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F. A. Ringwald
Dartmouth College

J. R. Thorstensen
Dartmouth College

R. K. Honeycutt
Indiana University - Bloomington

J. W. Robertson
Indiana University - Bloomington

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F. A. Ringwald,[1,2]★ J. R. Thorstensen,[2] R. K. Honeycutt[3] and J. W. Robertson[3]

[1] *Department of Physics, Keele University, Keele, Staffordshire ST5 5BG*
[2] *Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755-3528, USA*
[3] *Astronomy Department, Indiana University, Swain Hall West, Bloomington, IN 47405, USA*

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ABSTRACT

Long-term light curves of the cataclysmic variable BK Lyn = PG 0917 + 342 from the Indiana Automated CCD photometric telescope ('RoboScope') and the Harvard College Observatory plate archive reveal no dwarf nova outbursts. Two radial velocity studies show its orbital period to be 107.97 ± 0.07 min, confirming that it does have an orbital period shorter than the period gap for cataclysmic variables. Whether this is the first nova-like variable below the period gap or a dwarf nova with rare outbursts resembling WZ Sge is still unclear, however.

Key words: binaries: spectroscopic – stars: individual: BK Lyn – stars: individual: PG 0917 + 342 – novae, cataclysmic variables.

1 INTRODUCTION

Cataclysmic variables are binary stars in which a K–M dwarf fills its Roche lobe and spills gas on to a white dwarf. The red star, also called the secondary, spills gas on to a white dwarf via an accretion disc. Recent reviews of cataclysmic variables (hereafter CVs) include those of La Dous (1993) and Livio (1994).

The most energetic CVs are the classical novae, which have thermonuclear explosions in the accreted matter on the surface of the white dwarf. Nova outbursts can have amplitudes of 15 mag or more, and last from days to years. The second general type of CV are the dwarf novae, which have outbursts with amplitudes of 2–5 mag that last for days and recur over weeks to months. These are gravity-powered and occur in the accretion discs. Some authors use a subclass of dwarf novae called the WZ Sge stars, which have outbursts only rarely, on the intervals of years. O'Donoghue et al. (1991) argue that there are no real physical differences between the WZ Sge stars and other dwarf novae, aside from the rarity of the outbursts. Some WZ Sge stars, such as BC UMa (Mukai et al. 1990), have spectra in which the red stars are readily visible, unlike in WZ Sge. Other WZ Sge stars, such as GK Lib (Duerbeck & Seitter 1987) and WX Cet (O'Donoghue et al. 1991) do have spectra that resemble WZ Sge, in which the optical and UV continua are dominated by the white dwarf, and the Balmer lines show broad absorption wings flanking the emission cores, formed in the accretion disc. In this paper, we will use the term 'WZ Sge stars' specifically to mean the latter group, those that resemble WZ Sge spectroscopically as well as photometrically.

The third general type of CV are the nova-like variables, which do not have outbursts. Unfortunately, in the past the term 'nova-like' has been used to describe stars such as η Carinae and P Cygni, which have little physical resemblance to canonical CVs. Here we use the term specifically to mean non-magnetic CVs that do not show outbursts, such as UX UMa. Nova-likes generally have spectra resembling those of dwarf novae in outburst, with relatively weak lines on a power-law continuum (Williams 1983).

BK Lyn was discovered by the Palomar-Green survey (Green, Schmidt & Liebert 1986), and was listed as PG 0917+342 in an early compilation of CVs from this survey (Green et al. 1982). This compilation gives a finding chart, as do Downes & Shara (1993). It was named by Kazarovets & Samus (1995). In this paper, we present two long-term light curves for BK Lyn, from the Indiana Automated CCD photometric telescope (hereafter RoboScope), and from sky patrol plates from the Harvard College Observatory archive. We also present two radial velocity studies, carried out in 1991 and 1994, and discuss the claim by Dobrzycka & Howell (1992) that BK Lyn is the first nova-like with an orbital period below the CV period gap, the well-known range of orbital periods between 2 and 3 h in which CVs are rare (Whyte & Eggleton 1980). Distinguishing whether BK Lyn is a nova-like or a WZ Sge star is also discussed.

