THREE FUNDAMENTAL PERIODS IN AN 87 YEAR LIGHT CURVE OF THE SYMBIOTIC STAR MWC 560

ELIA M. LEIBOWITZ AND LILIANA FORMIGGINI

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; elia@astro.tau.ac.il

Received 2015 May 12; accepted 2015 June 15; published 2015 July 22

ABSTRACT

We construct a visual light curve of the symbiotic star MWC covering the last 87 years of its history. The data were assembled from the literature and from the AAVSO data bank. Most of the periodic components of the system brightness variation can be accounted for by the operation of three basic clocks of the periods $P_1 = 19,000$ days, $P_2 = 1943$ days, and $P_3 = 722$ days. These periods can plausibly, and consistently with the observations, be attributed to three physical mechanisms in the system: the working of a solar-like magnetic dynamo cycle in the outer layers of the giant star of the system, the binary orbit cycle, and the sidereal rotation cycle of the giant star. MWC 560 is the seventh symbiotic star with historical light curves that reveal similar basic characteristics of the systems. The light curves of all these stars are well interpreted on the basis of the current understanding of the physical processes that are the major sources of the optical luminosity of these symbiotic systems.

Key words: binaries: symbiotic – stars: individual (MWC 560)

1. INTRODUCTION

The remarkable symbiotic system MWC 560 (V 694 Mon) was discovered by Merrill & Burwell (1943) as an object with bright hydrogen lines. The blue continuum and observed TiO bands led to its classification as a symbiotic system (Sanduleak & Stephenson 1973). It was quite neglected by observers until early 1990 when a 2 mag rising in brightness brought it back into attention (Tomov 1990). The long-term light variations show a period of about 1930 days (Doroshenko et al. 1993) assumed to be the binary orbital period of the system. It is commonly believed that the system is a binary one consisting of an M-type giant and a white dwarf with an accretion disk around it. It has been also suggested that the 1930-day period is that of a precession of an accretion disk around the hot component (Doroshenko et al. 1993; Iijima 2002) or the period of pulsation of the M giant of the system (Doroshenko et al. 1993).

Its optical spectrum shows highly variable absorption features. The blueshifted ones are interpreted to be due to a jet outflow along the line of sight (LOS; Tomov 1990). Jets and jet outflows are known to exist in several symbiotic systems (Leedjärv et al. 2003), but only for MWC 560 is the jet axis nearly parallel to the LOS to the star (Schmid et al. 2001). Short term flickering activity with quasi periodic modulation from minutes to hours was detected during and after the outburst of 1990 (Tomov 1990; Michalitsianos et al. 1991, 1993; Dobrzycka et al. 1996; Tomov et al. 1996; Zamanov et al. 2011).

More recently, Gromadzki et al. (2007) analyzed the data from 1990 to 2007. Beside the main period of 1931 days, they found a period of 340 days in $J$, $H$, $K$, and $L$ photometry. Frackowiak et al. (2003) announced a discovery of a 161.3-day periodicity in the light curve (LC) of the system, which they have attributed to pulsations of the giant star.

In this paper we collected all the available photometric data of MWC 560 from 1928 to 2015 with the aim of analyzing the long-term photometric behavior of this star.

2. THE DATA

Luthardt (1991) published an LC of MWC 560 obtained from 750 plates of the Sonnenberg sky patrol, covering the period from 1928 to the beginning of 1990. Tomov (1990) and Tomov et al. (1996) obtained photoelectric data during and after the outburst of 1990. According to Doroshenko et al. (1993), a shift of 9.44 m is needed to transform plate magnitudes of Luthardt data to the photoelectric system of Tomov and of his own observations. Visual observations by the American Association of Variable Star Observers are available in the archive of the organization from April 1990 up to the present day. Most of the photoelectric measurements of Tomov were performed in a time interval JD 2447985–2448385, already covered by the AAVSO data. We found that the two data sets are virtually the same along their common time interval, at a level of accuracy of 0.05–0.1 mag, which is the level of our interest in this work.

With the correction factor suggested by Doroshenko et al. (1993), we were thus able to connect all the data at hand to magnitudes on a single common scale, the visual magnitude scale of the published AAVSO data.

