HUBBLE SPACE TELESCOPE SPECTRA OF GW LIBRAE: A HOT PULSATING WHITE DWARF IN A CATACLYSMIC VARIABLE

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ABSTRACT

We have obtained Hubble Space Telescope UV spectra of the white dwarf in GW Lib, the only known nonradially pulsating white dwarf in a cataclysmic variable and the first known DAZQ variable. The UV light curve reveals large-amplitude (10%) pulsations in the UV with the same periods (646, 376, and 237 s) as those seen at optical wavelengths, but the mean spectrum fits with an average white dwarf temperature (14,700 K for a 0.6 \( M_\odot \) white dwarf) that is too hot to be in the normal instability strip for ZZ Ceti stars. A better fit is achieved with a dual-temperature model (with 63% of the white dwarf surface at a temperature of 13,300 K and 37% at 17,100 K) and a higher mass (0.8 \( M_\odot \)) white dwarf with 0.1 solar metal abundance. Since the blue edge of the instability strip moves to higher temperature with increasing mass, the lower temperature of this model is within the instability strip. However, the presence of accretion likely causes abundance and atmospheric temperature differences in GW Lib compared to all known single white dwarf pulsators, and the current models that have been capable of explaining ZZ Ceti stars may not apply.

Subject headings: novae, cataclysmic variables — stars: individual (GW Librae) — stars: oscillations — ultraviolet: stars

1. INTRODUCTION

With the discovery (van Zyl et al. 2000) of GW Lib as the first nonradially pulsating white dwarf in a cataclysmic variable (CV), asteroseismology could be applied, for the first time, to understand the internal structure of an accreting white dwarf. However, GW Lib does not easily relinquish its secrets. The six optical observing runs of van Zyl et al. (2002, hereafter VZ2002) showed that the pulsation spectrum was highly unstable on timescales of months, which is common in cool, hydrogen atmosphere white dwarf pulsators (ZZ Ceti stars or DAVs). While they could identify clusters of signals with very close (2 s) spacing, and some frequencies that were repeatedly present in the optical runs (periods of 236, 376, and 648 s), they could not disentangle the various modes to interpret the pulsations. The presence of fine-structure, linear combination modes and changes in modes on monthly timescales all indicate that, in the optical at least, GW Lib is typical of ZZ Ceti stars. However, cool pulsators usually have the largest amplitudes. The relatively low amplitude of oscillation (5–17 mmag) in GW Lib could be due to some dilution of the white dwarf optical light by an accretion disk. VZ2002 concluded that they would need a much longer baseline of data (e.g., Kleinman et al. 1998) to solve the problem.

Since GW Lib is too faint for a Whole Earth Telescope (Nather et al. 1990) campaign, a consortium of larger telescopes will be needed to make progress from the ground. But the UV offers unique opportunities, as the white dwarf usually contributes close to 100% of the light in this portion of the spectrum for low mass accretion rate systems (Szko\-dy et al. 2002b, hereafter S2002b), and comparison of the UV and optical amplitudes of pulsation can identify the modes of DAVs (Robinson et al. 1995, hereafter R1995; Nitta et al. 2000, hereafter N2000). Thus, GW Lib became an integral part of our Hubble Space Telescope (HST) study of white dwarfs in short-period dwarf novae. This project uses the Space Telescope Imaging Spectrograph (STIS) to obtain UV spectra that can be modeled to determine the temperature, gravity, mass, rotation, and composition (see Gän\-sicke et al. 2001; Howell et al. 2002; S2002b; Szkody et al. 2002a, hereafter S2002a for results).

