Part 1. Stellar Pulsation in a Broad Context

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Unsolved Problems in Stellar Pulsation Physics

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Abstract. Unsolved problems of theoretical stellar pulsations are briefly reviewed for pulsators in six regions of the Hertzsprung-Russell diagram. Only a small selection is included in the discussion of them, and the emphasis is mostly on theoretical problems. The problem of the pulsations of Mira stars, and the mode in which it pulsates is reviewed in more detail together with some new calculations that illustrate the difficulties. Finally an extensive discussion is made for the pulsation mechanism of the white dwarf (DA and DB) pulsators. A new interpretation is advocated, which unfortunately is not tractable by linear nonadiabatic calculations because during the pulsation cycle it involves the turning off and on of convection with a short time scale relative to the pulsation period. Most of the theoretical problems involve the time dependence of convection, a topic still without any concise and practical way of convenient implementation.

1. Introduction

Theoretical interpretations always depend greatly on observations. Fortunately these observations tend to guide theoretical investigations to relevant theories and prevent considerable waste of theoretical time and effort. However theoreticians must be aware that advertised observations may not always be accurate or interpreted correctly. But there is a price we pay for ignoring possibilities that can lead to major advances in stellar pulsation theory. Theoreticians should avoid complete reliance on observations. This review will almost completely neglect detailed observational data in order to concentrate on the theory.

There are some things that remain unsolved, but they are not included in this presentation. Linear theory discusses each mode separately, and cannot predict which of many pulsationally unstable modes a star actually selects. The thought that the stellar selection is indeed random may be correct. My experience with nonlinear theory that, in principle, can settle this question, shows that modes that are much more unstable do dominate, but when modes have almost the same growth rates, actual mode and limiting amplitude predictions may be impossible. Multimode pulsators seen to switch modes should indicate that mode growth rates are rapid on stellar time scales, but mostly for these stars the pulsation mechanism and growth rates are not predicted well or at all.

Another unsolved problem is the role of the so-called strange modes. It appears that these modes, with rather complicated interior structures, are mostly

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stable. Thus I usually ignore this problem, as I also do for the purely thermal modes (involving no or very small motions) that seem not to be important for our real stars.

2. Red giants and supergiants

An important unsolved problem for the reddest stars is an unequivocal identification of the Mira pulsation mode. This is discussed later in some detail, unfortunately without any good conclusion.

Many red giants and supergiants reveal periods of many years, much longer than expected for the slowest fundamental pulsation mode (Houck, 1963). Long periods can be predicted for stars (like the elusive solar g-modes), but for the reddest stars, the deep convection zone should probably make any g-mode variations unable to penetrate to the surface and be observed. Perhaps g-mode predictions should be studied by linear theory to settle this point. I am not satisfied that convection-induced thermal modes for these stars, suggested by Wood (2000), can be a response to this lack of a theoretical prediction, especially since none of his modes seem to be unstable.

A success of pulsation theory could be the prediction of the several modes that seem to be going simultaneously for the semi-regular red variables. Multimode pulsations are expected when mode growth rates are similar, but the lack of understanding of the red variable pulsations has prevented any such predictions so far.

3. Cepheids and RR Lyrae variables

For the yellow giant stars, an unsolved problem is how period changes can occur on time scales shorter than the evolution one. Cox (1998) addressed this problem, showing that internal composition structure changes can both decrease and increase periods. Mass loss and mass accretion can be some of the mechanisms for these outer structure changes. It appears that the rare case of a mass accretion changes the two periods in opposite directions for the double mode RR Lyrae variable V53 in M15. Mass loss can probably explain the Polaris period changes. What else is happening to Polaris as its pulsation amplitude is also changing?

Yecko et al. (1998) have undertaken calculations for time-dependent convection for Cepheids. This important work shows that Cepheid pulsations are significantly affected by convective flux, the turbulent (eddy) viscosity, and the mixing length. Apparently the turbulent energy and pressure play a lesser role. As the authors note, more studies are needed to predict the observed parameters in detail, and this is still an unsolved problem.

4. Solar oscillations

Prediction of oscillation frequencies for all the observed solar modes has become a very mature research area. Still there are small differences of typically several microhertz between the best predictions and observed frequencies. These may be due to the nonequilibrium between the matter and radiation temperatures in the very surface layers. An important advance was made by Guenther (1994) on this subject, but more detailed work using completely separate energy equations for the matter and radiation needs to be done for the Sun and for many other pulsators.

