Discovery of the 1.80 h spin period of the white dwarf of the symbiotic system BF Cyg

Liliana Formiggini and Elia M. Leibowitz

The Wise Observatory and the School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel Aviv University, Tel Aviv 69978, Israel

Accepted 2009 March 25. Received 2009 March 19; in original form 2008 December 31

ABSTRACT

We report on the discovery of a coherent periodicity in the B light curve of the symbiotic star BF Cyg. The signal was detected in some sections of the light curve of the star recorded in the year 2003 as double-hump periodic variations with an amplitude of $\simeq 7$ mmag. In the year 2004, the signal was also present in only a subsection of the light curve. In that year, the system was about twice as bright and the amplitude of the oscillations was about half of what it was in 2003. In 2004, the cycle structure was of a single hump, the phase of which coincided with the phase of one of the humps in the 2003 cycle. No periodic signal was detected in a third, short series of observations performed in the year 2007, when the star was 3 mag brighter than in 2003. We interpret the periodicity as the spin period of the white dwarf component of this interacting binary system. We suggest that the signal in 2003 originated in two hotspots on or near the surface of the white dwarf most likely around the two antipodes of an oblique dipole magnetic field of this star. Magnetic field lines funnelled accreted matter from the wind of the cool component to the pole areas, where the falling material created the hotspots. This process is apparently intermittent in its nature. In 2004, the activity near only one pole was enhanced enough to raise the signal above the threshold of our detection ability.

Key words: binaries: symbiotic – stars: individual: BF Cyg – stars: magnetic fields – stars: rotation – white dwarfs.

1 INTRODUCTION

A typical configuration of a symbiotic system (SS) comprises a red giant, a hot compact component, which in many cases is probably a white dwarf (WD), and a surrounding nebula. Quite a few modes of variations take place in SSs, mainly on long time-scales (Kenyon 1986). One mode is of cyclic variations, with periods of hundreds or thousands of days, indicating the binary nature of the system. The cool giant in the system can also show intrinsic variability such as radial pulsation (Mira type). Another type of variability is of an explosive character, in the form of a single outburst, as for symbiotic novae, or multiple events. Recent investigations, based on data assembled from many archival sources and historical data from old plate collections around the world, discovered a periodicity on time-scales of tens of years for the activity events of some SSs. This periodicity, detected in BF Cyg, YY Her and Z And (Formiggini & Leibowitz 1994, 2006; Leibowitz & Formiggini 2006, hereafter paper I; Leibowitz & Formiggini 2008) can be attributed to sun-like variability of the giant component of the system. Variability with time-scales of the order of minutes similar to the flickering typical of cataclysmic variables (CV) has been searched for in SSs. Although there are few objects that are known to show flickering with amplitude of tens to hundreds of mmag (e.g. T CrB, CH Cyg, RS Oph, o Ceti, MWC 560, RT Cru, V407 Cyg), most SSs show no detectable rapid optical variability down to a limit of a few mmag (Dobrzycka, Kenyon & Milone 1996; Sokoloski, Bildsten & Ho 2001; Sokoloski & Kenyon 2003; Gromadzki et al. 2006). Only for one system, Z And, a 28 min periodic variation has been detected and explained as the rotation of a magnetic WD which is the hot component of the system (Sokoloski & Bildsten 1999). This coherent oscillation was again detected by Gromadzki et al. (2006), but it was absent during the 2000–2002 fluctuation of Z And (Sokoloski et al. 2006).

Although its mechanism in SSs is not yet well understood, the short-time variability is believed to be related to the hot component of the symbiotic binary system, namely the WD and/or the accretion disc which in some cases is likely to surround it. However, the failure to detect flickering on most SSs may be due to either the absence of accretion disks or observational constraints. For instance, the emission of the nebula and/or nuclear burning material of the WD may reduce the amplitude of the variation and lower its detection probability.
We have started at the Wise Observatory of the Tel Aviv University an observational campaign on the short-term variability of SSs. The aim of this research is to target a few systems and observe them intensively in order to detect possible coherent short-term variability in their light curves (LCs). Since the amplitude of the expected variability is of the order of few mmag, it is mandatory to collect a consistent amount of data in order to obtain a good precision. Furthermore, the data analysis technique is of primary importance when searching for such small amplitude variability phenomenon. Actually, the search of a periodic signal over the total length of the observations hypothesizes a coherence that cannot be assumed a priori. We have developed a MATLAB script that allows us to analyse the structure of the short-time-scales variability of SSs. This analysis and the long time series of our observations have indeed given a new insight into the structure of the variability of SSs stars.

