THE EFFECT OF STRONG MAGNETIC FIELDS ON ACOUSTIC POWER IN THEIR SURROUNDINGS AT THE SURFACE OF THE SUN

C. J. Nicholas[1], **M. J. Thompson**[1], **and S. P. Rajaguru**[2]

[1]*Space and Atmospheric Physics Group, Imperial College, London, SW7 2AZ, UK*
[2]*Indian Institute of Astrophysics, Koramangala, Bangalore 560 034, India.*

ABSTRACT

A pixel-by-pixel analysis has been made of a time series of MDI Dopplergrams containing a sunspot. Power spectra from each pixel are binned by magnetic field strength and compared to derive the effect of the magnetic field on the oscillations. The initial results show the modulation of the acoustic power by the magnetic field in the sunspot and its vicinity. At intermediate field strength, this includes the suppression of power at low frequencies (2–5 mHz), corresponding to the main frequency range of p modes, and the increase in power at high frequencies (5–6.5 mHz). At high field strengths the power is suppressed at all frequencies. An unexpected variation of power in ostensibly 'quiet-sun' (low field strength) regions is particularly notable. We also present a comparison of the pixel-by-pixel results with helioseismic ring-diagram analysis work. The results generated in this study are used to make predictions of the degree of suppression in the ring results.

Key words: Sun; helioseismology; sunspots.

1. INTRODUCTION

It has been known for many years that the strong magnetic fields observed in active regions modulate the power of solar oscillations (Braun, Duvall & Labonte, 1987, 1988; Braun & Duvall, 1990; Braun, 1995; Hollweg, 1988; Jain, Hindman and Zweibel, 1996; Hindman, Jain & Zweibel, 1997). More recently, the power modulation has been quantified using ring-diagram analysis (Rajaguru, Basu & Antia, 2001, 2003). The power is altered in different ways at different frequencies. At the frequencies in which p-mode power is strongest (2–5 mHz), the power is suppressed at all magnetic field strengths, with the suppression being a strong function of the field strength. At higher frequencies (5–6.5 mHz), the results also depend on the variable that is used to take the measurements (Hindman & Brown, 1998; Thomas & Stanchfield, 2000). Using Doppler velocity measurements of the surface of the Sun, the acoustic power is seen to be increased at low to intermediate field strengths. However, at the highest field strengths, in the umbra of the sunspot, the power is seen to be decreased almost to the same level as at lower frequencies. Using continuum intensity measurements, the power is seen to be suppressed uniformly at all frequencies.

One effect of altering the acoustic power in patches on the surface of the Sun is to mask the normal power structure. When the Sun's oscillations are projected onto spherical harmonics there is leakage of power between modes of different wavenumber, caused in part by the fact that we cannot see the whole surface of the Sun at once (e.g. Howe and Thompson, 1998). Local modulation of power across the disk further alters leakage between modes. Studying this modulation may give us an insight into ways that component of the leakage can be modelled. For example, if the power modulation were a direct function of magnetic field, then the mode leakage might be calculated from magnetograms taken contemporaneously with the Doppler observations.

2. DATA AND ANALYSIS

The data used here are high-resolution (0.6″/pixel) SOHO-MDI Dopplergrams (Scherrer et al., 1995). We have nine hours of data at one minute cadence. The region observed is 700 pixels square, although we have cut several smaller regions from this for closer inspection (see Fig. 1). We also have the magnetograms for the same period. The effects of rotation and supergranulation have been removed from data. In order to analyse the data, a Fourier transform is taken in the time dimension. This is used to produce a power spectrum at each pixel within the region observed (Norton et al., 1999). We may average the spectra in two ways in order to remove the realisation noise. Firstly, the pixels can be binned according to their rms field strength, hence, an average power spectra is made for each field-strength bin. The bins are defined as 0–15 G, 15–25 G, 25–50 G, 50–100 G, 100–250 G, 250–1000 G and $>$1000 G. The lowest bin is

