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GALEX AND OPTICAL OBSERVATIONS OF GW LIBRAE DURING THE LONG DECLINE FROM SUPEROUTBURST*

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ABSTRACT

The prototype of accreting, pulsating white dwarfs (GW Lib) underwent a large amplitude dwarf nova outburst in 2007. We used ultraviolet data from *Galaxy Evolution Explorer* and ground-based optical photometry and spectroscopy to follow GW Lib for three years following this outburst. Several variations are apparent during this interval. The optical shows a superhump modulation in the months following outburst, while a 19 minute quasi-periodic modulation lasting for several months is apparent in the year after outburst. A long timescale (about 4 hr) modulation first appears in the UV a year after outburst and increases in amplitude in the following years. This variation also appears in the optical two years after outburst but is not in phase with the UV. The pre-outburst pulsations are not yet visible after three years, likely indicating the white dwarf has not returned to its quiescent state.

Key words: novae, cataclysmic variables – stars: individual (GW Lib) – stars: oscillations

Online-only material: color figures

1. INTRODUCTION

GW Librae was first thought to be a nova (Duerbeck 1987) because of the large amplitude of an outburst during its discovery in 1983, but a later spectrum at quiescence revealed it to be a dwarf nova. The lack of outbursts for the next two decades, combined with the large outburst amplitude argued for a classification as a WZ Sge type of dwarf nova (Howell et al. 1995). Time-resolved spectroscopy (Szkody et al. 2000; Thorstensen et al. 2002) revealed a very short orbital period of 76.78 minutes, consistent with this classification. However, the unique nature of GW Lib became apparent when it was discovered to have non-radial pulsations (Warner & van Zyl 1998) and it became the prototype of the small class of accreting, pulsating white dwarfs which currently contains 13 members. Exploration of its amplitude spectrum by van Zyl et al. (2000, 2004) identified three prominent pulsation periods at 648, 376, and 236 s along with fine structure of closely spaced frequencies around the 648 and 376 s periods. The amplitudes of the pulsations changed on monthly timescales, typical of most hydrogen atmosphere white dwarf pulsators (ZZ Ceti stars). Ultraviolet observations of GW Lib (Szkody et al. 2002) revealed a hot white dwarf with a temperature consistent with the theoretical instability strip at 15,000 K due to He II ionization (Arras et al. 2006). The best fit was achieved with a high-mass (0.8 $M_\odot$) white dwarf with 0.1 solar metal abundance and a dual temperature (63% of the surface at 13,300 K and 37% at 17,100 K). The UV data showed higher amplitude pulsations than at optical wavelengths with the same periods as evident in the optical. All stellar pulsators, including variable white dwarfs, reveal wavelength-dependent amplitudes whenever their atmospheres suffer from limb-darkening effects.

Recent studies of the temperatures of nine of the other accreting pulsators (Szkody et al. 2010) showed that their instability strip is wider than for ZZ Ceti stars and some stars appeared to stop pulsating during the *Hubble Space Telescope* (*HST*) observations. One possible explanation for at least one of the systems that did not show pulsations was that accretion heating from an outburst could have caused the white dwarf to move out of its instability strip. Outbursts are known to cause major heating of the white dwarfs (e.g., WZ Sge; Godon et al. 2006) which then take several years to cool to their quiescent values, even though the optical light reaches quiescence in only a few months.

On 2007 April 12, GW Lib went into outburst (Templeton et al. 2007), reaching 8th magnitude from its quiescent brightness near 17th magnitude. The outburst was

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followed spectroscopically (Nogami et al. 2009; Hiroi et al. 2009; van Spaandonk et al. 2010b) and photometrically (Copperwheat et al. 2009; Schwieterman et al. 2010) as well as with X-ray telescopes (Byckling et al. 2009). The spectroscopy revealed the usual prominent optically thick disk near outburst with a slow return toward quiescence over 3 months. However, the outburst was unusual compared to other dwarf novae and WZ Sge objects in several ways. The X-ray flux of GW Lib increased by three orders of magnitude during the outburst and remained one order of magnitude higher than pre-outburst even at two years past outburst. As Bykling et al. (2009) point out, GW Lib is the only dwarf nova other than U Gem that shows a larger X-ray flux during outburst than quiescence. The optical flux of GW Lib also remained about a half-magnitude higher than quiescence 2–3 years past outburst, whereas most WZ Sge stars return to optical quiescence in a few months (e.g., AL Com and WZ Sge; Szkody et al. 1998). Finally, there was no evidence of the echo outbursts that many WZ Sge stars show on the decline from outburst (e.g., EG Cnc; Patterson et al. 2002).

We observed GW Lib for three years following its outburst, using ultraviolet data from *Galaxy Evolution Explorer* (*GALEX*), and ground-based optical photometry and spectroscopy. Our aim was to understand the heating and cooling of GW Lib as it moved out of its instability strip and then reentered. As of the current time, the white dwarf has not yet resumed its pre-outburst character. Yet, the photometry has revealed some interesting facets of GW Lib during its decline from superoutburst.

2. OBSERVATIONS

2.1. *GALEX Data*

Ultraviolet data were obtained using the *GALEX* satellite in April–June of 2007, 2008, 2009, and 2010 (Table 1 lists the times). Both the near-ultraviolet (NUV; 1750–2800 Å) and the far-ultraviolet (FUV; 1350–1750 Å) detectors (Martin et al. 2005) were used, except for the 2010 data when the FUV detector was no longer operational. The mean magnitudes from each set of observations were used to construct a light curve over the three years (Figure 1). From the *GALEX* online documentation,[14] the zero point of the AB magnitudes is given by $m_0 = 18.82 = 1.40 \times 10^{-15}$ erg cm^{-2} s^{-1} Å^{-1} for FUV and $m_0 = 20.08 = 2.06 \times 10^{-16}$ erg cm^{-2} s^{-1} Å^{-1} for NUV.

In order to be able to analyze the data for any short-term periodicity related to pulsations, the time-tag data were binned (into 29 s exposures for the 2007 data and 59 s for the 2008–2010 data), calibrated, and measured with the IRAF[15] *qphot* routine. An 8 pixel radius aperture was used for the stars and an annulus of 10–13 pixels for sky measurements. Nine reference stars in the field were measured in the same way as GW Lib to serve as a check on any variations that could be due to the various satellite orbits.

2.2. *Optical Photometry*

Optical photometric data were obtained with multiple telescopes between 2007 and 2010, beginning four days after the outburst of GW Lib in April (Templeton et al. 2007). The primary telescope used was the robotic 1.0 m of New Mexico State University (NMSU) which utilizes an E2V 2048 × 2048 CCD. In 2007, the night typically began with 2–6 observations through U, B, V, R, and I filters. Longer observing runs were then obtained through the U filter. Beginning in 2008, a BG40 filter[16] was also used and in 2009, only the BG40 filter was employed. This filter is a Schott glass filter with a broadband response from 3500 to 6000 Å which allows better signal-to-noise ratio (S/N) than the U filter, while still permitting better detection of pulsations which have higher amplitude in blue light than in red (Robinson et al. 1995). Table 2 lists the ranges of exposures for each night, with the U-band images occupying the upper end of the range. Throughout each night, the exposure times were automatically adjusted to compensate for changing conditions such as air mass and cloud cover. Differential photometry with respect to calibrated standard stars in the field was used to obtain magnitudes with resulting photometric errors of up to a few hundredths of a magnitude.

