APSIDAL MOTION OF THE MASSIVE, BENCHMARK ECLIPSING BINARY V578 Mon

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ABSTRACT

V578 Mon is a system of two early B-type stars in the Rosette Nebula star-forming region (NGC 2244) and is one of only nine eclipsing binaries with component masses greater than 10 M⊙ whose physical parameters have been determined with an accuracy of better than 3%. It is therefore a benchmark system for evolutionary and stellar structure models of newly formed massive stars. Combining our multi-band light curves spanning 40 yr with previous light curve data from the literature, we fit a model light curve that for the first time includes the effects of apsidal motion of the system. We measure an apsidal period of 33.48 ± 0.06 yr. As a consequence of incorporating the apsidal motion into the modeling of the system’s orbital parameters, we determine an updated eccentricity of e = 0.07755 ± 0.00022, which differs significantly from the value previously reported in the literature. Evidently, the inclusion of apsidal motion in the light curve modeling significantly affects the eccentricity determination. Incorporating these key parameters into a comprehensive model of the system’s physical parameters—including internal structure constraints—will bring V578 Mon to the next level of benchmark precision and utility.

Key words: binaries: close – binaries: eclipsing – stars: early-type – stars: individual (V578 Mon) – stars: massive

1. INTRODUCTION

The analysis of apsidal motion in eccentric binary stars has been used for years to test stellar structure models. The periastron advance of an eccentric binary system is a direct consequence of the finite size of the stellar components, and of tidal interactions between them. Consequently, apsidal motion serves as a measure of the internal structure of stars (Sterne 1939). Specifically, measurement of apsidal motion in eccentric binary systems allows stringent tests of the internal structure constant k2 predicted by theory (e.g., Claret & Giménez 2010). Apsidal motion also provides a test of general relativity outside our solar system (e.g., Wolf et al. 2010).

The photometric variability of the 2.408 day period eccentric massive eclipsing binary (EB) V578 Mon (HDE 259135, BD+4°1299), comprising a B1 type primary star and a B2 type secondary star, was first identified by the study by Heber (1977) of NGC 2244 within the Rosette Nebula (NGC 2237, NGC 2246). The absolute dimensions of V578 Mon have been determined from three seasons of Strömgren ubvy photometry and one season of radial velocity data by Hensberge et al. (2000, hereafter H2000). An analysis of the metallicity and evolutionary status of V578 Mon was undertaken by Pavlovski & Hensberge (2005) and H2000. The masses and radii of V578 Mon determined from these data are 14.54 ± 0.08 M⊙ and 10.29 ± 0.06 M⊙, and 5.23 ± 0.06 R⊙ and 4.32 ± 0.07 R⊙, for the primary and secondary, respectively (H2000).

These masses and radii are accurate to better than 3%, making V578 Mon one of only nine EBs with M1 ≥ M2 > 10 M⊙ and with sufficient accuracy to be included in the Torres et al. (2010) compilation of benchmark-grade EBs. However, of these, V578 Mon is the only eccentric EB lacking an apsidal motion measurement.

Both the classical theory of tides and general relativity predict that a close, eccentric system such as V578 Mon will experience a certain amount of periastron advance. The angle of periastron, ω, is given by the equation ω(t) = ω₀ + ωt, where ω₀ is the angle of periastron at the reference epoch HJD₀ and t is the time since HJD₀. The apsidal period is given by U = 360°/ω × P, where P is the orbital period and ω is the apsidal motion in deg cycle⁻¹. The AAVSO research note by Heiser (2010) presented the first long-term photometry of V578 Mon that was used to identify apsidal motion in the system and to update its ephemeris. The author estimated a value of U ≃ 30.4 yr from 14 independent primary eclipse minima measured over a 40 year period. Here we present an analysis of the apsidal motion of V578 Mon using the state-of-the-art EB modeling software PHOEBE (Prša & Zwitter 2005), which updates and extends the venerable Wilson–Deviney code (Wilson & Devinney 1971; Wilson 1979). Traditionally, apsidal motion of EBs has been determined via eclipse timings (e.g., Gimenez & Quintana 1992; Giménez & Bastero 1999; Wolf & Zejda 2005). However, the apsidal motion of an eccentric EB causes not only the eclipse timings to vary but also the shapes and depths of the eclipses—as well as the morphology of the out-of-eclipse portions of the light curve—over time. Therefore, in principle, a full light curve model takes into account more of the apsidal information encoded in the light curve data, and should yield an extremely precise measure of the apsidal motion.

