CHAPTER 6

EXCITATION AND DAMPING OF SOLAR AND STELLAR OSCILLATIONS

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ABSTRACT. Variable stars can be broadly classified into two categories: (a) High amplitude pulsators like Cepheids and RR Lyrae variables, (b) Low amplitude pulsators like Sun and Sun-like stars. The study of stellar pulsations has opened the possibility of using the oscillatory modes to probe the internal structure and dynamics of these stars. The cause of pulsational instability for a majority of stars is the partial ionisation of the abundant elements present in the envelope of the stars, while some instabilities are driven by the transfer of momentum from the medium to the oscillating elements. Various mechanisms responsible for exciting and limiting the solar and stellar oscillations are discussed.

1. INTRODUCTION

It is well-known that stars in various parts of the Hertzsprung-Russell (H-R) diagram exhibit variability. These variable stars can be broadly classified into two categories:

(a) High amplitude pulsators,

(b) Low amplitude pulsators.

In category (a) we have the classical Cepheids and RR Lyrae stars which are characterised by the presence of only a few modes. These are mainly radial pulsators whose intensity varies by a good fraction of a magtitude, with a period in the range of a day to several tens of days.

For low amplitude pulsators, on the other hand, there is evidence for the simultaneous excitation of several modes. The most well-known example of this class is the set of acoustic modes observed in the Sun with their power predominantly around five-minute period, and also the p-modes revealed by the Sun-like stars (e.g. Alpha Centauri, Epsilon Eridani, Procyon). The rapid oscillations observed in Ap stars are in many ways similar to the solar five-minute oscillations. The study of ZZ Ceti stars has recently opened the possibility of using their oscillations in order to probe the internal structure of white dwarfs. Delta Scuti stars which pulsate at low amplitudes exhibit many

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characteristic radial and non-radial modes like the Beta Cephei variables. The analysis of stellar oscillatory modes is undoubtedly a very valuable diagnostic tool for checking the validity of theories of stellar structure and dynamics against direct measurements.

It turns out that for a majority of variable stars, the cause of pulsational driving is the cyclical ionisation of one or more elements present in the star. In fact, the classical κ- and γ-mechanisms are both associated with the ionisation of abundant constituents in the envelopes of stars. Basically, the partial ionisation of a dominant species holds the temperature in the ionisation zone sensibly unvarying, since most of the work of adiabatic compression goes into ionisation rather than into the thermal motion. The relative coolness in the compressive phase has two main consequences: it tends to inhibit the flow of radiation out of these regions, and secondly, the opacity also increases sharply as a result of partial ionisation of the dominant element (e.g. hydrogen). The net outcome is to effectively trap the radiation which then leads to a pressure-excess during the expansion phase, thus transforming part of the thermal energy into mechanical work manifesting as pulsation.

There is another class of instabilities which are driven by the transfer of momentum from the medium to the oscillating elements, and these involve a restoring force like a magnetic field or an elastic force (e.g. pressure), in the presence of thermal dissipation - these are broadly known as Cowling mechanisms (Unno et al., 1979). The pulsating stars are in the main driven by the κ- and γ-mechanisms, or some variant of the Cowling mechanism. In what follows we shall discuss various mechanisms that are responsible for driving and limiting the solar and stellar oscillations.

2. CEPHEIDS AND RR LYRAE STARS

The observational and theoretical properties of classical Cepheids and RR Lyrae variables have been extensively discussed in the literature (Cox, 1980). It is now generally accepted that the Cepheids and RR Lyrae stars are pulsationally unstable against radial and non-radial modes due to the κ- and γ-mechanisms operating in the hydrogen and helium ionisation zones. We expect the non-linear effects to be significant for these large amplitude pulsators and it has been demonstrated that in RR Lyrae stars the amplitudes are limited by a saturation of the driving mechanism.

One of the major problems concerning these stars is the role of the coupling between convection and pulsation. It has been known that in the absence of the effects of convection, the computed instability strip in the H-R diagram turns out to be much wider than what is indicated by the observations. Evidently, convection must in some way be responsible in fixing the red edge of the instability strip, and in fact, Baker and Gough (1979) addressed this problem to find that if the coupling between convection and pulsation is taken into account, the instability is indeed restored on the cool side of the instability strip. This is illustrated in Fig. 1 which shows the stability coefficient η = growth rate/frequency (taken positive for instability) against the effective temperature. It is clear from the plot that the stability coefficient become negative for values of $T_{eff} \leqq 6000$ K when convection-pulsation coupling is included. In the absence of coupling η never attains negative values on the cooler site.

