CHROMOSPHERIC SEISMOLOGY

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1. INTRODUCTION

The aim of the present study is to examine whether seismologic diagnostic techniques may be used to improve the models of the solar chromosphere. We are mainly concerned by oscillations observed in the cores of strong lines such as the resonance lines of Ca II or Mg II. It is intuitive, and confirmed by numerical simulations (Gouttebroze and Leibacher, 1980), that the displacements of the cores of these lines are strongly correlated with the vertical velocity of the atmospheric layer where the line center optical depth is equal to 1. With classical atmospheric models such as those of Vernazza et al. (1981) (hereafter VAL), these line cores are formed in the chromospheric plateau, around 1500 km for the Ca II lines and 1900 km for the Mg II ones.

From observations made so far, we may conclude that :

(i) in quiet and relatively dark regions of the solar disk, the periods of oscillations observed at chromospheric level are shorter (120 to 300 s) than that observed in pure photospheric lines (250 to 350 s) ;

(ii) in the same regions, there a negative correlation between the mean brightness (K-index for instance) and the frequency of oscillation ;

(iii) in the brightest parts of the supergranulation network, oscillations with longer periods (10 to 15 minutes) dominate the classical "5-minute" oscillation.

These different points were yet apparent in the first observations of oscillations in Ca II lines, made by Jensen and Orrall (1963), and confirmed by a number of subsequent studies. Similar conclusions were drawn for the Mg II lines by Artzner (1982). The gradual decrease of oscillation frequency vs. brightness is particularly visible on the diagrams given by Damé et al. (1984).

2. BASIC ASSUMPTIONS AND NUMERICAL METHODS

We assume that the nature of chromospheric oscillations is the same as that of 5-minute ones, i.e. arises from the trapping of acoustic-gravity waves by a temperature gradient. In this picture, the solar atmosphere

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contains two resonant cavities, one in the convective zone and the other in the chromosphere, coupled by tunnel effect through the temperature minimum region. At higher frequencies, these two cavities join together to form a single one (cf. Ulrich and Rhodes, 1977, Ando and Osaki, 1977, or Leibacher et al., 1982). The atmospheric models used in the following numerical computations are plane-parallel ones including a convective zone, a photosphere, a chromosphere, a transition zone and a corona. The convective zone is determined from a mixing-length theory, the photosphere and the chromosphere are given by a semi-empirical model, and the transition zone and corona are calculated assuming the balance between the radiative and conductive fluxes. The oscillation modes are computed under the adiabatic assumption, by numerical integration of the linearized Navier-Stokes equations with appropriate boundary conditions. This procedure yields eigenvalues (horizontal wavenumber k_H and circular frequency ω) and eigenfunctions (amplitudes of velocity and pressure perturbations as functions of altitude).

3. THE CHROMOSPHERIC RESONANCE AND ITS CONSEQUENCES

3.1. Plane-parallel atmosphere

As "5-minute" and chromospheric oscillations constitute a single dynamical system, their modal structure is the same : In the (k_H-ω) plane, it is a combination of oblique ridges, which are the modes of the lower cavity alone, and one quasi-horizontal line, which is the fundamental mode of the chromospheric cavity. The combination of these two systems of modes produces avoided crossings (Ulrich and Rhodes, 1977). But, in spite of this common modal structure, observations of oscillations in the photosphere and in the chromosphere may give different results because the distribution of oscillatory power between the modes depends strongly on the altitude where the velocity is measured : comparing the eigenfunctions relative to the different modes, for an arbitrary wavenumber $k_H = 0.8$ (Mm)$^{-1}$, we found that modes of order 1, 2, 3, 4 and 6 (ω = 0.0187, 0.0229, 0.0270, 0.0307 and 0.0345 s^{-1}) had their maximum kinetic energy density in the photosphere and upper convection zone, while that of order 5 (0.0322 s^{-1}), which corresponds to the resonance, had a strong maximum in the chromosphere, between 1 and 2 Mm of altitude. Thus, observations of dopplershifts in the Ca II K line core show principally the chromospheric resonance mode, contrary to measurements made in photospheric lines, and thus may constitute a tool to probe the chromospheric structure.

