ABSORPTION OF ACOUSTIC WAVES BY SUNSPOTS

II. Resonance Absorption in Axisymmetric Fibril Models

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Abstract. Observations of the scattering of acoustic waves by sunspots show a substantial deficit in scattered power relative to incident power. A number of calculations have attempted to model this process in terms of absorption at the magnetohydrodynamic Alfvén resonance. The results presented here extend these calculations to the case of a highly structured axisymmetric translationally invariant flux-tube embedded in a uniform atmosphere. The fractional energy absorbed is calculated for models corresponding to flux-tubes of varying radius, mean flux-density and location below the photosphere. The effects of twist are also included.

It is found that absorption can be very efficient even in models with low mean magnetic flux density, provided the flux is concentrated into intense slender annuli. Twist is found to increase the range of wave numbers over which absorption is efficient, but it does not remove the low absorption at low azimuthal orders which is a feature of resonance absorption calculations in axisymmetric geometry, and which is in conflict with observation.

These results suggest that resonance absorption could be an efficient mechanism in plage fields and fibril sunspots as well as in monolithic sunspots. At present it is too early to make any definite deductions about sunspot structure from the observations, but the possible future use of sunspot seismology to resolve open questions in the theory of sunspots is briefly discussed.

1. Introduction

The observation of trapped acoustic-gravity waves (p modes) in the Sun has made possible the direct determination of physical conditions in the solar interior. Theoretical techniques for inverting helioseismological data to determine the solar hydrostatic stratification and internal rotation are at an advanced stage of development and have been successfully applied to real solar data.

The study of the interaction of acoustic waves with inhomogeneities in the outer part of the Sun is a less well-developed field, and the stage has certainly not yet been reached where direct inversion of data to determine, for example, the sub-surface structure of sunspots or active areas is a viable possibility. At present it is more useful to calculate the scattering of acoustic waves in exemplary models in order to obtain some insight into the physics of the interaction, as performed here, than to attempt to make deductions based on highly tentative theory.

Observations of acoustic scattering by sunspots have been made by Braun, Duvall, and LaBonte (1988, hereinafter referred to as BDL). In a cylindrical polar coordinate system (s, \( \phi \)) centred on the spot, the Doppler velocity field in an annulus around the
spot was decomposed into components $\Psi_m$ of the form

$$\Psi_m = e^{im\phi} \int \int \left[ A_m(k_s, \omega)H_m^{(1)}(k_s) + B_m(k_s, \omega)H_m^{(2)}(k_s) \right] e^{i\omega t} dk \, ds \, d\omega,$$

(1)

where $H_m^{(1)}$ and $H_m^{(2)}$ are Hankel functions of the first and second kinds describing, respectively, waves which are inwardly and outwardly travelling. The quantity $1 - |B_m/A_m|^2$ then defines an apparent power absorption coefficient as a function of azimuthal order $m$, frequency $\omega$, and radial wave number $k_s$. The key result reported by BDL is that the power-scattering coefficient is significantly less than unity (about 50%) over a wide range of azimuthal order, frequency, and wave number.

The observation of this strong interaction between sunspots and $p$ modes provides for the possibility of using $p$ modes to probe sunspot structure. However, such a program cannot be begun until the mechanism responsible for the absorption has been identified. Any explanation offered must deal with a number of puzzling aspects of the observations. Possibly the key problem to be explained is the large horizontal size of the absorbing region, as deduced from the variation of absorption with azimuthal order. Within the spot, a partial wave of order $m$ will typically have an amplitude proportional to the Bessel function $J_m(k_s)$. Now the function $J_m$ is of low amplitude when the argument is much less than the order. Hence, the dimension of the region in which the absorption is occurring may be estimated by determining the value of $m/k_s$ at which the absorption coefficient approaches zero.

The estimated radius is usually larger, and for some spots much larger, than the size of the spot itself, suggesting either that the spot increases rapidly in radial dimension below the surface, or that absorption is occurring outside the spot (as well as inside), perhaps in the surrounding plage region. These considerations are clarified by reference to the work of Braun, LaBonte, and Duvall (1990) who analysed the local absorption of waves in a number of active regions, including two of those studied by BDL. The result of the local analysis is an absorption map showing the variation of absorbing efficiency across an observed region. The authors note that shadowing effects tend to produce an apparent absorbing region which is a factor $\sqrt{2}$ larger in radius than the true absorbing region. Thus their absorption map for the 24 October, 1986 spot implies that absorption occurs within a region about 55 Mm in radius. This is comparable with the radius deduced from the original BDL observations, and also with the observed size of the plage region around the spot shown on the accompanying magnetogram. The spot itself has a photospheric radius of only 15 Mm. For the observers' 23 February, 1983 spot, absorption occurred primarily within a radius of about 15 Mm, with some further slight absorption out to about 20 Mm. This is in broad agreement with the further analysis by Braun, LaBonte, and Duvall which shows a spot of radius 13.5 Mm within a plage region of radius about 19 Mm. The local absorption map for the same region implies an absorbing radius of about 20 Mm.

The conclusion from these results must be that efficient absorption is occurring not only in sunspots but also in surrounding plage. Such a conclusion is surprising, as the