Another unsolved problem is an accurate prediction of the pulsation stability and detectability of the still unobserved solar g-modes. It seems that the solar convection zone is so thick that any g-modes that might occur cannot penetrate to the surface to be observed. A firm prediction that these modes ought to be pulsationally unstable seems to me to be still not available.

5. Delta Scuti variables region

One of the most active areas of current research is in the δ Scuti region of the Hertzsprung-Russell diagram. The newly discovered γ Doradus stars have inspired creative thoughts about pulsation mechanisms. See Kaye et al. (1999) for a history of these variables.

Observations and theoretical predictions seem to agree well now, but there are still problems in both areas. Allowance for time-dependent convection might indicate that the convection blocking pulsation cause might be erased by a sufficiently rapid convection response. Fortunately the Guzik paper at this conference shows that for many cases the convection time scale is quite long, and for them the convection blocking must indeed occur. But then the viscous damping caused by the shearing of the horizontal motions might be an important effect to stabilize many of the numerous predicted modes. If we are lucky, the large number of predicted modes might be reduced to just those few that are observed.

Driving of pulsations depend on deep convection zones, but they may not be so deep for those λ Bootis stars that show both low metallicity and γ Doradus pulsations. It is still unsolved whether this low metallicity can be limited to just the very surface layers of these stars, and deep convection for more normal composition occurs anyway in the deep layers.

The δ Scuti variables present a difficult problem for nonlinear hydrodynamic investigations (Guzik, 1998). Damping of the motions occurs at great depth compared to all other pulsators, and these deep layers require more accuracy in the calculations than currently used. Until this detail can be solved, nonradial limiting amplitudes even for the purely radial cases cannot be predicted.

A very disappointing situation has occurred for the mode identifications of radial and nonradial δ Scuti modes (see Templeton et al., 1997 for δ Scuti itself). A complicating factor has been the rotational lifting of the degeneracy of the m parameter for nonradial modes. It seems that this mode identification problem may persist for a long time, awaiting firm observational mode assignments and very detailed theoretical predictions.

6. Massive blue stars

Luminous blue variables present an interesting unsolved problem concerning the microvariations observed in them. The speculation that these "pulsations" could occasionally grow to produce the observed large outbursts has been investigated to a limited extent (Cox et al., 1997, 1998). Super Eddington luminosities appear during the hydrodynamic cycle when convection is slow to increase the luminosity transport. This computationally intensive research remains an unsolved problem.

There are other observed near-main sequence supergiant pulsators both more and less luminous than the early B star β Cephei variables. Some work by Dorfi & Gautschy (2000) has been done, but more is required.

7. Compact objects

A glaring problem for me is to discover a mechanism that causes pulsation for the very hot GW Vir stars, consistent with the observed period spacings. Papers by Starrfield et al. (1983, for example) present the concept that the κ effect from the ionization of carbon and oxygen easily makes the stars pulsate. The presence of hydrogen and helium dilutes this opacity "bump" and stabilizes pulsations. Thus the surface layers of these highly evolved stars must contain probably less than ten percent by mass of helium. But the composition gradient between almost pure helium and the CO interior traps modes to produce period spacings that are observed. How can we reconcile these two requirements?

The prediction before the observation for pulsations of the hot compact B stars is a triumph for theory advanced by Charpinet et al. (1996, 1997) The eventual discovery of the real stars, called EC14026 stars confirmed this excellent prediction. This reminds me of a similar prediction before the observational discovery by Winget & Fontaine (1982) that there ought to be helium white dwarfs that pulsate (the DBV stars). I have been concerned that the diffusion concentrated iron-rich material in the deep layers of the EC14026 stars that produces the κ effect driving might be limited by its high opacity causing convection and subsequent dilution mixing. The papers advancing this pulsation driving do not mention convection, but maybe this issue was addressed.

8. Mira variable pulsation modes

A longstanding problem in pulsation physics is the identification of the pulsation mode for the bulk of the Mira variables. Early work by Wood (1974) found that numerical nonlinear calculations for the radial fundamental mode always indicated a rapidly growing amplitude to very large values. Thus it was stated that Mira stars pulsate in the smaller amplitude radial first overtone mode. The problem then was that the observed amplitude of the surface displacement was rather large, never as small as theoretical nonlinear calculations predicted. For most of 30 years, efforts have been expended to see if the outbursts calculated for the fundamental mode could be contained somehow.

Considerable work has been done by Tuchman and associates over many years. Their latest result (Ya'ari & Tuchman, 1996, 1999) has the internal structure of a Mira model evolving over several hundred pulsation periods (the thermal time of the pulsating layer) so that the amplitude and especially the fundamental mode period are reduced to that of a typical Mira variable. The static model structure might indeed be modified by all that motion and energy transport.