3. ANALYSIS

3.1. Full LC

Figure 1 is the visual light curve of MWC 560, constructed as described in the previous section. It covers a time interval of 31561 days, from 1928 September 27 until 2015 February 23, JD 2425516–2457077. There is a distinct division between two different sections in the LC, which we refer to as sections A and B. In 1989 April/May, around JD 2447700, the mean magnitude of the star, over a few hundred days, has brightened by about 1.2 mag. By coincidence, the two sections are also clearly different in the data sources that established them. Section A consists mainly of magnitudes measured on historical photographic plates, while Section B is mainly AAVSO visual measurements by members of this organization. The AAVSO data have been binned into 10-day-wide bins.
The upward step in a presumably DC component of the LC of the star introduces spurious peaks in the presentation of the LC in the Fourier space. Taking the power spectrum (PS) of the entire LC would therefore be a poor technique for searching for genuine periodic components in the LC. In order to inquire whether or not the LC includes periodic oscillations that are coherent throughout the entire duration of the measurements, we created an overall pseudo-observed LC by subtracting the mean magnitude of the star over the time duration of the respective section from each of the two sections. This procedure amounts to an assumption that the apparent oscillations of the star are superposed on a DC component of nearly steady brightness that underwent a discrete event, on a time scale of a few tens of days, of a stepwise increase in its brightness. The LC with the 0 mean magnitude of its two time scale of a few tens of days, of a stepwise increase in its nearly steady brightness that underwent a discrete event, on a time scale of a few tens of days, of a stepwise increase in its brightness. The LC with the 0 mean magnitude of its two sections was then detrended by subtracting from it a second order polynomial of second degree from the LC. It covers the time duration of the observations. It presents the LC of Section A. The dots display the folding of the Z LC, presented in frame (a) onto the two periods P and P2. The cycle is displayed twice. For reasons specified below, we consider the period P as one half of the period $P_1 = 2P = 19,000$ days.

The period $\sim 1943$ days has already been recognized in the LC of this star by a number of investigators (Doroshenko et al. 1993; Gromadzki et al. 2007). Our present analysis demonstrates that it is a coherent oscillation of the star throughout the 31561 days covered by the observations. It preserves the same phasing in the two sections of the LC in spite of the large difference of $\sim 1.2$ in their mean magnitude. This conclusion is also demonstrated visibly in Figure 2(b). Figure 2(d) shows in the same way that the 9500 periodicity is also preserving its phase throughout the entire LC duration. We note, however, that while the LC covers more than 16 cycles of P2, it covers only 3.3 cycles of P. Therefore, the question whether or not P is a persistent periodicity of the system must remain open. We shall return to this question in Section 3.2 of this paper.

### 3.2. Section A

Figure 3(a) presents the LC of Section A. The dots display the detrended series by subtracting a least-squares best-fitted polynomial of second degree from the LC. It covers the time interval of 22194 days from 1928 September to 1989 May, JD 2425516–2447710. We denote this series as the Ya function. The solid line will be discussed in Section 4.1.

The upper solid curve in Figure 3(b) displays the PS of Ya, in the frequency interval corresponding to the period interval 21914–250 days. The horizontal line is as in Figure 2(b). All peaks in the PS of Section A at higher frequencies up to a frequency 1/100 days$^{-1}$, which is a mean Nyquist frequency of this time series, are well below the horizontal line in the figure.

The lower, red line in the figure will be explained in Section 4.1.

### 3.3. Section B

Figure 4(a) presents the LC of Section B. It covers 9164 days from 1989 May up to February 2015, JD = 2447908–2457077. The dots are the detrended series by subtracting the linear trend from the data. We denote this LC as the Yb function. The solid line will be discussed in Section 4.1.

The upper solid curve in frame b is the PS of the Yb LC. The period range covered in the figure is 9164–250 days. The horizontal line is as in Figure 3(b). Here again, at all higher
Figure 2. (a) Detrended and diluted light curve (LC) of MWC 560 from 1928 September to 2015 February. The line is the synthetic LC constructed with the periods $P_1, P_2, P_4$, and six harmonics of $P_1$ (see Section 4.1). (b) Upper solid line is the power spectrum (PS) of the observed LC. Lower line is the PS of the synthetic LC. (c) The LC folded onto the period $P_1/2 = 9500$ days. The cycle is exhibited twice. (d) The LC folded onto the period $P_2 = 1943$ days.

Figure 3. (a) Points are the observed LC of Section A. The line is the synthetic LC. (b) Upper solid line is the power spectrum (PS) of the observed LC of Section A presented in frame a. Lower line is the PS of the synthetic LC.
frequencies not shown in the figure up to some mean Nyquist frequency of the series, there are no peaks higher than the horizontal line. The lower red line will be explained in Section 4.1.

4. THE TEMPORAL CONTENT IN THE LC

4.1. The Eight Basic Periods

Examination of periods corresponding to the highest peaks in the 3 PSa presented in Figures 2(b), 3(b), and 4(b) led us to suggest that most of the periodic content of the 87 year LC of MWC 560 can be accounted for by an interplay among three basic independent periodicities, \(P_1 = 19,000\), \(P_2 = 1943\), and \(P_4 = 1150\) days, with \(P_1\) present in the LC by its first six harmonics. We preserve the notation \(P_3\) for another periodicity to be introduced in Section 5.4. We therefore consider the following vector of periods

\[
V = (P_1, P_2, P_4, P_1/2, P_1/3, P_1/4, P_1/5, P_1/6) = (19,000, 1943, 1150, 9500, 6333, 4750, 3800, 3167) \text{ days}
\]

We construct a synthetic LC \(Y_{sa}\) by computing the value of a series of eight harmonic waves of the periods of vector \(V\), fitting it by least squares to the observed LC \(Y_a\). Because of the much shorter duration of Section B, fitting this series of eight different periods to it produces unrealistic large amplitudes of some of the series components. Therefore, in constructing the model \(Y_{sb}\) for \(Y_b\) we consider a six term series of the periods vector \(V^{-}\), which is the \(V\) vector, from which the component \(P_1\) and \(P_1/3\) have been omitted. Note that in the analysis of the LC of Section B alone, the full \(Y_b\) data, shown on the right hand side of Figure 1, were used, without applying the dilution operation.

