On the asymmetry of velocity oscillation amplitude in bipolar active regions

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ABSTRACT

The velocity field in the lower solar atmosphere undergoes strong interactions with magnetic fields. Many authors have pointed out that power is reduced by a factor between two and three within magnetic regions, depending on frequency, depth, the radius and the magnetic strength of the flux tube. Many mechanisms have been proposed to explain the observations. In this work, SDO dopplergrams and magnetograms of 12 bipolar active regions (βARs) at a 45 second cadence, are used to investigate the relation between velocity fluctuations and magnetic fields. We show that there is an asymmetry within βARs, with the velocity oscillation amplitude being more suppressed in the leading polarities compared to the trailing polarities. Also, the strongest magnetic fields do not completely suppress the five-minute oscillation amplitude, neither in the spot innermost umbrae.

Key words. Sun: activity, Sun: oscillations

1. Introduction

The study of the interaction between waves and magnetic fields plays an important role in the investigation of the mechanisms responsible for the solar corona heating.

It is well established that the amplitude of solar five-minute oscillations in the photosphere is reduced by a factor of two to three within ARs (Leighton et al. 1962; Woods & Cram 1981; Lites et al. 1982; Abdelatif et al. 1986; Braun et al. 1987; Tarbell et al. 1988; Braun et al. 1988; Title et al. 1992; Hindman & Brown 1998). The reduction is observed to depend on frequency, depth, and on the physical parameters that describe the flux tubes, i.e. their radius and magnetic strength (Brown et al. 1992; Hindman & Brown 1998). This behavior has been also found in small magnetic field concentrations (Roberts & Webb 1978; Spruit 1981; Bogdan et al. 1996; Hindman & Jain 2008; Jain et al. 2009; Hindman & Jain 2012).

It is also known that at higher frequencies, above the acoustic cutoff frequency in the low photosphere, the velocity oscillations amplitude is enhanced at the edges of ARs (Brown et al. 1992; Braun et al. 1992; Toner & Labonte 1993). Also, an enhancement of power in the three-minute band has recently been observed in the inner umbra of a pore (Stangalini et al. 2009).

Several mechanisms have been proposed to explain the observations (Hindman et al. 1997):

1) The intrinsic power inhibition due to local convection suppression. By using numerical simulations (Parchevsky & Kosovichev 2007), found that the reduction of wave excitation in a sunspot, can account up to 50% of the power deficit.

2) Partial p-mode absorption (Braun et al. 1987; Bogdan et al. 1993; Cally 1995; Cally & Andries 2010; Spruit & Bogdan 1992) showed that the wave absorption by sunspots can be interpreted in terms of p-modes mode conversion between the oscillations and MHD waves. Both models (Cally & Bogdan 1993) and simulations (Cameron et al. 2008) have shown that mode conversion is able to remove a significant amount of energy from the incident helioseismic wave, with an efficiency that depends on the angle of the magnetic field from the vertical, with a maximum at about 30° (Cally et al. 2003; Crouch & Cally 2003).

3) Opacity effects. Within a magnetic region, the line-of-sight optical depth experiences a depression (Wilson depression). Due to increasing density, the amplitude of the velocity fluctuations decrease with depth.

4) Alteration of the p-mode eigenfunctions at the hands of the magnetic field (Jain et al. 1996; Hindman et al. 1997).

We note that the majority of the studies on the interaction between solar oscillations and magnetic field have focused on the use of models and simulations. Because of the dependence of the velocity amplitude on magnetic strength, the most noticeable effects are observed within ARs, where the strongest magnetic fields are found. Among them, bipolar active regions (hereafter βARs) are particularly interesting, showing asymmetries in their morphology and physical properties, as several works have already pointed out (see, e.g., Bray & Loughhead 1979; Balthasar & Woch 1980; Ternullo et al. 1981; Zwaan 1985; van Driel-Gesztelyi & Petrovay 1990; Petrovay et al. 1990; Fan et al. 1993). Moreno-Insertis et al. (1994) conclude that morphological asymmetries are due to the different inclination with which the polarities of βARs emerge.

