The Astrophysical Journal Supplement Series, 181:238–243, 2009 March
doi:10.1088/0067-0049/181/1/238

REFINED ORBITAL SOLUTION AND QUIESCENT VARIABILITY IN THE BLACK HOLE TRANSIENT GS 1354–64 (= BW CIR)

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Received 2008 July 29; accepted 2008 October 27; published 2009 March 5

ABSTRACT

In Casares et al. we presented the first radial velocity curve of the companion star to BW Cir which demonstrates the presence of a black hole in this historical X-ray transient. But these data were affected by aliasing and two possible periods at 2.5445 days and 2.5635 days were equally possible. Here we present new spectroscopic data that enable us to break the 1-year aliasing and confirm 2.5445 days as the correct orbital period. We also present *R*-band photometry over 14 years, which reveals the presence of important flaring activity dominating the light curves.

Key words: accretion, accretion disks – binaries: close – stars: individual (BW Cir, GS 1354–64) – X-rays: binaries

1. INTRODUCTION

BW Cir (= GS 1354–64) was discovered in 1987 February by the *Ginga* satellite with an X-ray flux of ≃ 300 mCrab (Makino et al. 1987). It displayed X-ray properties reminiscent of black hole (BH) transients, i.e., a combination of a soft multi-BB component plus a hard power-law tail (Kitamoto et al. 1990). A new outburst was detected by the All-Sky Monitor (ASM) aboard the *Rossi X-ray Timing Explorer* (*RXTE*) in 1997 November but only reached a modest flux of 40–50 mcrab and stayed in the low/hard state throughout (Brocksopp et al. 2001). BW Cir also occupies the same region of sky as the X-ray sources MX 1353–64 and Cen X-2, discovered in 1971 and 1967 respectively. The latter, with a peak X-ray flux of ∼ 8 Crab, was the first X-ray transient ever discovered. However, the poor X-ray location, lack of optical counterpart and very different X-ray properties make the association of Cen X-2 with BW Cir disputable.

Dynamical evidence for a BH in BW Cir was first presented in Casares et al. (2004, C04 hereafter). Spectroscopic features of a G0-5 III donor are shown to move in a 2.5 days orbital period. Furthermore, the binary mass ratio was constrained to $q = M_2/M_1 = 0.13$ through resolving the rotational broadening of the companion's absorption lines. However, these data are affected by 1-year aliasing which results in two equally significant orbital solutions: $P_{orb} = 2.5445(2)$ days and 2.5635(2) days with velocity semiamplitudes $K_2 = 279 \pm 5$ km s^{-1} and $K_2 = 292 \pm 5$ km s^{-1}, respectively. These have some impact on the black hole masses and translate into lower limits of $7.9 \pm 0.5\ M_\odot$ and $8.8 \pm 0.6\ M_\odot$, respectively.[8]

In this paper we present new spectroscopic data that demonstrates that the shorter orbital period is the correct solution.

[8] Note that this number is slightly different to the value reported in C04 because that was affected by a small computation error.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Spectroscopy

In order to break the 1-year aliasing in the orbital solution of C04 we obtained data during early 2006. Eleven spectra of BW Cir were obtained in Service Mode on the nights of February 28, and 2006 March 10, 19, 21–23 using the FORS2 Spectrograph attached to the 8.2 m Yepun Telescope (UT4) at Observatorio Monte Paranal (ESO). Two spectra were collected every night, except for the night of March 10 when only one spectrum was obtained. Conditions were always good, with seeing varying between 0.5–1.2 arcsecs and integration times were fixed to 1376 s. The R1200R holographic grating was employed which, combined with a 1.0 arcsec slit, produced a wavelength coverage of λλ5870–7370 at 110 km s^{-1} (FWHM) resolution, as measured from Gaussian fits to the arc lines. All the images were debiased and flat-fielded, and one-dimensional spectra extracted using conventional optimal extraction techniques in order to optimize the signal-to-noise ratio of the output (Horne 1986).

