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EXCITATION MECHANISMS OF OSCILLATIONS IN STARS

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ABSTRACT Excitation mechanisms of oscillations in stars are discussed, in particular on the problems of the Beta Cephei pulsations and of the solar oscillations. A long-standing mystery about the excitation mechanism of the Beta Cephei pulsations seems to have finally been solved, which is due to availability of the new "OPAL" opacities. The very mechanism is the classical κ-mechanism, however, due to enhanced heavy element opacities at temperature around 2×10^5K. By using the new opacities, three independent groups have found pulsational instabilities for the fundamental radial mode and a few low-degree non-radial modes in Beta Cephei models. Stochastic excitation of solar oscillations by turbulent convection is then discussed. It is shown that the noise generation by quadrupole radiation concentrated at the top of the convection zone may well explain the frequency dependence of the observed solar acoustic power pumped into individual p-modes.

INTRODUCTION

Although most of classical pulsating variables such as Cepheid and Mira variables are giant or super-giant stars, pulsations and oscillation-related phenomena have been known in several groups of stars on the main sequence or close to it as well. They may be classified into three categories by spectral class of the relevant stars: (1) early-type pulsating variables with spectral class of O- and B-type, in which the Beta Cephei stars are the best known example of this type, (2) Delta Scuti stars and rapidly oscillating Ap stars in A- and F-type spectral range, and (3) global oscillations of the sun itself and oscillations in the sun-like stars in late spectral type. As for the excitation mechanisms of oscillations in stars are concerned, basically two different mechanisms have been known, and they are (1) the linear overstability of some particular eigenmodes of stars by the κ-mechanism, and the stochastic excitation of many modes by turbulent convection in stars with convective envelope.

In this review, I shall discuss on the excitation mechanisms of pulsations in these stars. In particular, I discuss two topics on excitation mechanisms of stellar oscillations in which great progress has been made very recently. They are the excitation mechanism of the Beta Cephei stars and the stochastic excitation of oscillations by turbulent convection in the sun.

EXCITATION MECHANISMS OF BETA CEPHEI PULSATIONS

The Beta Cephei stars are a small group of pulsating variable stars of early spectral type. They are unique because they are far away in the HR diagram from those classical pulsating variables such as Classical Cepheids, RR Lyrae stars, and Mira variables. However, recent observations with high-precision spectroscopy and photometry have revealed that pulsations and oscillation-related phenomena are quite common among early-type stars and some of them are called "line-profile variable stars" as they manifest their variability most clearly in variations in line-profiles. The Beta Cephei stars may be a tip of an ice-berg which appears most clearly as pulsating variable stars among early-type variable stars of smaller amplitude.

The biggest mystery related to the Beta Cephei stars for a long time was the very question why these stars do pulsate. Many attempts had been made to find the pulsational instability in stellar models corresponding to the Beta Cephei stars and various proposals for possible excitation mechanisms had been put forward but none of them had been successful (see, e. g., previous reviews by Osaki 1986 and by Cox 1987).

However, a breakthrough has recently occurred on this problem as a promising mechanism for the excitation of the Beta Cephei pulsations has finally been found. This mechanism is the well known κ mechanism but this time due to the heavy element opacity bump at temperature around $T \sim 2 \times 10^5$K which was discovered very recently. This new development is basically due to availability of a new opacity called "OPAL" by Lawrence Livermore National Laboratory. Full OPAL opacity tables have now been published in the Astrophysical Journal Supplement (Rogers and Iglesias 1992). They tabulate their opacities for many different chemical compositions and the tables are organized differently from the previous work. Instead of rows and columns of constant temperature and density, the tables follow tracks of constant $R \equiv$ density/(temperature)^3 with variable temperature.

The most important aspect of the new opacity in our interest is an enhancement of heavy element opacity by a factor of 2 to 5 over the Los Alamos opacity due to a large number of iron lines (Iglesias, Rogers, and Wilson 1987; Rogers and Iglesias 1992) at temperature around $T \sim 2 \times 10^5$ degree in the stellar envelope of the Beta Cephei region.