On 2007 May 29, a data set was taken with the 3.5 m Wisconsin, Indiana, Yale, National Optical Astronomy Observatory (WIYN) telescope through a BG39 filter which has similar transmission to the BG40. Observations were made with the MiniMo CCD with 2 × 2 binning and differential photometry was used for the reductions.

Observations with the 3.5 m telescope at Apache Point Observatory (APO) were made on 2007 June 1 and 2008 March 28. The data were taken through a BG40 filter with the Agile CCD and differential photometry was again used to obtain the magnitudes.

Data from the 1 m telescope at the United States Naval Observatory Flagstaff Station (NOFS) were also obtained in 2009. A high-speed camera was used on May 15 with a V filter, and the Tektronix 1024 × 1024 CCD with B filter was

Table 1
Summary of *GALEX* Data

UT Date	Mid-UT	Exp. (s)	FUV	NUV
2007 May 26	18:19:55	1088	14.439 ± 0.004	14.874 ± 0.004
	18:58:36	1120	14.446 ± 0.004	14.840 ± 0.004
	21:37:16	1136	14.420 ± 0.004	14.818 ± 0.004
2007 Jun 8	13:50:20	106	14.70 ± 0.01	15.07 ± 0.01
2007 Jun 18	03:40:31	221	14.79 ± 0.01	15.16 ± 0.01
	05:19:05	616	14.799 ± 0.007	15.165 ± 0.006
	06:57:41	1002	14.805 ± 0.006	15.179 ± 0.005
	08:36:16	1388	14.806 ± 0.005	15.192 ± 0.004
	10:14:53	1690	14.780 ± 0.004	15.180 ± 0.004
2008 May 13	17:52:59	1321	15.948 ± 0.009	16.179 ± 0.007
	19:31:39	1343	16.046 ± 0.009	16.222 ± 0.007
	21:12:16	1201	15.864 ± 0.008	16.110 ± 0.006
	22:51:21	1197	15.968 ± 0.009	16.136 ± 0.007
2008 Jun 3	11:50:28	1684	15.986 ± 0.007	16.175 ± 0.006
	13:29:03	1667	15.917 ± 0.007	16.142 ± 0.006
	15:07:39	1678	16.074 ± 0.008	16.261 ± 0.006
2008 Jun 13	10:05:33	1683	16.071 ± 0.008	16.276 ± 0.006
	11:44:09	761	16.02 ± 0.01	16.21 ± 0.02
2009 May 16	10:41:23	1498	16.23 ± 0.008	16.31 ± 0.005
	12:19:59	1498	15.88 ± 0.007	16.03 ± 0.004
	13:58:36	1503	16.27 ± 0.008	16.34 ± 0.005
2010 Apr 25	03:35:27	1488		16.35 ± 0.005
	05:14:03	1489		16.13 ± 0.004
	06:52:40	1460		16.50 ± 0.005
	08:35:13	1471		16.04 ± 0.004

[14] http:galexgi.gsfc.nasa.gov/tools/index.html

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

[16] http://www.us.schott.com/advanced_optics/english/download/schott_bandpass_bg40_2008_e.pdf

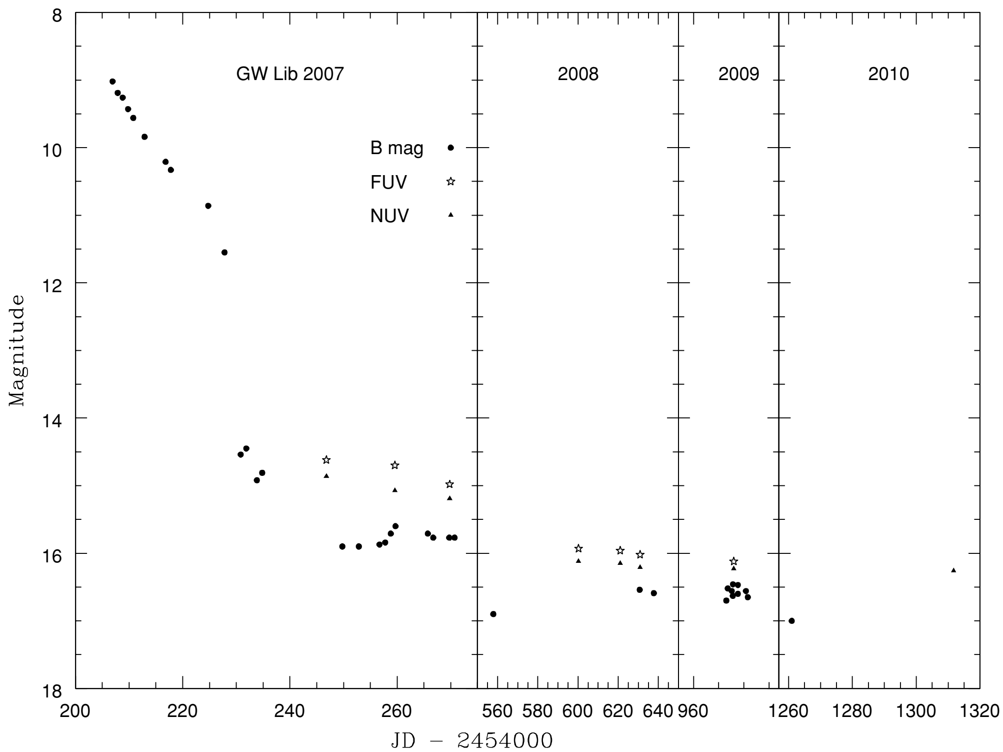

Figure 1. Means of ultraviolet and optical light curves from 2007 to 2010.

used on May 16 and 17. Additionally, the Sonoita Research Observatory (SRO) 0.5 m telescope was used on 2009 May 16. With this telescope, unfiltered images were taken with an SBIG STL 6303 CCD. Differential photometry was employed in both reductions.

Southern hemisphere observations were made with the 4.1 m Southern Astrophysics Research (SOAR) telescope on 2009 May 17. A combination of two E2V CCDs were used to make measurements through a *V* filter. Differential photometry using the IRAF *qphot* routine was used to obtain magnitudes. A second southern data set was obtained with the South African Astronomical Observatory (SAAO) 1.0 m Elizabeth telescope beginning 2009 May 18. A *B* filter was used with the STE4 CCD camera. Differential photometry was then used to obtain a light curve.

In 2010, two nights of photometry were obtained on March 4 and 5, using the KPNO 2.1 m telescope with a BG39 filter and the STA2 CCD. As with the other reductions, differential photometry was used.

