SOI Investigation Proposal

Title: Sunspot – p-Mode Scattering Measurements Using Hankel and Time-Distance Techniques

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Abstract / Technical Summary:

Our principal scientific objective is to measure the p-mode scattering properties of a few selected sunspots and plage regions using both the "Hankel decomposition" analysis and "time-distance" analysis. We will primary utilize the full disk Doppler images obtained by MDI-SOI during the 2 month/year Dynamics program for both the Hankel scattering (phase shift) measurements and the time-distance (travel time) mapping. Measurements of p-mode absorption by sunspots at very high degrees will also be made using one or more of the 8 hour "High Resolution-Field" scans made during campaign mode. The use of both the Hankel and time-distance analyses will enable a direct quantitative comparison between the two methods, which is necessary to understand and interpret the results obtained by both procedures.

Investigation Plan:

Active region seismology is concerned with the determination and interpretation of the interaction of the solar acoustic oscillations with near-surface target structures, such as magnetic flux concentrations, sunspots, and plage. Recent observations with high spatial resolution and long temporal duration have enabled the measurement of the scattering matrix for sunspots and solar active regions as a function of the mode properties (wavenumber, frequency and azimuthal order). From this information one may determine the amount of p-mode absorption, partial-wave phase shift, and mode mixing introduced by the sunspot. In addition, new techniques in the "time-distance" regime of helioseismology have been applied to studying local inhomogeneities, including sunspots.

There are two main parts of our proposed SOI investigation. First, we will employ the recently developed techniques of Braun et al. (1992) and Braun (1995) which have enabled determination of phase shifts, absorption, and mode mixing of p-modes which are *not* averaged over azimuthal order, wavenumber or frequency. The MDI-SOI data will allow measurements at higher spatial frequencies and with higher signal-to-noise levels, which will play a crucial role in the identification of the absorption mechanism and allow the modeling of wave speed perturbations below active regions. We will also measure mode mixing (both in radial and azimuthal order) in sunspots and other active regions and construct maps of the spatial distribution of the scattering properties for quantitative comparison with other active region parameters.

Second, we will perform "time-distance" analyses of the same active regions studied above. That travel times could be directly measured was only discovered recently (Duvall et al. 1993). Duvall (1995) found that travel times were reduced for waves traveling through a sunspot with the effect being almost independent of distance. In this case the waves were not measured in the spot at all but by looking at the second time-distance curve. Duvall et al. (1995) found travel times also reduced for waves traveling through spots and plage but in this case the measurements were made from locations in the spots and plage. The time deficits decreased with the distance for this study in contrast to the earlier one. The technique used in both of these studies will be applied to the same regions in an attempt to reconcile the various results.

a) Hankel Analysis of Sunspots and Active Regions

In this approach we consider the effect of the sunspot upon incident p-modes by a Fourier - Hankel decomposition of the acoustic waves in a polar coordinate system centered on the sunspot. The amplitudes and phases of the scattered p-modes provide the complete scattering properties of the sunspot. Typically, the Doppler signal is interpolated onto a spherical polar coordinate system (θ, ϕ) with the sunspot situated at one pole ($\theta = 0$). The analysis is confined to an annular region, defined by a range of polar angles $\theta_{min} < \theta < \theta_{max}$. For values of $\theta \ll \pi$, we may employ Hankel functions as approximations to the Legendre function decomposition (Braun 1995).

From the set of measured amplitudes of the incoming and outgoing modes we can deduce the scattering properties of the feature (e.g., sunspot) selected. As in quantum or classical theory, it is customary to characterize the scattering properties of an object by means of the scattering matrix. For each temporal frequency ω, we define a matrix $\mathcal{S}$ so that the amplitude B_i of an outgoing mode i (with azimuthal order m_i and radial order n_i) depends upon the complete set of incident mode amplitudes A_j as:

$$B_i(\omega) = \sum_j A_j(\omega)\mathcal{S}_{ji}(\omega).$$

The partial wave phase shifts are simply the arguments of the elements of $\mathcal{S}$:

$$\delta_{ji} = \arg(\mathcal{S}_{ji}).$$

If the different incoming wave amplitudes A_j are uncorrelated then the above phase shift can be determined from the observed amplitudes by simply taking the average of $\arg(B_i/A_j)$ over some small range of modes (i.e., the frequency width of a p-mode ridge at a measured wavenumber). The arguments of the diagonal components ($\mathcal{S}_{ii}$) represent the scattering phase shifts presented in Braun et al. (1992) and Braun (1995). The off-diagonal components of $\mathcal{S}$ characterize the amount of *mode mixing* introduced by the scatterer. For example, depth or azimuthal asymmetries of the spots (combined with the stratification of the solar atmosphere itself) will couple an incoming mode of given azimuthal order m and radial order n to outgoing modes with different m and n having the same temporal frequency.

