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PHOTOMETRIC PROPERTIES OF THE INTERACTING BINARY BO MONOCEROTIS: EVIDENCE FOR MAGNETIC ACTIVITY

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ABSTRACT

BO Monocerotis (BO Mon) is a severely neglected short-period (2.23 days) Algol-type eclipsing binary star system undergoing angular momentum variations that are likely due to the evolved secondary star experiencing cycles of magnetic activity. We present the first CCD light curves of BO Mon, which were observed at the Kutztown University Observatory (Kutztown, PA) in 2012 using B, V, and I filters. The analysis presented here is the first of its kind for BO Mon and provides the first physical model of the system's parameters. We also incorporate over 40 yr of published times of minimum light to provide a new ephemeris curve and perform a period study that greatly improves, while differing significantly from, an earlier ephemeris analysis that was done more than 13 yr ago. The observed variations in BO Mon's orbital period supply evidence for mass transfer and magnetic activity and our photometric model affords the basic properties of the system for use in future photometric and spectroscopic studies.

Key words: binaries: close – binaries: eclipsing – stars: individual (BO Mon) – stars: magnetic field – techniques: photometric

Online-only material: color figures

1. INTRODUCTION

Interacting binary stars make excellent laboratories for testing current theories of stellar evolution. A classic example is the resolution of the so-called Algol paradox (Crawford 1955) over the past half-century or so. The paradox resulted from the fact that astronomers were finding binary stars consisting of more massive but less evolved components paired with less massive and more evolved companions—the Algols. The accepted stellar evolution theories state that the more massive a star, the more rapidly it evolves. Since both stars in a binary system are presumed to have been created at the same time, and therefore are of the same age, the existence of the Algols presented an inconsistency. The solution to the paradox, of course, is that close binaries can interact, transferring mass from the originally more massive star to the other. Over time, the system undergoes a reversal of mass ratio and the mass-losing star (more evolved) eventually becomes the less massive one. While the Algol-type binaries are named for the first one discovered (β Persei), it is now known that many such systems are interacting and undergo mass transfer.

As mass is transferred in an interacting Algol, the location of the center of mass changes and, due to conservation of angular momentum, the orbital period of the system also changes. Since mass is being transferred from the less massive to the more massive star, the orbital period would increase under the conditions of conservative mass transfer (all mass lost by the donor is accreted by the gainer). This orbital period change can be detected photometrically by observing precise times of eclipse over many years and noting a consistent, gradual increase in the orbital period.

Additionally, ephemeris analyses have revealed alternating increasing and decreasing orbital periods in many close binary systems. Such variations that are strictly periodic may result from the light travel time effect (LTTE) due to the presence of a third body in the system, while other similar variations may be due to magnetic activity in a late-type component. Hall (1989) proposed magnetic activity to explain orbital period modulations by comparing similar effects in RS Canum Venaticorum (RS CVn) stars and Algols. He found that RS CVn systems, which are detached binaries and do not undergo mass transfer, and Algols, which do, both experience the same type of alternating period changes if their secondary components are convective (later than about F5 spectral class).

Applegate (1992) and Lanza et al. (1998) offered models that linked Hall's observed orbital period modulations with the changing shapes, and resulting gravitational quadrupole moments, of the late-type secondary stars. In their models, magnetic activity is responsible for the variations, which means that the frequencies of the orbital period modulations would correspond to those of the late-type stars' magnetic activity cycles.

Further evidence that magnetic activity affects Algol-type systems can be found in recent work by Richards et al. (2012). Their three-dimensional Doppler tomography reveals that the mass-donating secondary stars in β Per and RS Vul have strong magnetic fields that contribute significantly to the nature of the mass flow to, and accretion structures around, the accreting primary stars.

BO Monocerotis (BO Mon; BD −3 2158) is an important system to study because it has been severely neglected and its period variations can be explained as resulting from magnetic activity of its late-type secondary component. There are still some general questions regarding LTTE versus magnetic activity cycles as explanations for cyclic orbital period changes in many similar systems (Zavala et al. 2002), in addition to the possibility of the temporary storage of angular momentum during non-conservative mass transfer processes, and long-term detailed photometric and spectroscopic studies of this system will help us understand the causes of the orbital period variations in the case of BO Mon.

After its discovery by Hoffmeister (1934), BO Mon was observed visually by Soloviev (1941), Soloviev (1951), and Szafraniec (1972), and photographically by Gaposchkin (1953).