Approximate calibrated *B* magnitudes were obtained for all nights through a variety of methods. Generally, *B* and *V* magnitudes for comparison stars in the field were obtained from the AAVSO Variable Star Database and offsets computed to then calibrate the GW Lib light curves. With the NMSU data, offsets for each night could usually be obtained from the *B* filter. For the 2007 nights with no *B* filter, the offset was determined by comparison of the mean magnitude to the corresponding magnitude from the AAVSO light curve. On 2008 June 20, data were taken in both *B* and BG40 filters, which enabled a determination of the offset to transform the BG40 magnitudes of 2008–2010 to approximate *B* magnitudes. The AAVSO standards were also used to obtain a transformation of the clear filter of SRO to an approximate *B* magnitude. To transform the *V* filter data of SOAR and NOFS, it was assumed that the $B - V$ color of GW Lib was zero.

2.3. *Optical Spectroscopy*

An optical spectrum of GW Lib was obtained on 2008 April 17, using the R-C Spectrograph and grating KPGL1-1 on the CTIO 4 m telescope. Two 30 minute exposures were medianed together. The slit width was 1 arcsec, comparable to the seeing (determined from a slice across the spectrum). The air mass at the time of observation was 1.04 and the blue DA white dwarf EG274 (Hamuy et al. 1992) was observed at air mass 1.03 immediately following GW Lib. Due to the low air mass and the closeness in time of the standard, we estimate the flux uncertainty to be about 10%. The resulting calibrated flux at 5500 Å translates into a visual magnitude of 16.3, which is within the range of the AAVSO light curves during 2008.

Table 2 gives a summary of the dates and times for all the optical data.

3. LIGHT CURVES

Figure 1 shows the mean of the ultraviolet and optical blue light curves from the observations. The optical light undergoes a rapid linear decline in the first month after outburst, followed by a steep drop of 3 mag between May 7 and 10 (days 227–230 on the plot) and then a slower decline continuing for years after outburst. The steep drop is generally ascribed to large changes in the disk that bring it close to its pre-outburst state (Byckling et al. 2009). The *GALEX* coverage began after this steep drop had occurred. The ultraviolet brightness declines by 1.5 mag from 2007 June to 2008 June, while the optical changes by less than a magnitude during this time (the low point at day 560 is likely due to using a redder standard for calibration due to the smaller field of view of the detector during that observation as well as a different filter). The difference between the *GALEX* FUV and NUV magnitudes decreases from 0.4 mag in 2007 to 0.08 mag in 2009. The optical blue magnitude decreases slightly in 2010 while the ultraviolet NUV magnitude remains the same.

Table 2
Summary of Optical Data

UT	Site	JD−2450000	UT Range	Exp. (s)	Filters	Comments
2007 Apr 16	NMSU	4206	08:50:03–11:02:15	60	*U*	
2007 Apr 17	NMSU	4207	06:59:51–10:23:26	4.1–219.5	*U*	
2007 Apr 18	NMSU	4208	07:01:08–10:58:14	3.4–46.7	*UBVRI*	DFT in *U*
2007 Apr 19	NMSU	4209	07:02:39–09:50:54	3.7–93.6	*UBVRI*	DFT in *U*
2007 Apr 20	NMSU	4210	06:46:42–10:49:32	3.7–47.9	*UBVRI*	DFT in *U*
2007 Apr 22	NMSU	4212	09:05:40–10:23:21	3.5–50.7	*UBVRI*	DFT in *U*
2007 Apr 26	NMSU	4216	07:24:36–07:32:44	2.0–33.4	*UBVRI*	
2007 Apr 27	NMSU	4217	06:52:53–07:01:26	2.5–44.0	*UBVRI*	
2007 May 4	NMSU	4224	06:09:03–06:18:07	3.6–58.9	*UBVRI*	
2007 May 7	NMSU	4227	05:37:41–09:40:43	1.4–219.8	*UBVRI*	DFT in *U*
2007 May 10	NMSU	4230	05:50:58–09:54:46	3.0–138.7	*UBVRI*	DFT in *U*
2007 May 11	NMSU	4231	08:42:35–09:19:50	3.1–85.0	*UBVRI*	DFT in *U*
2007 May 13	NMSU	4233	08:17:08–09:33:15	4.3–162.7	*UBVRI*	DFT in *U*
2007 May 14	NMSU	4234	07:52:53–09:25:18	2.2–107.4	*UBVRI*	DFT in *U*
2007 May 29	WIYN	4249	05:43:44–07:57:11	15	BG39	
2007 Jun 1	APO	4252	08:09:56–09:02:56	10	BG40	
2007 Jun 5	NMSU	4256	05:01:46–05:13:30	9.4–92.8	*UBVRI*	
2007 Jun 6	NMSU	4257	04:55:34–06:36:60	21.6–228.4	*UBVRI*	
2007 Jun 8	NMSU	4259	03:32:41–05:20:45	4.4–91.4	*UBVRI*	
2007 Jun 14	NMSU	4265	03:47:07–06:41:49	8.2–155.5	*UBVRI*	
2007 Jun 15	NMSU	4266	03:59:38–07:13:52	3.1–124.8	*UBVRI*	
2007 Jun 18	NSMU	4269	05:30:39–05:40:28	7.5–63.1	*UBVRI*	
2007 Jun 19	NMSU	4270	04:59:26–05:09:59	5.3–103.0	*UBVRI*	
2008 Mar 29	APO	4554	07:56:43–11:25:53	10	BG40	
2008 Apr 17	CTIO	4573	07:08:19–08:09:19	2×1800		Spectra
2008 Jun 13	NMSU	4630	03:51:41–07:03:03	6.7–136.6	*UBVRI*	DFT in *U*
2008 Jun 20	NMSU	4637	04:01:36–06:16:10	3.0–112.3	BG40,*UBVRI*	DFT in BG40
2009 May 14	NMSU	4965	23:21:59–01:16:45	60	BG40	
2009 May 15	NOFS	4966	05:15:10–09:14:30	20	*V*	
2009 May 16	NMSU	4967	01:11:23–03:24:12	60	BG40	
2009 May 16	SRO	4967	04:34:30–09:50:26	45	Clear	
2009 May 16	NOFS	4967	06:04:55–09:45:49	45	*B*	
2009 May 17	NOFS	4968	04:51:22–09:19:45	45	*B*	
2009 May 17	SOAR	4968	05:04:24–09:58:28	8.9	*V*	
2009 May 18	SAAO	4969	21:47:40–01:39:30	40	*B*	
2009 May 19	NMSU	4970	05:19:52–08:28:29	60	BG40	
2010 Mar 4	KPNO	5259	10:07:09–12:36:21	15	BG39	
2010 Mar 5	KPNO	5260	10:03:19–11:36:37	15	BG39	

These declines are consistent with the cooling of a hot source that peaks in the FUV, while the NUV and optical comprise the tail of the flux distribution. The similarity of the NUV fluxes from 2008 to 2010 indicates the continued presence of a hot source.

Figure 2 shows the individual *GALEX* light curves in NUV and FUV filters for the various satellite orbits on a given date, while Figure 3 shows the optical light curves for the nights with data coverage longer than an hour.