★Present address: Planetary Science Institute, 620 North Sixth Avenue, Tucson, AZ 85705-8331, USA.
E-mail address: far@psi.edu

2 LONG-TERM LIGHT CURVES

2.1 RoboScope

RoboScope is a 41-cm telescope in Indiana equipped for unattended differential stellar photometry (Honeycutt et al. 1989; Honeycutt & Turner 1992). RoboScope's exposures are scheduled, executed, and reduced in an automated, unattended fashion. On a typical clear night RoboScope obtains 95–190 unguided exposures with a duty cycle of about 85 per cent. The faint magnitude limit for the 4-min exposures with a signal-to-noise ratio (S/N) of 10 and a moonless night is $V \approx 18$.

All exposures of the BK Lyn field were reduced by inhomogeneous ensemble photometry (Honeycutt 1992) using 116 exposures and 25 comparison stars. The error bars in Fig. 1 were calculated in the ensemble solution from the observed scatter in the constant comparison stars and are for differential magnitudes on the instrumental system. There is an additional error in the zero-point of 0.017 mag, established using the secondary standards of Henden & Honeycutt (1995).

The light curve of BK Lyn has 116 exposures on 98 separate nights between 1992 September 23 and 1995 April 6 (see Fig. 1). No data were acquired during the middle of the three observing seasons. The average measurement error for a single observation of BK Lyn (and for constant stars of similar brightness in the ensemble solution) is 0.017 mag, while the scatter in the brightness of BH Lyn about its mean magnitude is 0.036 mag. BK Lyn therefore showed low-amplitude variability but no outbursts or low states during this observing interval. These 0.036-mag variations are not coherent on the period established in Section 4, and are therefore likely due to flickering. Periodicities in the photometry with periods between 51 min and 1000 d were searched for with Lomb–Scargle periodograms (Press et al. 1992), but nothing convincing was found.

2.2 Harvard plate archive

Sky patrol plates were examined, with a total of 74 detections. These plates were from the RH and BM series, taken in a blue (photographic) bandpass in the years 1929–50, and centred on the $9^{h}30+30°$ field. There were also 38 non-detections, in which BK Lyn was fainter than various plate limits spread over $9.0 \leq m_{pg} \leq 13.5$. Times between observations varied widely, but were generally separated by weeks. Histograms of the detections, plate limits, and non-detections are shown in Fig. 2.

BK Lyn did not vary by more than $\Delta m_{pg} < 1.2$ in any of the detections, which were spread from 1933 to 1950. These magnitude estimates were done by eye, and calibrated with a sequence of stars in the field by the relation of King & Raff (1973) between B magnitude and spot diameter on Palomar Observatory Sky Survey prints. They are therefore accurate only to ± 0.3 mag, but dwarf novae vary by 2–5 mag on the time-scales on which these sky patrol plates were taken (Ringwald 1994), as do anti-dwarf novae, also called VY Scl stars (La Dous 1993).

If BK Lyn were a faint dwarf nova in which its outbursts took it into the range in which we detected it, it would not have spent such a large fraction of its time in this range, namely 74 detections in 112 plates, and with nearly all the non-detections being brighter than this 1.2 mag range. The detections are clearly more tightly clustered than their corresponding plate limits, and show that BK Lyn really does have little photometric variability.

3 SPECTRUM

3.1 1991 February

The 1991 spectra were taken with the 1.3-m McGraw-Hill telescope, Kitt Peak, Arizona and its Mark IIIa (black)

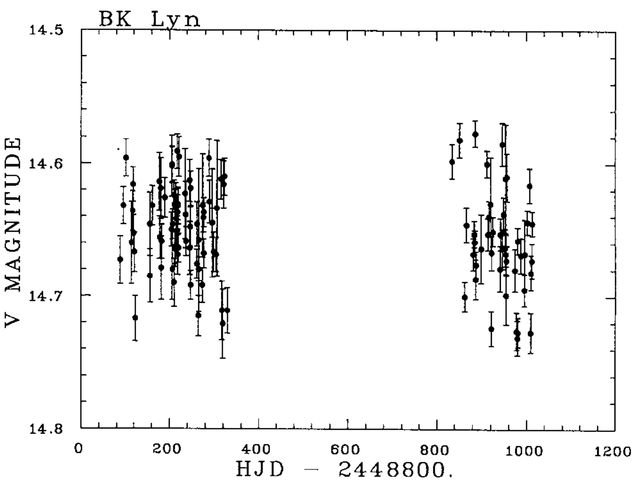

Figure 1. RoboScope light curve of 116 exposures from 1992 September 23 to 1995 April 6 UT. Note the vertical scale: there are no obvious dwarf nova outbursts, which occur typically on time-scales of weeks to months and have amplitudes of 2–5 mag.

