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DISCOVERY OF QUASI-PERIODIC OSCILLATIONS IN THE AM HERCULIS OBJECT BL HYDRI

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ABSTRACT

We obtained high-speed optical photometry of the AM Her object BL Hyi at the Las Campanas Observatory and the Cerro Tololo Inter-American Observatory during 1989–1996. BL Hyi was in its faint-luminosity state in 1989; it subsequently brightened and was in its high-luminosity state for our 1994–1996 observations. We discovered broad, 0.2–0.8 Hz quasi-periodic oscillations (QPOs) and narrower QPOs superposed on the broad QPOs when BL Hyi was in its high-luminosity state. The broad QPOs had widths of $\Delta f/f_p \sim 0.5$–1 and rms pulsed amplitudes of $\sim$1%–4%, where f_p is the frequency of the QPO peak. The narrow QPOs had widths of $\Delta f/f_p < 0.1$ and rms pulsed amplitudes of less than 1%. BL Hyi showed stronger QPOs and was slightly brighter in 1994 than in 1995–1996. The amplitudes of the broad and narrow QPOs were modulated on the orbital period of the system; they were strongest during the bright orbital phase. BL Hyi is the fifth AM Her system to show the short-period QPOs discovered by Middleditch.

Subject headings: accretion, accretion disks — novae, cataclysmic variables — stars: individual (BL Hydri, H0139−68) — stars: oscillations

1. INTRODUCTION

The AM Her objects are a subset of cataclysmic variables. They are short–orbital-period mass transfer binary systems composed of a magnetic white dwarf and a low-mass companion star (for a recent monograph on cataclysmic variables that includes a chapter on the AM Her systems see Warner 1995). The AM Her systems are characterized by polarized optical and infrared emission and intense soft and hard X-ray emission, all of which are modulated on the rotational periods of the white dwarfs. The key to our understanding of the AM Her systems lies with the intense magnetic fields ($B_* \sim 10$–230 MG) of the white dwarfs. The magnetic fields strongly couple the white dwarfs and the companion stars, which usually locks the rotational and orbital motions of the white dwarfs into synchronism. Further, the intense fields force field-aligned accretion onto the white dwarfs, starting from somewhere between the latter and the companion stars. The enforcement of the field-aligned flow occurs far enough from the white dwarf that accretion disks do not form in the AM Her systems. The bulk of the emission from the AM Her objects is thought to arise in shocks that form as the accreting plasma merges onto the white dwarfs.

This basic picture for the AM Her objects has been generally confirmed by observations; however, there are questions concerning several aspects of the emission region structures (e.g., see Warner 1995). As such, it is important to develop further diagnostics of the emission regions of the AM Her objects. Here we consider one such diagnostic.

The AM Her objects exhibit temporal variability on timescales ranging from seconds to years. There are periodic variations on timescales of hours, aperiodic variations on timescales ranging from seconds to years, and quasi-periodic oscillations (QPOs) on timescales of several seconds and several minutes. Of these, only the *clock* mechanism for the periodic features has been identified. The mechanisms for the aperiodic and quasi-periodic features are poorly understood. This is true even though the short-period (1–5 s) QPOs, first detected 15 yr ago by Middleditch (1982), have been the subject of several theoretical and observational studies since their discovery. The short-period QPOs attracted attention because it was recognized almost immediately that they were potentially powerful probes of the radiative shocks of the AM Her systems. The connection between the QPOs and the shocks of the AM Her systems was made because the oscillation periods of the QPOs were consistent with the cooling timescales for white dwarf–radiated shock waves (Langer, Chanmugam, & Shaviv 1982), and it was conclusively demonstrated that the QPOs arose in or near the shock emission region on the white dwarf in the VV Pup system (Larsson 1989).