Wood (1995), however, finds that his nonlinear calculations for well over 200 periods show no period evolution. His period seems always to be close to that from linear pulsation theory that relies on the static model accuracy. To try to understand this discrepancy, Guzik and I have made hydrodynamic calculations for additional models.

Ostlie & Cox (1993) presented a fundamental mode hydrodynamic calculation that does not blow up. But they did have to double the turbulent viscosity over the true physical value to contain it. Their calculations, and our new ones, include turbulent pressure and turbulent viscosity. A hope is that the well-known outbursts from numerical studies of the fundamental mode could be avoided. Tuchman does not include these two additional effects, and Wood, with his rather stable pulsations, does not either. Our results to date tend to favor the Wood result, but we have not calculated longer than about 85 linear theory fundamental mode periods. Tuchman and associates show that evolution to a shorter fundamental mode period occurs at about twice the time. Wood covers this time range, but we have not.

Table 1 gives details of the Ostlie model. Figure 1 shows the last five nonlinear cycles.

Table 1. Ostlie Mira Model at 1.0 Solar Mass, 5000 Solar Luminosities and Effective Temperature 3000 K.

Quantity	Value
Mass shells	60
Optically thin shells in hydrostatic model	4
Model photospheric radius	1.83×10^{13} cm
Degenerate core radius	6.4×10^{11} cm
Composition	X=0.70,Y=0.28
EOS and opacity	Ross-Aller (Cahn fit)
Convection mixing length	2.16 pressure scale heights
Convection zone bottom temperature	360000 K
Convection zone bottom density	3×10^{-6} g cm^{-3}
Convection zone bottom mass fraction	.17
Convection zone bottom thermal time scale	5×10^{8} s
Convection zone bottom convection time scale	6×10^{5} s
Linear theory period for fundamental mode	3.5×10^{7} s
Nonlinear theory period for fundamental mode	1.0×10^{8} s
$\Delta KE/KE$ growth rate	1.5 per period

We have discovered that inclusion of turbulent pressure in the static model involves zone centering problems. This has been fixed and done correctly during the first period of the nonlinear calculation. But that expands the model and changes the apparent mass concentration during these first few periods to increase its fundamental mode period considerably. Another result is that without

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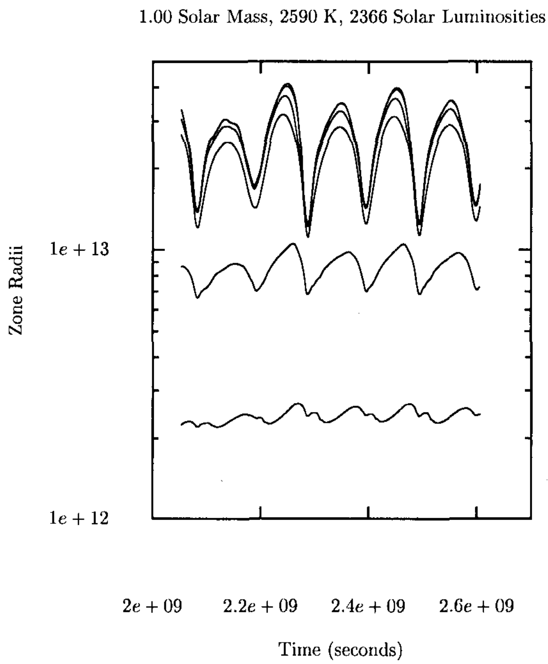

Figure 1. Radii versus time for zones 10, 20, 30, 40, 50, and 60 of the Ostlie Mira fundamental mode model. The static model radius is 1.83×10^{13} cm.

the turbulent viscosity, the Lagrange mass shells get close together and sometimes the numerical solution fails. Increasing the artificial viscosity, used by all hydrodynamic calculations, can solve this problem only if it is excessively large. The necessary spatial averaging of the convective luminosity to allow for nonlocal effects can appreciably affect the hydrodynamic calculation. Fortunately the time scale of the convection throughout the convection zone is short compared to the pulsation period, and our lagging procedure to allow for it gives only small corrections. Finally, we have learned that all equation of state and opacity tables used must be very smooth. Our use of the Stellingwerf (1975) and Cahn fits for the Ostlie model avoided this difficulty here.

