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PROGRESS AND PROBLEMS IN THE STUDY OF THE PULSATING WHITE DWARF STARS

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1. INTRODUCTION TO THE PULSATING WHITE DWARF STARS

We currently know of at least three distinct classes of degenerate pulsating variable stars; they occur with a practically uniform spacing in the log of the effective temperature and span nearly the full sweep of the white dwarf cooling sequence in the H-R diagram. The hottest of these variable stars are the pulsating PG 1159-035 stars. Extremely hot, compact, stars, they appear to be contracting and cooling on their way to becoming white dwarf stars. These proto-white dwarfs have photometric properties similar to the pulsating white dwarf stars, and are reviewed separately in these proceedings by A. N. Cox. The two remaining classes of compact pulsating variables are found in relatively narrow instability strips occupying distinct portions of the white dwarf cooling sequence after the constant radius, purely cooling, phase has been reached. These two classes of variable stars are the topic of this review. In this work I will use the concise notation introduced by Sion et al. (1983) to indicate the two classes of variables: the ZZ Ceti's, and the pulsating DB white dwarfs, become simply the DAV, and the DBV stars, respectively.

Since Arlo Landolt first puzzled over the anomalously long periods found in HL Tau-76 (Landolt 1968) the pulsating white dwarf stars have presented a series of enigmas. In spite of the magnitude of the problems, considerable work has been focused on their solution because of the wealth of information these pulsators have to reveal. The rich, multiperiodic, character of their light curves offers the possiblility of seismologically probing the interiors of white dwarf stars in unprecedented detail. Such studies are of intense interest because the white dwarfs contain an archeological record of the history of star formation in our galaxy. Fortunately, the timescale of the variations typical of these stars (100s $< P <$ 1,000 s), makes it easy to observe many cycles in a single night; thus, they also provide excellent laboratories for the study of nonradial pulsations. Because of the rapidly developing character of this field, in this brief review I will focus mainly on the work completed since the last major reviews of Van

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Horn (1984) and Robinson (1985).

2. PROGRESS AND PROBLEMS IN THEORY

2.1 The Pulsation Periods of the White Dwarfs

The puzzle of the long periods of the pulsating white dwarfs was soon solved. It was realized that the length of the observed periods, too long for radial pulsation periods, could be easily understood if the oscillations were the result of nonradial gravity modes. This result raised another problem: the spectrum of possible nonradial g-modes is richer than the observed spectra. The resolution of this problem was provided by consideration of more realistic compositionally layered models. The mechanism was the resonance of certain modes with the surface H and He layer thicknesses, selectively increasing the excitation rate (by decreasing the kinetic energy) of the modes trapped in the surface layers (Winget, Van Horn and Hansen 1981, Dolez and Vauclair 1981). These layered models also were pulsationally unstable, and thereby solved the problem of the nature of the destabilizing mechanism (see 2.2 below).

The resolution of the driving problem proved another embarrassment of riches. In addition to unstable nonradial g-modes with the correct periods, radial modes with periods less than about 0.1 s were also found to be unstable in the same layered models; and Robinson demonstrated definitively that they were not observed. Hansen et al. (1985), demonstrated that the hard sphere surface boundary condition is violated for periods shorter than about 0.1 s, resulting in energy leakage through the atmospheric layers which may damp the short period pulsations. They also pointed out that the low-frequency critical frequency limits the longest period modes which can be unstable and provides a theoretical red edge for the instability strips. This model has the virtue of not appealing to the "Great Unknown" (convection, rotation, or magnetic fields) to explain the red edge.

2.2 The Nature of the Driving Mechanism

The essentially chemically pure surface compositions of the DAV's (hydrogen) and the DBV's (helium), coupled with the location of the instability strips near the opacity maxima of their respective surface compositions, strongly suggests the partial ionization of the most abundant chemical species as the source of the driving for the pulsational instabilities. Indeed, work by a number of groups has established this conclusively for the DAV's (Dolez and Vauclair 1981, Winget et al. 1982a, Starrfield et al. 1982) and the DBV's (Winget 1981, Winget et al. 1983, Koester et al. 1985, Cox et al., preprint). In both instability strips the driving was identified with the usual kappa and gamma mechanisms operating near the bases of the partial ionization zones for models near the blue edges of the theoretical instability strips.

