Nonradial and radial oscillations observed in non-emission line OB dwarfs and giants

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1. Introduction

Only a decade ago, this talk could have concerned only the β Cephei stars which however populate a much more precisely defined strip in the Hertzsprung-Russel diagram (HRD). But recent reconnaissance surveys (Smith 1977; Smith and Penrod 1984; Waelkens and Rufener 1985; Baade, in preparation) show that perhaps only one, if any, sizeable region of the upper HRD is devoid of nonradially pulsating stars. The identification of the driving mechanism is still pending (cf. the parallel talk by Osaki), and apparently our knowledge about the internal structure of OB stars is incomplete. But, turning that argument around, it also is indicative of how much may be learned about OB stars from and through the solution of that fundamental problem. This seismologial potential, the ubiquity of the phenomenon, and the effect, as suggested by recent observations of some stars, of the pulsations on the mass loss of OB stars make the oscillations of OB stars one of the most important problems of current astrophysics. On the observational side, rotationally broadened spectral lines, large amplitudes, comparatively long periods, and high luminosities permit information to be gathered which otherwise is accessible only for the sun.

The pulsations observed in B stars were reviewed several times in recent years (Lesh and Aizenman 1978, Jerzykiewicz and Sterken 1980, Percy 1980, Le Contel et al. 1981, Smith 1981, Cox 1983). Work concerning B stars in general has been compiled to a comprehensive monograph by Underhill (1982). The properties of O stars connected to evolution and mass loss were the subject of IAU Symp. No. 82 (1979, Reidel).

2. The β Cephei stars

The historical name β Cephei stars can be retained as the one of a distinct group interspersed in the apparent quasi-continuum of oscillating OB stars only if that distinction is based on their pulsation properties. Following a suggestion made repeatedly by Smith (e.g.,

J.-P. Swings (ed.), Highlights of Astronomy, 255–263.

1980), I shall adopt the working definition that a pulsating B star is a β Cephei star if and only if one of its pulsation modes is radial. This definition has the disadvantage, however, that it is not based on a directly measurable quantity but on an inferred property which at least in the past was one of the most debated subjects among β Cephei star observers.

2.1. Identification of the radial mode and the evolutionary stage of β Cephei stars

The most commonly used mediators between theoretical and observable quantities are the pulsation constant, $Q = P \sqrt{\bar{\rho} / \bar{\rho}_\odot}$, and period-luminosity (PL) relations. In practice, it is often unavoidable that not for all stars considered a reliable identification of the radial mode is available. If spectral type and period are the only selection criteria, it must be kept in mind that a contamination by purely nonradial pulsators is inevitable which simply happen to have spectral types and periods consistent with real β Cephei stars.

Owing to the uncertainties involved in the luminosity calibration of early-type stars, variables in open star clusters take on an important role. NGC 3293 (9 stars, Balona and Engelbrecht 1983) and NGC 6231 (6 stars, Balona and Shobbrook 1983, Balona and Engelbrecht 1985) are the two most populous clusters searched for β Cephei stars. The variables in each cluster cover about the same range in effective temperature ($4.39 < \log T_{eff} < 4.44$ in NGC 3293). Thus, a certain surface temperature is a necessary conditions for a B star to be a β Cephei star. It is also not sufficient since in NGC 6231 there are about as many constant as variable stars in the instability zone. By contrast, in the HRD of NGC 3293 there is no constant star immersed between the pulsating stars. The variability is therefore not a transient phenomenon. Because the variables in NGC 6231 are still on the ZAMS, β Cephei type pulsations are not probably restricted to a particular evolutionary phase and do occur already in the core hydrogen burning stage. In addition to being less luminous, the variables in NGC 6231 also have considerably shorter periods than those in NGC 3293. The two effects combine in such a way that the variables of both clusters probably have about the same pulsation constant (Balona and Engelbrecht 1983). Which radial mode is excited does not, therefore, depend very critically on the evolutionary state.