The promise of the QPOs as probes of the radiating plasma has not yet been realized, in large part because of the small number of AM Her systems exhibiting QPOs. Here we present optical high-speed photometry of the AM Her object, BL Hyi, obtained at the Cerro Tololo Inter-American Observatory (CTIO) and the Las Campanas Observatory (LCO) over 1989–1996, which improve this situation. We discovered broad 0.2–0.8 Hz QPOs, with nar-

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rower QPOs superposed on the broad QPOs, when BL Hyi was in its high-luminosity state. The broad QPOs had widths $\Delta f/f_p = 0.5$–1, and the narrow QPOs had $\Delta f/f_p < 0.1$, where f_p is the frequency of the QPO peak. The QPOs appeared to be confined to the bright orbital phase of BL Hyi, which further strengthens the suggestion that the QPOs are associated with the accretion shocks in the AM Her systems. Our discovery raises the number of AM Her objects that exhibit short-period QPOs to five.

The remainder of our paper is organized as follows. The observations and our data analysis are presented in § 2. The observations are discussed in general terms and within the context of the shock model in § 3. Our conclusions are summarized in § 4.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. *Light Curves*

Optical photometry of BL Hyi was obtained using the 1 m and 1.5 m telescopes of the CTIO and the 2.5 m telescope of LCO. The observations were made using Hamamatsu or RCA 31034 GaAs phototubes through diaphragms of size 10″ (1.5 m), 13″.7 (1 m), and 7″ (2.5 m). The bandwidths for the observations, usually determined by the response of the GaAs phototubes, were 0.35–0.9 μ. The data were recorded at a rate of 50 Hz when using the Time Series Photometry system (TSPHOT) of CTIO (1995–1996 data). When using the Li'l Wizard Stellar Pulsarator data device (Middleditch & Kristian 1984), the data were recorded at rates of 500 Hz (1989 data) and 50,000 Hz (1994 data). The log for our observations is presented in Table 1.

The average brightness of BL Hyi varied by $\sim$2 mag from 1989 to 1996. In 1989, the average V magnitude of BL Hyi was $m_V \sim 17.7$, and BL Hyi was in its faint-luminosity state. In 1994 BL Hyi had an average R magnitude of $m_R \sim 15.5$, and in 1995–1996, it had an average $m_V \sim 16$, in its high-luminosity state. Representative high-state light curves are presented in Figure 1. The orbital phases Φ are based on the ephemeris of Schwope & Beuermann (as given in Schwope, Beuermann, & Jordan 1995b),

$$\mathrm{HJD} = 2{,}444{,}884.2176(6) + 0.07891518(4)E\ . \quad (1)$$

The data were accumulated in 1.28 s bins for presentation in Figure 1. The light curves were corrected for the sky background but not for the effects of varying air mass.

The unfiltered (white light [WL]) light curves are asymmetric, with rapid rises to maximum and slow declines to minimum. The R-band and V-band light curves are more symmetric but still show slow declines to minimum. There is strong flaring during the bright portions of the light curves in all bands. The high-state light curves are similar in appearance to those found for VV Pup. It has been shown for both VV Pup and BL Hyi that the modulation of the light curves can be interpreted as the occultation of an accretion hot spot by the body of the white dwarf (see, e.g., Warner 1995). Since both VV Pup and BL Hyi are thought to be two-pole emitters, based on their polarization light curves, it appears as though one pole always dominates the light, even during the high state.

For our 1995–1996 observations, the onset of the bright phase clearly fell at $\Phi \sim 0.8$–0.85. This is $\sim$15–20 minutes early, according to the Schwope & Beuermann ephemeris.

