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PULSATIONS OF B STARS-A REVIEW OF OBSERVATIONS AND THEORIES

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ABSTRACT

I discuss the observational and theoretical status for several classes of variable B stars. The older classes now seem to be better understood in terms of those stars that probably have at least one radial mode and those that have only nonradial modes. The former are the β Cephei variables, and the latter are the slowly rotating 53 Persei and the rapidly rotating ζ Ophiuchi variables. It seems that in this last class there are also some Be stars that show nonradial pulsations from the variations of the line shapes and their light. Among the nonradial pulsators, we must also include the supergiants which show pulsations with very short lifetimes. A review of the present observational and theoretical problems is given. The most persistent problem of the cause for the pulsations is briefly discussed, and many proposed mechanisms plus some new thoughts are presented.

I. INTRODUCTION.

In the last ten years there have been many reviews of the variable B stars. One of my favorites was the one by John Cox (1976) who was able at that time to cover most of the ideas about possible mechanisms for the pulsation driving that are still being discussed today. While there had been many reviews of the observational data before that time, those with some quantitative theoretical interpretations are all more recent. In 1978, Stamford and Watson (1978) showed that the light and velocity variations indicated that in some β Cephei stars the pulsation mode was radial or at least not a quadrupole sectorial mode. In that same year, Aizenman and Lesh (1978) pointed out that the β Cephei variable mode is likely to be the first or even second overtone, if radial, or a low order p mode, if nonradial with a low l value. An extensive review of the theories for these β Cephei variables was given by Aizenman (1980), while at the same conference, Smith (1980) reviewed the newly established line profile variations in 53 Per variables that indicate nonradial pulsations.

While the problems of the β Cephei variables remain with us almost the same as presented by John Cox ten years ago, the attention of many observers has moved to the line profile observations for the slowly rotating (53 Per) variables and the rapidly rotating ones (ζ Oph and Be stars). Sareyan, LeContel, Valtier, and Ducatel (1980) and Percy (1980) have both noted the great increase in the types of B stars that vary, from the supergiants, the line profile variables including the slow and rapid rotators and even the Be stars, to the short period B stars. All the aspects of the B star variability were discussed at a conference on pulsating B stars in Nice, and the report is given by LeContel, Sareyan, and Valtier (1981).

Further reviews were given by Osaki (1982), Cox (1983), and Osaki (1985ab) with emphasis on possible mechanisms. Underhill (1982) has written a comprehensive review of all B stars. The most recent reviews of the observational data are by Baade (1986) and Smith (1986), who

detail the many problems in the line profile variable stars, and by Maeder (1985b) who gives data and interpretations for the Wolf-Rayet stars and the early type supergiants.

General parameters for the variable stars are that they have masses ranging from a little less than $3 M_{\odot}$ to over $20 M_{\odot}$. The radii range from about 3 to almost 15 solar radii, with the supergiants as much as 5 times larger. Luminosities then are from just less than 100 to over 10,000 solar luminosities for the main sequence B stars and up to 100,000 solar luminosities for the supergiants. Spectral classes for these variables actually go into the O stars at about 50,000K, and go cooler to just over 10,000K at spectral class B7.

The internal composition for most of the variable B stars consists of normal solar-type composition surface layers. Watson (1971) showed this for the β Cephei variables. Deeper there is a gradient with increasing helium down to either a convective core highly depleted in hydrogen or a hydrogen exhausted isothermal core. For a few B stars the atmosphere layers are helium poor, caused presumably by gravitational settling. For others, all of which are probably magnetic, the helium is enhanced (Osmer and Petersen, 1974) by the action of a stellar wind that blows away more hydrogen than helium (Vauclair, 1975). The Wolf-Rayet and hot R CrB stars are different, because they are highly evolved with almost all the surface layers blown away to uncover helium, carbon, nitrogen, and even oxygen layers, the result of extensive thermonuclear burning of hydrogen and helium.

II. CLASSES OF VARIABLE B STARS.

There have been many suggestions for different classes of the variable B stars, and here I will try to sort out these into those few that fit into the current ideas about these massive upper main sequence stars.

