THE ASTROPHYSICAL JOURNAL, 391:L33–L36, 1992 May 20

MAXIMUM RATES OF PERIOD CHANGE FOR DA WHITE DWARF MODELS WITH CARBON AND OXYGEN CORES

P. A. BRADLEY AND D. E. WINGET
McDonald Observatory and Department of Astronomy, The University of Texas at Austin, Austin, TX 78712–1083

AND

M. A. WOOD
Department of Physics and Space Sciences, Florida Institute of Technology, 150 West University Boulevard, Melbourne, FL 32901-6988

Received 1991 December 27; accepted 1992 March 2

ABSTRACT

Observational investigations of the rates of period change in several DAV (≡ZZ Ceti) stars are fast approaching theoretically interesting limits. Although the known observational errors are still large, in three of these objects the best current observational values for rates of period change ($\equiv \dot{\Pi}$) are of order 10^{-14} s s^{-1}—substantially larger than published calculations for carbon core white dwarf models (1 to 4×10^{-15} s s^{-1}).

In this *Letter*, we explore the *maximum* rates of period change expected from theoretical evolutionary models of 0.5 and 0.6 $M_\odot$ DAV stars with core compositions (carbon and oxygen) suggested by standard evolutionary theory.

The largest rates of period change occur for nontrapped modes in models near the observed blue edge of the DAV instability strip ($T_{\rm eff} \sim 13{,}000$ K). As expected from simple scaling arguments, models with pure oxygen core composition have the largest rates of period change, up to 9×10^{-15} s s^{-1}. Trapped modes have $\dot{\Pi}$ values ranging from 1 to 4×10^{-15} s s^{-1}, about half the values we obtain for nontrapped modes.

Observationally, we find that the hottest DAVs have power spectra dominated by short-period (∼100–300 s) low-amplitude modes—a result of short thermal time scales in the driving region—these short-period modes are *not* trapped in the models. Thus, observational rates of period change in hot DAVs may be more easily detected than previously suspected. Our results also suggest that measured rates of period change may provide a useful probe of mode trapping in the DAV instability strip.

Subject headings: stars: evolution — stars: variables: other — stars: white dwarfs

1. INTRODUCTION

The DAV (pulsating hydrogen atmosphere ≡ ZZ Ceti stars) white dwarfs constitute the coolest known class of pulsating white dwarf stars. As these stars cool, their pulsation periods lengthen; the rate at which the pulsation periods change provides a measure of their evolutionary cooling time scales. Recent observations of several DAV white dwarfs yield upper limits on their rates of period change ($\equiv \dot{\Pi}$) that are rapidly converging on theoretically interesting values. The best observational upper limits suggest that $\dot{\Pi}$ may be as large as 1×10^{-14} s s^{-1}, a factor of 2–3 bigger than previously published results for 0.6 $M_\odot$ models with carbon cores (Wood & Winget 1988; Bradley & Winget 1991, hereafter BW; Brassard et al. 1991).

In principle, measuring the rate of secular evolution in DAV stars allows us to determine the mean atomic number of the core material once the mass and effective temperature are known. Wood (1992) shows that determining the composition of the core is critical if we are to use white dwarf stars as clocks for measuring the age and star formation history of the local Galactic disk (Winget et al. 1987). Although the ^{12}C(α, γ)^{16}O reaction rate (Caughlan & Fowler 1988) within standard stellar evolution theory suggests that the cores of the white dwarf stars should be an oxygen-rich C/O mixture (see, e.g., D'Antona & Mazzitelli 1989, 1990), this has not been observationally confirmed. A determination of the core composition of white dwarfs would provide direct constraints on the ^{12}C(α, γ)^{16}O reaction rate. Observations (Fontaine et al. 1982; Greenstein 1982) suggest that most DA white dwarfs in the DAV instability strip pulsate (but see Dolez, Vauclair, & Koester 1991). Therefore, the DAV stars are likely to be otherwise typical white dwarfs, and as such, their properties should be representative of DA white dwarfs as a group.