A He+Ne+Hg+Cd comparison lamp image was obtained with the telescope in park position to provide the wavelength calibration scale. This was derived by a fourth-order polynomial fit to 31 lines, resulting in a dispersion of 0.74 Å pix^{-1} and an rms scatter of 0.03 Å. Instrumental flexure in our target spectra was monitored through cross-correlation between sky spectra and it was always less than 5 km s^{-1}. However, we note that the slit width corresponds to 110 km s^{-1} and hence the positioning of the star within the slit, under very good seeing conditions, can be another source of systematics in the velocities. This was tested by cross-correlating the Telluric absorption features present in our spectral range but the velocity variations obtained are always less than 6 km s^{-1}. All these velocity drifts were removed from each individual spectrum, and the zero point of the final wavelength scale was fixed to the strong OI skyline at λ6300.304. Finally, the heliocentric correction was applied to all the spectra.

Table 1
Local Standards

Star	R.A.(J2000)	Decl. (J2000)	V	err	$B-V$	err	$V-R$	err	$V-I$	err
A	13:58:05.4	−64:44:22.8	18.482	0.015	1.783	0.042	0.936	0.030	1.760	0.021
B	13:58:07.7	−64:44:07.3	18.642	0.020	1.173	0.034	0.706	0.040	1.334	0.036
C	13:58:06.9	−64:43:59.9	18.994	0.018	1.549	0.043	0.881	0.040	1.619	0.030
D	13:58:04.0	−64:44:02.0	18.327	0.010	1.777	0.026	0.966	0.020	1.899	0.013
E	13:58:12.3	−64:44:05.5	18.284	0.011	1.244	0.021	0.714	0.020	1.384	0.018

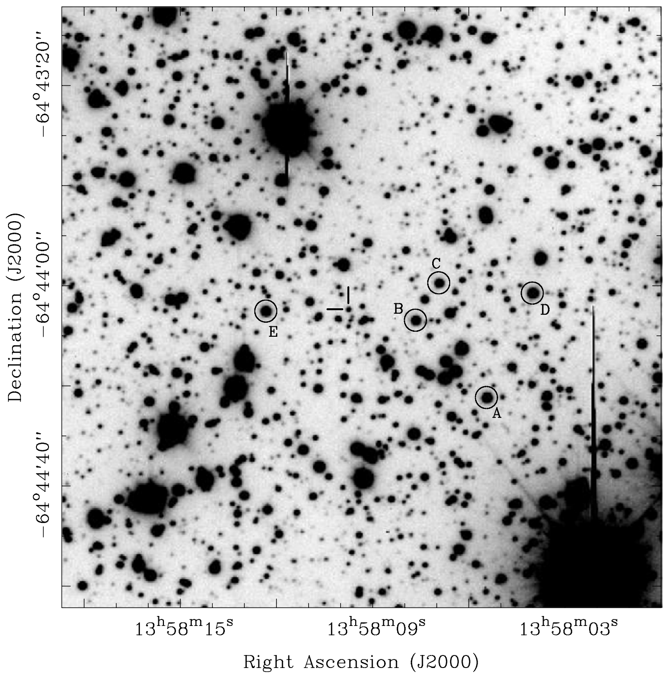

Figure 1. Finding chart of BW Cir obtained with VLT+FORS1 on 2000 June 4. The target is indicated with hash marks. The magnitudes of stars A–E are listed in Table 1.

