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USING NONRADIAL PULSATIONS TO DETERMINE THE ENVELOPE COMPOSITION OF VERY EVOLVED STARS+

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ABSTRACT

Recent observational and theoretical studies of the ZZ Ceti variables (DA degenerate dwarfs), the DBV variables (DB degenerate dwarfs), and the GW Vir variables (DO degenerate dwarfs) have shown them to be pulsating in nonradial g^+-modes. The pulsation mechanism has been identified for each class of variable star and, in all cases, involves predictions of the stars envelope composition. The ZZ Ceti variables must have pure hydrogen surface layers, the DBV stars must have pure helium surface layers, and the GW Vir stars must have carbon and oxygen rich surface layers.

1. Introduction

In this paper I will present and discuss our current knowledge about the nonradially pulsating degenerate and predegenerate variable stars. The three classes of these stars are the ZZ Ceti stars (DA degenerate dwarfs with pure hydrogen atmospheres), the DBV stars (degenerate dwarfs with pure helium atmospheres), and the GW Vir variables (formerly known as the PG1159-035 variables). The ZZ Ceti variables inhabit a narrow instability strip with an effective temperature around 11,000K and a spread of about 1,000K [10]. The temperature boundaries of the instability strip are still in dispute. Their gravities are $\sim 10^8$ cm/s^2 implying a mass of $0.6M_\odot$. The DB variables inhabit a hotter instability strip with an effective temperature of ~25,000K and, again, the boundaries of the instability strip are not well known. The GW Vir variables are much hotter with effective temperatures ~100,000K. Their atmospheric composition has not, as yet, been determined. They do not show evidence for any hydrogen in their atmospheres but they are so hot that one cannot set an upper limit to the hydrogen abundance. They show lines of helium, carbon, and oxygen and their ultraviolet spectra show numerous metal lines. One member of this class is the central star of a planetary nebula (K1-16) and all of the evidence indicates that the other members of the class were recently planetary nebula central stars. There have been a number of reviews of the properties of these variable stars [4,27,34,35,38,39] so that in this paper I will mainly discuss the recent results.

2. The ZZ Ceti Variables

The first of the nonradially pulsating degenerate stars to be discovered was HL Tau-76 [18]. It had a period of ~750 sec; much longer that the radial periods predicted for a degenerate dwarf and this result went unexplained for some years. In 1972, Chanmugam [6] and Warner and Robinson [36] suggested that these stars must be pulsating in nonradial g^+ modes. Over the next few years, the Texas group came to the realization that most of the nonradially pulsating stars existed in the temperature range where the hydrogen opacity was the largest. There are now 18 known ZZ Ceti stars [38].

It was not until the late 1970's that any progress was made in identifying the cause of the pulsations. In an attempt to understand the structure and excitation of white dwarf envelopes, Starrfield, Cox, and Hodson [28,29, see also 24] used modern opacity tables and a linear, nonadiabatic, radial pulsation code [3] to investigate DA envelopes for instabilities. They were successful and attributed the excitation mechanism to the kappa and gamma mechanism in the hydrogen partial ionization zone.

Meanwhile, Saio and Cox [25] had developed a new numerical technique for the rapid analysis of linear, nonradial, nonadiabatic perturbations on stellar envelopes. Winget, <u>et al.</u> [37,38,39,43] applied this technique [see also 7,30] to a variety of stellar models. As summarized in Winget [38]: they found that the pulsations of the ZZ Ceti variables were caused by the partial ionization of hydrogen near the stellar surface and also attributed the basic physical mechanism to the kappa and gamma effects operating near the base of the surface convective zone. They found that there was an upper limit to the amount of mass of the hydrogen surface zone of $10^{-8} M_\odot$. If the surface hydrogen zone was more massive than this, the models were stable. This produced a strong disagreement with evolutionary calculations which predict surface hydrogen masses of order $10^{-4} M_\odot$ or larger [14].

The disagreement between pulsation and evolution theory was so severe that it seemed important to redo Winget [37]. Such a study has now been done [5] and they find both agreement and disagreement with Winget [37]. First, they found that the nonstandard convection theory used by Winget assumed very inefficient convection. What was done was to choose the mixing length to be the smaller of the pressure scale height or the distance to the surface. This reduces the ratio of mixing length to scale height to very small values near the surface. Cox, et al., assumed standard theory [2]. Second, Cox, et al. used both the Saio and Cox [25] code and a new Lagrangian Code [22]. They find a blue edge at about 12,000K for models which assume very efficient convection: l/h_p=2 to 3. However, the blue edge does not depend on the amount of hydrogen envelope mass and, in fact, stellar models with M_e=$10^{-4}M_o$ are pulsationally unstable. This completely removes the theoretical discrepancy between the evolution and pulsation calculations.