The solid curves in Figures 3(a) and 4(a) present the theoretical LCs so constructed as models for the observed ones \(Y_a\) and \(Y_b\). The lower red curves in Figures 3(b) and 4(b) are the PSs of these theoretical LCs.

As mentioned above and as seen in Figure 1, in 1989 April/May the stellar system MWC 560 underwent a dramatic event of a sudden tripling its optical luminosity. In analyzing the full LC of the system we consider two possibilities. (I) The 1989 event did not affect the coherence of the periodicities that underline the star periodic behavior. (II) The 1989 event has not changed the periodicities, but for some of them the event was associated with a measurable phase shift.

For modeling \(Y_z\) in case I we fitted the series of the harmonic waves of the \(V\) vector denoted \(Y_{szI}\) to the \(Y_z\) LC shown as dots in Figure 2(a). To take into account the case II possibility, we created a model for \(Y_z\), denoted \(Y_{szII}\) by combining \(Y_{sa}\), the synthetic LC for \(Y_a\), with \(Y_{sb}\), the synthetic LC for \(Y_b\). The combination was conducted in the same procedure which we applied in the creation the \(Y_z\) LC from the observed \(Y_a\) and \(Y_b\) LCs, including the dilution of the function \(Y_{sb}\), as explained in Section 3.1.

The solid curve in Figure 2(a) is the synthetic LC constructed for case II and the lower red curve in Figure 2(b) is its PS. The corresponding curves for case I are nearly indistinguishable by eye from those of case II shown in the figure.

4.2. Reality of the Model

The apparent good fit of the synthetic LCs and their PSa to the observed LCs and the corresponding PSa as presented in Figures 2–4 is not too surprising. The fitted synthetic functions have quite a large number of adjustable parameters, namely, the amplitude and phase of each of the eight periods considered, or the 6 in the case of \(Y_b\). In this section we argue that notwithstanding this limitation, our suggestion that the three
periods $P1$, $P2$, and $P4$ are truly dominating the long-term variability of the star is well founded.

First we note that five out of the eight periods considered are not independent of the other three, but are harmonics of $P1$. Second, the very same periods are fitted both to the Yz and to the Ya functions, albeit that their PSA are not identical. The six periods of the series fitted to the Yb LC, the PS of which is not identical to either one of these two, are also a subgroup of the same eight periods fitted to the other LCs.

Our main argument for the reality of our suggestion is based on the fact that the LCs constructed out of the three basic periods as described above fit the observed LCs better than harmonic series of similar or greater number of independent periods, the values of which are taken directly from the PSA of the observed LCs themselves.

Our second major evidence lies in the fact that the periods of a number of high peaks that stand out in the observed PSA are beats of pairs of periods from our suggested triple basic ones.

4.3. Fit Quality

We measure the quality of a fit of a model to an observed LC by the value of the parameter $S_{ps}$, the standard deviation (StD) of the difference between observed and theoretical values on all times of the observations. Similarly we use the parameter $S_{ps}$ the StD of the differences between the PSA of the corresponding LCs, as a measure of the fit of the PS of the theoretical LC to that of the observed LC. We note already at this stage that $S_{ps}$ measures the fitting of details of the LC, in particular it takes into account differences between the theoretical and the observed LCs on all time scales of the light variations, including those that are due to all sources of noise. In contrast, $S_{ps}$ is a measure of the fit of the major underlying harmonic content of the model to that of the observed LC.

As reference for the quality of our suggested synthetic LC Ysa we have considered another series of eight harmonic waves with periods corresponding to the eight highest peaks in the “clean” PS of the observed LC Ya, which we denote as Yta.

In “clean” PS we mean a PS from which peaks associated with periods that are merely aliases of periods corresponding to higher peaks in the PS are eliminated due to the unequal spacing between the observations on the time axis. This is performed by a computer program that we have developed in the following way. For the period of each high peak in the PS of the observed LC, beginning with the highest one, the routine fits a harmonic wave of that period to the observed LC by the least-squares procedure. High peaks in the PS of this timeseries associated with periods others than the period of the generated wave itself, are considered aliases and their counterparts in the PS of the observed LC are eliminated. Our program is essentially a variation on the theme of the “CLEAN” type procedures that are much in use in the astronomical literature (Roberts et al. 1987).

As reference for the fit quality of our synthetic LC Ysb, we constructed in a similar way a series of six harmonic waves of the six highest “clean” peaks in the PS of Yb. Another synthetic LC, YtzI, is an eight-term series of the eight highest peaks in the “clean” PS of the observed LC Yz. Note that the eight periods taken from the PS of Ya and used in the construction of Yta are not identical to the eight periods that are fitted to Yz. Similarly, the six periods from which Ysb is created are not a subgroup of the eight periods of Ya, neither are they a subgroup of the eight periods of Ysz. This is in contrast to the relation among the periods at the basis of our suggested models for Ya, Yb, and Yz, that are all the same, or among the same eight periodicities. Thus, in addition to the fact that the periods used in the reference LCs are drawn directly from the observations, the number of adjustable parameters in the reference LCs is much higher.