In this paper, we present the results of the observational campaign on one of our targets, the BF Cyg system.

2 THE SYMBIOTIC SYSTEM BF Cyg

We remind here that BF Cyg is one of the prototype symbiotic stars that was well observed at practically all frequencies of the electromagnetic spectrum (Mikołajewska, Kenyon & Mikolajewski 1989; Fernandez-Castro et al. 1990; Gonzáles-Riestra, Cassatella & Fernandez-Castro 1990).

The system consists of an M giant star and a hot compact star, possibly a WD, with an orbital period of 757.3 d. The nature of the hot component of BF Cyg is not known, but from the optical and International Ultraviolet Explorer spectra a temperature of 60 000 K is inferred, as for a hot WD.

The historical LC of BF Cyg has been analysed in details in paper I and we remind here some of the findings. Its long-term LC shows a general decline, following its major outburst in 1894, as for a symbiotic nova system. Superposed on this decline, there are several brightenings of the system by one or more magnitudes, of a typical duration of a few years. A periodicity in the occurrence of the outburst events of 6 376 d has been discovered and interpreted as a sign of a dynamo generated magnetic activity occurring in the cool giant component, similar to the solar cycle. It was pointed out in paper I, however, that the magnetic cycle is far from being strictly periodic, as in the case of the Sun. The 6 376 d period detected in paper I allowed the prediction of the occurrence of an outburst event with maximum height in mid-year 2007, around JD 245 4236. Indeed, on 2006 July 31 the system entered into a new active phase which continued during the years 2007 and 2008 (Munari et al. 2006; Skopel et al. 2007). Up to now, the maximum light was reached around JD 245 4724. When the ongoing outburst is completed and the system returns to its quiescent state, a better estimation of the mean period of the magnetic cycle can be obtained. Another periodicity of 798.8 d is explained as the rotation period of the giant star in the system (see paper I).

BF Cyg is one of 35 objects observed by Sokoloski et al. (2001). While for most of these targets no variability was detected up to a limit of a few mmag, BF Cyg was classified among the four new candidate flickers, in need of further observation. The system was observed by Sokoloski et al. (2001) three times in the B filter, near phases 0.89, 0.47 and 0.44 of its photometric cycle, where zero is the phase of the minimum light according to the ephemeris Min = JD 241 5065+757.3 × E (Pucinskas 1970). The Sokoloski et al. (2001) total observation time was ≃ 12 h, and variability was detected in two runs, with variance twice that expected from noise and instrumental effects, but no periodicity has been identified.

3 HIGH-SPEED PHOTOMETRIC OBSERVATIONS

Time-resolved photometry was conducted for 21 nights during four runs from 2003 August to September, on eight runs in 2004 July and August and on six short runs in 2005 May. Their duration varied from less than 1 h up to ~ 9 h. The total observation time of BF Cyg is 112.7 h for the year 2003, 58.45 h for 2004 and 5.0 h for the year 2007. Altogether, more than 176 h of time-series data were obtained. Table 1 gives a listing of all the runs.

The photometry was carried out with the 1 m telescope at the Wise Observatory, using the Tektronix CCD camera. A Johnson filter B was used for all the observations. The exposure time was almost always 120 s. The CCD frames were processed in a standard way for bias removal and flat-field correction. Aperture photometry was performed using the IRAF DAOPHOT procedure. Differential magnitudes have been calculated relative to a set of reference stars, using the Wise Observatory reduction program DAOSTAT (Netzer et al. 1996). The star GSC 02137—00847, discovered to be a pulsating δ Scuti by Sokoloski et al. (2002), was excluded from the set of comparison stars. In fact, it was outside the field of our frames in most of the observations.