First of all, we must note that there are only two ways of making the observations: photometry and high resolution spectroscopy. Luminosity variations are generally not large. Even most β Cephei variables do not show much amplitude in the light variations, but that is partly due to the fact that at maximum luminosity the stars are bluer with an even smaller fraction of their light being able to pass through the atmosphere and telescope filter. Data from above the atmosphere in the ultraviolet show much larger variations in luminosity amplitude. The 53 Per variables and the supergiants also have light variations of less than about 10 percent (Smith and Buta, 1979). Line profile data divide naturally into those from slowly and rapidly rotating stars, where in the last category, we must include those known to be Be stars.

I suggest that there are really only three classes of B star variability—those that show at least one radial mode and two classes that display only nonradial modes. The first class clearly deserves the name β Cephei or β Canis Majoris variables (Frost 1902). The other two classes seem to be the slow rotators (53 Per variables, Smith and Karp 1976) and the fast rotators (ζ Ophiuchi variables, Walker, Yang, and Fahlman, 1979). Stars in these three classes can exhibit both light and line profile variations but the line profile variations are easier to detect.

With these classes, other kinds of variable B stars can be included as indicated here. The very early proposed Maia variables (Struve, 1955) are just 53 Per variables with both luminosity and line profile variations. The Abt (1957) supergiants would be either 53 Per or ζ Oph variables but not β Cephei variables. They are known from their radial velocity and light variations with periods typical of nonradial modes. The ultrashort B star variables (Jakate 1979) and the 53 Psc variables (Sareyan et al. 1980) would be just 53 Per variables. The Be stars of which there are examples ζ Oph (Vogt and Penrod, 1983), λ Eri (Smith and Penrod, 1985) and many others

would be in the ζ Oph class and they just happen to have emission at least occasionally in the $H\alpha$ line. The slow variables found photometrically by Waelkens and Rufener (1985) are in the 53 Per class as suggested by them.

Stars such as the helium variables and the Wolf-Rayet variables also vary in light and spectrum, but they are not normal upper main sequence stars because of their highly evolved surface compositions. I do not discuss these stars much here, mostly because their pulsations are not yet well observed. It appears to me that the Wolf-Rayet variables can be radial pulsators (Maeder, 1985a), but nonradial g mode pulsations that have been reported (Vreux et al., 1985) seem unlikely in a star that has such an extensive convective core that cannot support these pulsation motions.

III. BETA CEPHEI VARIABLES.

While there has been considerable new observational data on the line profile variable B stars, the key to understanding the variability seems to lie with the β Cephei variables. This is mostly because the radial mode oscillations are easier to interpret theoretically. For example, if the periods are between about 0.15 and 0.25 day, as they all are for the β Cephei variables, it seems at least that they cannot be low degree g modes. In eight β Cephei variables they observationally do not seem to be nonradial - $m=l=2$ p modes either because of their light versus wavelength variation (Stamford and Watson, 1978). Some tentative l and m values are compiled by Cox (1983).

In addition to a well known list of 16 β Cephei variables that are slowly rotating and a list of 6 that are rapidly rotating, there are dozens of other candidates that have been proposed at one time or another. A few of these β Cephei variables are seen in galactic clusters, and the recent discoveries by Balona and Englebrecht (1982), Balona (1983), Balona and Shobbrook (1983), and Balona and Englebrecht (1985), of 10 in NGC 3293 and 6 in NGC 6231 have been extremely valuable for settling the question of the evolutionary stage of these variable stars. Observed luminosities of 10,000 solar luminosities imply a mass of about $11 M_{\odot}$, with a range seen from the field stars, of 8 to about $16 M_{\odot}$. Not all the stars in this luminosity and mass range are observed to vary, however, just as suspected from field star data. Actually, for the more evolved NGC 3293 variables, all the stars in a effective temperature luminosity box in the Hertzsprung-Russell diagram vary, whereas, at the younger age of NGC 6231, the variables are mixed among non-variables near the main sequence. Observable variability can occur over a range of luminosity, but it is not a sure occurrence among stars that otherwise look identical.

A few of the multiperiodic β Cephei variables are suspected to display nonradial modes mostly because the close periods cannot all be from radial modes. These nonradial modes must be low degree p modes however, to be observable. Unfortunately, no mode, radial or nonradial, has been definitively identified.

