Dissertation Proposal

Solar f-mode Wave Scattering Off Linear Source Boundaries

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ABSTRACT

The underlying question driving this work is whether coronal holes are purely atmospheric features or whether they extend into the solar interior. I propose to develop a linear-source local helioseismology technique to theoretically investigate how a linear scattering center changes the signatures of a scattered wave. I will then apply this method to coronal hole observations with the scientific goals of determining how coronal hole boundaries influence the propagation of f-mode waves. Specifically, I will look at how the scattered wave amplitude changes with various parameters, including boundary length, change in the magnetic field properties across the boundary, wavelength of the f-mode wave, and angle of incidence of the wave to the coronal hole boundary. Ultimately, I will determine whether f-mode wave scattering can be detected off the boundary of a coronal hole.

1. Introduction & Background

1.1. Coronal Hole Overview

Coronal holes (CHs) are regions of open magnetic field along which solar plasma particles flow freely away from the Sun. This outflow causes the density and electron temperature in the CHs to be lower than in the ambient corona and chromosphere (the solar "atmosphere") (Munro and Withbroe, 1972). They are the source of the fast solar wind, dynamically change with the solar cycle, and are key to understanding the Sun's magnetic dynamo process.

Polar coronal holes (PCHs) are long-lived features that primarily appear at latitudes above $\pm 50°$ (Waldmeier, 1981). These holes have a fixed rate of rotation distinct from the polar plasma rotation (Navarro-Peralta and Sanchez-Ibarra, 1994), which suggests that the field lines are less prone to twisting and distortion from sub-surface flows. PCHs are dominant during solar minimum. Equatorial coronal holes (ECHs) are more transient features, lasting hours up to weeks, and are more common during solar maximum. This type of hole is subject to magnetic disturbances caused by flares and coronal mass ejections. ECHs also rotate at the same rate as the solar differential rotation (Navarro-Peralta and Sanchez-Ibarra, 1994). Polar hole extensions share similar properties to the PCHs (fixed rotation rate, long-lived) but stretch down into lower latitudes where ECHs dominate.

During solar minimum, the Sun's magnetic field is quasi-dipolar. The open magnetic field is collected at either pole and large, stable PCHs are visible in EUV and X-ray wavelengths. As the solar cycle progresses into maximum, the magnetic field gets wrapped around in the high-β plasma of the convection zone, turning the poloidal field into a toroidal one. The PCHs break apart and move down to lower latitudes as small, more transient ECHs. Zhou and Smith (2009) found that the amount of open polar magnetic field at minimum is roughly the same as the amount of globally open field at maximum.

There are two viewpoints about the structure and origin of CHs. Some in the scientific community assert that CHs are purely atmospheric features that are created and destroyed in the corona and only extend down to the top of the photosphere (the Sun's "surface"). The other camp believes that CHs are driven by internal processes in the Sun and their defining open magnetic fields propagate into the convection zone. It is possible that both arguments are correct to some extent.

Examining CHs from below the surface could provide an answer to this highly debated topic. Recent research in local helioseismology (see Section 1.2) has been successful at finding wave scattering signatures off of strong, closed magnetic flux below the photosphere. It is possible that similar wave scattering occurs at sub-photospheric CH boundaries, since the closed-to-open magnetic field boundary acts as a discontinuity that could reflect some incoming waves.

1.2. Helioseismology Overview

Helioseismology is the study of the solar interior from surface observations of naturally-excited internal acoustic and surface-gravity waves (Gizon and Birch,

2005) (see Section 1.3 below for relevant details on wave modes). Local helioseimology, a term coined by Lindsey, Braun, and Jefferies (1993), involves the study of small regions on the solar disk and is used to create a detailed picture of the interior in that particular region. There are multiple methods used in local helioseismic research, including ring diagram analysis, time-distance techniques, and acoustic holography (Pijpers, 2006). All current local helioseismic techniques assume wave scattering off of a point source disturbance.

The specific local technique that will be used in this dissertation is called time-distance (T-D) helioseismology, first developed by Duvall *et al.* (1993). T-D helioseismology computes correlations in far-field wave patterns between two surface points. A recent review on this technique is presented by Gizon, Birch, and Spruit (2010).