GW Lib is one of the WZ Sge–type dwarf novae with very infrequent and extreme amplitude outbursts (Howell, Szkody, & Cannizzo 1995, hereafter HSC1995). Its only known outburst occurred in 1983 (Duerbeck 1987). Recent ground-based time-resolved spectra (Szko\-dy, Desai, & Hoard 2000, hereafter SDH2000) revealed an orbital period near 79 minutes, one of the shortest of disk accreting CVs (Warner 1995). Subsequent data with longer time coverage refines this period to 76.78 minutes (Thorstensen et al. 2002). The optical spectra show broad absorption troughs (from the white dwarf) surrounding narrow Balmer emission lines (from the low-inclination disk), consistent with a low mass transfer rate system. SDH2000 fitted the absorption with an 11,000 ± 1000 K white dwarf at a distance of 114 pc. This temperature was within the general location of the ZZ Ceti instability strip (11,200–12,900 K; Koester & Holberg 2001, although the edges vary slightly with different authors) but dependent on the estimated disk contribution to the optical

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1 Based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under NASA contract NAS 5-26555.
TABLE 1

| Orbit | UT Start | Time (s) |
|-------|----------|----------|
| 1     | 01:52:00 | 2105.19  |
| 2     | 03:14:04 | 2603.19  |
| 3     | 04:50:15 | 2603.20  |
| 4     | 06:26:25 | 2580.20  |

light. Surprisingly, the HST data reveal a much hotter white dwarf as well as the first known DAZQ variable.

2. OBSERVATIONS

HST was scheduled to observe GW Lib for four successive orbits using the STIS G140L grating and the 52" × 0.2 aperture to obtain wavelength coverage from 1150 to 1720 Å with a resolution of 1.2 Å. Problems with guide star or target star acquisitions resulted in two failed observations, but the third attempt on 2002 January 17 was successful (Table 1). The data comprise complete coverage of the binary orbit but are interrupted owing to the low Earth orbit of HST. An optical spectrum obtained at Apache Point Observatory on January 9 showed GW Lib was deep in quiescence, similar to the past data in SDH2000.

The data from the four orbits were combined into a single spectrum (Fig. 1). This spectrum shows the typical broad Lyα absorption from the high-gravity atmosphere of a white dwarf, the quasi-molecular H2 absorption at 1400 Å that is indicative of temperatures below 18,000 K, as well as a whole range of narrow photospheric low-ionization absorption lines (C i and II at 1280, 1335, and 1657 Å, O i at 1300 Å, Si II at 1260, 1300, and 1530 Å, and Al II at 1670 Å). One strong absorption feature near 1355 Å remains unidentified. The presence of metals means that the white dwarf in GW Lib is a DAZQ (Sion et al. 1983) and different than ZZ Ceti stars that have pure H compositions. It is noteworthy that the H2 absorption feature at 1600 Å is typically present in CV white dwarfs at temperatures below 13,000 K (S2002a) and that is evident in the ZZ Ceti star BPM 37093 (N2000; see Fig. 1) is absent. In addition, the typical high-excitation emission lines observed in low-M CVs are present, even though relatively weak (He II at 1640 Å, C III and IV at 1175 and 1550 Å, N V at 1240 Å, and Si III and IV at 1206 and 1400 Å).

The data were acquired in time-tag mode, and a background-subtracted light curve was constructed using all source photons except for a small region around Lyα (Fig. 2). This light curve shows evidence for strong and multiple periodicities.

3. PULSATION

The Fourier transform of the light-curve data (Fig. 3) shows significant power at three periods (646, 376, and 237 s with FWHM of ~7 s). These periods are identical to those seen in the optical (VZ2002), but the amplitudes in the UV are much higher (Table 2 summarizes the UV and optical pulses). According to Kleinman (1999), DAVs come in two period groupings; hot DAVs and cool DAVs. Both types show periods with ~50 s spacing spanning 120–360 s (hot) and 300–650 s (cool). Only one DAV is known (G29-38) that has observed periods spanning the entire hot-cool range. Kleinman presents a compilation of the available DAV periods together with the results for a 0.6 \( M_\odot \) (hydrogen layer mass of \( 10^{-4} M_\odot \)) DAV model by Brassard et al. (1992) for a series of \( I = 1 \) modes. The model periods generally match those observed in both the hot and cool
DAVs. The periods observed in GW Lib, like those in G29-38, span the entire period range and approximately agree with both hot and cool DAV periods. G29-38 is a poorer match at the shortest (hot) periods, while GW Lib does well at both long (646 s) and short (236 s) periods and is within 2 $\sigma$ of the model period at 389 s.