2.2. Photometry

BW Cir was observed with the Danish Faint Object Spectrograph and Camera (DFOSC) attached to the Danish 1.54 m telescope at the European Southern Observatory (ESO) on the nights of 1995 May 3–6 and 8. The Tektronix TK1024M CCD was used with a Gunn *i* filter, giving a 6.7 × 6.7 arcmin^2 field of view, with a scale of 0.39 arcsec pixel^{-1}. A total of 48 images were obtained with integration times varying between 600 and 1200 s depending on seeing and weather conditions. Fourteen additional frames were also obtained using a Gunn *r* filter. The brightness of BW Cir was measured with respect to three reference stars that were calibrated through observations of the standard star BS 5105 during photometric conditions. The telescope has significant pointing restrictions which resulted in $\leqslant$4.6 hr on target per night. In order to extend the baseline we obtained additional photometry using the 1 m telescope at the South African Astronomical Observatory (SAAO) on the nights of 1995 May 2–3. A total of 47 frames were collected with a RCA 53612 CCD and a Johnson–Cousins I filter using 900 s integrations. Despite the different photometric systems used at SAAO and ESO, one should note that the effective wavelength of Gunn-i when used with a TEK CCD comes down to almost exactly the same as Johnson–Cousins I. This is confirmed by two simultaneous datapoints from the night of May 3 which are consistent within 0.02 mags.

Additional photometry was obtained on the nights of 2003 May 30–31 using the Magellan Instant Camera (MagIC) and a Harris *R* filter on the 6.5 m Magellan telescope at Las Campanas Observatory. A total of 94 images were obtained with 200 s integration times. Seeing varied between 0.5–1$''\!.$2. The brightness of BW Cir was measured with respect to local reference stars which were calibrated through seven Landolt fields observed with the CTIO 1.5 m telescope on 1997 June 29 during photometric conditions. Figure 1 shows a deep *R*-band image of the field of BW Cir obtained with VLT+FORS1 on 2000 June 4 (see below). The target is marked with a circle and the local standards are labeled A, B, C, D, and E. The calibrated magnitudes of these stars are listed in Table 1.

These are the two main photometric datasets. In addition, we also observed BW Cir with the Gun *r* filter on the Danish 1.5 m telescope at La Silla on the nights of 1994 May 1–6 (55 frames), 1996 June 5–7 (18 frames), 1998 March 27–29 (27 frames), using integration times between 600 s and 1800 s and the same instrumental setup described above. Also six 200 s *R*-band frames were obtained at the Magellan telescope on 2002 August 4 and 6 and 25 × 600 s images with the 1.9 m telescope at SAAO on 2008 May 7. Furthermore, we extracted Bessell *R* magnitudes from the FORS2 acquisition images of our spectroscopic runs on 2000 August 23–24, 2003 June 22–23, 2004 May 14–15 & 25–27 and 28 February, and 2006 March 10, 19, and 21–23. Finally, 20 *R*-band magnitudes were collected from archival images on 1995 April 4, 1995 June 5, 1996 March 25–26, 1996 May 24 and 22 November 1997 on the 3.5 m NTT at La Silla, 1997 June 28–29 and 1997 July 1 on the 1.5 m at CTIO and 2000 June 4 using FORS1 on the 8.2 m VLT (UT1) at Monte Paranal.

All databases were debiased and flat-fielded in the standard way and the point-spread function fitting algorithm DAOPHOT (Stetson 1987) was employed to extract the instrumental magnitudes.

3. THE ORBITAL PARAMETERS REVISITED

Our 11 spectra were processed in the same way as described in C04 and individual radial velocities were extracted by cross-correlation with the same G5III radial velocity template HD 62351. The new velocities were added to those reported in C04 to make a final database of 66 radial velocity points. Figure 2 presents the χ^2 periodogram in the region 0.35–0.45 cycles d^{-1}, which can be compared with Figure 1 of C04. Here we have rescaled the error bars by a factor of 1.7 so that the minimum reduced χ^2 is 1.0. This corresponds to 0.393 d^{-1} or P = 2.5445 days. The new velocities enable us to rule out the P = 2.563 days peak (0.390 d^{-1}) at the 99.9 percent significance since it has $\chi^2_\nu = 1.57$ for 62 degrees of freedom. For comparison, in C04 the 2.5445 days period was only significant at the 20 percent level. A least-squares sine-wave fit to the radial velocity curve yields the following parameters:

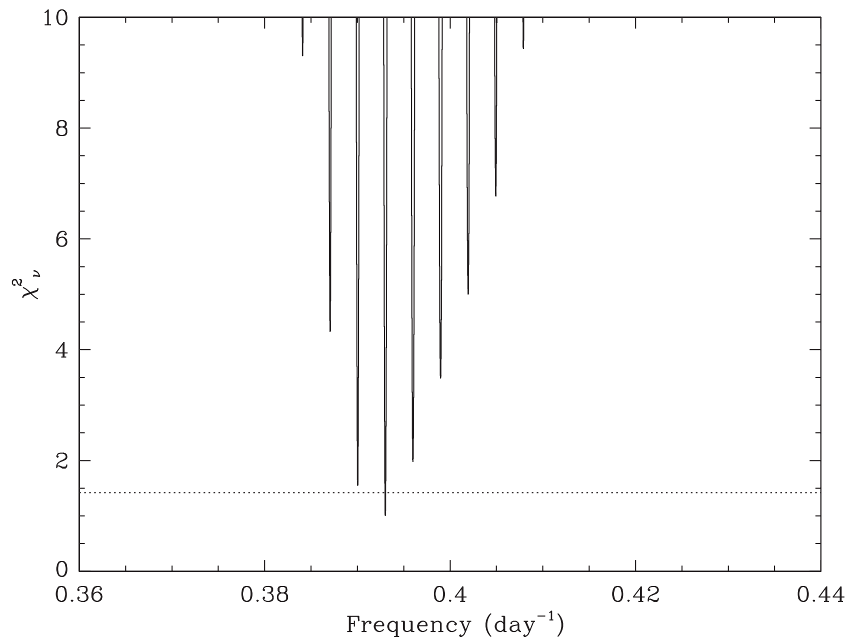

Figure 2. χ^2 periodogram of the 66 radial velocity points. The dashed line represents the 99.9% confidence level and hence the peak at 0.390 d^{-1} (2.564 days) can be confidently rejected.

$$\gamma = 102.0 \pm 4.0 \text{ km s}^{-1}$$
$$P = 2.54451 \pm 0.00008 \text{ d}$$
$$T_0 = 2453140.986 \pm 0.012$$
$$K_2 = 279.0 \pm 4.7 \text{ km s}^{-1},$$

where T_0 corresponds to standard phase 0, i.e., the inferior conjunction of the optical star. All quoted errors are 68 percent confidence. Figure 3 displays the radial velocity points folded on the 2.54451 days period with the best sine fit superimposed. The open circles mark the velocities corresponding to the 2006 database. The updated mass function of BW Cir is hence $f(M) = M_1 \sin^3 i/(1+q)^2 = PK_2^3/2\pi G = 5.73 \pm 0.29\, M_\odot$.

At this point we decided to look back at the $V \sin i$ constraint derived in C04 to test whether it was biased by the comparatively low resolution of the data. In order to do so we applied the least-squares deconvolution (LSD) method to the summed spectrum of C04, Doppler corrected into the rest frame of the companion star. The LSD method effectively stacks the n absorption lines of the spectrum into a single "average" absorption profile with signal-to-noise increased by $\sqrt{n}$. Another LSD profile is also computed for the template's spectrum, which was observed with identical instrumental resolution. Subsequently, the optimal subtraction technique yields the best $V \sin i$ required for the template's LSD profile to match the object's profile. Shahbaz & Watson (2007) showed that this method is safe from systematics even when using low-resolution low signal-to-noise data. The LSD method provides $V \sin i = 69 \pm 8$ km s^{-1}, in excellent agreement with C04 but more conservative errors. Another potential source of systematics is the assumption of continuum limb-darkening coefficient in the computation of the rotational profile. Absorption lines in late-type stars are expected to have smaller core limb-darkening coefficients than the continuum (Collins & Truax 1995) and, therefore, assuming the continuum limb-darkening coefficient could bias the result. We also tested this by repeating the above analysis using zero limb-darkening as a conservative lower limit and obtain $V \sin i = 65 \pm 8$ km s^{-1}. This demonstrates that the error in $V \sin i$ is dominated by the signal-to-noise of the spectra rather than the choice of limb-darkening. Furthermore, Shahbaz (2003) showed that, for the case of N Sco 94 (whose donor has similar $T_{\rm eff}$ to BW Cir), the true $V \sin i$ is only slightly lower than the value obtained assuming continuum limb-darkening and, hence, we decide to take $V \sin i = 69 \pm 8$ km s^{-1} as the final value.