The spatial and temporal resolution of the MDI-SOI instrument will allow measurements of p-mode scattering, mode mixing and absorption for a wide range of frequency and wavenumber. We will use observing sequences with the High-Resolution Field of a few sunspots to measure p-mode absorption up to very high degree ($l > 1000$). Detailed measurements of the absorption of p-modes by sunspots is very likely to be a crucial element in identifying the absorption mechanism. Spruit and Bogdan (1992) and Cally and Bogdan (1993), for example, predict *multiple* absorption minima along the p-mode ridges. As noted by Braun (1995) the observations tentatively confirm what may be the first minimum at 5 mHz. Further analysis of better quality data is required.

As was first noted by Bogdan et al. (1993) it is important to separate the effects of finite p-mode lifetimes from the absorption measurements. We propose to do this in the following manner. Incoming p-modes entering the outer boundary of the annulus most likely have ranges which in general decrease with increasing degree (we define the range to be the distance traveled by the mode during its lifetime). Modes with ranges comparable or smaller than the annulus dimensions should show smaller values of measured absorption, since their "local" nature implies they interact more with the convection in their immediate environment than with a distant sunspot. The full disk images obtained during the Dynamics Program will allow the measurement of p-mode absorption as a direct function of annulus size. In a preliminary test using the 1988 South Pole data we repeated the scattering analysis performed for sunspot group NOAA 5254 with a variety of different annulus dimensions (Bogdan and Braun 1995). It is quite striking that while p-modes with degrees less than about 300 show very nearly the same levels of absorption over the range of annulus sizes, this is not the case for higher degree modes which show a marked decrease in the absorption with mean annulus radius. The different behavior for modes above and below l=300 is consistent with the picture put forward by Bogdan, et al. (1993) which considered p-modes below 300 to be "global" in nature while modes with l considerably greater than 300 to be "local". Employing an "acoustic transfer equation" (along the lines suggested by Cally, Bogdan and Zweibel 1994) it is possible to model the decrease in α to yield both the true absorption (α_o) produced by the sunspot and the p-mode range, or lifetime. For example, if I_- is the (steady state) acoustic intensity of an incoming mode with a range Δ it is straightforward to show that the outgoing mode intensity at a given angular distance θ from the spot is $I_+(\theta) = I_-(1 - \alpha_o e^{-\theta/\Delta})$. The measured absorption as determined by integrating the intensities over an annulus with mean radius $\overline{\theta} = (\theta_{max} + \theta_{min})/2$ has the form $\alpha(\overline{\theta}) = \alpha_o e^{-\overline{\theta}/\Delta}$. We stress that in addition to determining the true sunspot absorption, required for comparisons with models of the absorption mechanism, the technique will yield measurements of p-mode ranges (and knowing their group velocities, the lifetimes as well) in a manner independent of interpreting mode line profiles in observed power spectra. Knowledge of mode amplitudes and lifetimes are required for a complete understanding of the interaction of p-modes with convection and its relation to acoustic excitation in the Sun.

Data taken during the SOI-MDI 2 month/year Dynamics Program will allow substantial improvement in the measurement of p-mode scattering (phase shifts and mode mixing) from sunspots. This database will provide the temporal continuity required for the phase shift measurements as well as allow a range of active region targets. Scattering phase shifts measured using the Hankel techniques will also be compared directly with the phase shift inferred from travel time measurements of acoustic rays isolated by time-distance analysis (see the next section). Improved measurements of scattering phase shift by active regions will be used to model the subsurface structure of the perturbations in the acoustic properties of the medium introduced by the local magnetic fields. Initial modeling efforts, which solve the inhomogeneous wave equation for the scattered waves using the standard Green's function method under the simplification of the Born approximation, have been highly successful (Fan, Braun, and Chou 1995). It is found that the variation of scattering phase shifts with degree and radial order yields direct information about the depth variation of the inhomogeneities in pressure and wave speed induced by the sunspot.