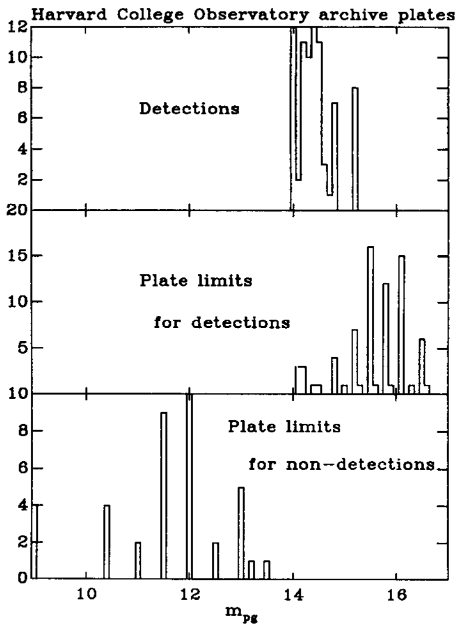

Figure 2. Histogram of magnitudes from the Harvard plate magnitude estimate, of both detections and non-detections. Nearly all magnitudes are within a 1.2 mag range. Again, no dwarf nova outbursts are seen.

spectrograph. This all-transmission Cassegrain instrument was used with a grism with 300 line mm^{-1} and blazed at λ6400 Å and a Hoya Y-50 order-blocking filter. Slit rotation was never used, although atmospheric dispersion effects should be small near Hα, the line used for the radial velocity study. A slit 2.17 arcsec wide was used for all spectra, and velocity errors were minimized by autoguiding to within 0.2 arcsec.

These spectra covered $\lambda\lambda$6200–9000 Å and were taken on 1991 February 26 and 27 UT. The detector was the TI-4849 CCD in the BRICC camera (Luppino 1989). Both nights had 1–2 arcsec seeing, with cumulus clouds intermittently present throughout the first night and at the ends of both nights. This was unfortunate because a time baseline as long as possible modulo one day is important for time series work (see Thorstensen & Freed 1985).

The spectra had 5 Å $pixel^{-1}$ dispersion, 11-Å resolution, and 15-min exposure times. They were reduced and calibrated in the same way as by Ringwald (1994). While relative spectrophotometry should be accurate to a few per cent, the absolute scale is uncertain by a magnitude, because of the clouds. Spectra of the hot star BD + 26 2606 (Oke & Gunn 1983) were taken to map and remove the telluric absorption bands (see Wade & Horne 1988).

No red star was visible in the grand average for the 1991 spectra (see Fig. 3), despite S/N > 180 near Hα and S/N > 140 near λ7600 Å, where the strongest TiO bandhead would lie. On average, the individual spectra had S/N = 32 near Hα. All lines were weak: the equivalent width of the emission core of Hα was measured to be 5.0 ± 1.0 Å. He I λ6678 Å is present in emission, with an equivalent width of 0.5 ± 0.2 Å. O I λ7773 Å may be present in absorption, with an equivalent width of 0.8 ± 0.2 Å.

3.2 1994 December

Further spectra were obtained on 1994 December 3, 4, 8 and 9 UT with the same telescope and spectrograph. This time the detector was a 2048^2 Loral CCD, and a 600 line mm^{-1} grism yielded a higher dispersion of ~1.3 Å per 15-μm pixel and a FWHM resolution of 4 Å. The spectra covered $\lambda\lambda$4280–6900 Å, but the focus degraded noticeably shortward of about λ4700 Å. Again we were careful to maintain an accurate wavelength calibration, and to span the largest possible range of hour angle. Because the approximate period was already known, we did not obtain long continuous series of measurements, but only observed the object when it rose in the east and when it had passed the meridian in the morning. Because of the relative faintness of the object at this dispersion, we took relatively long exposures (600 s or about 0.1 cycle) to minimize the effects of readout noise.

