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Internal composition of pulsating stars

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Abstract. Stellar pulsation helps understand many aspects of stellar structure, including the internal composition of stars. A review of several cases in years past, where the helium and sometimes other element abundances can be determined will be presented using pulsation data and theory. The present controversy about the masses and helium content in the surface layers of the hottest GW Virginis variable stars, like PG 1159-035, will be discussed in some detail. Finally, the problem of observed new lower metallicity solar abundances will be presented together with several of the proposed new solar models that use these data and new theoretical concepts. These last two cases involve observations that reveal serious discrepancies between stellar evolution and pulsation studies, indicating many theoretical problems still remain.

Key words. Stars: pulsations – Stars: compositions – Stars: structure – Stars: opacities

1. Introduction

A look at stars does not reveal much about what we may want to know about them. Photographs may reveal their parallax and proper motions, and spectrographic studies can reveal surface compositions. Stellar evolution calculations can even reveal some details about the internal structure. But stellar pulsations probe in most detail about what really is happening inside stars. Early pulsation studies immediately were able to learn about stellar masses, and now we can determine many details of internal composition structure as well.

Internal compositions can be inferred rather easily from the fact that a star is actually observed to pulsate. Many pulsating giant stars derive their driving by the κ and γ effects from the ionization of hydrogen and/or helium near the surface. For these stars, the presence of pulsations can indicate hydrogen and helium compositions of the pulsation driving layers. Near-main sequence stars derive their pulsation driving from other effects, such as stochastic convection motions in the Sun and solar-type stars, the iron ionization for the β Cephei variables, the luminosity blocking effects at the bottom of the convection zone for γ Doradus variables and white dwarfs, and carbon, oxygen, and maybe iron group element ionization κ effect for the very hot pre-white dwarfs.

All of these driving effects cause self-excitation pulsations except for the Sun and solar type stars. These later stars are basically pulsationally stable with small pulsation perturbations decaying rather rapidly as they occur. It is only the continual "jabbing" of the convection motions that repeatedly, but temporarily, create normal mode motion structures that are observed over a significant period range for a long enough time to be detected.

Pulsation periods of the variables are influenced to a lesser degree by internal compositions, but they are detectable, since periods are sensitive to composition-induced internal structure as well as by the stellar masses and mean densities.

2. Cepheids

Recent theoretical studies of Cepheids at the Rome Observatory (Fiorentino et al. 2002 and Romaniello et al. 2005) have shown that metallicity, as measured by the iron abundance, can slightly affect the stellar structure, the pulsation periods, and even influence the Freedman et al. (2001) Cepheid period-luminosity relation. This theoretical result has the Cepheids with the normal solar iron abundance fainter than those very iron poor. It therefore seems important to consider the metallicity of the brightest Cepheids observed in distant galaxies when measuring the scale of our universe to high accuracy. This work is at the frontier of the universe size research though, because some observations confirm and others conflict some with this theoretical work.

More classical studies done long ago by Cox, King, & Tabor (1973) show that the Cepheids will not pulsate unless the helium content is at least $Y=0.25$. This fits with galactic evolution theory that predicts these massive and young stars have been born with at least some enhancement of primordial helium in the material from earlier stellar evolution. A similar discussion of the existence of pulsations of the sister group, the δ Scuti variables, show that the minimum helium abundance in the pulsation driving layers must also be in this same range. The Cepheids do not display many higher overtone modes, and show no nonradial modes at all, unlike the δ Scuti variables, and thus these latter variables do not define their minimum helium content so clearly. These lower mass stars are not appreciably older than the Sun, and they should be enriched at least some in helium like the Sun.

3. β Cephei Variables

For almost 30 years I attempted to explain the pulsation mechanism for the 10-20 $M_\odot$ main sequence stars called the β Cephei variables. I tried many different compositions, but none could drive the stars into pulsations. Stellingwerf (1978) suggested that the very final stages of helium ionization at about 150,000 K might give a bump in the opacity versus temperature curve and cause κ effect pulsations. That never worked.

With the realization by our Livermore friends that the Los Alamos opacities used from 1965 to 1990, deliberately did not include the same-shell bound-bound electron transitions, they were able to add an important opacity bump at about 200,000 K occurring mostly in the iron M shells. Immediately at the Bologna pulsation meeting in 1990, I announced that this new effect increased the opacities just where they were needed to produce the β Cephei pulsations. The work both improved stellar opacities and confirmed a normal solar abundance in the pulsation driving layers of these hot stars. When the iron opacity improvement was announced, Stellingwerf (1990) got pulsations also. Extensive calculations of the β Cephei instability have since been made by Pamyatnykh (1999).