Table 1 presents the values of the two fitting parameters $S_{lc}$ and $S_{ps}$ for these six synthetic LCs that we have constructed. In the two left columns one sees that the PS of our suggested model for the Ya LC fits the PS of the real data better than a series with the same number of terms, built upon the peak periods of the PS of the real data. The $S_{lc}$ number shows that the fit of our model LC to the observed one, in the time domain is slightly worse than the fit of the reference artificial LC Yta, which uses peak periods derived from the real data.

The middle two columns of the table show that our suggested model for Yb fits the observed data less well than the artificial LC built upon observed periods. The rightmost two columns show that under the case I assumption, in its real time presentation as well as in its approximate presentation in the Fourier space as manifested by the PS function, our suggested model fits the real data better than the artificial LC built upon periods derived directly from the data.

For the analysis of case II, for comparison with our model YszII we created two additional artificial LCs that are combination of LCs that are fitted to the observed Ya and Yb LCs separately. The first one, YtzII, is the combination of artificial LCs Yta and Ytb performed in the process described above. The second one, YifzII, is an eight-term series of the periods corresponding to the eight highest peaks of the “clean” PS of Yz fitted to Ya, combined with a six-term series of the same eight periods, from which the largest and the third largest periods were omitted, fitted to the Yb function.

Table 2 presents the Std values for these three artificial LCs that we have so constructed for case II.

Here one should compare the numbers in the third column to those in the first and the second columns. One sees the our model fits the observed LC and its PS better than a combination of the fit of the observed peak periods, fitted independently to Ya and Yb. One sees further, that even when we combine the fit of the observed period of Ya, with the observed periods of Yb which are different from the Ya periods, our model still produces a better fit to the observed PS of Yz, and only very slightly higher value of the $S_{lc}$ parameter that measures the fit to the LC itself.
Thus, the PSa of all our eight period models, except for the short LC of Section B, fit the PSa of the corresponding observed LCs better than the PSa of LCs that are built upon similar or larger number of periods derived directly from the “clean” PSa of the observed data.

4.4. Beats

The first column of Table 3 lists all six possible beats among the three periods $P_1$, $P_2$, and $P_4$ that we are suggesting to be underlying the variability of the MWC 560 stellar system in the last 87 years. The second column lists the corresponding period values. In the last three columns we present period values of clearly distinguishable peaks in the PSa of the corresponding LCs listed at the head of each of these columns. These peaks are marked in Figures 2(b), 3(b), and 4(b) by arrows and the corresponding peak period values, presented without brackets. The similarity between any number presented in either one of the last three columns of the table, and the number in column 2 on the same line, can hardly be ignored.

The two marked peaks in Figure 4(b) rise above the horizontal line, indicating that formally they are statistically significant at the 95% confidence level. The marked peaks in Figures 2(b) and 3(b) are all beneath the horizontal line, meaning that each one of them by itself cannot be regarded as a statistically significant period of the system. However, in their entirety, all the marked peaks are among the most pronounced ones in the PSa in which they appear, some of them are among the periods considered in constructing the various Yt reference LCs.

In the lower curves in Figures 2(b), 3(b), and 4(b), we see that in the PS of our model LCs there are no peaks corresponding to the ones in the upper curve marked by the numbers without brackets. The small feature flanking on both sides of the 1150 day peak in the lower curve of Figure 3(b) are of a much lower height than the marked peaks above them, and their peak periods are different, albeit slightly, from the peak periods in the observed PS. Similarly the two apparent weak features seen in the lower curve of Figure 4(b) underneath the marked peaks 1244 and 1074 in the upper curve are much lower than the observed peaks and their peak periods do not coincide with the indicated numbers in the figure.

The absence of the marked peaks in the upper curves from the corresponding lower curves is of course not surprising, since we have not introduced these periodicities into our Ys LCs. The marked peaks in the upper curves must therefore be genuine features of the observed LC and are not artifact of an interference among the periods that we are considering.

Each one of the above-mentioned agreements between numbers in the three last columns of Table 3 and the numbers in column 2 on the corresponding same line may be a random coincidence. However, the overall number of all these agreements, always with beats of two periods out of the same triple $P_1$, $P_2$, and $P_4$ periods, is unlikely to be a random coincidence. We believe that it gives credence to our claim that the triple periods are indeed real characteristics of the MWC 560 stellar system.

Note also that the eight periods that we are considering in our suggested models do not include any of the marked beat periods, which are of a noticeable signal in the observed LCs as evident by the distinguishable features in the corresponding PSa. Nevertheless the general fit of the PSa of our models, excluding that for Yb, are still better than the fit of the Yt functions.

4.5. Coherence

As described in Section 4, we constructed the synthetic LCs Ysa and Ysz by least-squares fitting of series of eight waves of the eight periods of the period vector $V$, to the observed Ya and Yz LCs. We eliminated the periods $P_1$ and $P_1/3$ from the vector $V$ and fitted a series of six waves of the $V^{(1)}$ vector of the remaining six periods to the observed Yb LC. In the resulting Yb LC, the amplitude of the P4 wave is negligibly small. Indeed, a glance in Figure 4(b) reveals that there is no discernable peak at this periodicity in the PS of Yb.