No large fluctuation or flare activity occurred in the system during our 2003 and 2004 photometric coverage, while the 2007 data were obtained during an outburst epoch. Fig. 1(a) presents the visual LC of BF Cyg obtained by averaging the American Association of...
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Variable Star Observers (AAVSO) data over a time interval of 24 d. The instrumental magnitudes of BF Cyg in the B filter, as measured at the Wise Observatory in the years 2003, 2004 and 2007, are superposed on the AAVSO LC, applying an arbitrary shift. One can see that the 2003 observations caught the star as its brightness was declining towards minimum light in its 757 d binary cycle. In 2004, the star was on the ascending branch of its binary photometric cycle and it was brighter than in the year before by about 1 mag. By the year 2007, it was nearly 3 mag brighter than in 2003, as the system was undergoing an outburst activity.

4 TIME SERIES ANALYSIS

Fig. 1(b) is zoomed in on the time axis of the 2003 data. The 21 nights of our observations in that year, as well as the relative mean magnitude of each night, are well resolved in this frame. The arrow points at one night, the LC of which is shown in Fig. 2(a). Here, the scale of the time axis allows the display of all individual measurements at that night. The rectangles in Fig. 1(b) will be explained in Section 4.1. Fig. 1(c) depicts the 2004 LC, with the arrow pointing at the night, the high-resolution LC of which is shown in Fig. 2(b). An eye inspection of Figs 2(a) and (b) is enough to realize that the star light at these two nights was varying on time-scale of 1 h with a relative amplitude of 1 per cent of its total brightness.

4.1 Periodicities

In order to further investigate the nature of these variations, we computed the power spectrum (PS) of the LC of each year (Scargle 1982), within the frequency range \( 5 - 40 \, \text{d}^{-1} \). Our procedure consists of pre-whitening the LC by subtracting from each night magnitude values, a polynomial of second degree that was fitted to the observed data by least squares. This operation is performed in order to remove from the data variations on time-scale of one night (a few hours) that may be present in the data at the level of 1 per cent magnitude, due to temperature variation during the night, stability of the voltage in the CCD camera and residual colour effects in the atmospheric extinction correction applied to the measured magnitudes. Heliocentric Julian days were calculated. Fig. 3(a) displays the PS of the 2003 LC in the above mentioned frequency interval. The highest peak, around frequency \( f = 26.6 \, \text{d}^{-1} \), is statistically significant at a better than 99.9 per cent confidence level. The confidence level is the false alarm probability calculated according to Scargle (1982) and Horne & Baliunas (1986). This quantity represents the probability that the data contain a signal with respect to a data set of pure white noise. Figs 3 and 4 show that in the frequency

Figure 1. (a) The LC of BF Cyg: points are 24 d averaged AAVSO magnitudes, filled squares are our instrumental B magnitudes. (b) The 21 nights of our observations in the year 2003. (c) The eight nights of our observations in the year 2004. The arrows and the rectangles are explained in the text.

Figure 2. Differential LCs for the nights marked by an arrow in Figs 1(b) and (c). Vertical lines represent the estimated error range in the displayed magnitudes.
The frequency appears as a measure of the goodness of fit, and scanning the LC where these values are obtained.

Inspecting the details of the fit of a sine wave with the peak periodicity to the observed data, we noted that there are subsections of the LC in which the cycle does not seem to represent well the variations in the data points. We have therefore developed a MATLAB script for finding out periodicities in subsections of a given LC. The program scans the time axis of the LC with a window, the width of which varies from a few cycles of the period of the highest peak in the PS of the overall LC up to a window size that covers the entire LC. The window is moved over the time axis in steps of 1 cycle, and the program computes the PS of the section of the LC that is contained in each position of the window. The program finds the window position at which the highest peak in the PS is higher than the peaks in all other positions. We thus have for each window size the frequency and the power of the highest peak and the section in the LC where these values are obtained.

In this way, we have discovered that the 26 d\(^{-1}\) oscillations appear in the data between two well-defined times. The corresponding section of the LC is marked by the large rectangle in Fig. 1(b).

If we extend the subsection under consideration either to the right or to the left of the rectangle, the power in the highest peak is reduced. When we consider the nights that are out of the rectangle, no significant peak is present in the PS at all. However, aperiodic flickering is detected in these nights. The 26.6 d\(^{-1}\) frequency appears again in the LC, in the subsection marked by the small rectangle on the right-hand side of Fig. 1(b).

