SOLAR FIVE-MINUTE OSCILLATIONS OF LOW, INTERMEDIATE, AND HIGH DEGREE*

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Abstract. The overstability of acoustic modes trapped inside the Sun is studied with mechanical and thermal effects of turbulence included in an approximate manner through the eddy diffusivities. Many of the acoustic modes are found to be overstable with the most rapidly growing modes occupying a region centred around 3.3 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 arbitrary degree. It is demonstrated that these oscillations are most likely to be driven by a simultaneous operation of the κ-mechanism and the convective Cowling mechanism, the dominant contribution to the generation of self-excited acoustic waves arising from the turbulent diffusion.

1. Introduction

The discovery of solar five-minute oscillations by Leighton *et al.* (1962) has provided a very valuable tool to probe the interior of the Sun. Later, Deubner (1975) resolved the spatial and temporal structure of these oscillations, thus initiating the science of helioseismology. A detailed power-spectrum of the five-minute oscillations of high degree (spherical harmonic degree $l \gtrsim 150$) was provided by the work of Deubner *et al.* (1979), while the low-degree oscillations ($l \leq 3$) were detected by Claverie *et al.* (1981) and Grec *et al.* (1983) using integrated sunlight. The gap between observations of high degree and those of low degree was bridged by the recent observations of solar five-minute oscillations of intermediate degree ($1 \leq l \lesssim 150$) by Duvall and Harvey (1983).

The important question of the excitation mechanism responsible for these oscillations was addressed by Ando and Osaki (1975) and Ulrich and Rhodes (1977). These authors investigated the stability of non-radial oscillations of high degree for a realistic solar envelope model by including the full effects of radiative exchange, but neglecting the interaction between turbulent convection and oscillations. This situation was remedied by Goldreich and Keeley (1977) by incorporating the influence of turbulent convection on the stability of acoustic modes which were shown to be stabilized by the presence of turbulent viscosity.

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2. Frequencies of Five-Minute Oscillations and the Excitation Mechanism

It is well known that, except for the top few tens of kilometers, a major fraction of the total flux in the solar convection zone is transported by convection. Furthermore, the turbulent conductivity is much larger than the radiative conductivity for the most part of the convection zone. Turbulence is, therefore, expected to play a major role in modulating the heat flux and the oscillatory motion. It should be recognized that both radiative and turbulent diffusion mechanisms have their origin in the strongly super-adiabatic sub-surface layer, but the efficiency of the turbulent diffusion mechanism turns out to be significantly larger (cf. Unno, 1976). This motivated Antia *et al.* (1982) to undertake a study of the overstability of acoustic modes in the solar envelope by approximately including the mechanical and thermal effects of turbulence by means of eddy transport coefficients. We investigate the stability of acoustic modes, of arbitrary degree, trapped inside the Sun by adopting for the present Sun the following characteristics: $X = 0.744$, $Z = 0.018$, $T_c = 1.52 \times 10^7$ K, $\rho_c = 145 \text{ g cm}^{-3}$, $X_c = 0.360$, $L = z + 486$ km. Here L is the mixing length and z the distance measured downwards from the level $\tau = 1$. The solar model was constructed using a non-local prescription, and also including the contribution from the turbulent pressure (cf. Antia *et al.*, 1983).

The results of the stability calculations are displayed in Figures 1 and 2. It is gratifying to note that the theoretically computed frequencies are in reasonable agreement with the observations of five-minute oscillations by Deubner *et al.* (1979) for high degree acoustic modes and those by Duvall and Harvey (1983) for intermediate and low degree modes. For the intermediate and low values of l, the departure of theoretically calculated

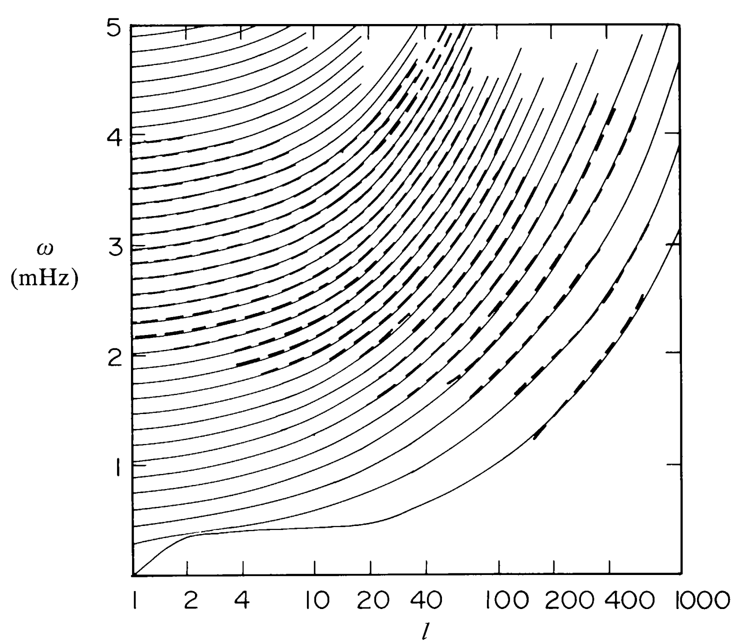

Fig. 1. The frequencies ω as a function of l for the first 35 acoustic modes ($f - p34$). The continuous lines represent the theoretically calculated frequencies, while the dashed lines observed frequencies.