Local helioseismology has been used to look at magnetic structure in the solar interior through flow anomalies, which sparked the initial idea for this dissertation through the work of Ilonidis, Zhao, and Kosovichev (2011). Their research employed a time-distance analysis technique and was able to predict emerging flux associated with active regions up to two days before the appearance of sunspots. Howe *et al.* (2012) used a point source analysis technique, called the ring-diagram method, to look at differences between quiet sun regions and CH regions. They found that while there was no apparent change in wave frequency and mode amplitude between quiet sun and CHs, there is evidence of less scattering from points within the CH. They attribute this to the simple magnetic field geometry and fewer emerging flux disturbances from within the hole areas. This leads to intriguing questions about what occurs at the boundary between CHs and quiet sun regions and whether we can use alternative local helioseismology techniques to investigate the subsurface properties below CHs. I propose to look at the CH boundaries as linear source disturbances to see how the contrasting field configurations influence the propagation of subsurface waves.

1.3. Wave Modes & Scattering Overview

There are three kinds of waves used in helioseismology, each of which generates a different resonant wave mode. p-modes are acoustic oscillations, driven by pressure gradients; g-mode oscillations use gravity as the restoring force; f-mode oscillations are surface-gravity waves. Each type of wave mode samples different depths of the solar interior. There are many harmonic resonance patterns within each mode category.

I will focus on f-mode waves for the purpose of this dissertation. f-modes are surface waves that propagate horizontally across the photosphere, with gravity acting as the restoring force. A simple schematic is shown in Figure 1, attributed to Feynman, Leighton, and Sands (1963). Surface waves are a reasonable starting point for this research because, as mentioned in Section 1.1, the research question is how deep below the photosphere do CHs make their presence known.

f-mode waves have a radial order of $n = 0$ (there are no nodes in the radial eigenfunction of the mode) (Duvall and Gizon, 2000). On the Sun, the peak of

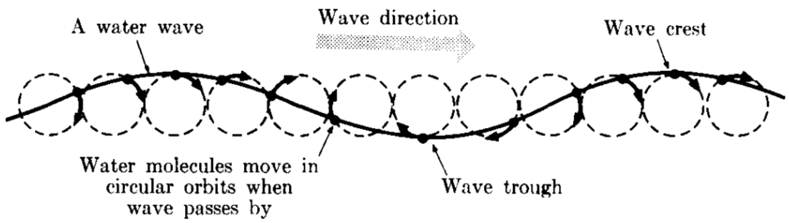

Figure 1. This is Figure 51-9 from Feynman, Leighton, and Sands (1963). f-mode waves are similar to deep-water surface waves in the ocean. The wavefronts propagate horizontally across the surface while the particle motion is circular. As mentioned in the attributed text, the circular motion decreases in radius with increasing depth until the motion disappears completely.

the f-mode frequency envelope is about 3 mHz, with a FWHM of 1mHz. This corresponds to a spherical harmonic degree range of $600 \leq l \leq 1200$, with a peak at about $l = 880$. It is interesting to note that there are no observable frequencies below 0.661 mHz ($l = 41$) (Schou, 2004).

The dispersion relationship for f-mode waves is similar to that of deep-water surface waves (in the limit that the wavelength is small compared to the water depth):

$$\omega^2 = gk, \tag{1}$$

where ω is the angular temporal frequency, g is the gravitational acceleration at the photosphere, and k is the horizontal wavenumber. Note that $k = (l + 1/2)/R_\odot$, where l is the spherical harmonic degree and $R_\odot$ is the solar radius (Duvall and Gizon, 2000). f-mode oscillations are sensitive to both horizontal flow components, which allows more accuracy for scattering detections than Doppler measurements that only see along the line-of-site (LOS). Also, the f-mode has known eigenfunctions, so the depth that is being averaged is well defined.

The following explanation of the wave scattering equations is primarily attributed to Morse and Feschbach (1953). A more in-depth discussion in terms of solar physics can be found in Yang *et al.* (2012).