For a tidally-locked Roche-lobe-filling star $V \sin i$ scales with K_2 as a function of q and can be used to constrain the latter (see Wade & Horne 1988). Our refined $V \sin i$ value yields $q = 0.12^{+0.03}_{-0.04}$ which, in turn, sets an upper limit to the binary inclination $i \leqslant 79°$ through the absence of X-ray eclipses. Therefore, a secure lower limit to the black hole mass becomes $M_1 \geqslant 7.6 \pm 0.7\, M_\odot$.

4. THE LIGHT CURVES AND ACCRETION DISC VARIABILITY

Even in quiescence BW Cir displays a large photometric variability. This is clearly demonstrated in Figure 4, where we show the long-term light curve between 1994 and 2008. The open circles mark the magnitudes of the 1997 outburst, as reported in Brocksopp et al. (2001). BW Cir shows variability of several tens of magnitude over one night and also on different nights, with an interval of minimum brightness during years 2002 and 2003. Figure 5 shows the 1995 SAAO+ESO i-band and 2003 Magellan R-band light curves of BW Cir, folded on the spectroscopic ephemeris. These are the two datasets with best quality and phase coverage. The light curves are dominated by large flaring activity with a characteristic timescale of ~ 3 hr which conceals the classic double-humped ellipsoidal modulation. For the purpose of comparison, we overplot in Figure 5 an ellipsoidal model for $q = 0.12$, a typical inclination of $i = 60°$ and veiled by 56% (solid line). This behavior is reminiscent of the 6.5 d BH binary V404 Cyg (Wagner et al. 1992; Pavlenko et al. 1996; Zurita et al. 2004) and also, to some extent, to all quiescent X-ray transients when inspected at sufficient time resolution (see Zurita et al. 2003). The origin of this variability is not yet fully understood, although

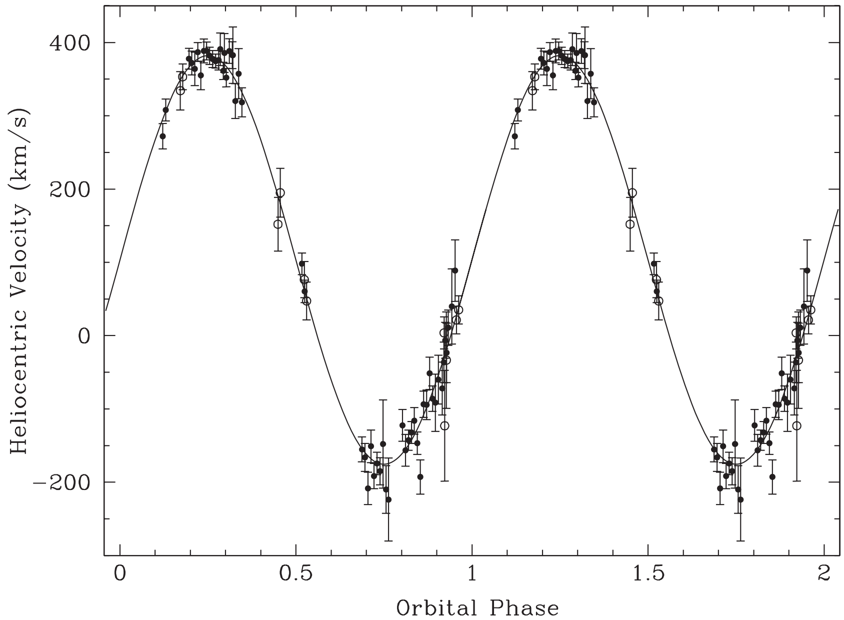

Figure 3. Radial velocity curve of the companion star in BW Cir and best sine wave fit. Open circles indicate the new velocities obtained during the 2006 campaign.