Based on this new opacity, at least three independent groups have studied pulsational stability of stars in the Beta Cephei region and they have found that these stars are really pulsationally unstable for the radial fundamental mode. These three groups are Cox, Morgan, Rogers, and Iglesias (1992), Moskalik and Dziembowski (1992), and Kiriakidis, El Eid, and Glatzel (1992). Their results agree with each other in the fundamental point; stars in the Beta Cephei region are found to be pulsationally unstable both for the radial fundamental mode and for low-degree non-radial modes having similar periods as that of the radial fundamental.

Evidently the most important here is the large enhancement of opacity at temperature near $\log T \sim 5.3$ found in the OPAL code. It gives an opacity enhancement of a factor of 3 to 4 over the Los Alamos opacity at the relevant temperature and density range in the envelope of stellar model of the Beta Cephei variables with the population I chemical composition of $X = 0.7$ and $Z =$

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0.02. Similar opacity enhancement has also been confirmed by an independent opacity project called "Opacity Project" (Seaton 1992).

It is natural to ask what makes such a big difference between the Los Alamos code and the two new codes. According to Rogers and Iglesias (1992), the main cause of this difference is due to the atomic physics used. The OPAL code takes into account explicitly the term splitting by LS coupling for heavy elements which was neglected by the Los Alamos opacity. Beside that, the Los Alamos code used the hydrogenic oscillator strengths which are identically zero for the same shell $\Delta n = 0$ transitions where n is the principal quantum number of the jumping electron. The opacity enhancement at $\log T \sim 5.3$ in OPAL code is produced by a tremendous number of same M-shell iron lines (from $n = 3$ to $n = 3$) at the 60 eV photon energy (see, figure 22 of Rogers and Iglesias 1992). Rogers and Iglesias (1992) have discussed the uncertainty of their new OPAL code. In generating the atomic data, they assumed the pure LS coupling. But the spin-orbital coupling becomes more important with the increasing atomic number. They then recalculated the opacity based on the intermediate coupling (i.e., the j-j coupling) and compared with those of the LS coupling. It was found that the calculations based on the intermediate coupling increased the opacity by $\sim 20\%$ at most.

Although there remains still some uncertainty in the new opacity, the basic aspect of the large enhancement of opacity by the heavy elements, in particular by the iron lines, at temperature $T \sim 2 \times 10^5 - 4 \times 10^5$ will not be changed and the κ-mechanism due to this heavy element opacity bump may very likely be a correct explanation of the Beta Cephei pulsations.

Retrospect

If we accept the above conclusion, it may be instructive to trace back the road that has led us to the present state about the problem of excitation mechanisms of the Beta Cephei stars because it gives us one of good examples of "asteroseismology".

In fact, this conference was devoted to the study of internal structure of stars and my talk was presented in the session of asteroseismology. We thus examine stellar oscillations from the asteroseismological standpoint. That is, we want to learn something about stellar structure from observed oscillations in stars. As far as the helioseismology is concerned, we have learned a lot about the internal structure of our Sun from observations and theories of solar oscillations, particularly from the very precise measurements of frequencies of oscillation modes. However, we are not so much fortunate as far as the stellar case is concerned. The main reason for this is that the number of observed modes of oscillations is very much limited in the case of stellar pulsations and moreover we do not know the basic parameters such as the mass and the radius of the relevant star while we know those quantities with a great accuracy in the case of the sun. In this respect, the problem of the excitation mechanism of pulsating stars can serve most to asteroseismology in inferring the internal structure of stars. The classical Cepheid instability strip and its theoretical explanation based on the so-called κ mechanism of the hydrogen and helium ionization zones give us a good confidence about the internal structure of these stars. The problem of the Beta Cephei stars has turned out to be another good example.

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As a matter of fact, I gave review talks twice on this subject in the past, in 1982 at pulsation conference in Boulder Colorado (Osaki 1982) and in 1985 at IAU general assembly in New Delhi (Osaki 1986). In both of these talks, I had to conclude my talks by stating that the theory of the Beta Cephei stars was unsatisfactory. This meant that something was wrong in our understanding of the stellar interior of these early type stars. Most likely place which we should blame for this insufficiency was opacity. The opacity available for a long time used to be only one opacity calculation by the Los Alamos group. Badly needed was an independent opacity calculation other than that of Los Alamos. To see this situation, let me here quote my concluding remarks of the review talk on "Beta Cephei variables" given at the IAU general assembly in New Delhi in 1985; "Something seem wrong or insufficient with our present knowledge about the internal structure of very massive stars......... As for the excitation mechanism of β Cephei variables, I suspect some kind of κ mechanism, which is still unknown but which may operate at temperature around $T \sim 2 \times 10^5$K". My suspicion has fully been confirmed by the recent works as seen above.