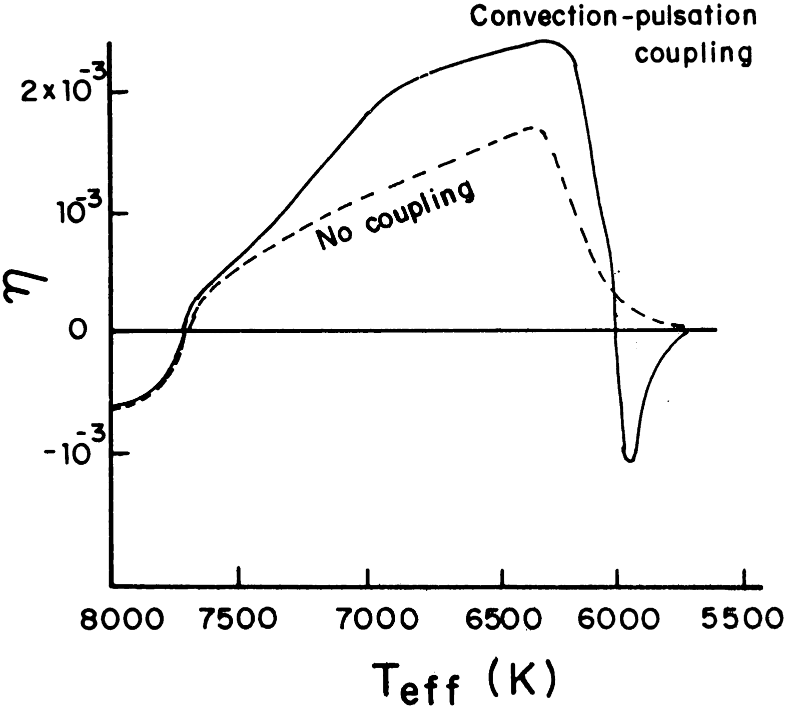

Figure 1. The stability coefficient η (= growth rate/frequency) is shown as a function of T_{eff} with the inclusion of convection-pulsation coupling (shown by the solid line) and neglecting the coupling (indicated by the dashed curve).

Gonczi and Osaki (1980), on the other hand, concluded that the convection-pulsation coupling described by Unno's theory is inadequate to produce the requisite red edge of the Cepheid instability strip, and that the coupling sometimes works to stabilise the modes and at times goes to destabilise the modes. In a later calculation, Gonczi (1981) introduced the effects of turbulent viscosity to produce a reasonably correct red edge of the strip. A valiant attempt has been made by Deupree (1977 a,b) to treat the problem of convection in pulsating stars. Here the description of convection is in terms of large two-dimensional eddies whose motion is limited by a time-varying eddy viscosity. Deupree's non-linear models produce the desirable return to stability on the redward side when the convection becomes strong enough to effectively throttle the instability. It is not unreasonable to surmise that our understanding of the pulsation phenomenon in Cepheids and RR Lyrae variables has reached a satisfactory level.

3. SUN AND SUN-LIKE STARS

The discovery of solar five-minute oscillations by Leighton, Noyes and Simon (1962) has provided a valuable tool to probe the interior of the Sun and Sun-like stars. The subject of helioseismology was ushered by the work of Deubner (1975) who resolved the spatial and temporal structure of five-minute oscillations of high degree (spherical harmonic degree $\ell \geqq 150$). The low degree ($\ell \leqq 3$) oscillations were detected by Clavarie et al. (1979) and Grec et al. (1983) using integrated sunlight, while the gap between the observed low-degree and high-degree p-modes was bridged by Duvall and Harvey (1983) with their measurements of five-minute oscillations of intermediate degree ($1 \leqq \ell \leqq 150$).