The total wave function ψ is equivalent to the sum of the incident wave function ψ_i and resulting scattered wave function ψ_s. A simple schematic of the incident and scattered waves off of a point source is illustrated in Figure 2. Assuming the incident wave is a plane wave, the three-dimensional incident wave function is

$$\psi_i = e^{ikz}, \tag{2}$$

where ψ_i satisfies the Helmholtz equation $\nabla^2\psi_i + k^2\psi_i = 0$, $k = 2\pi/\lambda$ is the wavenumber, and λ is the wavelength.

In the limit of $r \to \infty$, the scattered wave satisfies the boundary conditions of a wave diverging from a point source in the scattering region. This boundary condition applies whether the scattering region is actually a point source or not.

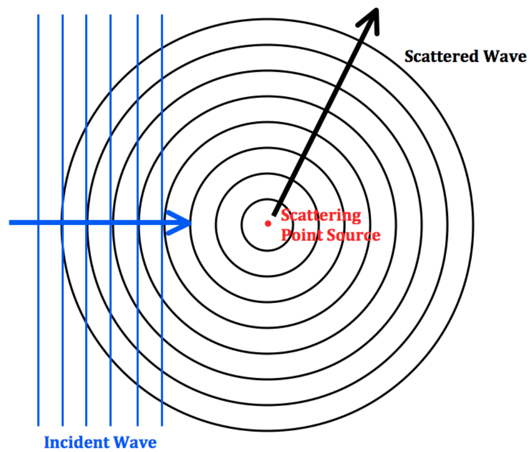

Figure 2. Scattering of an incident plane wave off of a point source scatterer. The resultant wave is radially symmetric about the point source in the far-field.

This condition requires that

$$\psi_s \to f(\vartheta, \phi)\frac{e^{ikr}}{r}; \quad r \to \infty, \tag{3}$$

where r, ϑ, and ϕ represent spherical coordinates with the origin in the scattering region. The function f is called the scattering amplitude. For a surface perturbation, it is represented to first order in three dimensions by the integral equation

$$f(\vartheta, \phi) = -\frac{i}{4\pi}\int e^{-i(\mathbf{k}_i - \mathbf{k}_s)\cdot\mathbf{r}_0}(\mathbf{n}_0 \cdot \mathbf{k}_i)dS_0. \tag{4}$$

This equation describes the interaction of an incident wave on a reflecting surface and the corresponding wave equation ψ is often referred to as the Kirchhoff approximation. Note that S_0 describes the element of surface area of the scattering region, $\mathbf{n}_0$ is the normal vector to the scattering surface, $\mathbf{r}_0$ is the radial vector of the scattering region, and $\mathbf{k}_i$ and $\mathbf{k}_s$ are a the wave vectors in the incident and scattered directions, respectively.

Multiple scattering sources lead to wave interactions between the incident wave and all of the scattered waves produced by individual scattering sources. A simple example of this is the double-slit experiment for light waves. The same principle applies to acoustic and gravity waves. In fluid dynamics, surface-gravity wave propagation is described by Airy (or linear) wave theory (Craik, 2004).

The images in Figures 3-4 were created using a basic IDL code I wrote, called sphr_wav.pro. The plots only show the transmitted waves from a scattering region, without the incident wave. All four plots show amplitude (not intensity) and, to emphasize the wave characteristics, a factor of $1/r$ was left out of the wave equation used to calculate these amplitudes.