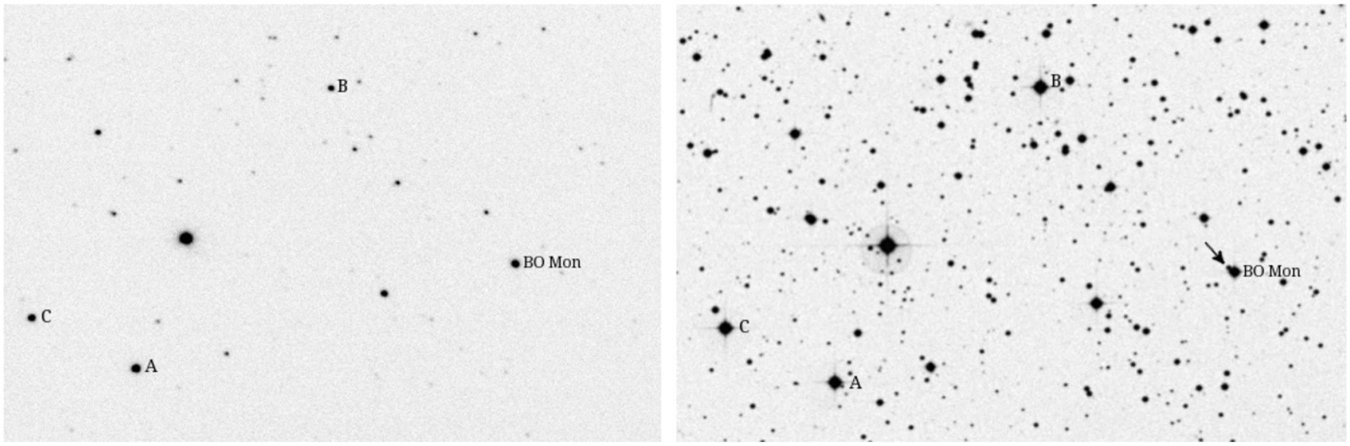

Figure 1. Left: a sample image of the KUO differential photometry field for BO Mon. This field of view is 14′.2 × 9′.5. The known properties of the comparison stars (A, B, and C) are given in Table 1. Right: a similar field obtained from the DSS of the Space Telescope Science Institute, taken with the 1.2 m UK Schmidt Telescope. The arrow indicates the location of a third light contribution that was resolved in the DSS image.

Since then there have been no known light curves or spectroscopic studies of any kind published. Qian (2000) performed a period study of BO Mon using 26 yr of published times of minimum ranging from 1972 through 1998 and found an overall *decreasing* orbital period with several sudden period changes superimposed.

In this work, we present the first complete CCD light curves of BO Mon in *B*-, *V*-, and *I*-bands (Section 2) along with a consistent orbital solution that was modeled using a combination of Binary Maker 3 and PHOEBE (Section 3). In Section 4, we perform an ephemeris analysis that extends the photometric baseline to 41 yr and indicates significant change over the past 15 yr. Our results are discussed in Section 5.

2. OBSERVATIONS

New CCD photometric observations of BO Mon in *BVI* bands were collected at the Kutztown University Observatory (KUO) in Kutztown, PA. A total of 4481 data images were collected over 12 nights between 2012 January 3 and 2012 March 11 using the 0.46 m modified Cassegrain optical telescope at KUO. An additional 744 images were taken on 2012 December 14 using KUO's 0.61 m Ritchey–Chrétien optical telescope. The purpose of the latter set of observations was to establish a new accurate time of primary eclipse and to determine an updated linear ephemeris. Both instruments were equipped with a thermoelectric- and water-cooled CCD camera with 3072 × 2048 (9 μm) pixels and an internal filter wheel. The configuration of the 0.46 m instrument yields a field of view of 14′.2 × 9′.5, and that of the 0.61 m is 19′.5 × 13′.0.

The exposure times were 20 s, 12 s, and 8 s, for *B*, *V*, and *I*, respectively, and the CCD was kept at an operating temperature of −15°C. Dark, flat, and bias calibration frames were applied to all data images. We used three comparison stars, the coordinates and known properties of which are given in Table 1. The locations of BO Mon and the comparison stars are labeled in a sample KUO data image (left side of Figure 1) and in an image retrieved from the Digitized Sky Survey (DSS; right side of Figure 1). We used the latest observed primary eclipses (which are plotted in Figure 2) to determine a new, updated linear ephemeris. Our new ephemeris of $\mathrm{HJD}_{\mathrm{PrMin}} = 2456275.8592 + 2.225260 \times E$ was used to calculate the orbital phase values for our observations. To check for interstellar reddening, we used the maps of Schlegel et al. (1998) and found that, in the direction of BO Mon, the Galactic reddening correction is $E(B-V) = 0.0390(\pm 0.0008)$. The observed *B*, *V*, and *I*-band light curves are shown in Figure 3 and the $(B-V)$ and $(V-I)$ color curves are plotted in Figure 4.