Using simulations, Fan et al. (1993) have studied area asymmetries, and predict that the leading polarity must have a strength about twice larger than the trailing polarity, at the same depth. This result, which is a consequence of the Coriolis force action on the magnetic structure, is able to account for the trailing spot fragmentation, its lower flux magnitude and shorter lifetime. MDI observations of 138 bipolar magnetic regions have recently...
quantitatively shown that the areas of leading polarities are typically smaller than those of trailing polarities (Yamamoto 2012). This area asymmetry could be produced by the Coriolis force during a flux tube’s rising motion in the solar convection zone.

In this work we investigated the velocity oscillation amplitude reduction by the magnetic field within βARs. We analyzed 12 βARs from SDO-HMI data, both in the Northern (N) and Southern (S) hemispheres, and we found that the leading polarity systematically has a greater reduction in amplitude than the trailing. In addition, we studied the amplitude reduction as a function of the field inclination for AR11166.

2. Method and analysis

The selected regions around each βAR were co-registered using a FFT technique ensuring sub-pixel accuracy. Inspection of the co-registered data shows that the strong magnetic structures remain in the same position during the entire duration of the acquisition. The amplitude of velocity oscillations was estimated pixel-by-pixel through their integrated spectrum. Specifically, we selected a spectral window centered at 3 mHz (five-minute band), having a width of 1 mHz, and then we integrated FFT amplitude spectrum in that frequency range

\[ A_{xy} = \sum A_{x} d\nu \]

We then divided the data into bins of magnetic field, each 25 G wide, and averaged the amplitude of velocity oscillations in each bin, thus obtaining \( A_B = \langle A_{xy} \rangle \), \( B \). We consider only pixels with \( |B| > 25 \) G. Since all the amplitude distributions within the respective magnetic bin have a Gaussian-like shape (see inset in Figure 2), we use \( \sigma / \sqrt{n} \) as error on \( A_B \), where \( \sigma \) is the standard deviation and \( n \) are the counts in each bin.

4. Results and Discussion

4.1. Oscillation amplitude VS magnetic field strength

In Figure 2, we show the integrated amplitude \( A_{xy} \) scatter plot (black dots), and \( A_B \) for each magnetic bin (red line), for the βARs shown in Figure 1. Hereafter, we refer to the \( A_B \) plot as the amplitude profile. The amplitude shows a decreasing trend up to a plateau, that is almost always reached in the range 0.5-1 kG (as in the case of Figure 2b). This feature suggests that the amplitude is independent of the magnetic field strength above a threshold value, which is different for each βAR and each polarity in the same βAR.

For every polarity present in the 12 βARs analyzed, we computed the oscillation amplitude reduction as the ratio \( d = A_{1000}/A_{25} \), where \( A_{1000} \) and \( A_{25} \) are, respectively, the mean oscillation velocity around \( B = 1000 \) G, and that around \( B = 25 \) G, the minimum observable strength. Averaging the \( d \) values over all the βARs, we obtained \( d = 0.54 \pm 0.06 \), which agrees with the oscillation amplitude reductions in magnetic environments quoted in the literature (e.g. Woods & Cran 1981; Lites et al. 1982; Braun et al. 1987; Tarbell et al. 1988).

The plateau in the amplitude profiles for high \( B \) values, is intriguing. By visual inspection, we verified that it takes place almost exclusively in the βAR spot umbrae, as can be expected given the high magnetic field values. We can exclude an instrumental effect, since the magnetic strength threshold changes with each βAR and even with the polarity in the same βAR, and we are well above the 20 m/s error on the velocity...
Table 1. Details of SDO-HMI data used. The fourth column shows the leading to trailing polarity area ratio.