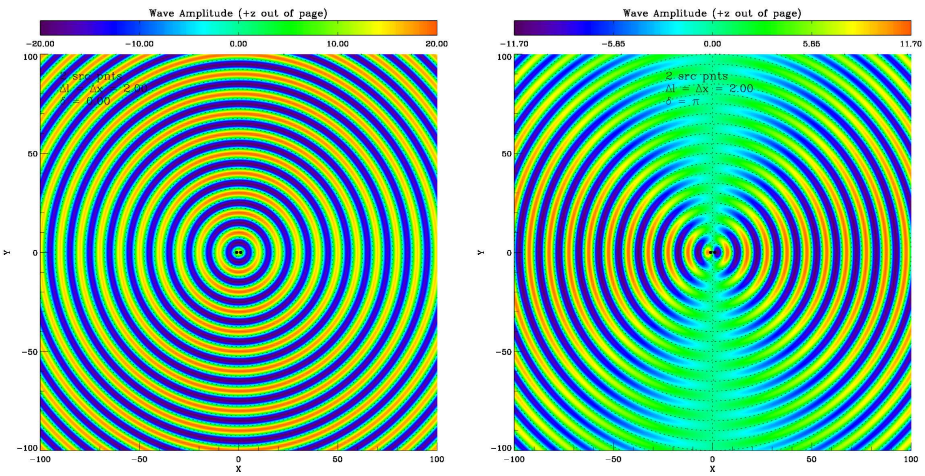

Figure 3. Both images show the interacting wave amplitude of surface-gravity waves emanating from two point sources, separated by a distance $\Delta l = \Delta x = 2$. The black dotted lines indicate fully destructive interference, where the superimposed wave amplitudes cancel out. The left image displays two sources that have no relative phase shift ($\delta = 0$), while the two sources in the image to the right have a relative phase shift of $\delta = \pi$. The wave interference from the unshifted points approximates the symmetric amplitude propagation from a single point source. The two out-of-phase sources have an interference with a "dipolar" symmetry. Note that the wave amplitude ranges of the two plots are not the same.

Figure 3 shows the interacting wave amplitude of surface-gravity waves emanating from two point sources, separated by a distance $\Delta l = \Delta x = 2$. The left image displays two sources that have no relative phase shift ($\delta = 0$), and the combined amplitudes approximate the symmetry of the wave amplitude from a single point source. To the right, the two sources have been phase-shifted $\delta = \pi$. In this case, the interfering amplitudes take on a "dipolar" signature. A multi-point source interference effect is demonstrated in Figure 4, which shows the wave amplitude interaction from 50 in-phase scattering points spaced equidistant from each other along a horizontal line. When the scattering is entirely in-phase (signifying that the incident wavefront is parallel to the sources), as shown in the lefthand plot, the scattered wavefronts become a linear interference pattern parallel to the line of scattering points. At the ends of the finite scattering region, the integrated wave pattern returns to a spherically symmetric configuration. When each scattering point is exactly out of phase with its neighbors (signifying that the incident wave is not parallel to the sources), illustrated in the righthand plot, a more complex interference pattern results.

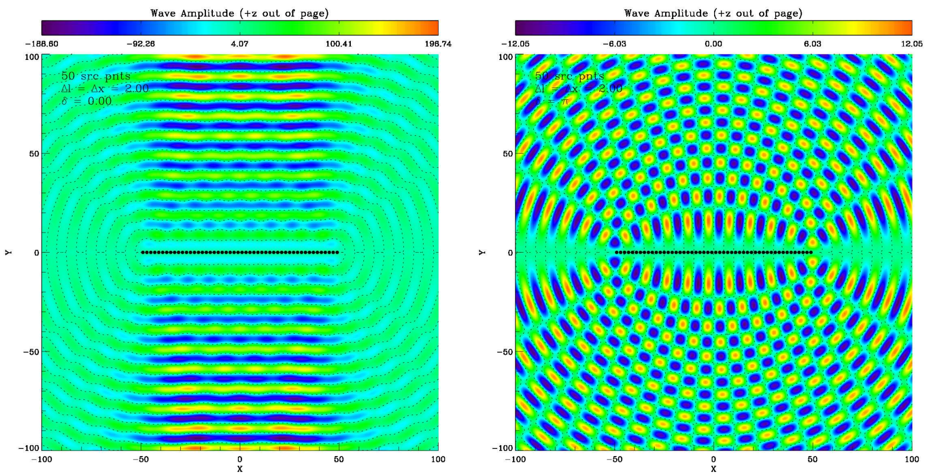

Figure 4. When multiple point scatterers are aligned and a plane wave is scattered off of them, each point contributes its own resulting symmetric wave. The various wave signatures interact and produce regions of additive and subtractive amplitudes. The interference pattern is dependent on the separation of the point source scatterers and the phase shift between points. If enough point source scatterers are sufficiently close together and in-phase ($\delta = 0$), they begin to act as a linear source scatterer, as shown on the left. The resultant waves that scatter from a linear source are plane waves, except for in the regions around the ends of the linear source (assuming it is not infinitely long). At these locations, the incident wave sees the ends of the scattering source as point sources. The plot on the right shows the interference pattern when each scattering point is exactly out-of-phase ($\delta = \pi$) with its neighbors. The black dotted lines indicate fully destructive interference, where the superimposed wave amplitudes cancel out. Note that the wave amplitude ranges of the two plots are not the same.