Table 1
The Known Properties of the Comparison Stars Used for the Differential Photometry of BO Mon

	Comparison Star Label		
	A	B	C
R.A. (J2000)	08:00:25.96	08:00:07.53	08:00:35.79
Decl. (J2000)	−03:31:04.2	−03:24:28.8	−03:29:50.7
B	11.832 (±0.014)	11.218 (±0.138)	11.489 (±0.027)
V	10.604 (±0.008)	11.054 (±0.028)	10.845 (±0.014)
I	9.338 (±0.008)	10.754 (±0.099)	10.075 (±0.014)
$(B-V)$	1.228 (±0.016)	0.164 (±0.141)	0.644 (±0.030)

Note. The quoted apparent magnitudes were obtained from the AAVSO Variable Star Database (A. A. Henden 2010, private communication).

3. PHOTOMETRIC MODEL

3.1. The BO Mon System

We determined the orbital solution for BO Mon using a beta version of the Binary Maker 3 program (Bradstreet & Steelman 2002) with a differential corrections feature (BM3DCbeta), obtained from David Bradstreet, in combination with the Physics of Eclipsing Binaries (PHOEBE) program (Prša & Zwitter 2005). BM3DCbeta is very easy to use and produces physically accurate models, while PHOEBE also allows for the simultaneous modeling at multiple wavelengths and has a scripting feature for determining errors. Both BM3DCbeta and PHOEBE are based on the Wilson–Devinney code (Wilson & Devinney 1971).

Outside of primary eclipse, the color index $(B-V)$ was observed to be 0.25, so we assumed this to be the color index of the primary star which corresponds to an effective surface temperature of 7500 K. We would note that, although the primary eclipse is total (with totality lasting 56 minutes), the color index $(B-V)$ during the primary eclipse does not provide an accurate estimate of the secondary's effective surface temperature due to the increased wavelength-dependent contribution of a third light (the properties of which are discussed in Section 3.2). With the primary star's temperature set to 7500 K, we let BM3DCbeta fit

