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GW LIBRAE: STILL HOT EIGHT YEARS POST-OUTBURST

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ABSTRACT

We report continued *Hubble Space Telescope* (*HST*) ultraviolet spectra and ground-based optical photometry and spectroscopy of GW Librae eight years after its largest known dwarf nova outburst in 2007. This represents the longest cooling timescale measured for any dwarf nova. The spectra reveal that the white dwarf still remains about 3000 K hotter than its quiescent value. Both ultraviolet and optical light curves show a short period of 364–373 s, similar to one of the non-radial pulsation periods present for years prior to the outburst, and with a similar large UV/optical amplitude ratio. A large modulation at a period of 2 hr (also similar to that observed prior to outburst) is present in the optical data preceding and during the *HST* observations, but the satellite observation intervals did not cover the peaks of the optical modulation, and so it is not possible to determine its corresponding UV amplitude. The similarity of the short and long periods to quiescent values implies that the pulsating, fast spinning white dwarf in GW Lib may finally be nearing its quiescent configuration.

Key words: stars: dwarf novae – stars: oscillations (including pulsations)

1. INTRODUCTION

GW Librae was known as an ordinary low accretion rate dwarf nova with infrequent large amplitude outbursts (Gonzalez & Maza 1983) and a very short orbital period of 76.78 minutes (Thorstensen et al. 2002), until it became highlighted as the first accreting white dwarf in a cataclysmic variable to show non-radial pulsations (Warner & van Zyl 1998). Further monitoring at quiescence over several years revealed relatively stable pulsations at 648, 376, and 236 s (van Zyl et al. 2000, 2004) and *Hubble Space Telescope* (*HST*) ultraviolet observations showed the same periods with higher amplitudes (Szkody et al. 2002), consistent with the source of the variation being modulation of the temperature of the white dwarf photosphere (Robinson et al. 1995). The temperature of the white dwarf in GW Lib at quiescence was determined from the *HST* spectra to be near 15,000 K (for log $g = 8$). Although this temperature is outside the normal instability strip for ZZ Ceti pulsators with a pure hydrogen atmosphere, it is within the instability strip(s) for accreting white dwarf pulsators that have an atmosphere with a solar composition (Arras et al. 2006).

In 2007 April, GW Lib underwent a second outburst of 9 mag (Templeton et al. 2007), the largest known for any dwarf nova. Subsequent optical and ultraviolet observations have provided a long-term record of the impact of this large outburst amplitude on the white dwarf. The heating/cooling and its effect on the white dwarf pulsations have now been followed for 8 years. Ground-based optical observations were available over most years (Copperwheat et al. 2009; Schwieterman et al. 2010; Bullock et al. 2011; Vican et al. 2011; Szkody et al. 2012; Chote & Sullivan 2016), and ultraviolet monitoring took place with *GALEX* in 2007–2010 (Bullock et al. 2011) and with *HST* in 2010, 2011 (Szkody et al. 2012), and 2013 (Toloza et al. 2016). Both of these wavelength regions showed some interesting and surprising results.

In the optical, a period of 296 s was marginally detected on one night in 2008 June (Copperwheat et al. 2009) at the 10 millimodulation amplitude (mma) level. The next time this short period (280–290 s) was seen was in optical data obtained in 2010 March, 2011 April, and 2012 May (Szkody et al. 2012; Chote & Sullivan 2016) with amplitudes of 9 mma, and in *HST* ultraviolet data in 2010 March and 2011 April with amplitudes of 20 and 50 mma, respectively. Strong signals (25 mma) at 19 minutes were evident in optical data obtained by several groups throughout 2008 March–July, but then this period disappeared until its reappearance in 2012 April–June (Chote & Sullivan 2016) at the 50 mma level. An even longer period at about 2 hr was identified prior to outburst (Woudt & Warner 2002; Hilton et al. 2007; Copperwheat et al. 2009), and strong modulations at periods of 3–4 hr were observed after outburst in both optical and *GALEX* UV data (Schwieterman et al. 2010; Bullock et al. 2011; Vican et al. 2011; Chote & Sullivan 2016; Toloza et al. 2016).