This opacity improvement for the β Cephei variables also helped with the anomalous period ratios for double-mode Cepheids and δ Scuti variables. Another very small change (in the hydrogen line shapes) was apparently important only for the RR Lyrae variables. Thus pulsations help both with sometimes discovering internal compositions and with verifying opacities. Fortunately the quarter century pioneering work exploring stellar evolution based exclusively on Los Alamos opacities was hardly affected. Now with the improved Los Alamos opacities including same-shell transitions for all relevant cases, the Livermore OPAL and Los Alamos LEDCOP opacities agree to within a few percent (Neuforge et al. 2001).

4. δ Scuti Variables

The δ Scuti variables display many different surface compositions. It was discovered long ago that many metals appear greatly enhanced due to the shrinking of the surface convection zone and the accompanying large decrease in the time scale for radiation levitation of these elements. The shrinking of the convection zone is caused by settling of helium below its bottom, and that helium loss changes its deep equation of state (mostly the Γ_1) so that the bottom layers become subadiabatic. This effect is larger than the effect of increasing the superadiabaticity as the lower helium content actually increases the opacity. The δ Scuti variables have considerable pulsation driving by the κ effect from the helium ionization, and the loss of the helium and even the convection zone can reduce and even eliminate pulsations.

Several of us (Cox, Hodson, & King 1979) investigated long ago whether the observed appearance of metallicity might imply that no pulsations can occur because the helium is absent. We found for stars that are near the blue edge of the instability strip, the helium loss can indeed stabilize the stars. But less helium is needed at the red side of the strip, mostly due to the increased fraction of the driving by hydrogen ionization there, and even a loss of all the helium does not stabilize the pulsations. Thus in about the coolest third of the instability strip, but only there, both metallicity and pulsations can occur theoretically. For the hotter part of the δ Scuti instability strip, if a star is not pulsating, it is likely significant helium has settled below the driving region. Here the simple observation of pulsations or none can roughly determine an internal stellar helium abundance, and it is possible that some hotter stars in the pulsation instability strip will not be seen to pulsate.

Observational confirmation of this metallicity effect and observation of non-pulsating (presumably surface helium deficient) stars redward of the blue edge has been made by many, especially by Kurtz (2000).

An internal composition effect for δ Scuti variables was found by Cox, McNamara, & Ryan (1984). For the double-mode variable VZ Cancri, the ratio of the overtone/fundamental periods was much larger than normal for these variables. It was found that if the helium sinks to deeper layers, for a limited range of this depth, there is good sensitivity of this depth to the period ratio, and a rough idea of the internal helium composition structure can be determined.

5. GW Virginis Stars

A current frontier for stellar pulsation and internal compositions is the exploration of the GW Virginis variables. These stars are surface hydrogen deficient and have the PG 1159-035 spectrum. The two names are for the same star. The best measurements of the hydrogen surface composition X is less than two percent, Y=0.33, carbon mass fraction of 0.50, and oxygen mass fraction 0.17. Fig. 1 shows a recently calculated (Althaus et al. 2005) evolution track on the Hertzsprung-Russell diagram. Extensive mass loss on the asymptotic giant branch during the dozen or so helium shell flashes reduces this original 2.7 $M_\odot$ model to only 0.59 $M_\odot$ The more or less regular spacing of the helium shell flashes may result in a flash occurring late as the model contracts to the hot white dwarf region, or very late (VLTP) when the white dwarf structure has already been attained, but not yet cooled to a normal white dwarf. This last thermal pulse occurrence, pictured here, results in almost all of the surface hydrogen being burned to helium, and it is this case that seems to produce the observed hydrogen deficient pulsating GW Virginis variables. GW Virginis is at about $\log L/L_\odot = 2.5$ on the final track section in the figure.

Fig. 2 shows different, earlier, Falk Herwig (1999, 2001) calculations using the coordinate of surface gravity instead of the stellar luminosity. The resulting tracks for original 2 $M_\odot$ and 1 $M_\odot$ on the ZAMS in the hot white dwarf region of Hertzsprung-Russell diagram are here for 0.604 and 0.535 $M_\odot$. Note that the 0.535 $M_\odot$ track (only shown before a very late thermal pulse) barely gets hotter than 10^5 K, whereas the 0.604 $M_\odot$ pre-white dwarf tracks get to almost 190,000 K.