The most striking feature of oscillations in solar type stars is their very small amplitudes, e.g., the amplitudes observed in the Sun are at most about 25 cm s^{-1}. It is evidently important to understand the main processes that are responsible for exciting the solar p-modes and further limiting their amplitudes to such low values. This will enable us to gain an insight into the general driving mechanism of stellar pulsations. The excitation mechanism for the solar p-modes has been the subject of study by a number of authors. The observation of high degree modes undoubtedly indicate that these represent non-radial p-modes trapped in a cavity in the solar envelope. Ando and Osoki (1975) and Ulrich and Rhodes (1977) investigated the stability of non-radial oscillations for a realistic solar envelope model with full effects of radiative dissipation included in the calculations. They found many overstable acoustic modes with their power centred mainly around a period of 300 s and spread over a wide range of horizontal length scales. However, the interaction between convective turbulence and pulsation was neglected in these calculations. This situation was remedied by Goldreich and Keeley (1977) and Berthomieu et al. (1979) who examined the influence of turbulence on the stability of acoustic modes to conclude that the modes are all stabilised by the effect of turbulent viscosity.

In the solar envelope, except for the top several tens of kilometers, a major fraction of the flux is transported by convection. Furthermore, the turbulent conductivity is much larger than the radiative conductivity for the most part of the convection zone. The convective turbulence is, therefore, expected to control both the excitation and damping of solar oscillations. Antia, Chitre and Narasimha (1982) studied the overstability of acoustic modes in the solar envelope model with mechanical and thermal effects of turbulence incorporated, in an approximate manner, through the eddy transport coefficients. It was demonstrated that the p-modes in the five-minute range are excited by a simultaneous operation of the κ-mechanism and the turbulent conduction (convective Cowling) mechanism (Unno, 1976), the latter making a dominant contribution to the generation of self-excited waves. Recently, Antia, Chitre and Gough (1986) set out to address the question of the stability of p-modes by introducing the framework of time-dependent convection for the study of non-radial oscillations. The approach is based on the idea that the expression

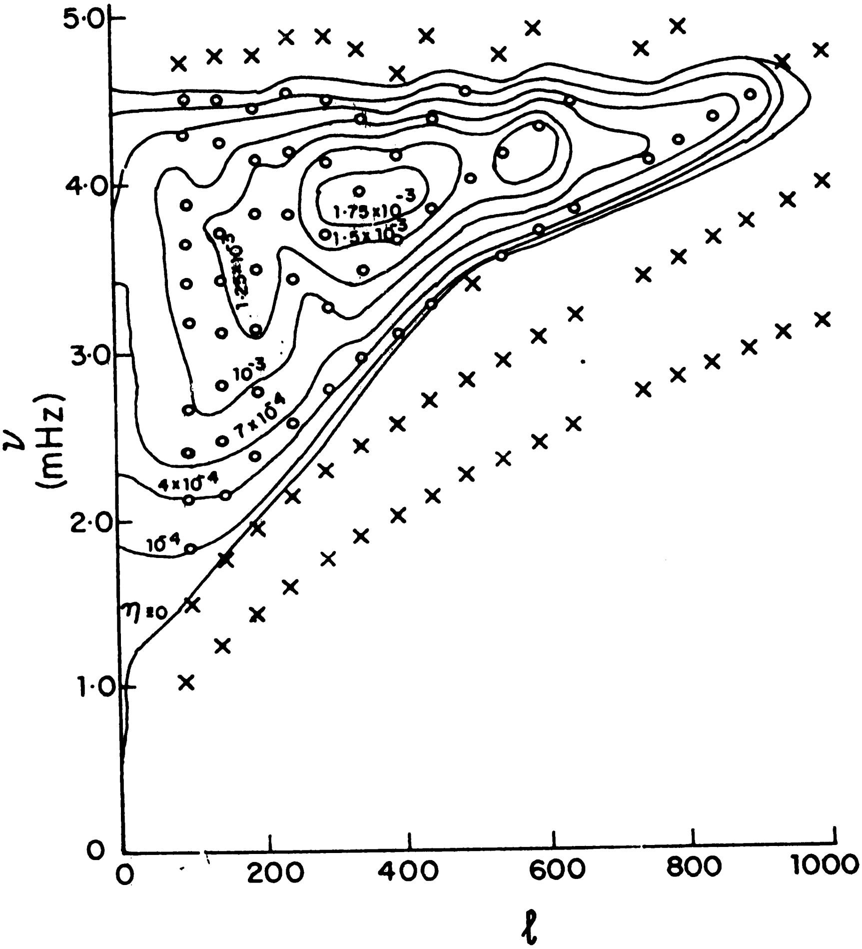

Figure 2. Contours of constant stability coefficient η are shown in the frequency (ν) vs. spherical harmonic degree (ℓ) plot where the crosses (×) denote stable modes and open circles (o) unstable modes. The outermost contour refers to the marginally stable case of $\eta = 0$.