Fig. 3(b) depicts the PS of the LC consisting of the two rectangles together. The relative strengthening of the periodic component in this LC is hardly in need of further elaboration. The satellite peaks on the two sides of the main peak are of course due to 1-d aliases of the true cycle frequency.

We found that when considering first the PS of the data points within the first rectangle and then adding up the points in the second rectangle, the power of the high peak in the PS grows without changing its position. This fact indicates that the phase of the periodicity in the two rectangles is the same. In the next section, we discuss the coherence of the periodicity in more quantitative terms.

The inset in Fig. 3(b) is zoomed in on the highest peak of the main graph. It shows that the main peak is in fact a doublet. The frequencies of the two components are 26.620 and 26.576 d\(^{-1}\). The uncertainty in these values, as judged by the half width at half maximum of the corresponding peaks, is ±0.006. We also made a second estimation of the uncertainty in the frequency value on the basis of a sample of 10,000 bootstrap pseudo-LCs (Efron & Tibshirani 1993), which gave us a similar value for a 90 per cent uncertainty interval.

We applied a second period search routine, computing by least squares the residuals of the observed data points from an harmonic wave consisting of the first two harmonics of a given frequency. Using the χ\(^2\) value as a measure of the goodness of fit, and scanning the above mentioned frequency range, we found deep minima in the plot of χ\(^2\) versus frequency at the frequencies \(f' = 13.310\) d\(^{-1}\) and \(f = 13.288\) d\(^{-1}\), respectively. Their second harmonics are exactly the frequencies of the two highest peaks in the PS of this LC. The two frequencies, as well as the frequencies of the corresponding second harmonics, are aliases of each other, due to the ~20 d gap between the mean times of the two major groups of successive nights of our observations, seen within the large rectangle of Fig. 1(b). The interdependence between these two frequencies is manifested by the fact that if one of them is removed from the data, in the PS of the residuals, the peak of the other one is being removed as well. For reasons explained below, we believe that the major periodicity in the LC of 2003 is the one corresponding to the lower of the two peaks seen in the inset of Fig. 3(b), namely the one of the frequency 2\(f = 26.576\) d\(^{-1}\). Fig. 4(a) is the PS of the 2004 LC, within the same frequency interval. The highest peak is concentrated around the frequency 13.31 d\(^{-1}\). Applying again our search script on these data, we find that the highest peak in the PS is obtained in the subsection of the LC delimited by the rectangle in Fig. 1(c). No significant peak is found in the PS of the LC measured in the nights outside that rectangle.

Fig. 4(b) presents the PS of the delimited section of the 2004 LC. The highest peak is much more pronounced here and it is clearly very significant. Its formal statistical significance of better than 99 per cent confidence level is computed as described above for the 2003 LC. The inset in Fig. 4(b) is zoomed in on the highest peak of the main graph. It shows that this major peak is in fact a multiplet. The two highest components of similar peak power are...
at the frequencies 13.323 and 13.285 d\(^{-1}\) with an uncertainty of ±0.018. Here again, the two frequencies are aliases of each other, due to the ∼26 d interval between the first three nights and the fourth night seen in the rectangle in Fig. 2(b). With our second periodogram routine that finds the frequency of a sine wave whose two first harmonics are fitted simultaneously to the data, we obtain the deepest minimum of the \(\chi^2\) value at the frequency 13.324 d\(^{-1}\) and a second minimum of nearly equal depth at the frequency 13.286 d\(^{-1}\). The frequency 13.286 d\(^{-1}\) is nearly equal to the \(f = 13.288\) d\(^{-1}\) frequency, that is found in the independent LC of the year 2003.

We also computed the PS of the 2007 LC of BF Cyg. No significant peak is present in that PS.

The analysis presented in this section implies that a periodicity with the frequency \(f = 13.288\) d\(^{-1}\) and of twice this frequency was intermittently present in the LC of BF Cyg in 2003 as well as in 2004.

### 4.2 Phases

In this section, we turn to the crucial question of how coherent the 13.3 frequency was during our two observing seasons. We denote by S1 the set of the nights of our observation in 2003 shown within the large rectangle in Fig. 2(b). The set of the two nights in the other rectangle is denoted by S2. The PS of the S1 LC is similar to the PS of the LC of the entire 2003 observing season. In particular, the oscillating component has the same frequency 2\(f\) as that of the entire 2003 LC.

