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PULSATIONAL INSTABILITIES IN ACCRETING WHITE DWARFS

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ABSTRACT

The detection of *g*-mode pulsations in accreting white dwarfs (WDs) in cataclysmic variables (CVs) with a large range of effective temperatures ($T_{\rm eff}$) has shown these WDs to be a more diverse class than their isolated counterparts, the ZZ Ceti and DB pulsators. The simplest contrast of CV to isolated pulsators is an envelope of solar-like composition (of various helium enrichments if the donor is evolved) rather than pristine hydrogen or helium. A range of WD masses is expected, from low-mass He core WDs to massive WDs. We investigate the impact of this diversity on the range of $T_{\rm eff}$ for which *g*-modes are unstable. Motivated by earlier theoretical studies, we compare a fiducial *g*-mode period to the thermal time at the base of the convection zones created by H and first He (H/He I) ionization or second He (He II) ionization zones. We find that (for solar composition envelopes), relative to a fiducial WD mass 0.6 $M_\odot$, the blue edge for a 0.4 $M_\odot$ He core WD shifts downward by ≈1000 K, while that for a massive ≈1.2 $M_\odot$ WD shifts upward by ≈2000 K. Surprisingly, increasing Y by only 10% relative to solar creates an "intermediate" instability strip near 15,000 K.

Subject headings: binaries: close — gravitational waves — novae, cataclysmic variables — white dwarfs

1. INTRODUCTION

As they cool in isolation, WDs cross regions of pulsational instability and undergo nonradial oscillations, in particular, *g*-modes (see Gautschy & Saio 1996). Those with pure H atmospheres (DAV) cross the ZZ Ceti instability strip when $T_{\rm eff} \approx$ 11,000–12,000 K (see Mukadam et al. 2004; Gianninas et al. 2005), whereas those with pure He envelopes (DBV) become unstable when $T_{\rm eff} \approx$ 22,400–27,800 K (Beauchamp et al. 1999). The composition of these envelopes is rather pure, and the range of WD masses is that expected from isolated stellar evolution, favoring $M \approx 0.6\ M_\odot$. Careful analysis of the adiabatic pulsations for these WDs yields accurate measurements of the WD masses (M), shell masses, and spin (see, e.g., Bradley 2001 and Kepler et al. 2003).

The recent discoveries of similar period pulsations from accreting WDs in CVs provides us with a window to their internal properties. The accretion of $>0.1\ M_\odot$ over 10^9 yr impacts both the WD's rotation rate and mass, parameters easily diagnosed through seismic studies. Starting with the initial discovery (van Zyl et al. 2000) of three oscillation periods in the WD primary of GW Lib, there are now 10 (Warner & Woudt 2003; Woudt & Warner 2004; Araujo-Betancor et al. 2005; Patterson et al. 2005; Szkody et al. 2005; Vanlandingham et al. 2005; Gänsicke et al. 2006) pulsating WDs in CVs. These are all found in CVs below the period gap, where a quiescent spectrum shows evidence of a WD with $T_{\rm eff} < 25{,}000$ K (Sion 1991, 1999). Calculations of WD heating by prolonged accretion (Townsley & Bildsten 2004) explain the $T_{\rm eff}$ at these orbital periods, and they were employed for the first adiabatic analysis of GW Lib, yielding both the WD and accreted layer masses (Townsley et al. 2004).

We show here that the expected diversity of WD masses and accreted layer compositions (in particular, enriched He abundance from an evolved donor) in these systems will lead to a broad range of $T_{\rm eff}$ where WDs will pulsate. For example, low-mass He core WDs can pulsate at $T_{\rm eff} \approx 10{,}000$ K, well below the ZZ Ceti instability strip. The enhanced helium abundance from an evolved secondary can also push the instability strip as high as 20,000 K. These effects likely explain why many of the observed pulsators in CVs are "outside" the conventional ZZ Ceti strip appropriate to pure H envelopes (Szkody et al. 2002).

In § 2, we clarify the influence of WD mass and envelope composition on mode driving. Assuming that Brickhill's convective driving mechanism operates, we explore the depth of the convection zone as a function of composition and surface gravity. A near-solar mix of elements allows both H/He I and He II ionization zones, opening up additional frequency ranges for instability of hotter and/or rapidly rotating WDs. Section 3 contains a discussion of the expectations for the occurrence of He core WDs in CVs and explains why many CVs can have an evolved donor that provides He-rich material to the WD envelope. We close in § 4 by summarizing our new understanding and discussing future work.

