Perturbations in the wave parameters near active regions

M. C. Rabello-Soares¹, R. S. Bogart², P. H. Scherrer²

¹Physics Department, Universidade Federal de Minas Gerais, Belo Horizonte, MG 30380, Brazil,
²W. W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305, USA
E-mail: cristina@fisica.ufmg.br

Abstract. The wave characteristics derived from ring-diagram analysis of HMI Doppler data in magnetically quiet regions near active regions are compared with those with no nearby active regions using 5° patches during 2.5 years of cycle 24 ascending phase. We search for perturbations that may be associated with propagation of the acoustic oscillations through the nearby sunspot. We observe significant variations in the mode parameters and flows. We analyse their dependence on the direction of the wave propagation. The observed mode dependence of the variations in mode amplitude, line width and frequency does not have the same functional form as that observed for the differences between quiet and active regions.

1. Introduction
The characteristics of solar acoustic waves are modified as they propagate through a sunspot. Braun, Duvall & LaBonte ([1]) were the first to observe that sunspots absorb up to half of the incident p-mode power. Since then the variation of mode characteristics and flows in active regions has been extensively studied using different local helioseismology techniques (see [2] and references therein). Although much progress has been done, the physical origin of the changes in the mode parameters is not well understood. Here, instead of studying the wave characteristics in active regions, we look at quiet regions close to an active region using ring-diagram analysis of HMI/SDO data. We search for perturbations in the wave characteristics as the solar acoustic oscillations are affected as they propagate inside the nearby sunspot. Understanding the variations due to the nearby active region will help us understand the interaction of the acoustic waves with the active region; they may also shed some light on the determination of wave parameters made in the presence of strong magnetic field. Next, we describe the data and method used (section 2), present our results (section 3) and summarize our conclusions (section 4).

2. Data and Method
We use the wave characteristics obtained by the HMI ring-analysis pipeline ([3]) during Carrington rotations 2097 to 2130 (from May 2010 to November 2012). The data consist of full-disk Dopplergrams obtained at a 45-second cadence by HMI/SDO. Small patches of the solar disk with size 5° × 5° were tracked at the Carrington rotation rate for 9.6 hours.
The wave parameters were estimated using two different methods for parametric fitting of the ridges in the 3-D power spectrum. Module ‘rdfitc’ fits a 13-parameter model including an asymmetry term ([4]). While module ‘rdfitf’, fits only 6 parameters ([5]). Both methods use a Lorentzian profile. In the case of rdfitc, there is the addition of an asymmetry term (S):

\[ P(k_x, k_y, \nu) = \frac{A}{R^2 + 1} \left[ S^2 + (1 + R^2S^2) \right] + B(k) \] (1)

where \( R_\nu = (\nu - \nu_0 + k_xU_x + k_yU_y)/\gamma \). The value at the maximum is A, \( \gamma \) is the half width at half maximum, \( U_x \) and \( U_y \) are zonal and meridional flows respectively and \( B(k) \) is the background term. In rdfitf, \( S=0 \), \( \gamma = \exp(\nu) \) and \( A = \exp(a)/\exp(\nu) \); the 6 fitted parameters are: \( a, w, \nu_0, U_x, U_y \) and one background term. In rdfitc, \( A = \exp[A_0 + A_1(k-k_0) + A_2(k^2/k)^2 + A_3(k^3/k^2)] \), \( \gamma = w_0 + w_1(k-k_0) \) and the mean frequency \( \nu_0 = ck^0 \). The 13 fitted parameters are: \( A_0, A_1, A_2, A_3, c, p, U_x, U_y, w_0, w_1, S \) and two background terms. In this work, we re-write \( A \) in the form \( A = \exp[a_0 + a_2 \cos(2\theta) + a_3 \sin(2\theta) + A_1(k-k_0)] \) where \( a_0 = A_0 + A_2/2, a_2 = A_2/2 \) and \( a_3 = A_3/2 \).