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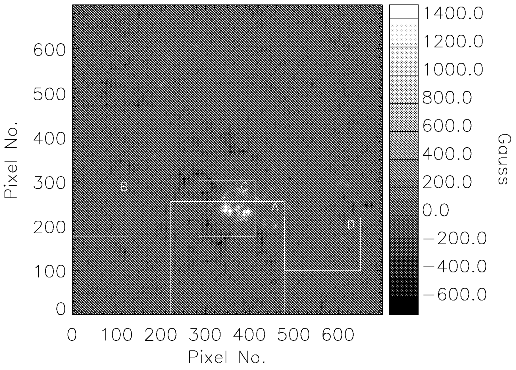

Figure 1. A magnetogram of the area under study. Four small regions have been cut out of the main area for closer inspection. Region A is the main region of study.

called the quiet-sun bin. Secondly, the power can be averaged over a range of frequencies at each pixel. This produces two-dimensional power maps of the region observed.

3. RESULTS AND DISCUSSION

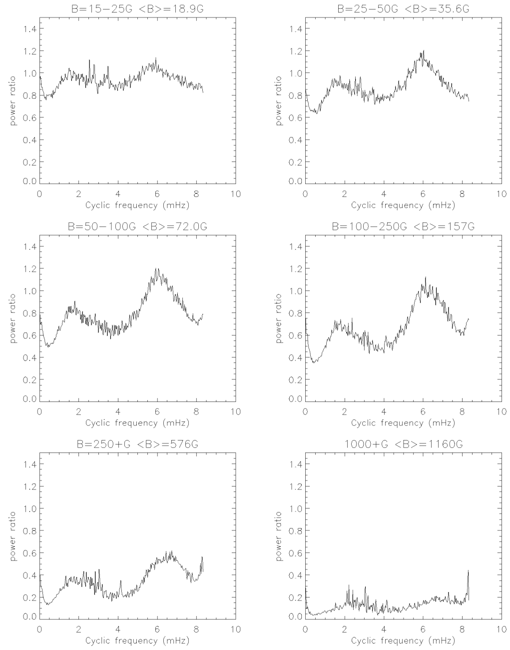

Figure 2. Ratios of acoustic power in magnetically active sun compared with power in quiet-sun. The ratios are made using bins from Region A.

Our first results follow those of Hindman and Brown (1998). A series of plots have been made that show the ratio of power in the higher field-strength bins to that in the quiet-sun bin in Region A (Fig. 2). In the p-mode frequency range, the power is found to be reduced as a function of field strength. In the high frequency range the power is slightly increased at low to intermediate field strengths, then decreased at the highest field strengths. These results agree qualitatively with results from previous studies. The power reduction seen is more acute than that in most previous studies, possibly due to the fact that we are observing all modes together and narrowing the region of observation to only the magnetic region itself.

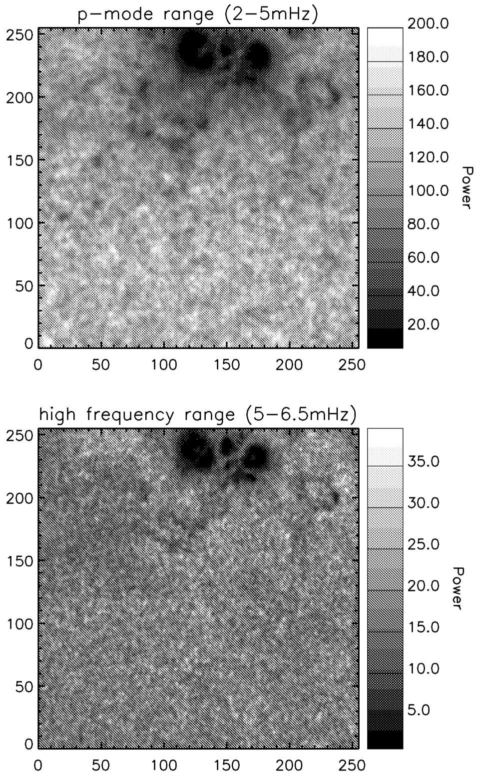

Figure 3. Power maps of Region A for p-mode frequencies (2–5 mHz) and high frequencies (5–6.5 mHz). The units of power are arbitrary. Most important is the contrast between regions of low power within the sunspot and regions of high power far from the sunspot.

