B STAR PULSATION – THEORY AND SEISMOLOGICAL PROSPECTS

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1. Introduction

Progress in understanding B-type pulsators has been reviewed at several recent meetings (e.g. Dziembowski, 1993, 1995; Moskalik, 1995). Not much happened afterwards. Owing to further improvement in the stellar opacity calculations (Iglesias and Rogers 1996), the theoretical pulsation-instability domain in the upper Main Sequence is now more precisely determined. In the next section I will compare the predicted domain with the positions of various B-type pulsators in the H-R diagram.

There has been no progress in nonlinear modeling of B-type stars and therefore our understanding of pulsation is still limited to identification of the driving mechanism for the observed modes. However, we do not understand, in particular, how amplitudes of the unstable mode are determined. In the last section I will discuss needs for going beyond the linear approximation.

Most of this review is devoted to applications of B star pulsators to probing stellar systems and to testing stellar evolution. Some progress has been achieved but much remains to be done.

2. B star instability strip

The opacity mechanism acting in the metal-bump zone at $T \approx 2 \times 10^5$ K is the cause of pulsation excitation in the whole range of Main Sequence B stars. In stellar models corresponding to the B3–B9 spectral type range the instability is found only for high order g-modes. Periods of the unstable dipole ($\ell = 1$) modes extend from about 1 to 5 days. For the $\ell = 2$ mode the range is 0.5 - 3 days. Both the spectral type and pulsation period ranges agree with those of Slowly Pulsating B (SPB or 53 Per) stars.

In hotter stars the instability occurs also in low order p- and g-modes with periods in the 0.1-0.3 day range. Excitation of such modes is responsible for the existence of β Cep type pulsators. The two instability domains for modes with $\ell \leq 2$ are shown in Fig. 1.

As expected, the extent of the instability domains is very sensitive to the metal abundance, Z. It should be noted that even at $Z = 0.01$ there is a sizable SPB domain. The corresponding β Cep domain is limited to the high luminosity range.

F.-L. Deubner et al. (eds.), New Eyes to See Inside the Sun and Stars, 355–360.