R1995 and N2000 have previously used HST and optical data together with the fact that the pulsation amplitude ratio at different wavelengths is solely a function of the spherical harmonic index $l$ to attempt mode determination for two single DAVs. From HST High Speed Photometer filter observations at 1570 and 5500 Å, R1995 were able to use the observed pulse amplitude ratio of $\sim$6 for these wavelengths to obtain a nice match to an $l = 1$ (dipole) mode model for the 12,500 K, $\log g = 8$ white dwarf in G117-B15A. N2000 used our instrumental setup of STIS with G140L and found amplitudes near 1500 Å of 4–16 times the optical amplitudes for the different pulsation periods in BPM 37093 (the most massive white dwarf pulsator known with $\log g = 8.7$ and $T = 11,500$ K). While they could rule out $l \geq 3$ modes, the wavelength dependence of the different periods did not allow a clear mode identification. Although the best results are obtained for simultaneous HST and optical observations (since the pulsation amplitudes are known to vary in the optical, VZ2002), we can obtain some estimate for GW Lib from the available nonsimultaneous data, since the UV and optical periods are the same. Table 2 shows that the ratio of the UV/optical amplitudes ranges from 6 to 17, similar to the data on G117-B15A and BPM 37093 but contrary to the models that show decreasing amplitude ratios for higher temperatures (R1995). Thus, at least in observed periods and the UV/optical amplitude ratio, GW Lib is similar to single pulsating white dwarfs.

### TABLE 2

| Period (s) | Amplitude (%) | Period (s) | Amplitude (%) |
|-----------|---------------|-----------|---------------|
| 646       | 10            | 648       | 0.6–1.75      |
| 376       | 7             | 376       | 0.5–1.1       |
| 237       | 7             | 236       | 0.6–0.8       |

* Values from VZ2002.
* $A = 2P^{1/2}/\text{mean}$, where $A$ is amplitude and $P$ is power spectrum.

4. SPECTRAL FIT

Fitting white dwarf model spectra (Hubeny & Lanz 1995) to the mean STIS spectrum of GW Lib, assuming a canonical white dwarf mass of $M_{\text{WD}} \approx 0.6 M_{\odot}$ ($\log g = 8$) results in $T_{\text{WD}} = 14,700$ K, 0.1 times solar metal abundances, and in a distance of 171 pc. Using 0.15 for the fraction of the accretion energy that would go into heating the white dwarf (Sion 1985), the resulting accretion rate for this temperature and white dwarf mass would be $4 \times 10^{-11}$ $M_{\odot}$ yr$^{-1}$, a value consistent with the low accretion rate of tremendous outburst amplitude dwarf novae (HSC1995).

While the fit is acceptable in the continuum and in the wings of Ly$\alpha$, there are clear deviations around 1400 Å and in the core of Ly$\alpha$ (Fig. 1). The quality of fit increases significantly ($\chi^2$ decreases from 3.8 to 2.0) if a two-temperature model is used, allowing for a variation of the temperature over the white dwarf surface. Again assuming $\log g = 8$, the best fit is achieved for $T_{\text{low}} = 13,300$ K and $T_{\text{high}} = 17,000$ K, comprising 80% and 20% of the white dwarf surface, respectively. While a dual-temperature approach could in principle explain the match of the periods of GW Lib to those of both hot and cool DAVs, the most surprising result from these spectral fits is that GW Lib is pulsing at all, as both $T_{\text{low}}$ and $T_{\text{high}}$ are located out of the traditional instability strip for ZZ Ceti stars! It is perhaps not so surprising that an accreting white dwarf should have an internal structure different than single white dwarfs, but as noted earlier, the similarity of the periods and UV/optical amplitude ratios does imply a similar pulsation mechanism and hydrogen layer mass in GW Lib and single DAVs.