Early versions of the PL relation for β Cephei stars showed considerable scatter, and several observers attempted to reduce that scatter by including a color term (PLC relation). But it was demonstrated by Jerzykiewicz and Sterken (1980) that the claimed improvement is only the result of the temperature-luminosity relation which enters via the orientation of the β Cephei strip in the HRD, and they conclude that a PL relation probably does not exist. Opposed to the Hβ index used by most previous workers, Waelkens (1981) obtained independent observations in the Geneva photometric system and arrived at a much tighter PL relation. When combined with the theoretical PL relations calculated by Lesh

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and Aizenman (1974), all but one of Waelken's points lie in the strip of the second harmonic. Lowering Waelken's luminosities by $0^{m}.6$ as suggested by the work of Shobbrook (1983a,b) shifts the empirical PL relation close to the theoretical one for the first radial overtone. At least for Waelken's sample, the empirical width of the PL relation now is comparable to or even less than the theoretical one for one mode (the theoretical width is finite, too, because of the stars' evolution).

The sign and rate of period variations can, in principle, reflect structural changes and therefore identify the evolutionary state of a star. Because both period increases and decreases have been reported for various stars, they do not actually, taken at face value, help to locate the β Cephei phenomenon more precisely. But an interesting result was reported by Chapellier (1984) from the analysis of O-C curves of nine β Cephei stars. The apparent period variations found in six stars are better described not as a continuous, slow process but as occasional, sudden jumps after which the periods remain constant for one to at least five decades. Chapellier argues that this constancy identifies the β Cephei stars as being in the core hydrogen burning stage whereas according to model calculations by Sweigart and Renzini (1979) for RR Lyrae stars which show a similar behaviour, the apparently erratic period jumps could be due to individual mixing events which change the composition profile of the star. β CMa is perhaps an example of how the rotational splitting of two nonradial modes may change in the same fashion.

2.3. Relationship between radial and nonradial modes

All investigators agree (cf. Cox 1983, p. 11) that the nonradial modes seen in quite a few, but not all, β Cephei stars are of low degree, ℓ, not exceeding 3. Their periods are in no case substantially different from those of the radial modes (cf. Cox 1983, p. 11). Smith (1980) therefore described this situation as one of a near-resonance which leads to a redistribution of the pulsation energy between several modes. But it appeared difficult (Smith 1980) to conclude that the nonradial modes somehow are just the by-product of the radial pulsation since in 12 Lac the amplitude of the radial mode is not the largest one (Smith 1980, Jerzykiewicz et al. 1984). On the other hand, the surface amplitude alone is not a measure of the energy contents of a mode.

Furthermore, it appears that low-order modes in β Cephei stars, as a rule, have shorter periods than in purely nonradially pulsating stars. When plotted in the theoretical PL diagram by Lesh and Aizenman (1974) for nonradial modes, Waelken's (1981) PL relation (cf. above) suggests that the nonradial modes of β Cephei stars are p-modes. Such an identification is not, however, possible for the much longer periods often seen in purely nonradial pulsating stars (cf. Sect. 3.1). An investigation if that difference and the occurrence of a radial mode are related appears worthwhile.

3. Purely nonradially oscillating OB dwarfs and giants

3.1. Mode analysis

The first important step beyond the limits of the β Cephei instability strip was Smith's (1977) detection of variable line profiles in a large proportion of stars with spectral types between O8 and B5. The line profile variations could be successfully modelled in terms of low-order NRP's. The spectral types, the absence of a radial mode, and long periods in the range from 0.5 to over 2 days found in all stars studied showed these stars to be clearly different from the classical β Cephei stars. With the exception of 53 Per (Smith et al. 1984), the line profile variations appeared dominated by a single mode at a time. But the apparent instability of the periods often hardly justified the usage of the term pulsation mode. Variations, mostly by a factor of two and other "magic" numbers, occurred every few weeks. Confirmation of these irregularities from longer series of observations with a higher time resolution appears desirable, though.