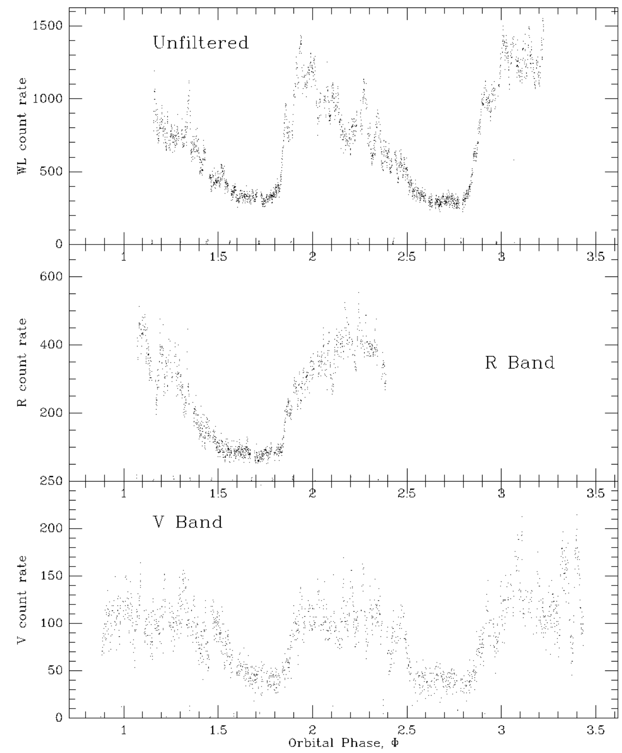

FIG. 1.—BL Hyi light curves based on data acquired using the 1 m telescope of the Cerro Tololo Inter-American Observatory in 1996 September. The unfiltered (white light) light curve is from 1996 September 14. The R-band light curve is from 1996 September 15. The V-band light curve is from 1996 September 16. The light curves were binned in time intervals of 1.28 s and corrected for the sky background.

TABLE 1

LOG OF OBSERVATIONS

Date	UT[a]	Φ[a]	Duration (h)	Filter	Star + Sky (c/s)	Sky (c/s)	Telescope
1989 Aug 1	06:49:30	0.29	3.2	WL	550	300	1.5 m, CTIO
1994 Nov 11......	00:27:36	0.20	0.27	WL	11700	3210	2.5 m, LCO
1994 Nov 12......	00:25:27	0.85	0.81	WL	9600	3890	2.5 m, LCO
1994 Nov 13......	00:22:57	0.50	1.13	700 LP[b]	3250	950	2.5 m, LCO
1994 Nov 14......	00:20:26	0.15	0.68	R	5200	1350	2.5 m, LCO
1994 Nov 15......	00:25:45	0.87	0.63	R	2650	1150	2.5 m, LCO
1995 Oct 31	00:16:06	0.93	2.5	WL	3080	2150	1 m, CTIO
1996 Sep 14	05:43:32	0.15	5.0	WL	1250	590	1 m, CTIO
1996 Sep 15	04:16:12	0.05	2.5	R	535	150	1 m, CTIO
1996 Sep 16	04:29:51	0.84	4.9	V	180	87	1 m, CTIO

[a] At start of observation.

[b] $\lambda \sim 0.7$–0.9 μ.

This shift also appears to be present in our 1994 data, but it is not as apparent, because of the short lengths of the observations. Schwope et al. (1995a) reported a similar shift for an R-band light curve that they acquired in 1993. Since Schwope et al. (1995a) reported that data acquired in the years up to and including 1992 were consistent with their ephemeris, it appears as though the dominant accretion hot spot in BL Hyi drifted by $\sim 30°$ in longitude between 1992 and 1993 (Schwope et al. 1995a) and has remained stable since.

2.2. *Timing Analysis*

Power spectra for each night of the 1994 November data are presented in Figure 2. The power spectral densities are normalized so that the Poisson noise level is unity. There are broad QPOs over the range $f = 0.2$–0.8 Hz, with narrower QPOs superposed on the broad QPOs for the WL and R-band data. The QPOs appear to peak around $f_p \sim 0.4$ Hz, with a hint that the R-band QPOs have a slightly higher f_p than do the WL QPOs. The data for the 700 LP filter (which straddles the R and I bands), does not show broad QPOs but does show the narrow features. The broad QPOs have rms pulsed amplitudes of 3%–4% for the data taken on November 12 (WL) and 15 (R band). Similar broad QPOs and superposed narrow features also appear in the WL data from 1995 October and 1996 September. The broad QPOs have rms pulsed amplitudes of 1%–1.7% for the data taken in 1995–1996. There is at best only weak evidence for QPOs in the faint-state data from 1989 August.