The temperature of the white dwarf as determined from *HST* spectra is a function of the gravity (mass) assumed. Recently, Toloza et al. (2016) reanalyzed all of the available *HST* spectra of GW Lib using a common log $g = 8.35$, which is consistent with the most recent mass estimates of 0.8 $M_{\odot}$ (van Spaandonk et al. 2010; Szkody et al. 2012). They obtained values of 14,695 K from the 2002 quiescent data, as well as 17,980 K in 2010 and 15,915 K in 2011 for the 3 and 4 year post-outburst data. Each of these values showed a 500 K variation in temperature in the spectra phased at the peak versus the troughs of the short period pulsations that were present. Surprisingly, the three orbits of *HST* data in 2013 showed much larger changes in flux (a factor of 2) and temperature (15,975–18,966 K), with a mean temperature (16,937 K) larger

[7] Based on observations obtained with the Apache Point Observatory (APO) 3.5 m telescope, which is owned and operated by the Astrophysical Research Consortium (ARC).

Table 1
Summary of 2015 April Observations

UT Date	Obs	Instr.	Time	Exp (s)
21	APO	DIS	06:42–07:03	2x600
21	APO	Agile	07:42:26–11:42:26	20
21	UCMJO	Puoko-nui	12:59:30–13:32:00	30
21	AAVSO	CCD	11:52:49–16:15:05	120
22	*HST*	COS	05:02:20–05:38:20	time-tag
22	*HST*	COS	06:31:40–07:16:50	time-tag
22	*HST*	COS	08:07:10–08:52:20	time-tag
22	APO	Agile	06:58:28–08:49:11	20
22	UCMJO	Puoko-nui	09:16:30–10:45:00	30

than the 2011 data. The large flux changes appeared to be related to the 4 hr variability that was evident at that time.

In order to continue to monitor GW Lib during its return to quiescence, we obtained further *HST* and optical observations in 2015.

2. OBSERVATIONS

Once the *HST* date was set, ground-based observations were coordinated with nights before and during the observation. The observations obtained are summarized in Table 1.

2.1. *HST* Data

Three *HST* orbits on April 22 were used to collect data with the Cosmic Origins Spectrograph (COS) using the G140L grating in time-tag mode. Useful spectra were obtained in the range 1130–2020 Å with a resolution of about 0.75 Å. Light curves were created by summing the fluxes over all of the continuum wavelengths in this range in 5 s bins, leaving out the strong geocoronal emission line of Lyα and the strong CIV emission line from GW Lib. These light curves were then divided by the mean and one was subtracted so that a fractional amplitude scale was produced that could be used for Discrete Fourier Transform (DFT) period analysis. The amount of noise was determined by using a shuffling technique to find a 3σ limit (see Szkody et al. 2012 for further details).

2.2. Optical Data

The American Association of Variable Star Obervers (AAVSO) posted alerts and monitored the optical brightness prior to the *HST* observations to ensure that the system remained at quiescence. The mean magnitude during April was 16.7. Optical photometry was accomplished on April 21 and 22 using the 3.5 m telescope at Apache Point Observatory (APO) and the 1 m telescope at the University of Canterbury Mt. John Observatory (UCMJO). Instruments at both places incorporated similar frame transfer CCDs with negligible time lost to readout, and a BG-40 broadband blue filter: Agile at APO (Mukadam et al. 2011) and Puoko-nui at UCMJO (Chote et al. 2014). Cloudy weather resulted in lower-quality data at APO on April 22 compared to April 21.

The APO optical reductions were accomplished using standard IRAF[8] routines to extract sky-subtracted light curves from the CCD frames using weighted circular aperture photometry (O'Donoghue et al. 2000). For the short period analysis of the APO data, the light curves were converted to fractional amplitude in the same manner as for the *HST* data. The UCMJO data utilized the reduction pipeline tsreduce described in Chote et al. (2014).

Spectra were obtained on 2015 April 21 using the Double Imaging Spectrograph (DIS) at APO. The high-resolution grating was used to provide simultaneous blue and red spectral coverage with a resolution of 0.6 Å pixel^{-1} for blue wavelengths of 4000–5000 Å and red wavelengths of 6000–7200 Å. Flux standards and HeNeAr lamps were used for calibration and the IRAF tasks under *ccdproc*, *apall* and *onedspec* were used to correct the images, extract the spectra to 1-d and calibrate them.