3.2 Inhomogeneous chromosphere

The existence of strong inhomogeneities in the chromosphere may, however, alter significantly the preceding scheme, since the variations of temperature and thickness from place to place will change the frequency of resonance. These variations may break the spatial coherence of the chromospheric mode, so that, in the (k_H-ω) diagram, the sharp and quasi-horizontal ridge, expected from the preceding theory, may be replaced by a broad band. On the contrary, observations of chromospheric oscillations with high angular resolution may provide a measure of the local resonance frequency, since this frequency is almost independent of the wavenumber.

4. OSCILLATORY PROPERTIES OF SOME ONE-DIMENSIONAL MODELS

In order to determine the relations between the structure (temperature, thickness) of the chromosphere and its oscillatory properties, we computed the oscillation modes corresponding to different atmospheric models. Those labelled A, C and F are deduced from the corresponding models of VAL : we retained the mass-temperature relations of VAL and recompute the altitudes assuming hydrostatic equilibrium without microturbulent pressure. These 3 models have significantly different temperatures, but similar geometrical thicknesses. We also computed the modes for the original model C of VAL, i.e. including microturbulent pressure. This model, labeled C', is thicker than C by about 240 km. The results are summarized in Table 1 (limited to the minimum number of significant parameters). The mean temperature is represented by its value at $m = 10^{-4}$ g cm^{-2}, and the thickness by the altitude at the base of the transition region. The resonance frequency (which depends weakly on the wavenumber) is given only for $k_H = 1$ (Mm)$^{-1}$. In this table, we indicate also the result obtained by Ulrich and Rhodes (1977) for a much thicker model (labelled UR).

TABLE 1 : SUMMARY OF RESULTS

Model	Mean temperature (K)	Thickness (Mm)	Resonance frequency (s^{-1})
A	5950	2.13	0.0324
C	6300	2.03	0.0321
F	6700	1.95	0.0319
C'	6300	2.27	0.0310
UR		2.7	0.0263

The 3 models A, C and F give very similar resonance frequencies, the difference between the cooler and the hotter being about 1.5%. The differences of thickness appear to have a stronger effect on the resonance frequency : that of C' is lower than that of C by 3%, and that of UR by almost 20%.

5. DISCUSSION

Let us compare successively the preceding results with the 3 observational points mentioned in the Introduction :

(i) the frequency range : the resonance frequencies of all models under study lie within the range of observed ones. Concerning the series of

models given by VAL, it should be noticed that they all resonate at approximately the same period (near 200 s). This is probably due to the fact that these models have all nearly the same geometrical thickness. Another series of models, with more important geometrical differences, seem thus necessary to account for wide range of oscillation periods observed (about 120 to 300 s).
(ii) the decrease of frequency with mean brightness : It was suggested by Damé et al.(1984) that an increase of temperature could lower the frequency of resonance via a decrease of the acoustic cut-off frequency. If we compare the resonance frequencies of A, C and F, we conclude that such an effect exists, but that it is too weak to explain the differences between dark and bright points. This suggests the existence of a positive correlation between the mean temperature (or another parameter acting on brightness) and the thickness of the chromosphere.
(iii) oscillations in the bright chromospheric network : The model F, proposed by VAL to represent bright network points, has practically the same oscillatory properties than the other models. This is in contradiction with the observations, which show that, in these regions, the oscillatory field is dominated by long period (10 to 15 mn) oscillations. It is difficult to know whether this discrepancy is due to an inadequacy of the model, or to a failure of the present theory which neglects magnetic fields, whereas they are known to be intense in the chromospheric network.

In conclusion, it appears that a set of chromospheric models in hydrostatic equilibrium, with quasi-constant geometrical thicknesses, is unsufficient from the point of view of seismology, since it fails to explain both the diversity of resonance frequencies and their negative correlation with the intensities in the K line core. This inadequacy may be due either to temperature-vs.-mass fluctuations in the chromosphere much larger than those presently assumed, or to the existence of large departures from hydrostatic equilibrium (perhaps produced by magnetic fields or mass flows). Concerning the decrease of frequency vs. brightness, one may remark that a set of models where the geometrical thickness would increase with the mean temperature (rather than decrease as in the case of VAL) would give more satisfactory results.

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