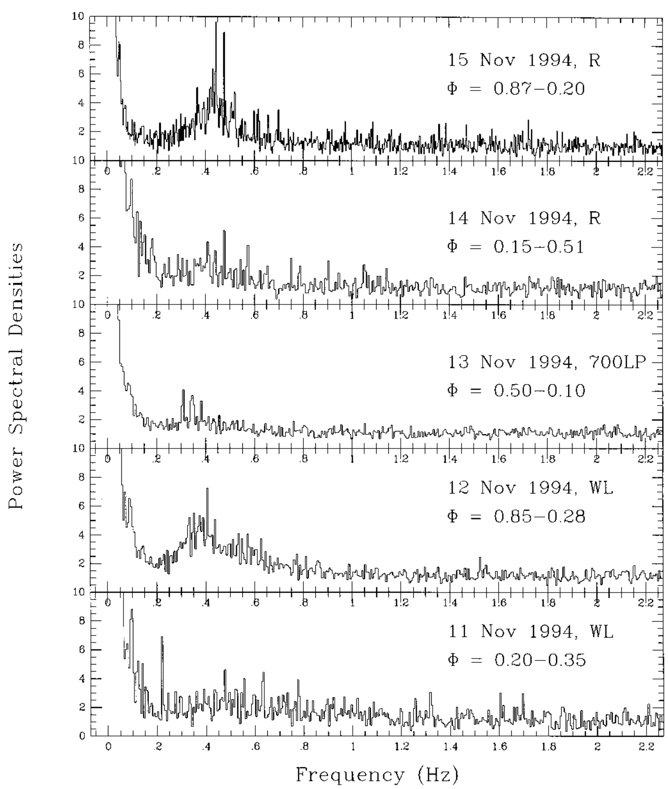

FIG. 2.—Power spectral densities (PSDs) for the 1994 November BL Hyi data acquired using the 2.5 m telescope of the Las Campanas Observatory. The 1994 November 14 and 15 data were taken through an R filter, the November 13 data were taken through a 700 LP filter, and the November 11 and 12 data were for unfiltered light. The 700 LP filter straddles the R and I bands. The PSDs were normalized in such a way that Poisson noise had a power level of 1. Notice the broad QPOs and the superposed narrow QPOs.

Note that the pulsed amplitudes for the 1995–1996 data are deduced by a comparison to the count rate averaged over all Φ, while for the 1994 data the reference level is the average count rate over $\Phi \sim 0.8$–0.2.

The amplitude of the broad QPOs is modulated on the orbital period of BL Hyi in a manner similar to that shown by VV Pup (Larsson 1989). This can be inferred from Figure 3, where the 1996 September 14 WL power spectra, binned into intervals of $\Delta\Phi = 0.2$, are presented. The broad QPOs are strongest over the interval $\Phi = 0.8$–0.4 and are consistent with zero amplitude at other phases. This suggestion is further supported by the 1994 November data, where strong, broad QPOs are detected only in the November 12 and 15 data sets. On these dates, $\Phi \sim 0.5$–0.2. On November 11 and 14, $\Phi \sim 0.2$–0.5, and the broad QPOs are much weaker, or, perhaps, completely absent. The 700 LP data (November 13) span the range $\Phi = 0.50$–0.10 but do not show clear evidence for broad QPOs. The above constitute strong evidence that broad QPOs are visible only when the dominant pole is in view. However, note that we do not rule out the possibility of QPOs when the second pole is in view. Given the low amplitude of the QPOs, if the second pole produces QPOs of an amplitude that is similar to the dominant pole's QPO amplitudes, then we would not have been able to detect them because of the lower count rates during the faint phase.

The narrow QPOs superposed on the broad QPOs appear in several of the data sets. The narrow QPOs sometimes appear at the same frequencies, even in data sets separated by over a year. The features do not maintain phase, however. The narrow QPOs are present in the bright orbital phases but may also be present when BL Hyi is in its faint phase. For example, compare the 1994 November 11