The most important result of Cox, et al. is that the cause of the instability is neither the kappa nor the gamma mechanism resulting from the partial ionization of hydrogen but is a new physical effect which they call "convection blocking." In essence, the interaction of pulsation and convection can act to block the flow of energy in a compression or release it in an expansion just like the normal kappa and gamma mechanisms.

3. The Pulsating DBV Stars

Currently there are 4 known pulsators with pure helium atmospheres [38]. They are called the DBV stars and their discovery is a direct result of the theoretical predictions [37,42]. Both ultraviolet and optical atmospheric analyses have been performed on these stars and the instability strip ranges from an effective temperature of 24,000K to about 28,000K [19]. However, the boundaries are rather uncertain and probably could vary by as much as 2,000K [19]. Koester, et al. [17] find a somewhat cooler instability strip.

Theoretical analyses of these stars [5,38] are in essential agreement but with the same differences in interpretation as found for the ZZ Ceti variables. In essence, the cause of instability is ultimately the partial ionization region of helium and hydrogen cannot be present in the driving region to rather stringent limits. This is because hydrogen can easily "poison" the pulsations in this temperature range and, in addition, if there were any hydrogen it would float to the surface on a rather rapid time scale.

4. The GW Vir (PG1159-035) Variable Stars

The first member of this class was found to be pulsating in a number of modes with periods around 500 seconds [20]. Spectroscopic studies showed no evidence for any hydrogen in the atmosphere, that the gravity was $\sim 10^7$ cm/s^2 or larger, and that its effective temperature exceeded 100,000K [1]. Winget, et al. [40] have measured a period change in GW Vir of -2.34×10^{-14} s/s. This has now been interpreted [15] as caused by a shrinking, rotating star pulsating in a low order l mode (l is the number of node lines on the surface). They obtain a rotation velocity of ~35 - 50 km/sec which does not seem unreasonable for a white dwarf. Other members of this class [9,44] include the central star of the planetary nebula K1-16 which is pulsating at periods of ~1700 sec, much longer than those found in GW Vir.

Starrfield, et al. [29-33] identified the pulsation driving mechanism as the partial ionization of the last two electrons of both carbon and oxygen. Both codes [22,25] were used to analyze stellar envelopes in the effective temperature range from 70,000K to 150,000K (and hotter). The mass of the star was assumed to be $0.6M_\odot$ and the composition of the envelope was assumed to be either half helium and half carbon (by mass), pure carbon, half carbon and half oxygen, or ninety percent oxygen and ten percent carbon. They found instability strips for these stars in the above temperature range. They also predicted that if GW Vir were as hot as suggested by the xray observations, then a significant amount of oxygen was required at the surface in order for these stars to pulsate. This prediction was confirmed [26] by the discovery of strong oxygen lines in the spectrum. The actual abundance of oxygen is unknown since no abundance analysis has been done for these stars. A recent study of K1-16 has found the same lines but they are in emission. Starrfield et al. [33; and in preparation] have also done a linear, nonadiabatic, nonradial analysis of K1-16 and found instability strips for this star at high luminosity. In order for K1-16 to be pulsating at periods of ~1700 sec it must have an effective temperature around 130,000K.

5. Conclusions

The observational studies of these stars have shown both that they are pulsating in nonradial g^+ modes and also that these modes are of low order in l and high order in k (the number of nodes in the radial eigenvector). The principal argument in favor of these conclusions is that the periods calculated for stellar models in the observed temperature range are quite close to those that are observed. The discovery and analysis of these stars has markedly improved our understanding of the last stages of evolution of stars like the sun. In order to analyze these stars and demonstrate that they are pulsating in nonradial modes, it was necessary to develop new numerical techniques and use the latest stellar opacities and equations of state. In addition, it was necessary to apply diffusion theory to the outer envelopes of DA white dwarfs. Now it appears that a time dependant theory of the interaction between convection and pulsation will have to be developed in order to accurately determine the theoretical boundaries of the ZZ Ceti and DBV instability strips.

The theoretical analysis of these stars has provided us with two new pulsation driving mechanisms. In the case of both the ZZ Ceti and DBV variables it is "convection blocking" which occurs as a result of the interaction between convection and pulsation. Detailed analysis of the driving regions in both classes of variables shows that convection cannot adjust instantaneously to either a compression or an expansion and the result is a blocking or release of energy out of phase with the envelope motions.

In the case of the GW Vir variables it is the action of a kappa and gamma mechanism that drives the pulsations, but it is the partial ionization of carbon and oxygen that causes the pulsational instability and evidence has now been obtained that shows that these stars have oxygen present at the surface. This implies that these stars have probably suffered a great deal of mass loss in order for them to have eliminated their entire hydrogen and helium burning layers.

Finally, the observations of these stars show that there is helium present in the surface layers. The fraction of helium has yet to be determined but is probably small; otherwise, it would poison the pulsational instability. Nevertheless, it seems likely that with time it will float to the surface and finally poison the driving and halt the pulsations. As the star cools, however, it will pass through the DBV instability strip and again become a pulsating variable star.

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