Recently, Kepler et al. (1991) detected the rate of period change for the 215 s period in G117-B15A, obtaining a value of $(12 \pm 3.5) \times 10^{-15}$ s s^{-1}. Fontaine et al. (1991) took the detected $\dot{\Pi}$ at face value and suggested that it was too large to be consistent with existing $\dot{\Pi}$ results for carbon-core models or results scaled using the oxygen-core evolutionary timescales given in Wood (1990). They also noted that simple scaling of ages with Mestel theory (Mestel 1952; Van Horn 1971) gives an estimate of $\dot{\Pi}$ as a function of the mean atomic weight A:

$$\dot{\Pi} \approx \frac{A}{16} 5.6 \times 10^{-15}\ , \quad A > 16\ ,$$

which suggests a core composition for G117−B15A considerably heavier than oxygen, in conflict with the results from standard stellar evolution theory. With this in mind, we decided to go beyond simple scaling arguments and to compute theoretical $\dot{\Pi}$ values using carbon and oxygen core evolutionary models to see how large the theoretical $\dot{\Pi}$ value can be in 0.5 and 0.6 $M_\odot$ models.

2. MODELS AND PULSATION CALCULATIONS

We use an updated version of the White Dwarf Evolution Code (≡ WDEC; Lamb & Van Horn 1975; Wood 1990), which is designed to evolve white dwarf models using the best available input physics. Recent additions to WDEC include

TABLE 1

Parameters of Models Used in This Work

Core	$M_*/M_\odot$	$\log(M_{He}/M_*)$	$\log(M_H/M_*)$	Designation
C	0.5	−4	−6	c50406
O	0.5	−4	−6	o50406
C	0.5	−4	−10	c50410
O	0.5	−4	−10	o50410
C	0.6	−4	−6	c60406
O	0.6	−4	−6	o60406
C	0.6	−4	−10	c60410
O	0.6	−4	−10	o60410

the capability of evolving C/O cores with a prespecified composition profile and the inclusion of realistic transition zone profiles within the framework of diffusive equilibrium. In addition, we also have a choice of convective efficiencies within the confines of mixing-length theory (see Bradley, Winget, & Wood 1992, hereafter BWW). We use efficient (ML3, see BW) convection in all of our models as this provides the best match between the effective temperatures of the theoretical and observed instability strips (e.g., Winget & Fontaine 1982; Bradley, Winget, & Wood 1989). We do not consider the nonadiabatic pulsation properties of models here, since this is beyond the scope of our investigation.

To determine the oscillation periods of the evolutionary models for our rates of period change, we use a fourth-order Runge-Kutta-Fehlberg code (called RKF) developed by C. J. Hansen (see Kawaler, Hansen, & Winget 1985; Kawaler 1986). RKF solves the nonradial oscillation equations described in Saio & Cox (1980) in the adiabatic approximation (i.e., entropy and luminosity perturbations set to zero). Our previous experience with RKF (BW; BWW) shows that it computes adiabatic periods accurate to better than 0.01% and does not miss any modes in the range of interest for this paper. We compute the pulsation periods for several models in each evolutionary sequence, with temperatures ranging from 14,000 to 12,000 K and use linear differencing of the pulsation periods from consecutive models to compute our theoretical rates of period change.

In this *exploratory* calculation, we examine several parallel carbon and oxygen core 0.5 and 0.6 $M_\odot$ DA evolutionary sequences (see Table 1). We refer the reader to BW and Brassard et al. (1991) for comprehensive surveys of the pulsation properties of DA white dwarf models. We compare our results to existing theoretical rates of period change (see BW and Brassard et al. 1991). Our carbon core results provide a lower limit on $\dot{\Pi}$ for the limiting case where carbon does not react further to produce oxygen. At the other extreme are the oxygen-core models, which give us a larger rate of period change for an otherwise fixed set of model parameters. In practice, the extreme case of pure oxygen is not unreasonable, because the $^{12}C(\alpha, \gamma)^{16}O$ reaction is favored at lower temperatures (Caughlan & Fowler 1988). Indeed, pure oxygen cores are similar to the core composition suggested by recent stellar evolution results (Mazzitelli & D'Antona 1986; D'Antona & Mazzitelli 1989).

