BETA CEPHEI VARIABLES

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ABSTRACT. Problems of Beta Cephei variables and of related pulsating B stars are discussed. In particular, various excitation mechanisms of both radial and nonradial oscillations so far suggested are critically examined. The present state of theory for these variables is found unsatisfactory.

1. INTRODUCTION

Beta Cephei stars are a small group of classical pulsating variables of early spectral-type. They used to be only known pulsating variables among early-type stars. However, recent observations with high-precision spectroscopy and photometry have revealed that pulsations and pulsation-related phenomenon are quite ubiquitous among early-type stars (see, e.g., Smith 1986; Waelkens and Rufener 1985). In fact, it is now suspected that most of early B stars show some sort of variations in line-profile, if examined very carefully. In particular, those stars which exhibit characteristic variations in line-profile are called "line-profile variable stars", and their variations are now believed to be caused by nonradial pulsations in rotating stars.

The most fundamental problem of Beta Cephei stars and of related pulsating B stars is that there is no definitive mechanism known which can drive pulsations in these stars. In other words, we still do not know the reason why these stars do pulsate. This is certainly a big challenge to those working on stellar pulsation and stellar structure. Here, we shall discuss various excitation mechanisms so far suggested in relation to pulsating B stars.

2. SOME OBSERVATIONAL ASPECTS OF PULSATING B STARS

2.1. Beta Cephei Stars

The classical β Cephei stars are believed to be confined in a narrow "instability strip" on the HR diagram. However, there has existed some

J.-P. Swings (ed.), Highlights of Astronomy, 247–254.

https://doi.org/10.1017/S1539299600006511 Published online by Cambridge University Press

controversy concerning the width and the exact location of the instability strip ; how narrow it is and where it is located on the HR diagram. This sort of questions have a direct relevance about the excitation mechanisms of pulsation because they will give an observational clue about the seat of driving of pulsations. For instance, if the instability strip is very narrow and it is located at a special stage of stellar evolution, it will indicate the deep interior as the seat of driving. In fact, one of popular conjectures was that the instability strip of β Cephei stars coincided with the so-called S-bend stage of stellar evolution where the evolutionary path of a massive star with $M \simeq 10 - 15\ M_\odot$ crosses three times. Balona and Engelbrecht (1985) have recently observed β Cephei stars in two galactic clusters NGC 6231 and NGC 3293. By constructing HR diagrams for stars in these clusters, they have demonstrated that β Cephei stars are not confined to the S-bend region but some of them are rather very close to the zero-age main-sequence. Their observations now seem to settle the controversy and establish that β Cephei stars are normal main-sequence stars in the core hydrogen burning stage.

The next question concerns the pulsation mode of β Cephei stars, that is, whether they are radial or nonradial, and if radial, whether they are the fundamental mode or the first harmonics. Smith (1980a) has argued that the main pulsation of β Cephei stars is radial, and he has then put forward a proposal that β Cephei stars be defined as those early-type variables whose main pulsation is radial (Smith 1980b). However, some β Cephei stars show multi-period beating, and this indicates that nonradial pulsations must be involved as well in some of β Cephei stars. It is not known what kind of role the nonradial pulsations play in β Cephei stars.

Another important quantity for the mode identification is the pulsation constant or the Q-value. Various observations indicate that the Q-value of β Cephei pulsations ranges from 0.025 day to 0.04 day, which indicates either the radial fundamental mode or the first harmonic mode, if they are radial. Observational uncertainties particularly in absolute luminosities and hence in masses of the stars do not allow us to decide the pulsation mode unanimously. It may be quite possible that either the fundamental mode or the first harmonic mode or the both are involved depending on individual stars.

2.2. Line-Profile Variable Stars

Among pulsating B stars, the most closely related to β Cephei variables are line-profile variable stars. As mentioned before, line-profile variabilities in these stars are understood in terms of nonradial pulsations in a rotating star. These stars surround the β Cephei instability strip on the observational HR diagram. There is then an intriguing possibility that nonradial pulsations responsible to the line-profile variable stars might exist in all β Cephei stars as well but they might simply be concealed by the main pulsation of β Cephei type. In this respect, the most interesting is Spica (α Vir). This star was once found to be a β Cephei star before 1970 but it has stopped pulsating since early 1970s (or its β Cephei pulsation amplitude has reduced to a very low level).

This same star has recently been found to show line-profile variation characteristic to the nonradial pulsations (Walker et al. 1981; Smith 1985). Two different interpretations may be possible concerning this phenomenon : either that nonradial pulsations has appeared in Spica only after the main radial pulsation had died out or that they have existed all the time but they were concealed by the main radial pulsation when the latter had a large amplitude. It will be important to examine very carefully whether or not line profile variations due to nonradial pulsations may exist in other β Cephei stars as well.