Using our own light curve data spanning 40 yr together with previous light curves from the literature, we measure an apsidal period for V578 Mon of 33.48 ± 0.06 yr. Furthermore, as a consequence of including the apsidal motion for the first time into the analysis of the orbit of V578 Mon, we report an updated eccentricity of e = 0.07755 ± 0.00022, which differs from the previous literature value of 0.0867 ± 0.0006 (H2000). These fundamental orbital parameters set the stage for follow-up analyses to determine the internal structure of the stars in V578 Mon for the first time, and to re-determine the stellar radii, for detailed tests of stellar evolution models with this benchmark system.

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The dashed line represents a linear fit using the equation \( \omega(t) = \omega_0 + \dot{\omega} t \), where \( t \) is the time since the reference epoch, HJD0. This results in \( \omega = 0.0718 \pm 0.0012 \) deg cycle\(^{-1} \) and \( \dot{\omega} = 33.06 \pm 0.58 \text{ yr}^{-1} \).

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**Table 1**

| Observatory | Year   | Filter | \( \sigma_0 \) | \( \sigma \) | \( N \) |
|-------------|--------|--------|----------------|------------|--------|
| KPNO\(^a\)  | 1967–1984 | Johnson \( U \) | 0.004 | 0.016 | 251 |
|             |        | Johnson \( B \) | 0.004 | 0.012 | 256 |
|             |        | Johnson \( V \) | 0.004 | 0.013 | 217 |
| SAT\(^b\)   | 1991–1994 | Strömgren \( u \) | 0.0029 | 0.0067 | 248 |
|             |        | Strömgren \( b \) | 0.0023 | 0.0046 | 248 |
|             |        | Strömgren \( v \) | 0.0023 | 0.0054 | 248 |
|             |        | Strömgren \( y \) | 0.0030 | 0.0053 | 248 |
| APT\(^c\)   | 1994–1995 | Johnson \( V \) | 0.0037 | 0.0022 | 260 |
|             |        | Johnson \( B \) | 0.001 | 0.0040 | 254 |
|             |        | Johnson \( V \) | 0.002 | 0.0035 | 95  |
|             |        | Johnson \( B \) | 0.001 | 0.0037 | 96  |
|             |        | Johnson \( V \) | 0.002 | 0.0058 | 259 |
|             |        | Johnson \( B \) | 0.001 | 0.0078 | 246 |
|             |        | Johnson \( V \) | 0.002 | 0.0036 | 284 |
|             |        | Johnson \( B \) | 0.001 | 0.0044 | 283 |

**Notes.**

\(^a\) 16 inch telescope at Kitt Peak (KPNO).

\(^b\) 0.5 m telescope at La Silla (SAT).

\(^c\) TSU–Vanderbilt 16 inch telescope at Fairborn University (APT).

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In Section 2, we present the photometry used in this paper. In Section 3, we perform the light curve analysis of all photometry. In Section 4, we present the apsidal period and orbital eccentricity along with an error analysis. We conclude in Section 5 with a discussion and summary.