3. RESULTS

3.1. *HST* Ultraviolet and APO Optical Spectra

Figure 1 shows the average spectrum from the three *HST* orbits in 2015 overplotted on the average of the three orbits from 2013. These average spectra separated by two years are very similar. Using the same procedure to fit the average spectrum in 2015 as was done for all of the previous data (Toloza et al. 2016) results in a mean temperature of 17560 $\pm$ 9 K. This implies that the white dwarf has still not returned to quiescence eight years after its outburst. The optical spectrum obtained 24 hr prior to the *HST* spectra is shown in Figure 2. The overall spectral shape is similar to the quiescent spectra taken with the same spectrograph (Szkody et al. 2000) while the blue fluxes are between the quiescent values and those obtained in 2010 (Szkody et al. 2012). The FWZI of Hβ (20 Å) is wider while the equivalent width (18 Å) is smaller than quiescent values, numbers that are consistent with a higher-temperature white dwarf and a larger contribution from the inner, higher-velocity disk regions.

3.2. Optical and UV Light Curves

The optical light curves from APO, UCMJO, and the AAVSO, as well as the UV light curve constructed from the *HST* spectra are shown in Figure 3. Constants were added to the magnitudes of the APO, UCMJO, and *HST* light curves to bring them all to the approximate AAVSO magnitude for each night. The optical data show a consistent 20% amplitude modulation at 2 hr that persists from the preceding night through the time of the *HST* observations. While the UV shows a mean change of about 10% over the 3 orbits, the times of peak optical flux unfortunately did not fall into the *HST* observation windows. Thus, it is impossible to tell if the large increase seen in the 2013 UV data existed in 2015. However, the length of the large UV flux increase in 2013 was at least 100 minutes and the gaps in the 2015 data are only about 50 minutes, and so some increase should have been visible if the same phenomenon was present. The optical, and especially the UV, light curves do show the presence of a shorter timescale variation.

3.3. Optical and UV Pulsations

The DFT results are shown in Figure 4 for the UV data and Figures 5 and 6 for the APO data obtained on April 21 and simultaneous with *HST* on April 22. All of the data sets show a significant period between 364 and 373 s, which is one of the

[8] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, under cooperative agreement with the National Science Foundation.

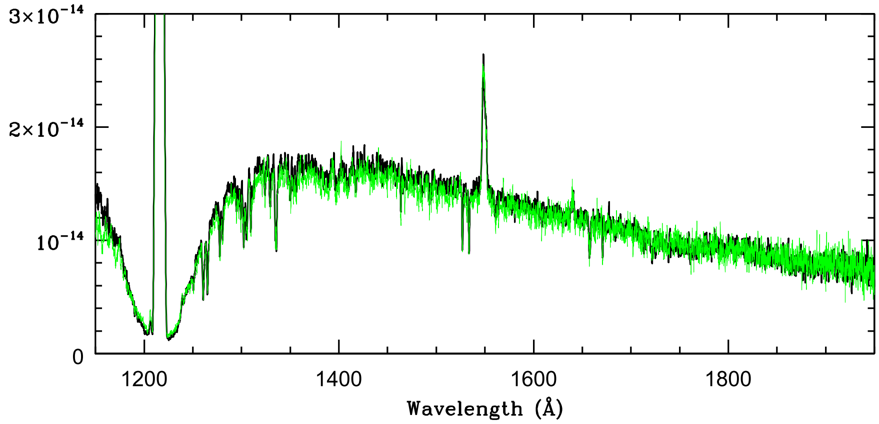

Figure 1. Average 2015 April COS spectra from three orbits (black) overplotted on the average 2013 May COS spectra from three orbits (green). Vertical axis is F_λ in units of erg cm^{-2} s^{-1} $\mathrm{Å}^{-1}$.