The individual *GALEX* light curves are flat throughout the 2008 May and June observations. The optical light curves are also relatively flat from 2007 April 16 to 22 (Figure 3(a)), which corresponds to the timescale of the linear decline in Figure 1. The flat light curves are consistent with the domination of the system light by the optically thick uniform accretion disk. On May 7, at the start of the steep optical decline (Figure 1), the optical light curves go through major changes (Figure 3(b)). On May 7, the decline starts to appear during the 4 hr of observation. Three nights later, at the end of the rapid decline on May 10, the light curve shows large fluctuations of several tenths of a magnitude, with a double-hump appearance repeating at a timescale near 80 minutes. On May 14, a slow sinusoidal type modulation is apparent near 80 minutes that is also visible on May 29. This is the same interval in which Kato et al. (2008) find a stable period of 77.98 minutes which they call a "late superhump" period. The erratic fluctuations in our May 10 data may be the disk transitioning from its early to late superhump state. Kato et al. (2008) note the strange stability and longer than usual period increase of this superhump compared to normal WZ Sge stars. Copperwheat et al. (2009) note a similar long period in their 2007 July data but with a lower amplitude modulation than we see in May. These longer period superhumps have been postulated to be due to some amount of gas being outside the 3:1 resonance radius, which causes a tidal instability leading to an eccentric disk (Whitehurst 1988). The lack of modulation of the NUV and FUV data during this time implies that the inner, hotter disk areas are not affected. As the superhump amplitude decreases with time, the amount of mass in this outer area of the disk may be shrinking or there may be less irradiation of the disk as time progresses, although the low inclination of GW Lib (∼11°; van Spaandonk et al. 2010b) should present a view of the disk that does not change much during the orbit. It is also intriguing that GW Lib did not show the series of rebrightening events (echo outbursts) following its steep optical decline that are often observed in WZ Sge systems (Patterson et al. 2002).

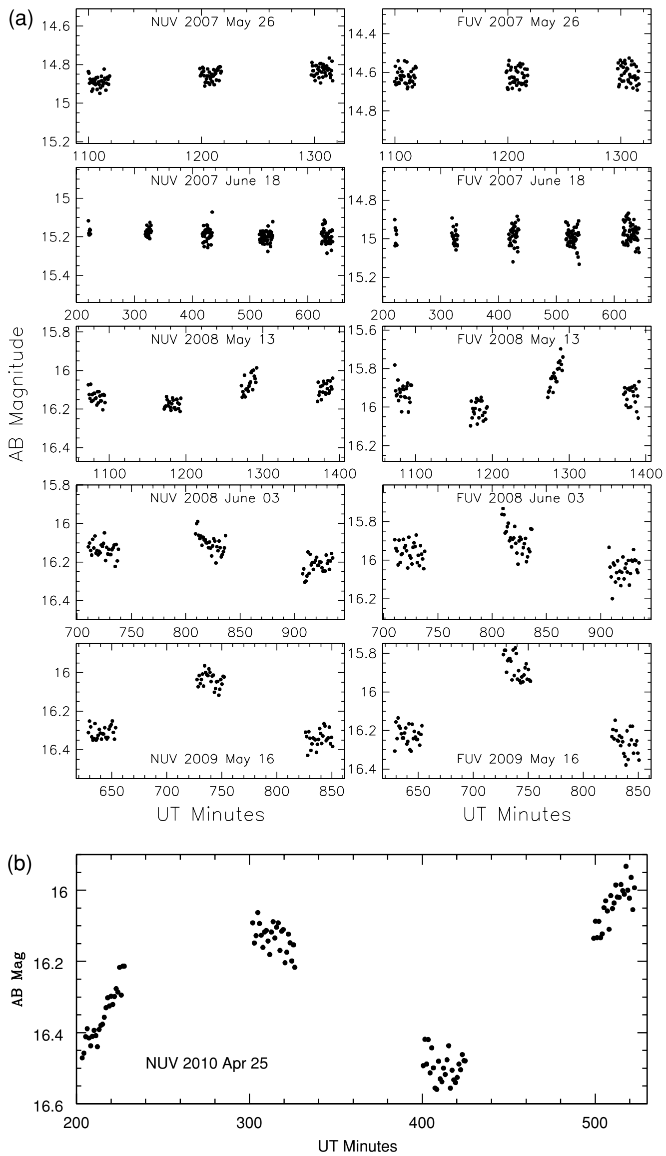

Figure 2. (a) *GALEX* NUV (left) and FUV (right) light curves. Each point in 2007 data is a 29 s integration, in later data is a 59 s integration with error bars for each orbit listed in Table 1. The magnitudes are on the AB system as explained in the text. (b) *GALEX* NUV light curve in 2010. Details as in panel (a).

A year later, when GW Lib was again observable, the *GALEX* data began to show a long (hr) timescale variation that became even more pronounced in 2009 and 2010. In 2008 and 2009, the amplitude in FUV is larger than the NUV, implying that the innermost hot areas of the disk are involved in the cause of this variation. On 2008 March 29 (Figure 3(b)), a long-term modulation that is not well defined (as it is about the length of the 3 hr light curve) appears in the optical data, and there is an even more puzzling feature: a distinct pulse-like periodicity. The Discrete Fourier Transform (DFT; Figure 4) indicates a period of 19.08 ± 0.03 minutes. Copperwheat et al. (2009) also report a consistent signal from March 30 to April 29 at 19.2 ± 0.2 minutes with an amplitude in *g* of 2.2%, which declines in amplitude throughout their April data. In addition, Schwieterman et al. (2010) show a similar (19.7–19.9 minutes) but not identical period in three out of eight nights from 2008 May 30 to June 13. As the frequency is not stable, we regard this as a quasi-periodic feature that is similar in timescale to those that have been reported in several nova-like systems (Garnavich & Szkody 1992; Taylor et al. 1999; Andronov 1999).

After the disappearance of the 80 minute and 19 minute phenomena, the optical light curves in 2008 June and throughout 2009 exhibit a longer modulation near 4–5 hr (Figures 3(c) and 3(d)) with amplitude of 0.2–0.3 mag peak-to-peak which is neither consistent nor coherent. This timescale is about double the 2.1 hr period first discovered by Woudt & Warner (2002) and then studied further in the pre-outburst data of Copperwheat et al. (2009). Figure 3(d) shows that while this modulation is very prominent on 2009 May 17, it completely disappears on May 18 and 19 (as evidenced on data obtained on two different telescopes). Both *GALEX* and optical data exist on 2009 May 16 (although not simultaneously), showing that a similar modulation is apparent in both (Figures 2(a) and 3(c) and Table 3). However, while the periods are similar on the same date (the combined optical data from May 14 to 17 fit with a period of 191.5 ± 0.2 minutes and the *GALEX* data give periods of 218 ± 11 minutes (FUV) and 210 ± 9 minutes (NUV)), the phases do not seem to match up. The peak of the *GALEX* data occur near 730–740 UT, which would imply the previous peak occurred at 530–538 UT, while the optical peak is closer to 450 UT. While the origin of this modulation is not understood, the fact that it changes phase on timescales of days and sometimes disappears entirely, points to an origin in the accretion disk. If it is related to an eccentricity of the disk, the changes mean that the disk is still not in a steady configuration two years after the superoutburst.