9. The DAV and DBV pulsation mechanism

The reason why the DAV and DBV white dwarfs pulsate is not known, in spite of claims even from this author as early as 1987 (Cox et al., 1987). This unsolved problem, at least for me, concerns the detailed mechanism for driving white dwarfs. Many theoreticians do not seem to worry about this, and the standard thought is that these stars pulsate by the κ mechanism (Bradley & Winget,

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1994). This is clearly incorrect, because the usual κ (and γ) mechanisms that operate on the radiation luminosity have very little of this kind of luminosity near 10000 K where convection is strongly dominating the energy transport. Here I propose that the pulsation mechanism is due to convection turning off and on during the pulsation cycle, temporarily blocking radiation when convection is turned off. Then the enhanced pressure resulting from the blocked energy converts luminosity to motions.

Cox et al. (1987) discovered that the pulsation driving occurs at the bottom of the surface convection zone that ranges between 50000 K and 400000 K for, respectively, the hottest and coolest known pulsating white dwarfs. In this paper the mechanism was named "convection blocking". It was changed to convective blocking by Pesnell (1987) who first published details on how the bottom of the convection zone can periodically block and transmit luminosity to produce mechanical motions similarly to how the convectional κ and γ mechanisms work for the yellow giants. This mechanism has also been discussed by Li (1992) and most recently by Guzik et al. (2000).

Brickhill (1991 and in 5 other papers from 1983 to 1992) and more recently Wu & Goldreich (1999) have discussed a mechanism that Brickhill calls "convective driving". The plot of the work to produce mechanical motions, presented by Wu & Goldreich (1999), clearly shows that the driving is located right at the convection zone bottom. Thus whatever they call it, it is once again convection blocking dating back to 1987 and not the Brickhill (1991) paper.

Table 2 gives model details for a 0.6 solar mass model used for the discussion in this review. The hydrogen surface layer depth is set in this model so that it does not reach temperatures where it can undergo thermonuclear reactions. Note that the convection zone is rather shallow compared to models from other researchers, even though the mixing length here is quite large. Radial pulsations for white dwarfs are in the range of only one second, and these are not observed. Since the only available pulsation mechanism is convection blocking deep at the convection zone bottom, and the radial modes have motions only very near the stellar surface, these modes are not predicted to be pulsationally unstable. The g-modes that have activity always deeper are driven to produce the observed hundreds of seconds pulsation periods.

Figure 2 presents the work to produce pulsations versus Lagrangian mass shell, along with the luminosity fraction structure of the convection zone and the real and imaginary parts of the radial motion eigenvector. The usual linear theory normalization can be seen where the surface δr is set to the entire stellar radius. The standard assumption of no variation of the convection, that is, it is "frozen-in," gives convection blocking and more pulsation driving than the damping found in the deeper layers. Note that the damping and driving is in the outer 10^{-7} of the model mass, in the layers that by diffusion over the life of the white dwarf has become pure hydrogen. Deeper, the high density and the high gravity make it difficult for any motions and pulsation driving to exist.

An interesting feature appears in the nonadiabatic case both with frozen-in and varying convection to be discussed later. A node appears near zone 520, whereas the adiabatic eigensolution gives the node nearest to the surface much deeper near zone 470. This is an occasionally met case where the node positions are different in the adiabatic and nonadiabatic eigensolutions.

Table 2. 0.6 Solar Mass White Dwarf Model at 11,500 K.

Quantity	Value
Mass shells	600
Optically thin shells in hydrostatic model	13
Model photospheric radius	$1.06\text{x}10^9$ cm
Luminosity	$1.4\text{x}10^{31}$ ergs s^{-1}
Degenerate (CO core) radius	$9.1\text{x}10^8$ cm
Hydrogen layer mass fraction thickness	$1.0\text{x}10^{-6}$
Hydrogen to helium ramp mass fractions	$1.0\text{x}10^{-6}$ to $3.7\text{x}10^{-4}$
Helium to CO ramp mass fractions	0.01 to 0.02
Convection mixing length	3.0 pressure scale heights
Convection zone bottom temperature	74000 K
Convection zone bottom density	$3\text{x}10^{-5}$ g cm^{-3}
Convection zone bottom mass fraction	$6\text{x}10^{-14}$
Convection zone bottom thermal time scale	90 s
Convection zone bottom convection time scale	1 s
Linear theory period for ℓ=1, g_6	560 s
$\Delta KE/KE$ growth rate	$1.7\text{x}10^{-5}$ per period