### 2. DATA

The available time-series photometry of V578 Mon covers nearly 40 yr and more than one full apsidal motion period. A summary of the various light curve epochs, including filters and observing facilities used, is presented in Table 1. Photometry from Heiser (2010) includes multiband light curves spanning 1967–2006 from the 16 inch telescope at Kitt Peak National Observatory (KPNO) and from the Tennessee State University (TSU)–Vanderbilt 16 inch Automatic Photoelectric Telescope (APT) at Fairborn Observatory. The KPNO Johnson \( UBV \) light curves comprise 725 data points spanning 1967–1984 with average formal uncertainties per data point of 0.004 mag. The APT Johnson \( BV \) light curves span 1994–2006 and consist of 1783 data points with formal uncertainties per data point of 0.001 mag for \( B \) and 0.002 mag for \( V \) (Heiser 2010). Light curves from H2000 span 1991–1994 from the 0.5 m Strömgren Automatic Telescope (SAT) at La Silla, with 248 data points in each of the \( ubv \) filters and an average formal uncertainty per data point of 0.003 mag (H2000). Table 2 lists these formal uncertainties, \( \sigma_0 \), as reported by the original authors. However, from our light curve fits (see below) we found that these formal errors were in most cases underestimated. Thus, we also report as \( \sigma \) in Table 1 the uncertainties that we ultimately adopted for each light curve (see Section 3.2 for details).

### 3. LIGHT CURVE ANALYSIS

Here we determine \( \dot{\omega} \) with the light curve modeling program PHOEBE using all of the available photometry (Table 1). We perform the light curve fitting in two separate approaches. In the first approach (Section 3.1), we determine \( \dot{\omega} \) by finding the linear change in \( \omega(t) \) from fits to individual light curve epochs. In the second approach (Section 3.2), we determine \( \dot{\omega} \) by finding a global light curve solution simultaneously to all of the light curve data in Table 1.

All fixed parameters are listed in Table 2. For fixed parameters in both approaches, we adopt the spectral type of the primary to be B1V, which implies \( T_1 = 30,000 \text{ K} \) (H2000, and references therein). We adopt gravity brightening \( (g_1, g_2) \) and surface albedos \( (A_1, A_2) \) of 1, as appropriate for stars with radiative envelopes. The rotational synchronicity parameters \( (F_1, F_2) \) are fixed at \( 1.13 \pm 0.03 \) and \( 1.11 \pm 0.03 \) for the primary and secondary, respectively, based on the \( v \sin i \) and radii determined by H2000. Our limb-darkening coefficients follow the square-root law for fully radiative stars (Claret 2000). In all cases, we also adopt the semimajor axis \( (a) \) and the mass ratio \( (q = M_2/M_1) \) from H2000 because these parameters are determined principally from the radial velocity curves. We do...
not include star spots in any of the light curve modeling; as discussed below, the variations in the light curve data are fully reproduced through the effects of apsidal motion.

3.1. Fits to Individual Light Curve Epochs

To obtain an initial simple estimate of the apsidal period, we first determined $\dot{\omega}$ by finding the linear change in $w$ from the individual Johnson $BV$ light curve epochs 1973–1976, 1994–1995, and 2005–2006 (Table 1). We chose these epochs because they span one full apsidal period, and because these light curves were obtained using the same instrument and filter set. Johnson $BV$ light curve epochs 1973–1976 are a portion of the KPNO 1967–1984 light curve listed in Table 1.

The free parameters were the angle of periastron $w$, the inclination of the orbit $i$, the secondary temperature $T_2$, and the surface potentials $\Omega_1$ and $\Omega_2$. The starting values for these parameters are from H2000 (see Table 2). Note that we fit for the surface potential of the stars (i.e., $\Omega \propto R^{-1}$) as well as $T_2$ in order to give the light curve model full freedom to fit the eclipse widths and depths, however, we regard the best-fit values of these parameters as preliminary. We fixed $e = 0.07755 \pm 0.00022$, as determined in the global solution to all light curve data described in Section 3.2. We set the orbital period, $P$, to the value from Heiser (2010), and we used the primary minima eclipse times from Heiser (2010) as the HJD0 values for each light curve epoch.