4. PULSATION SEARCH

A period search was conducted on all the optical and ultraviolet data, primarily to search for the return of the pre-outburst pulsations. For this, the light curves were converted to a fractional amplitude scale by dividing by the mean count rate and then subtracting one. Then a DFT was computed for each light curve up to the Nyquist frequency (half the sampling frequency). The best-fit periods and amplitudes were found by using linear and non-linear least-squares fitting. To find the significance of any period, the 3σ white-noise limits were determined by using a shuffling procedure (Kepler 1993; Mukadam et al. 2010a). This involves shuffling the intensities of a light curve (with all the periodicities subtracted out), while keeping the times constant in order to produce a pure white-noise light curve. The DFT of this light curve is then computed to find the average amplitude between zero and the Nyquist frequency to yield a 1σ measure. Repeating this process 10 times produces an empirical, reliable 3σ limit.

Table 3 lists all the 3σ noise levels and any significant results obtained for the ultraviolet and optical data. There is no consistent period that is evident as a non-radial pulsation up to three years past outburst in either the ultraviolet or the optical data. The amplitudes of the 650 s period evident prior to the outburst were 100 mma (millimodulation amplitude) in the UV and 10–15 mma in the optical. Figures 5 and 6 show the DFTs of the latest data.

Copperwheat et al. (2009) also obtained photometry in 2007 June and July and 2008 March–June. In their last data set (2008 June 21), they note a period of 290 s with an amplitude of 1.25%. There is no consistent evidence for a pulsation near this period in our longest data sets (Table 3). Thus, this period is likely associated with flickering noise.

van Spaandonk et al. (2010a) recently used VLT spectroscopy to determine a spin period of 97 ± 12 s from an analysis of

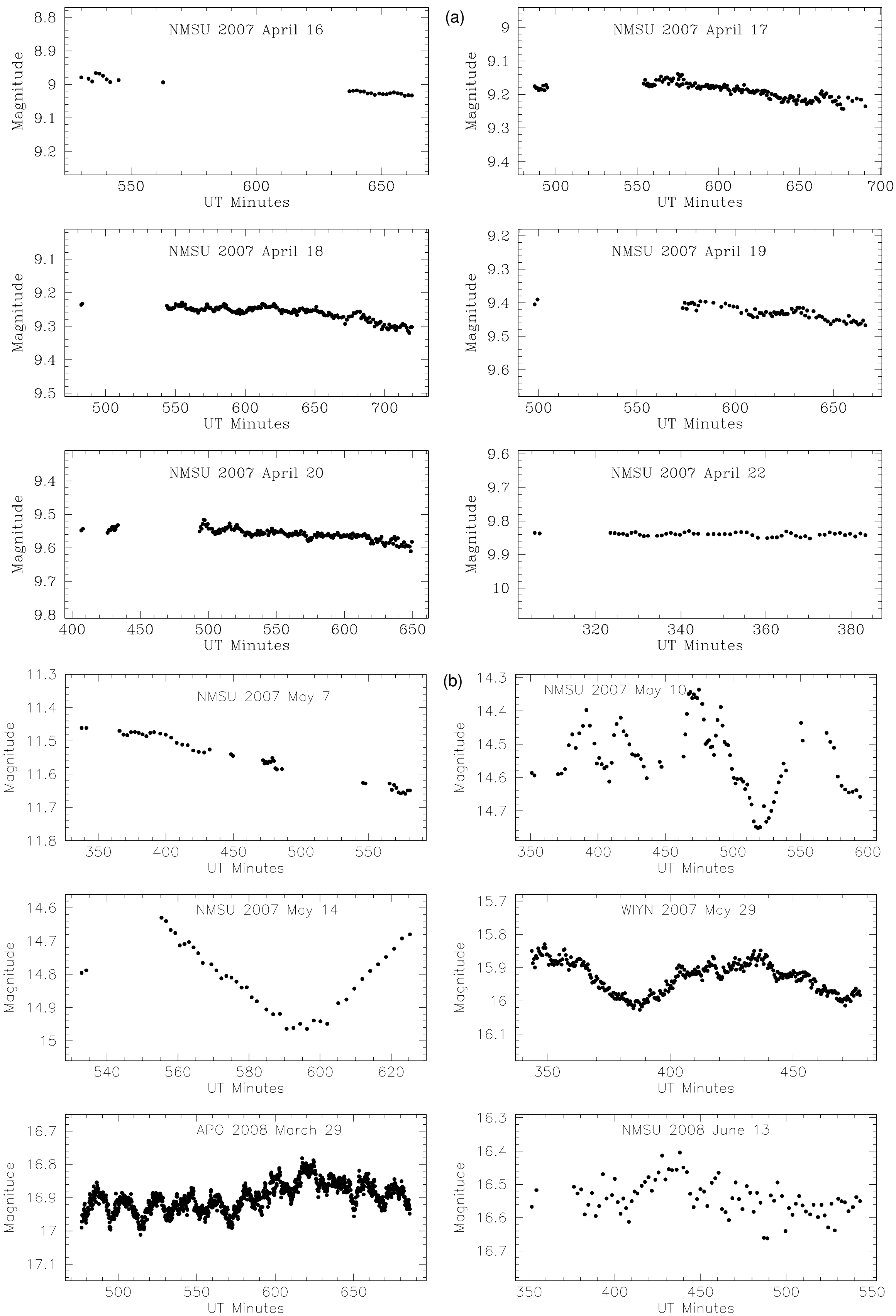

Figure 3. Individual optical light curves obtained from 2007 to 2010. Error bars are generally a few hundredths of a magnitude. Filters are as listed in Table 2, with filter same as for DFT if more than one on a night. Dates increase across each row and then down the column.