| βAR number | Observation Date | Location | S₁/S₂ |
|-------------|------------------|----------|-------|
| AR11166     | 2011.03.08       | N11 W01  | 0.88  |
|             |                  | T11:00-14:00 |       |
| AR11283     | 2011.09.05       | N13 W01  | 0.86  |
|             |                  | T17:00-20:00 |       |
| AR11302     | 2011.09.28       | N13 W06  | 0.96  |
|             |                  | T17:30-20:30 |       |
| AR11319     | 2011.10.15       | N09 E02  | 0.95  |
|             |                  | T07:00-10:00 |       |
| AR11316     | 2011.10.15       | S12 E01  | 0.90  |
|             |                  | T07:00-10:00 |       |
| AR11330     | 2011.10.27       | N09 E04  | 0.83  |
|             |                  | T18:30-21:30 |       |
| AR11338     | 2011.11.06       | S14 W00  | 0.92  |
|             |                  | T20:00-23:00 |       |
| AR11341     | 2011.11.11       | N08 W00  | 1.05  |
|             |                  | T07:00-10:00 |       |
| AR11362     | 2011.12.03       | N08 W06  | 1.10  |
|             |                  | T20:00-23:00 |       |
| AR11367     | 2011.12.07       | S18 W05  | 0.90  |
|             |                  | T20:00-23:00 |       |
| AR11375     | 2011.12.13       | N08 W03  | 0.82  |
|             |                  | T19:00-22:00 |       |
| AR11389     | 2012.01.03       | S22 W05  | 0.97  |
|             |                  | T16:00-19:00 |       |

To visualize differently the asymmetry, we can fix a value |B| for the magnetic strength, and compute the amplitude difference, i.e. the difference between the respective averaged amplitudes for both polarities in each βAR, namely A|B| − A−|B|. In Figure 3, we show these differences versus the absolute value of magnetic strength for all βARs of Table 1. This plot confirms that the asymmetry is lower where the field is weaker. At 25 G the difference is about 10 m/s and typical values for velocity amplitudes up to 600 m/s; at 1000 G the difference rises to over 50 m/s, while the amplitudes are ~ 200 m/s. Both in N and S hemispheres the oscillation amplitude in the trailing polarity is higher than that in the leading polarity. This fact implies that A|B| > A−|B| in the N hemisphere and viceversa in the S hemisphere, and that the amplitude reduction is less efficient in the trailing polarity.

Such an asymmetry suggests that the amount of oscillation reduction within magnetic environments is not a function of the local magnetic field strength only. If this were the case, we would observe the same oscillation amplitudes for B and −B magnetic fields. This would imply both the plots of Figure 3 to
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Fig. 3. a) Midpoints for normalized velocity oscillation amplitude. b) Difference between oscillation amplitude for both polarities against the magnetic strength. Bars represent errors. Red line with diamonds, refers to Southern \( \beta \)ARs, blue line with plus signs to Northern \( \beta \)ARs.

lie on the line through 0 G (a) and 0 m/s (b), respectively.

The simulations of Fan et al. (1993) about area asymmetries of \( \beta \)ARs, predicted a pronounced difference in the field strength between the leading and the trailing polarities, and ensuing differences in their fragmentation and lifetimes. This suggests that the asymmetry we found could derive from non-local properties, i.e., on the whole magnetic environment topology and even its surroundings.

We therefore computed the area asymmetry in our magnetograms following Yamamoto (2012), with a threshold \( B > 500 \) G. The results are reported in the fourth column of Table 1. We found that, on average, the area of the leading polarity is \( \sim 90\% \) of the trailing area, regardless the hemisphere which the \( \beta \)AR belongs to. This quantifies how much a trailing polarity is spread with respect to its leading polarity. We can speculate that a relation may exist between the area and the oscillation suppression, due to a different interaction of acoustic waves with sparser or denser active region polarities.

4.3. Oscillation amplitude VS magnetic field inclination

The case of AR11166

To support the findings reported in sec. 4.2, we studied the dependence of the oscillation amplitude on the magnetic field inclination angle \( \theta \) in an \( \beta \)AR. For this purpose, we considered the AR11166 (Figure 1a) as a case study. We used the LOS inclination maps provided by the VFISV (Very Fast Inversion of the Stokes Vector, Borrero et al. 2011) inversion of HMI vector magnetic field data.

In Figure 4 we show the magnetic field inclination map of AR11166. The inclinations retrieved by the VFISV span the range 10° < \( \theta < 172° \). Following the most used sign convention, the leading polarity (negative) ranges from 90° to 180°, and the trailing polarity (positive) from 0° to 90°. As expected, the innermost umbrae are mostly line of sight, as the \( \beta \)ARs were selected as close as possible to the disk center.