Column 1 of Table 4 lists the values of the five input periods that are common in the establishment of the Ysa and Ysb LCs, for which the best fit procedure yields appreciate amplitudes in both synthetic LCs. For these periods the resulting phases from the least-squares procedure is therefore meaningful.

Column 2 of Table 4 presents for each of these five periods the difference in phase between the eight terms fit to Ya and the six terms fit to Yb. As explained in Section 4.1, these fittings are performed independently of each other.

Column 3 of Table 4 lists the five high peak period values, as determined by the “clean” PS of the observed Yz LC, that correspond to our five input periods listed in column 1. Column 4 presents the difference in phase of the corresponding best fitted waves, between the fit of the eight “clean” periods of Yz to the LC Ya, and the six “clean” periods of Yz fitted to Yb.

Comparing columns 2 and 4 of Table 4 we observe that there is no shift in the phase of $P1/2$ and $P1/4$ between sections A and B, while with the corresponding “clean” periods 9507 and 4664 the phases between the two sections of the LC do not match.

The higher harmonics of $P1$ are more contaminated by higher frequency oscillations of the star and/or by high
frequency noise fluctuations in this observed LC which is of limited time duration.

4.6. Additional Periods

4.6.1. The ~ 1940 Periodicity

Gromadzki et al. (2007) conducted a period analysis of the visual LC of MWC 560, as well as of LCs of a few IR bands in the radiation of the system. They proposed a period $P_d = 1931$ days in the visual LC, a value that is similar to the one also suggested by Doroshenko et al. (1993). In Section 3 we derived from a much longer LC of the star the value $P_2 = 1943$ days. We believe that our value for this periodicity is slightly closer to the true period in the LC of the star.

In Section 3 we showed that a few notable features in the PSa of the observed LCs, marked in Figures 2(b), 3(b) and 4(b), appear at periods that are beats of the period $P_2$ with $P_1$ or $P_4$. If $P_d$ is taken as the period beating with $P_1$ and $P_4$ instead of $P_2$, the periods of the marked features in the PSa do not fit the resulting beat periodicities as well as when $P_2$ is taken as the beating period.

The last line of Table 4 shows that when fitting the $P_2$ period to sections A and B of the LC, along with the other seven periods of our suggested model, the resulting $P_2$ wave is found to be coherent throughout the entire 87 years of observations in this star. In contrast, when the period $P_d$ is considered, along with the other seven periods corresponding to the highest peaks in the PS of the Yz LC, there is a difference of 0.06 in the phase of the $P_d$ wave between the two sections of the Yz LC.

We have also fitted a single sine wave of period $P_d$ to Section A of our LC and independently also to Section B of the LC. There is a shift of 0.1 in the phase between these two waves. When performing the same calculations with the $P_2$ periodicity, the phase shift found between the two waves is only 0.06.

We consider the better coherence of the $P_2$ wave throughout the whole time interval covered by the observations as a further evidence in favor of the value $P_2$ over $P_d$ as the periodicity of this order in the light of the star. We suggest the following ephemeris for maximum light of this cycle:

$$\text{maxlight} = JD2455799 + 1943 * E.$$  

The ephemeris for maximum light in the $P1/2$ cycle is:

$$\text{maxlight} = JD2456536 + 9500 * E.$$  

4.7. Claimed Periodicities

4.7.1. The 339 and 308 Periodicities

Gromadzki et al. (2007) suggested also the period $P_p = 339$ days as another characteristic of the system, possibly the period of pulsations of the cool component. They also raised the possibility that $P_q = 308$ days is another characteristic of the system. We also find traces of features at these periods in PSa of some of the LCs that we have considered but we regard it rather doubtful that these two periods are real characteristics of the MWC 560 stellar system.

As regards to the 308 period, Gromadzki et al. (2007) themselves drew attention to the possibility that it is an alias of the $P_2$ period due to the 1 year cycle in the distribution of the observational points on the time axis. Indeed we have: $1/(1/365 + 1/1943) = 307.28$.

In Figures 2(b), 3(b), and 4(b), a peak corresponding to the 308-day period in the PS of the observed LCs in marked with the number in brackets. The fact that the 308 periodicity is an alias of the $P_2$ period is also particularly apparent in the fact that a peak at this period appears in Figures 2(b) and 3(b) also in the lower curves. These are the PSa of our synthetic models for the Yz and the Ya LCs, in which the 308 period has not been planted and therefore the signal at this period must be an artifact.

The 339-day period is also suspected to be a mere alias due to the yearly cycle of the observations. The peak corresponding to this period in the upper curve in Figures 2(b), 3(b) and 4(b) is marked with the number in brackets. As seen in the lower curves in these figures, there is a signal around this periodicity also in our corresponding synthetic LCs, in which the 339-day period has not been included. It is therefore very likely that the 339-day feature in the PS of the real data is also due to the yearly cycle in the observations.