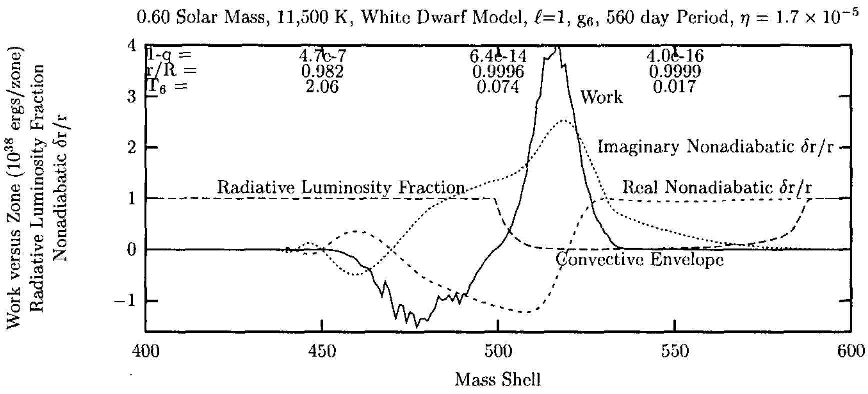

Figure 2. The convective envelope luminosity structure, the real and imaginary parts of the radial eigenvector, and the work for the frozen-in convection case.

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A big problem, usually ignored, is the question of how convection can and does carry luminosity during pulsations. The stellar model indicates that in the convection zone, the radiative luminosity is often much less than one percent of the total. The model also reveals that the time scale of the convection, the ratio of the mixing length to the mixing length mean convective velocity, is only a few seconds. Thus it has been known from even the earliest calculations by Winget (1981) that the variation of the convection luminosity surely needs to be considered in a realistic pulsation prediction. I present an approximate result here.

I believe that all linear theory investigations using time-dependent convection (see Balmforth (1992) for solar oscillations and Yecko et al. (1998) for Cepheids) concern only radial pulsations. The problem for nonradial oscillations is knowing how the cyclical horizontal flow of convection luminosity affects the pulsations and its driving. Frozen-in convection eigensolutions show that the horizontal motions are maybe 500 times the surface displacements. In my work here (and that of Brickhill), this possibly very large convection variation is ignored. From the white dwarf model, derivatives of the convection luminosity with respect to density and temperature on both sides of a convecting mass shell interface is calculated. The logarithmic derivatives are very large, maybe over 100, but this is unrealistic for both the model and the pulsating case because convection is very non-local. Nevertheless, large derivatives are used for the convection luminosity in the nonradial energy equation

$$i\omega T\delta S = \delta\epsilon - \delta\left(\frac{\partial L}{\partial m}\right),$$

with L being the sum of the radiation and convection luminosities.

Figure 3 gives a plot of the convection zone luminosity fraction, the real and imaginary parts of the radial eigenvector and the much reduced and all damping work for the time-dependent convection case. As expected, pulsations are no longer predicted, and this focuses the unsolved problem for white dwarfs. My result is approximate due to problems discussed above, and small spatial oscillations can be seen in the radial eigenvector. This is due to the fact, not shown here, that the time scale for the convection term is maybe a million times smaller than the $i\omega T\delta S$ left-hand side, and the $\delta(\partial L_c/\partial m)$ term is about a million times larger. In this case, spatial oscillations occur on scales slightly shorter than the mixing length, an unphysical situation discussed by Baker & Gough (1979) and Saio (1980). Such a case arises because of my excessively large convection luminosity derivatives from the stellar model. But the general result is valid, because no one would expect convection just to remain static and continue its effective luminosity blocking.

Note that this approximate calculation gives a much larger period (648 instead of 560 seconds). The period weight lies mostly between zones 400 and 450, but the several nodes there are sufficiently affected to cause this period change. Could it be that, if ever accurate time-dependent convection eigensolutions are obtained for white dwarfs, periods generally considered correct from adiabatic calculations are inappropriate? Considerable effort has been expended by many to calculate white dwarf periods, assuming the adiabatic theory is valid for them.

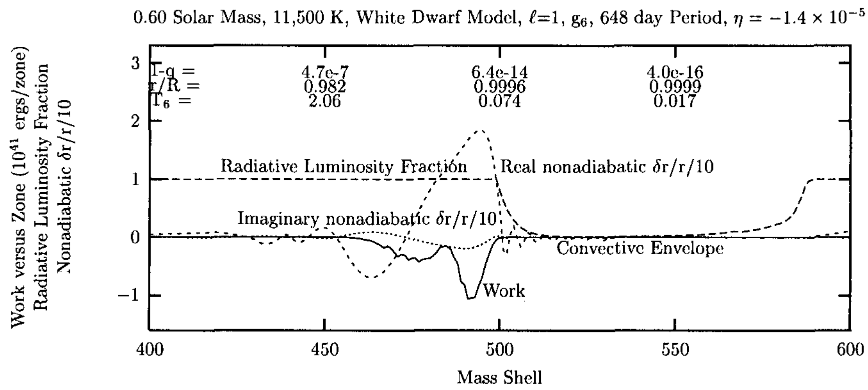

Figure 3. The convective envelope luminosity structure, the real and imaginary parts of the radial eigenvector, and the work for the time-dependent convection case.

