AN EXCITATION MECHANISM FOR SOLAR FIVE-MINUTE OSCILLATIONS OF INTERMEDIATE AND HIGH DEGREE

H. M. Antia, S. M. Chitre and D. Narasimha
Tata Institute of Fundamental Research
Homi Bhabha Road, Bombay 400 005
India

ABSTRACT: The overstability of acoustic modes trapped in the solar convection zone is studied with mechanical and thermal effects of turbulence included, in an approximate manner, through the eddy transport coefficients. Many of these acoustic modes are found to be overstable with the most rapidly growing modes occupying a region centred around 3.2 mHz and spread over a wide range of length-scales. The numerical results turn out to be in reasonable accord with the observed power-spectrum of the five-minute oscillations of intermediate and high degree. The oscillations are probably driven by a simultaneous operation of the κ-mechanism and the turbulent conduction (convective Cowling) mechanism, the dominant contribution to the generation of self-excited acoustic waves arising from the convective Cowling mechanism.

The velocity fields on the solar surface provide a very valuable tool to probe the solar interior. In this connection the discovery of five-minute oscillations by Leighton, Noyes and Simon(1962) has been especially important. The science of solar seismology originated with the observations of Deubner(1975) who resolved the spatial and temporal structure of the sun's five-minute oscillations. The later work of Rhodes, Ulrich and Simon(1977) and Deubner, Ulrich and Rhodes(1979) provided a detailed power-spectrum of the five-minute oscillations of high degree (spherical harmonic degree $\ell > 150$). The observations using integrated sunlight by Claverie et al.(1979) and Grec et al.(1980) revealed the existence of five-minute oscillations of low degree($\ell < 3$). Recently Duvall and Harvey(1983) provided the power spectrum of the five-minute oscillations in the intermediate range($1 < \ell < 150$), and this bridged the gap between the observations of high degree and those of low degree.

The observations have undoubtedly confirmed the suggestion of Ulrich(1970) and Leibacher and Stein(1971) that these oscillations represent non-radial acoustic modes in the solar envelope. The important question of the excitation mechanism responsible for these modes has been examined by various authors. Ando and Osaki(1975) and Ulrich and Rhodes(1977) investigated the stability of non-radial oscillations in a realistic solar envelope model with full effects of radiative heat exchange. However, the interaction between turbulent convection and oscillations was neglected in these studies. This situation was remedied by Goldreich and Keeley(1977) and Berthomieu et al.(1979) who incorporated the influence of turbulent convection on the stability of acoustic modes to conclude that the turbulent viscosity stabilizes all of these modes.

In the solar envelope, except for the top few hundred Kilometers, major fraction of the total flux is carried by convection; also the turbulent conductivity is much larger than the radiative conductivity for the most part of the convection zone. The turbulence is, therefore, expected to modulate the heat flux in an appreciable manner. This prompted Antia et al.(1982) to undertake a study of the overstability of acoustic modes in the solar envelope with mechanical and thermal effects of turbulence included, albeit in an approximate manner, through the eddy transport coefficients. Many of the acoustic modes trapped in the solar envelope turned out to be overstable with the most unstable modes occupying a region centred around a period of 300 s. Our stability calculations indicated that turbulent heat exchange must play an important role in destabilizing the acoustic modes. Ando and Osaki (1975) had concluded from their analysis that the acoustic modes are largely overstabilized by the κ-mechanism operating in the hydrogen ionization zone, while we recognized that a simultaneous operation of the κ-mechanism and the turbulent conduction mechanism is responsible for exciting the five-minute oscillations. The dominant contribution to the generation of self-excited acoustic waves seemed to arise from the so-called convective Cowling mechanism. It should be emphasised that both the radiative and convective Cowling mechanisms have their origin in the strong superadiabaticity prevailing in the sub-surface layers, but the efficiency of the convective Cowling mechanism is larger by a factor (cf. Unno, 1976)

$$\frac{F^{conv}}{F^{rad}} \quad \frac{\nabla}{\nabla - \nabla_{ad}} .$$

We have been mainly concerned with the stability and driving of the acoustic modes rather than matching the calculated frequencies with observations. Our principal attempt was directed towards the choice of a model which yielded convective modes that are in reasonable accord with the observed features of granulation and supergranulation. Both the convective and acoustic modes are studied adopting the usual linearization procedure and we have included the perturbation in the convective flux in our analysis.

