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An Analytic Theory of Adiabatic p-modes in the Atmospheres of the Sun and Sun-like Stars

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Abstract. An analytic theory of resonant transmission has been used to study adiabatic, non-vertical oscillations in a realistic model of the solar or a stellar atmosphere and subphotosphere. Basic observed features of solar p-modes can be explained in this way.

1. Basic assumptions and analysis

The height profile of temperature T in a realistic solar or solar-type stellar model, extending from the subphotosphere through the atmosphere up to the corona, has been piecewise approximated by various nonlinear and linear functions for the different regions. Solving the basic equations of adiabatic, non-vertical oscillations for these regions in the Cowling approximation we obtained the eigenfunctions for the p-modes in exact analytic form in terms of known functions. One of the advantages of this solution is an adequate matching of the complicated region around $T_{\min}$ — with steep gradients of T on both sides — by one smooth function. The complete solution is obtained by matching to each other the partial solutions for the different layers. This solution provides the base for a detailed discussion of the reflection and transmission of waves through the acoustic barrier and above the barrier for higher frequencies ν. The consideration of a lower reflecting boundary is not necessary in such a model of resonant transmission.

2. Results

Using the exact solution it has been demonstrated, that the mechanism of resonant transmission by itself is sufficient to explain the main features of the observed frequency spectrum of the solar p-modes, including the 5-min oscillations and the power peaks in the high-frequency tail between 5 and at least 10 MHz. The dependence of the power spectrum on the height z, on the frequency ν, and on the degree l has been demonstrated. The first resonant frequencies always correspond to the 5-min oscillations.

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It has been shown that the upper turning point of the resonator for low frequencies $\nu \lesssim 4$ mHz does not coincide with the boundary of the acoustic potential barrier, the latter extending from the steep gradient of T at the upper subphotosphere up to that above the minimum T_{min}. The wakes of the waves penetrate deep into the barrier (up to a height of 500 km in the solar atmosphere) and are reflected from there. High frequencies are reflected from the chromosphere-corona transition region. For not any frequency there exists a total reflection; with increasing frequency there is an increasing leakage of wave energy into the corona.

It has been shown that all observable characteristics of oscillations depend directly on the phase shift $\Delta\phi$ between upward and downward running waves. With changing height and frequency $\Delta\phi$ changes in jumps; the resonance peaks in the spectrum arise at $\Delta\phi = 0$.

3. Discussion

The phases of the waves can be modified by various mechanisms such as reflections, nonadiabatic effects (mainly interaction with radiation, if acoustic waves are considered), scattering at structural inhomogeneities, etc. A theoretical model consistent with the observed data should take into account all of these mechanisms or at least the first and second of them. So far our simple model considers the first effect only.

Apart from the neglect of nonadiabatic effects, the power spectra resulting from our present model turn out to be satisfactory and to reflect basic features of the observations. A conclusive comparison with ground-based and space-borne observations, however, should be postponed until the nonadiabatic effects have been taken into account. In other papers we considered nonadiabatic effects, that is the interaction between radiation, acoustic and thermal waves, in great detail, but only for a homogeneous mean model without gravitational stratification (Dzhalilov et al. 1994; Staude et al. 1994; Zhugzhda et al. 1993). In a future investigation both the gravitational stratification and the nonadiabatic effects are planned to be taken into account. That analysis will provide the basis for facing our modelling with measurements of ground-based velocity data and of luminosity oscillations planned to be measured aboard the satellites CORONAS-F and SOHO.

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