In the conventional classification scheme for linear, adiabatic, NRP's (see Cox 1980), which may be not all applicable to the stars in question (!), the length of the periods implies either r or g-modes. Smith (1982) has presented arguments why the observed profile variations cannot usually be adequately modelled as r modes. If g-modes, a very high radial overtone is implied (cf. Cox 1980), and in view of the density of g-modes in that domain of the frequency space it is not clear why only one mode dominates the pulsation. This problem is similar to the situation found in Ap and ZZ Ceti stars (see the parallel talks by Kurtz and Winget, respectively). Also, by definition (cf. Cox 1980), the horizontal-to-vertical amplitude ratio of g-modes is large whereas line profile fitting consistently suggests that this value is of order 0.15 or smaller. - More detailed reviews of those early results were given by Smith (1979, 1981) and Le Contel et al. (1981).

a) m-commensurable periods in broad-lined stars

In stars with large or intermediate v sin i, the rotational Doppler effect permits the observation also of higher-order modes (Vogt and Penrod 1983, Baade 1984). Regularly spaced bumps traversing photospheric line profiles within a few hours were first seen in Zeta Oph (Walker et al. 1979)., their correct explanation was given by Vogt and Penrod (1983). Baade (1984) and Baade and Ferlet (1984) furthermore noticed that in the B2e star Mu Cen and the B1Ib supergiant γ Ara both a high (m=10) and a low-order (m=2) mode were present. Unexpectedly, in either star the two modes appeared coupled since their periods were commensurate with the mode orders, m, i.e. $m \times P_m \approx$ const. The constant, later called the "superperiod" by Smith (1985c), is different for different stars and equivalent to the time needed for the pulsation pattern to complete one full circuit about the star.

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From a larger series of observations of ε Persei (B0.7 III), Smith (1985a) confirmed the existence of period commensurability also in "normal" stars. But he found that the periods of the ℓ=4 and the ℓ=6 modes are (approximately) commensurable only when averaged over one supercycle. The phase residuals of the ℓ=6 mode with respect to the stable ℓ=4 "clock" are the largest when the two modes interfere constructively. Because the sum of the two amplitudes exceeds the sound speed, Smith suggests that non-sinusoidal waveforms may lead to the impression of non-equidistant waves. However, Smith was not forced to adjust the phases of individual waves but, in a given observation, could use the same phase correction for all ℓ=6 waves. This is compatible with the alternative interpretation that the relative phasing of the two modes is modulated not in space (i.e. variable wavelength as suggested by Smith) but in time (i.e. variable period). In the latter case, the origin of the phase jitter cannot be a surface phenomenon but must be located deeper in the star.

It was pointed out by Baade (1984) and Baade and Ferlet (1984) that the rotational m-mode splitting in fast rotators may significantly increase the probability of near-resonances between otherwise different eigenfrequencies. This concept of the rotation as a passive filter which would also explain why only few eigenmodes dominate the observed pulsation spectrum, was developed by Smith (1985b, cf. below) into an active filtering effect of the rotation in the frame work of Osaki's (1974) model where NRP's are driven by a resonant interaction between the oscillatory convection of the stellar core and the rotation. The period commensurability is also reminiscent of the clustering in β Cephei stars of the nonradial mode periods around the one of the radial mode. For a better understanding of the two problems it could be useful to search for high-order (m) nonradial oscillations and period commensurabilities also in sufficiently rapidly rotating β Cephei stars (which would first require that radial oscillations are unambiguously detected in a rapid rotator).

A very nice example of the phenomena described above is Spica in which Smith (1985b) recently identified two commensurable ℓ=8 and ℓ=16 modes. Formerly, Spica used to be classified as a β Cephei star but must have undergone a substantial change of its mode spectrum. (To me, the evidence that Spica has ever been pulsating in a radial mode does not appear completely indisputable.) Spica's radius, inclination angle, v sin i and, hence, its surface rotation rate are rather well known so that one can determine the intrinsic pulsation frequency of modes "rooted" near the surface. Assuming g-modes and that also the intrinsic periods are m-commensurable, one can then, at least formally, deduce the rotation rate of deeper layers if they are the "carriers" of other modes. Developing these arguments, Smith (1985b) showed that Spica's rotation rate probably decreases towards the surface.