The resulting best-fit $\omega$ at specified HJD0s and formal errors from each light curve epoch are given in Table 3. A least-squares line fit to these $\omega$ versus orbital cycles (Figure 1) initially gave a reduced chi-square $\chi^2_{\text{red}} = \chi^2/N = 19.0$, where $N$ is the number of data points. This indicates that the uncertainties on the individual $\omega$ values are underestimated. This is not surprising because the formal uncertainties on $\omega$ here do not take correlations with other parameters into account as we do in our global light curve solution below. Therefore, we scaled the uncertainties in Table 3 to achieve $\chi^2_{\text{red}} = 1$. The slope of the
fitted line gives $\dot{\omega} = 0.0718 \pm 0.0012 \text{ deg cycle}^{-1}$ and thus an apsidal period of $U = 33.06 \pm 0.58 \text{ yr}$.

### 3.2. Global Fit to All Light Curve Data

Next we performed a global light curve solution fit simultaneously to all epochs and filters of available light curve data (see Table 1). The free parameters were $e$, $\omega_0$, $i$, $T_2$, $\Omega_1$, $\Omega_2$, and $\dot{\omega}$. The initial values for these parameters are from H2000 except for $\dot{\omega}$, for which we used $\dot{\omega} = 0.0780 \text{ deg cycle}^{-1}$ calculated from the estimated apsidal period from Heiser (2010). We again fixed $P$ and HJD$_0$ to the values from Heiser (2010).

We performed two global light curve fitting iterations. For the first iteration we used the formal photometric uncertainties, $\sigma_0$ in Table 1, which yielded a total $\chi^2_{\text{red}} = 3.25$, indicating underestimated photometric errors. Thus, for the second iteration we scaled the photometric errors to make the $\chi^2$ of each light curve to equal the number of data points $N$ of the light curve. The scaled photometric errors $\sigma$ listed in Table 1 reflect more realistic, conservative values given the quality of our photometry. Effectively this causes $\chi^2_{\text{red}}$ of each light curve to be approximately unity. This yielded a total $\chi^2_{\text{red}} = 0.97$ for the final fit.

The best-fit global solution is plotted over multiple light curve epochs in Figures 2–5. The resulting apsidal motion is $\dot{\omega} = 0.07089^{+0.00021}_{-0.00013} \text{ deg cycle}^{-1}$, giving an apsidal period $U = 33.48^{+0.10}_{-0.06} \text{ yr}$. The quoted uncertainties are from a detailed $\chi^2$ analysis (see Section 4.3). In Table 2, we list the full set of system parameters resulting from the global light curve model fit.

Note that the changes in the shapes, depths, and timings of the primary and secondary eclipses—as well as the changes
in the out-of-eclipse portions of the light curves—are due to apsidal motion effects and are very well reproduced by the model. These variations over time due to apsidal motion are clearly demonstrated in Figure 6, which displays the global light curve solution for the Johnson $B$ light curve epochs 2005–2006, 1999–2000, 1995–1996, 1994–1995, and 1973–1976.

4. RESULTS

4.1. Apsidal Period of V578 Mon

We have determined the apsidal motion, $\dot{\omega}$, of V578 Mon via model fits to the available light curve data. Calculating the linear change in $\omega(t)$ by fitting individual light curve epochs spaced over one apsidal period results in $\dot{\omega} = 0.0718 \pm 0.0012$ deg cycle$^{-1}$ and $U = 33.06 \pm 0.58$ yr. Calculating $\dot{\omega}$ via a global light curve solution results in $\dot{\omega} = 0.07089^{+0.00021}_{-0.00013}$ deg cycle$^{-1}$ and $U = 33.48^{+0.10}_{-0.06}$ yr. The two values are consistent within the uncertainties. We adopt the latter value as it incorporates the full data set, is more precise, and furthermore, our error analysis accounts for correlations in the fitted parameters (see below).