Fig. 4 shows the mean spectrum, calibrated by comparison with spectrophotometric standards. Occasional clouds, slit losses, and atmospheric dispersion make the absolute flux scale uncertain by a factor of about 2. Hβ and He I λ5876 Å both show strong central absorption, while Hα is almost filled in. The emission core of Hα is nearly triangular in a profile with a FWHM of 18 Å. Despite the unusually short orbital period, there is little in the spectrum to differentiate it from the longer period UX UMa stars (e.g. Williams 1983).

4 RADIAL VELOCITY STUDIES

4.1 1991 February

To measure the velocities of Hα, given in Table 1, we used the double-Gaussian convolution method of Schneider & Young (1980), optimized for the observed Hα linewidth. The velocities measured are given in Table 1. A Lomb–Scargle periodogram (Press et al. 1992) was computed for these velocities, and is shown in Fig. 5. The peak corresponding to a period of 0.075 d is highest, and Fig. 6 shows the velocities folded on this period and the best-fitting sinusoid.

The contrast between this peak and either of its 1 cycle d^{-1} aliases did not have an overwhelmingly clear choice, so

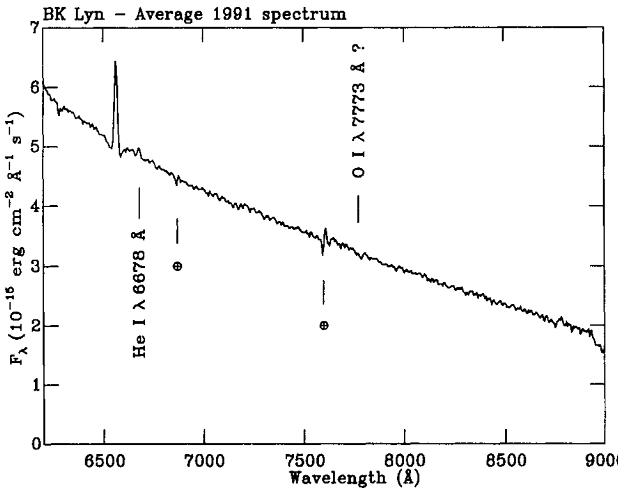

Figure 3. Average of all spectra from 1991, of 8.0 h total exposure time over 8.6 h. While the telluric absorption bands are mapped and removed with the spectrum of a hot star, the removal was imperfect: the residual bands are marked with Earth symbols. There are no obvious TiO bands near λ7150 Å or λ7600 Å.

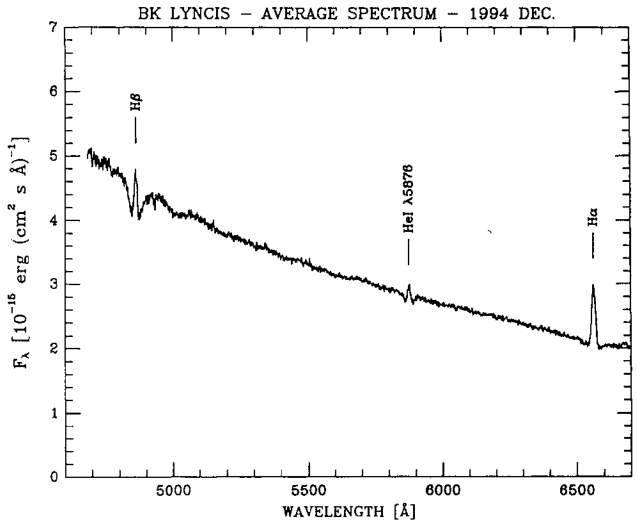

Figure 4. Average blue spectrum of BK Lyn, from the 1994 spectra. The absolute scale of the vertical axis is uncertain by as much as a factor of 2 because of occasional clouds and unknown slit losses. Spectral lines are marked.