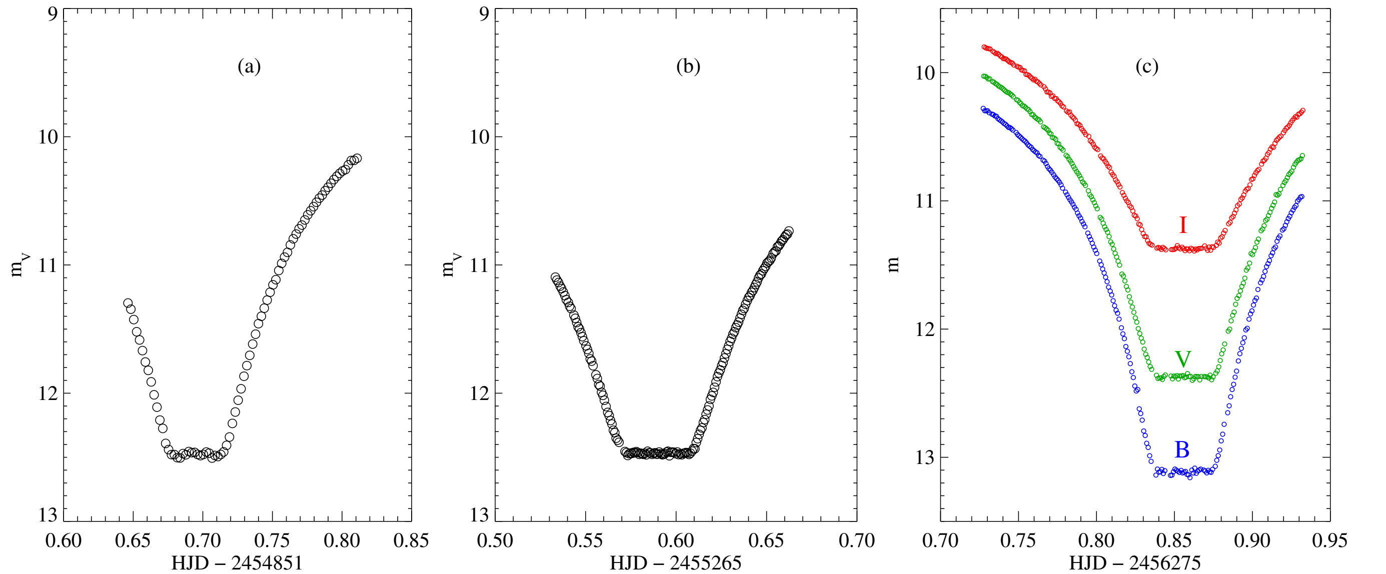

Figure 2. The light curves showing the newly observed primary eclipses. The data for (a) and (b) were collected from the AAVSO archive. The data for (c) were obtained at the KUO.

(A color version of this figure is available in the online journal.)

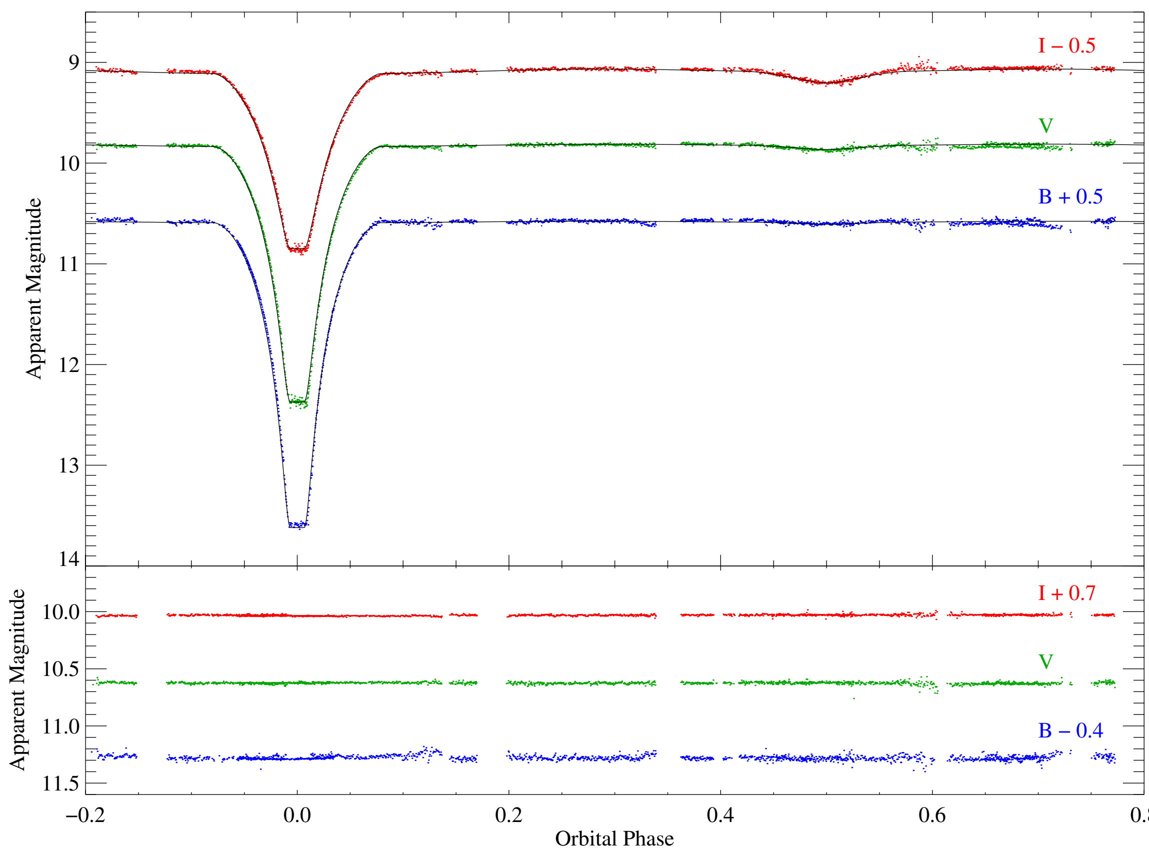

Figure 3. Top: the observed *BVI* light curves of BO Mon. The solid line represents the synthetic models obtained using Binary Maker 3 and PHOEBE. Bottom: the light curves for the comparison star labeled "A" in Figure 1 and Table 1.