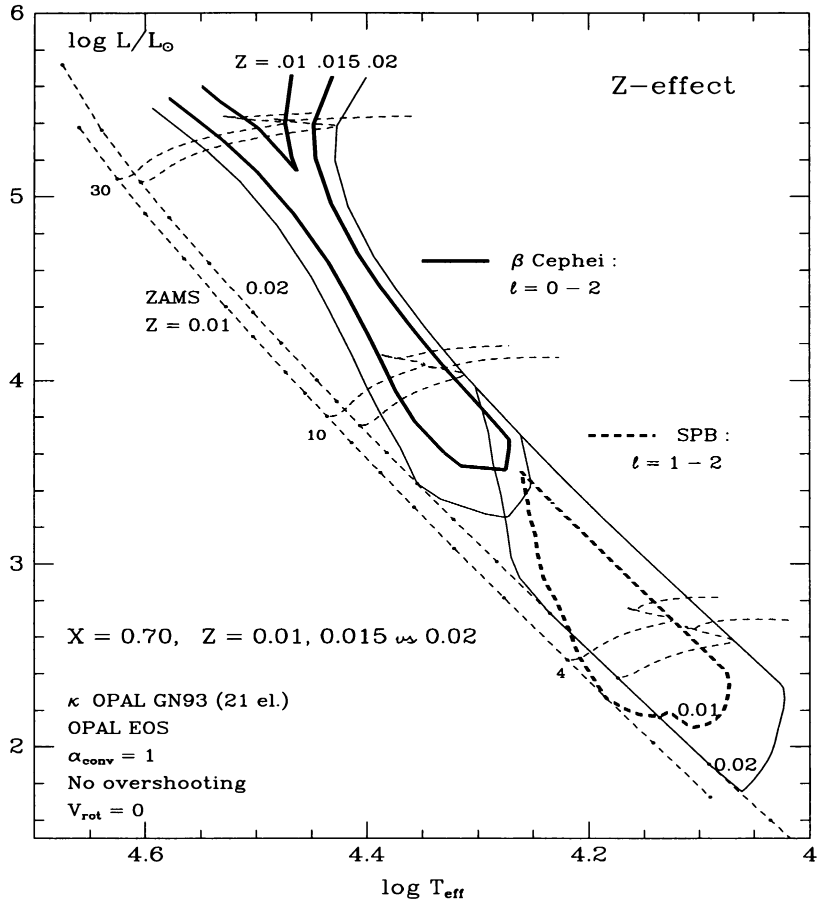

Figure 1. Domains of the pulsation instability in the upper part of the Main Sequence band as determined for models with the three indicated values of the metal abundance parameter, Z. The red boundary of the β Cep domain is identified with the Terminal-Age Main Sequence line. The instability continues into the Hertzsprung gap. For the SPB stars the instability terminates at the TAMS. Models were calculated with a standard stellar evolution code ignoring effects of overshooting and rotation. For $Z = 0.01$ and 0.02, the ZAMS lines and evolutionary tracks for the three indicated values of $M/M_\odot$ are shown (from Pamyatnykh, 1997).

This area, however, is apparently avoided by real objects. At $Z = 0.02$ there is a small overlap of the two instability domains. An object with the two types of modes excited simultaneously has not yet been discovered.

The instability to high order g-modes is indeed more common and more SPB than β Cep variables have been predicted. However, due to their long periods and lower amplitudes the former stars are much more difficult to discover, which explains why, until recently, we knew only 8 such stars. The situation changed after analysis of Hipparcos data which led to discovery of 72 [1] new SPB stars and only 4 β Cep stars (Waelkens et al., 1997). Now the numbers of known objects of the two types are comparable. The newly discovered SPB stars fill up the theoretical instability domain for $Z = 0.02$.

There is an agreement between observations and the theory that β Cep type pulsation is an episode in life of massive stars at the end of their Main Sequence evolutionary phase. The instability, in fact, extends beyond the Main Sequence phase. However, because the post-MS evolution is very fast we do not expect to find objects past the Terminal Age Main Sequence (TAMS) line in the H-R diagram. The position of this line is sensitive to the assumed extent of the convective overshooting from the stellar core. A small amount of overshooting helps to accommodate photometric data on some β Cep stars, however this may be accomplished also by taking into account the effects of rotation and/or by adjustments in the chemical composition parameters. More stringent constraints on the overshooting distance are expected from construction of seismic models of multimode β Cep stars.

The apparent paucity of β Cep type pulsations in stars with $\log L/L_\odot > 5$, in spite of the fact that the instability strip widens at high luminosities, calls for an explanation. Perhaps the instability has different consequences at the highest luminosities. The common low amplitude variability in blue supergiants is probably connected with the same driving mechanism (Kiriakidis et al., 1993).

3. Applications to probing stellar systems

The strong sensitivity of the instability domain boundaries to the Z-value suggests that the occurrence of B type pulsators in a stellar system may be used to determine the lower limit of metal abundance. This potential application remains to be explored. So far there is no confirmed discovery of a β Cep or SPB star outside our Galaxy, and within the Galaxy the inventory of B-type pulsators is incomplete.

Another application is in dating stellar systems. We may expect β Cep stars in a specified period range only in a certain time interval of the stellar system's life. In Fig. 1 we see that for $Z = 0.02$ at zero age we may have only low mass and, therefore, short period objects. The next group to enter the instability domain are massive, long-period objects, which follows from the shape of the blue boundary of the domain and the speed of stellar evolution. Then come the objects with typical β Cep masses of 10 to $15 M_\odot$. After some 15 Myr all but stars with masses less than $10 M_\odot$ leave the instability domain. Thus, by studying properties of β Cep stars in a stellar system we may determine its age.

Recently, Balona et al. (1997) analyzed the data on β Cep star in three young clusters (NGC 329s, NGC 4755, NGC 6231) which are abundant in this type of star. These authors determined the ages by isochrone fitting and by making use of pulsational data; they concluded that the latter method is more accurate.