for the convective flux applicable to a non-pulsating star,

$$F_c = K_t \beta ,$$

where K_t appears as a diffusion coefficient and β is the superadiabatic temperature gradient, can be generalised to a vector equation for the pulsating case, by writing

$$\underset{\sim}{F}_c = K_t \underset{\sim}{\beta} .$$

The generalised eigenvalue problem can be tackled numerically. In Fig. 2 are displayed the contours of constant stability coefficient η of a p-mode in a frequency (ν) versus spherical harmonic degree (ℓ) plot. The outermost contour corresponds to the marginally stable case ($\eta = 0$) within which all the modes are unstable, while modes outside this region are stable. We make the plausible assumption that only those modes with significant growth rates will have substantial power. It is interesting to notice that the region in which $\eta \geqq 10^{-4}$ in Fig. 2 approximately coincides with the region where a significant amount of power has been observed.

The high frequency cut-off indicated by our stability analysis, around 4-5 mHz is more or less independent of ℓ, and this is in rough agreement with the observations of Duvall and Harvey (1983). The lack of power at the high frequency end is probably due to the efficient radiative damping in the solar atmosphere. It is tempting to imagine that this high frequency cut-off might eventually serve as a valuable diagnostic for probing solar atmosphere. Another important observational feature is the linewidths of the peaks in the power spectrum which are indicators of the lifetime of the modes. In Fig. 3 we show the linewidths for radial modes calculated by Kidman and Cox (1984), and Antia, Chitre and Gough (1986). Here the growth rates are taken to be a measure of the linewidths which appear to be consistent with those measured by Isaak (1986),except that for higher frequencies beyond 4 mHz the growth rates calculated by Antia, Chitre and Gough (1986) show a decreasing trend. It should perhaps be stressed that Antia et al. assumed the radiation intensity to be equal to the Planck function in the equilibrium model and if this assumption is relaxed, Christensen-Dalsgaard and Frandsen (1983) find all the acoustic modes to be stable. A calculation that includes both the convective flux perturbation and the appropriate treatment of the radiative condition is in progress.

Clearly, the oscillation amplitudes, the linewidths and their variation both with frequency and spherical harmonic degree should be able to provide a handle on the underlying mechanism responsible for the observed pulsation. However, it must be admitted that the situation regarding the driving of the solar p-modes is rather unclear, and the excitation mechanism of these modes is still an unresolved issue. If the modes are indeed overstable, we should necessarily address the question of the damping process that limits the amplitudes to such low values that are observed. The mechanism of stochastic excitation by turbulent convection proposed by Goldreich and Keeley (1977), on the other hand, yields amplitudes of individual modes that are smaller than those observed by at least an order of magnitude. But then the equipartition argument used by Goldreich and Keeley (1977) is somewhat approximate and the calculations will almost certainly have to be refined to include the non-linear coupling between modes, the interaction between oscillatory modes and the background turbulence, and the damping effects of turbulent viscosity. Equally, it is conceivable that we may not be able to generalise from the solar case, if the driving turns out to be a sensitive function of stellar parameters. It is quite plausible that processes somewhat different from those working in the Sun might be operating in other stars like, for example, the rapidly oscillating Ap stars where the stellar magnetic field could make a contribution to the excitation of modes.