(A color version of this figure is available in the online journal.)

the mass ratio, orbital inclination, surface potentials, effective surface temperature of the secondary star, and the third light contribution in the *V*-band. After repeating the process for the *B*- and *I*-bands, we used the average BM3DCbeta values as initial conditions with PHOEBE in order to verify the results for all three bandpasses and to determine the formal errors. The secondary's surface temperature was determined to be 3660 K (±150) and a summary of the remaining orbital parameters can be found in Table 2. It should be noted that the differences between the BM3DCbeta and PHOEBE values are within the reported errors. The models are plotted as solid lines in Figure 3.

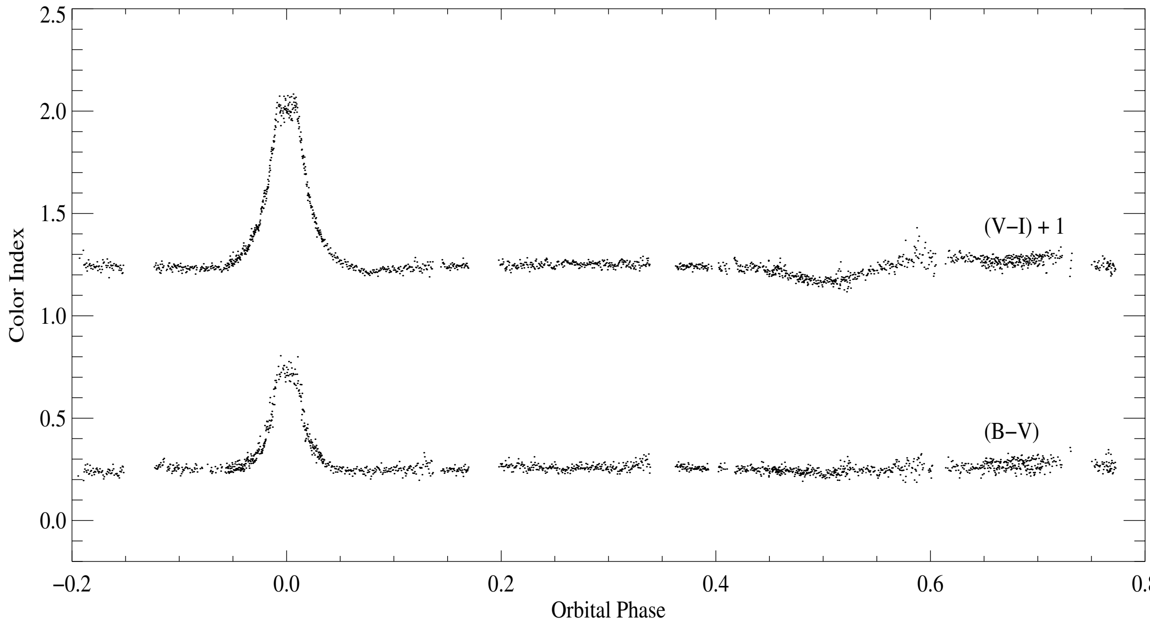

Figure 4. The color curves of BO Mon. The upper curve is $(V - I) + 1$ and the lower curve is $(B - V)$.

Table 2
The Light Curve Parameters, as Determined Using Binary Maker 3 and PHOEBE

Parameter	System	
	Primary	Secondary
Orbital period	2$^{\rm d}$.22526(0)*	
Inclination	87°.8 (±1.1)	
Mass ratio	0.283 (±0.038)	
Surface temp.	7500* K	3660 (±150) K
Radius (back)	0.205 (±0.020)	0.300 (±0.011)
Radius (side)	0.204 (±0.020)	0.268 (±0.010)
Radius (pole)	0.203 (±0.019)	0.257 (±0.010)
Surface potential (Ω)	5.198 (±0.426)	2.248 (±0.087)
Third light (*B*)	0.050 (±0.010)	
Third light (*V*)	0.067 (±0.009)	
Third light (*I*)	0.090 (±0.013)	

Note. The values marked with an asterisk were fixed during the modeling.