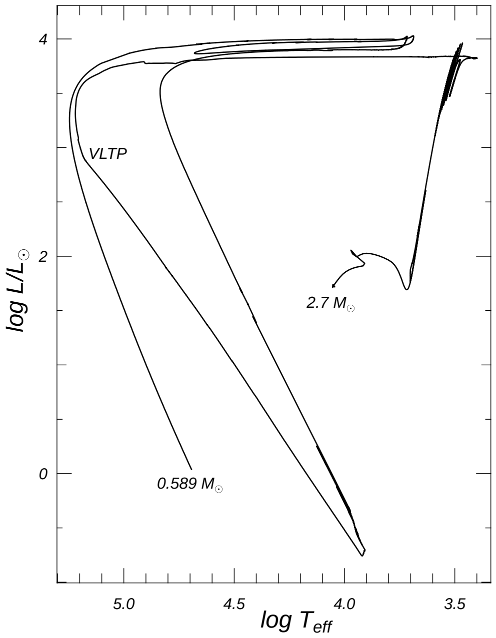

Fig. 1. The complete stellar evolution track of a 2.7 M$_\odot$ stellar model from the zero age main sequence to the white dwarf stage with the final mass only 0.589 M$_\odot$.

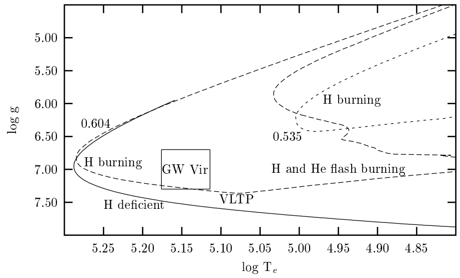

Fig. 2. Stellar evolution tracks calculated by Falk Herwig for initial stellar masses of 2 and 1 M$_\odot$, and final masses as 0.604 and 0.535 M$_\odot$. The position of GW Virginis in somewhere in the box.

A problem since the discussion by Cox (1986) and work by Stanghellini, Cox, & Starrfield (1991) is that a large abundance of helium smooths the carbon and oxygen opacity bumps with temperature and does not give enough pulsation driving to overcome the ever-present radiative damping. The star would then not be predicted to pulsate. Recent researches by Quirion, Fontaine & Brassard (2004) and by Gautschy, Althaus, & Saio (2005) find that these stars can be made to pulsate with the large actual observed surface helium abundance if the model mass is significantly less than the expected 0.59 M$_\odot$. A Hertzsprung-Russell diagram for many models at a mass of 0.56 M$_\odot$ in Fig. 3 shows the Quirion et al. instability region for 0.4 mass fraction of carbon, 0.1 mass fraction for oxygen, and two values of the solar Z value adapted from their publication. They report, as found by the earlier papers of Starrfield, Cox, Hodson, & Pesnell (1983); Starrfield, Cox, Kidman, & Pesnell (1984); Bradley & Dziembowski (1996), more carbon and/or oxygen and less helium increases driving. It is not clear if, at the observed log g=7.0 and 140,000 K, their models might just barely pulsate with the actual GW Virginis HeCO abundances with less He and more C and O than they used.

My Los Alamos calculations using the latest theoretical compositions with solar iron, plus its s-process evolution to neighboring elements, and opacities show that pulsations occur only for model masses at or less than 0.57 M$_\odot$. Kawaler & Bradley (1994) analyzing only observed periods find that the GW Virginis mass is very close to 0.59 M$_\odot$. Indeed the observed white dwarfs that evolve from these hot models are more likely to have these larger masses.

The Gautschy et al. tracks are given in Fig. 4 for a number of masses. It is important to note here that for their masses of 0.53 to 0.64 M$_\odot$, the tracks are very close together, whereas,

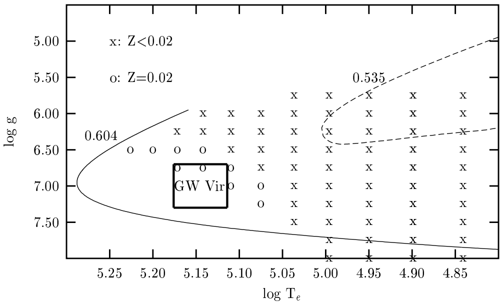

Fig. 3. Quirion et al. 0.56 $M_\odot$ models for X_{helium} ≥0.48, X_{carbon}=0.40, and X_{oxygen}=0.10 GW Virginis compositions plotted on the H-R diagram. Pulsationally unstable modes are given by x or o marks for, respectively, the solar Z<0.02 and Z=0.02.

the very recent calculation by Herwig produces a much cooler track for the 0.53 $M_\odot$ as mentioned above. It seems that something is wrong with these Gautschy et al. tracks that actually are derived form a single evolution track at 0.59 $M_\odot$. These Gautschy et al. models, all looking somewhat like 0.59 $M_\odot$, but with a lower actual mass for the pulsation calculations only, exhibit pulsations only where the thick lines are drawn.