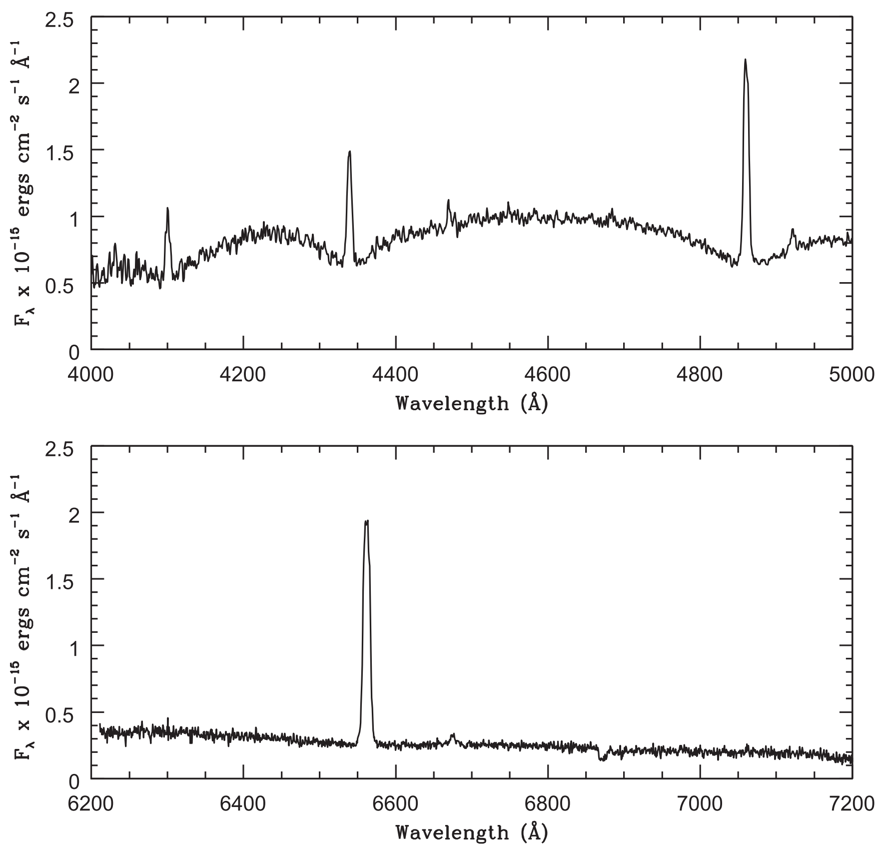

Figure 2. DIS blue and red spectra obtained April 21 showing the typical Balmer emission lines flanked by absorption from the white dwarf.

periods that is visible before the 2007 outburst. The UV/optical amplitude ratio is $100/15 = 6.7$, a ratio similar to that observed at quiescence for the 376 s period (Szkody et al. 2002).

4. DISCUSSION

Prior studies have addressed the question of the origin of the three main periodicities visible after the outburst. While the short 280–370 s periods are usually ascribed to a non-radial pulsation mode, the origin of the intermittent longer periods at 19 minutes and 2–4 hr have been harder to interpret as due to pulsations or quasi-periodic oscillations of the accretion disk. The Chote & Sullivan (2016) observations obtained over a timescale of 3 months in 2012 and their interpretation support a pulsation mode for the 19 minute period. Their arguments hinge on the similarity of the period between 2008 and its return in 2012, and the similarity of the behavior of the period (amplitude modulation and slight frequency shifts) to that seen in cool DAV stars (Kleinman et al. 1998) and to the flare events that repeat every few days in DAV white dwarfs recently reported by Bell et al. (2015) and Hermes et al. (2015).

Toloza et al. (2016) also argue that the 2–4 hr modulation that appears and disappears is related to pulsations. They fit the large amplitude of the variation with an increase in the