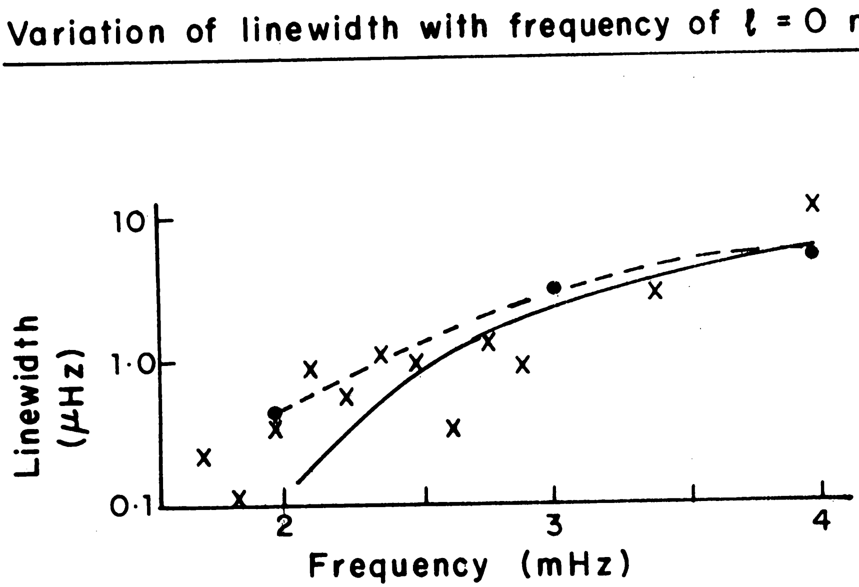

Figure 3. The variation of linewidth with frequency for ℓ = 0 modes is shown: observations of Isaak are indicated by crosses, with the solid line showing the theoretical computations by Kidman and Cox (1984) and the dashed curve of Antia, Chitre and Gough (1986).

The variation of the oscillation amplitude with stellar mass and age would undoubtedly be of great value in understanding the basic excitation mechanism. This prompted Christensen-Dalsgaard (1982) to give theoretical estimates of pulsation amplitudes, periods and frequency separation for a number of stellar models. He based his calculation on the premise that the solar p-modes are not self-excited, but rather they are excited stochastically by convective turbulence. Later Christensen-Dalsgaard and Frandsen (1983) demonstrated that on the zero-age main sequence, the product $R\Delta\nu$ is approximately constant, where R is the stellar radius and $\Delta\nu$ is the mean frequency spacing. It is remarkable that the observed frequency spacing is reasonably close to the prediction based on the scaling from a solar model to a star with an independent measurement of its radius.

In the case of acoustic modes the cyclic frequency ν for spherical harmonic degree ℓ very much smaller than the radial order n, satisfies the asymptotic relation

$$\nu = \nu_o \, (n + \ell/2 + \alpha) + \varepsilon \, (n,\ell) \, ,$$

where
$$\nu_o = \left[2 \int_o^R dr/c_s \right]^{-1}$$

and α depends on the stellar structure, and $\varepsilon/\nu = 0\,(1/n^2)$, for large n. Note that the modes of a given degree ℓ but successive order n occur at discrete frequencies approximately spaced by ν_o, while successive peaks in the power spectrum produced by modes of alternating odd and even ℓ are approximately uniformly separated by $\Delta\nu = \frac{1}{2}\nu_o$. The whole-disk observations reported by Claverie et al. (1979) reveal this property in the solar oscillations with $\Delta\nu \cong 67.8$ μHz. We have now some tentative indications of similar oscillations existing in other stars. Thus, Noyes et al. (1984) have found evidence for solar-like p-mode oscillations in the K2 V star Epsilon Eridani. Since $R\,\Delta\nu/R_\odot$ is calculated to be 72.5 μHz for the zero-age main sequence, and that, for the present Sun, $(\Delta\nu)_\odot = 67.8$ μHz, we expect $\Delta\nu$ for Epsilon Eridani to be ~ 84-90 μHz, using Lacy's (1977) estimate of the radius of this star to be $R = 0.81\ R_\odot$ with about 10 per cent uncertainty. This is indeed in good agreement with the observed mean frequency spacing $\Delta\nu$ of ~ 86 μHz.

Fossat, Gelly and Grec (1986) find evidence for p-modes on Procyon where the measurements are consistent with the theoretical predictions of the scaling law. However, the observations of Alpha Centauri A by Fossat et al. (1984) which show the presence of a p-mode like set of discrete frequencies in the five-minute range do not seem to conform to the scaling pattern. Alpha Centauri A is of the same spectral type G2 V as the Sun, but is slightly more massive ~ 1.1 $M_\odot$ than the Sun. According to the scaling argument of Christensen-Dalsgaard and Frandsen (1983), the mean frequency spacing for Alpha Centauri, $\Delta\nu$ should have been 71 μHz along the zero-age main sequence and from the scaling law $R\,\Delta\nu/R_\odot = 72.5$ μHz, its radius should have been $R = 1.03\ R_\odot$. However, from the measured value of the mean frequency spacing of 81.3 μHz and with the homologous relation $R^{3/2}\,\Delta\nu$ = constant, one deduces the present radius to be $R \sim 0.93\ R_\odot$. This decrease in the radius is at variance with the measurement by Blackwell and Shallis (1977) of the radius of Alpha Centauri to be $R = 1.23 \pm 0.04\ R_\odot$. We thus have a puzzle here - either there is a drastically different constitution of Alpha Centauri from what the theory of stellar structure tells us or there is some misinterpretation of oscillation frequencies.

