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THE EVOLUTION OF VARIABLE STARS

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ABSTRACT

Throughout the domain of the H R diagram lie groupings of stars whose luminosity varies with time. These variable stars can be classified based on their observed properties into distinct types such as α Cephei stars, δ Cephei stars, and Miras, as well as many other categories. The underlying mechanism for the variability is generally felt to be due to four different causes: geometric effects, rotation, eruptive processes, and pulsation. In this review the focus will be on pulsation variables and how the theory of stellar evolution can be used to explain how the various regions of variability on the H R diagram are populated. To this end a generalized discussion of the evolutionary behavior of a massive star, an intermediate mass star, and a low mass star will be presented.

PULSATIONAL VARIABLES AND THEIR LOCATION IN THE H R DIAGRAM.

There are many types of variable stars whose variability mechanism is known or believed to be due at least in part to pulsation. Using Glasby (1971), Hoffmeister, Richter, and Wenzel (1985), Kholopov (1984) and information presented at this conference as a guide, Figure 1 was constructed to show the approximate locations of the various types of pulsational variable stars on a M_{bol} vs. $\log T_e$ H R diagram. $\log T_e$ was used instead of spectral type on the abscissa in order to better represent the stellar evolution tracks. Approximate boundaries of the spectral type classes (Lang 1980) are illustrated at the top of Fig. 1, and one can clearly see the nonlinear relationship between temperature and spectral type. The appearance of Fig. 1 changes considerably if spectral type or color index is used on the abscissa as can be seen on p. 265 of Hoffmeister et. al. (1985) and Figure 1 of Kholopov (1984).

Figure 1. The approximate position of various types of pulsational variable stars on a M_{bol} vs. $\log T_e$ H-R diagram. Spectral class boundaries are given at the top of the diagram. The solid curved line represents the Zero-Age Main Sequence with numbers corresponding to the mass of the representative star in solar units. The dashed curves are the evolutionary tracks of 1, 7, and 15 $M_{\odot}$ models.

Detailed definitions of the various classes of variable stars are given in Hoffmeister et. al. (1985), Kholopov (1984) and in these proceedings. For convenience a short summary is presented in Table 1.

TABLE 1. PULSATIONAL VARIABLE STARS.

S Dor:	High luminosity eruptive variables whose mass loss may be due to a global pulsational instability.
α Cyg:	Quasi-periodic supergiants having amplitudes of 0.1 mag, possibly showing several modes and nonradial modes.
β Cep:	Early B pulsating giants having periods of hours and amplitudes of around 0.1 mag, some showing multiple modes and possibly nonradial modes.

- X Cen: Possible class of B subgiant variables having periods less than an hour and amplitudes of 0.02 mag.
- Be stars: Rapidly-rotating, mass-losing B stars some of which show variability which may be due to pulsation. Example LQ And.
- MAIA: Struve's hypothetical variable sequence between δ Cep and δ Sct. Probably doesn't exist, see McNamara this conference.
- SRd: Semiregular yellow giants and supergiants some of which show emission lines, exhibit periods of 30 to 1100 days and amplitudes up to 4 mag. Example: S Vul.
- δ Cep: Radially pulsating (Pop I) variables having well-defined periods of 1 to 135 days and amplitudes generally from 0.1 to 2 mag. Some show multiple modes.
- δ Sct: Dwarf to giant A-F stars having periods of hours and generally amplitudes < 0.1 mag. Some show multiple modes and possibly nonradial modes.
- PV Tel: Helium supergiants that appear to pulsate with periods on the order of days but with small amplitude ~ 0.1 mag
- R Cor Bor: Hydrogen-deficient eruptive variables which also may show quasi-periodic pulsational behavior having periods of 30-100 days and amplitudes > 1 mag.
- RV Tau: Supergiant Pop II variables exhibiting a double wave light curve with periods generally from 30 to 150 days and amplitude up to 5 mag.
- W Vir: Radially pulsating stars somewhat similar to δ Cep but arising from stars of much smaller mass. Periods generally 12 to 35 days.
- BL Her: Radial pulsators related to W Vir class but show a bump on the descending part of the light curve and periods of 1 to 8 days.
- Anomalous Cepheids: RR Lyrae like variables of higher luminosity found almost exclusively in dwarf metal-poor spherical galaxies like Draco.
- RR Lyrae: Radially pulsating A-type giants of disk and Pop II composition having periods of about 1 day and amplitudes < 2 mag. Some show double mode behavior.
- SX Phx: Subdwarf Pop II equivalent of the δ Sct class having periods of hours and amplitudes < 0.7 mag. Some show multiple modes and possibly nonradial modes.
- Lc: Slowly irregularly varying supergiants of type M showing amplitudes of 1 mag. Example TZ Cas.
- SRc: Semiregular pulsating supergiants having periods of 30 to several thousand days and amplitudes of about 1 mag. Examples: α Ori, OH-IR stars.