2. GRAVITY WAVE EXCITATION

Accreting WDs consist of a geometrically thin, mostly nondegenerate accreted envelope overlying a degenerate core. The envelope composition (of mean molecular weight μ) is inherited from the donor star, while the core composition can be helium for low-mass ($<0.45\ M_\odot$) WDs or a mixture of carbon and oxygen for larger masses (0.6–1.1 $M_\odot$). A luminosity from "compressional heating" of accretion is generated deep in the envelope and core (Townsley & Bildsten 2004); hence, the luminosity is nearly constant at the shallow depths where mode driving (and damping) occurs.

The composition discontinuity at the base of the accreted envelope (where the temperature is T_b) separates the WD into two resonant cavities: the envelope and the core (Townsley et al. 2004). The highest frequency gravity wave (*g*-mode) lives mainly in the envelope (and has no radial nodes there) and has a frequency $\omega \sim (gH)^{1/2}k_\perp \sim 2\pi/(100\ {\rm s})$ (for $l = 2$), where H is the scale height at the base, $(gH)^{1/2} \simeq (k_{\rm B}T_b/\mu m_p)^{1/2}$ is roughly the sound speed at the base, and $k_\perp = [l(l+1)]^{1/2}/R$ is the horizontal wavenumber. Internal gravity waves trapped in the envelope have frequencies proportional to $1/n$, where n is the number of radial nodes there.

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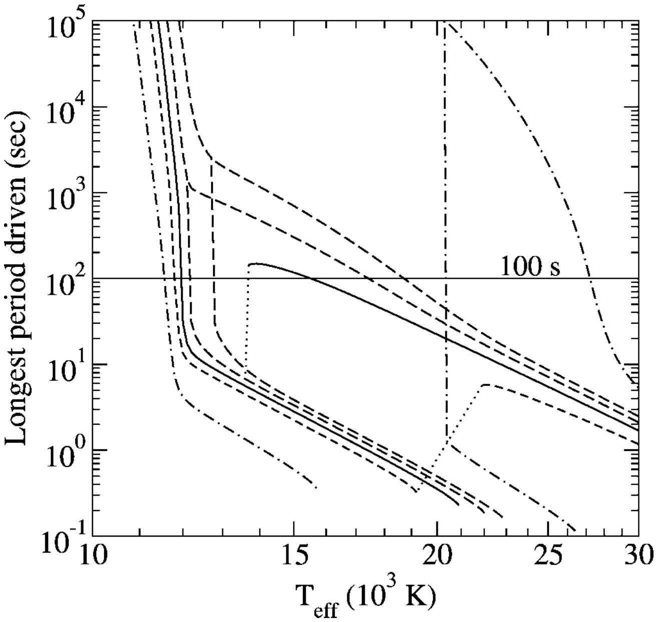

FIG. 1.—Longest period driven mode, $8\pi\tau_{\rm th,\,bcz}$, vs. $T_{\rm eff}$ for different H to He ratios, but fixed gravity $g = 10^8$ cm s^{-2} and metallicity $Z = 0.02$. A fiducial shortest period *g*-mode, shown at 100 s, is driven when the curve is above the horizontal line. There can be two convection zones associated with second He ionization (He II, *upper branches*), or first He ionization and/or H ionization (H/He I, *lower branches*). Lines are shown for $Y = 0.0$ (*leftmost dot-dashed line*), solar composition ($Y = 0.28$, *leftmost dashed line*), $Y = 0.38$ (*solid line*), 0.48 (*middle dashed line*), 0.58 (*rightmost dashed line*), and 0.98 (*rightmost dot-dashed line*). Dotted lines only connect related curves and do not represent convection zone boundaries.