2. Proposed Work

2.1. Scientific Goals & Questions

The underlying question driving this work is whether CHs are purely atmospheric features or whether they extend into the solar interior. Furthermore, it is possible that the structure of an ECH is fundamentally different than the structure of a PCH or extension. The determination of general CH structure and the identification of structural classes between CH types is the universal goal of this research.

To begin answering these questions, I propose to develop a new linear source analysis technique using T-D helioseimology, then apply the new approach to solar data. As discussed in Sections 1.1 and 1.2, local helioseismology has found that wave scattering occurs in the presence of strong magnetic flux below the photosphere and it is possible that CH boundaries could similarly reflect incoming waves. The recent research by Howe *et al.* (2012) shows a depletion of wave-scattering within CHs versus in quiet sun regions. The point-source analysis that Howe *et al.* used assumes that the scattering signature will be spherically symmetric in nature, which is a reasonable assumption for a point source, in general. However, if the scattering occurs between distinct regions, the boundary between the two regions acts as a discontinuity and can reflect incident waves. The boundary is approximately a linear source. Similarly, the magnetic properties change across the boundary of a CH, which could result in the scattering of incident waves. The scattered wave would appear to be the result of the wave interaction along the linear boundary, not simply at one point source location. Consequently, to best detect scattering between CHs and quiet sun, we should treat the CH boundary as a linear source scatterer. This justifies the need for a linear source T-D technique for this research; however, the same method could be extended to helioseismic studies of other linear features (Duvall, personal communication).

It follows that the first question this dissertation aims to answer is how wave signatures scattered off of a linear source differ from those scattered off of a point source. Changing various parameters to see their theoretical affect on the scattered wave amplitude will be an integral aspect of answering this question. Upon developing the theory and computational method for a linear-source helioseismic analysis (see Section 2.2.1), the next step is the application of the theory to data (see Section 2.2.2). After finding the applied results, we will be able to answer our second principle question: can we detect any expected f-mode wave scattering off the boundary of a CH?

2.2. Methods & Data

2.2.1. Theoretical

I intend to theoretically show that the scattering interference from linearly-aligned point sources extrapolates to a linear source signal (Duvall, personal communication). I will look for signatures of how various parameters affect the scattered wave amplitude (Equation 4). The variable parameters will include the change in magnetic field strength between the open and closed regions (ΔB), the linear source length (L), the separation of the point scattering sources (Δl), the wavelength (λ), and the angle of incidence (θ_i). I will use available T-D local helioseismology code, supplemented by my own code as needed, to develop a linear source analysis routine based on my theoretical results.

As time permits, a further optional component for this work will be to experimentally test the T-D linear source code by applying it to an available simulation. This will allow me to test my computational results of f-mode plane waves scattering off of a linear source disturbance, prior to applying the code to observational data.

2.2.2. Application

I will use AIA 193 Å data[1] to determine a region of interest with a suitable test-case CH (Lemen *et al.*, 2012). The test-case must be a long, linear, well-defined, and temporally stable CH near disk-center. Location on the solar disk is important because geometric effects increasingly obscure the LOS view towards the

[1]http://docs.virtualsolar.org/wiki/VsoIDL

limb. This effectively reduces the accuracy in detecting CH boundary locations and wave amplitude signals (Thompson, W. T., 2010; Jackiewicz *et al.*, 2007). For this reason, helioseismology techniques do not work well at latitudes higher than 60°. Therefore, PCHs are not preferable test-cases for this research since they are limited to latitudes above ±50°. An ECH could suffice; however, a long, large polar hole extension is more desirable due to its longevity. Using the theoretically predicted results as guidelines, I will apply my linear method to helioseismic data corresponding to the test-case CH boundary region. The helioseismic data will be provided by the Joint Science Operations Center (JSOC) Time Distance Full-disk Data pipeline[2] (Zhao *et al.*, 2011).