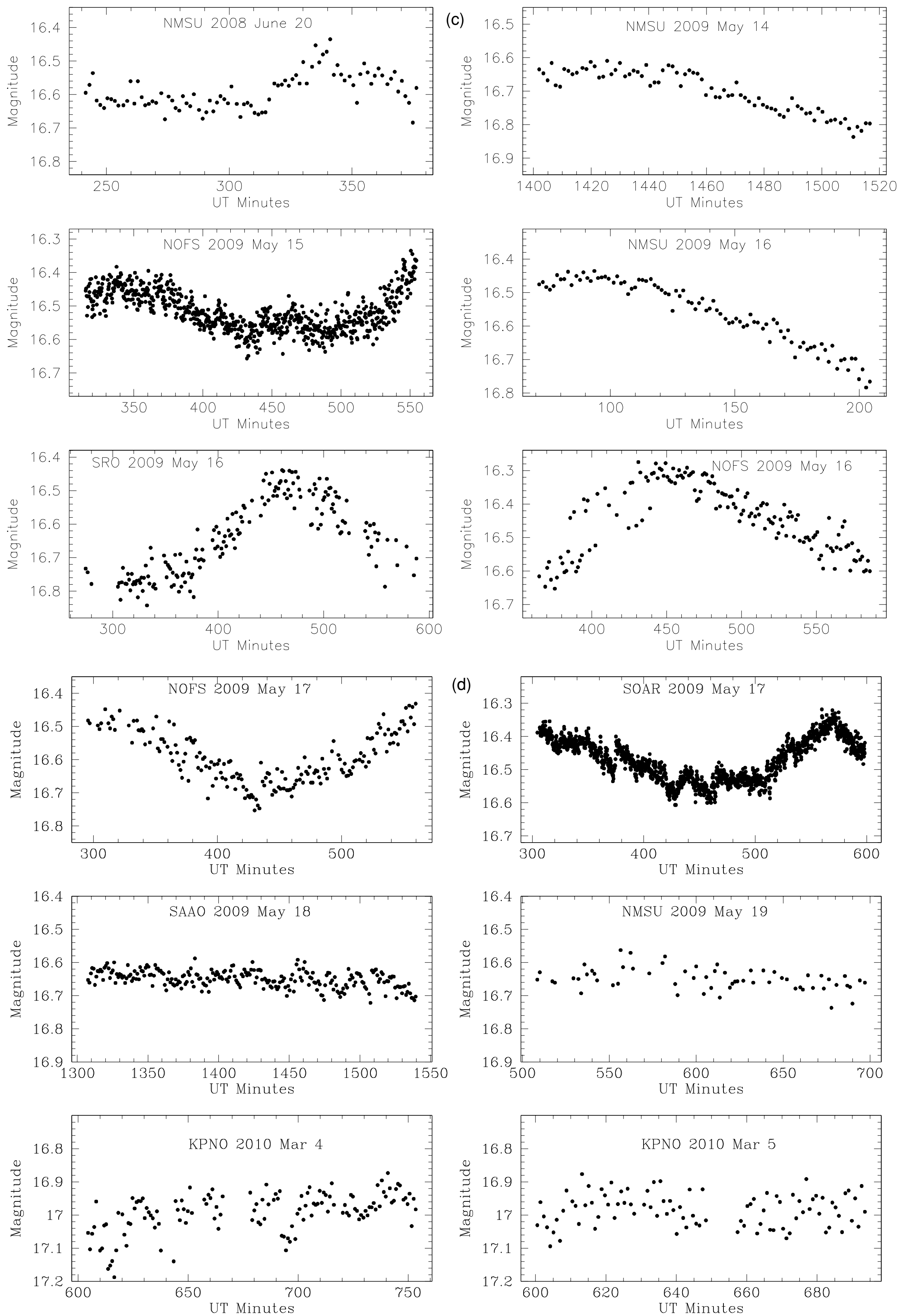

Figure 3. (Continued)

Table 3
Summary of Observed Periods and Limits

UT	Data	N	3σ (mma)	Periods (minutes)	Amp. (mma)
070416	NMSU	28	14.0	...	...
070417	NMSU	145	9.2	...	...
070418	NMSU	199	6.9	...	...
070419	NMSU	70	11.2	...	...
070420	NMSU	192	5.6	...	...
070422	NMSU	52	3.6	...	...
070510	NSMU	96	49.1	80.1 ± 1.3	100 ± 9
070514	NMSU	41	73.9	83.3 ± 1.3	137 ± 3
070526	*GALEX* NUV	120	17.1	32.3 ± 0.4	21 ± 3
070526	*GALEX* FUV	120	26.9	...	...
070529	WIYN	311	12.8	82.9 ± 0.9	52.8 ± 1.5
070601	APO	278	14.3	...	...
070618	*GALEX* NUV	294	36.2	154 ± 2	78 ± 7
070618	*GALEX* FUV	294	44.4	...	...
080329	APO	1255	5.7	204 ± 4, 85.2 ± 1.8, 19.08 ± 0.03	39.5 ± 0.8, 14.7 ± 0.7, 24.9 ± 0.8
080513	*GALEX* NUV	88	33.6	327 ± 9	67 ± 6
080513	*GALEX* FUV	88	52.5	291 ± 9	96 ± 10
080603	*GALEX* NUV	87	39.3	275 ± 22	66 ± 7
080603	*GALEX* FUV	87	49.5	219 ± 8	106 ± 22
080613	*GALEX* NUV	42	38.7	215±27	55 ± 18
080613	*GALEX* FUV	42	48.6	...	...
080620	NMSU	89	27.1	124 ± 6	53 ± 6
090514–15	NMSU	78	34.3	...	...
090515	NOFS	719	10.9	248 ± 7	60 ± 2
090516	NMSU	90	47.7	308 ± 108	144 ± 50
090516	SRO	187	49.2	293 ± 10	128 ± 5
090516	NOFS	169	41.2	206 ± 11	109 ± 7
090516	*GALEX* NUV	78	81.7	210 ± 9	150 ± 8
090516	*GALEX* FUV	78	105.7	218 ± 11	191 ± 9
090517	NOFS	200	27.6	283 ± 30	78 ± 11
090514–17	Multi	1438	...	192 ± 3	54 ± 2
090518–19	SAAO	239	8.0	...	...
090519	NMSU	61	20.5	...	...
100304	KPNO	132	13.9	79.0 ± 3.5, 40.2 ± 0.9	21 ± 3, 23 ± 3
100305	KPNO	90	16.2	...	...
100425	*GALEX* NUV	30.5	103	229 ± 4	205 ± 8

an Mg II 4481 absorption feature. In contrast to the obvious presence of the spin period in the accreting pulsator V455 And (Araujo-Betancor et al. 2005), there is no indication of this spin period in any of our data on GW Lib.

5. WHITE DWARF COOLING

The UV data obtained following the outburst of the dwarf nova WZ Sge showed that its white dwarf takes more than 3 yr to cool to its pre-outburst temperature (Godon et al. 2006). As with all dwarf novae near the peak of outburst, the UV flux is dominated by the accretion disk and it is only after the flux has dropped down from the plateau region of the outburst that the white dwarf becomes visible. Nogami et al. (2009), Hiroi et al. (2009), and van Spaandonk et al. (2010b) discuss the spectra of GW Lib from pre-outburst to the slower decline phase up to 3 months post-outburst. Our spectrum (Figure 7) obtained one year after outburst is similar to quiescent spectra in showing the absorption from the white dwarf flanking the emission from the accretion disk, but there is a steeper blue continuum than at quiescence. As the emission lines are relatively narrow and single-peaked, the inclination of GW Lib is generally taken to be low (∼11°) and the mass to be high (near 1 $M_{\odot}$; Szkody et al. 2000; Thorstensen et al. 2002; Steeghs et al. 2007; van Spaandonk et al. 2010a, 2010b).