Table 1. BK Lyn – Hα emission radial velocities.

HJD[a]	V (km s^{-1})	HJD[a]	V (km s^{-1})	HJD[a]	V (km s^{-1})	HJD[a]	V (km s^{-1})
1991 February[b]							
8313.614	34	8313.704	58	8314.619	−70	8314.731	−105
8313.625	83	8313.715	15	8314.630	−109	8314.742	−59
8313.636	−12	8313.727	−43	8314.642	−124	8314.754	27
8313.647	2	8313.738	−74	8314.653	−83	8314.765	26
8313.659	−90	8313.749	−66	8314.664	−96	8314.777	−130
8313.670	−60	8313.760	−27	8314.675	−30	8314.788	−182
8313.681	−97	8314.597	−10	8314.709	−157	8314.799	−123
8313.692	26	8314.608	−86	8314.720	−205	8314.810	−29
1994 December[c]							
9690.021	72	9690.826	42	9691.034	−109	9694.823	78
9690.025	129	9690.834	165	9691.044	−43	9694.830	−15
9690.029	37	9690.997	15	9694.783	−123	9695.034	168
9690.805	−10	9691.004	−44	9694.790	−8	9695.040	124
9690.809	−92	9691.012	−125	9694.798	67	9695.046	102
9690.813	−69	9691.019	−126	9694.805	75		
9690.819	−40	9691.027	−128	9694.815	84		

[a]Heliocentric Julian Date of mid-integration, minus 2 440 000.
[b]Double-Gaussian algorithm, separation 650 km s^{-1}.
[c]Double-Gaussian algorithm, separation 820 km s^{-1}.

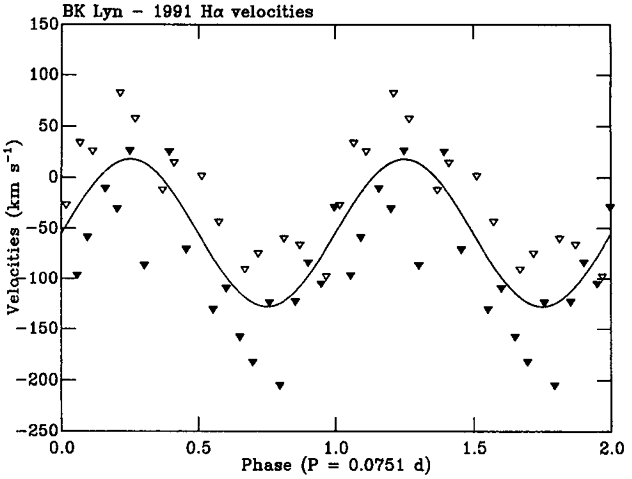

Figure 6. Least-squares fit of Hα velocities from 1991 to a sinusoid, of period 0.075 d. Open triangles represent velocities from February 26; filled triangles, from February 27.

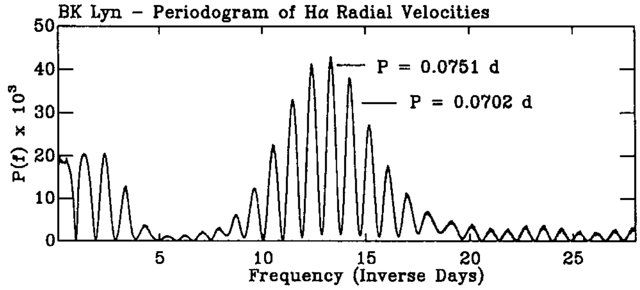

Figure 5. Periodogram of Hα velocities from 1991, using the Lomb–Scargle algorithm (Press et al. 1992).

the alias choice was in doubt. The alias of 0.075 d (108 min) was slightly preferred, since it fitted a sinusoid better, as α in Table 2 shows, but the alias at 0.070 d (101 min) could not be excluded. These two aliases bracketed the period of 104 min found by Dobrzycka & Howell (1992). The problem with discriminating between 1 cycle d^{-1} aliases was not with measuring velocities, but with the short (5.3-h) time-base modulo one day, caused by the clouds on the longer of the two nights. A Monte Carlo simulation of the measurement after the prescription of Thorstensen & Feed (1985), with the noise level chosen to match that of the best fit around the poorer fitting 0.070-d period, gave a discriminatory power of only 76 per cent and correctness likelihood of 89 per cent, both of which are less than compelling.