The 339 periodicity in the optical LC may well be a beat of the period of 365 days with the $P1/4 = 4750$-day periodicity, which is rather pronounced in the LC of the star: $1/(1/365 + 4/19000) = 338.95$.

4.7.2. The 161 days Periodicity

Frackowiak et al. (2003) identified a 161.3-day periodicity in the NIR LC of the system that they have analyzed. They have attributes this period to pulsations of the giant. Their LC extends over the period 1990–1999, about 40% of the duration of our Yb LC. We do not find a significant signal at the frequency corresponding to 161 day period. A very weak feature at this frequency can be seen in the PS of a partial section of our Yb function covering the 1990–1999 time interval. One must bear in mind that Frackowiak et al. (2003) found the signal in the IR band while we analyze the visible light of the star.

5. DISCUSSION

5.1. The Pacemakers

Cyclic variations in the brightness of MWC 560 are known already for quite some time as major components of the LC of this variable star (Doroshenko et al. 1993; Gromadzki et al. 2007). In this work we show that the major variations in the LC of the star during the last 87 years may well be interpreted as manifestations of three basic periodic oscillations, together with a few harmonics of one of them and some beats between pairs among them.

The question what is the nature of the clocks responsible for these three periods is now naturally suggesting itself.

It has been suggested that the MWC 560 binary system is seen at very low inclination, possibly close to a pole on situation. This could be the reason why there are no spectroscopic observations so far that enable determination of the binary orbital period of the system with certainty. It has been suggested by a few investigators that $P_2 = 1943$ is the one (Doroshenko et al. 1993; Gromadzki et al. 2007), but so far it seems that there is no compelling proof for such an identification.

The ignorance, or at least the uncertainty, in the knowledge of such a fundamental parameter as the binary period of the system, makes it even harder to determine the nature of the three distinguishable periods that are identified in the data.
At this level of our understanding of the MWC 560 stellar system we can discuss the findings of this paper only in qualitative terms, by taking into account the order of magnitude of the three periodicities and by possible analogies with other multi-periodic symbiotic systems for which the nature of the major cycles operating in the system may be slightly better understood.

5.2. The 19000 Day Periodicity

On account of its length alone we suggest that the \( P_1 \) periodicity is that of a Solar-like magnetic dynamo operating in the outer layers of the cool component of the system.

The length of the \( P_1 \) period is about twice the length of the full 22 year cycle of the global magnetic field of the Sun. The time interval covered by all the observations in the star amounts to no more than 1.6 cycles of this periodicity therefore its persistence in the LC of the star must remain questionable. The reality of this period during the time interval of the observations is however suggested by the appearance in the reality of this period during the time interval of the persistence in the LC of the star must remain questionable. The reality of this period during the time interval of the observations is however suggested by the appearance in the LCs of the system of beats of this periodicity with the \( P_2 \) or the \( P_4 \) periods, as discussed in Section 4.4. Also the observed LC includes 3.3 cycles of the \( P_1/2 = 9500 \) day periodicity, the effect of which on the LC is undeniable as demonstrated in Figure 2(c).

The \( P_1/2 = \sim 26 \) year period is an analogue of the 11 years magnetic cycle of the Sun. The brightness of the star is correlated with this period since as in the Sun, the mass loss rate and hence the accretion rate onto the hot component environment is modulated by the surface magnetic variability (see, for example Schwenn 2006 for a review of the complex interrelation between solar cycle and solar wind). A magnetic cycle of this length is not uncommon in stars. For example, Olah et al. (2009) found in the star V833 Tau, a magnetic cycle of 27–30 years. This K5V star with a rotation period of 1.788 days is admittedly rather different from our M5 III giant rotating with a period of 100 days, but it demonstrates that magnetic cycles of a time scale of tens of years are not uncommon in stellar physics.

The peak in the PS of the Yz LC representing the full \( P_1 \) period, is due to the fact that the two successive maxima of the \( P_1/2 \) cycle within one cycle of the \( P_1 \) period are different in their amplitude.

Recently, Hric et al. (2014) have raised some doubts regarding our suggestion of the operation of a solar type magnetic cycle in the outer layers of the giant star in the AG Dra symbiotic system, in an analogy to our suggestion here. We do share their doubts mainly for the reason given by these authors, namely, the present lack of a direct evidence for a magnetic field or of magnetic activity in the atmosphere of the cool components of symbiotic stars. However, the lack of evidence is certainly not an evidence for the lacking. Direct detection of the operation of magnetic cycle in stars other than the Sun is a difficult undertaking. For one thing, it requires a very long time base for any type of observations. A major tool for detecting an operation of a magnetic cycle is an intensive monitoring of the emission components at the center of the CaII H and K lines in the spectrum of the star (Wilson 1978). In the complex absorption and emission spectrum of symbiotics, these lines can hardly be observed, if at all, much less their intensity can be measured.

As the case of the Sun shows, and as described in details in the Schwenn (2006) review, the magnetic cycle may modify extensively the characteristics of the solar wind through its dramatic effect on local fields, without affecting drastically the intensity of the global magnetic field of the star. In symbiotic systems such as AG Dra and MWC 560, variations in the rate and the dynamics of the giant stellar wind, if indeed driven by solar type magnetic dynamo, are translated into large variations in the optical brightness of the system due to the presence of the close WD neighbor and the accretion process onto its environment. Thus, if our suggestion turns out to be a correct interpretation of the thousand-day variability of symbiotics, these systems may serve as laboratories for studying the operation of magnetic cycles in the atmospheres of giant stars.