b) Apparent selection rules for mode degrees and orders

In all stars with high-order spheroidal modes only sectorial modes (|m|

= ℓ) have been diagnosed. Because m is the number of node lines intersecting the equator at a right angle and $\ell-|m|+1$ is the number of belts parallel to the equator, only m is directly accessible through the rotational Doppler imaging. For $\ell-|m|$ an upper limit is usually derived from the argument that contributions to the bumps by belts pulsating in antiphase partly cancel out. In order to reproduce the observed bump strength, the velocity amplitude can therefore with increasing $\ell-|m|$ soon have to be unreasonably large. The period commensurability is of course very useful in resolving the typical ±1 uncertainty in m.

In the case of m-commensurable periods, only even m's seem to exist, except for an occasional ambiguity between dipole (ℓ=1) and quadrupole (ℓ=2) modes. This could mean that odd-even mode coupling is very inefficient or that of all possible pairwise mode couplings those of each single mode with the quadrupole mode is the most important one. In the latter case, one could speculate if it is essentially that quadrupole mode which is directly driven and from which the other modes are "spawned". Finally, there is much less, if any, evidence than in β Cephei stars for the simultaneous excitation of modes belonging to the same ℓ-multiplet.

In agreement with most observations of slowly rotating stars, theoretical analyses prefer direct modes. But Penrod (Smith and Penrod 1984) finds that in stars with v sin i $\leqslant$ 200 km/s retrograde modes are the rule. Apart from possible implications for the identification of the mechanism(s) that drive and/or filter out the observed modes, a more profane aspect of retrograde modes is that they rule out surface and/or circumstellar inhomogeneities which are still sometimes suggested as substitute-explanations of the observed line-profile variability.

3.2. Photometric signature of the variability

Information about activity on a small spatial scale is not easily recovered from the light variability integrated over the stellar disk. Other difficulties arise from periods of the order of a half day or longer. The advantages of high-quality photometry are different: (i) The relative ease of Fourier analyses which provide an independent check on the periods, amplitudes and their stability, (ii) a less ambiguous detection of temperature variations than with spectroscopy alone (very important for the detection of pressure variations, i.e. the distinction between spheroidal and toroidal modes) and (iii) the feasibility of a long-term monitoring program and the mapping of the upper HRD in the pulsation parameter space. First results nicely confirm these expectations but also clearly show the necessity to do observations with different techniques simultaneously.

The up to date largest survey of the photometric variability of OB stars has been undertaken by Waelkens and Rufener (1985). Unlike typical searches for β Cephei stars, it did not a priori exclude the detection of the slow variability of purely nonradially pulsating stars. Most interesting in the context of this review is a group of seemingly normal stars with mid-B spectral types (B3 - B7). In 7 stars a single period between 1.2 and 2.8 days was found (in the three stars observed in two different seasons no period change occurred) with amplitudes between 25 and 85 m.mag in V. Color curves are in phase with the light curve, the amplitudes reach up to 60 m.mag in U-B but are an order of magnitude smaller in B-V. There are changes in the light amplitudes which are accompanied by changes of the color amplitudes so that the color-to-light amplitude ratio is practically maintained.

4. Summary and conclusions

NRP's are an ubiquitous phenomenon in OB stars. Only towards cooler stars there is a rather sharp cut-off around spectral type B7 (McNamara 1985 and references therein; Baade, in preparation) so that there is no convincing connection ("Maia stars") between the line profile variable OB stars and the δ Scuti stars. (This gap does not probably exist for very luminous stars.) Blueward of that limit, no structure can at this moment be discerned in the two-dimensional HRD, except for the radial oscillations in the classical β Cephei strip. There are indications that further subdivisions may be possible on the basis of additional parameters like rotational velocity, emission line-star characteristics, luminosity, etc. But the proper mapping of the pulsation characteristics still remains to be done.