Figs 5(a), (b) and (c) present the S1, S2 and the 2004 LCs, respectively, folded onto the \(P = 1/f\) periodicity. All three plots refer to the same zero time at HJD = 245 2859.00. The cycle is shown twice. Fig. 5(d) presents the binning of each of the folded LC shown in the upper frames into 22 bins. The coincidence of the phases of maximum light of the three curves is quite evident in the figure.

The statistical significance of the similarity of the phases of the three LCs may be estimated in quantitative terms, by evaluating the probability of a null hypothesis that they are independent of one another. By least square procedure, we compute the phases of the two first harmonics of the frequency \(f = 13.288\) d\(^{-1}\) fitted simultaneously to the S1 data points. In a presentation of each harmonic component as \(A \times \sin[2\pi t/P + \phi]\), we find the phase value \(\phi = 0.1291\) for the major, second harmonic of this frequency, taking HJD = 245 2859.00 as zero time. In a similar way, we independently compute the phases of these two harmonics, when fitted to the S2 data. The phase of the second harmonic in S2 is 0.1454. When considering the entire 2003 sample, the second harmonic phase is 0.1322.

We then compute the phases of the two harmonics fitted to the 2004 data. Here, the phase of the first component is 0.8327.

Consider first the phases of the S1 and the S2 LCs. The difference between them is 0.0163. For two independent phase values, the probability that they fall at random within an interval in phase space of width 0.0163 is \(p = 0.0323\).

Consider now the phase relation between the first and the second harmonics of a sine wave. Let \(\phi_1\) be the phase of the \(f\) component and \(\phi_2\) the phase of the \(2f\) component. The \(2f\) component has two minima (phases of maximum light in magnitude units) within one cycle of the \(f\) component. The first minimum of the \(2f\) cycles coincides with the minimum of the \(f\) cycle when the two phases are related as follows: \(\phi_1 - \phi_2/2 = 3/8\). The second minimum of the \(2f\) wave coincides with the minimum of the \(f\) cycle when \(\phi_1 - \phi_2/2 = 7/8 = 0.875\). The corresponding measured difference between the phases of the 2004 LC and that of the 2003 LC is 0.7666. The difference from the coincidence value 0.875 is −0.1084. The probability that the phases of two independent frequencies \(f\) and \(2f\) will differ from one another, as a random event, by a number that is within a distance of 0.1084 from one of the two values of strict coincidence of maximum light is \(p^2 = 4 \times 0.1084 = 0.4337\).

The probability that the phases of the S1, S2 and the 2004 LCs are independent of one another is therefore the product \(p1 \times p2 = 0.0140\). The null hypothesis that the three phases are independent of one another can therefore be rejected at a 98.6 per cent confidence level.

We note that, since the observations of the two years are separated by ∼4400 cycles, the fit of the phases between the two years is very sensitive to the exact value of the frequency. If we take \(f = 13.2877\) instead of 13.288, the phases of the two years are within 0.011 of the exact fit value. With this value of the frequency, the probability of a random coincidence of the three phases is reduced to a value less than 0.48 per cent.

### 4.3 Amplitudes

The amplitude of the cyclic oscillations, in magnitude units, was 0.007 in 2003. In 2004, it was 0.004.

### 5 DISCUSSION

Our time series analysis of the BLC of BF Cyg in 2003, 2004 and 2007 revealed cyclic variations in the first two years and none in

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**Figure 5.** (a) The section S1 of the 2003 LC folded on to the period corresponding to \(f = 13.288\) d\(^{-1}\). (b) The section S2 of the 2003 LC folded on to the same period with the same zero time. (c) The 2004 LC inside the rectangle folded on to the same period with the same reference time. (d) The three curves display the folded LCs in (a), (b) and (c), each one binned into 22 bins. Continuous line refers to (a), dashed line to (b) and dot–dashed line to (c).
the third one. Within the rather narrow range of uncertainty in the frequency of the oscillations in 2004, its value is one half of the frequency measured in 2003. In both years, the cyclic oscillations were highly coherent, retaining a constant phasing within each year, and very likely also between the two consecutive years. The stability of the phase is particularly remarkable in view of the fact that the cyclic variations themselves were present in the LC only in some fractions of the entire LC, while being absent from some other subsections of the measured LC. In the year 2007, when the star was 3 mag brighter than in 2003, no variability above the observational noise and in particular no cyclic variations seem to be present at all in the LC.