The power maps (Fig. 3) mentioned previously (Hindman & Brown, 1998; Thomas & Stanchfield, 2000), show a major reduction of power in the umbra of the sunspot. In the low frequency power map, the power is reduced to some degree in all regions where there is magnetic field and possibly in areas outside the magnetic region. The high frequency power map shows a halo of increased acoustic power around the umbra, which may also extend beyond the edge of the magnetic region. This possible neighbourhood effect of the magnetic field is analysed in some detail.

A mask is created to compare acoustic power within regions with strong magnetic fields, those neighbouring such magnetic field, and those far from any significant magnetic region (Jain & Haber, 2002). In order to make this mask, firstly, we make a map of the rms magnetic field in which all pixels with field strength greater than

15 G are set to a value of one and those below 15 G are set to zero. This map is smoothed such that only regions of field that are reasonably continuous are shown. All the extraneous regions of field on the edge of the active region are smoothed off. The edge of this mask is used as a reference in the construction of 20-pixel-width concentric haloes around the magnetic region. An average power spectrum is calculated within each halo using only pixels that contain quiet rms field (<15 G). A ratio is taken between all the average power spectra created, and the power spectrum farthest from the edge of the magnetic region. The number of pixels within each halo is fairly small, so it is normally better to average over a specific frequency range for the purpose of further reducing the amount of noise. The results of this analysis are shown in Fig. 4. In the low frequency range the power is reduced out to a distance of 80 pixels (30–35 Mm) from the edge of the magnetic region. An explanation for this power reduction is that the pixels close to the sunspot are in the spot's acoustic shadow. If we consider a point on the surface of the Sun, there are acoustic waves coming to this point from all directions. The sunspot suppresses power in low-frequency modes almost completely; therefore, a point on the Sun reasonably close to the spot will see no low-frequency waves coming from the direction of the sunspot. The further away from the sunspot the point is, the smaller the angular extent of the sunspot from the point and the smaller the amount of modulation seen. In addition to this, at greater distances from the spot there is more room for modes to be excited between the spot and the observation point. In the high-frequency range the power shows some sign of being increased near the edge of the magnetic region. However, the error bars are large and it is difficult to say if this is a real effect. If this effect is real, the reason is unknown, but it is evidently not caused by shadowing.

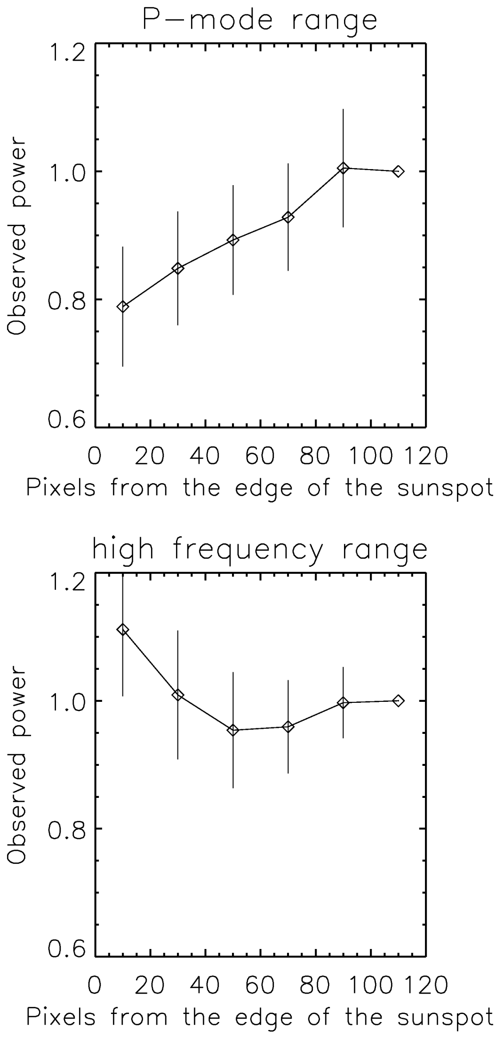

Figure 4. Quiet-sun power as a function of distance from the edge of the magnetic region. The power is shown as a ratio against the power in the range that is farthest from the sunspot.

