Interaction of Helioseismic Waves with Sunspots: Observations and Numerical MHD Simulations

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Abstract. We investigate how helioseismic waves that originate from effective point sources interact with sunspots. For observations, the waves from point sources are reconstructed by cross-correlating observed photospheric Doppler signals. For numerical simulations, the waves are generated by simulating perturbation propagation from a pulse near the surface and propagate through magnetostatic and magnetohydrodynamic (MHD) sunspot models. For both cases, we study f-mode and p-mode waves separately. We also study different cases when the point source is located outside the sunspot, and when the source is located inside the sunspot. Our results nicely visualize how the waves, including both wave amplitudes and phases, interact with the magnetic field, thermodynamic and flow structure of sunspots, and how the waveform evolves before, during, and after the propagation through sunspots. Our analysis of wave–magnetic-field interactions also extends below the sunspot’s surface. This brings us new rich information of how the waves respond to the magnetic field below the surface, but also poses new challenges for local helioseismology to infer the sunspot’s interior properties from waveform observations.

1. Introduction

Local helioseismology analyses have been used to investigate interior structures of solar active regions based on measured acoustic travel-time shifts or phase-shifts. However, a picture of how helioseismic waves, including both the surface-gravity (f-mode) waves and acoustic (p-mode) waves from an effective point source, interact with the active region (AR), or magnetized plasma, has not been widely studied and visualized observationally. An observational study of such interactions will undoubtedly improve understanding of how helioseismic waves respond to the presence of a magnetic field along the traveling paths of the waves, and moreover, guide numerical simulators to improve their simulations by changing interior physical conditions of their models to match surface observations.

Meanwhile, a number of numerical simulations have been carried out to understand how helioseismic waves interact with magnetic fields (e.g., Cameron et al. 2008; Khomenko et al. 2009). However, a three-dimensional simulation with a more realistic sunspot, magnetic-field configuration and hydrodynamic structure, is badly needed to substantially improve our understanding of wave–sunspot interactions. Such a numerical simulation should be directly compared with the observed point-source wave–sunspot interactions, and then will also be used to facilitate interpretation of local helioseismic observational facts obtained, in particular, by time-distance analyses.
In this paper, we summarize our recent efforts in both observation analyses and numerical simulations. Section 2 presents some observational facts, and for full details of the analysis procedures and results, the readers should refer to a recent paper by Zhao et al. (2011b). Section 3 introduces some recent results from numerical simulations, and readers should refer to Parchevsky et al. (2011) for more details. Summary and conclusions are given in Sect. 4.

2. Results from Observation Analyses

2.1. Data and Method

For this analysis, we select a stable, long-lived active region, National Oceanic and Atmospheric Administration AR 9787, observed by the Solar and Heliospheric Observatory Michelson Doppler Imager. Our analysis period covers 00:00 UT, January 22 through 23:59 UT of January 26, 2002, a total of five consecutive days. The entire data sequence is divided into ten 12-hour segments, and each segment is analyzed separately. The cross-correlation functions are obtained from each data segment, and then these functions are averaged to get the final waveforms.

As shown in Fig. 1, the sunspot located in this active region is not perfectly round but close enough to be considered as axisymmetric. If we select the location “A” as a wave source, we can reconstruct the wavefront, which originates from point “A”, by cross-correlating solar oscillation signals at “A” with signals observed everywhere else. Similarly, we can reconstruct the wavefront originating from location “B” by a similar approach. If we assume the sunspot is axisymmetric, then the parts of waves interacting with the sunspot will be identical for waves originating from “A” and from “B”, and this part of the wave is of interest for our analysis. Actually, all waves originating from the dashed circle shown in Fig. 1 have the same property. Thus, we can get a better signal-to-noise ratio by reconstructing all wavefronts from the locations around that circle and then average the wavefronts after certain rotation of these reconstructed wavefronts. In practice, this averaging method was used in many different studies (e.g., Zhao et al. 2011a).
Interactions of Waves and Sunspots

Figure 2. *Upper row:* Selected snapshots showing the interaction of p-mode waves with the sunspot when the wave source is located outside of the sunspot. Left panel shows a two-dimensional image of the waveform, with black contours showing the sunspot umbral and penumbral boundaries. The gray circle shows the travel distance obtained for this moment from the time-distance relations of the quiet Sun. The middle panel shows the waveform of the quiet Sun (black) and sunspot (gray) obtained from a horizontal cut. The vertical dashed lines represent the boundaries of the sunspot. The right panel shows oscillation signals obtained at the wavefront for the quiet Sun (black) and for the sunspot (gray). The dark vertical line indicates the acoustic travel time fitted from the quiet-Sun reference curve. *Middle row:* Same as the upper row but when the wave source is located at the boundary of the sunspot and the quiet Sun. *Lower row:* Same as the upper row but when the wave source is located inside the sunspot umbra.