The discovery of mode mixing in the observed p-mode scattering (Braun 1995a,b) was an unexpected result and we intend to devote more time to exploring this interesting phenomenon. We intend to improve the data reduction techniques to measure the strength of the mode mixing (rather than just the mode mixing phase shifts). One method will be to perform a least squares fit of outgoing mode amplitudes to the appropriate sum of incoming amplitudes, in order to directly measure the scattering matrix components. The absence in the SOI data of the degrading effects of the terrestrial atmosphere will be crucial in performing these mode mixing measurements, since it is necessary to know the the true p-mode amplitudes as a function of degree (seeing effects will reduce the amplitudes of higher degree modes relative to those at lower degree). Our models of p-mode scattering using the Green's function solution can also be readily extended to compute the off-diagonal elements of the scattering matrix for a model sunspot. Thus, by a comparison of the observed $\mathcal{S}$ matrix with those computed by our "forward" modeling effort, we hope to deduce further constraints on the internal and subsurface conditions of sunspots.

It is our goal to measure the absorption and scattering properties of a variety of solar activity, ranging from plage to pores and sunspots. A plage observed by Braun (1995) in 1988 South Pole data showed absorption but no measurable phase shifts. We wish to quantitatively relate the amount of scattering and absorption to parameters of the active regions, most notably mean magnetic flux (from MDI-SOI magnetograms), and the presence and size of sunspots. For one or more complex active regions we plan on spatially mapping both the absorption and phase shifts (which to first order may be considered a measure of the sound speed perturbation) using a procedure developed by Braun, LaBonte and Duvall (1990) which will be modified to allow phase shift measurements. In addition to providing a quantitative comparison between the scattering properties and magnetic field, the mapping technique can reveal scattering sources which may be associated with the active regions but do not have a visible surface manifestation. These maps will also be compared with wave speed maps, constructed from travel time measurements discussed in the next section.

b) Time-Distance Analysis

Most work in helioseismology to date uses the measurement and prediction of the frequencies of the acoustic normal modes to decipher the solar interior structure. It has been known for several years that solar activity affects these frequencies (Woodard and Libbrecht, 1993). Increased solar activity leads to an increase of the mode frequencies. One might make the simplification that an increase in the wave speed in the mode's trapping cavity would cause the normal mode frequency to increase. The increase of the normal mode frequencies is a strong function of frequency but only weakly dependent on the spatial scale of the modes. This signature is that of a near-surface effect, as the height in the atmosphere of the reflection of waves is also a function mostly of frequency. One possible effect is a change in the depth of the reflecting surface. If the reflecting surface moves down, the trapping cavity becomes smaller, and the mode frequency increases. Another way of saying that the reflecting surface is moving down is to say that the acoustic cutoff frequency is increasing at a given depth.

A new approach to the study of solar activity uses measurements of travel times between different surface locations to attempt to isolate subsurface inhomogeneities. At first this promising new technique for studying local effects was used to study global phenomena, in particular it was found that waves of sufficiently high frequency were not reflected by the solar atmosphere (Duvall et al. 1993) and that it was possible to uncover the near-surface atmospheric structure by measuring the frequency dependence of the travel times (Jefferies et al. 1994). The first uses of the technique for local problems were to measure that sunspots caused a decrease in the travel time through the region (Duvall 1995), an inconclusive study of the travel times through active regions (Korzennik et al. 1995), and a rudimentary search for subsurface convective motions (Duvall 1995).

In the present work, we would like to tie up a few of the "loose ends" of the previous time-distance work. Described above, phase shifts were not observed in a plage region, but travel time deficits are detected in plage regions (Duvall et al. 1995). A naive first thought might be that phase shifts would be related to travel times through a simple relation like $\phi = \omega t$, where ϕ is the phase shift, ω is the frequency of the wave, and t is a travel time. If one puts in $\phi = 90\,\mathrm{deg}$ (a typical phase shift observed in a sunspot), $\omega = 2\pi(3mHz)$, one finds a time of 83 seconds which is of the order of the travel time deficits measured. By using the different analysis procedures on the same regions, we could hope to eliminate different regions as the source of a difference.

References

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