Gravity waves become overstable when part of the escaping heat flux is converted into mechanical motion. This occurs near ionization zones, either due to a rapid outward increase in opacity in radiative zones ("the κ-mechanism"; Dziembowski 1977) or, more likely, due to a convection zone caused by such a rapid increase in opacity (Brickhill's "convective driving" mechanism; Brickhill 1983; Wu & Goldreich 1999). We focus on Brickhill's mechanism, where the key quantity is $\omega\tau_{\rm th,\,bcz}$, the product of the mode frequency and the thermal time, $\tau_{\rm th,\,bcz}$, at the base of the convection zone. When $\omega\tau_{\rm th,\,bcz} \gtrsim \frac{1}{4}$ (Wu & Goldreich 1999), the thermal adjustment time in the convection zone is longer than the mode period, and flux perturbations are absorbed by the convection zone, which is acting to put energy into the oscillation. In this Letter, we adopt the instability criterion $P \leq 8\pi\tau_{\rm th,\,bcz}$, where $P = 100$ s is the fiducial shortest period *g*-mode. We will not calculate the "red edge" $T_{\rm eff}$ of the instability strip, below which the pulsations are unobservable. For isolated DAVs, the instability strip is quite narrow (≈1000 K; Mukadam et al. 2004), and for DBVs, it is much broader (≈5000 K; Beauchamp et al. 1999). Finally, when two convection zones are present, we only consider driving by the inner convection zone as this most closely resembles the theory derived for the DAVs (Brickhill 1983; Wu & Goldreich 1999). However, driving may also be possible by the outer convection zone, if the radiative layer between the two convection zones does not contribute too much damping. We leave this issue for future studies.

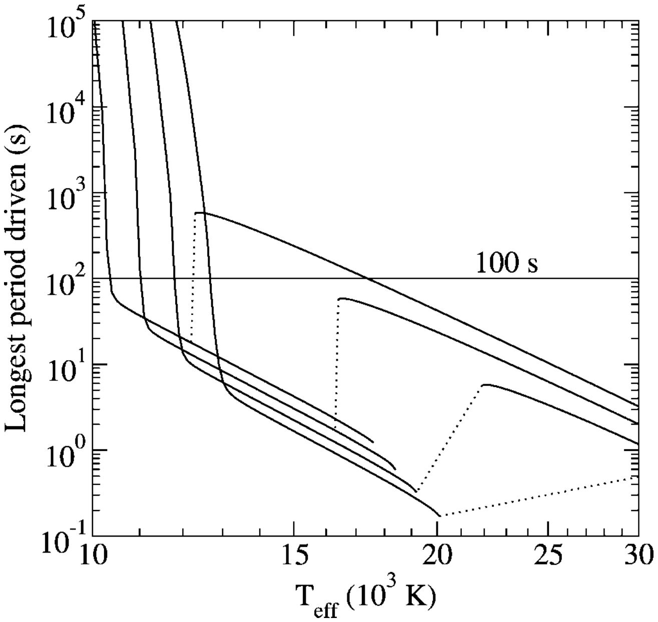

FIG. 2.—Longest period driven mode, $8\pi\tau_{\rm th,\,bcz}$, vs. $T_{\rm eff}$ for different gravity, but fixed (solar) composition $Y = 0.28$ and $Z = 0.02$. The gravity for each line is, from left to right at low $T_{\rm eff}$, $g = 10^{7.0}$, $10^{7.5}$, $10^{8.0}$, and $10^{8.5}$ cm s^{-2}. Dotted lines only connect related curves and do not represent convection zone boundaries.

The variation of $\tau_{\rm th,\,bcz}$ with g and Y is found by constructing atmosphere models that use the OPAL opacity and equation of state (Iglesias & Rogers 1996) with solar metallicity ($Z = 0.02$). These are plane-parallel, constant gravity and flux envelopes, using the ML 2 mixing-length prescription (Bergeron et al. 1992) in convective regions, in which the mixing length is set equal to the pressure scale height.

Figure 1 shows the longest driven mode period, $8\pi\tau_{\rm th,\,bcz}$, as a function of $T_{\rm eff}$ for $g = 10^8$ cm s^{-2} and a range of Y. At a given $T_{\rm eff}$ there can be two distinct convection zones: an outer convection zone due to H and first He ionization (H/He I) at short thermal times, and an inner convection zone due to second He ionization (He II) at long thermal times. The six different lines show $Y = 0$ to $Y = 0.98$, from left to right. For solar abundance ($Y = 0.28$, *leftmost dashed line*), we find that $8\pi\tau_{\rm th,\,bcz}$ exceeds 100 s for $T_{\rm eff} \lesssim 12{,}000$ K; the blue edge is not raised significantly by the addition of a solar fraction of He relative to a pure H atmosphere. At a solar He fraction, the inner He II convection zone is only present at high temperatures ($\gtrsim$22,000 K) and only drives $\ell \gg 1$ modes with periods $P \lesssim 10$ s, which are unobservable. However, increasing Y above solar, even by a moderate amount, has a dramatic effect on the He II convection zone. For $Y = 0.38$ (*solid line*), the inner He II convection zone is present down to $T_{\rm eff} \simeq 14{,}000$ K and raises the blue edge to near 16,000 K. We call this the "intermediate" instability strip.