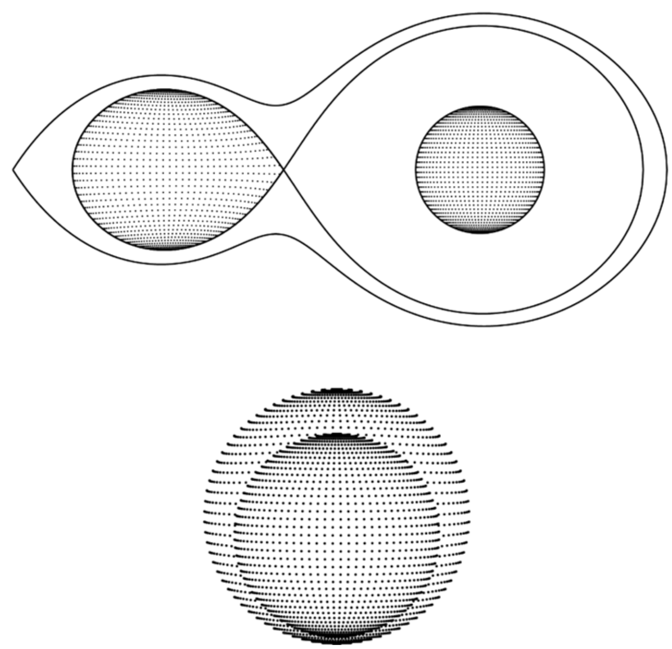

Figure 5. Top: an overhead view of BO Mon showing the geometry of the model, including two equipotential surfaces. The inner surface is the critical Roche lobe containing the first Lagrange point. The secondary star fills its Roche lobe. Bottom: the modeled line-of-sight view of BO Mon during secondary eclipse (at phase 0.5). These images were created using Binary Maker 3.

Our analysis determined that the system has an orbital period of 2.23 days with an orbital inclination of 87°.8 (±1°.1) and a mass ratio of 0.283 (±0.038), which results in a totally eclipsing semi-detached system with the secondary star filling its Roche lobe, as shown in Figure 5. Assuming that the primary is a main-sequence star, it would be classified with a late A (A8 or A9) spectral classification and would have a mass of around 1.75 $M_\odot$. The evolved secondary would then have a mass of about 0.5 $M_\odot$ and would be classified as very late K or early M. Of course, a spectroscopic study would be required to verify these masses and spectral class estimates.

3.2. The Third Light

The BO Mon light curves cannot be modeled with a consistent set of system parameters unless a third light contamination is accounted for. The intensity of the third light is quite negligible outside of eclipse, when BO Mon is at its brightest, but during the total eclipse the system's overall apparent magnitude drops by almost two magnitudes (in *I*) to over three full magnitudes (in *B*). The third light therefore contributes a relatively significant amount to our signal when BO Mon is in eclipse. We determined this contribution of the third light to be 5% in *B*, 6.7% in *V*, and 9% in *I*, which corresponds to a $(B-V)$ color index of 0.53 and a temperature of about 6200 K. The source of this third light is not bound to the BO Mon system, but rather it is a background/foreground star.

While not resolved as an independent light source in our KUO images, the probable source of the third light contamination can easily be seen in the archival data supplied by the DSS. The right-hand image of Figure 1 is part of the DSS and was taken

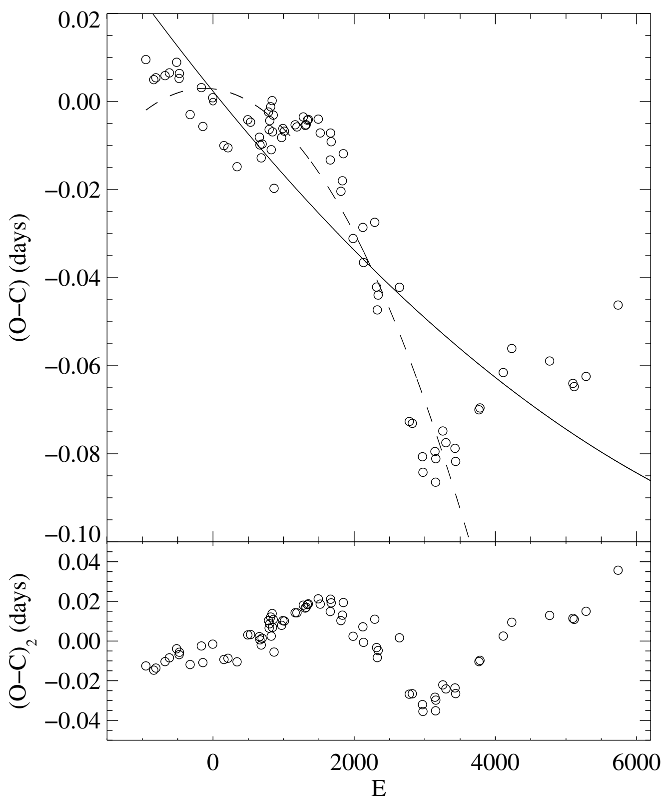

Figure 6. Top: the ephemeris curve for BO Mon. The solid line is our new best-fit quadratic curve using all available times of minimum to date. The dashed line is a plot of the best-fit quadratic found by Qian (2000), which had up to just $E = 3437$ available at the time. Bottom: the $O-C$ residuals after subtracting our new quadratic fit.