We prefer the approach of fitting the full light curves because it incorporates all available light curve data in Table 1, not just the eclipse timings. As shown across multiple observing seasons in Figures 2, 3, and 5, the shapes, depths, and timings of the primary and secondary eclipses change with time due to $\dot{\omega}$. Furthermore, the light curves show variation in the out-of-eclipse data over time which are very well reproduced by the light curve model. The model light curves do not include star spots, showing that the out-of-eclipse variations in the light curve of V578 Mon are indeed a manifestation of apsidal motion.

4.2. Orbital Eccentricity of V578 Mon

The eccentricity from our light curve model fit incorporating apsidal motion is $e = 0.07755^{+0.00022}_{-0.00027}$ (Table 2), which differs significantly from the previously reported value of $0.0867 \pm 0.0006$ (H2000).

To further investigate the H2000 eccentricity, we performed a light curve fit within PHOEBE using only the SAT photometry (the same data used in H2000). We set $\dot{\omega}$ to zero and $a$, $q$, $w_0$, $i$, $T_2$, $\Omega_1$, and $\Omega_2$ to values from H2000. The only free parameter is $e$. This PHOEBE fit converges to a light curve solution with $e = 0.0867$, reproducing the $e$ found by H2000. Evidently, accounting for the effects of apsidal motion yields a different $e$. The $e$, $\Omega_1$, and $\Omega_2$ are correlated parameters in light curve analysis, meaning that our significantly different $e$ could yield different radii for the stars. The new, tentative radii we compute are approximately $5.14 \ R_\odot$ and $4.70 \ R_\odot$ for the primary and secondary as compared to the literature values of $5.23 \pm 0.06 \ R_\odot$.
and $4.32 \pm 0.07 R_\odot$ (H2000). Thus there is an indication that the updated $e$ together with the $\dot{\omega}$ newly reported here may result in a significantly different $R_\odot$. This will be the subject of an in-depth analysis in a forthcoming paper.

4.3. Uncertainties for $\dot{\omega}$ and $e$

In order to determine realistic uncertainties for $\dot{\omega}$ and $e$, we performed a detailed analysis of the $\chi^2$ space around the best-fit values. We varied $\omega$ over 0.0702–0.0716 deg cycle$^{-1}$ with step length 0.00006 deg cycle$^{-1}$, and we varied $e$ over 0.0765–0.0787 with step length 0.000084. For each of the 625 combinations of $\omega$ and $e$, we recomputed the global light curve fit as before.

Figure 7 shows the resulting contour plot of $\chi^2$ for $e$ versus $\dot{\omega}$. Contours are drawn at $\Delta \chi^2$ values corresponding to $1\sigma$, $2\sigma$, and $3\sigma$ uncertainty for a $\Delta \chi^2$ distribution of two parameters of interest (Press 1988). The contour shapes indicate that $\dot{\omega}$ and $e$ are not strongly correlated given our analysis. Moreover, Figure 7 clearly demonstrates that the previously reported value of $e = 0.0867 \pm 0.0006$ (H2000) lies well beyond the $3\sigma$ contour and can therefore be ruled out with very high statistical significance.

5. DISCUSSION AND SUMMARY

The accurate apsidal period of 33.48$^{+0.10}_{-0.06}$ yr and updated orbital eccentricity of $e = 0.07755^{+0.00023}_{-0.00027}$ of V578 Mon underscores the value of a long time baseline of photometric observations for eccentric EB stars. The traditional eclipse timing method (e.g., Giménez & Bastero 1995) uses the timing of the primary and secondary eclipse of an eccentric binary star system to calculate $e$ and $\dot{\omega}$ among other parameters. In this paper, we use the eclipse timings but also the changing shapes, widths, and depths of the primary and secondary eclipse due to $\dot{\omega}$, as well as the light curve variations in the out-of-eclipse phases to determine realistic constraints on $\dot{\omega}$ and $e$. Furthermore, we demonstrate that including the apsidal motion parameter in light curve fitting can affect the eccentricity measurement of EB systems.