3. RESULTS AND DISCUSSION

The observational upper limits and detections for $\dot{\Pi}$ are for pulsation periods shorter than 300 s. Because of this, we restrict our investigation to g-modes of $l = 1, 2$, and 3 with low radial overtone (k values). We primarily consider models with effective temperatures near 13,000 K, consistent with the observed temperatures of G117-B15A, L19-2, and R548 (Daou et al. 1990[1]).

3.1. *Theoretical Trends*

The $\dot{\Pi}$ values from all of our models show several general trends. (See Tables 2 and 3 for our $\dot{\Pi}$ values of 0.5 and 0.6 $M_\odot$ models, respectively.) First, $\dot{\Pi}$ tends to increase with increasing

---

[1] Bergeron, Wesemael, & Fontaine (1992) have shown that the derived effective temperatures for the DAV stars are extremely sensitive to the assumed convective efficiency and must be regarded with caution.

TABLE 2

Pulsation Periods and Rates of Period Change for Selected Modes: 0.6 $M_\odot$

		c60406, 13,090 K		o60406, 13,090 K		c60410, 13,210 K		o60410, 13,060 K	
l	k	Π (s)	$\dot{\Pi}$ (s s^{-1})	Π (s)	$\dot{\Pi}$ (s s^{-1})	Π (s)	$\dot{\Pi}$ (s s^{-1})	Π (s)	$\dot{\Pi}$ (s s^{-1})
1	1	198.3(T)	1.24	195.6(T)	1.38	246.2(T)	2.36	232.8(T)	5.54
1	2	242.8	3.47	239.8	3.85	274.3	6.17	287.5	7.92
1	3	274.4	6.45	285.7	7.85	343.0	8.10	353.6	9.92
2	1	114.5(T)	0.71	112.9(T)	0.79	143.3(T)	1.14	134.8(T)	3.17
2	2	141.0	1.85	139.0	2.14	177.2	4.40	183.5	5.37
2	3	177.9	4.51	182.5	5.30	214.4	4.23	219.2	5.13
2	4	216.7	5.11	220.5	4.53	240.4	2.98	240.0	4.44
2	5	231.0(T)	1.96	229.8(T)	3.41	272.8	5.44	280.2	7.73
2	6	258.9	4.81	260.2	4.84	305.2	3.19	304.4	4.15
2	7	283.9	4.96	288.7	6.39	326.4	4.75	329.6(T)	5.74
3	2	100.0	1.27	100.0	1.71	133.4	3.35	136.7	4.09
3	3	134.2	3.50	136.3	4.02	160.7	2.20	160.8	2.82
3	4	160.8(T)	1.71	159.5(T)	1.49	176.3	3.12	179.1	4.45
3	5	168.2	3.49	170.7	4.28	204.9	3.22	207.1	4.16
3	6	189.8	2.76	190.1	3.08	220.5	2.88	222.1	4.61
3	7	211.8	4.55	215.6	5.15	237.1(T)	2.85	237.3(T)	3.15
3	8	229.4(T)	1.85	227.9(T)	2.34	251.4	4.34	255.8	7.40
3	9	246.4	5.88	250.1	6.61	277.0	3.96	278.8	4.73
3	10	270.3	3.53	271.4	3.64	297.2	4.76	301.6	8.57
3	11	285.1	4.36	286.2	4.61	324.4	4.91	327.8	5.90

Note.—All $\dot{\Pi}$ values are in units of 10^{-15} (s s^{-1}).