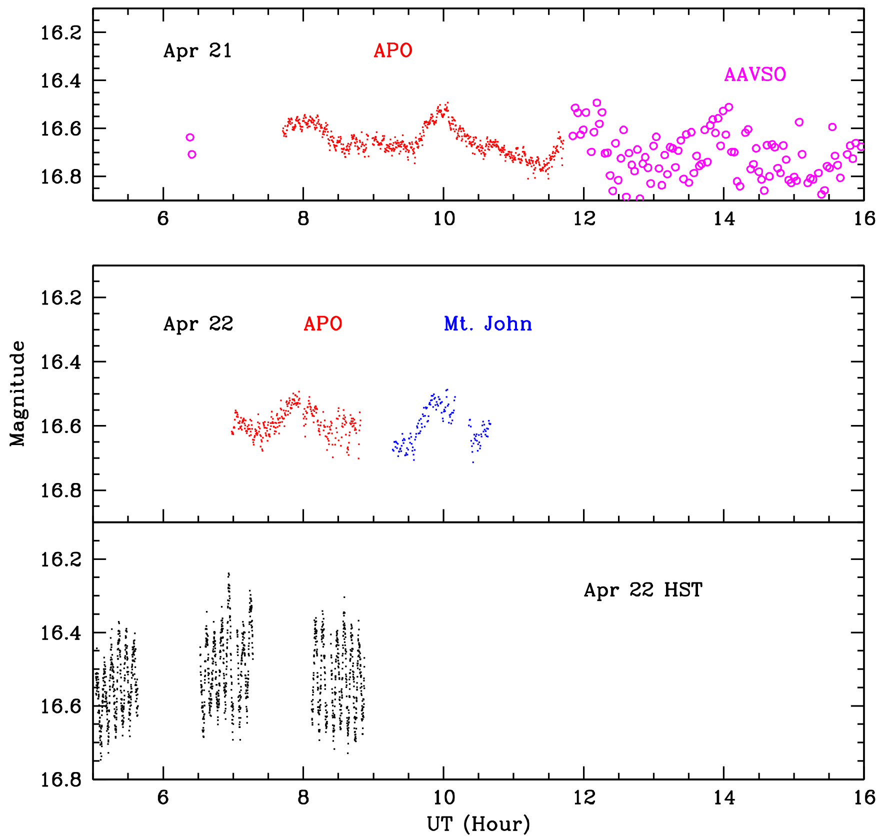

Figure 3. Light curves in the optical and UV for April 21 and 22. The dense red points are from APO, the open magenta points are AAVSO data, the blue are UCMJO, and the black are *HST*.

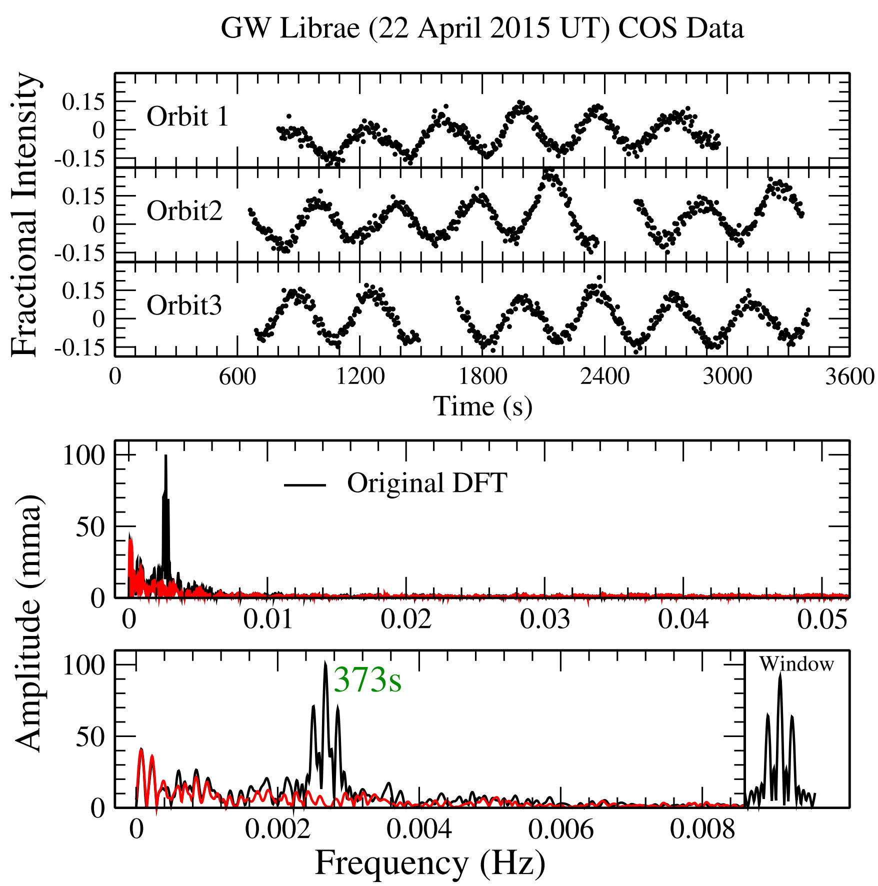

Figure 4. Intensity light curves (top) and DFT for the UV data from three *HST* orbits on April 22. Bottom is an expanded area around the main period.