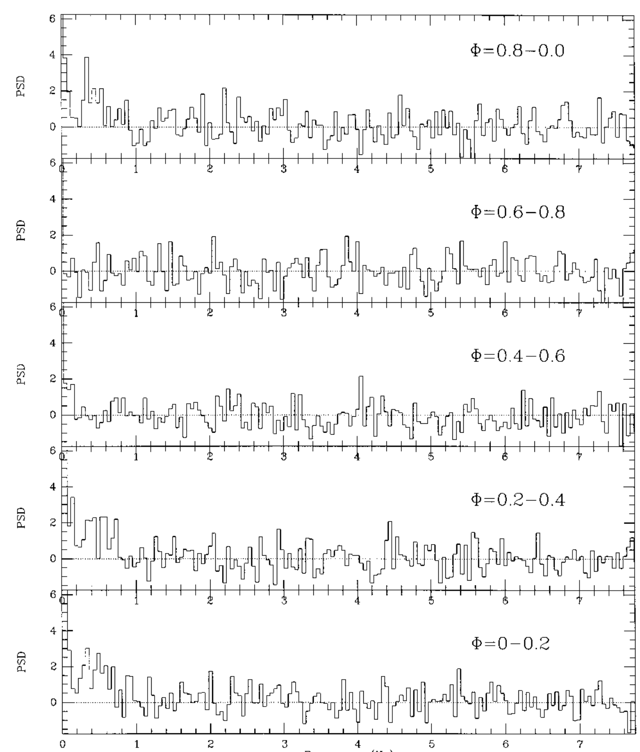

FIG. 3.—Power spectral densities as a function of the orbital phase for the BL Hyi white-light data taken on 1996 September 14. The power spectra were normalized in such a way that the Poisson noise had a level of 1, and were corrected for counting statistics.

and 12 power spectra to each other and the November 14 and 15 power spectra to each other. Whether the narrow QPOs appear or do not appear at all Φ is an important question. If their amplitude is not modulated on the orbital period, this would suggest that they are produced in a region that is not occulted when the dominant accretion hot spot is occulted. As such, QPOs of narrow and broad features might have different production mechanisms.

The flickering properties of BL Hyi are next characterized. There are no persistent QPO peaks for frequencies between ~ 0.1 mHz and 0.1 Hz. Soft X-ray QPOs with amplitude of 50% and $f = 3.6$ mHz have been detected in BL Hyi (Singh, Agrawal, & Riegler 1984). There is power at low frequencies, however, in the optical data. The WL and V-band power spectra are roughly power laws in nature, with slopes of ~ -2, while the R-band power spectrum shows a similar power law below 1 mHz but is flat between ~ 1 mHz and 0.1 Hz. Over the range of the QPOs, the pulsed power in the noise per hertz is on the order of 10%–30 % of the Poisson noise level.

3. DISCUSSION

3.1. *General Properties*

The properties of the BL Hyi system are similar to those of the other QPO sources. BL Hyi has $P_{\text{orb}} = 113.6$ minutes, $B_* = 12$ MG in the accretion region (Schwope et al. 1995b), $M_V = 8.8$ at maximum light, and a soft blackbody temperature of $kT_s = 27^{+1}_{-6}$ eV (Ramsay et al. 1994). The other QPO sources, EF Eri, VV Pup, V834 Cen, and AN UMa, have the following properties, respectively: $P_{\text{orb}} = 81.0$, 100.4, 101.5, and 114.8 minutes (see Warner 1995); $B_* = 13$, 31, 23, and 29 MG (see Beuermann et al. 1995); $M_V = 8.6$, 8.2, 9.5, and less than 8.3 (see Warner 1995); and $kT_s = 26^{+2}_{-5}$, 32^{+1}_{-2}, 38^{+7}_{-11}, and 23^{+5}_{-5} eV (Ramsay et al. 1994). It is interesting that all of the QPO sources have $P_{\text{orb}} < 2$ hr, which, according to current ideas, suggests that the Alfvén radius for the white dwarfs is greater than the distance to the inner Lagrangian points in the systems.