The $Y = 0.38$ line also indicates a feature of mode driving in CV WDs, in which a single object can have two instability strips. The upper strip in $T_{\rm eff}$, arising from the He II convection zone, has a red edge determined by the truncation of the He II convection zone at lower $T_{\rm eff}$, rather than Brickhill's (1983) red edge due to a vanishing flux perturbation at the surface. Instability can then reappear at $T_{\rm eff} \lesssim 12{,}000$ K. This only occurs over a limited range of Y. At $Y = 0.48$ (*middle dashed line*), the He II convection zone is not truncated, and below the blue edge, it extends across $8\pi\tau_{\rm th} = 100$ s. Rather than the H/He I convection zone rising up to create another instability strip, the two convection zones merge when the radiative region between them disappears. The presence of H will, however, create an extremely wide instability strip by keeping the convection zone thin compared to the $Y = 0.98$ case (*right dot-dashed line*).

A similar experiment is shown in Figure 2, where g varies from $g = 10^{7.0}$ to $10^{8.5}$ cm s^{-2}, keeping a solar composition ($X = 0.7$, $Y = 0.28$, $Z = 0.02$). A gravity of $g = 10^{7.5}$ cm s^{-2} corresponds to a $M \approx 0.4\,M_\odot$ WD, while $g = 10^{8}$ cm s^{-2} gives $M \approx 0.6\,M_\odot$, and $g = 10^{9}$ cm s^{-2} gives $M \approx 1.2\,M_\odot$. As in Figure 1, the blue edge is the intersection of a curve, with the horizontal line representing the fiducial shortest period g-mode. As discussed by Arras et al. (2005), the blue edge for the H/He I ionization zone moves up (down) by ≈2000 K for a factor of 10 increase (decrease) in gravity. Hence, a blue edge range of ≈4000 K is expected from the lowest mass He core WD to the massive $\gtrsim 1.1\,M_\odot$ carbon/oxygen WD. In short, the range of WD masses expected in CVs should extend the H/He I instability strip to be both well above and below the isolated WD ZZ Ceti instability strip. For the He II ionization zone, note the appearance of the "intermediate" instability strip at ≈15,000 K for low-mass WDs. Since $\tau_{\rm th,\,bcz}$ decreases as g increases, the blue edge for He II ionization decreases with higher g. This behavior is the opposite of that found in the nearly pure He case, where $\tau_{\rm th,\,bcz}$ increases as g increases (see Fig. 3).

To elucidate the sensitivity of the blue edge to the wide range of gravities and enrichments possible for CV WDs, Figure 3 shows contours of constant blue edge $T_{\rm eff}$ in log g and Y space. At small Y, driving occurs due to the H/He I convection zone, while at large Y, driving is due to the He II convection zone. For low and moderate g, the transition occurs abruptly when the He II convection zone extends above 100 s, causing the blue edge to jump up by several thousand kelvins. The dashed line indicates the Y above which the He II convection zone is always present. As discussed above, there is a small region, indicated on the plot, where there are two separate instability strips. Dotted lines show the blue edge of the lower instability strip. We find that starting from solar abundance ($Y = 0.28$, *dot-dashed line*), g must be increased significantly, half an order of magnitude, in order to increase the blue edge $T_{\rm eff}$ by 1000 K. In contrast, a modest increase in Y can effect a very sharp increase in the blue edge. There are thus two types of accreting pulsators, those with a blue edge $T_{\rm eff} \gtrsim 15{,}000$ K that are slightly enriched and those closer to solar composition with a blue edge $T_{\rm eff} \lesssim 15{,}000$ K, more similar to normal ZZ Ceti stars. Observationally, these two instability strips may overlap in $T_{\rm eff}$ depending on the location of the red edge.