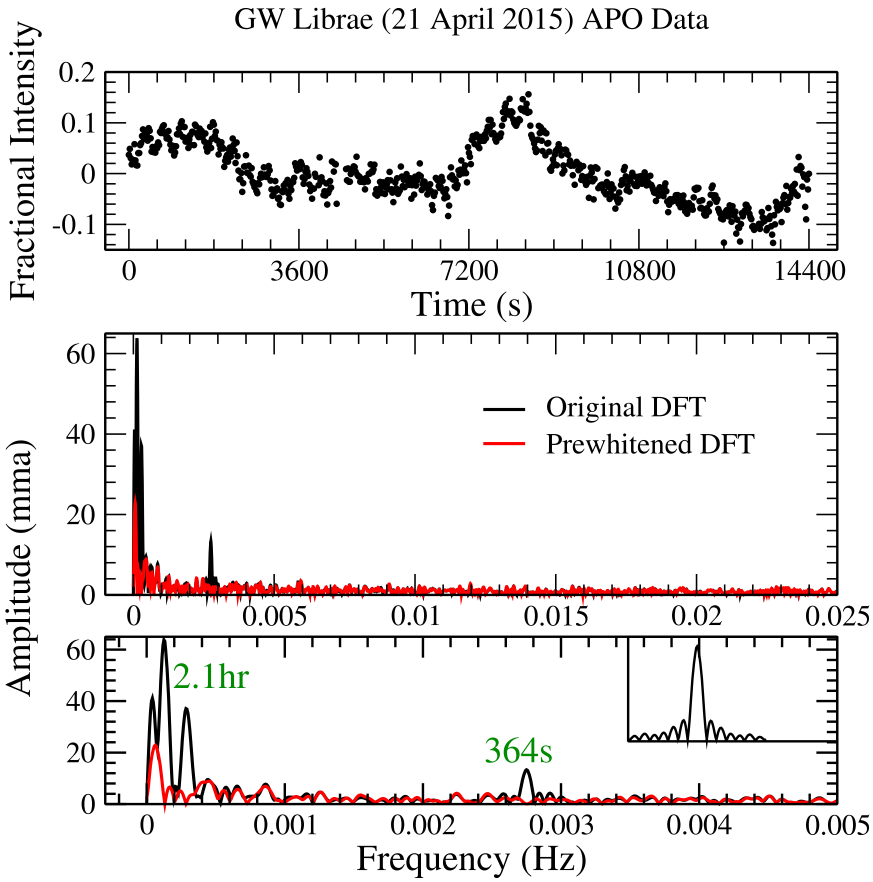

Figure 5. Intensity light curve (top) and DFT for the Agile optical data taken on April 21.