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Recent work by Pesnell, Cox and collaborators, however, has shown that the kappa and gamma mechanisms do not provide most of the instabilities found in the theoretical models. This work, employing a new Lagrangian nonradial pulsation code developed by Pesnell (preprint), and applied to static white dwarf envelope models by Cox et al. (preprint) indicates that the instabilities found in models where the convection carries most of the flux - which is the case for all models significantly cooler than the blue edge - are spurious in the sense that they result from the steep gradient in the radiative flux, and not from the kappa or gamma mechanism. In other words the neglect of the perturbation of the convective flux is ignored in the theoretical calculations, so that the steep decrease in the radiative luminosity at the base of the partial ionization zone, effectiviely blocks the energy transport in the models. Cox et al. refer to this mechanism as "convective blocking" and point out that a more realistic treatment of the perturbation to the convective flux may stabilize many of the instabilities found in the theoretical models. This may provide another way to reconcile the theoretical models with the observed instability strip; it also underscores the desperate need for a reasonable theory of pulsation convection interaction.

2.3 The Mass of the Surface Hydrogen Layer in the DAV Stars

Aside from their necessary pulsations, the DAV and DBV stars are completely normal white dwarf stars and are therefore representative of their respective spectroscopic classes (DA and DB white dwarfs). Thus any conclusions drawn about their structure and composition based on examination of their pulsation properties are likely to be valid for all white dwarfs, pulsating and nonpulsating, of that spectral type. This is particularly important in the case of the DAV stars where comparison of the location and properties of the observed instability strip with the theoretical models has been used to place limits on the surface hydrogen layer masses (Winget 1981; Dolez and Vauclair 1981; Winget et al. 1982a; see also the review by Winget and Fontaine 1982). Precisely the same effect which traps individual modes in the surface hydrogen layers (see 2.1) resuces the amplitude of all the eigenfunctions in the layers below. This, in turn, reduces the effect of radiative damping region below the driving zone. Thus, the theoretical blue edge of the instability strip is sensitive to the mass of the surface hydrogen layer, as described in detail by Winget and Fontaine (1982): models with $M_H/M_\odot$ less than 10^{-8}, pulsate at temperatures serveral thousand degrees hotter than those with more massive surface hydrogen layers. This result, alone, does not restrict the mass of the surface hydrogen layer, because if we select any given hydrogen layer mass, the effective temperature of the blue edge can be made to agree with the observations by adjusting the convective efficiency in the models. For this reason, as recently pointed out by Cox et al., there is no inconistency - on purely theoretical grounds - between the pulsation results and the standard evolutionary calculations which indicate surface hydrogen layer masses of order 10^{-4} $M_\odot$ for all DA white dwarfs (cf. Iben and Tutukov 1984, Iben and

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McDonald, preprint).

A glaring inconsistency develops, however, when the theory is compared with the observations. Any claimed distribution of surface hydrogen layer masses must satisfy two important observational constraints: there are no known nonvariables within the instability strip, and below 10,000 K there is a reversal of the ratio of DA to non-DA white dwarfs. The first fact argues that the DAV's are representative of most, and perhaps all, DA white dwarfs. Further, it implies that the DA's must either have $M_H/M_\odot << 10^{-6}$, or $> 10^{-6}$ (hereafter referred to as "thin" and "thick" hydrogen layers, respectively). If there were significant populations of both thick and thin surface hydrogen layer white dwarfs, the sensitivity of the temperature of the blue edge to the surface hydrogen layer mass, would imply that we would observe an admixture of variables and nonvariables within the DAV istability strip. Next, we assume that the cooling times of the DA and non-DA white dwarfs are similar - reasonable since the work of Weidemann and Koester (1984) points out that the mean mass of the DA's and DB's are indistinguishable. Then the reversal of the ratio of DA's to non-DA's below the red edge implies that a large fraction of the DA white dwarf population must convectively mix below 10,000 K. In order for this mixing to occur $M_H/M_\odot$ must be $<< 10^{-7}$ (Vauclair and Reisse 1977; and Koester 1976); thus when taken together, the two observational facts argue that most, and perhaps all, DA white dwarfs must have thin surface hydrogen layers. This result is directly in conflict with the remnant mass of hydrogen from the standard evolutionary calculations $M_H/M_\odot \cong 10^{-4}$).