The apsidal motion of V578 Mon can provide an accurate test of theoretical calculations of the internal structure constant ($k_2$). For example, Claret & Giménez (2010) find generally good agreement between the theoretically predicted and measured $k_2$ when they consider EBs with radii to $\pm 2\%$ accuracy. Comparing against EBs with very accurately measured radii is critical, because the theoretically predicted $k_2$ is highly dependent upon the stellar radii ($k_2 \propto R^3$). Currently, only 18 eccentric EBs have stellar radii and $\dot{\omega}$ measured with sufficient accuracy to stringently test theoretical internal structure models. Of these, only EM Car, V478 Cyg, V453 Cyg, and CW Cep have masses greater than 10 $M_\odot$, well constrained $\dot{\omega}$, and radii accurate to $\pm 2\%$ (Claret & Giménez 2010, and references therein). A detailed reanalysis of V578 Mon will yield accurate radii and, combined with our $\dot{\omega} = 0.07089^{+0.00021}_{-0.00023}$ deg cycle$^{-1}$, will yield an accurate $k_2$, with which to test theoretical internal structure models of high-mass stars.

There is still much to know about high-mass stellar evolution, especially at young ages, making V578 Mon an important testbed for stellar evolution models given the large amount of precise photometry and radial velocity data on the system. To date, there are only nine EBs with component masses greater than 10 $M_\odot$ whose masses and radii are accurate to $\pm 3\%$ (Torres et al. 2010). Stellar evolution models for stars with masses greater than 10 $M_\odot$ thus remain poorly constrained by EBs. Future reanalysis of V578 Mon will include a precise calibration of high-mass evolution models similar to the work on V453 Cyg by Southworth et al. (2004). Finally, V578 Mon’s...
location allows for precise age and distance constraints of the Rosette Nebula, similar to previous work on V578 Mon by H2000. A follow-up paper will incorporate the accurate orbital parameters newly determined here in order to re-determine all of the physical properties—including internal structure parameters—of this important, benchmark EB.

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Figures 2–6 were produced incorrectly in the published article. For Figures 2–5, the \((O-C)\) residuals are now plotted in the correct sense of data — model. For Figure 5, the \((O-C)\) residuals were scrambled in the original figure. Here they are corrected. Furthermore, in Figure 5 the light curve epoch is correctly listed as 1973–1976 but 38 data points from 1977 to 1978 were incorrectly included in the figure. Those data points have been removed from the figure. Additionally, the abscissa range of Figures 2–5 has been expanded to show the full range of 0.0–1.0 in phase. For Figure 6, the phase in the original figure was offset by +0.1. Figure 6 is now corrected such that the primary eclipses are correctly centered around phase 0.0 instead of 0.1. The originally published captions for Figures 2–6 are correct. None of the analysis or results are affected by these graphical errors.

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Figure 2. Representative fits to light curves from 2005 to 2006, 1999 to 2000, 1995 to 1996, and 1994 to 1995 in the Johnson B passband from global fits to all light curve data, offset for clarity (see Section 3.2). The residuals to the fits \((O-C)\) are shown above.
Figure 3. Same as Figure 2, but showing Johnson V-band light curves and fits.

Figure 4. Same as Figure 2, but showing Strömgren uby light curves and fits.
Figure 5. Same as Figure 2, but showing 1973–1977 Johnson UBV light curves and fits.

Figure 6. Representative light curve model fits in the Johnson $B$ passband from our global light curve solution (see Section 3.2). Note the variation of the shapes, depths, and timing of the primary and secondary eclipses. The out-of-eclipse portions of the light curves also vary, due to the apsidal motion, not star spots. Solid lines represent fits to the 2005–2006 and 1973–1976 epochs. The dashed, dash-dotted, and dotted lines represent fits to the 1999–2000, 1995–1996, and 1994–1995 epochs, respectively.