4. Seismic models of β Cep stars

Applications of β Cep stars to testing massive star evolution were attempted soon after the cause of their pulsation had been identified. Two problems are of particular interest. The first (the extent of the overshooting from the core) was already mentioned

[1] This number was recently increased to 100 (Aerts, de Cat and Waelkens, this volume).

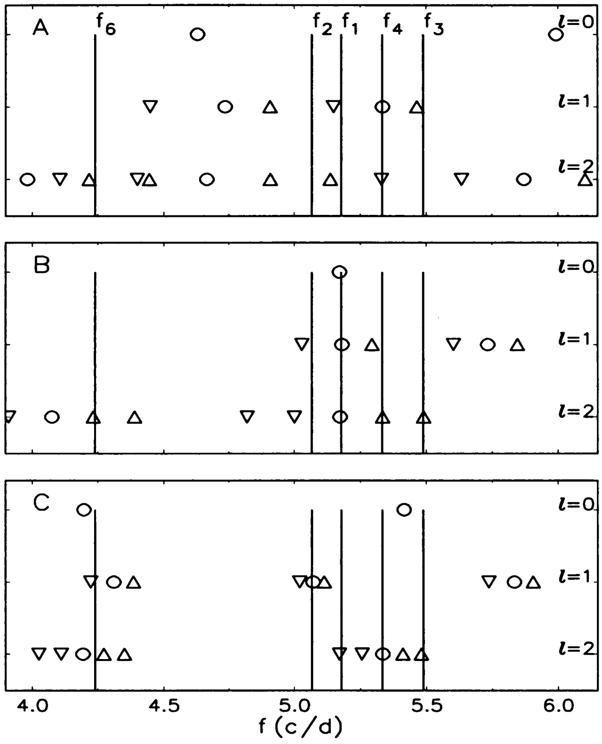

Figure 2. Measured frequencies for DD Lac (Jerzykiewicz, 1978) (vertical lines), compared with calculated frequencies of low degree modes ($\ell \leq 2$) in three models. The $f_5 = f_1 + f_4$ frequency is not shown. Circles denote centroid modes, upward and downward triangles denote prograde and retrograde modes, respectively. The three panels correspond to the following different identifications of the observed equidistant triplet (f_1, f_4, f_3) and to different stellar parameters. In model A it is the $\ell = 1$, p_1 triplet; in model B it is a part of the $\ell = 2$, g_1 quintuplet and in C a part of the $\ell = 2$, p_0 quintuplet. Models are characterized by the following parameters. A: $M/M_\odot = 11.84$, $\log T_{\rm eff} = 4.37$, $\log L/L_\odot = 4.21$, $V_{\rm rot} = 114$ km/s; B: $M/M_\odot = 10.44$, $\log T_{\rm eff} = 4.35$, $\log L/L_\odot = 4.03$, $V_{\rm rot} = 67$ km/s; C: $M/M_\odot = 12.24$, $\log T_{\rm eff} = 4.37$, $\log L/L_\odot = 4.28$, $V_{\rm rot} = 40$ km/s.

in Section 2. We do not have a credible theory of this phenomenon, nor adequate numerical models. The overshooting causes element mixing beyond the convective core boundary which has far-reaching consequences for stellar evolution. The second problem is the evolution of angular momentum. Also, in this case we lack good theory. In particular, we do not know how nonuniform may be the rotation rate in stellar interiors. Amongst modes that may be driven in β Cep stars there are ones with large amplitude in the chemically inhomogeneous zone surrounding the convective core. These modes are of particular interest here.

For several multimode β Cep stars, Mike Jerzykiewicz and I undertook a program of constructing seismic models, i.e., models reproducing all measured frequencies. Our first work (Dziembowski and Jerzykiewicz, 1996) was devoted to EN Lacertae, a star with four mode frequencies measured. The star is also an eclipsing and single-lined spectroscopic binary and this yields additional constraints on its model. We could reproduce all measured frequencies only upon assuming rather substantial increase of the rotation rate toward the center. We plan to revisit the star with our improved treatment of effects of rotation and with use of one additional frequency that has been recently determined (Jerzykiewicz and Pigulski, 1997).