with the 1.2 m UK Schmidt Telescope. The source of the third light is identified with an arrow in the figure.

The archive of the Two Micron All Sky Survey (2MASS) lists the third light suspect as 07595067–0328305 and provides observed 2MASS magnitudes of $J = 15.296(\pm 0.078)$, $H = 15.201(\pm 0.125)$, and $K = 14.838(\pm 0.141)$ (Skrutskie et al. 2006). Using the color transformations given by Bilir et al. (2008) to transform between 2MASS and *BVRI* photometric systems, we find that the $(B - V)$ color index for the third light source, as observed by 2MASS, is $(B - V) = 0.529$. This is in very good agreement with the third light component required to fit the eclipses of our new *BVI* light curves of BO Mon and therefore provides further support for our photometric model.

4. EPHEMERIS ANALYSIS

In addition to the times of minimum light considered by Qian (2000), we have added an additional 15 yr of more recent data to our ephemeris curve (Figure 6), which now spans over 41 yr. These additional observations are listed in Table 3. Three new times of minimum light were determined during this study using the method of Kwee & van Woerden (1956); the data for two of which (2009 January 20 and 2010 March 10) were retrieved from the archives of the American Association of Variable Star Observers (AAVSO). The eclipse on 2012 December 14 was observed at KUO. The light curves for all three of the new eclipses are plotted in Figure 2.

When calculating the times of minimum light, we used the linear ephemeris given by Mallama (1980) of $\mathrm{HJD}_{\mathrm{PrMin}} = 2443507.5970 + 2.2252193 \times E$, which is the same one used by Qian (2000) and therefore allows for direct comparison to Qian's ephemeris curve. The solid line of Figure 6 is our best-fit quadratic curve, while the dashed line is a reproduction of Qian's best-fit quadratic which was limited to data ending in 1998, or $E = 3437$. The most notable difference is that, with the addition of 15 yr of newer data, the overall quadratic form is positive, while that of Qian is negative. The case of the negative trend, as noted by Qian (2000), cannot be explained as resulting from conservative mass transfer from the more evolved and less massive secondary component of this Algol system to the less evolved and more massive primary. The positive trend in our new study indicates an overall period increase, as expected in Algols, and therefore might be indicative of mass transfer. Thus, for completeness, we have calculated the rates of period change and (conservative) mass transfer.

Our best-fit quadratic curve (the solid line in Figure 6) is given by

$$O - C = (0.0024) - (1.99 \times 10^{-5})E + (9.03 \times 10^{-10})E^2,$$

which corresponds to an average rate of period increase (over the past 41 yr) of

$$\dot{P} = \frac{2C_2}{P} = \frac{2(9.03 \times 10^{-10})}{2.2252193} = 8.12 \times 10^{-10}\ \text{days day}^{-1}\ .$$

If we assume the masses we suggested in Section 3, with the understanding that a spectroscopic study is required to verify these values, we can estimate the average rate of conservative mass transfer to be

$$\dot{M} = \frac{\dot{P} M_1 M_2}{3P(M_1 - M_2)} = \frac{(8.12 \times 10^{-10})(1.75)(0.5)}{3(2.2252193)(1.75 - 0.5)}$$
$$= 8.51 \times 10^{-11}\ M_\odot\ \text{day}^{-1},$$

or

$$\dot{M} = 3.11 \times 10^{-8}\ M_\odot\ \text{yr}^{-1},$$

which would be consistent with an interacting Algol undergoing fairly rapid mass transfer. According to Albright & Richards (1996), Algols generally transfer mass at rates ranging from $\sim 10^{-11}\ M_\odot\ \text{yr}^{-1}$ to $\sim 10^{-7}\ M_\odot\ \text{yr}^{-1}$.