3. EXCITATION MECHANISMS OF PULSATING B STARS

As emphasized before, no definitive excitation mechanisms for pulsations of early-type stars have so far been discovered yet, although various possibilities have been suggested by various authors. In fact, almost all destabilizing mechanisms known in stars have been proposed as possible mechanisms for pulsations of β Cephei stars and of related variables, but all of them have turned out to be unsatisfactory. They include (1) the κ-mechanism, (2) the ε-mechanism, (3) convection (or unstable stratification with $\nabla > \nabla_{ad}$) under some restoring force, (4) shear instability in a differentially rotating star, (5) tidally forced oscillation and non-linear coupling between modes, (6) the jolt mechanism and subsequent damped oscillation, and so on. Since these mechanisms have thoroughly been discussed by the present author (1982) and no new mechanisms have seemed to be put forward since then, we shall here examine this problem from a slightly different view point. To do so, we classify various excitation mechanisms in three different categories : (i) linear overstability of radial modes, (ii) linear overstability of nonradial modes, and (iii) non-linear mode coupling. We shall discuss them in this order.

3.1. Linear Overstability of Radial Modes

Since the main pulsation of β Cephei variables is thought to be of radial mode, it will be appropriate to begin with linear overstabilities of radial modes. It seems now well established that eigenfunctions of radial modes are essentially confined to the stellar envelope in any realistic stellar models of pulsating B stars and hence the vibrational stability of radial modes will basically be determined by the envelope structure. In other words, those mechanisms which are seated in the deep interior, such as the ε-mechanism, cannot play an important role in this case.

Furthermore, if pulsations in β Cephei stars are of radial fundamental or first harmonic mode, a simple argument based on the "transition zone" (see Osaki 1982) and detailed numerical calculations show that the most important layers for pulsational stability are the transition layers between the quasi-adiabatic interior and the fully non-adiabatic exterior which are located in this case around the temperature $T \simeq (1.5 - 2) \times 10^5$ K. In this respect, only the mechanism so far suggested which takes place in this temperature range is the κ-mechanism due to the helium opacity bump suggested by Stellingwerf (1978).

The Stellingwerf mechanism of the helium opacity bump occurs at the temperature $T \simeq 1.5 \times 10^5$ K, and it has been examined as a possible excitation mechanism for β Cephei stars by various people (Stellingwerf 1978; Saio and Cox 1980; Dziembowski and Kubiak 1981; Lee and Osaki 1982). Although different authors have different viewpoints on this mechanism, results of numerical calculations are basically similar. They are summarized as follows : (1) Although this mechanism works in the direction to drive pulsation locally, it is not sufficient to destabilize the star as a whole ; (2) least stable models by this mechanism have surface temperature slightly cooler than that of the observed β Cephei strip. We therefore conclude that the helium opacity bump mechanism is not sufficient to explain the excitation of β Cephei pulsations.

3.2. Linear Overstability of Nonradial Modes

As far as the pulsational stability is concerned, the nature of the nonradial p-modes is essentially the same as that of radial modes, and discussions given above for radial modes apply to these modes as well. A completely different situation appears for nonradial modes having the g-mode character. The most important aspect of these modes is a phenomenon called "mode-trapping" in which their eigenfunctions can be confined in a narrow zone of the stellar deep interior. This usually occurs at the μ-gradient zone where the steep gradient of the chemical composition formed by the receding convective core gives rise to a local maximum in the Brunt-Väisälä frequency (local buoyancy frequency). Then, mechanisms deeply seated in the stellar interior may have a chance to be effective in such a case.

One of such possibilities is that nonradial g-mode well trapped in the stellar deep interior may be energized by the ε mechanism in the shell hydrogen burning phase of stellar evolution. This possibility was examined by Shibahashi and Osaki (1976b), and they have found that some nonradial modes are indeed pulsationally unstable due to the ε-mechanism of the hydrogen-burning shell in very massive stars. However, their pulsational instability is only short lived, and modes which become overstable are restricted to those with high spherical harmonic degree of $\ell \sim 10$. Furthermore, unstable modes are found to be those modes whose eigenfunctions have negligible amplitudes at the stellar surface because of their well-trapped nature. We then conclude that this mechanism itself cannot explain observed pulsations of early-type stars.