- Lb: Slowing varying irregular giants exhibiting no indication of periodicity. Example: CO Cyg.
- SRa: Semiregular giants showing MIRA-like behavior but smaller amplitudes < 2.5 mag and periods of 35 to 1200 days. Example: Z Agr.
- SRb: Semiregular giants showing periods of 20 to 2300 days that come and go. Example: AF Cyg.
- MIRA: Radially pulsating red giant and supergiant stars of disk and Pop II composition having amplitudes > 2.5 mag and periods of 80 to 1400 days.
- GW Vir: Multiperiodic, nonradially pulsating white dwarfs of very high temperature.
- DB Variables: Multiperiodic, nonradially pulsating, helium white dwarfs.
- ZZ Ceti: Multiperiodic, nonradially pulsating, hydrogen white dwarfs showing periods on the order of minutes and amplitude from 0.001 to 0.3 mag.

The reader should keep in mind that some overlap in the domains of the various classes of variables may exist. In addition, some stars which reside in a given region of variability may not be observed to be variable (see e.g. Bidelman 1985). This behavior is due to other factors besides luminosity and temperature (such as composition and total mass) playing a role on whether a given star is pulsationally unstable. For example, a Pop I star of intermediate-mass would be pulsationally unstable inside the δ Cepheid instability strip but not within the W Vir instability strip due to the fact that the latter requires stars to have much lower total mass. Finally, it should be noted that our understanding of what excitation mechanism drives the observed pulsations of variable stars ranges from fairly well understood in the case of Cepheid variables (see e.g. Cox 1985) to still being investigated as in the case of the δ Cep stars.

EVOLUTION OF MASSIVE STARS ($M_* > 10 M_\odot$).

The mass-losing $15 M_\odot$ model of Brunish and Truran (1982) has been used in Fig. 1 to represent the general features of a massive star evolutionary track. Massive stars essentially begin their lives on the Zero-Age Main Sequence (ZAMS) when the pressure generated by

nuclear burning of H by the CNO cycle has balanced the opposing force of gravity and star ends its earlier phase of gravitational contraction. The interior of a massive star on the main sequence consists of a large convective H-burning core which may be surrounded at various times by a semiconvective shell (depending on how convective overshoot and rotation are treated) and a radiative outer region. As the star evolves while burning H, the convective core shrinks in size and becomes hotter while the star becomes brighter and cooler. For whatever reason many massive stars become β Cep variables after evolving off the ZAMS. If the star is a rapid rotator, it may also manifest itself as a Be star. The most massive stars will evolve into the S Dor regions of variability.

The evolution of a massive star proceeds to the right in the H-R diagram until the H abundance in the convective core becomes about 5% at which point the whole star begins to contract again and the evolutionary track reverses course and undergoes a short excursion to the left. This phase of increasing luminosity and temperature ends when the convective core disappears and H is exhausted at the center. About 90% of a massive star's total lifetime is spent during the core H-burning phase. Once H is exhausted in the center, a H-burning shell forms around an inert He core and the star evolves redward in the H-R diagram. Some massive stars will become α Cyg variables, SRd variables, and even long period Cepheids as they evolve toward the red supergiant region.

Massive stars are known to lose mass at significant rates and depending on the rate of mass-loss and the treatment of convective overshoot, core He-ignition may occur before or after a star becomes a red supergiant. If core He-ignition occurs before becoming a red supergiant, evolution will continue toward the red on a slower nuclear time scale and the lifetimes of the various variable phases will be much longer than they would have been if only the H-burning shell was active. The most massive stars lose mass at such a large rate that they are unable to become red supergiants and consequently, the upper right portion of the H-R diagram is left unpopulated. For these stars, once the H-rich envelope is evaporated the redward evolution stops and reverses to the blue toward the domain of the WR stars. Perhaps some R Cor Bor and PV Tel variables are due to H-deficient

massive stars evolving blueward. If instead the star ignites He as a red supergiant it may remain as a red supergiant or it may in some cases develop a blue loop during the core He-burning phase.

Once He is ignited, a convective He-burning core forms which slowly grows in time unlike the previous convective H-burning core. He is consumed by the triple alpha and various alpha capture reactions. Surrounding the convective core is a radiative He shell on top of which is the still active H-burning shell followed by a H-rich radiative layer, and depending on where the star is in the H-R diagram, possibly a convective envelope. The core He-burning phase occupies most of the remaining 10% of a massive star's lifetime. Upon becoming a red supergiant a massive star may become a Lc or SRC type variable.