There have been reports that periods of the β Cephei variables are both increasing and decreasing. These data tabulated by Lesh and Aizenman (1976) and recently by Chapellier (1984) may not be wholly believable, but they may very well indicate internal changes in the structure of the semiconvection zone.

A recent advance has been made by Englebrecht and Balona who have found that one of the β Cephei variables in NGC 3293 is an eclipsing variable with the primary eclipse of about 0.1 magnitude and the secondary of about 0.02 magnitude. The star 16 Lac is also an eclipsing β Cephei variable, discussed in some detail by Jerzykiewicz (1980), but it has only one very

shallow eclipse visible. More data for the cluster variable HD 92024 are needed, but it appears that the pair of stars have masses about 15 and 3 $M_{\odot}$. The mode identifications are possibly the first and second overtone for the massive star, but it is also possible that the two observed periods indicate that $l=2$ and $m=+2$ and -2 . These data reinforce the current ideas about the mode identifications, but they are mostly based on theoretical pulsation constants.

We need to also mention my favorite star Spica. It seems that the recent decay of its pulsations (see Sterken, Jerzykiewicz and Manfroid, 1986, for recent data) may actually be due to the precession of the rotation axis in such a way that a presumed zonal mode with $l=2$ ($m=0$) would be hidden for perhaps 10 to 20 years starting in the early 1970's. If this suggestion by Balona (1986) is correct, one of the main line β Cephei variables is not really a radial pulsator.

The eclipsing variable 16 Lac also seems to have decaying amplitudes for at least two of its three modes. Applying the same precession model as for Spica would seem very appropriate because it is also a binary of short period. Balona (1986), however, notes that a rather high angle between the rotation and orbit axes is necessary to get this precession. With a high angle the m value would not necessarily be zero. If the two most rapidly amplitude varying periods differ by unity in m , the Ledoux and Walraven (1958) C value for the coriolis effect on the periods can be calculated to be a very reasonable number, 0.318.

IV. SLOWLY ROTATING NONRADIAL PULSATORS.

The nonradial pulsating B stars are usually easily identified as nonradial g mode pulsators because they have periods up to a few days, too long for either the radial modes or the p modes. The location of the nonradial pulsators on the Hertzsprung- Russell diagram, surrounds the β Cephei variables. The frequent occurrence all over this region is surprising, because for the yellow giants, pulsation occurs only in a well defined instability strip.

Often the assumption is that the nonradial modes can be interpreted in terms of spherical harmonics, with the quantum numbers l and m giving the surface structure of the modes. This expectation is supported by the fact that these modes satisfy the hydrodynamic equations of motion in the gravitational field of the star. It is also possible, however, that the modes could be toroidal with essentially no radial motion, because these modes are also mathematically acceptable.

For rotation speeds of less than 200 km/s, the all modes (except maybe 22 Ori) are prograde with $-m=l=2$. Higher degrees are seen, but with the slow rotation, it is not easy to see their many crests of the sectorial modes. Smith has studied many of the 53 Per variables and believes that he has been successful in identifying the few l and m values displayed. However, there has been a problem in the apparent mode switching, because the changes seem very rapid (in a matter of days or months) compared to some theoretical expectations. Even within a mode, it seems that the amplitude changes are too rapid also.

An interesting observational fact is that the superperiod mP is apparently constant for all modes with different values of $-m=l$. This means that crests stay lined-up, and for low l the period is much longer. It also appears that only even values of m participate in the superperiod phenomenon. These observations must be of value in generating theoretical models, because perhaps not all of the modes seen need be pulsationally unstable by themselves.

I need to point out that Balona (1985) has photometrically observed many of the 53 Per variables, and rarely is he able to detect the periods that are used to model the line profile variations. He questions many of the identifications, proposing that they may be aliases instead.

For ϵ Per, however, a recent campaign by Smith, Fullerton, and Percy has shown that the strongest period at 3.85 hours, identified as $n=l=4$, is seen in both light and line profile fitting. Balona suggests that the line profile fitting may require allowance for temperature as well as geometric effects and Balona and Englebrecht (1986) even wonder if some of the line profile variations are due to star spots.