TABLE 3

Pulsation Periods and Rates of Period Change for Selected Modes: 0.5 $M_\odot$

		c50406, 12,910 K		o50406, 13,150 K		c50410, 13,150 K		o50410, 12,940 K	
l	k	Π (s)	$\dot{\Pi}$ (s s^{-1})	Π (s)	$\dot{\Pi}$ (s s^{-1})	Π (s)	$\dot{\Pi}$ (s s^{-1})	Π (s)	$\dot{\Pi}$ (s s^{-1})
1	1	236.3(T)	1.57	231.9(T)	1.82	255.7(T)	7.08	263.3(T)	6.52
1	2	261.2	7.05	262.2	7.46	289.3	5.39	297.0	6.78
1	3	296.8	5.00	297.9	6.28	345.8	8.78	358.3	9.81
2	1	136.6(T)	0.86	134.0(T)	1.02	153.8(T)	3.34	155.9(T)	3.07
2	2	158.0	3.38	156.9	3.52	179.3	3.99	183.8	4.74
2	3	183.6	3.65	183.5	4.41	216.4	5.79	224.9	6.37
2	4	220.6	5.69	222.8	6.43	260.1	5.79	266.6	5.35
2	5	265.7	5.56	265.6	4.08	283.5	4.82	291.8	6.63
2	6	278.4(T)	3.53	276.4(T)	5.98	323.8	8.92	335.6	8.02
3	2	114.0	2.06	112.8	2.18	133.0	3.15	135.8	3.58
3	3	136.2	2.93	135.5	3.36	163.9	4.42	169.8	4.74
3	4	167.2	4.46	168.4	4.98	192.6	3.18	194.9	3.27
3	5	193.7(T)	1.80	190.7(T)	1.78	210.6	4.65	216.8	5.70
3	6	204.5	4.68	205.6	5.20	241.9	5.21	247.6	4.32
3	7	230.4	3.71	229.4	4.07	258.9	3.88	262.7	5.75
3	8	252.7	5.77	254.6	6.31	277.3(T)	4.64	278.6(T)	5.34
3	9	274.5(T)	2.27	270.6(T)	2.76	291.3	6.88	301.6	7.93
3	10	291.2	6.89	294.0	7.76	322.2	6.44	328.4	6.19

Note.—All $\dot{\Pi}$ values are in units of 10^{-15} (s s^{-1}).

period (k value), although $d \ln \Pi/dt$ varies by less than a factor of 2. Modes with wavelengths resonant with the thickness of the hydrogen or helium layer can be trapped by that layer; these modes have much lower kinetic energies than others. (See Winget, Van Horn, & Hansen 1981 and BW for further details.) These *trapped modes*, denoted by a "(T)" in Tables 2 and 3, have smaller $\dot{\Pi}$ values because their eigenfunctions are determined by the depth of the transition zone, which changes gradually compared to thermal changes associated with evolutionary cooling. The average value of $\dot{\Pi}$ is relatively insensitive to the hydrogen layer mass because the degeneracy boundary has not reached the base of the hydrogen layer in any of the models we consider.

First, we compare the $\dot{\Pi}$ values from 0.6 $M_\odot$ carbon core models to existing results from BW and Brassard et al. (1991). Our $\dot{\Pi}$ values are ~30% larger than theirs, because the models in BW and Brassard et al. use analytic approximations for the equation of state (EOS) in the core, which gives larger specific heats, leading to longer cooling times and smaller rates of period change as a consequence.

A comparison of $\dot{\Pi}$ results from our 60410, 60406, and 50406 carbon and oxygen core sequences (see Tables 2 and 3) shows that on average, $\dot{\Pi}$ is about 15%–20% larger in our oxygen core models than our carbon core models. This difference in $\dot{\Pi}$ is mirrored by the age difference between models with similar effective temperatures and the difference in between the heat capacity of carbon and oxygen in our models. Based on Mestel theory, we would expect to see oxygen core models with $\dot{\Pi}$ values about 33% larger. However, Mestel theory assumes that the ions are an ideal gas, whereas the ions actually are in a liquid state where Coulomb effects are important. The Coulomb effects are stronger for oxygen, causing the heat capacity ratio to drop from 1.3 to ~1.2. This also implies that using Mestel theory for scaling $\dot{\Pi}$ may lead to overestimates of $\dot{\Pi}$ values for other core compositions heavier than carbon.