Ten GW Vir-type variables are indicated on this plot with their uncertainty displayed by the size of their boxes. The box for GW Virginis itself seems a bit larger than Werner (private communication) currently suggests. These authors find the only problem variable star is GW Virginis. The heavy lines barely enter its box only at the lowest mass, and that track may be displayed much too hot.

From Fig 2, it appears that the minimum mass for GW Vir is near 0.57 $M_\odot$, and my calculations and those of others just barely allow pulsations at this mass. If we are to believe the larger Kawaler and Bradley mass and white dwarf observations, an additional pulsation driving source is needed for larger masses than used by Quirion, Fontaine & Brassard (2004) and Gautschy, Althaus, & Saio (2005). I have (Cox 2003) suggested enhanced iron caused by its radiation levitation for the only difficult case of GW Virginis itself. The increased iron group abundance also helps with

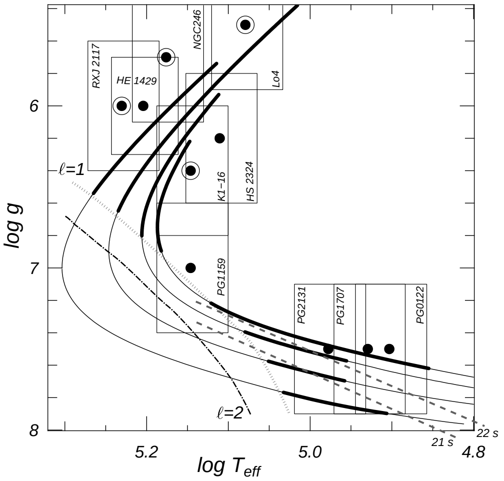

Fig. 4. Gautschy et al. tracks for the basic calculation at 0.59 $M_\odot$ and for ones approximated for 0.53, 0.55, 0.59, and 0.64 $M_\odot$. Heavy lines denote pulsational instability regions. The ℓ=1 and 2 blue edges and period spacings are indicated.

the hard problem of pulsationally exciting periods observed as long as almost 1000 seconds.

It seems also useful to point out that the old Los Alamos opacities were defective in neglecting those same-shell, bound-bound transitions important only for elements with significant electrons in their M-shell. The HeCO opacities used by the Los Alamos team before 1990 differ by less than 5 percent in the important temperature-density layers, as found by comparing the new and old ones today.

6. Sun

Recently Asplund et al. (2005) and others have redetermined abundances in the surface layers of the Sun, and they have found that the carbon and oxygen abundance are significantly lower than thought previously. Other less abundant elements are also decreased, but they are less important for determining the solar structure. These revised abundances upset greatly all the precision solar modeling that has been done for the last 20 years. The observed solar oscillation frequencies no longer agree with theoretical predictions.

Many papers have investigated proposals to somehow make oscillation frequencies compatible with the new compositions. One of the latest is by Guzik, Watson, & Cox (2005) where opacity and especially element diffusive settling modifications are discussed. It is currently thought that the three teams for calculating stellar opacities (Los Alamos, Livermore, and the United Kingdom OP Project) obtain opacities at the critical layer at the bottom of the solar convection zone near a temperature $2{\times}10^6$ K and density near 0.5 g/cm^3 that differ by less than 5 percent. An opacity increase of 10-20 percent would be needed to reestablish agreement.

Our best fit to the new abundances and their decreased opacities is with the thermal part of the diffusive settling enhanced for helium by a factor of 1.5 and for elements CNONeMg by a factor of 4. Such enhancements and the corresponding decreases in the binary thermal resistance coefficients seem well beyond any reasonable amount.

Other quantities in the solar convection zone, its density, its sound velocity, and even its helium abundance are affected by the new abundances. However, they can be restored by opacity or element settling increases.

7. Solar-Like Stars

Experience with the Sun has shown that the frequency spacing of the nonradial p-modes of intermediate degree can reveal the convection zone helium abundance. The concept is that the slight variation of the Γ_1 from the second ionization of helium can act as a disturbance for these p-modes that have considerable weight in the convection zone, and this disturbance can slightly trap modes to change their frequencies. Application of this method has shown that the solar helium mass fraction is about 0.24. That is consistent with an original Y of 0.27 and the diffusive settling of helium during its lifetime. Basu, et al. (2004) have now considered the case for stars similar to the Sun (0.8 to 1.4 $M_\odot$), and they have found that they can measure the helium content to within 0.01-0.03 if one can make a good guess of the star's age and mass as well as having low degree (like ℓ=1, 2 or 3) oscillation frequencies accurate to better than one part in 10^4. The age and mass quantities can come from the position of the star in the Hertzsprung diagram. This important helium abundance measurement can inspire observers to get reliable oscillation frequencies, even though these are very hard to observe because of their small amplitudes and always with considerable background problems.

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