The level of magnetic activity in each patch is given by the Magnetic Activity Index (MAI), which is the unsigned average of all HMI magnetogram pixels with a flux greater than 50G, \( |B_z| \leq 50G \) taken every 48 minutes (i.e. each 64th HMI magnetogram) and using the same temporal and spatial apodizations as the ones used in ring-diagram power spectra calculation. The MAI for each patch has the contribution from about 12 images. For a detailed description, using MDI magnetograms, see [6]. We select all quiet patches (MAI < 5G) in our data that have at least one large magnetic active patch (MAI > 100G) in its vicinity and it is not more than \( 8^\circ \) away. We will call these quiet tiles with a nearby active region “target” tiles from now on and the angle of the nearby active region (AR) in relation to quiet regions has been well studied. For comparison with the results obtained for MAI = 100G, and call them from now on, ‘AR’ variation.

When mapping patches of the solar disc from their surface spherical coordinates to the plane, those located farther away from disk center will have a larger geometric foreshortening and a lower effective spatial resolution, affecting the power spectrum that will be fitted. To avoid these geometric effects, we will analyse the wave characteristics differences between the target tile and a set of quiet tiles (ranging from 2 to 6 tiles) with no nearby active region, but at the same latitude and Stonyhurst longitude as the target patch (from now on, ‘comparison’ tiles). For a given target patch, the fitted ring parameters obtained for its comparison patches are averaged for each mode and subtracted from the fitted parameters obtained for the target patch. For control purposes, we arbitrarily pick up one of the comparisons for each target patch and used it as the “target”. We repeat the calculation above, by calculating the mean (excluding the randomly chosen patch) and subtracted from the chosen one (from now on, ‘control’ set).

Each relative parameter \( p \) difference, \( (p[\text{target}] - p[\text{comparison}]) / p[\text{comparison}] \), is averaged over intervals of \( 10^\circ \) in \( \theta_{AR} \) for each mode, the results are discussed in section 3.2. Outliers larger than \( 3\sigma \) are removed from the average. We next average over all \( \theta_{AR} \) for each mode, the results are in section 3.1.

As mentioned in the introduction, the variation of the mode parameters in active regions in relation to quiet regions has been well studied. For comparison with the results obtained for the target tiles (from now on, ‘nearby’ variation), we also calculate the difference in the fitted parameters between patches with MAI > 100G and a set of quiet tiles (2 to 6 tiles) at the same latitude and Stonyhurst longitude. Each parameter difference for each mode is fitted as a function of its MAI (see Fig. 1 in [7] where a similar fit was done for \( 15^\circ \) tiles). We use the results of our fitting for MAI = 100G, and call them from now on, ‘AR’ variation.
3. Observed perturbations in the wave parameters

3.1. Mode dependence

**Amplitude.** Fig. 1 (left panel) shows the ‘nearby’ variation of mean power in the ring given by the constant term in $A$ defined in equation (1). There is a good agreement between rdfitc and rdfitf results. The relative amplitude variation is mainly a function of frequency. Comparing with the ‘AR’ variation (Fig. 1 right panel), the maximum of attenuation around 3 mHz is displaced towards lower frequencies (specially for the $f$ mode) and it is, as expected, much smaller (almost an order of magnitude smaller). At frequencies higher than $\approx 5.2$ mHz, the ‘AR’ variation is positive. This is known as the “acoustic halo” effect. Enhanced power surrounding active regions has been observed at frequencies above the photospheric acoustic cut-off by several authors (see [8] and references therein) and it is often thought to be the result of acoustic to magnetoacoustic mode conversion ([9]). The ‘nearby’ variation, on the other hand, becomes positive at a much lower frequency, around 4.1 mHz.

**Linewidth.** There is also a good agreement between rdfitc and rdfitf in the ‘nearby’ variation of mean half-width of the ring given by the constant term in $\gamma$ (equation 1). Like the amplitude, the relative ‘nearby’ linewidth variation is approximately a function of frequency alone. As the amplitude, the ‘nearby’ width variation changes sign around 4 mHz, from 2% around 3 mHz to -7% around the cut-off frequency.

**Frequency.** Fig. 2 (left panel) shows the ‘nearby’ variation of mode’s central frequency given by $\nu_0$ in equation (1). Although they are not completely dissimilar, there is a clear disagreement between rdfitc and rdfitf. In the presence of strong magnetic fields, it is well observed an increase of the mode frequency which is larger at larger frequencies until near the cut-off frequency where it sharply decreases (Fig. 2 right panel). The ‘AR’ frequency variation is an order of magnitude larger than the ‘nearby’ variation.