Here, I will consider in greater detail another object from our program, DD Lac (Dziembowski and Jerzykiewicz, in preparation, see also our poster paper in this volume). The most conspicuous feature of the amplitude spectrum is the equidistant frequency triplet (f_1, f_4, f_3). There are conflicting conclusions regarding the ℓ and m values of the three modes. However, the observers agree that the f_1 mode is nonradial. Therefore, we assumed only that the three frequencies represent either a rotationally split $\ell = 1$ triplet or a part of an $\ell = 2$ quintuplet. With the observational constraint on $T_{\rm eff}$ we still had to consider 11 distinct identifications for the modes in the observed triplet. Three examples are shown in Fig. 2. Other possibilities involve the $\ell = 1$, g_1 triplet and four different choices of subsets of the $\ell = 2$ quintuplets for two possible radial orders.

For each identification we may find a model which best fits all measured frequencies. In the cases of the three models in Fig. 2 the fit was only preliminary as may be easily noticed. The only stellar parameters adjusted were mass M and initial angular momentum – the quantity translated to the current equatorial velocity of rotation $V_{\rm rot} = R\Omega$. The fit may be improved by adjusting $T_{\rm eff}$ and chemical composition parameters, X and Z. The models were calculated with the standard Population I values: $X = 0.7$, $Z = 0.02$. There should be also room for parameters describing nonuniform rotation and convective overshooting.

Model C seems quite close to a good fit. However, prospects for achieving the frequency fit at level of the observational frequency errors (10^{-4} c/d) are in fact quite distant. One problem is the accuracy of the perturbation treatment of the rotation effects on oscillations. Here we rely on the second order perturbation theory in Ω, and our calculated frequencies are reliable only to 10^{-3} c/d.

There is another, more interesting, problem. The data yield for frequency separation $\Delta f = f_4 - (f_1 + f_3)/2 = -0.0001 \pm 0.0003$ c/d. The frequency splitting is equidistant within the errors. This is not predicted by model calculations. If the $(f_3 - f_1)$ difference is used to assess the value of Ω, then model values of Δf range, depending on identification, from 0.002 to 0.05. The lowest value corresponds to the $\ell = 2$, p_0, $m = 0$ identification. It is possible that in this case an agreement may be achieved with very specific model parameters. However, there is an alternative possibility which implies a limitation for use of frequencies calculated with the linear theory. Buchler et al. (1995) showed that a nonlinear interaction between modes in a rotationally split triplet may lead to a limit cycle with constant (not equal) amplitudes and the phase lock causing the frequencies to appear exactly equidistant while the linear frequencies are only approximately equidistant.

5. The need for nonlinear theory

The fact that the linear approximation may not be sufficient for the high precision frequency calculation is bad news for asteroseismic applications. Nonlinear calculations are far more complicated than the linear ones. Furthermore, if we do not have credible determination of the ℓ's and m's for the modes, we cannot be even sure that what we are observing is a rotationally split triplet. The phase lock leading to exactly equidistant frequency separations may occur for any three modes whose linear frequencies satisfy an approximate relation $\nu_2 \approx (\nu_1 + \nu_3)/2$, providing that the integral of $|Y_1|^2 Y_2 Y_3$, where Y_k's denote spherical harmonics of the respective modes, is nonzero.

The nature of the triplet in DD Lac must be explained before we may construct the seismic model of the star. A reliable determination of the ℓ's and m's would be of great help. However, development in nonlinear theory seems a necessity. This effort is important for interpretation of the oscillation for this and other β Cep stars, as well as for many multimode pulsators of different types. For variable white dwarfs we have abundant data which may be interpreted only within the framework of nonlinear theory of nonradial oscillations (S.O. Kepler, D.E. Winget. private communications).

Perhaps the most interesting application of β Cep stars is for testing nonlinear theories of multimode stellar pulsation. These stars are the best for starters because they are the simplest amongst stars showing this type of pulsational behavior. The observed pulsation spectra do not exhibit the complexity encountered in variable white dwarfs. Furthermore, the effects of convection and magnetic fields, which always present formidable problems for the theory are, most likely, unimportant in β Cep pulsations.

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