4.2 1994 December

The 1994 spectra were taken to resolve the period ambiguity of the 1991 spectra. Again the velocities were measured by the Schneider & Young (1980) method, optimized for the observed Hα linewidth, and are listed in Table 1. Fig. 7 (top panel) shows a period search on these velocities, computed by the Lomb–Scargle prescription. The strongest peak (solid arrow) is near $P = 0.075$ d, in agreement with the best period given above, while the 0.070 d alias (dashed arrow) appears only weakly. The mean square scatter around the best fit of this alias is 2.4 times larger than that around the 0.075 d period's fit. A Thorstensen & Freed (1985) Monte Carlo simulation, with the noise level chosen to match that of the best fit around the poorer fitting 0.070-d period, gave a discriminatory power of 94 per cent and a correctness likelihood of more than 99.9 per cent for the alias choice. Another test, with artificial data sets constructed around the best-fitting alias, showed the 2.4 times ratio of variances to be typical. The data therefore look just as expected if the 0.075-d period is correct, and are inconsistent with a 0.070-d period, so the ambiguity is resolved.

Several other periods appear more strongly in Fig. 7 than the 0.070-d period. To see if these might be real periodicities, we constructed a pure sinusoid on the ephemeris of the 0.075-d period and sampled it the same way as our observations. The lower panel of Fig. 7 shows the periodogram of this artificial time series, which appears similar to that of the real data. Thus there is no evidence for additional periods in the velocities.

Fig. 8 shows the velocities folded on the period and the best-fitting sinusoid. The velocity amplitude measured in 1994 is larger than that measured in 1991, to 4σ significance. While the higher dispersion might account for this, one would expect the higher resolution spectra to fit closer to the line core, not the lower resolution spectra. This may represent a physical change in the star – spectrum variability had been noted by Green et al. (1982) and by Szkody & Howell (1992) – and should reinforce the usual caution against using these velocities to estimate the masses of the binary components. The γ velocities for the 1991 and 1994 observations are also inconsistent, although radial velocity standards were not taken, so errors in the wavelength scale of 20–30 km s^{-1} could be present.

The period's precision is a consequence of the 5-d span of the observations. However, 1380 d separate the 1991 and

Table 2. BK Lyn – derived orbital parameters, for Hα velocities[a]

	P_{orb} (days)	K_{em} (km s^{-1})	γ_{em} (km s^{-1})	T_0 (HJD – 2440000)	σ (km s^{-1})
1991 February[b]	0.0751 ± 0.0002	73 ± 13	-55 ± 9	8313.834 ± 0.002	48
Alias 2	0.0702 ± 0.0004	71 ± 14	-55 ± 9	8313.823 ± 0.002	52
1994 December[c]	0.07498 ± 0.00005	128 ± 14	-8 ± 9	9691.0431 ± 0.0012	43

[a]Velocities fit to $V(t) = \gamma_{em} + K_{em} \sin[2\pi(t - T_0)/P_{orb}]$. All measurements use double-Gaussian method. Gaussian widths are 640 km s^{-1}. All errors are estimated to 68 per cent confidence (see Thorstensen & Freed 1985). Here σ is the uncertainty in a single measurement as derived from the scatter around the best fit, and the parameter uncertainties are purely formal (see Cash 1979).
[b]Gaussian separation 650 km s^{-1}.
[c]Gaussian separation 820 km s^{-1}.