The newly found mechanism is the κ-mechanism due to heavy element opacities which works at the temperature around 2×10^5 K. This is the very temperature region at which the κ-mechanism was suspected to operate for excitation of the Beta Cephei pulsation. If the κ mechanism is responsible for the excitation of the Beta Cephei pulsations, one can show by a very simple argument based on the "transition zone" (see e.g., Osaki 1982) that the crucial layer for the pulsational stability is the transition layer between the quasi-adiabatic interior and the fully non-adiabatic outer layer, which is located in this case around the temperature $T \simeq (1.5 - 2) \times 10^5$ degree.

In this respect, Stellingwerf (1978) was the first to suggest a possible κ mechanism but in his case due to the helium opacity bump. He realized that there exists a small opacity bump at a temperature close to 1.5×10^5 K, which originates from the coincidence of the frequency maximum of radiation with the second ionization edge of helium at 54.4 eV. The Stellingwerf mechanism for the excitation of the Beta Cephei pulsations was examined by various people (Stellingwerf 1978; Saio and Cox 1980, Dziembowski and Kubiak 1981; Lee and Osaki 1982). These results were basically similar and they are summarized as follows; (1)although this mechanism works locally to the direction to drive the pulsation, it is still insufficient to destabilize the star as a whole; (2) the least stable stellar models by this mechanism are slightly too cool to explain the Beta Cephei pulsation. These two points suggest that what we needed was somewhat larger opacity bumps which would operate at temperature slightly higher than 1.5×10^5 of the Stellingwerf helium opacity bump.

Then came a monumental paper by Simon (1982) who argued that if the heavy element opacity was larger by a factor of 2-3 than that given by the Los Alamos opacity, it would then resolve the problem of Cepheid mass anomalies and it would also explain the excitation of the Beta Cephei pulsations. Simon (1982) thus made a plea for reexamining heavy element opacities in stars as there existed great uncertainty in the Los Alamos opacity calculations in the treatment of heavy element opacities. However, it took nearly a decade for his plea to be answered fully by two groups: the OPAL project at Lawrence Livermore National Laboratory and the "Opacity Project". As seen above, Simon's (1982) suggestion has been confirmed by the OPAL opacities, which have finally solved the long-standing problem of the excitation of the Beta Cephei pulsations.

Summary of the β Cephei excitation and impact of the new opacities

We here summarize the excitation mechanism of the Beta Cephei stars. Based on the new opacities by the OPAL code (Rogers and Iglesias 1992), the three independent groups mentioned above have examined the pulsational stability of stellar models relevant to the Beta Cephei stars. Their results are basically similar to each other and they are summarized as follows:

(1) Massive early-type stars are pulsationally unstable for the radial fundamental mode and for a few lower-degree non-radial modes having periods similar to that of the radial fundamental.

(2) The instability strip by this mechanism agrees with observed location of the Beta Cephei stars.

(3) The stability results are very sensitive to the heavy element abundance. In particular, pulsational instability is not expected in stars with low heavy element abundance such as in those stars in the Magellanic Clouds.

The new opacities have given a great impact on the stellar structure and the stellar pulsations. As seen in other talks presented in this conference, the new opacities may be able to solve various long-standing problems such as the Cepheid period ratios. It is clear that almost all calculations of the stellar structure and evolution and in particular calculations of all stellar pulsations should be reexamined based on the new opacities.

STOCHASTIC EXCITATION OF SOLAR OSCILLATIONS

Let us now discuss the excitation mechanisms of solar oscillations. Two different excitation mechanisms have been discussed for solar oscillations: (1) the linear overstability of eigenmodes due to the κ-mechanism at the hydrogen ionization zone, and (2) the stochastic excitation by turbulent convection. The latter possibility is now more favoured than the former possibility and here we mainly discuss the stochastic excitation by turbulent convection.

Observational evidence which is unfavorable for the linear overstability in the case of solar oscillations is that so many p-modes are observed with very small amplitude. On the other hand, linear overstability is the very mechanism responsible for pulsations of the Cepheid stars and the Cepheid variables show only one or two pulsation modes excited with large amplitude. If the sun were pulsationally unstable for certain modes, it would be difficult for such modes to be kept rather in such low amplitude as observed on the sun (Kumar and Goldreich 1989).