2.3. Possible Outcomes

Regardless of the ability to detect CH boundary scattering, the development of a linear-source analysis technique for T-D helioseismology will be beneficial to other local helioseismology research. This technique could potentially be applied to research other linear features. For example, scattering off of magnetic neutral lines could increase our understanding of filaments (Duvall, personal communication). The technique could also be used to obtain other helioseismic results besides visible wave scattering, such as subsurface flows.

There are two possible outcomes of the proposed research from the application of a linear source technique to CH boundaries. If scattering signatures are seen in the data, this will confirm that CHs penetrate, at least, below the photosphere, and potentially further into the solar interior. If scattering is not detected, this implies either that CHs are strictly atmospheric features, that the data resolution is too low to detect any scattering, *or* that the change across the hole boundary is too insignificant for detectable scattering to occur.

3. Summary

There are two theories about CH structure. First is that CHs are purely atmospheric features. Second is that the CHs' open magnetic field propagates into the solar interior. The primary motivation of the proposed research is to determine which is correct. The specific research questions described in this proposal are meant to be a foundation on which further research can be conducted in the future. The main goal is to establish whether any surface wave scattering can be detected by the boundaries of CHs. This will be accomplished by developing a linear-source scattering technique for T-D helioseismology to test the predicted effects of scattering at CH boundaries. The next step will be to apply the new linear technique to solar helioseismic data and look for expected scattering signatures that are predicted by the theoretical results. Beyond providing insight about CH structure, the linear source technique will be a useful analysis tool for the local helioseismology community.

[2]http://jsoc.stanford.edu/new/HMI/TimeDistance.html

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References

Craik, A.D.D.: 2004, The origins of water wave theory. *Annual Review of Fluid Mechanics* **36**(1), 1 – 28. doi:10.1146/annurev.fluid.36.050802.122118. http://www.annualreviews.org/doi/abs/10.1146/annurev.fluid.36.050802.122118.

Duvall, T.L. Jr., Gizon, L.: 2000, Time-distance helioseismology with f modes as a method for measurement of near-surface flows. *Solar Phys.* **192**, 177 – 191.

Duvall, T.L. Jr., Jefferies, S.M., Harvey, J.W., Pomerantz, M.A.: 1993, Time-distance helioseismology. *Nature* **362**, 430 – 432. doi:10.1038/362430a0.

Feynman, R.P., Leighton, R.B., Sands, M.: 1963, *The Feynman Lectures on Physics: Volume 1*, *The Feynman Lectures on Physics* **1**, Addison-Wesley, Boston, 7. Chap. 51.

Gizon, L., Birch, A.C., Spruit, H.C.: 2010, Local helioseismology: Three-dimensional imaging of the solar interior. *Ann. Rev. Astron. Astrophys.* **48**, 289 – 338. doi:10.1146/annurev-astro-082708-101722.

Gizon, L., Birch, A.C.: 2005, Local helioseismology. *Living Reviews in Solar Physics* **2**(6). http://www.livingreviews.org/lrsp-2005-6.

Howe, R., Haber, D., Bogart, R.S., Zharkov, S., Baker, D., Harra, L., van Driel-Gesztelyi, L.: 2012, Can we detect local helioseismic parameter shifts in coronal holes? In: *Alphabetical list of abstracts*, GONG 2012 - LWS/SDO 5 - SOHO 27, Palm Cove, Queensland, 52. Eclipse on the Coral Sea: Cycle 24 Ascending. http://moca.monash.edu/eclipse/index.php?page=program.

Ilonidis, S., Zhao, J., Kosovichev, A.: 2011, Detection of emerging sunspot regions in the solar interior. *Science* **333**, 993 – . doi:10.1126/science.1206253.