V. RAPIDLY ROTATING NONRADIAL PULSATORS.

For the B stars with rapid rotation, nonradial modes of very high degree $l=m=16$ have been suggested. They can be seen as doppler imaged crests on the stellar surface because of the large variations of radial velocity across the disc. Surprisingly, many of these modes seem to be retrograde, in spite of the rapid rotation, and theoretical interpretation of the mode excitation in terms of some aspect of a rapidly rotating core seems out of the question. Observationally, it seems that the difference between a Be and a Bn variable, both of which are rapidly rotating and display nonradial pulsations, is that the Be star has in addition to high l modes (actually only m is detected) an $l=2$ mode which somehow is essential for the mass loss and emission. Perhaps this low l and m puffs-up the star to allow the radiation and pulsation effects to promote mass loss.

The Be stars (recently reviewed by Percy 1985) are in this category, and they exhibit both line profile and luminosity variations. A current line of investigation is to see if the nonradial pulsations cause mass loss seen in the Be stars and others. There are a number of observational problems, including the apparent unequal spacing between crests of the sectorial modes, the occasional masking of a crest that results in either an amplitude change or even a disappearance often accompanying a Be star outburst, and again rapid mode switchings.

VI. CURRENT THEORETICAL PROBLEMS.

In spite of many recent papers on the evolution of massive main sequence stars, there are still a number of questions concerning the mass loss by stellar winds, possible overshooting and mixing at the edge of convective core, and other mixing due to rotation. It seems certain that for the most luminous B stars a radiation driven wind causes extensive mass loss. However, at the lower luminosities of the β Cephei variables, there may be difficulty getting the wind started. Persistent suggestions that pulsations may cause mass loss should probably be taken seriously. The exact internal structure of the star modified by mixing and mass loss processes in the B star pulsation instability region may be essential to discover the cause of the pulsations.

The situation is that some internal mixing is necessary to match evolution calculations with color-magnitude observations of clusters, but too much will prevent evolution into the giant and supergiant region of the Hertzsprung-Russell diagram. However, the μ gradient that is left behind, exterior to the shrinking homogeneous composition convective core, is a strong barrier to the penetration of hydrogen downward and helium upward. Thus mixing should be minimal, and I believe the small amount now being included in the evolution calculations must be about right.

Mixing by rotation which gives slow interior currents must also be ineffective and probably small. Again the μ barriers are difficult to penetrate, and the material that is actually mixed-in is essentially all the same composition even if from a different part of the star.

Additional problems of a theoretical nature involve the interpretation of observations of the line profile variations. The apparent lack of horizontal motions in the line profiles (detected at

the stellar limb) has led to the proposal that the observed motions are not of the spheroidal type but toroidal. This recent suggestion by Osaki (1985c) can produce line profile variations during the pulsation cycle similar to those observed, but detailed analyses by Smith (1986) seem to rule them out. A big problem is that there should be very little light variations for these modes, but most often there is at least some detected.

VII. DEEP PULSATION MECHANISMS.

The most severe problem in understanding B star pulsations is discovering their driving mechanism. I here review, very briefly, the six most discussed deep mechanisms and the three envelope ones. I close with three recent ideas that I have thought, of all of which need more development.

It has often been suggested that a star pulsates by the modulation of its thermonuclear energy source at the stellar center or in energy producing shells. We know that the amplitude of the motions is usually very small there, and only for the very massive main sequence stars, where the central mass concentration is only slight, does this mechanism effectively operate. Nevertheless, many papers have suggested that this ϵ mechanism can be strong enough to at least help make the B stars pulsate. In my investigations, it seems that for low order g modes with amplitudes still significant in the evanescent convective core, there is almost enough driving to overcome the radiative damping in the composition gradient zone and in the normal damping layer near the surface. For realistic models it seems however, that the ϵ effect cannot produce enough driving for any radial or nonradial mode.

Another mechanism that was found to be destabilizing is the slow shrinking of the central convective core. The conversion of hydrogen to helium results in less pressure per gram, less support, and a slow core compression under the weight of the outer layers of the star. There are actually two aspects of this slow collapse: the strengthening of the apparent spring constant and the release of potential energy each cycle to the form of heat. The first aspect actually is damping, but the second produces pulsation driving. Definitive studies by Aizenman and Cox (1975) show that this thermal imbalance does not give enough pulsation driving to destabilize B stars.