VFISV also provides the error \( \sigma_\theta \) associated to the inclination, for each pixel (Borrero et al. 2011; Press et al. 1986). To avoid polarity flips due to the inversion error, we discarded all those pixels where \( \theta \pm 3\sigma_\theta \) causes the field to flip its inclination from positive to negative (or vice-versa). We stress that VFISV is a Milne-Eddington code, therefore blind to any \( B \) and \( v \) line of sight gradients, which produce asymmetries in the Stokes profiles. This happens most often in regions filled by weak fields (Viticchié et al. 2011; Viticchié & Sánchez Almeida 2011). Moreover, the inversion of low signal to noise Stokes profiles is usually problematic (see Landi Degl’Innocenti 1992; Borrero et al. 2011, for more details). For noisy Stokes profiles, and therefore low \( B \) values, VFISV (and any inversion code) tends to be biased toward \( \sim 90° \) inclinations (Borrero & Kobel 2011). For these reasons and to be consistent with the threshold used in 3, we rejected the pixels with \( B < 25 \) G and \( 75° < \theta < 105° \). After this selection, about 17% of the initial pixels were selected for the analysis.

We plotted \( A_\theta \) and its average in each \( \theta \) bin \( A_{\theta} \) against the magnetic field inclination \( \theta \) (shown in Figure 5). For ease of comparison, in the upper panel of Figure 5 we show again \( A_\theta \) versus \( \theta \) in the range [10°, 75°]. Both \( A_\theta \) smoothly decrease from \( \sim 250 \) m/s to \( \sim 140 \) m/s, from almost horizontal to almost vertical fields, respectively, but the oscillation amplitude reduction is more effective for the leading polarity (red curve).
There is no evident relation between the asymmetry $\Delta A$ and the inclination $\theta$. For any $\theta \lesssim 45^\circ$ the oscillation amplitude asymmetry is positive and around 15 m/s. We interpret the drop at $\approx 45^\circ$ as the combined effect of the VFISV preference to associate weak fields with larger inclinations (Borrero & Kobel 2011), and of the amplitude difference to be small for weak fields (see Figure 3). Also, an incorrectly retrieved weak $B$ may result due to unresolved magnetic structuring in the pixel (e.g. Sánchez Almeida 1998, Socas-Navarro & Sánchez Almeida 2003, Viticchié et al. 2011), and we recall that a VFISV hypothesis is that the magnetic field is constant within the pixel. Schunker & Cally (2006) and Stangalini et al. (2011) have demonstrated that, due to mode conversion, there exists a preferred angle at which the power is significant larger. In our case, we indeed focus on the amplitude asymmetry between the two polarities, instead of considering the proper amplitude dependence that may be affected by biases due to the magnetic field strength.

5. Conclusions

In this work we focused on the velocity oscillation amplitude reduction in $\beta$ARs, reaching the following conclusions.

The oscillation amplitude reduction found in magnetic environments of $\beta$ARs is $0.54 \pm 0.06$, which agrees with the values quoted in the literature (e.g. Woods & Cram 1981, Lites et al. 1982, Braun et al. 1983, Farbell et al. 1988).

The five-minute amplitudes are not completely suppressed in the strongest magnetic fields of the spot innermost umbra. It would be very important to understand why a plateau appears in the oscillation amplitude profiles for strong fields.

There exists a leading-trailing polarity asymmetry in $\beta$ARs. The asymmetry suggests that the reduction in oscillation amplitude does not depend on the field strength only, but may depend also on non-local conditions, such as the area on which the field spreads, for instance.

The trailing polarity systematically shows a higher oscillation amplitude than the leading polarity, regardless the hemisphere which the $\beta$AR belongs to.

The plot of the velocity oscillation amplitude as a function of the magnetic field inclination confirms such an asymmetry in $\beta$ARs. Apparently, the asymmetry does not evidently depend on the inclination.

We took advantage from HMI full-disk data at a 45 s time cadence, and at 1 arcsec spatial resolution. The analysis of these data revealed a possible saturation of the oscillation amplitude reduction for strong $B$, and an asymmetry in such a reduction for leading-trailing polarities. These results have to be accounted for in modeling the power reduction in magnetic environments, the emergence and the evolution of $\beta$ARs.

Acknowledgements. We thank professor Stuart M. Jeffries (IfA, University of Hawaii) for useful discussion and critical reading of the early version of this manuscript.

SDO-HMI data are courtesy of the NASA/SDO HMI science team. We acknowledge the VSO project (http://vso.nso.edu) through which data were easily obtained.