Jackiewicz, J., Gizon, L., Birch, A.C., Duvall, T.L. Jr.: 2007, Time-distance helioseismology: Sensitivity of f-mode travel times to flows. *The Astrophysical Journal* **671**(1), 1051. http://stacks.iop.org/0004-637X/671/i=1/a=1051.

Lemen, J.R., Title, A.M., Akin, D.J., Boerner, P.F., Chou, C., Drake, J.F., Duncan, D.W., Edwards, C.G., Friedlaender, F.M., Heyman, G.F., Hurlburt, N.E., Katz, N.L., Kushner, G.D., Levay, M., Lindgren, R.W., Mathur, D.P., McFeaters, E.L., Mitchell, S., Rehse, R.A., Schrijver, C.J., Springer, L.A., Stern, R.A., Tarbell, T.D., Wuelser, J.-P., Wolfson, C.J., Yanari, C., Bookbinder, J.A., Cheimets, P.N., Caldwell, D., Deluca, E.E., Gates, R., Golub, L., Park, S., Podgorski, W.A., Bush, R.I., Scherrer, P.H., Gummin, M.A., Smith, P., Auker, G., Jerram, P., Pool, P., Soufli, R., Windt, D.L., Beardsley, S., Clapp, M., Lang, J., Waltham, N.: 2012, The Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO). *Solar Phys.* **275**, 17 – 40. doi:10.1007/s11207-011-9776-8.

Lindsey, C., Braun, D.C., Jefferies, S.M.: 1993, Local helioseismology of subsurface structure. In: Brown, T.M. (ed.) *GONG 1992. Seismic Investigation of the Sun and Stars*, *Astronomical Society of the Pacific Conference Series* **42**, 81.

Morse, P.M., Feschbach, H.: 1953, In: Harnwell, J.P. (ed.) *Methods of Theoretical Physics*, McGraw-Hill Book Company, Inc., New York, 1064 – 1076. Chap. 9.3.

Munro, R.H., Withbroe, G.L.: 1972, Properties of a coronal "hole" derived from extreme-ultraviolet observations. *Astrophysical Journal* **176**, 511. doi:10.1086/151653.

Navarro-Peralta, P., Sanchez-Ibarra, A.: 1994, An observational study of coronal hole rotation over the sunspot cycle. *Solar Phys.* **153**, 169 – 178. doi:10.1007/BF00712499.

Pijpers, F.P.: 2006, *Methods in helio- and asteroseismology*, Imperial College Press, London. ISBN 1-86094-755-7.

Schou, J.: 2004, Low frequency modes. In: Danesy, D. (ed.) *SOHO 14 Helio- and Asteroseismology: Towards a Golden Future*, *ESA Special Publication* **559**, 134.

Thompson, W. T.: 2010, Precision effects for solar image coordinates within the fits world coordinate system. *A&A* **515**, A59. doi:10.1051/0004-6361/200810357. http://dx.doi.org/10.1051/0004-6361/200810357.

Waldmeier, M.: 1981, Cyclic variations of the polar coronal hole. *Solar Phys.* **70**, 251 – 258. doi:10.1007/BF00151332.

Yang, M.-H., Chou, D.-Y., Zhao, H., Liang, Z.-C.: 2012, Phenomenological study of interaction between solar acoustic waves and sunspots from measured scattered wavefunctions. *The Astrophysical Journal* **755**(1), 10. http://stacks.iop.org/0004-637X/755/i=1/a=10.

Zhao, J., Couvidat, S., Bogart, R.S., Parchevsky, K.V., Birch, A.C., Duvall, T.L., Beck, J.G., Kosovichev, A.G., Scherrer, P.H.: 2011, Time-distance helioseismology data-analysis pipeline for Helioseismic and Magnetic Imager onboard Solar Dynamics Observatory (SDO/HMI) and its initial results. *Solar Physics* **275**(1-2), 375 – 390. doi:10.1007/s11207-011-9757-y.

Zhou, X., Smith, E.J.: 2009, Solar cycle variations of heliospheric magnetic flux. *Journal of Geophysical Research (Space Physics)* **114**, 3106. doi:10.1029/2008JA013421.