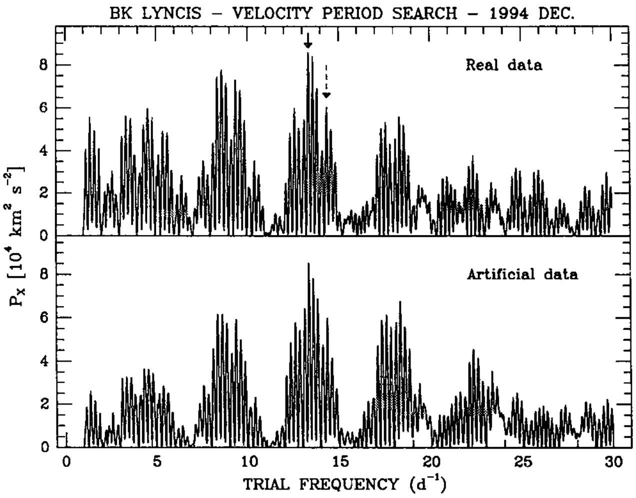

Figure 7. (Upper panel) Lomb–Scargle periodogram of the Hα velocities from 1994. The period we adopt is indicated by the solid arrow; the dashed arrow shows the 0.070 d alias which could not be ruled out with the 1991 observations. (Lower panel) Lomb–Scargle periodogram of a sinusoid with the parameters of the 1994 fit in Table 2, and sampled in time in the same way as the data. There is no evidence for periodicities other than that at 0.075 d.

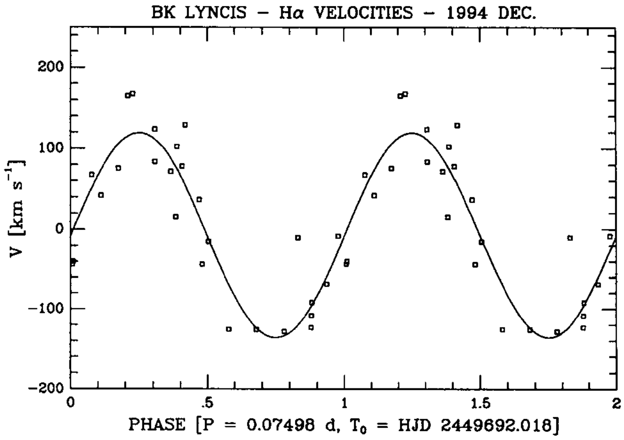

Figure 8. Radial velocities of Hα from 1994, folded on the adopted period, with a best-fitting sinusoid superimposed.

1994 observations, resulting in a 1σ uncertainty of ± 13 cycles in the intervening cycle count. A long-term ephemeris would require more observations.

5 DISCUSSION

Dobrzycka & Howell (1992) claimed that BK Lyn is the first UX UMa star to be found below the CV period gap, with a spectroscopic period of 104 ± 8 min. We confirm and improve the measured period to 107.97 ± 0.07 min, so it is indeed below the period gap.

There was little evidence to show whether BK Lyn really was a nova-like variable, however, since the only photometry discussed by Dobrzykca & Howell (1992) was a single 4-h run (Howell et al. 1991). Six months later, Szkody & Howell (1992) obtained spectra over three nights that were of consistent brightness, but spectrum variability was seen. A change in the lines from emission to absorption was also seen by Green et al. (1982) but they did not note a change in brightness.

Some evidence that BK Lyn may be a nova-like was found by Skillman & Patterson (1993). In a campaign from 1992 February to 1993 February, they took time-resolved photometry on 25 nights. Other than flickering, they saw little variability from epoch to epoch, with average variations between observing sessions of $\Delta V < 0.17$. They did detect a coherent photometric modulation with a period of 113.11 ± 0.01 min, which they attributed to permanent superhumps from a precessing elliptical disc (see Patterson & Richman 1991). The difference between this photometric period and our spectroscopic period is significant to 73σ confidence: the photometric period is 4.75 ± 0.07 per cent longer than the spectroscopic period, as expected for a superhump.