There is an effect that I do not believe has been discussed in the literature by any researcher in the field of white dwarfs. Hints of this effect, though, can be found in the first Brickhill (1983) paper. Even for the white dwarfs that display a light amplitude of only one percent of their luminosity, the variation of the linear theory normalized temperature gradient ($\nabla = d\log T/d\log P$), reduced by a factor of 10^3 to 10^4 to match the actual pulsating white dwarf observations, is appreciable. The factor comes from the $\delta\nabla = 100$ at the convection zone bottom and $\delta L/L$ at the surface also is about 100, both at the usual eigensolution normalization of $\delta r/r = 1$. For a one percent light variation, the scaling needs to be a factor of 10^4. Near the peak of the expansion phase, the ∇ becomes less than the adiabatic gradient, and convection turns off quickly. This is a phenomenon that is not tractable with linear theory, because the assumption is always that variations are infinitesimal, and so convection never turns off.

Brickhill (1983) also allows convection to adapt instantaneously in his approximate (non-spherical) nonlinear calculations that ignore horizontal energy flow, but include horizontal motions with the arbitrarily imposed pulsation period. He then gets a variation of the convection zone thickness, implying convection turnoff as proposed here.

Some theoretical progress can be made by assuming that for a small part of each cycle convection disappears. Maybe for multimode white dwarfs one mode can turn off convection and the others have to cope with that fact. Near the convection zone bottom the luminosity changes in a short distance from entirely due to radiation to one almost entirely due to convection. In this later layer, near the bottom of the convection zone, radiation typically carries less than one percent of the total emergent luminosity. The existing temperature gradient often cannot adjust rapidly enough to carry this radiation when convection is turned off, and now the radiation luminosity is periodically blocked similar to the classical κ and the convection zone bottom convection blocking effects.

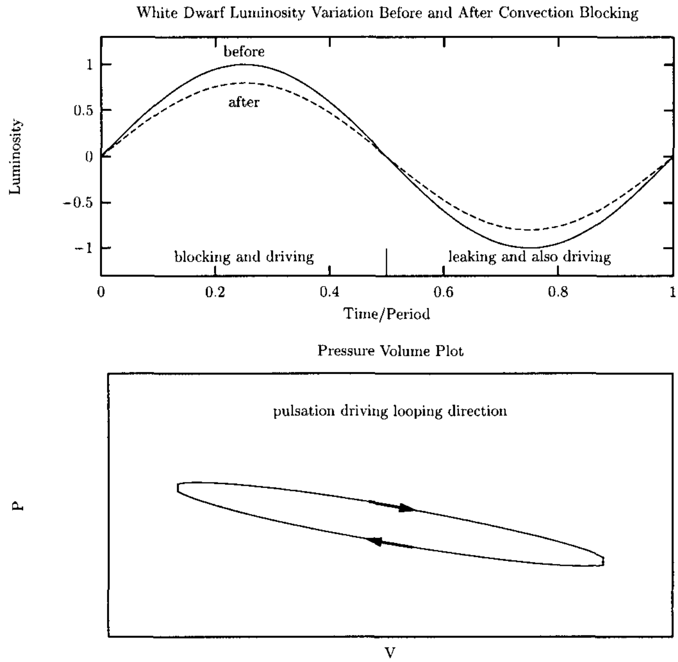

Figure 4. The luminosity variation with and without the standard κ effect and a schematic P-V diagram looping for a cycle.

Some theoreticians claim that the pulsation driving blue edge depends sensitively on the mass. Presumably the instability strips for white dwarfs with masses between about 0.5 and 0.7 solar mass mostly, but not completely, overlap. The possible presence of a few non-pulsating white dwarfs in the known instability strip also can be explained by suggesting that for very low amplitude variations the convection never is turned off. Then convection transmits the emergent luminosity at all times, and there is no unconventional radiation blocking for any part of the pulsation cycle.

