Wave absorption and moat flow in AR9787

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Abstract. We present the results of a study of the wave absorption and the moat flow around the sunspot in AR9787 (the "HELAS sunspot", so-called because it has been the object of in-depth study at a HELAS workshop) using Fourier-Hankel decomposition of the oscillatory wave field. We carry out inversions both for the flow speed and for the sound speed perturbation as a function of depth. The results are compared with results from time-distance helioseismology.

1. Introduction

Recently, the comparison of measurements of wave speed and flows in the sunspot in NOAA Active Region 9787 was the object of an in-depth study at a HELAS (European Helio- and Asteroseismology Network) workshop in Freiburg. The results were that the oscillation amplitudes are reduced in the sunspot at all frequencies [1]. In the surrounding plage region there seems to be enhanced acoustic power above the acoustic cutoff frequency of the quiet-Sun atmosphere [2], which could be caused by the conversion of \( p \) modes into magneto-acoustic waves. Detailed studies of the absorption of solar oscillations in this sunspot show that a significant fraction of the \( p \) and \( f \) modes passing through the sunspot are absorbed. One particularly puzzling result was a possible disagreement of standard ring-diagram analysis [3] and time-distance helioseismology [4] based on phase-speed filters when comparing the resulting relative wave speed perturbation caused by the active region [5].

We continue studying this sunspot in AR 9787 by probing the moat flow with Fourier-Hankel decomposition, i.e. we measure average frequencies of acoustic waves traveling inward and outward in an annular region around the sunspot. We implement this technique with a SOLA (Subtractive Optimally Localized Averages) inversion method [6], in order to determine the flow properties from the Doppler shift affecting the wave frequencies.

2. Data

The data and the data processing is described in [5]. The data consist of MDI full disk Dopplergrams covering the time span of 2002 January 20 – 28. The remapping of the images was done with a Postel projection with a map scale of 0.12°. The motion of the sunspot (Carrington longitude \( \varphi \sim 133° \) and latitude \( \lambda = -8.3° \)) was tracked and the re-mapping employed a cubic convolution interpolation. Missing data were linearly interpolated. For each day a temporal average was subtracted from each Dopplergram. The resulting data cube of Doppler velocity measurements consists of 512 x 512 x 1440 data points per day. These final data sets are available on the European Helio- and Asteroseismology Network (HELAS) web site at http://www.helas-eu.org/ → NA4.
3. Fourier-Hankel Decomposition

The Fourier-Hankel decomposition was originally developed by [7] for the seismic probing of sunspots. The decomposition of the wave signal into incoming and outgoing waves is based on Hankel functions

\[ \Phi(R, \theta, \phi, t) = \sum_{L,m,\nu} e^{i(m\phi - \nu t)} A_{L,m,\nu} H_m(L\theta) + B_{L,m,\nu} H_m^*(L\theta), \]  

where \( R \) is the solar radius, \( \theta \) and \( \phi \) are the spherical polar coordinates with the sunspot centered at \( \theta = 0 \), \( L = \sqrt{l(l+1)} \) is the spatial wavenumber, \( m \) the azimuthal order, \( \nu \) the temporal frequency, and \( t \) is time. The complex amplitudes of the incoming and outgoing waves are given by \( A_{L,m,\nu} \) and \( B_{L,m,\nu} \), respectively. Hankel functions can be approximated in the far field by

\[ H_m(L\theta) \approx \sqrt{\frac{2}{\pi L\theta}} e^{i(L\theta - m\pi/2 - \pi/4)}. \]  

The further data reduction is carried out according to [8] and [9] on an annular region around the sunspot. The radii of the inner and outer boundary of the annulus are 30 and 137 Mm. The annulus properties were selected according to [9] in such a way that it is possible to measure a Doppler shift within an area restricted to the spatial extent of the moat flow only but also allows isolating the individual \( f \) and \( p \) mode ridges in the resulting diagnostic diagrams.

For our further studies \( p \) and \( f \) modes in the range of harmonic degree \( l = 70, \ldots, 1500 \) and azimuthal orders \( m = -10, \ldots, 10 \) are selected.

For studying the mode absorption by the sunspot we define an absorption coefficient according to

\[ \alpha = \frac{\int W(P_{in} - P_{out}) \, dv \, dl}{\int W P_{in} \, dv \, dl}, \]  

where the window function \( W \) selects either a ridge with radial order \( n \) or a certain wavenumber, and the power of the ingoing and outgoing waves with frequency \( \nu \) and degree \( l \) is given by \( P_{in} \) and \( P_{out} \).

4. Results

One of the results is a ridge and wavenumber-dependent absorption of acoustic waves due to the sunspot. Figure 1 gives an overview on the resulting absorption coefficients. From ridge to ridge the absorption varies with the \( f \) mode being absorbed most. As a function of wavenumber we find that higher wavenumbers are absorbed strongest. This slope may be due to a change in the vertical structure of the sunspot. Investigating several other sunspots, [1] found a similar functional dependence of the wave absorption on the wavenumber.