With core He exhaustion a He-burning shell forms around an inert C-O core. This core contracts and heats up and soon C-burning begins which is quickly followed by respective phases of neon, oxygen, and silicon burning until an iron core is formed. Eventually the iron core becomes unstable and collapses which may then cause the star to become a supernova. These final evolutionary phases take place on a rapid timescale so that the probability of detecting a given star at this stage of evolution is small. The post core He-burning phases are represented by the near vertical segment of the $15 M_{\odot}$ track at the right portion of the H-R diagram. For more details on evolutionary models of massive stars see the references listed in the review article by Iben and Renzini (1984).

EVOLUTION OF INTERMEDIATE-MASS STARS ($10 M_{\odot} > M_{\star} > 2.25 M_{\odot}$).

The $7 M_{\odot}$, $(Y, Z) = (0.28, 0.02)$ model in Becker (1981) has been used in Fig. 1 to represent some of the general features of an intermediate-mass star evolutionary track. The core H-burning phase of intermediate-mass stars and massive star are very similar except that mass-loss and semiconvection do not play much of a role for the former during this phase. The more massive intermediate-mass stars may become δ Cep and χ Cen variables as well as Be stars as they evolve

off the ZAMS. The total lifetime of the intermediate-mass stars are much larger than the massive stars and the main sequence phase for this case comprises about 80% of the total lifetime.

Unlike the case for many massive stars, the H-burning shell phase for intermediate-mass stars lasts from the end of the main sequence to the red giant area. During this phase the first passage of the Cepheid instability strip occurs on a thermal time scale with a lifetime of around 10^3 to 10^5 yrs. Upon becoming a red giant the evolutionary track changes from a horizontal to a more vertical slope known as the red giant branch (RGB). Core He ignition occurs at the top of the RGB and a convective He-burning core forms surrounded by an inert He shell, a H-burning shell, a radiative H-rich layer and a convective envelope. After a period of adjustment to two central energy sources, many intermediate-mass stars evolve off the giant branch on tracks that have been given the name blue loops. Some intermediate-mass stars will evolve to a sufficiently high surface temperature that they will again intercept the Cepheid instability strip. The second crossing of the Cepheid strip is generally the longest lived and can be greater than 10^6 yrs in duration. As a Cepheid, a star may undergo a significant amount of mass-loss driven by pulsation (see Brunish and Willson in these proceedings). The blueward evolution stops when the convective core has nearly exhausted its supply of He. In general the blue loop extends to a greater temperature as the mass of the star increases. Some lower mass intermediate-mass stars will not show blue loops and they will remain on the RGB for all of their core He-burning lifetime.

As He is exhausted in the core, intermediate-mass stars evolve back toward the RGB which completes the first blue loop track. A third crossing of the Cepheid strip is possible and when it occurs it is generally the second longest in duration. All told, the core He-burning phase of an intermediate-mass star occupies about 15% of the total lifetime.

Upon becoming a red giant again a He-burning shell forms around an inert C-O core and this energy source gradually overtakes the H-burning shell as the principle energy source. For certain intermediate-mass stars, depending on how much mass is lost and how

convective overshoot is treated, a second blue loop (not shown in Fig. 1) may take place lasting less than $1/20$ as long as the first blue loop. The second blue loop track may allow for two additional crossings of the Cepheid strip.

Ultimately the star will evolve onto the asymptotic giant branch (AGB) and the H-burning shell will reestablish itself as the main energy source. The He-burning shell essentially becomes dormant except when it undergoes periodic shell flashes. Depending on the total mass of the star, the AGB track will extend into the region of the MIRA, SRA, SRb, Lb, SRC, and Lc variables. The big uncertainty in the evolution at this point is the rate of mass-loss which controls the duration of this phase and how far the AGB extends. It now appears that the stellar envelope is usually lost before the degenerate C-O core can grow to the Chandrasekhar limit of $1.4 M_{\odot}$ (which otherwise would lead to a C-deflagration supernovae). Once the H-rich envelope is evaporated, the H and He-burning shells quickly run out of fuel and the star will evolve off the AGB essentially horizontally across the H-R diagram. During this evolution the star might become an R Cor Bor, W Vir, and a PV Tel type variable. Finally, this horizontal evolution ends when the white dwarf (WD) cooling sequence is reached and evolution then proceeds along this path. As the remnant star cools, it may become a GW Vir, DB, or ZZ Ceti WD variable. For more details on evolutionary models of intermediate-mass stars, see Becker (1979), Iben (1967a, 1974), and Iben and Renzini (1983, 1984).