The properties of the QPOs of BL Hyi are similar to those of the other QPO sources. The QPOs are broad, spread over the frequency range 0.2–0.8 Hz, with a peak frequency of $f_p \sim 0.4$ Hz and rms pulsed amplitudes of 1%–4 %. As in VV Pup, the QPOs in BL Hyi are modulated on the orbital period of BL Hyi. Overall, for the group of QPO sources, the f_p are roughly the same, spanning only an octave in frequency space. However, within this range, the f_p appear to increase with the B_* of the white dwarf (Larsson 1992). In order of increasing B_*, we have $(f_p, B_*) = $ (0.4 Hz, 12 MG), (0.37 Hz, 13 MG), (0.55 Hz, 23 MG), (0.65 Hz, 29 MG), and (0.76 Hz, 32 MG) for BL Hyi, EF Eri, V834 Cen, AN UMa, and VV Pup, respectively. The f_p, other than for BL Hyi, were taken from Larsson (1992). BL Hyi fits into the sequence proposed by Larsson, but given the uncertainties in the determination of f_p, the verification of this relationship requires observations of many more QPO sources.

The behavior of V834 Cen nicely illustrates the apparent constraint on the possible values of f_p. For V834 Cen, we have detected QPOs when it was in luminosity states ranging from the ultrahigh state to the extremely faint state. Amazingly, the f_p of the QPOs were fairly similar, despite the change of several magnitudes in the optical emission (Middleditch et al. 1991). A similar effect was seen in BL Hyi but at a much more modest level. The f_p for the QPOs in BL Hyi remained around 0.4 Hz in the face of 0.5 mag changes in the optical light.

3.2. *Radiating Shock Models*

The most well-developed model for the QPOs is the driven-shock model (Wolff, Wood, & Imamura 1991; Wu, Chanmugam, & Shaviv 1992; Wood, Imamura, & Wolff 1992). According to the driven-shock model, QPOs are produced when accretion noise drives low-order oscillatory modes of the accretion shocks. The shocks are efficient amplifiers of the accretion noise (amplification factors of 2–3) for systems with high $\dot{M}$ and B_* of up to least 30 MG (Wood et al. 1992; Wolff et al. 1994). Since the QPO systems have $B_* < 32$ MG and large M_V, compared to the other AM Her systems, driven shocks are consistent with this aspect of the observations.

The suggested dependence of f_p on B_* and the relative insensitivity of f_p to luminosity state are not predicted directly by the shock model. In radiating shocks, the QPO frequency is determined by the mass accretion flux, $\dot{S} = \dot{M}/A_{\text{cap}}$, the white dwarf mass M_*, and B_*. Here, A_{cap} is the area covered by the footpoint of the accretion funnel (Wood et al. 1992). Therefore, if the observed QPO frequency is to depend mainly on B_*, the combinations of $\dot{S}$ and M_* for the individual sources cannot be arbitrary. For example, if $\dot{S}$ were the same as, or increased with, B_*, and the M_* values were roughly the same for the different sources, then an f_p-B_* relation similar to the proposed one would follow, while if $\dot{S}$ were independent of B_*, then any f_p-B_* correlation would most likely be smeared out, even if M_* were the same from system to system. It is not currently possible to determine unambiguously how $\dot{S}$ varies with accretion rate or with B_* based solely on the observations.

A potential use of the QPO observations, when coupled with shock models, is that constraints may be placed on $\dot{S}$ and the effective temperature kT_{eff} of the soft X-ray component of the white dwarf. This is useful because kT_{eff} values are not currently derived directly from the observations of the AM Her systems. What are found are color temperatures, kT_s, from blackbody spectra fitted to the observed UV and soft X-ray spectra. Williams, King, & Booker (1987) have shown that for X-ray–illuminated white dwarf atmospheres, kT_s values derived from blackbody fits are 2–5 times larger than the kT_{eff} values. The use of kT_s to infer soft X-ray luminosities then leads to errors that can be as large as factors of 2—the errors are not larger because A_{cap}, as well as kT_s, are determined in the process of the spectral fitting. The errors in the two quantities tend to compensate for each other, since kT_s is overestimated while A_{cap} is underestimated. Given these problems, the development of independent methods for the determination of kT_{eff} are needed.