Another result is an obvious shift of the frequencies due to the moat flow around the sunspot. Figure 2 displays two examples of \( p \)-mode power spectra, which were also shown by [9] for another sunspot. The power spectra of the outward propagating modes displayed were corrected for the effect of absorption. We note that the power spectra displayed are the average over the single spectra for modes with different azimuthal order \( m \).

Compared to the inward propagating modes, the modes traveling away from the spot are shifted by approximately 10 \( \mu \)Hz to higher frequencies due to the advection of the moat flow. This frequency shift can be described by [9; 10]

\[ \Delta \nu_{nl} = \frac{l}{\pi R_\odot} \int \bar{U}(r) K_{nl}(r) \, dr, \]  

where the frequency shift \( \Delta \nu_{nl} \) is the difference between the frequencies of the outward and inward propagating modes with radial order \( n \) and harmonic degree \( l \). The mean moat flow
Figure 1. Absorption coefficient $\alpha$ as a function of radial order $n$ (left) and as a function of wavenumber (right).

Figure 2. Power spectra in arbitrary units of inward (solid line) and outward (dashed line) propagating $p$ modes. The two modes shown are $l = 288, n = 3$ (left) and $l = 452, n = 2$ (right) (compare with [9]).

over the annulus $\vec{U}(r)$ is directed outward and depends on the radius $r$ inside the Sun. The sensitivity kernel $K_{nl}(r)$ is the energy density of a given mode as a function of radius.

We measure the frequency shift by fitting Lorentzian profiles to the individual power spectra and calculating the frequency differences between outward and inward propagating waves. From these frequency shifts we can estimate the moat flow around AR9787 by applying a standard 1D SOLA inversion [6]. The result is shown in Figure 3. The moat flow seems to have an almost constant amplitude of approximately 50 m/s in the first 4 Mm below the surface. Going deeper, the estimated flow amplitude shows indications for a higher amplitude at depths greater than 5 Mm. In these depths the amplitude is close to 60 m/s even though the error bars also increase. Time-distance measurements of the same sunspot as they are described in [5] result in a flow amplitude of approximately 30 m/s near the surface and approximately 50 m/s at a depth of 5 Mm.

In a final step, we apply an asymptotic inversion for the sound speed perturbations to the mean frequencies of the ingoing and outgoing waves. Based on our measurements, the sound speed perturbations in the moat around AR9787 are compatible with zero.
Figure 3. Flow profile of the moat flow around the sunspot in AR 9787 as determined by inversion. Vertical error bars are derived from the error magnification of the frequency shift via the SOLA inversion; horizontal bars correspond to the width of the averaging kernels.

5. Conclusions
We used the Fourier-Hankel decomposition technique to study the moat flow around AR9787 (“HELAS sunspot”, [5]). The basis for our analysis are power spectra obtained for waves traveling toward and away from the sunspot. We conclude that in the moat around AR9787 waves are absorbed as less acoustic power is emitted in this area as received. Moreover the radially directed moat flow shifts the frequencies of the waves. Analyzing measured frequency shifts and by carrying out for the first time a SOLA inversion for the flow amplitude as a function of depth we find that the moat flow is in the order of 50 m/s down to 4 Mm depth. The flow shows indications of an increase between 4 – 8 Mm depth. These flow measurements are compatible with measurements from time-distance helioseismology. It seems that the sound speed is not significantly perturbed in the moat.

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References
[1] Braun D C, Duvall Jr T L and Labonte B J 1988 Astrophys. J. 335 1015–1025
[2] Braun D C, Lindsey C, Fan Y and Jefferies S M 1992 Astrophys. J. 392 739–745
[3] Hill F 1988 Astrophys. J. 333 996–1013
[4] Duvall T L, D'Silva S, Jefferies S M, Harvey J W and Schou J 1996 Nature 379 235–237
[5] Gizon L, Schunker H, Baldner C S, Basu S, Birch A C, Bogart R S, Braun D C, Cameron R, Duvall T L, Hanssage S M, Jackiewicz J, Roth M, Stahn T, Thompson M J and Zharkov S 2009 Space Sci. Rev. 144 249–273 (Preprint 1002.2369)
[6] Pijpers F P and Thompson M J 1994 Astron. Astrophys. 281 231–240
[7] Braun D C, Duvall Jr T L and Labonte B J 1987 Astrophys. J. Lett. 319 L27–L31
[8] Braun D C 1995 Astrophys. J. 451 859–+
[9] Braun D C, Fan Y, Lindsey C and Jefferies S M 1996 ArXiv Astrophysics e-prints (Preprint arXiv:astro-ph/9603078)
[10] Gough D O and Toomre J 1983 Solar Phys. 82 401–410