4. RAPIDLY OSCILLATING Ap STARS

The development of helioseismology has led to searches of solar analogue of five-minute oscillations in other stars. The observations of rapidly oscillating Ap stars may be regarded as the first successful detection of solar type oscillations in a general class of stars. Their characteristics may be summarised as follows. The rapidly oscillating Ap stars falling in the spectral type from late B to early F are strongly magnetic (fields in the range of 100-1000 gauss) with periods between 4 and 15 minutes. They show low amplitude light variations of a few thousandths of a magnitude. A significant difference between the oscillations in the Sun and Ap stars is that there are only a very few modes excited unlike the Sun where we see a broadband of frequencies. The oscillation patterns in Ap stars are also observed to be axisymmetric with respect to the magnetic field and they seem to rotate synchronously with the magnetic field. An important issue for these stars is why only very few modes are excited to observable amplitudes and why the oscillations are apparently aligned with the magnetic field.

Kurtz (1982) addressed this question in the framework of an oblique pulsator model and suggested that the oscillations are non-radial p-modes of low degree with the axis of oscillation aligned with the magnetic axis of the star. The alignment can thus be explained if the modes are standing waves that rotate at the same speed as the star. It is, however, difficult to imagine why the standing wave pattern should rotate exactly with the star. This has led Dolez and Gough (1982) to propose that the pattern is naturally expected to precess with respect to the rotating star, but that it would manifest only when the axis of symmetry is aligned with the magnetic axis and would vanish when it is misaligned, so that the pattern is observed to rotate synchronously with the star. The modes are thus excited to significant amplitudes only when they are properly aligned with the magnetic field, thus maintaining the phase between the magnetic field and the wave pattern. The effect of the magnetic field on the eigenfunctions was not included in the work of Dolez and Gough (1982), a situation which was later remedied by Dziembowski and Goode (1985). These authors generalised the oblique pulsator model by taking into account the effect of the internal magnetic field on the eigensolutions to find that the oscillations in Ap stars are dominated by the magnetic field rather than by rotation. These stars hold a promise for asteroseismology by providing a handle on the properties of internal stellar magnetic fields.

The excitation of oscillations in these stars is attributed by Dziembowski (1984) to the conventional κ-mechanism in the helium ionisation zone, although the presence of the magnetic field is liable to influence the character of instability of the oscillatory modes. Shibahashi (1983) proposes the overstable magnetic convection as the driving mechanism for Ap stars. The time-scale for magnetic overstability in these stars is of the order of 10 min, and the observed modes are simply those with frequencies closest to those of the resonantly excited magnetically overstable modes. As this mechanism is likely to be most effective at the magnetic poles of the star, it naturally explains the alignment of the oscillation pattern with the magnetic field. The detection of a weakly magnetic rapidly oscillating star in the same part of the H-R diagram as the Ap stars would weaken the case for the magnetically driven instability mechanism. It is thus plausible that, despite some similarities to solar oscillations, the excitation mechanism in Ap stars might differ from that in the Sun.

Since the amplitudes of Ap stars are so much lower than those of Cepheids, it seems unlikely that the dominant limiting non-linear effect is the saturation of the driving mechanism. There is already a strong hint of mode coupling in the observations from the 2:1 resonance between unstable modes and higher order stable modes. This feature is suggestive of non-linear interaction and it is not unlikely that the higher frequency mode is driven by the lower frequency mode through resonant coupling (Dziembowski and Goode, 1985).

The oscillations discovered in Ap stars are in many ways reminiscent of the solar five-minute oscillations. Thus, for the Ap star HR 1217, Kurtz and Seeman (1983) have found six approximately uniformly spaced frequencies with a mean frequency separation of 34.7 μHz. These are very much like the acoustic modes of low degree and high order observed in the Sun where modes of both odd and even degree are present and successive peaks in the power spectrum are separated by $\Delta\nu = \frac{1}{2}\nu_0 \cong 67.8$ μHz. For a typical Ap star with $M \cong 2M_\odot$ and $R \cong 2R_\odot$, and under homologous transformation with ν_0 scaling as $(GM/R^3)^{\frac{1}{2}}$, we expect the mean frequency spacing to be about half of that of the Sun, i.e. ~ 34 μHz, which is just what is observed.

