High frequency power in HMI ring diagrams

Charles S. Baldner¹, Richard S. Bogart², and Sarbani Basu¹

¹ Astronomy Department, Yale University, P.O.Box 208101, New Haven, CT, 06530-8101
² Hansen Experimental Physics Laboratory, Stanford University, Palo Alto, CA, 94305
E-mail: charles.baldner@yale.edu

Abstract. Coherent power above the photospheric acoustic cut-off frequency (at \( \nu \sim 5.3 \text{mHz} \)) is known to exist in solar helioseismic observations. The arrival of high quality velocity data with high temporal and spatial resolution from the Helioseismic & Magnetic Imager (HMI) on the Solar Dynamics Observatory (SDO) spacecraft allows the high frequency regime to be explored with greater precision than previously. We analyse mode frequencies, widths, and amplitudes from HMI ring diagrams at high frequencies, and compare them to earlier results.

1. Introduction

Solar normal modes of oscillation with frequencies below the acoustic cut-off frequency (\( \nu \sim 5.2 \text{mHz} \)) are trapped in the solar interior and are used in helioseismology to infer the interior structure and dynamics of the Sun. Modes with higher frequencies are not trapped and penetrate the chromosphere. High frequency coherent power has nevertheless been observed in the Sun [1, 2, 3, 4].

The high frequency \( p \)-modes have been found by [1, 4] to have fairly constant line widths above the cutoff frequency. The ridges have been found to obey a dispersion relation derived for completely trapped modes [1]. The authors [4] found evidence for an avoided crossing at frequencies slightly higher than the acoustic cutoff.

In this work, we use ring diagrams from the science commissioning observations of the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory (SDO) to study temporal and spatial frequency power in the solar oscillation spectrum.

2. Method

The ring diagrams used here are constructed from \( 16^\circ \times 16^\circ \) degree line-of-sight Dopplergram data taken with the HMI instrument. These rings are standard data products from the HMI local helioseismology pipeline. The data are tracked for 1728 minutes at a 45 second cadence. The regions are centred at the equator, and cross disk centre at the mid-time of the tracking interval. The data are projected to a rectilinear grid using Postel’s projection and appodized to a circular region \( 15.36^\circ \) in diameter. The ring diagram itself is the three dimensional Fourier transform of this data cube. For this work, 40 individual ring diagrams were averaged together to improve as much as possible the signal to noise.
Figure 1. The fitted frequencies and uncertainties to the averaged HMI power spectrum. The fitted ridges are the $f$-mode and the first 9 $p$-modes.

3. Results

In order to fit the spectra, we azimuthally average the ring. The ridges are fit with a symmetric Lorentzian at constant wavenumber $k$:

$$P(\nu) = \frac{A \Gamma}{(\nu - \nu_0)^2 + \Gamma^2} + B,$$

where $A$ is the amplitude, $\Gamma$ is the width of the ridge, $\nu_0$ is the central frequency, and $B$ is the background power. Each ridge is fit independently. The fits minimise the squares of the differences between the data and the model profile using a Levenberg-Marquardt algorithm.

An $\ell - \nu$ diagram of the fitted ridges is shown in Figure 1. The ridges are not symmetric, particularly at low temporal frequency, and the frequencies we measure here are underestimated somewhat. At higher frequencies, however, particularly above the acoustic cutoff, the ridges become more or less symmetric and our estimates of the frequencies are therefore reasonable. Figure 1 shows fits to the $f$-mode ridge and the first 9 $p$-mode ridges. We succeed in fitting some ridges up close to the temporal Nyquist frequency.

Figure 2 shows the amplitude $A$ and the width $\Gamma$. The amplitudes peak at approximately 3.5mHz, as expected, and fall off for higher frequencies. The slope of the amplitudes as a function of frequency above the acoustic cutoff is shallower than the slope below the cutoff. The widths of the $f$-mode ridge are substantially different than the $p$-mode ridge widths. The $p$-mode widths
behave differently below the acoustic cutoff frequency than above. The widths are larger above the acoustic cutoff.

To see clearly the avoided crossing above the acoustic cutoff frequency, we plot the difference of the \( n \)th ridge and \( n - 1 \) ridge in Figure 3. The bump above the acoustic cutoff shows up in all \( p \)-mode ridges and is a signal of the avoided crossing.

4. Conclusions

We have fit high temporal and spacial frequency \( p \)-mode ridges from HMI ring diagram data. We are able to fit the first 9 \( p \)-mode ridges, as well as the \( f \)-mode. We find that the \( p \)-modes clearly extend well above the acoustic cutoff frequency at \( \nu \sim 5.3 \text{mHz} \).

Earlier work has found that mode widths become roughly constant as a function of frequency above \( \nu \sim 5.3 \text{mHz} \) [1]. In this work, we find that widths as a function of frequency do become substantially flatter above \( \nu \sim 5.3 \text{mHz} \), but they are not constant. We find a peak in width just above the cutoff, and a slight negative slope or flat slope up to approximately \( \nu \sim 7 \text{mHz} \). Widths then increase with frequency. This is not inconsistent with [1], since we probe higher frequencies than that work.

Following the work of [4], we examine the frequency differences \( \nu_n - \nu_{n-1} \). As they did, we find a bump between 5 and 6 mHz, which could be evidence of an avoided crossing above the acoustic cutoff frequency.

This work was performed with the HMI data that was available. As more data becomes available, better signal-to-noise can be achieved. Further more, the effects of solar activity on high frequency power can be explored. Further theoretical work to understand what information is contained in the high frequency power is, however, the most necessary component of further research.

Acknowledgments

CB is supported by a NASA Earth & Space Sciences Fellowship NNX08AY41H. SB is supported by NASA grant NNG06GD139 and NSF Career grant ATM-0348837. The Helioseismic and
Figure 3. The frequency differences of adjacent modes with the same degree. Above the cutoff frequency, there is a distinct bump in all p-modes – evidence for an avoided crossing. The magnitude of the bump decreases with increasing $n$.

Magnetic Imager (HMI) project on SDO is supported by NASA grant NAS5-02139 to Stanford University.

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