3. HELIUM ENRICHMENT IN EVOLVED CVs

Both theory and observation (see Townsley & Bildsten 2003) tell us that nonmagnetic CVs need to be below the period gap ($P_{\rm orb} \leq 2$ hr) to reach the $T_{\rm eff} < 25{,}000$ K range where pulsations are possible. This is indeed where the known pulsating WDs in CVs occur. We showed in the previous section that, due to the dependence on Y and g, the instability strips for accreting WDs will be richer than those in isolated DA or DB WDs.

The first type of diversity to consider is that of the WD mass. The expectation (see Howell et al. 2001, hereafter HNR) is that WDs below the period gap will have a large range of masses, even low-mass He core WDs ($M < 0.45\,M_\odot$). HNR's population synthesis showed that as many as 20% of the CVs with $P_{\rm orb} < 2$ hr will have low-mass He WDs. These will have surface gravities much lower than any of the isolated DAVs, for which the recent tabulations (Mukadam et al. 2004; Gianninas et al. 2005) show no DAV with log $g \leq 7.7$–7.8. The pulsator HS 2331+3905 has a low $T_{\rm eff} \simeq 10{,}500$ K (Araujo-Betancor et al. 2005), which from Figure 3 is quite reasonably inside the instability strip for a solar abundance with log $g \lesssim 7.5$. The inferred low mass of $0.4\,M_\odot$ makes HS 2331+3905 a candidate He core WD.

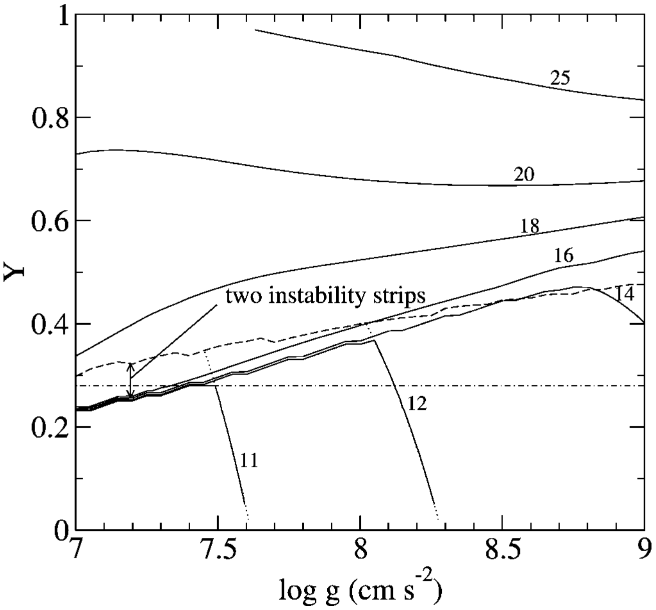

FIG. 3.—Contours of constant $T_{\rm eff}$ for the blue edge of the instability strip in gravity, log g, and helium mass fraction, Y. The blue edge is approximated by the $T_{\rm eff}$ for which $8\pi\tau_{\rm th,\,bcz} = 100$ s. For large Y, driving is due to the He II convection zone, while for small Y, it is due to the H/He I convection zone. The dashed line indicates the Y above which the He II convection zone is always present. The sudden increase of the blue edge with Y occurs where the He II convection zone reaches above 100 s. Between this and the dashed line, there will be two separate instability strips caused by the absence of the He II convection zone at some $T_{\rm eff}$. The blue edge of the lower instability strip is shown by the dotted lines. Solar composition, $Y = 0.28$, is indicated by the dash-dotted line.

The instability strip is also sensitive to the He abundance in the WD envelope. At accretion rates $\gtrsim 10^{-14}\,M_\odot$ yr^{-1} for $T_{\rm eff} \gtrsim 11{,}000$ K, there is no time for relative H/He separation (Paquette et al. 1986). Since even the small amount of quiescent disk accretion exceeds this rate, the envelope He abundance is set by the donor star. If the donors were unevolved, then the range would be narrow, $Y = 0.25$–0.3, depending only on the initial metallicity of the donor. However, Pylyser & Savonije (1989) raised the distinct possibility of initial donor masses for CVs with $M \geq 1\,M_\odot$, which, depending on the age of the system at the onset of mass transfer, could have undergone nuclear burning in the core to raise the He abundance. Such donors are required to explain supersoft sources as stably burning WDs (van den Heuvel et al. 1992). By the time such donors are below the period gap and fully convective, such a core He enrichment will be evident at the surface and in the accreting matter. This gives us a reason to explore the range of $Y = 0.3$–1.0.