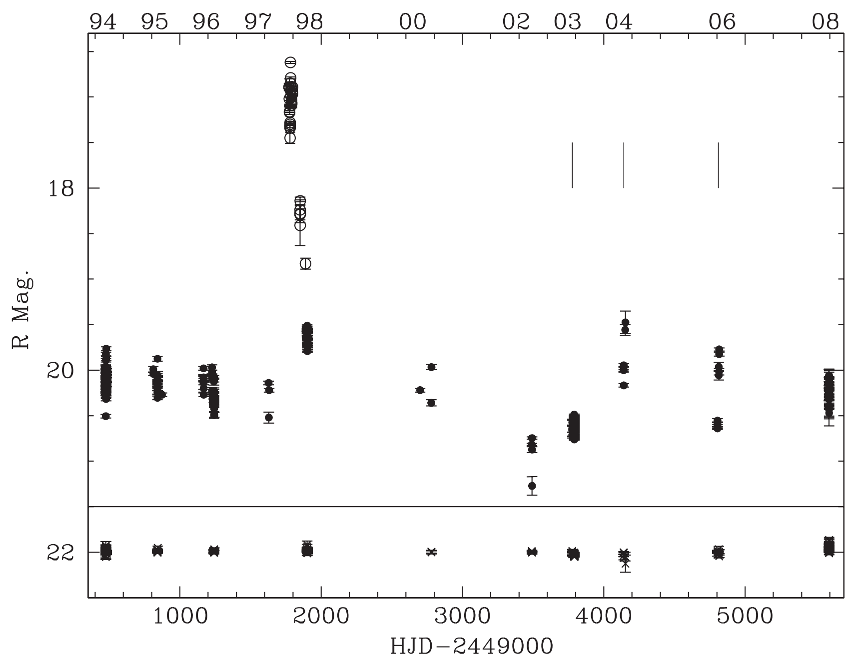

Figure 4. Long-term light curve of BW Cir over 14 years. Open circles show the 1997 outburst, as reported in Brocksopp et al. (2001). The bottom panel displays the light curve of a comparison star similar in brightness to the target and offset for the sake of display. The vertical lines mark the times of our spectroscopic observations.

it appears to be associated with the accretion disc, for which possible scenarios include magnetic reconnection events (Zurita et al. 2003), X-rays reprocessing (Hynes et al. 2004), and direct synchrotron emission from an advective dominated flow (Shahbaz et al. 2003). The amplitude of the flaring activity appears to be larger in the *i*-band than in the *R*-band. However, BW Cir was ∼ 0.5 mags brighter (in the *R*-band) during the 1995 dataset (see Figure 4) and this seems to suggest that the amplitude of the flaring activity increases with brightness. As a matter of fact, this type of short-term variability has been seen to disappear in A0620-00 when the binary gets faint enough (Cantrell et al. 2008). And indeed, the lower envelope of the Magellan data that should show the donor star with minimum disc contamination, seems to trace the ellipsoidal modulation. Clearly more data at minimum brightness is required for a formal ellipsoidal fit.