In β Cephei stars, the prevailing (maybe only?) radial mode is the first harmonic overtone. In the presence of a radial mode, the spectrum of the nonradial modes appears different from purely nonradial pulsators. The periods of the nonradial modes cluster around the one of the radial mode and usually are shorter than those of low-order modes in purely non-radially pulsating stars. Observations of open star clusters suggest that the β Cephei phenomenon neither is a transient one nor restricted to a particular evolutionary phase. It does occur in the core hydrogen burning stage. The line doubling of some β Cephei stars, initially one of the strongest motivations to study NRP's of stars, reflects only the response of the atmosphere (shocks) to supersonic velocities associated with radial pulsations (see, e.g., Smith 1981).

An interaction also between nonradial modes is seen in the form of mode order-commensurable periods in many purely nonradial pulsators. It is not known if the same also happens in the presence of a radial mode. Pulsation amplitudes of purely nonradial oscillators are usually fairly variable, maybe even on time scales of weeks. The initial impression of a very substantial period variability, however, may have to be revised in view of that amplitude variability and the relative period stability emerging from longer stretches of data.

The interaction between modes may be one of the few properties shared by almost all pulsating OB stars. It clearly provides an additional constraint on theoretical models and may hence prove useful. But it must also serve as a warning that the modes observed at the surface do not directly reflect those driven deeper in the star.

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Appendix

Osaki (1985, in D. Gough (ed.): "Oscillations of the sun and distant stars", Cambridge, in press) has shown that for a star seen at intermediate inclination, line profile fitting of travelling bumps may not be able to discriminate between toroidal modes and p-modes. The following is an attempt to slightly generalize this discussion.

1) The observed bumps usually are roughly equally spaced, and their spacing does not change much with phase of the pulsation. (a) With spheroidal modes, this can be reproduced by either the radial or the latitudinal (if k×m large) velocity component V_r or V_θ. For stars seen equator-on, the bumps due to the two velocity components are in phase. At small inclinations, however, they interfere destructively so that at intermediate inclinations each bump can attain a strange double-wave pattern. (b) For sectorial spheroidal modes, the effect of $m \times k \times V_\theta$ is weaker than the same value of V_r. (c) In toroidal modes, only V_θ needs to be considered because V_r is vanishing. (d) For sectorial modes, particularly at large inclinations, the effect of V_θ is less pronounced for spheroidal than for toroidal modes because the line-of-sight component of the former is anti-symmetric with respect to the equator (if $i=90°$) so that the effects due to the motions on the two hemispheres partly cancel out.

2) In both spheroidal and toroidal modes V_ϕ, too, can lead to travelling bumps. However, in order to produce them also in the line center, V_ϕ must be very large and increasingly so with increasing v sin i. Then, line width variations in the wings become very conspicuous. The spacing of the bumps varies strongly with phase. Both the latter effects are not in agreement with existing observations.

3) For smaller values of V_ϕ and certain combinations with v sin i and m, azimuthal motions near the equator only produce deep absorption spikes near the line wings (cf. Smith's observations of Spica: 1985, ApJ **297**, 224). Best candidates (in order to minimize the amplitudes needed) are sectorial spheroidal and tesseral ($\ell-|m|=1$) toroidal modes. For most inclinations, the V_θ of such tesseral toroidal modes will additionally lead to strong bumps chopping up the entire profile.

To summarize, V_ϕ cannot be the sole cause of travelling bumps. V_θ is not very likely either as a general explanation because of the pronounced dependence of the profile variations on the inclination. The, thus far, fairly homogeneous appearance of the phenomenon in various stars is most easily explained with radial motions. In the frame work of the classical categories of p-, g-, and r-modes, it seems difficult to push the horizontal-to-vertical amplitude ratio beyond 0.5 so that the identification of long-period low-order modes with conventional g-modes remains problematic. However, the most powerful discriminator between vertical and horizontal motions should be temperature variations deduced from simultaneous (!) photometry since these are not expected from horizontal motions. If other types of modes have to be considered in future, points 1) to 3) provide preliminary observational constraints on their surface velocity fields.