On the other hand, in the stochastic excitation mechanism, the sun is regarded as an acoustic resonator having many eigenmodes. These eigenmodes are considered to be damped oscillators and they can be excited only when they are driven externally. As it is well known, the outer 30% in radius of the sun is covered by the convective zone and the turbulent convection there generates broad-band "acoustic noise" in frequency. Oscillations at resonant frequencies are then picked up by the acoustic cavity and they give rise to many peaks in the observed power spectrum. This is the basic picture of the stochastic excitation by turbulent convection. The stochastic excitation of solar oscillations was first investigated extensively by Goldreich and Keeley (1977).

If we write the velocity of a particular mode of damped oscillator at the solar surface by v_q, we find its time dependence as

$$v_q \propto \exp(i\omega_q t - \gamma_q t), \tag{1}$$

where ω_q and γ_q are the eigenfrequency and the damping rate of the mode, respectively, and the subscript q signifies a particular eigenmode. If we inject acoustic noise having a power spectrum $P_{\rm noise}(\omega)$ into the cavity, we obtain the correspondent response of the form (Christensen-Dalsgaard et al. 1989)

$$| A |^2 = \frac{P_{\rm noise}(\omega)}{(\omega^2 - \omega_q^2)^2 + 4\omega^2\gamma_q^2}, \tag{2}$$

where A is the amplitude of oscillation. If the acoustic noise generated has a broad-band power in frequency, many modes are simultaneously excited at resonant frequencies of the cavity. This model can thus explain following two points very nicely: (1) millions of modes are excited, and (2) their amplitudes are expected rather low.

One can write more explicitly the energy conservation of a particular oscillation mode;

$$\frac{dE}{dt} = G - \Gamma E, \tag{3}$$

where E is the oscillation energy of a particular mode, G is the acoustic power pumped into the mode, and $\Gamma = 2\gamma_q$ is the (energy) damping rate of the mode. In steady state, we find

$$E = \frac{G}{\Gamma}. \tag{4}$$

The energy of a mode is determined by the acoustic energy generation rate at the particular mode divided by the damping rate of the mode. The central question in this model is how to determine the damping rate Γ and the acoustic noise generation rate G.

Damping rate

Several different factors contribute to the damping rate of oscillation but we may divide it into two parts

$$\Gamma = \Gamma_{\rm dyn} + \Gamma_{\rm therm}, \tag{5}$$

where $\Gamma_{\rm dyn}$ and $\Gamma_{\rm therm}$ stand for the damping rate due to the dynamic cause through the momentum equation and that due to non-adiabatic effects of oscillations through the thermal equation, respectively. As for the dynamical damping, the viscous dissipation by the eddy viscosity of turbulence and wave leakage at the boundary of the cavity are two of important mechanisms of damping. On the other hand, the thermal damping $\Gamma_{\rm therm}$ is due to thermal coupling of oscillation with radiation field and convective energy transport. As already discussed before, the thermal damping $\Gamma_{\rm therm}$ could be negative if modes are thermally overstable as known "negative dissipation". Most uncertain in the damping rate is the thermal coupling of oscillation with convection. Here we need time-dependent convection theory, which still remains one of the major unsolved problems in astrophysics.

Acoustic noise generation rate

Acoustic noise generation from homogeneous turbulence was first discussed by Lighthill (1952) and this mechanism is thus known as the Lighthill mechanism. According to this theory, the acoustic noise generation rate ε per unit volume from turbulence is given by

$$\varepsilon = \frac{\rho v_\lambda^3}{\lambda} M^{2n+1}, \tag{6}$$

where ρ is the mass density, v_λ is the characteristic velocity of turbulent convection, λ is the characteristic scale of the turbulence, and $M = v_\lambda / c_s$ is the Mach number of turbulence. The index n in the above equation is the multipole index. As for this index, the lowest three indices are (1) the monopole radiation $n = 0$ which occurs if there is mass source in fluid, (2) the dipole radiation $n = 1$ which occurs if external force acts on the fluid, and (3) the quadrupole radiation $n = 2$ which occurs when the turbulent Reynolds stresses act as a source term. In the original Lighthill mechanism, the quadrupole radiation is the lowest order multipole generated by turbulence.