3.2. Anisotropy

Only the variation in the flow (given by $U_x$ and $U_y$) and the non-constant terms of the amplitude in rdfitc (given by $a_2$ and $a_3$) are anisotropic in relation to nearby active region ($\theta_{AR}$).

**Amplitude.** The anisotropic terms in $A$ defined in equation (1) is given by $a_2$ and $a_3$ (rdfitc): $A_{\theta} = \exp(a_2 \cos(2\theta') + a_3 \sin(2\theta'))$, where $\theta' = \theta + \theta_{AR}$. Fig. 3 (top left panel) shows $A_{\theta}$ variation for a given mode as a function of $\theta'$ where the different colors are for different $\theta_{AR}$. As expected, the amplitude of the waves propagating in the direction of the nearby active region are...
Figure 2. Relative ‘nearby’ (left panel) and ‘AR’ (right panel) frequency variation obtained using rdfitc (circles) and rdfitf (diamonds) for f (red), p₁ (green), p₂ (blue), p₃ (cyan), p₄ (salmon) modes.

attenuated in relation to ones propagating perpendicular to it. The variation given by the control set (black crosses) is much smaller than the target variation. Fig. 3 (top right panel) shows Aθ variation in the direction of the nearby active region for all modes. For frequencies smaller than ≈4.2 mHz, the anisotropic variation is of the same order of magnitude as the constant term in A (Fig. 1 left panel). For larger frequencies, the anisotropic variation is small (about 20%) compared with the variation in the constant term in A, with a slight amplification in the waves propagating in the direction of the nearby active region and a slight attenuation in the direction perpendicular to it (Fig. 3 top right). As a result, the modes are amplified (acoustic halo) if there is an active region nearby with very little dependence on their propagation direction. Fig. 3 (bottom panels) shows Aθ plus the variation of the constant term (given by Fig. 1 left panel) in the direction of the nearby AR (left panel) and perpendicular to it (right panel).

Flow. The fitted zonal and meridional flows (Uₓ and Uᵧ) are expressed in relation to the direction of the nearby active region as Uₓ and Uᵧ. We do not observe any variation in Uᵧ. The variation in Uₓ varies from -20 to 5 m/s and it is much larger than the control set. The two different fitting methods give different results. The results for both methods show no clear dependence on frequency, degree or ν/l.

4. Conclusions
We compare the wave characteristics obtained by the HMI ring-analysis pipeline for magnetically quiet 5° patches, that have at least one large magnetic active region (MAI > 100G) in their vicinity, and it is not more than 8° away, with those with no nearby active regions, but at the same latitude and Stonyhurst longitude. The parameter variations were averaged over all visible sunspots observed during 2.5 years (or 34 Carrington rotations) of the ascending phase of cycle 24. We found significant variations in the mode parameters.

Their amplitude varies from -20% to +20% depending on the frequency and direction of the wave propagation in relation to the nearby active region. Waves propagating in the direction of the nearby active region and with frequencies around 3 mHz present the largest attenuation. While modes with frequencies around 5 mHz present the largest amplification, with those propagating in the direction of the nearby active region ≈20% more than those propagating perpendicular to it. The linewidth varies a few percent and it is mainly a function of frequency. The mode lifetime increases with frequency for ν ≤ 4.5 mHz. The frequency varies within ±0.2%
Figure 3. Top panels: Relative $A_\theta$ variation for a given mode ($n=0$, $l=615$ and $\nu=2488$ $\mu$Hz) on the left where the different colors are for different $\theta_{AR}$ and, on the right, in the direction of the nearby active region for all modes where red, green, blue, cyan and salmon correspond to $n = 0, 1, 2, 3$ and $4$ respectively. The black crosses are the results for the control set. Bottom panels: Variation of $A_\theta$ plus the constant term in the amplitude (given by Fig. 1 left panel) in the direction of the nearby active region (left panel) and perpendicular to it (right panel). The colour scheme is same as for the top right panel.

(or $\pm 10$ $\mu$Hz). The variation of the flow in the direction of the nearby active region is less than 20 m/s and has no clear dependence with the lower turning point depth. There is no flow variation in the perpendicular direction.

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