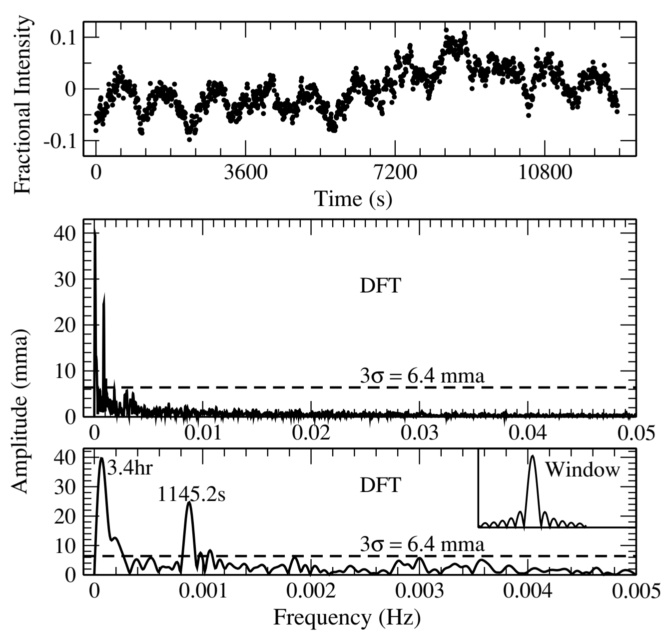

Figure 4. Fractional intensity (top), DFT (middle), and enlargement of low frequencies (bottom) of APO optical data on 2008 March 29 showing the 19.08 minute (1145 s) period. Dashed line is the 3σ noise limit.

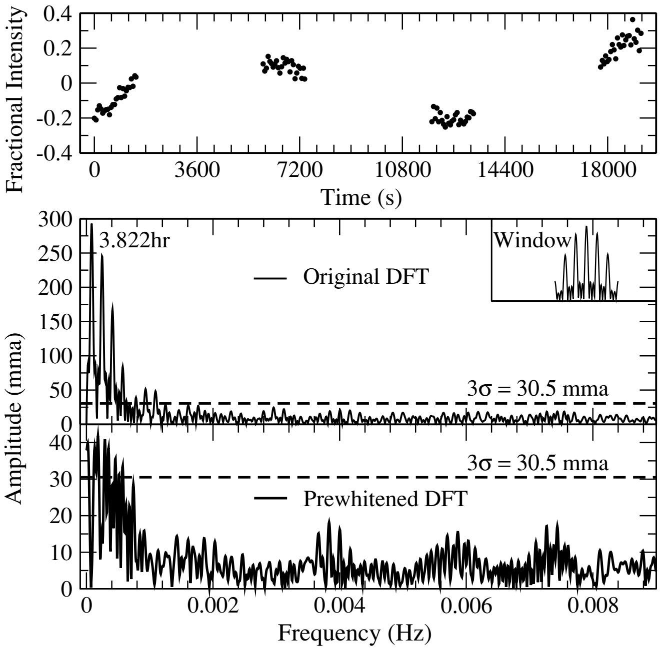

Figure 5. Fractional intensity (top), DFT (middle), and DFT with 3.822 hr period removed (bottom) of 2010 April 25 *GALEX* NUV data. Dashed lines show the 3σ limits for the noise.

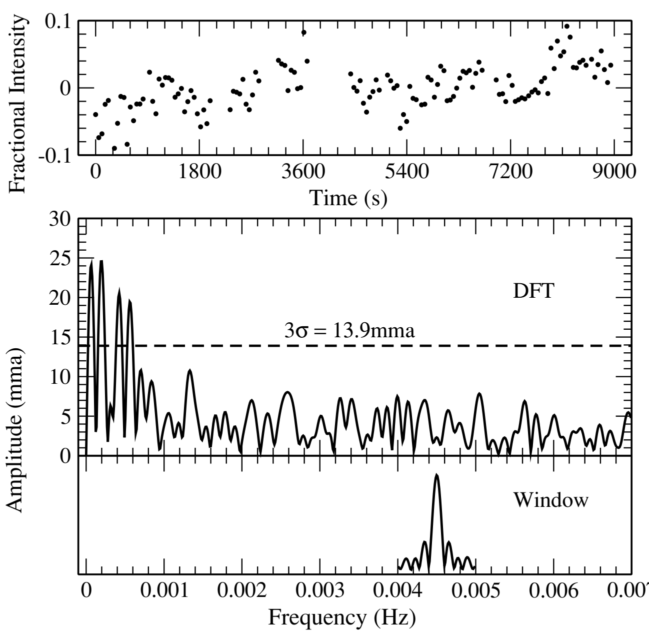

Figure 6. Fractional intensity (top), DFT (middle), and window function (bottom) of 2010 March 4 optical data along with the 3σ noise limit (dashed line). The pre-outburst pulsations were all at frequencies larger than 0.001 Hz.

We modeled the optical spectrum of GW Lib using a two-component approach. The emission from the disk is described with an isothermal and isobaric slab of hydrogen (Gänsicke et al. 1997). For the white dwarf, we used a grid of model spectra spanning a wide range in effective temperatures and surface gravities, computed using TLUSTY195 and SYNSPEC45 (Hubeny & Lanz 1995) and adopting metal abundances of 0.1 the solar values, as determined from our previous *HST*/STIS observations (Szkody et al. 2002), and using the distance of $104\pm^{30}_{20}$ pc as determined by Thorstensen (2003). Free parameters in this model are the temperature and column density of the hydrogen slab, which determine the equivalent widths of the emission lines as well as the Balmer decrement (see Gänsicke et al. 1999 and Rodriguez-Gil et al. 2005 for more details), and the white dwarf effective temperature and surface gravity. The surface gravity, along with the flux scaling factor between models and observation and a white dwarf mass–radius relation (Wood 1995) give the white dwarf mass.

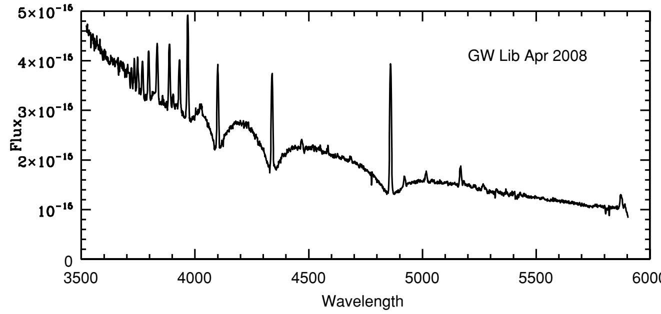

Figure 7. CTIO spectrum of GW Lib. Note the broad absorption from the white dwarf flanking the emission from the accretion disk.

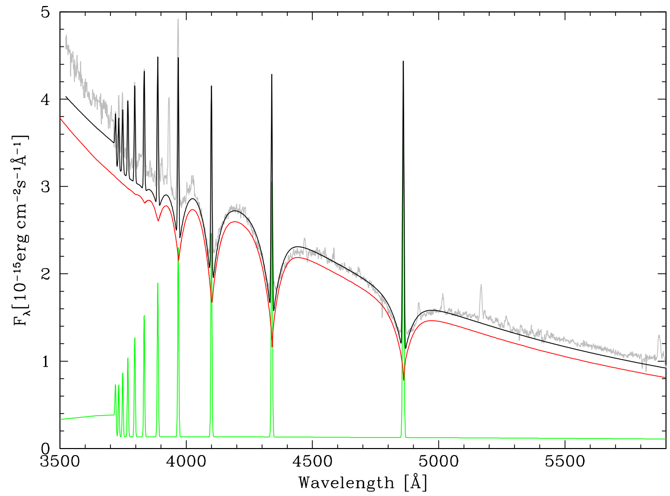

Figure 8. CTIO spectrum (gray) fit with a 25,000 K, $\log g = 8.55$ white dwarf at 104 pc (red), and an optically thin emission line component (green).