Consider BL Hyi. For BL Hyi, $f_p \sim 0.4$ Hz and $B_* = 12$ MG, with no estimate available for M_*. Using the shock calculations tabulated in Wood et al. (1992) and Wolff et al. (1994), we find $kT_{\text{eff}} < 10$, 17, or 26 eV if $M_* = 0.3$, 0.6, or 1 $M_\odot$, respectively, if the shock is oscillating in the lowest order mode (the fundamental mode), and $kT_{\text{eff}} < 7.6$, 12, or 20 eV if $M_* = 0.3$, 0.6, or 1 $M_\odot$, respectively, if the shock is oscillating in the first overtone mode. The kT_{eff} were determined from the models under the assumption that half of the accretion energy was thermalized in the surface of the white dwarf and reradiated as blackbody radiation. The given $kT_{\rm eff}$ are thus upper limits. The range of $kT_{\rm eff}$ values implied by the QPO observations are factors of $\sim$1–3.5 times smaller than the kT_s observed for BL Hyi: 27^{+1}_{-6} eV. The estimated $kT_{\rm eff}$ values can be further pinned down if one uses the estimate that the optical luminosity is roughly 30% as great as the hard X-ray luminosity in BL Hyi (see Ramsay et al. 1994). In this case, the high-mass models, $M_* \sim 1\ M_\odot$, are preferred, since only they can produce cyclotron-to-bremsstrahlung ratios greater than 10% for $B_* \sim 12$ MG, which implies that $kT_{\rm eff} \sim$ 20–25 eV $\sim kT_s$ in BL Hyi.

The nature and the origin of the driving noise required for the driven-shock model were not discussed by Wolff et al. (1991) and Wood et al. (1992). It was only noted that there had to be power over the bandwidth of the QPO. Here we briefly address the issue of the driving noise. First, note that several AM Her systems also exhibit long-period QPOs, P = 4–10 minutes, which are thought to be produced by some *gating* mechanism that operates in the neighborhood of the inner Lagrangian point of the systems (e.g., see Warner 1995). Interestingly, several of the systems that show these long-period QPOs also show short-period QPOs (EF Eri, BL Hyi, and VV Pup). It is conceivable that the mechanism generating the long-period QPOs also generates the high-frequency noise needed to drive the shock oscillations that are responsible for the short-period QPOs (e.g., Steiman-Cameron et al. 1994). On the observational side, recall that the extension of the low-frequency noise spectrum to 0.1–1 Hz fell only 1–2 orders of magnitude below the Poisson level, which meant that the noise over the bandwidth of the QPOs had a pulsed power of 10%–30 % of the Poisson level. This level of noise is sufficient for driving 1%–4 % QPOs.

4. SUMMARY

We obtained optical high-speed photometry of BL Hyi during 1989–1996 at the LCO and CTIO. During this time, BL Hyi was in both its faint and high states. We discovered broad and narrow QPOs over the frequency range f = 0.2–0.8 Hz while BL Hyi was in its high state. At best, there was only weak evidence for QPOs in data taken while BL Hyi was in its faint state. The narrow QPOs were superposed on the broad QPOs, which had widths of $\Delta f/f \sim$ 0.5–1 and amplitudes of 1%–4%. The narrow QPOs had widths of $\Delta f/f < 0.1$ and amplitudes of less than 1%. The exact relationship between the narrow and broad QPOs is not clear. What their relationship is and how it manifests itself in terms of theoretical models of the QPO generation mechanism need further study.

The QPOs were modulated on the orbital period of BL Hyi in a manner similar to that seen in VV Pup (Larsson 1989). They were strong over Φ = 0.8–0.4 and much weaker or perhaps absent during Φ = 0.4–0.8. This is strong evidence for the QPOs' association with the dominant accretion shock. This, when combined with the fact that the timescales for the QPOs are consistent with the cooling times for typical white dwarf radiative shocks, suggests that the broad QPOs are likely to be formed in the cooling regions of the accretion shocks that are formed as the plasma merges onto the surfaces of the white dwarf in the BL Hyi system. The high-state BL Hyi is, therefore, a potentially powerful probe of the physics of the energetic, strongly magnetic plasmas of the AM Her systems, making BL Hyi another prime candidate for future study.

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