In order to calculate the acoustic power G pumped in a particular mode in equations (3) and (4) from the acoustic noise generation rate ε, we must first resolve this into the specific power $P(k_h, \omega)$ in horizontal wavenumber and frequency and multiply the band-widths of the particular mode in horizontal wavelength and frequency and then integrate it spatially to count for the whole contribution over the convection zone. In particular, as for the contribution from the source outside the acoustic cavity, a proper care must be taken of attenuation effects of wave energy by evanescent zone between the source and the cavity.

Goldreich and Keeley (1977) was the first to try to estimate theoretically amplitudes of individual modes based on the stochastic excitation by turbulent convection. For the damping rates of oscillations, they used the turbulent viscous damping and they then estimated the forcing term based on the quadrupole radiation due to turbulent Reynolds stresses by properly taking into account eigenfunctions of modes. By combining the damping rate to the noise generation rate, they estimated theoretical amplitudes of individual modes of solar oscillations. Their results were, however, found to give too small amplitudes as compared with recent observations obtained by Libbrecht (1988). However, there existed several uncertainties in numerical factors of order unity in their formulation which can easily affect the final results by a large factor. It thus remained rather uncertain whether the stochastic excitation mechanism was quantitatively sufficient or not.

Observations and comparison with theories

Libbrecht (1988) demonstrated that the quantity G can be obtained directly from observations. In the stochastic excitation model we find from equation (3) $G = E\Gamma$ in steady state. Since the quantities E and Γ can be obtained from observations of the amplitude of the particular mode and its line width, we can obtain the acoustic power G pumped into an individual mode from observations. Libbrecht (1988) presented his results of observations for G as a function of frequency ν in his figure 3 (Libbrecht, 1988). It was found that the quantity G is insensitive to degree ℓ (or the horizontal wave number) of the mode but it is very sensitive to mode frequency. The acoustic power G pumped into individual modes has a sharp peak at frequency around 3.5 mHz which corresponds to the period of five minute and it has a power law dependence of $G \propto \nu^8$ for the low frequency side with $\nu < 3$mHz and another power law dependence $G \propto \nu^{-5.3}$ for the high frequency side with $\nu > 4$mHz.

Osaki (1990) has demonstrated that the observed frequency dependence of the acoustic power G can naturally be explained in terms of the quadrupole radiation generated by turbulent convective motion at the top of the solar convection zone. He has first argued that the dipole radiation suggested by Goldreich and Kumar (1988) may not be important because of cancellation effects between rising and sinking convective elements. He then examined the acoustic power G pumped into an individual mode based on the quadrupole radiation of the original Lighthill mechanism. As for the high frequency noise power G is concerned, it is shown that the quadrupole radiation with Kolmogoroff spectrum for turbulence can predict the power law dependence with an index of -5.5 which is in a good agreement with observations.

On the other hand, the power law dependence of $G \propto \nu^8$ for the low frequency side can be explained by the propagation effects of waves if the source of acoustic energy generation is concentrated at the top of the convection zone where waves are evanescent for modes with frequency $\nu < 3$mHz. It is shown that a simple attenuation effect of waves through the evanescent zone between the noise source and the acoustic cavity can give rise to the power law dependence of the form $G \propto \nu^{2m}$ where m is the effective polytropic index specifying the density stratification of the solar envelope. The effective polytropic index m in the relevant zone of the solar envelope is estimated to be near 4, that is in a good agreement with the observed power law dependence. A similar power-law dependence for the low frequency power was also obtained by Goldreich and Kumar (1990).

Balmforth (1992) has recently reexamined the stochastic excitation mechanism by quantitatively estimating modal amplitudes. It was shown that the theoretical results for acoustic power spectra could be made to agree with observations by adjusting various theoretical parameters. However, a following difficulty exists in Balmforth's result; if adjustable parameters in his theory are chosen such that the theoretical amplitudes at the peak frequency around 3mHz agree with observed ones, an agreement on the frequency dependence of the acoustic power between theory and observation is then broken in the sense that the theoretical acoustic power has a flatter spectrum as compared with observations. This may be related with his rather extended source distribution because much sharper power peak was obtained by Osaki (1990) who assumed a locally concentrated source at the top of the solar convection zone.

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