Our 0.5 $M_\odot$ models have $\dot{\Pi}$ values about 40% larger than those for a comparable 0.6 $M_\odot$ sequence (see Table 2). This is a consequence of their ~25% larger surface area and lower total heat capacity. The dominant contribution to the heat capacity comes from the ions. In this temperature range, well above crystallization, when we reduce the stellar mass at the same effective temperature, the heat capacity is affected primarily by the reduction in the number of ions.

3.2. *Comparison to Observations*

We compare our theoretical results to the recent observational results for three hot DAV white dwarfs with the best upper limits for their rates of period change. These three stars (G117-B15A, L19-2, and R548) have relatively simple period structures, making it easier to determine the period structure and demonstrate the stability of a given pulsation period.

The best observed $\dot{\Pi}$ detection is for G117-B15A, with $\dot{\Pi} = (12.5 \pm 3.5) \times 10^{-15}$ s s^{-1} (Kepler et al. 1991) for the dominant pulsation mode at 215.2 s. G117-B15A has an effective temperature near 13,200 K and log $g \sim 7.8$ (Daou et al. 1990), the latter implying a mass near 0.5 $M_\odot$. Trapped modes with periods near 215 s in our O-core 0.5 $M_\odot$ models have $\dot{\Pi}$ values near 2–3 × 10^{-15} s s^{-1}, considerably lower than the observational detection *if* taken at face value. Nontrapped modes near 215 s have $\dot{\Pi}$ values around 5–7 × 10^{-15} s s^{-1}, less than 2 σ away from the observational detection. If we assume the 215 s mode is not trapped, we then have to explain its relatively large amplitude by something besides mode trapping. G117-B15A is one of the hottest DAV stars; thermal time scale arguments (see Winget 1981 and Winget & Fontaine 1982) imply that only short-period modes will be pulsationally unstable. This could allow only the $k = 1$ mode for $l = 1$ to be unstable. For example, it is possible that the 215 s mode is an $l = 1$, $k = 1$ mode that is not trapped with a $\dot{\Pi}$ value of order 5–7 × 10^{-15} s s^{-1}; we note with caution that no model in our limited survey has an $l = 1$, $k = 1$ mode near 215 s. Nonadiabatic calculations suggest that when the $k = 1$ mode is the only unstable $l = 1$ mode, several $l = 2$ and 3 modes are also unstable because they have shorter periods. Although it is a large leap from growth rates to amplitudes, it is an interesting possibility to consider that the other five modes of G117-B15A may be unstable $l = 2$ and 3 modes; geometric effects could explain their lower amplitudes. Confirmation of these ideas will require detailed modeling and nonadiabatic calculations; this work is currently in progress.

Only upper limits to $\dot{\Pi}$ are available for L19-2 and R548. O'Donoghue & Warner (1987) find $\dot{\Pi} = 18 \pm 30 \times 10^{-15}$ s s^{-1} for the 192 s period and $15 \pm 20 \times 10^{-15}$ s s^{-1} for the 113 s period of L19-2. The best upper limit for R548 is $1 \pm 19 \times 10^{-15}$ s s^{-1} for the 213.133 s period; the other three are considerably more uncertain (Tomaney 1987). The value of $\dot{\Pi}$ we quote is twice that of Tomaney due to his nonstandard definition of $\dot{\Pi}$. Daou et al. (1990) estimate the temperature and mass of L19-2 to be approximately $T_{\rm eff} \approx 13{,}300$ K and $M \approx 0.6\ M_\odot$, whereas for R548 they find $T_{\rm eff} \approx 12{,}800$ K and $M \approx 0.5\ M_\odot$. The maximum theoretical $\dot{\Pi}$ value we find for modes near 192 s is $\sim 5 \times 10^{-15}$ s s^{-1}, with slightly smaller values for the 113 s mode. However, based on period ratios, BW suggested that the 192 s and 113 s modes of L19 − 2 are the same radial overtone $l = 1$ and $l = 2$ modes. A look at our c60406 and o60406 models suggest that we could be dealing with $l = 1$ and $l = 2$, $k = 1$ modes, although our grid of models is too limited to say for certain. If so, these modes would have theoretical $\dot{\Pi}$ values around $1\text{–}2 \times 10^{-15}$ s s^{-1}, much smaller than the current observed upper limits. Our models suggest values of $\dot{\Pi}$ for the 213 s doublet of R548 between 2 and 6×10^{-15} s s^{-1}, similar to the values the models suggest for the 215 s mode of G117-B15A. However, the theoretical evolutionary rates of period change could be as large as 9×10^{-15} s s^{-1} for the 274 s doublet; this could be detected in the near future.