Furthermore, we notice variations in the accretion disc activity as derived from the H_α EW and the continuum veiling in our spectra. Significant changes are also apparent in the mean line profiles (Figure 6). The EWs of the H_α line display mean values of 48 Å in 2003, 58 Å in 2004 and 47 Å in 2006, with a ∼ 20 percent variability on a timescale of ∼ 3 hr. On the other hand, the mean veiling factors (i.e., fractional contribution of the accretion disc's light to the total flux) are 56% in 2003, 67% in 2004, and 50% in 2006. Therefore, we conclude that significant accretion disc variability is observed in BW Cir, with our 2004 database showing the highest activity. This is again reminiscent of V404 Cyg, where correlated variability in the H_α

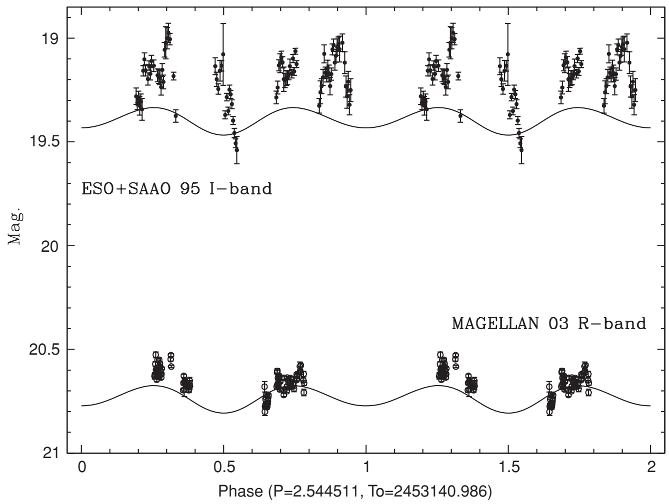

Figure 5. Light curves of BW Cir folded on the new spectroscopic ephemeris. Top light curve shows the 1995 *I*-band datapoints from SAAO+ESO whereas the bottom light curve is the 2003 *R*-band from Magellan. An ellipsoidal model computed for $q = 0.12$, $i = 60^{\circ}$ and veiled by 56% is overplotted. This figure illustrates the dominance of the aperiodic flaring activity over the ellipsoidal modulation.

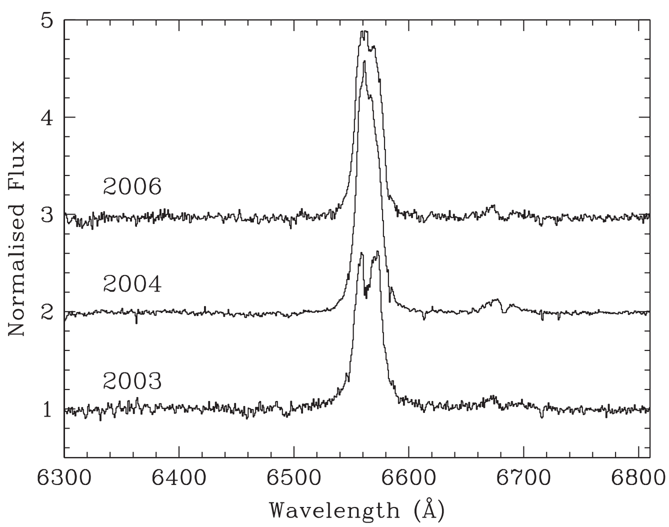

Figure 6. Average spectra obtained in 2003, 2004, and 2006. Note the changing strength and profile of the H_{α} line which traces accretion disc variability. The spectra have been rectified to the continuum and offset in the vertical direction for the sake of display.

line and the continuum has been reported (Hynes et al. 2002, 2004).

5. DISCUSSION

Unfortunately, the strong photometric variability precludes us from being able to fit ellipsoidal models to the light curve and derive the orbital inclination, the only missing parameter for a BH mass determination. Given the strength of the variability the best prospects for a reliable constraint to the inclination require fitting an ellipsoidal model to the lower envelope (as in V404 Cyg by Pavlenko et al. 1996) of a new database obtained during a period of minimum activity. Nevertheless, the large mass function and the lower limit greater than 7.0 $M_{\odot}$ places BW Cir among the larger group of massive BHs; only five out of 15 BHs with accurate mass determinations are less massive than $\sim 7\ M_{\odot}$ (e.g., see Casares 2007).