The residuals of the ephemeris curve, after subtracting our quadratic fit (the solid line), are plotted in the bottom panel of Figure 6. Something is clearly causing an alternating increase and decrease in orbital period. As suggested by Hall (1989), such behavior is somewhat common in close binaries with late-type (later than F5) secondaries and probably results from magnetic activity cycles. Some details regarding the possible magnetic activity observed in BO Mon will be discussed in Section 5.

5. DISCUSSION AND CONCLUSION

We presented the first complete CCD light curves of BO Mon and modeled the system as a typical Algol binary consisting of a less massive and more evolved secondary star filling its Roche lobe and presumably transferring mass to the more massive and less evolved primary. We also identified a wavelength-dependent third light contribution. While our photometric study provides insight about the masses and spectral classes of the components, a spectroscopic study (of which none has ever been performed) would substantiate our estimates. The nature of BO Mon's ephemeris curve makes it an important system for

Table 3
Recent Observed Times of Primary Minimum of BO Mon

Observed Time of Pr. Min. HJD −2,400,000	Date	Epoch	Filter	Observer/Reference
51889.9281 (±0.0001)	2000 Dec 11	3767	V	Nelson (2001)
51921.0816	2001 Jan 11	3781	V	Nagai (2002)
52655.4120 (±0.002)	2003 Jan 15	4111	V	Diethelm (2003)
52924.6690 (±0.005)	2003 Oct 12	4232	V	Diethelm (2004)
54117.3837 (±0.0001)	2007 Jan 16	4768	V	Doğru et al. (2009)
54851.7010 (±0.0001)	2009 Jan 20	5098	V	AAVSO*
54891.7542 (±0.0002)	2009 Mar 01	5116	V	Diethelm (2009)
55265.5934 (±0.0001)	2010 Mar 10	5284	V	AAVSO*
56275.8598 (±0.0002)	2012 Dec 14	5738	B	Reed & Yuhas (this paper)*
56275.8602 (±0.0001)			V	Reed & Yuhas (this paper)*
56275.8575 (±0.0001)			I	Reed & Yuhas (this paper)*

Note. The times marked with an asterisk were determined in this study.

studying the effects of magnetic activity, as well as any other process that can affect the system's orbital angular momentum.

Magnetic activity would affect the system's angular momentum, and therefore its orbital period, through the mechanisms described by Applegate (1992) and Lanza et al. (1998). These mechanism can explain orbital period modulations as changes in the gravitational quadrupole moment of the secondary star due to its magnetic activity. As such, the modulation of the system's orbital period would correspond to that of the secondary star's magnetic activity. Referring to the bottom of Figure 6, we can estimate that the secondary star's magnetic activity cycles would last approximately 3000 orbital cycles, or about 18 yr.

Of course, the secondary star would have to be convective in order to produce the magnetic fields required for the Applegate mechanism to work, and with an effective surface temperature of 3660 K, BO Mon's secondary star is certainly late enough to be convective. Another condition set by Applegate (1992) is that the orbital period modulations should be of amplitude $\Delta P/P \sim 10^{-5}$ over timescales of decades or longer. The period modulations we observe for BO Mon have an amplitude of $\Delta P/P = 2\pi(O - C/P_{\mathrm{mod}}) = 2.34 \times 10^{-5}$ and therefore it is reasonable to suggest that such a mechanism is contributing to BO Mon's oscillating orbital period variations.

The validity of magnetic activity affecting the angular momentum of the system can be corroborated by considering some other (long-term) predictions made by Applegate (1992). Since the Applegate mechanism requires that luminosity is converted into differential rotation, the luminosity of the secondary star, and ultimately of the system as a whole, should vary with the same frequency as the ephemeris. In addition, it should appear bluer when more luminous and redder when less luminous. Long-term (about a decade) photometric monitoring of BO Mon (light curves, color curves, and ephemeris curve) should detect such variabilities.

This interesting, important, and neglected system is in dire need of further study and certainly deserves future photometric and spectroscopic investigations. We will continue to monitor BO Mon, as well as other similar systems, and we encourage other investigators to do the same. The latest previous study of BO Mon by Qian (2000) raised serious questions about its apparently decreasing orbital period. With over a decade of more recent observations, however, we now see an overall increasing orbital period that can be explained by mass transfer, which is expected, with smaller oscillations superimposed. A true understanding of the effects of magnetic activity cycles, or other possible mechanisms, on these observed variations will require plenty of data that extends over long time periods in the future.

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