We have also compared our results with ring-diagram analysis results to help judge the validity of our method. The ring-diagram results come from Rajaguru et al. (2001). In Fig. 5 the ratio of power is shown for each radial order as inferred by ring-diagram analysis (the symbols in the figure). The pair of lines in this figure represent predictions generated from the above pixel-by-pixel results. To make these, firstly, the fractional area occupied by each field-strength bin is calculated using a magnetogram of the ring-diagram analysis region. Ratios similar to those in Fig. 2, but taken between all the bins in Region C and the quiet-sun bin in Region B, are multiplied by their corresponding fractions and added together. We do this in two ways: the dashed line shows a prediction in which the ratio of the 0–15 G bin (not shown in Fig. 2) is assumed to be unity, whereas for the

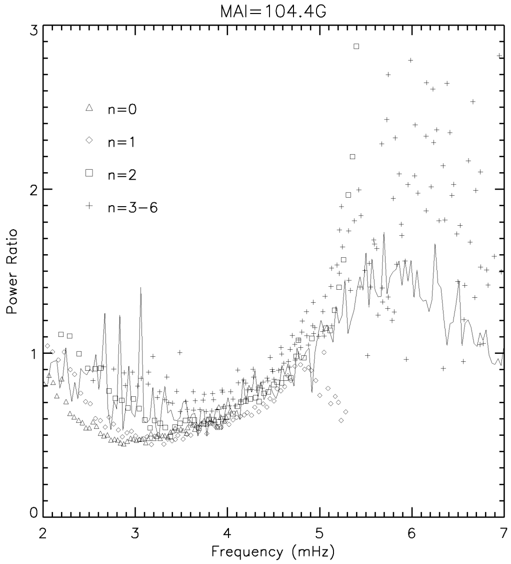

Figure 5. Power modulation measured from ring-diagram analysis (symbols): Rajaguru et al. (2001). The solid and dashed lines are predictions from our pixel-by-pixel analysis, as explained in the text.

solid line the quiet-sun ratio is actually calculated between the quiet-sun bins in Regions C and B. The solid line is by far the better prediction: it matches the ring-diagram results almost perfectly if we collapse the results from each radial order onto a single curve. The better fit by the solid line than the dashed one confirms that the active region has had a strong effect on the quiet-sun in its vicinity. The good agreement between the ring-analysis results and our solid-line "prediction" based on the pixel-by-pixel analysis, which was conducted on completely different magnetically active regions, supports the idea that power suppression in different parts of the Sun and at different epochs can be predicted to reasonable accuracy on the basis of local magnetic field strengths.

4. CONCLUSION

Acoustic power is severely modulated by the strong magnetic field present in a sunspot. The results presented here show qualitative agreement with those presented before; however, they show a greater reduction of power at the highest magnetic field strengths. The power maps show evidence of modulation of the acoustic power in ostensibly non-magnetic areas in the vicinity of an active region. This effect has been quantified as a function of distance from the edge of the magnetic region. It is proposed that the power modulation in this region is caused by shadowing from the sunspot itself, and a rough estimate based on angle subtended by the spot as function of distance from it supports our acoustic-shadowing hypothesis. There is some additional effect from diffraction and from sources in between the magnetic region and the observation point.

The comparison of ring-diagram analysis with this method has shown that it is possible to compare the power calculated using different techniques and data sets. It has also confirmed the effect of the sunspot on its quiet-sun neighbourhood.

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