5. ZZ CETI STARS

The ZZ Ceti stars are a class of variable luminosity while dwarfs which offer the exciting possibility of seismologically probing the internal structure of degenerate stars. These low amplitude variables exhibit multiperiodic character with the observed periods in the range from 110 sec to 1200 sec (Winget, 1986). It is widely accepted that the variability of the ZZ Ceti stars is caused by the non-radial pulsation of gravity modes (Chanmugam, 1972; Warner and Robinson, 1972). Osaki and Hansen (1973) and Brickhill (1975) demonstrated that the low-order g-modes could account for the short periods (~ 200 sec) exhibited by some of the ZZ Ceti stars, while the g-modes of higher order may explain the longer periods (~ 1000 sec).

The basic problems concerning the ZZ Ceti stars are the nature of the 'filter' which selectively excites certain modes, and the nature of the excitation mechanism responsible for driving the non-radial g-modes. Winget, Van Horn and Hansen (1981) invoked the compositional stratification to act as a filter whereby the resonance of certain modes with the thickness of the hydrogen and helium layers in the surface is supposed to selectively enhance the excitation rates of the modes trapped in the surface layers.

The DA white dwarfs with their hydrogen-rich atmospheres and the DB white dwarfs with their helium-rich atmospheres are most probably driven by the envelope ionisation mechanisms - the κ- and γ-mechanisms operating near the base of the partial ionisation zones of hydrogen and helium in the compositionally stratified surface layer. But the recent work of Cox, Starrfield, Kidman and Pesnell (1986) raises some questions about the effectiveness of the envelope ionisation mechanisms generating most of the instabilities found in the theoretical models. It is known that in models of ZZ Ceti stars, the external layers become unstable to convection and indeed, in these zones convection is able to transport most of the energy flux. The perturbation of the convective flux will have to be included in any consideration of the driving mechanism. A realistic treatment of convection-pulsation coupling will almost certainly have a significant influence on the stability characteristics and might even provide a way of reconciling theoretical models with the observed instability strip. It appears from the work of Cox et al. (1986) that a certain amount of convection blocking is needed to make the theoretical models of ZZ Ceti stars pulsationally unstable.

6. DELTA SCUTI AND BETA CEPHEI STARS

The Delta Scuti stars lying in the spectral range F0-F5 pulsate at low amplitudes and exhibit a simultaneous excitation of many characteristic modes which may explain their observed complicated light curves. The theoretical models computed for these stars show instability against some modes of radial and non-radial pulsations due to the κ-mechanism with the helium ionisation zone playing a dominant role in driving (Stellingwerf, 1979). The growth rates calculated for the models of Delta Scuti stars turn out to have very small values, and consequently the pulsations could be limited by even a small amount of dissipation. Dziembowski (1979) has estimated that non-linearities developed by any single mode are inadequate to limit its amplitude to the observed low value; however, the non-linear interaction between various modes may be responsible for the low amplitudes.

The Beta Cephei stars with the spectral type B0.5-B2 lying in a strip just above the main sequence appear to pulsate in both radial and non-radial modes. A number of driving mechanisms have been proposed to account for the radial and non-radial pulsations observed in the Beta Cephei stars which include Envelope ionisation (Cox, 1976), Rapidly spinning core (Osaki, 1974), Kelvin-Helmbultz instability (Papaloizou and Pringle, 1978).

The conventional ionisation mechanism simply does not work for these stars, because their temperatures are so high that the ionisation zones of hydrogen and helium are located too close to the surface and these have too little mass for destabilising the entire star. Osaki (1974) has proposed an excitation mechanism for non-radial pulsations of Beta Cephei stars in which a non-radial eigenmode of the star could be excited by the resonant coupling with overstable convection in the rapidly spinning core of a massive star. It is not clear whether such an oscillation will not be effectively damped in the presence of radiative dissipation in the atmosphere.

Another excitation mechanism in which rotation plays an important role is the Kelvin-Helmholtz instability. An attractive feature of this mechanism is that different oscillation patterns can rotate round the equator with the same speed, but such a shear instability is liable to be quenched by a stable stratification. The shear instability also generates modes which tend to alter the rotation field very rapidly in such a manner as to suppress the instability, and this probably weakens the underlying mechanism. It is fair to conclude that there is as yet no satisfactory theoretical proposal to explain the mechanism responsible for driving the instability in Beta Cephei stars.

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