Bradley & Winget (1994) have explored the dependence of the blue edge of the instability strip on stellar mass, on the hydrogen and helium layer masses, and on convection. While there was little change with H/He layer masses, they found the blue edge of the instability strip moves to higher temperatures for increasing convective efficiency and increasing stellar mass. With their highest mass models ($0.8 M_{\odot}$) and efficient convection (ML3), the blue edge reaches 13,500 K. Thus, our two-temperature white dwarf could be in the instability strip if it has a higher mass than normal for single DAVs. To explore this further, we fit our spectrum with an $0.8 M_{\odot}$ (or $\log g = 8.4$) white dwarf at a distance of 148 pc (Table 3). The 0.8 $M_{\odot}$ model results in a hotter (15,500 K) single-temperature white dwarf (which would remain outside the instability strip unless the Bradley & Winget model was extrapolated to the Chandrasekhar limit) or a two-temperature white dwarf with 63% at 13,300 K and 37% at 17,100 K (fit shown in Fig. 4). Taking the results of the 0.8 $M_{\odot}$ two-temperature fit at face value, the majority of the white dwarf surface has a temperature that is within the ZZ Ceti instability strip. Thus, a higher mass can resolve the dilemma of pulsation, but the origin and effect

### TABLE 3

| Model | $M_{\text{eff}}$ ($M_{\odot}$) | $T$ (K) | Surface (%) | $\chi^2$ |
|-------|-----------------------------|---------|-------------|---------|
| Single-temperature | 8.0 | 0.6 | 14,700 | 100 | 3.8 |
| Dual-temperature | 8.0 | 0.6 | 13,300 + 17,000 | 20 + 20 | 2.0 |
| Single-temperature | 8.4 | 0.8 | 15,500 | 100 | 3.6 |
| Dual-temperature | 8.4 | 0.8 | 13,300 + 17,100 | 63 + 37 | 1.9 |

FIG. 4.—Best two-temperature model fit to the data, for a $\log g = 8.4$ ($0.8 M_{\odot}$) white dwarf. The two temperatures are 13,300 K from 63% of the white dwarf surface and 17,100 K from 37% of the white dwarf surface. The emission lines are approximated by Gaussians.
of the dual temperatures remains to be explained. Rather than a multitemperature surface, the dual temperatures may be related to averaging over a temperature change during the pulsation. Ongoing work on phase-resolving the time-tag spectra at the pulsation periods should provide clues to the correct interpretation.

It is also possible that the dual temperatures could be due to a hot accretion spot on a magnetic, spinning white dwarf. Using the Si and C lines at 1335, 1527, 1533, and 1657 Å, we find a lower limit on the white dwarf rotation of \( v \sin i < 300 \text{ km s}^{-1} \), typical for the white dwarfs in CVs (S2002b). While this allows us to rule out large rotation velocities, the low resolution of the G140L grating does not allow us to eliminate any of the observed pulsation periods or fine structure (VZ2002) in the periods as due to rotation. Overall, the instability of the periods and the inability to explain them all with spin/beat interactions does not support a magnetic interpretation for the observed periods, but it is possible that there is some contaminating influence on the pulsation period structure due to interaction of the binary and spin periodicities. It will certainly require further observations, especially at X-ray wavelengths, to sort out this complication in addition to the usual pulsation structure.

5. CONCLUSIONS

Our STIS data on the only apparent nonradial pulsator in an accreting close binary show that the pulsations in the UV are of large amplitude and have the same periods as seen in the optical. These periods match with those evident in both hot and cool single nonradially pulsating DA’s, implying general similarities in structure to single ZZ Ceti stars, whereas the UV spectrum indicates a DAZQ white dwarf with an inhomogenous temperature distribution over its surface, or with a change in temperature during its pulsation. The average UV/optical pulse amplitude ratio is similar to what has been observed and predicted for DAVs in the \( l = 1 \) mode. While the fit of the spectrum to white dwarf models substantiates a dual-temperature structure (13,300 K from 63% of the white dwarf surface and 17,100 K from 37% of the surface), both temperatures are hotter than evident for known single DAVs of 0.6 \( M_\odot \). However, the cooler of the two temperatures is within the instability strip for more massive white dwarfs (\( \geq 0.8 \ M_\odot \)). Thus, GW Lib may represent a system containing a more massive and spotted white dwarf as compared to typical single DAVs. The mass difference may help to explain why other white dwarfs in CVs that contain similar or cooler temperatures than GW Lib are not pulsating—e.g., HV Vir, EG Cnc, VY Aqr (S2002a; Howell et al. 2002). The identification of GW Lib begs for time-dependent, nonadiabatic, nonradial pulsation models of white dwarfs undergoing accretion at a low rate.

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