EVOLUTION OF LOW-MASS STARS ($M_{\star} < 2.25 M_{\odot}$)

Low-mass stars are ones that develop degenerate He cores prior to core He ignition. As a result such stars evolve onto a common RGB which extends to nearly $10^3 L_{\odot}$. Because of their very long lifetimes low-mass stars can be either Pop I or Pop II composition. The models of Iben (1967b), Sweigart and Gross (1978), and Despain (1981) were used to construct the general features of a $1 M_{\odot}$ track shown in Fig. 1.

On the main sequence low-mass stars can be divided into two groups. Stars $> 1.2 M_{\odot}$ will have H-burning convective cores driven by the CNO cycle and the outer region of the star will be radiative. The core H-burning behavior will be very much like that of the intermediate-mass stars. As they evolve off the main sequence, some stars in this grouping will evolve through the hypothetical MAIA region and the domain of the δ Sct variables. Some of the more massive Pop II stars will also become SX Phx variables.

Low-mass stars $< 1.2 M_{\odot}$ behave differently as they evolve off the main sequence. These stars burn H in radiative cores driven by the pp cycle and they have convective envelopes. Unlike stars with convective cores, radiative H-burning stars get hotter as well as brighter as they evolve off the main sequence.

For either case, once H is exhausted in the core the star evolves to lower temperatures in the H-R diagram toward the RGB powered by a H-burning shell. Due to the effects of conduction and neutrino losses, the inert He-core becomes degenerate and the core needs to grow to about $0.5 M_{\odot}$ before He ignition can occur. As the He core grows in size the star evolves up the RGB. Stars undergoing this phase have deep convective envelopes. Such evolution is illustrated in globular cluster H-R diagrams. While climbing the RGB significant mass-loss may occur.

Core He ignition is a dynamic event when it takes place in a degenerate core and depending on initial conditions some envelope ejection and mixing between the H and He layers may occur. During the adjustment to core He ignition, the luminosity of the star drops and a nondegenerate convective He-burning core forms. Eventually conditions in the interior stabilize to the presence of both a He-burning core and a H-burning shell and the luminosity decline stops. Depending on how much mass remains in the outer envelope of the star and opacity conditions, the continued evolution of low-mass stars can go in two directions. Stars with thick outer envelopes will remain as red giants for the rest of their core He-burning lifetime. Some of these may become Lb, SRa, and SRb variables. If, however, the outer envelope is thin and the opacity conditions are favorable the star can

leave the red giant region and evolve onto the horizontal branch. The horizontal branch can extend much further to the blue than is illustrated in Fig. 1 into the RR Lyrae region. Anomalous Cepheids are RR Lyrae like variables that arise from extremely metal-poor stars of about $1.3 M_{\odot}$ evolving onto their equivalent horizontal branch (Hershfeld 1980). Stars burning He in the RR Lyrae region can have lifetimes in excess of 10^7 yrs.

Once He is exhausted in the core, a He-burning shell forms and low-mass stars will again evolve toward the red giant domain. Some stars evolving out of the RR Lyrae region will intersect the BL Her region during this phase of evolution. Ultimately the H-burning shell re-establishes itself as the primary energy source and evolution will then proceed onto the AGB. At this evolutionary stage such stars might be observed as MIRA, semiregular and irregular variables. When the mass of the stellar envelope becomes $< 10^{-3} M_{\odot}$, He-shell flashes in some cases may cause looping evolution away from the AGB. These loops may intersect the W Vir and RV Tau domains. In any case once the outer envelope is nearly exhausted the star must evolve off the AGB and begin a nearly horizontal track to the left in the H-R diagram. If the atmosphere is still H-rich the star might become a W Vir or RV Tau variable during this phase. If the atmosphere is H-poor, the star may appear as a R Cor Bor and then a PV Tel variable during this evolution. Ultimately the stellar remnant will become a WD and evolve down its cooling sequence. If the atmosphere has no H the star can become a GW Vir and then a DB variable as it cools. If H is present, the star will evolve eventually into the ZZ Ceti domain. For more details on the evolution of low-mass stars see Renzini (1977) and Iben and Renzini (1984).

THEORETICAL UNCERTAINTIES AND OBSERVATIONAL CONSTRAINTS

Although these topics were included in my original presentation, space limitations prevented their inclusion here. The interested reader is invited to see Becker (1985) for a similar discussion applied to Cepheid evolution.

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