(A color version of this figure is available in the online journal.)

The disk parameters are adjusted to reproduce the observed Hβ and Hγ fluxes, and the white dwarf parameters are varied to fit the broad Balmer absorption lines as well as the slope of the continuum. As the ionization fraction of hydrogen depends both on the temperature and the pressure within the atmosphere, the white dwarf effective temperature and its surface gravity are strongly correlated parameters, and acceptable fits are found for a 15,000–25,000 K white dwarf, corresponding to masses of 0.57–0.97 $M_\odot$. The best fit was achieved for a 0.97 $M_\odot$, 25,000 K white dwarf (Figure 8). Even at this temperature, the bluest wavelengths are not fit well, implying some other component may be contributing.

Although the *GALEX* and optical data were not simultaneous, we tried to constrain any hot component by combining the closest data sets. Figure 9 shows the CTIO data from April 17 plotted with the *GALEX* data from May 13 (fluxes are plotted in frequency to show the data better), with the observed range of variability of the *GALEX* data. The UV data do not follow the upturn at the bluest optical wavelengths. A hot 25,000 K model lies far above the *GALEX* points. This could mean that either there is a large reddening (not very feasible given the small

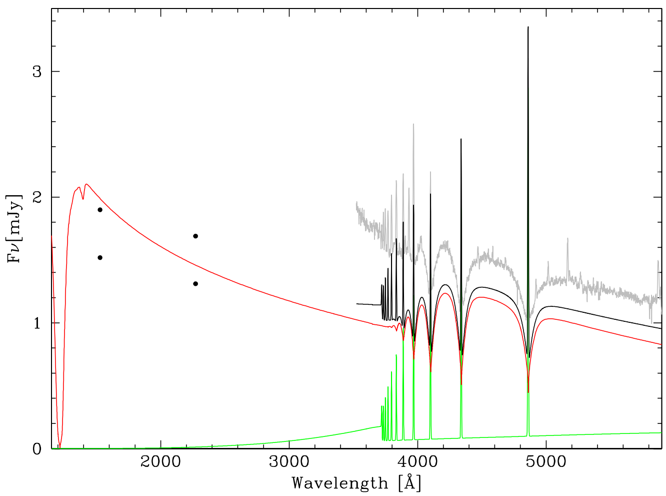

Figure 9. *GALEX* data range from 2008 May 13 (solid points) combined with the CTIO spectrum from April 17 (gray) fit with a 19,000 K, log $g = 8.36$ white dwarf at 104 pc with a reddening of $E(B - V) = 0.03$ (red line), and an emission line component (green).

(A color version of this figure is available in the online journal.)

distance of GW Lib), or there was a large change in the *GALEX* or optical fluxes between the two measurements (also not very feasible), or the model parameters are not correct. Using the best determination of mass from van Spaandonk et al. (2010b), i.e., mass of 0.84 $M_{\odot}$, and the distance of 104 pc with a small amount of reddening ($E(B - V) = 0.03$) yields the fit shown in Figure 9 for a temperature of 19,000 K. In this model, the optical sum of the white dwarf and disk falls below the observed values. However, this could be possible if the disk contributes a greater portion of the optical continuum flux. The fitting of UV spectra has shown that the white dwarfs in accreting pulsators contribute 75%–89% of the UV light and 42%–75% of the optical (Szkody et al. 2010) during quiescence. In the model shown in Figure 9, the white dwarf contributes 80% of the flux near 4500 Å. Since GW Lib was not yet at quiescence, the disk contribution could be larger than normal.

Given all the uncertainties (10% in optical flux calibration, 20%–30% in distance, unknown changes in the month between the *GALEX* and CTIO observation times, unknown reddening, and unknown disk contribution and flux distribution), it is not worth pursuing a more detailed fit at this time. It is clear that there is a hotter component (likely the white dwarf as the dominant contributor to the flux) than at quiescence a year after its outburst. In WZ Sge, the white dwarf was about 4000 K hotter than at quiescence one year after its outburst (Godon et al. 2006). Given the similar physical characteristics of the two systems, including both having massive white dwarfs, it is interesting to determine if GW Lib remains hotter at the same time post-outburst than WZ Sge. Since the cooling is related to the amount and depth of the accreted mass, the larger outburst amplitude of GW Lib (9 mag) versus WZ Sge (7.5 mag) may indicate that more material was accreted during the outburst of GW Lib. In addition, the much lower inclination of GW Lib provides a better view of the disk radiation at outburst. The determination of the actual cooling of the white dwarf in GW Lib compared to WZ Sge will come from ultraviolet spectra.

A soft X-ray component was seen with Swift (Byckling et al. 2009) within a few days of outburst that was consistent with an optically thick boundary layer. The hard X-ray flux was abnormally large at outburst (1000 times its pre-outburst value) and was still an order of magnitude larger than pre-outburst through 2009 March. Whatever caused the increased X-ray luminosity could result in a slower cooling of the white dwarf in GW Lib compared to WZ Sge.

6. CONCLUSIONS

Our UV and optical data on GW Lib during the three years following its outburst have shown the following unique traits.

1. The accretion disk shows large optical variability following the steep decline part of its post-outburst light curve.
2. A superhump modulation evident only in optical, not ultraviolet, follows this transition.
3. One year post-outburst, a 19 minute quasi-period is visible in the optical for 2–4 months.
4. The ultraviolet begins to show variability on ∼4 hr timescales a year after the outburst and the amplitude of this variability increases in the second and third years after outburst.
5. The optical begins to show a 4 hr variation two years after outburst which is similar to the ultraviolet but not in phase and this variation can disappear from one night to the next.
6. At one year past outburst, the white dwarf likely remained hotter than at quiescence, although a range of temperatures and disk components is possible.
7. There is no evidence of the return of the pre-outburst pulsations for the three years following outburst.

The very large outburst amplitude, the long-lasting X-ray emission, the hot white dwarf, the lack of post-outburst rebrightenings, the presence of quasi-periodicities, and the long-period modulation all point to a large accretion episode, resulting in a hot white dwarf and a massive accretion disk. While the structure of the disk that results in all the periodicities observed is not known, following the detailed transitions in systems like this provides some clues to the types of phenomena that the disk undergoes as it transitions from its dominant optically thick emission state to its minor quiescent contribution to the system light. Obtaining the pulsation periods and amplitudes when the white dwarf cools enough to resume its modes will reveal the effect of the accretion event on the interior layers of the white dwarf.

It is interesting to compare the behavior of GW Lib after its outburst to that of two other similar systems that also had recent outbursts and contain pulsating white dwarfs. SDSS0745 + 45 had an outburst in 2006 October, showed no visible pulsations one year post-outburst (Szkody et al. 2010) but pulsations at the same pre-outburst periods had returned by 2010 February (Mukadam et al. 2010b). V455 And had an outburst in 2007 September and its pulsation return is currently being monitored. A comparison of the outburst amplitudes and return timescales and characteristics of the pre- and post-outburst pulsations of these three systems should provide some clues to the depth of heating and interaction of the accretion event with the driving zone of the pulsations.

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