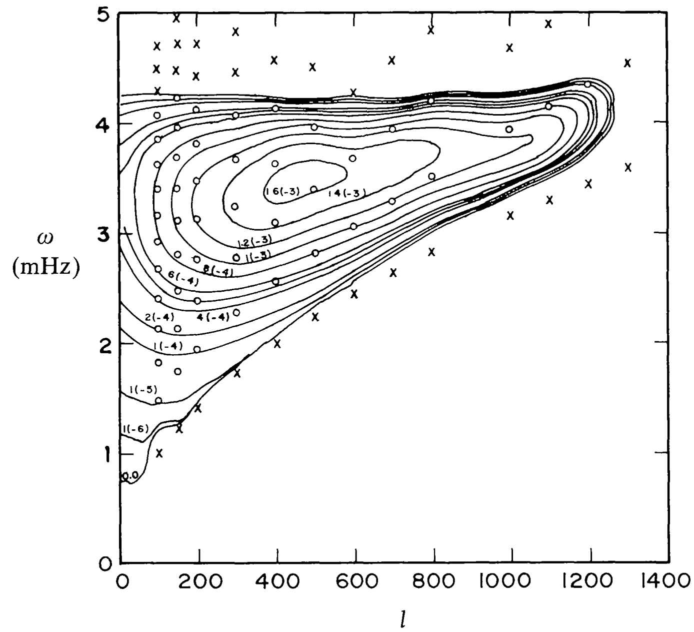

Fig. 2. The contours of equal stability coefficient η are shown in the $(\omega - l)$ plot where the crosses (×) denote stable modes and open circles (○) unstable modes. The outermost contour refers to the marginally stable case of $\eta = 0$.

frequencies is no more than 0.7% of the observed frequencies and in most cases the agreement is to within 15 μHz. However, for the high degree modes the observed frequencies were read from the power-spectrum plots, which can contribute errors comparable with the discrepancy between the observed and theoretical values, but nevertheless the agreement seems to be good.

The contours of constant stability coefficient η (≡ growth rate/frequency) of a given acoustic mode are shown in Figure 2 in a frequency (ω)-spherical harmonic degree (l) plot. The outermost contour corresponds to the marginally stable case ($\eta = 0$), within which all the modes are unstable, while the modes outside this region are stable. We make the plausible assumption that only those modes with significant growth rates will have substantial observed power. It is interesting to note that the region in the figure where $\eta \gtrsim 10^{-4}$ approximately coincides with the region where a substantial amount of power has been observed. In particular, the high-frequency cut-off yielded by our analysis around 4.3 mHz, more or less independent of l, is in rough agreement with the observations of Duvall and Harvey (1983). Furthermore, for 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 analysis is generally in agreement with the earlier results of Ando and Osaki (1975), save for a significant difference in that we get closed contours of the stability coefficient η, with a distinct and pronounced peak (having $\eta = 1.66 \times 10^{-3}$) around $l = 475$ and $\omega = 3.5$ mHz, while Ando and Osaki have open contours with η increasing with l. This is clearly the influence of turbulent viscosity included in our work which becomes effective at short wavelength and depresses the growth rates at high l.

3. Conclusions

The stability of acoustic modes trapped inside the Sun is investigated in the framework of a linearized theory, by incorporating in an approximate manner, the mechanical and thermal effects of turbulence on the mass flow through turbulent transport coefficients. Several of these acoustic modes are found to be overstable, with the most rapidly growing modes occupying a region centred around 3.3 mHz with a wide range of horizontal length-scales. The theoretical frequencies turn out to be in reasonable accord with the observed power-spectrum of the five-minute oscillations of low, intermediate, and high degree. The numerical results reveal that the acoustic modes which are stable for the viscous case when only the κ-mechanism is present, are significantly destabilized when turbulent diffusion is included. Likewise, in the inviscid situation the degree of instability of acoustic modes is stronger by a substantial amount when the full effects of radiative and turbulent diffusion mechanism are present over the case when only the κ-mechanism operates. We, therefore, conclude that the five-minute oscillations are driven by a combination of the κ-mechanism and the convective Cowling mechanism, the dominant contribution to the generation of self-excited acoustic waves arising from the diffusion mechanism.

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