Following Goldreich and Keeley(1977) we have adopted the turbulent viscosity of the form

$$\nu_t = \sigma_t \alpha W L [\min\{ 1, (\frac{1}{\omega t_c})^2 \}] ,$$

where σ_t is the turbulent Prandtl number, α is an efficiency factor of order unity appearing in the mixing-length formalism, W the mean convective velocity, L the mixing length and $t_c = L/W$ is the turn-over time for the convective element at that depth and ω the frequency of the oscillatory mode in question. The factor in the square brackets ensures that the contribution from only those eddies with turn-over time shorter than $(1/2\pi)$ times the period of the given mode is included. We have adjusted the value of σ_t so as to obtain the best possible agreement between the length and time-scales of calculated convective modes with the corresponding observed features associated with granulation and supergranulation. This value of σ_t turns out to lie in the range of 0.2 - 0.3 for an envelope model which has a convection zone ≈ 200,000 km deep. It is encouraging to find that the same model yields frequencies of acoustic modes which agree reasonably with the observations of Deubner, Ulrich and Rhodes(1979) for high degree (ℓ) acoustic modes and with Duvall and Harvey(1983) for intermediate values of ℓ. There still remains a marked disagreement with higher harmonics at low ℓ, but this is most probably due to our neglect of the solar interior regions.

We have displayed the results of the stability calculations in Figure 1 which shows the contours of constant stability coefficient η = (growth rate/frequency) of a given acoustic mode in the $k_h - \omega$ diagram. The outermost contour corresponds to the marginally stable case $\eta = 0$, within which all the modes are unstable, while the modes outside the region are stable. We make the plausible assumption that only those modes with significant growth rates will have substantial observed power. It is then interesting to notice that the region where $\eta > 10^{-4}$ in the Figure approximately coincides with the region where significant amount of power has been observed. In particular, the high frequency cut-off implied by our stability analysis at around 4 - 5 mHz, more or less independent of ℓ is in rough agreement with the observations of Duvall and Harvey(1983). Also, at low ℓ, the lower harmonics are either stable or have an extremely small growth rate, which is consistent with the low observed power in these harmonics.

Our stability analysis bears out the results obtained earlier by Ando and Osaki(1975) that the most unstable p-modes are spread over a region centred mainly around 3.2 mHz with a wide range of horizontal length scales. There is one noticeable difference in our results, namely, we get closed contours of the stability coefficient η with a distinct peak, while Ando and Osaki have open contours with η increasing with ℓ up to $\ell = 1500$. This is clearly the influence of turbulent viscosity which because of its effectiveness at small length scales brings the growth rates down sharply at high ℓ.

It is not altogether clear why the amplitudes of these modes are observed to be small. But then it should be remembered that we are dealing with a large number of simultaneously excited modes and we do not know how the modes interact with each other and with the background turbulence in the convection zone.

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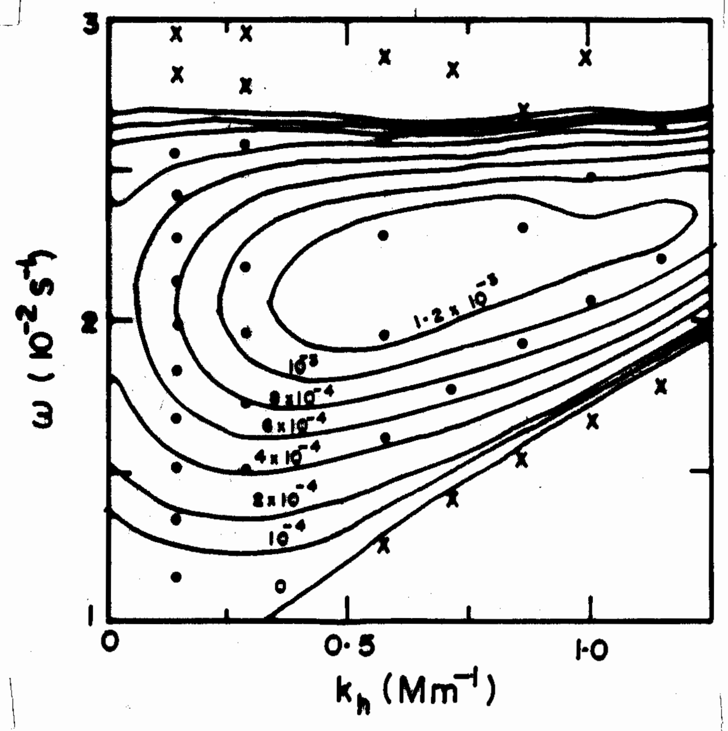

Fig. 1: The contours of equal stability coefficient η are indicated by numbers; the stable modes are labelled by crosses and unstable ones by open circles.