Wu & Goldreich note that the observed pulsating white dwarfs vary at the instability strip blue edge if the thermal time scale of this layer at the bottom of the convection zone is about $1/(4\omega)$ where $\omega = 2\pi/period$ is the angular pulsation frequency. They did not discuss that this is about 1/24 the approximate thermal time scale criterion used for yellow-giant pulsation driving through κ-effect radiation-luminosity blocking. Pulsations in the middle of the instability strip have deeper convection and a longer thermal time scale. The yellow giant κ effect is much less efficient than the very strong, almost complete, blocking of radiation when convection disappears, and thus this white dwarf radiation blocking can occur at a level with a much shorter thermal time scale than the classical κ effect.

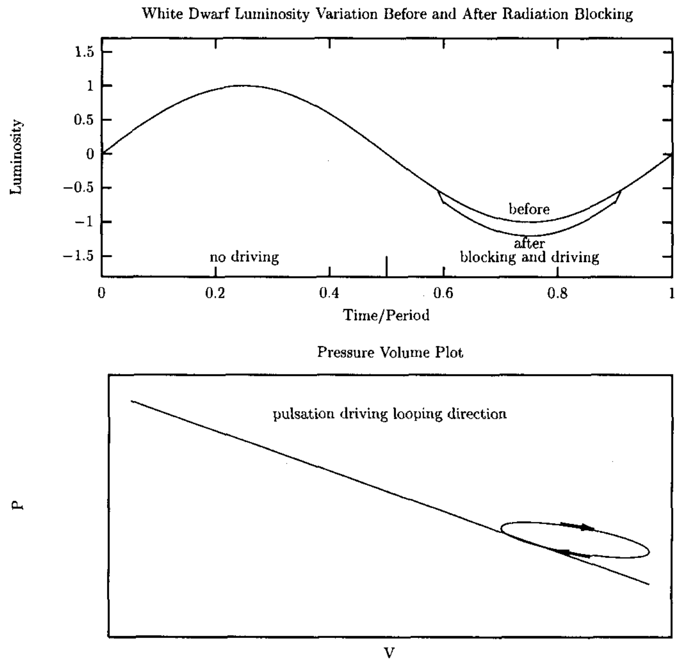

Figure 5. A schematic representation of the radiation blocking pulsation driving during part of the expansion phase when convection is turned off by the pulsation amplitude and the assumed elliptical P-V looping during approximately 30 percent of each cycle.

Figures 4 & 5 show how the classical κ and the radiation blocking effects operate. The sinusoidal luminosity variation of linear theory is affected by the κ effect that periodically blocks and then leaks radiation each pulsation cycle. The P-V diagram shows driving at both compression and expansion phases. The largest variation above the adiabatic case (represented here by merely a straight line) is half way from the maximum to the minimum density at the driving layer. Such a luminosity lag is well known from observations at the stellar surface, and it is caused by nonadiabatic effects near 10000 K where the yellow giant driving mostly occurs.

The last figure illustrates the effect that occurs when convection usually transmits all the luminosity easily except when the layer suddenly becomes subadiabatic and turns off. Then this radiation blocking occurs for a part of the local expansion phase. The P-V diagram now looks much different, mostly because in the deeper layers above 50000 K my calculations show that there is little lag of the luminosity peak after the density maximum. Now the luminosity reaches its minimum at minimum density. The P-V driving loop occurs in this time frame with the pressure at a maximum above the assumed straight line, purely transmitting case, and at a minimum (but still blocking radiation luminosity) as the density is increasing again.

This driving occurs in only half or less of the cycle, and therefore should be smaller than the usual driving discussed by Winget, Cox et al., Brickhill, and Wu & Goldreich. This may be a problem, because mode amplitude changes are often observed on short time scales. Presumably a mode will grow at the linear theory driving rate of typically only one part in 10^5. For periods of a few hundred seconds, this means a mode will e-fold its kinetic energy in about a year. Faster growth rates are sometimes predicted or may even come from nonlinear mode coupling, but the solution to some rapid mode changes may lie with the currently intractable case where convection is turned off by other modes and strong driving for a particular mode occurs almost full time.

A potential problem for my particular model at 11500 K is that the thermal time scale at the bottom of the convection zone is only about 90 seconds, but the pulsation period is about 600 seconds. Can the gradient rapidly adapt to carry the incoming radiation luminosity just as convection carries it when it is on? We must remember that the thermal time scale comes into play only after the convection is stopped and the temperature gradient tries to steepen to carry the emergent radiation.

