI. The decrease in amplitudes between the temperatures of O III and Mg X may be due to a dissipation of energy, possibly in the form of heating, at these temperatures.

From an analysis of time series at two time periods, A and B, in a sunspot umbral region, we find that there is some evidence for upwardly propagating disturbances. We tentatively suggest that these apparently upwardly propagating disturbances seen in time periods A and B, between the temperatures of TRACE 1700 (upper photosphere) and Fe XVI (corona), are due to non-linear magnetoacoustic waves. We base this assessment on the increasing time delays seen between oscillations from the photosphere/chromosphere (TRACE data) and the corona (CDS data, Mg IX, Mg X, Fe XVI).

References

O'Shea, E., Banerjee, B., Doyle, G., Fleck, B. & Murtagh, F., 2001, A&A, 368, 1095

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