The prevalence of evolved donors among CVs with $P_{\rm orb} <$ 8 hr depends on many factors, including the efficiency of the common envelope phase, the outcome of the rapid thermal timescale mass transfer expected at the onset of Roche lobe filling, and the nature of magnetic braking in the pre-CV stage (Schenker et al. 2002; Podsiadlowski et al. 2003; Andronov & Pinsonneault 2004; Kolb & Willems 2005). Podsiadlowski et al. (2003) performed a binary population synthesis calculation that allowed for evolved donors with a range of initial He abundances among initially massive ($M > M_\odot$) donors. They found that these could actually be the dominant population for $P_{\rm orb} > 5$ hr but that the large number of CVs injected at shorter orbital periods dilutes their fraction at shorter periods. Below the period gap, between 1 in 10 and 1 in 3 would have evolved companions with $Y > 0.5$. The previously discussed observables for evolved donors are of a later spectral type (at a fixed orbital period) and are composed of exposed material that is nitrogen-enhanced and carbon-poor due to the CN cycle. This latter hypothesis has been tested by Gänsicke et al. (2003) through measurements of UV line ratios in a diverse set of CVs, both above and below the period gap. They concluded that as many as 10%–15% of their sample could have evolved donors.

We are introducing here an additional probe of evolution, which is the impact of the He abundance on the instability strip. More evolved donors will show pulsators at hotter $T_{\rm eff}$ than those that are unevolved. In the absence of more detailed population study predictions of the He abundance (typically calculated but not reported in depth since, until now, no observational probe of He abundance was available), we can say very little. For mass transfer stability, the donor stars for a He core WD should be initially low mass and thus unevolved. Hence, the correct low gravity models to consider are $Y =$ 0.25–0.3, but no higher. In the opposite sense, we expect highly evolved donors to have preferentially more massive WDs. Whether these correlations lead to a range of $T_{\rm eff}$ or other correlations remains to be seen.

4. CONCLUSIONS AND FUTURE WORK

We have shown that detecting pulsations in accreting WDs below the period gap promises to reveal the diversity expected in both the WD masses and the accreted He abundance. We do not expect one instability strip, as known for isolated DA WDs, but rather a revealing diversity of $T_{\rm eff}$. In particular, hot CV primaries like that in GW Lib with $T_{\rm eff} \simeq 14{,}000$ K can pulsate due to enhanced helium abundance or extreme surface gravity (large or small). Cool CV primaries like that in HS 2331+3905 with $T_{\rm eff} = 10{,}500$ K can pulsate due to low surface gravity. Both of these possibilities are naturally present in the diversity expected within the population of CVs. Indeed, some systems can have two separate instability regions in $T_{\rm eff}$.

Little is known with certainty about the WD mass distribution, but evolutionary models can provide us with a reasonable expectation for the level of helium enrichment of the accreted material. CVs in which the companion is the remaining core of a slightly evolved star can have significantly enriched He. Below the period gap, between one in 10 and one in three CVs should have evolved companions with $Y > 0.5$ (Schenker et al. 2002; Podsiadlowski et al. 2003).

Important work that remains to be done is the validation of our assumption that the numerical factor relating $\tau_{\rm th,\,bcz}$ to the driven mode period does not vary significantly with either g or Y. A large variation (more than unity) is not expected, but quantifying this is necessary for using the presence or absence of modes to constrain properties of particular systems. Additional damping due to the opacity effects of metals in the radiation zone may affect this prefactor, shifting the blue edges evaluated here to lower $T_{\rm eff}$. Inefficient convection in surface layers would decrease the rate of convective driving, causing the blue edge to shift downward.

The WDs in CVs are expected to be rotating rapidly due to the angular momentum gain from long-term disk accretion. This can qualitatively change the frequency spectrum of nonradial oscillations. Dziembowski (1977) showed that g-modes with large numbers of angular nodes, and hence large frequencies, can be driven even in relatively hot WDs by the κ-mechanism acting in the He II ionization zone. Such modes are unobservable in nonrotating stars due to averaging over the stellar disk. Rotationally modified g-modes, which are squeezed into an equatorial band, may be both unstable and observable, since they can have large horizontal wavenumbers (and frequencies) for a small number of angular nodes.

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