Osaki (1974) has suggested that the turbulent convection in the hydrogen depleted core is actually more ordered due to the rapid rotation. This oscillatory convection has a time scale of the rotation, and it has been suggested that the periodicity can couple with a low order mode of the envelope to produce the observed B star pulsations. Further investigations on this general idea have been made by Lee and Saio (1986) who derive eigensolutions consisting of combinations of spherical harmonics. A paper in these proceedings describes this work.

Ando (1981) has championed the idea that the Kelvin-Helmholtz instability at the surface of the uniformly rotating convective core can excite envelope pulsations. It seems to me that this process will surely operate, but will not produce any periodic effect.

I (Cox, 1980) have made the suggestion that a sudden jolt, caused by overshooting at the surface of this convective core, may mix hydrogen into the surface layers of the core. The increased pressure then would push out the core and envelope a bit, and upon recollapse more mixing would occur. This process would give self-excitation of a normal mode until additional mixing is no longer possible with the limited hydrogen available in the immediate layers of the composition gradient. This series of jolts would be driving, but is there enough to produce observable amplitudes at the surface? My calculations show that the jolts do not have enough

energy to cause the observed pulsations. Thus overshooting events, which actually must occur to a limited extent, do not seem to be the cause of B star pulsations.

Finally I must mention the Kato (1966) mechanism that operates in composition gradient layers that are superadiabatic. The dynamic instability of convective elements starts them moving, but the μ gradient prevents a very large excursion. During the time that a convective eddy is away from its equilibrium layer, it either loses or gains heat depending on the relative temperature between it and its surroundings. The μ gradient forces the eddy to return to its equilibrium level, but when it does, it is either hotter or colder than its surroundings even there, and overshooting of its position occurs. This pulsation driving is only local, and most attempts to have these motions couple to destabilize the entire star give, at best, instability in very high degree unobservable modes.

VIII. ENVELOPE PULSATION MECHANISMS.

There are three well discussed envelope mechanisms that seem to apply, and I suggest three other possibilities that might be significant in causing B star pulsations. The three well known ones are the κ , γ and radius effects. All operate to restrain the flow of luminosity at minimum radius, and then release the energy flow during the expansion phase. The energy flow timing then causes the pressure to peak after maximum compression, and to reach a minimum after maximum expansion.

With solar type composition, the operation of the first two of these mechanisms at the appropriate mass depth where there is enough mass involved, but not too deep for the energy flow to be too slow, results in very little pulsation driving. This appropriate mass depth is at a level where the temperature is about 250,000K, and no ionization process for an abundant element occurs at that temperature for the density of the layers. There has been much hope that a small "bump" in the opacity versus temperature, due to the ionization of the last electron from helium at about 150,000K might give enough κ effect, but this Stellingwerf (1978) bump is just not large enough to make the observed B stars pulsate (see Lee and Osaki, 1982).

In spite of the results of Watson (1971) which show that the surface layers of the B stars have solar-like compositions. I have tried over the years to see if any special composition could be found to give the κ mechanism periodic radiation blocking that causes at least the yellow giants to pulsate. The element that would give strong ionization at 250,000K would have an effective nuclear charge of the square root of $250,000/40,000 = 6$ times the $Z=2$ for helium which has its strong ionization at 40,000K. The only possible candidate is carbon that actually has both K and L shell electrons ionizing in layers of the star where pulsation driving can occur. Can we have enough carbon in most all B stars to make pulsations occur?

Figures 1, 2, and 3 give the work per zone plots for three composition structures in a $11.5 M_{\odot}$ B star model at 24,700K and 6.074×10^{37} ergs/s. The first figure uses the composition $X=0.70$ and $Y=0.28$, essentially the solar composition, down through a mass fraction of 0.425 of the star to the top of the evolution-caused hydrogen depleted gradient. One sees that the outer 10^{-4} of the mass for this first radial overtone mode is strongly damping for pulsations. Changing the composition to $Z=0.044$ to obtain some carbon and other heavier element enhancement in a layer between 10^{-8} and 10^{-5} of the mass deep, produces less damping. Finally, making this layer 90 percent helium and 10 percent carbon by mass, one can see actual driving from helium (above 10^{-6} of the mass deep) and from carbon (above 10^{-5} of the mass deep). Since such

outrageous compositions seem out of the question below the thin (10^{-9} of the mass) convection zone, it appears that the κ and γ effects do not cause B star pulsations.