A fourth star (GD 165) also has a relatively simple period structure (Bergeron & McGraw 1990); but the timespan of observations on this star is only ~ 1 yr, much shorter than the 10+ yr available for the others. The simple period structure and high temperature of GD 165 make it an ideal candidate for continued monitoring toward an eventual $\dot{\Pi}$ determination.

4. SUMMARY AND CONCLUSIONS

Observations into the rates of period change in several DAV stars are approaching theoretically interesting upper limits. Although the errors are still large, the best current observational $\dot{\Pi}$ values are of order 10^{-14} s s^{-1}—considerably larger than previously published calculations. Here we explore the maximum values of $\dot{\Pi}$ expected from evolutionary models of 0.5 and 0.6 $M_\odot$ DAV stars with carbon and oxygen core compositions expected from standard stellar evolution theory.

For models near the blue edge of the observed instability strip, we find that $\dot{\Pi}$ for nontrapped modes can be as large as $7\text{–}9 \times 10^{-15}$ s s^{-1}; our oxygen-core models have $\dot{\Pi}$ values about 20% larger because of their lower heat capacity. The larger surface area and lower integrated heat capacity of our 0.5 $M_\odot$ models causes them to have $\dot{\Pi}$ values about 40% larger than those of our 0.6 $M_\odot$ models. Mode trapping reduces our theoretical $\dot{\Pi}$ values to $1\text{–}4 \times 10^{-15}$ s s^{-1}. Overall, these theoretical $\dot{\Pi}$ values are considerably larger than previously published estimates and suggest that observational rates of period change resulting from thermal evolution may be more easily detected than previously thought.

Our work implies that observed $\dot{\Pi}$ values below 10^{-14} s s^{-1} can be accommodated by secular evolution in models consistent with standard stellar evolution theory; larger values require either core compositions heavier than carbon and oxygen—in conflict with the expectations of standard stellar evolution—or appealing to effects other than secular evolution.

We obtain theoretical $\dot{\Pi}$ values around $5\text{–}7 \times 10^{-15}$ s s^{-1} for nontrapped modes of O-core 0.5 $M_\odot$ models with periods similar to the dominant 215 s mode in G117-B15A, less than 2 σ away from the detected value. Because G117-B15A is near the observed blue edge of the instability strip, we expect that only short-period modes are excited, possibly eliminating the need for mode trapping to explain the relatively large amplitude of the 215 s mode.

The observed upper limits of $\dot{\Pi}$ for L19-2 are considerably larger than the theoretically suggested $\dot{\Pi}$ values of $< 5 \times 10^{-15}$ s s^{-1} for a model at the effective temperature and mass of L19 − 2. The theoretical $\dot{\Pi}$ values for a model representative of R548 are larger: they range from 2 to 5×10^{-15} s s^{-1} for the 213 s doublet and up to 9×10^{-15} s s^{-1} for the 274 s doublet. Based on these values, an observational detection of $\dot{\Pi}$ for the 274 s doublet may be possible in a few years.