5.3. The 1943 Periodicity

It is by now commonly assumed by most investigators of the star MWC 560 that the \( P_2 = 1943 \) day period is that of the orbital revolution of this binary system. We tend to accept this assumption but not without some caution remembering that so far there is no observational compelling evidence that this is in fact the case.

5.4. The 722 Day Periodicity

It should be noted that on the basis of the information at hand, the period \( P_4 \) that we discover in the LC of MWC 560 may not be a fundamental periodicity of the system. A more fundamental one could be any one of the six beating periods of \( P_4 \) with the \( P_1 \) or \( P_2 \) periods, as presented in Table 3. In such a case the \( P_4/3 \) periodicity would be a beat period of that more fundamental one with the corresponding \( P_1 \) or \( P_2 \) period.

We suggest that this is indeed the case and the fundamental periodicity of the system is \( P_3 = 722 \) days. The main reason for this identification lies in the fact that the signal of the \( P_3 \) period is clearly present in all three observed LCs that we are analyzing. Furthermore, when we fit \( P_3 \) by least squares to the Ya LC and independently also the Yb LC, the two resulting waves have virtually the same phase.

Gromadzki et al. (2007) have also found a period of 741 days in the PS that they analyzed, which is a partial section of our Yb function. However, they did caution that being close to a two terrestrial-year duration, this periodicity may be an artifact of the observational materials.

In assessing this possibility we first note that along the 87 years of observations there is no obvious reason why a 2 year cycle, rather than 1 year, should leave a mark on the observed LC.

As a test for this possibility we fitted the two periods, 722 and 730 days, to each of the two sections of the LC, independently of one another. Table 5 presents the amplitude of each wave in each of the two sections, as well as the difference in phase between the two waves. We see that \( P_3 \) preserves its phase throughout the 87 years of the observations, while the 2 year cycle is incoherent. We consider this result as evidence for the reality of the 722 day cycle in the system.

| Period | Amplitude A | Amplitude B | Phases B–Phase A |
|--------|-------------|-------------|-----------------|
| 722    | 0.0800      | 0.0701      | 0.063           |
| 730    | 0.1110      | 0.0719      | 0.239           |
Table 6
Comparison of the Properties of Seven Symbiotic Systems

| Name   | Sp.Ty | References | Bin Per References | Giant Spin Per References | Tidal Wave Per References | Solar-type Per References |
|--------|-------|------------|--------------------|---------------------------|----------------------------|--------------------------|
| Z And  | M4 III| 1          | 759.0              | 5                         | 482                        | 8                        | 1317                     | 8                         |
|        |       |            |                    |                           |                            |                          | 14580                    | 6                         |
| BF Cyg | M5 III| 1          | 757.3              | 6                         | 798.8                      | 6                        | 7825                     | 7                         |
| YY Her | M4 III| 1          | 593.2              | 7                         | 551.4                      | 7                        | 373.5                    | 10                        |
|        |       |            |                    |                           |                            |                          | 5300                     | 10                        |
| BX Mon | M5 III| 1          | 1256               | 4                         | 656                        | 9                        | 1373                     | 9                         |
| AG Dra | K2 II | 3          | 548                | 5                         | 1160                       | 10                       | 373.5                    | 10                        |
| AX Per | M4.5 III | 1    | 681.48             | 11                        | ...                       | ...                      | ...                      | ...                      |
|        |       |            |                    |                           |                            |                          | ...                      | 11586^a                  |
| MWC 560| M5.5 III | 1    | 1943               | 12                        | 722                        | 12                       | 1150                     | 12                        |

Note. ^a This number is one half the period value presented in the AX Per paper (11) where it was suggested that it is a pulsation period of the star. However, as pointed out in that paper, it may also be the period of a solar-like magnetic cycle.

References. (1) Mürset & Schmid (1999), (2) Mürset et al. (1991), (3) Zhu et al. (1999), (4) Fekel et al. (2000b), (5) Fekel et al. (2000a), (6) Leibowitz & Formiggini (2006), (7) Formiggini & Leibowitz (2006), (8) Leibowitz & Formiggini (2008), (9) Leibowitz & Formiggini (2011), (10) Formiggini & Leibowitz (2012), (11) Leibowitz & Formiggini (2013) and (12) this paper.

5.5. Qualitative Model

As suggested above the brightness variations of the system with the \( P_1 \) period and its harmonics is following the magnetic dynamo cycle in the outer layers of the giant. The magnetic activity modulates the mass loss rate from the giant and also its dynamics and hence of the accretion rate onto the hot component.

The modulation at the binary period \( P_2 \) is primarily due to the eccentricity of the binary orbit. Zamanov et al. (2010) estimated it to be as high as 0.68. Close to periastron passages of the system, the L1 point of its equi-potential Roche lobes is getting closer to the giant center, exposing deeper layers of the giant atmosphere to the gravitational pool of the companion. At such phases of the orbital period, accretion onto the hot component assumes particular high rate, while at apastron, accretion occurs at lower rate.