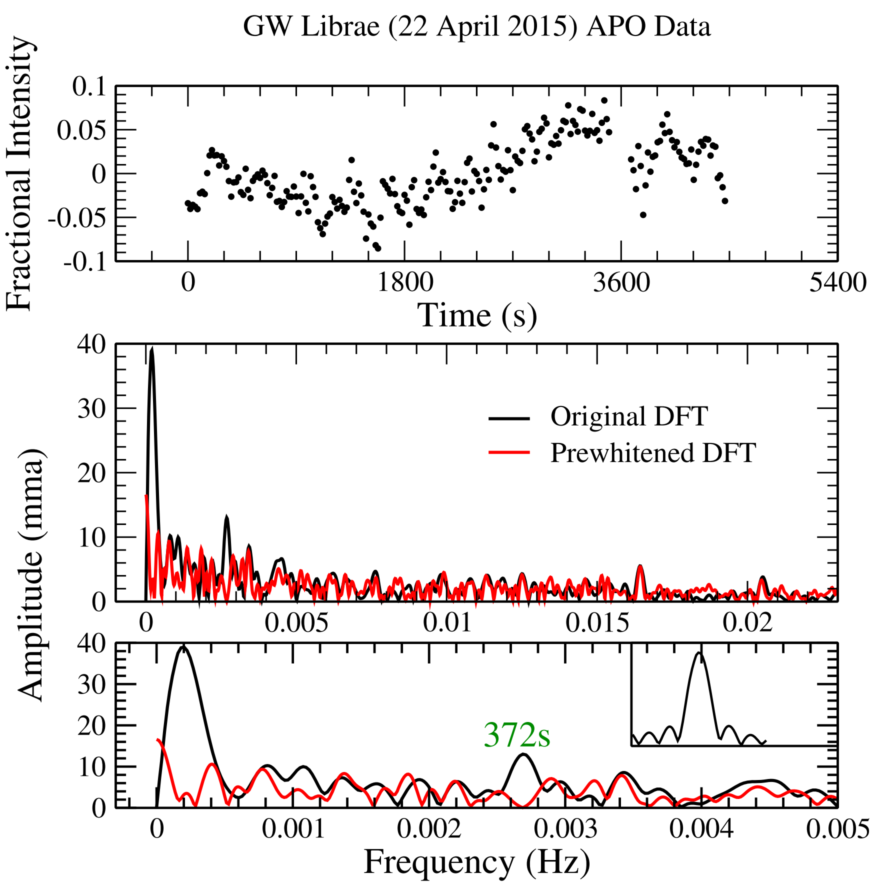

Figure 6. Intensity light curve and DFT for the Agile optical data obtained simultaneously with *HST*.

temperature of the white dwarf over a fraction of the white dwarf surface. They speculate that this variation could be caused by a splitting of the *g*-modes due to the rapid rotation of the white dwarf in GW Lib (200 s; Szkody et al. 2012) that results in a traveling wave moving counter to the rotation. In both cases, the similarity of the periods, when they are present, coupled with the lack of a regular recurrence time rule out phenomena such as disk precession or beating between periods.

However, the theoretical details of the long period pulsations remain to be delineated. These include reasons why the 19 minute period remains for months and then disappears for years, why the longest period changes from 2 hr (Woudt & Warner 2002; this work) to 3 hr (Chote & Sullivan 2016) to 4 hr (Bullock et al. 2011; Toloza et al. 2016), and why the 4 hr optical variation can disappear from one night to the next and be out of phase with the ultraviolet (Bullock et al. 2011). It is possible that the changes in period may be related to the outburst and subsequent cooling. The period of 2 hr was evident prior to outburst, then it was 4 hr in 2008–2010, 3 hr in 2012, and 2 hr in 2015.

5. CONCLUSIONS

Our *HST* ultraviolet and ground-based optical coverage of GW Lib eight years after the largest known dwarf nova outburst reveals that the white dwarf has not yet reached its quiescent pre-outburst temperature. Its mean temperature for the 2015 observation remains similar to what it was in 2013, that is, about 3000 K above its quiescent value. The ultraviolet and optical light curves both show a short period of 364–373 s, similar to one of the persistent periods observed during quiescence and with a similar ratio (7) of UV/optical amplitudes. A large (0.2 mag peak-to-peak) modulation at a period of 2 hr is apparent in the optical light curves preceding and simultaneous with the *HST* data, and is coherent over these two nights. Unfortunately, the *HST* observation times did not cover the peaks of the optical modulation, and so it is not possible to tell if, or how, the 2 hr modulation appears in the UV. Neither the 19 minute period that was evident in the optical in 2012 nor the large 4 hr modulation that was present in the 2013 *HST* data are observed. The 19 minute period has yet to be seen at ultraviolet wavelengths, and a much longer series of optical and ultraviolet observations will be needed to sort out the recurrence timescales and wavelength dependence of the 2–4 hr modulations. The return of the short and long periods to their pre-outburst values may be a signal that the white dwarf is finally returning to its quiescent configuration.

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