We thank R. E. Nather and S. O. Kepler for their encouragement and valuable discussions. This research was supported by the National Science Foundation through grants AST 85-52557 and 90-14655 through the University of Texas and McDonald Observatory.

REFERENCES

Bergeron, P., & McGraw, J. T. 1990, ApJ, 352, L45
Bergeron, P., Wesemael, F., & Fontaine, G. 1992, ApJ, 387, 288
Bradley, P. A., & Winget, D. E. 1991, ApJS, 75, 463 (BW)
Bradley, P. A., Winget, D. E., & Wood, M. A. 1989, in IAU Colloq. 114, White Dwarfs, ed. G. Wegner (Berlin: Springer), 286
———. 1992, in preparation (BWW)
Brassard, P., Fontaine, G., Pelletier, C., & Wesemael, F. 1991, in Proc. of the 7th European Workshop on White Dwarfs, ed. G. Vauclair & E. M. Sion (Dordrecht: Kluwer), 193
Caughlan, G. R., & Fowler, W. A. 1988, Atomic Data Nucl Data Tables, 40, 334
D'Antona, F., & Mazzitelli, I. 1989, ApJ, 347, 934
———. 1990, ARA&A, 28, 139
Daou, D., Wesemael, F., Bergeron, P., Fontaine, G., & Holberg, J. B. 1990, ApJ, 364, 242
Dolez, N., Vauclair, G., & Koester, D. 1991, in Proc. of the 7th European Workshop on White Dwarfs, ed. G. Vauclair & E. M. Sion (Dordrecht: Kluwer), 361
Fontaine, G., Brassard, P., Wesemael, F., Kepler, S. O., & Wood, M. A. 1991, in Proc. of the 7th European Workshop on White Dwarfs, ed. G. Vauclair & E. M. Sion (Dordrecht: Kluwer), 153
Fontaine, G., McGraw, J. T., Dearborn, D. S. P., Gustafson, J., & Lacombe, P. 1982, ApJ, 258, 651
Greenstein, J. L. 1982, ApJ, 258, 661
Kawaler, S. D. 1986, Ph.D. thesis, Univ. of Texas
Kawaler, S. D., Hansen, C. J., & Winget, D. E. 1985, ApJ, 295, 547
Kepler, S. O., et al. 1991, ApJ, 378, L45
Lamb, D. Q., & Van Horn, H. M. 1975, ApJ, 200, 306
Mazzitelli, I., & D'Antona, F. 1986, ApJ, 308, 706
Mestel, L. 1952, MNRAS, 112, 583
O'Donoghue, D., & Warner, B. 1987, MNRAS, 228, 949
Saio, H., & Cox, J. P. 1980, ApJ, 236, 549
Tomaney, A. B. 1987, in IAU Colloq. 95, The Second Conference on Faint Blue Stars, ed. A. G. D. Philip, D. S. Hayes, & J. Liebert (Schenectady: L. Davis), 673
Van Horn, H. M. 1971, in IAU Symp. 42, White Dwarfs, ed. W. Luyten (Dordrecht: Reidel), 97
Winget, D. E. 1981, Ph.D. thesis, Univ. of Rochester
Winget, D. E., & Fontaine, G. 1982, in Pulsations in Classical and Cataclysmic Variable Stars, ed. J. P. Cox & C. J. Hansen (Boulder: Univ. of Colorado Press), 246
Winget, D. E., Hansen, C. J., Liebert, J., Van Horn, H. M., Fontaine, G., Nather R. E., Kepler, S. O., & Lamb, D. Q. 1987, ApJ, 315, L77
Winget, D. E., Van Horn, H. M., & Hansen, C. J. 1981, ApJ, 245, L33
Wood, M. A. 1990, Ph.D. thesis, Univ. of Texas
———. 1992, ApJ, 386, 539
Wood, M. A., & Winget, D. E. 1988, in Multimode Stellar Pulsations, ed. G. Kovács, L. Szabados, & B. Szeidl (Budapest: Konkoly Observatory: Kultura), 199