2.2. Results from p-mode Analysis

For the p-mode waves, we study different cases: when the wave source is located outside the sunspot, at the boundary of the sunspot and the quite Sun, and inside the sunspot umbra.
We briefly summarize our results for all the three cases. When the wave source is located outside the sunspot (an example is shown in the upper-row panels of Fig. 2), the wave does not differ from waves in the quiet Sun before the wavefront encountering the sunspot boundary. After the encounter, the wave starts to show a reduction in amplitude and the wavefront moves ahead of the quiet-Sun counterpart. Soon after the wave passes through the sunspot area and appears on the other side of the sunspot, the wave appears very similar to the waves of the quiet Sun as if it does not have much interaction with the magnetized plasma beneath the sunspot’s surface.

When the wave source is located at the boundary of the sunspot and quiet Sun (an example is shown in the middle-row panels of Fig. 2), the wave shows substantial amplitude reduction during and after passing through the sunspot. The wave shows a faster traveling speed when it crosses the sunspot, but does not show much travel-time difference relative to the quiet-Sun reference when it emerges again on the other side of the sunspot.

When the wave originates from inside the sunspot umbra (an example is shown in the lower-row panels of Fig. 2), the wave also shows substantial amplitude reduction during the wave traveling inside the sunspot and after the wave leaves the sunspot. The

Figure 3. Selected snapshots showing the f-mode wave–sunspot interaction when the wave source is located outside of the sunspot. Left panels show two-dimensional images of wave propagation, with the white contours showing sunspot umbral and penumbral boundaries. In the right panels, the curves show horizontal-cut waveforms for the quiet Sun (black) and for the sunspot (grey). The vertical dashes lines indicate the locations of sunspot boundaries.
wave shows significantly shorter travel times, roughly 1 minute or less, than the waves originating from and traveling inside the quiet Sun.

### 2.3. Results from f-mode Analysis

The f-mode waves behave differently from the p-mode waves, so we analyze the f-mode waves separately. Figure 3 shows a couple of selected snapshots when the wave source is located outside the sunspot. At the 90th minute when the wave is entirely inside the sunspot, in addition to the wave amplitude reduction, the first two peaks of the wave move ahead of the reference wave, while the latter three peaks stay behind the reference wave. At the 144th minute when the wave has passed the sunspot region completely, the reduced wave amplitude does not recover like the p-mode waves. And, the first two peaks of the wave move even further ahead of the reference wave, and the latter three peaks lag very obviously behind the reference wave.

This is a good example of how one waveform can show different behaviors at different wave locations when encountering a magnetized plasma. If one only looks at the travel time measured from a selected peak of the waveform, it may not be possible to get all the information these waves actually contain.

![Figure 4](image-url)

Figure 4. (a) Snapshot of a simulated acoustic wave interacting with a magnetic field. This simulation uses a periodic boundary condition. The contours show magnetic field strength with magnitude of 100, 300, 500, and 700 Gauss. (b) Comparison of waves interacting with the magnetic field (dark) and waves in the quiet region (grey). The dark curve is a horizontal cut connecting the wave source and the sunspot center. (c) Vertical cut of simulated acoustic wave interacting with magnetic field. Black lines show magnetic field lines, and grey arrows show interior flow fields. The waves are a mixture of fast MHD and slow MHD waves. It can also be seen that the right part of the wavefront is skewed by the background flows.
3. Results from Numerical Simulations

Numerical simulation of acoustic wavefronts has become an important tool to validate local helioseismology analyses, and to help interpret the results from these techniques properly. On the other hand, helioseismic analysis of these simulations is also an important way to assess how close the simulation models are to the Sun. In this sense, the helioseismic analysis and the numerical simulations are complementary and mutually beneficial to each other.

Parchevsky et al. (2011) have performed a three-dimensional MHD simulation, with a realistic sunspot model having background flows and a point wave source excited. The simulation clearly shows wave amplitude reduction when waves encounter the sunspot, and shows a faster wave propagation speed relative to the quiet-Sun regions (see Fig. 4a and 4b). These are similar to what has been observed (Zhao et al. 2011b), although the exact quantities of travel-time shifts and waveform changes are still worth more detailed comparisons.

In addition to the comparison with solar photospheric observations, the simulation shows more detailed information of the interior wave–magnetic-field interactions. Figure 4c shows one snapshot of this interaction. The acoustic wave is converted into a mixture of Alfvén wave and MHD waves, which includes both fast- and slow-modes. This information will provide a more reliable interpretation of what we observe in the photosphere as well as a better derivation of the physical conditions and wave conversions in the interior magnetized plasma.

4. Conclusion

We have designed a method to reconstruct the helioseismic wave–sunspot interactions observationally. The observed wavefront shows many details of how waves respond to magnetized plasma before, during, and after the encounter. Also, we find it is very useful to observe the responses of the entire waveform instead of just looking at one travel time value fitted from the waveform, because different parts of the wave may have different responses.

Three-dimensional MHD simulations of wave–sunspot interactions are crucial in understanding the observed phenomena in the photosphere, because the observed wave changes are clearly due to a combination of a few different factors, including magnetic field, flow field, and structure perturbations. A joint study of observational analyses and numerical simulations will provide an improved understanding of the interior physical conditions of sunspots.

References