The coincidence of the frequency $f$(2003) with twice the value $f(2004)$ leads us to conclude that the oscillations in the two years are of the same fundamental period, with a two-hump cycle in 2003 and one-hump cycle in 2004. The period is $P = 1.806$ h. The high degree of coherence of the cyclic oscillations, well indicated by the conservation of the phase over thousands of cycles between the two years 2003 and 2004, requires a driving clock of very high precision. The spin of the hot component of the binary system of BF Cyg, the WD star, suggests itself as this time-keeping clock.

We hypothesize that the cyclically oscillating component in the light of BF Cyg originates at one or two antipodal regions on the surface of the rotating WD star. These could be areas around the two opposite poles of an oblique dipole magnetic field of the star. The two hotspots are created by accretion of matter from the wind of the giant star of the system. The matter is funnelled by the WD magnetic field to the areas near the poles. The hot zones are on the surface of the star or at the top of accretion columns, where the falling material hits the ground.

The accretion flow in 2003 was two headed, with matter directed to the two poles of the magnetic field, while in 2004 matter was impinging the ground mainly around only one of the poles. It seems, however, that the accretion process itself was also taking place between the episodes of coherent oscillations as indicated by the aperiodic variability of the LC during the time intervals outside the rectangles in Figs 1(b) and (c).

In Section 4, we reported that the amplitude of the cyclic oscillations in 2003 was 0.007 mag, while in 2004 it was 0.004 mag. In 2004, the star brightness in the B filter was about twice the value in the previous year, see Fig. 1(a). These numbers are consistent with the notion that the absolute brightness of the hotspots does not change much in time. The decline in the amplitude of the oscillations is due entirely to the brightening of the background DC luminosity of the system. This may also well explain the reduction of the amplitude of the variability of the LC of the year 2007 to the level of the noise in the measured magnitude values. In this year, the system was some 3 mag brighter than in 2003. The background luminosity reduces the relative brightness of the varying component to below our detection ability.

A detailed theoretical model of the dynamics of the accretion, as well as further observations, is obviously required in order to substantiate the qualitative scenario that we are suggesting here.

## 6 CONCLUSIONS

This work is a report of the discovery and measurement of the spin period of the WD in the symbiotic stellar system BF Cyg. The period is found to be 1.806 h. BF Cyg is the second SS for which a stable periodic oscillation was found thus far. The other symbiotic with known WD spin periods is Z And, with a WD spin period 28 min (Sokoloski & Bildsten 1999). For Z And, the serendipitous discovery occurred in a particular state of the system, during the decrease from a small outburst, while the oscillations disappeared near optical maximum (Sokoloski et al. 2006).

We believe that the periodic signal already detected for Z And and BF Cyg is not unique to these particular systems. The long temporal baseline of our observations and the fact that the data were obtained in many consecutive nights enabled us to discover the phenomenon.

It also seems that the total brightness and/or the binary phase of the system at the time of the observations are critical for the detection of a periodic signal in the LC.

With just two SS systems with known WD spin period, one can hardly arrive at a meaningful conclusion about the significance of the value of this parameter for our understanding of the evolutionary stage that symbiotics are in the history of binary stars. It may be of significance that in the two known cases the spin period of the WD is of the order of an hour. When a larger statistic is assembled, it would be of interest, for example, to compare it with the spin period of the WD in another class of highly interacting binary systems, namely the family of dwarf and classical novae.

## ACKNOWLEDGMENTS

We acknowledge the anonymous referee for his/her helpful suggestions. We are grateful to Yiftah Lipkin for his help in collecting the observations and to Margie Goss for her careful reading of the manuscript. We acknowledge with thanks the variable star observations from the AAVSO International Database, contributed by observers worldwide and used in this research. This research is supported by ISF – Israel Science Foundation of the Israeli Academy of Sciences.

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