Further thoughts about how a pulsating star handles the case of temporarily disappearing convection each cycle can confirm or refute this unconventional suggestion. An earlier suggestion that time-dependent convection itself could produce luminosity blocking and white dwarf pulsations was advanced by Cox (1993). This can happen if the growth of convection during pulsations is slow enough to temporarily impede the luminosity flow as other mechanisms do. The main difficulty with this suggestion is that this convection needs to occur in deeper layers where, for example, carbon and oxygen with their higher opacity can create a convection shell. The CO convection would then appear at a layer of $3\text{x}10^{-6}$ deep, but this is much too shallow according to convectional white dwarf helium layers. Whether this blocking can be both in the CO core and not too deep so nonadiabatic effects can occur has never been investigated.

References

Balmforth, N.J. 1992, MNRAS, 255, 603

Baker, N.H. & Gough, D.O. 1979, ApJ, 234, 232

Bradley, P.A. & Winget, D.E. 1994, ApJ, 421, 236

Brickhill, A.J. 1983, MNRAS, 204, 537

Brickhill, A.J. 1991, MNRAS, 251, 673

Charpinet, S., Fontaine, G., Brassard, P., & Dorman, B. 1996, ApJ, 471, L103

Charpinet, S., Fontaine, G., Brassard, P., Chayer, P., Rogers, F.J., Iglesias, C.A., & Dorman, B. 1997, ApJ, 483, L123

Cox, A.N. 1993, in New Perspectives on Stellar Pulsation and Pulsating Variable Stars, eds. J.M. Nemec & J.M. Matthews, (Cambridge University Press), 107

Cox, A.N. 1998, ApJ, 496, 246

Cox, A.N., Guzik, J.A., & Soukup, M.S. 1997, in ASP Conf. Ser., Vol. 120, Luminous Blue Variables: Massive Stars in Transition, eds. A. Nota & H. Lamers, (San Francisco ASP), 133

Cox, A.N., Starrfield, S.G., Kidman, R.B., & Pesnell, W.D. 1987, ApJ, 317, 303

Cox, A.N., Guzik, J.A., Soukup, M.S., & Despain, K.M. 1998, in ASP Conf. Ser., Vol. 135, A Half Century of Stellar Pulsation Interpretations: A Tribute to Arthur N. Cox, eds. P.A. Bradley & J.A. Guzik, (San Francisco ASP), 302

Dorfi, E.A. & Gautschy, A. 2000, ApJ, 545, 982

Guenther, D.B. 1994, ApJ, 422, 400

Guzik, J.A., Kaye, A.B., Bradley, P.A., Cox, A.N., & Neuforge, C. 2000, ApJ, 542, L57

Guzik, J.A. 1998, in New eyes to see inside the Sun and stars, eds. Deubner, F.-L., et al., (Kluwer Academic Publishers), 331

Houck, N. 1963, AJ, 68, 253

Kaye, A.B. Handler, G., Krisciunas, K. Poretti, E., & Zerbi, F.M. 1999, PASP, 111, 840

Li, Y. 1992, A&A, 257, 145

Ostlie, D.A. & Cox, A.N. 1993, in New Perspectives on Stellar Pulsation and Pulsating Variable Stars, eds. J.M. Nemec & J.M. Matthews, (Cambridge University Press), 208

Pesnell, W.D. 1987, ApJ, 314, 598

Saio, H. 1980, ApJ, 240, 685

Starrfield, S.G., Cox, A.N., Hodson, S.W., & Pesnell, W.D. 1983, ApJ, 268, L27

Stellingwerf, R.F. 1975, ApJ, 195, 441

Templeton, M.R., McNamara, B.J., Guzik, J.A., Bradley, P.A., Cox, A.N., & Middleditch, J. 1997, AJ, 114, 1592

Winget, D.E. 1981, PhD thesis, University of Rochester

Winget, D.E. & Fontaine, G. 1982, in Pulsations in Classical and Cataclysmic Variables Stars, eds. J.P. Cox and C.J. Hansen (Boulder: University of Colorado)

Wood, P.R. 1974, ApJ, 199, 609

Wood, P.R. 1995, in ASP Conf. Ser., Vol. 83, Astrophysical Applications of Stellar Pulsation eds. R.S. Stobie & P.A. Whitelock, (San Francisco ASP), 127

Wood, P.R., 2000, in ASP Conf. Ser., Vol., 203, The Impact of Large Scale Surveys on Pulsating Star Research, eds. L. Szabados & D.W. Kurtz, (San Francisco ASP), 379

Wu, Y. & Goldreich, P. 1999, ApJ, 519, 783

Ya'ari, A. & Tuchman, Y. 1996, ApJ, 456, 350

Ya'ari, A. & Tuchman, Y. 1999, ApJ, 514, L35

Yecko, P.A., Kolláth, Z., & Buchler, J.R. 1998, A&A, 336, 553