The variability of BW Cir has implications for its distance, which was estimated in C04 mostly based on the high activity 2004 spectra. If we assume that the 2003 spectra are representative of the true quiescent state, the $\sim$ 27 percent veiling difference with respect to C04 translates into 0.34 magnitudes for the G5III donor star. Using our FORS2 acquisition images we measure $R = 20.65 \pm 0.03$ for the 2003 spectra which is 0.15 mag fainter than assumed in C04. Therefore, our previous lower limit to the distance of 27 kpc now turns into a slightly more conservative $d \geqslant 25$ kpc. Nevertheless, the conclusions outlined in C04 remain unaffected, namely: (i) the large distance argues against BW Cir and Cen X-2 being the same object since it would make the 1967 outburst substantially super-Eddington for a 10–20 $M_{\odot}$ BH and (ii) the large distance enables us to explain the observed γ-velocity without invoking any kick velocity during the formation of the BH because the Galactic differential rotation, for a distance of 25 kpc, is 108 km s^{-1} (Nakanishi & Sofue 2003). Note that this lower limit to the distance assumes an interstellar reddening $E_{B-V} \simeq 1$ based on the work of Kitamoto et al. (1990) where the optical colors of the 1987 outburst were compared to those of luminous LMXBs. Although this may seem uncertain, we show in C04 that the EWs of several IS absorptions are indeed consistent with $E_{B-V} \simeq 1$. An upper limit to the distance $(d/10\ \mathrm{kpc}) < 1.93 \pm 0.03(M/M_{\odot})^{0.5}$ is given by Kitamoto et al. (1990) by demanding that the maximum X-ray luminosity of the 1987 outburst must be sub-Eddington. For a plausible 10 $M_{\odot}$ BH this gives $d < 61$ kpc which is not very constraining.

The large distance, coupled with a Galactic latitude $b = -2^{\circ}\!.78$ places BW Cir $>$ 1.2 kpc above the Galactic plane. This is quite unusual for a BH binary, only comparable to XTE J1118+480 and H 1705-250 with $z \sim 1.6$ kpc and 1.3 kpc respectively (Jonker & Nelemans 2004). Based on accurate radio measurement of the proper motion of XTE J1118+480, Mirabel et al. (2001) derived the space–velocity components and proposed that the binary formed in the Galactic halo. However, recent work favors an origin in the Galactic disk, followed by a super/hypernova explosion to propel the binary to its current position. Haswell et al. (2002) presented evidence for CNO processed material, implying a $\sim 1.5\ M_{\odot}$ companion initial mass which is difficult to reconcile with an origin in the halo (see also Gualandris et al. 2005). Furthermore, chemical analysis of the companion's spectrum yield supersolar abundances of Mg, Al, Ca, Fe, and Ni which favor a metal-rich supernova progenitor (González-Hernández et al. 2006). Unfortunately, the faintness of BW Cir precludes a similar abundance analysis being able to solve the problem of its birth location. This will have to wait for high-resolution spectrographs on a new generation of ELT telescopes.

This work is based on observations made with ESO telescopes at La Silla and Paranal observatories under programmes ID 53.6-0006, 55.D-0465, 57.D-0488, 60.D-0495, 65.H-0509(A), 71. D-0372(A), 073.D-0431(A), 073.D-0819(A), 076.D-0388(A). It also uses observations made at the SAAO and Las Campanas Observatory. We thank Andy Martin and Frank van der Hooft for their assistance with the 1995–1996 ESO photometry reported here. We also thank Chris Watson for computing the LSD spectra of BW Cir and the template star. J.C. acknowledges support by the Spanish MCYT grant AYA2002-0036.T.S. acknowledges support by the programme Ramón y Cajal. M.R.G. acknowledges NASA Contract NAS8-03060 to the *Chandra* X-ray Center for support of this work. *MOLLY* and *DOPPLER* software developed by T. R. Marsh is gratefully acknowledged.

Partly based on data collected at the European Southern Observatory, Monte Paranal, Chile.

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