We now suggest that the \( P_3 = 722 \) days is the sidereal rotation period of the giant. Zamanov et al. (2010) estimated the rotation period of the giant as 144–360 days. While our suggestion is about twice their upper value it is qualitatively in agreement with their conclusion that the rotation of the giant is rather far from synchronization with the binary revolution. The weak variability of the system with the \( P_3 \) period may accordingly be due to spots on the surface of the giant. For such an interpretation, the rotation axis of the giant must be inclined with respect to the LOS, due to an inclination of the binary plane and/or an inclination of the giant rotation axis with respect to that plane. The second period \( P_4 = 1150 \) days satisfies \( P_4 = 1/1(P_3 - 1/P_2) \) (see Table 3), i.e., it is the synodic rotation period of the giant for a prograde rotating star. At a given location on the surface of the giant, for example, the environment of the North or the South pole of an oblique dipole magnetic field, or a big spot on the star surface, \( P_4 \) is the time interval between two successive passages through that location of the tidal bulge in the atmosphere of the giant that is due to the gravitation pool of the companion. If a local magnetic field induces intense mass ejection from the giant surface at its locality, as the case is for some components of the Solar wind (Schwenn 2006), its effect is mostly pronounced at the tidal bulge of the star where the stellar outer layers are gravitational less bound to the star. This could be the origin of a modulation of the mass accretion rate onto the hot component at the \( P_4 \) periodicity, and hence to the \( P_4 \) period in the LC of the star.

It should be noted, however, that one cannot rule out the possibility that the 1150 day period is the fundamental one after all, being the sidereal rotation period of the giant. In that case, 722 days is the synodic rotation period of a retrograde rotating star.

5.6. Coherence 2

In our analysis in Section 4.1 we consider two possibilities regarding the phases of the periodic variation before and after the large brightening event of spring 1989. We call case I the possibility that this event has not affected the periodic content of the LC. Case II denotes the possibility that the brightening event was accompanied by a change in the phase of one or more of the periodic waves underlying the LC. We find, even under the analysis that allows the case II situation, that the three fundamental periods of the system, \( P_1, P_2, \) and \( P_3 \) preserve the same phase before and after the 1989 event.

For the \( P_4 \) periodicity we find a phase shift of 0.2 between Ya and Yb. In Table 4 we see that for the high harmonics \( P_1/5 \) and \( P_1/6 \) there is also a non-negligible phase difference between the two sections of the LC. We are unable to determine whether or not these phase differences are significant, namely, that they testify on some reset process of the pacemakers operating in the system that accompanied the 1989 event. Alternatively these phase differences may be due to contamination of a pure representation of these periodicities in the LC of the star by brightness fluctuations on smaller time scale and by noise in the observational data. The data at hand do not allow us to ascertain whether cases I or II prevail in the system.

6. SUMMARY

We present in this paper an 87 year light curve of the symbiotic star MWC 560. We showed that most of its observed optical variability may be accounted for by the operation of three clocks in the system and some beats between pairs of their periods. The longest period \( P_1 = 19,000 \) days appears in the LC with its six lowest harmonics. Establishing that these three periods are the seeds of the historic oscillatory behavior of the star is the main result of this work. It should be noted, however, that no explanation is being suggested in this paper for the 1989 cataclysmic event, whereby the overall optical luminosity of the star suddenly tripled its value within a few dozen days.
In way of interpretation we suggest that $P_1$ is the length of a solar-like magnetic dynamo cycle that operates in the outer layers of the giant member of the system. $P_2 = 1943$ days is the orbital period of the binary system and $P_3 = 722$ days is the sidereal rotation period of the giant. The optical broadband output of the system is correlated with the mass accretion rate from the giant onto the hot component environment, which in turn is modulated directly by the first two of these periods. The mass accretion rate is also modulated by the period $P_4 = 1150$ days, which is the synodic rotation period of the giant, the period of rotation of the gravitational tidal bulge in the atmosphere of the giant, as measured by an observer at a fixed location on the surface of the rotating giant. As Table 3 shows, the varying accretion rate with the $P_4$ periodicity is also modulated with the first and the second harmonics of the $P_1$ cycle.

MWC 560 is joining a group of six other symbiotic stars with recorded LCs that cover tens to over hundreds of years, the data of which we have assembled from the literature and from the invaluable treasures of AAVSO. We found in the LCs of all seven stars traces of similar cycles that affect in similar ways their optical luminosity. Table 6 presents the value of some basic parameters that characterize the seven members of this group of symbiotic stars.

If in the next few years, no cataclysmic event similar to the one in 1989 is taking place in the system; by extrapolating into the future the synthetic LC shown as solid curve in Figure 2(a), we can predict that the mean, over a few hundred days, of the visual brightness of the star will continue to rise, reaching a maximum value around the end of the year 2016.

We are indebted to the American Association of Variable Stars Observers and to its dedicated members for the use that we made in the treasures of their data archive, without which this work could not have been done.

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