It remains unclear, at present, whether or not this is a serious problem. Another interesting possibility, due to Michaud and Fontaine (1984), is that diffusion induced hydrogen-burning after the planetary nebula ejection phase can reduce a surface hydrogen layer with an initial mass of 3×10^{-4} to 3×10^{-7} $M_H/M_\odot$. This idea is a follow-up to the work of Iben and Tutukov (1984), who showed that, contrary to previous ideas, hydrogen-burning may be present in the white dwarfs down to relatively cool temperatures. Michaud and Fontaine (1984) were able to demonstrate that the steep concentration gradient in the H-shell burning region would cause additional hydrogen to diffuse downward into the nuclear burning region. In this way, by nibbling away at the inner edge of the hydrogen abundance distribution, the nuclear burning can produce a thin surface hydrogen layer DA from a thick one well before the effective temperature of the DAV's is reached. However, the calculations of Michaud and Fontaine did not incorporate the diffusion in a time dependent way in evolutionary calculations. An attempt to incorporate the diffusion in a self-consistent way by Iben and McaDonald (preprint) did not yield the lower surface layer masses indicated by Michaud and Fontaine. Thus the problem of the consistency of the pulsational and evolutionary hydrogen layer masses remains unresolved. On the other hand, it should be pointed that no attempt has been made to treat the mass loss in the planetary nebula stage in a self-consistent way, so that it is entirely

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possible that the mass loss during planetary formation, or during subsequent high luminosity evolution via winds, is sufficient to produce the necessary reduction in M_H. In this light, the apparent inconsistency may reflect only our well-established ignorance of the mass loss processes.

3. PROGRESS AND PROBLEMS IN THE OBSERVATION OF DAV AND DBV STARS

3.1 The Location and Statisitics of the DAV Instability Strip

Fontaine et al. (1982) and Greenstein (1982) have used Greenstein's multichannel color observations of the DAV's to establish the location and population of the DAV instability strip. These authors found that the instability strip is confined to the narrow interval between about 13,000 K and 11,000 K, with some uncertainty in the absolute values of these numbers depending on the adopted calibration (see the discussion in Weidemann and Koester 1984). Fontaine et al. (1982) concluded that the data was consistent with the assertion that most, and possibly all, DA white dwarfs within the observed instability strip are variable; this was strengthened by the observation of a larger sample of DA's by Fontaine et al. (1985), using a homogeneous set of Stromgren colors.

3.2 The Existance and Location of the DBV Instability Strip

Currently, there are 4 known DBV stars: the prototype GD 385 (GW Vir), PG 1654+160, PG 1115+158, and PG 1351+489. Recently, Liebert et al. (preprint) completed an analysis of the ultraviolet energy distributions of 12 hot, DB, white dwarfs - including the four known DBV stars. Their work serves to define an empirical instability strip for the DBV stars: they demonstrate that most or all the stars within a certain temperature range pulsate, and those outside do not. Using the IUE data, they obtain a temperature of 28,000 K + 2000 K for the blue edge, and 24,000 K + 2,000 K for the red edge. However, they point out that if the optical temperature scale is adopted the blue edge may up to 3,500 K cooler, and the red edge may be as much as 2,000 K cooler (see also Koester et al. 1985, and references therein, for a discussion of this). Some of the problems in determining T_e reflect theoretical uncertainties, and difficulties, in constructing model atmospheres for the DB's. In addition, the above mentioned authors have argued variously that (1) the optically determined temperatures are unreliable because the temperatures of these objects -by any estimate - are much hotter than $T_e=20,000$ K, above which the slope of the spectra in the optical become temperature insensitive, (2) the IUE results are unreliable because of calibration uncertainties, (3) there are uncertainties in the effects of reddening. Independent of calibration uncertainties, there is no way to fit both the short and long wavelength IUE data simultaneously with anyone's model atmospheres. Thus, in order to make additional progress on the location and statistics of the DBV's we need a breakthrough in the temperature determination problem, as well as simply a larger sample of hot DB stars.

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3.3 The Pulsation Properties of the DAV and DBV Stars

There are only four known DB's, a small number when compared with the 18 known DAV stars, but sufficient to demonstrate that the full range of photometric behavior found in the DAV's is found in the DBV's. In particular, a recent survey of the class properties of the DBV's by Hill (1986) demonstrates that the DBV PG 1351+489 has a light curve and power spectrum nearly identical with that of the DAV star GD 154. Both stars display power spectra dominated by a single peak. Hill also showed that the light curve and power spectra of the DBV PG 1115+158 is very similar to that of one of the most complex DAV stars, G29-38. Thus the simplicity and the complexity of the DAV stars are both found in the DBV stars.