Another possibility concerns the overstability of g-modes in the semi-convective zone of a very massive star. In the course of evolution of a very massive star, just outside the convective core develops the so-called semi-convective zone, where the temperature gradient is superadiabatic but it is stable against the ordinary thermal convection because of the stabilizing effect of the μ-gradient (i.e., $\nabla_{ad} < \nabla < \nabla_{ad} + (\beta / 4 - 3\beta) \nabla_{\mu}$ where β is the ratio of gas pressure to total pressure). It has been known as Kato's mechanism (Kato 1966) that oscillatory convection (or overstable convection) occurs in such a case. However, this problem is actually a problem of global overstability of g-modes, and Shibahashi and Osaki (1976a) have examined the stability of g-modes in this case by a global analysis. They have demonstrated that some of g-modes, which are well trapped inside the semi-convective zone, are in fact overstable. However, overstability of these g-modes cannot directly offer an explanation for observed pulsating B stars because of the same difficulty presented before in the case of overstable g-modes due to the hydrogen shell burning. Besides that, the problem of semi-convection in astrophysics is well known and well studied as that of double-diffusive convection in laboratories and geophysics (see, e.g., Huppert and Turner 1981). It is known there that a non-linear instability overtakes and dominates over a simple overstability discussed here, producing the step-wise profile in the chemical composition. The same situation may apply to the stellar semi-convection zone and overstability may not be realized at all.

Still another possibility suggested by the present author (Osaki 1974) concerns overstable convection in the rapidly spinning core of a very massive star, which may result from the stabilizing influence of rotation. He has suggested that an accidental coincidence in frequencies between oscillatory convection in the core and a global non-radial oscillation of the star may lead to resonance which could produce an appreciable amplitude in the stellar surface. This model was criticized by Dziembowski (1984) on the ground that the very resonance would stabilize the overstable convection. However, Lee and Saio (1986), by examining nonradial eigenmodes in a rotating massive star, have found that some of overstable eigenmodes have large amplitudes both in the convective core and near the surface, thus supporting Osaki's conjecture. Much work is needed to clarify the nature of nonradial oscillations in a rotating star with a convective zone.

3.3. Non-Linear Mode Coupling

In some of β Cephei variables, amplitudes of individual pulsation modes are found to vary with time, indicating that some kind of mode coupling is taking place in these stars. Mode decay and mode switching are quite often observed to occur in line-profile variable stars as well (see, Smith 1986). In this respect, one of interesting possibilities is that pulsations visible in these stars may be produced by non-linear coupling from some underlying modes which are invisible at the surface. It will be worth pursuing this possibility because all attempts have so far failed to find linear overstability which can explain observed pulsations of these variables.

One of models put forward along this line is a mechanism proposed by Kato (1974) in that a nonradial mode is excited from the tidally forced oscillation in a binary star through the non-linear three wave interaction, if a proper resonance condition is met among three waves. This mechanism cannot, however, be a complete solution for pulsations of β Cephei stars because observations show no preference of binary stars among β Cephei stars. However, it might be relevant to some nonradial oscillations observed in well known binary stars such as Spica.

We have not discussed two other mechanisms (i.e., the shear instability and the jolt mechanism), but we may not need to repeat their difficulties, as they have been discussed before (Osaki 1982, 1986). Only mention is made that the shear instability is different in one respect from most other mechanisms discussed here, as the former mechanism extracts necessary wave energy from the mean flow of rotation while the latter mechanisms do so from the stellar thermal energy.

4. CONCLUDING REMARKS

We have examined various excitation mechanisms so far suggested for β Cephei variables and related pulsating B stars, but all of them have been found unsatisfactory. Something seems wrong or insufficient with our present knowledge about the internal structure of very massive stars. We are unfortunately unable to offer any definitive solution to this difficult problem, but I wish to conclude this review by presenting my personal view for a possible direction of investigation.

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. The reason for this is that an envelope excitation mechanism seems to be definitely indicated by observations now available ; they are (1) radial nature of β Cephei pulsations, (2) narrow range in effective temperature (i.e., $T_{eff} \simeq 20{,}000$ - 30,000 K) for the β Cephei instability strip, (3) the existence of fairly reasonal pulsation constant $Q = \text{Period} \times \sqrt{\bar{\rho} / \bar{\rho}_\odot} = 0.025 - 0.04$ day, which is a parameter characterizing the envelope structure but not the deep interior. If this is accepted, then the discussion given in subsection 3.1 naturally leads to the above conclusion of the κ-mechanism.

As for the line-profile variable stars are concerned, I suspect that the most likely candidate for their excitation of oscillation will be some sort of interaction between rotation and convection. It is very likely that rotation plays a major role in this case because nonradial modes observed in these stars are those of traveling-wave type, i.e., either prograde mode or retrograde modes. Rotation (or a similar effect such as binary nature) can only provide necessary directivity to traveling-wave mode by differentiating otherwise degenerate nonradial modes having the same ℓ but different m. Another feature of the line-profile variation is its ubiquitous nature among early-type stars, and it is found both in rapid rotators and slow rotators. This suggests that the excitation mechanism itself is relatively insensitive to the detailed structure of stars and to the absolute value of rotational velocity. Convection is quite ubiquitous among early-type stars as it occurs in a convective core and a shallow surface convection zone. It may likely feed energy to waves (or oscillations) through unstable stratification. However, the detailed mechanism of interaction between rotation and convection and of wave generation is not well understood yet. Works along this line may turn out to be fruitful.

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