Another possible surface layer mechanism that I have considered when preparing this review is the continuous and possibly cyclical release of the overburden due to mass loss. Since all B stars display mass loss, this might be a good candidate. However, I have found that this weakening the effective spring constant with time and estimates of nonadiabatic effects are very small. This mass loss driving cannot be operating for the mid B class stars, because there the rate is very slow. Thus, as a universal mechanism for all B stars, this effect is not admissible. Similar conclusions have been discussed by Castor (1986).

I here suggest an entirely new mechanism that I have never seen discussed anywhere in the B star pulsation literature. The temperature gradient in the layers just below the surface convection zone is subadiabatic by a small amount approximately 0.05 in $d\log T/d\log P$. It is possible during the pulsations for this gradient to become superadiabatic so that convection is periodically started. The delay of the convection causes a luminosity lag similar to that for the κ and γ effects. Thus this is a driving mechanism, but it operates only if there is originally a large enough perturbation. I suggest that the B stars, all on which are not too subadiabatic in the pulsation driving part of the envelope, may pulsate by this hard self-excited mechanism.

Figure 4 shows the linear theory variation for the gradient $d\log T/d\log P$ in the envelope at mass levels above 1.0×10^{-6} of the stellar mass. This temperature is 260,000K and the density is just over 1.0×10^{-6} g/cc. Driving or damping of pulsations are effective in zones 200 to 300, with deeper ones being too adiabatic for periods seen for the β Cephei variables and more shallow ones having too little mass to affect global pulsations. The normalization for this variation is $\delta r/r=1.0$ as is customarily done. If the linear theory is adequate for representing the internal variations of the variables, and scaling down by a factor of about ten or so matches the actual B star pulsations, then indeed convection can be switched on and off each cycle with the equilibrium gradient being only 0.05 subadiabatic.

We need a mechanism to cause radial or nonradial pulsations in the period range of the low order radial or nonradial p or g modes for B stars of spectral type earlier than about B7. Apparently we need the same mechanism also for the O stars. As has been emphasized by many, especially Osaki (1986 and others earlier), this mechanism is not specific to a limited effective temperature or luminosity range. He then says that that indicates a deep mechanism, but is that really true? Actually, at luminosities just about one magnitude above that for the β Cephei variables, the convection is already transporting energy, and its slow onset and decay during the pulsation cycle may give driving that is not hard self-excited.

The problem is to get this cyclical convection going without a finite amplitude pulsation. I can only suggest that either rotation or, better yet, a binary companion can slightly influence the β Cephei star structure to produce an adiabatic temperature gradient in the pulsation driving region. Kato (1974, 1975) has commented on this and similar problems in binary systems. Previously it was thought that binaries could not play any role for the β Cephei stars because they were thought to exist only in a small part of the HR diagram, but with these variable stars now seen in a much wider region, the influence of unseen binaries may be admissible.

It is possible that this cyclical convection switching mechanism may operate properly in all early type stars to produce the observed prevalent pulsations. It is also possible that the unknown cause of pulsations in the hot helium stars (the hotter R CrB stars) is this convection switching in their envelopes that are very similar to the normal B star envelopes. Whether

this mechanism is significant in the Wolf-Rayet stars or the GW Vir variables needs further investigation.

Figure 1

Work/zone vs. external mass fraction for the first overtone radial mode with the composition $Y=0.28$ and $Z=0.02$.

Figure 2

Work/zone vs. external mass fraction for the first overtone radial mode with the composition $Y=0.354$ and $Z=0.044$.

Figure 3

Work/zone vs. external mass fraction for the first overtone radial mode with the composition $Y=0.90$ and $Z=\text{carbon only}=0.1$.

Figure 4

The variation of the gradient over the superadiabatic gradient during the nonradial p_3 mode pulsation vs. zone number. The peak at zone 310 just below the helium driving at 150,000K.

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