Hill's study also revealed two additional, very remarkable, results. He found that the precisely uniform frequency splitting observed in the star GD 358 by Winget et al. (1982b) - which they interpreted as rotational splitting - was repeated in his 1985 data on several occasions, but the splitting and indeed the periods themselves were different on different nights. Unless a mode is inherently unstable, the only way it can disappear is if it is composed of two or more closely spaced modes. If this explanation is invoked, it requires a "hyperfine" splitting of the modes already presumed to be rotationally split. This apparently could only be accomplished by the highly implausible accidental degeneracy in the frequencies of each of some 28 modes. Therefore the rotational splitting argument for sets of equally spaced modes in this object, and perhaps in some of the other variable white dwarfs, may be in serious trouble. In this case some other explanation must be found for this uniform spacing.

Hill also found that because of the essentially mono-periodic character of the light curve of the DBV PG 1351+489 he could construct an average pulse shape for the light curve of the star. He also notes that this technique could be profitably applied to the DAV stars GD 154 and G 191-16. It is interesting to note that the pulse shape for PG 1351+489 agrees qualitatively quite well with some of the pulse shapes published by Brickhill (1983): it has a saw-tooth character with a more rapid rise and a somewhat slower decline. This gives us, for the first time, a real motivation for pusuing the theoretical calculation of light curves for these pulsating stars. Since this is not a linear problem, progress beyond the preliminary explorations of Brickhill will be difficult.

3.4 Mode Switching in the DAV Stars?

The power spectra of some of the more complex DAV and DBV stars do not repeat on a night to night basis. This has led a number of authors to conclude that the periods in these stars are inherently unstable. The lure of measuring growth rates - for comparison with theory - has led to a great deal of observational interest in this subject. The problem

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is to determine if the periods in a given star are really inherently unstable, and if so on what timescale, or if the observed changes in the power spectra can be accounted for by the the beating of closely spaced modes. Unfortunately, as illustrated by the recent work of Kepler and O'Donoghue, proving anything one way or another requires an enormous amount of data on each object considered. Kepler (1984) examined the DAV star GD 385 and found that the instabilities previously claimed in this object (Fontaine et al. 1980) could be accounted for in terms of the beating of closely spaced modes. Kepler, Robinson, and Nather (1983) reached similar conclusions for the DAV G226-29. O'Donoghue (preprint) reached similar conclusions for the DAV BPM 31594. In each of these three cases, it developed that the pulsation modes were not unstable but were the result of beating of several closely spaced modes. Before drawing and quick generalizations, however, we note that O'Donoghue also pointed out that the strikingly unstable behavior of GD 154 reported by Robinson et al. (1978) could be explained by 9 closely spaced frequencies. Since the observation of 9 closely spaced modes is completely unprecedented in any other of these variables, this interpretation is weak. This makes the kind of extensive observational coverage, carried out by Kepler and O'Donoghue for the above stars, essential for GD 154.

4. FUTURE DIRECTIONS

Perhaps the most exciting prospect for the future is the measurement of the rates of period change in the pulsating white dwarf stars. These measurements will provide accurate determinations of the evolutionary timescales; these can be used to calibrate the theoretical evolutionary sequences. The first such measurement has been made for the hot pulsating pre-white dwarf star PG 1159-035 (Winget et al. 1985), and similar measurements are well under way for the DBV PG 1351+489 (Hill 1986), and the DAV star G117-B15A (Kepler 1984) and promise to yield detections within 2-3 years - if the theoretical evolutionary calculations are in the right ballpark. The experience gained in the measurement of the rate of period change in PG 1159-035 makes it clear that the alias problem can only be solved with extended coverage obtained from multi-site observations from observatories well distributed in longitude. This emphasizes and need for vigourous international collaboration if the scientific potential of this field is to be realized. This potential is large indeed; the calibrated ages of white dwarfs made available in this way will allow us to directly read the archeological record of star formation in the galaxy. This will also demand a new generation of evolutionary calculations incorporating state-of-the-art treatments of the physics of both the envelope and the interior; only then can we really begin to exploit the wealth of seismological information available from the new generation of observations.

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