Still, doubts remain over whether BK Lyn is a nova-like. The permanent superhumps suggest a high luminosity, but this phenomenon is not well understood. With enough tidal interaction, superhumps might conceivably occur in a quiescent disc. WZ Sge has outbursts only on time-scales of decades, so that outbursts could easily have been missed even in an extensive archival light curve of BK Lyn. WZ Sge has an optical spectrum that upon examination is not overly unlike that of BK Lyn (or UX UMa): both have Balmer lines with absorption wings flanking emission cores. The spectrum of BK Lyn fits a power law $f_\lambda = k\lambda^{-\alpha}$ of index $\alpha = 2.66 \pm 0.10$. This is not dissimilar to a steady-state disc continuum, which should be of index 2.33, but a white dwarf continuum, such as shown by WZ Sge, might mimic this in the optical range over $\lambda\lambda$6350–6500 Å and $\lambda\lambda$6650 and 8000 Å, in which this fit was made. A white dwarf continuum may find it difficult to mimic the observed spectrum variability, in which the absorption wings change width, but a luminous disc could easily do this. The absorption wings about Hβ of BK Lyn shown in Fig. 4 are about 80 Å wide, consistent with a full-width at zero-intensity of 2500 km s^{-1}, on the order of the orbital velocity for a white dwarf. WZ Sge has doubled peaks in its emission lines, which are broad and strong [W(Hα) = 123 Å; Williams 1983]; BK Lyn has single-peaked lines, which are narrow and weak (W(Hα) = 5.0 Å; see Section 3.1). This may support the interpretation that BL Lyn is a nova-like variable, but not necessarily. BK Lyn is known not to eclipse, because of the 4 h of time-resolved photometry of Howell et al. (1991). A face-on CV should have weaker lines (e.g. Horne & Marsh 1986); an optically thick disc continuum should be brighter when face-on, from geometry and limb darkening.

Some constraints on the system's absolute magnitude may be made with the non-detection of TiO at S/N = 140 described in Section 3.1. Assuming that a CV with a 108-min period has an M5 dwarf secondary (Patterson 1984), with $M_R = 13.2$ (Bessell 1991), a clear 4σ detection of the TiO bands would require that $M_R < 9.6$ for the system. Since $V-R \approx 0$ for CVs, the system's absolute magnitude is $M_V < 8.1$. A marginal 2σ detection would require that $M_R < 8.9$ and $M_V < 7.4$. None of these constraints can show whether BK Lyn is a dwarf nova or a nova-like, since $M_V \approx 8$ for dwarf novae and $M_V \approx 4$ for nova-likes.

Either of two observations could settle the matter definitively. If a dwarf nova outburst is ever observed, this star is a dwarf nova. Alternatively, one might obtain a UV spectrum, which so far has not been taken with either the *International Ultraviolet Explorer* or *Hubble Space Telescope* spacecraft. The presence of a power-law continuum and P Cygni profiles in the lines, especially C IV λ1549 Å, would show at a glance whether BK Lyn is a nova-like (see Córdova & Howarth 1987).

If BK Lyn were a nova-like, assuming that nova-likes have high mass transfer rates, it would show that there is a range in the quiescent mass transfer rate in CVs below the period gap. There should not be, if angular momentum loss is entirely due to gravitational radiation. The period gap has long been thought to be caused by the turn-off of magnetic braking in CVs, as their secondary stars become fully convective (Robinson 1983; Rappaport, Joss & Webbink 1983; McDermott & Taam 1989). In a compilation of the absolute magnitudes of CVs, Warner (1987) suspected that CVs with periods shorter than the period gap can have luminosities greater than can be accounted for by angular momentum loss by gravitational radiation alone. Osaki (1995a,b) also suspected high luminosities in CVs below the period gap, since high mass transfer rates in quiescence may explain the recurrent outburst behaviour seen in the dwarf novae RZ LMi and ER UMa. These stars may be to the Z Cam stars what the ordinary SU UMa stars are to the U Gem stars, and what BK Lyn may be to the UX UMa stars. This unified scheme for dwarf nova outburst behaviour would therefore depend on just two physical parameters: orbital period and quiescent mass transfer rate, itself dependent on angular momentum loss rate.

Anomalously high angular momentum loss below the period gap may imply that magnetic stellar wind braking still works below the period gap – but the CV secondary stars there should be fully convective, and therefore should not have magnetic braking. Recent UV spectra from *HST* (Linsky, Wood & Brown 1994) have shown evidence of flaring in the single star VB 10 (Gliese 752B), an unexpectedly faint red dwarf of type M8 Ve. VB 10 is nearly a brown dwarf: solar-type dynamo processes should not be present, but apparently are. If BK Lyn is a genuine nova-like CV beneath the period gap, it may provide additional evidence of magnetic activity occurring in the very faintest stars, here in an interacting binary.

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