A Photometric Study of the Near-Contact Binary XZ Persei

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Abstract  Presented are two sets of multi-band CCD photometry of the Algol-type binary XZ Persei. Photometric solutions were derived using the Wilson-Devinney program for each dataset. The solution results indicate XZ Per is a semi-detached, near-contact binary whose less-massive secondary star fills its Roche lobe. Asymmetries in the light curves were modeled by including a hot spot on the primary star. This spot is likely caused by impact heating from mass transfer. The orbital period was analyzed using 473 light minima spanning 90 years. Several alternating period changes were found superimposed on a long term secular period decrease. With continued mass and angular momentum loss, the separation between the stars will likely decrease until the primary fills its Roche lobe forming a contact binary.

1. Introduction

The General Catalogue of Variable Stars (GCVS; Samus et al. 2017) identifies XZ Persei (TYC 3328-3186-1, GSC 3328-3186) as a semi-detached Algol eclipsing system with an orbital period of 1.15163412 days and a spectral type of G1. Photometric orbital elements were first determined by Lavrov (1971). Geometric and physical parameters for this system were computed by Brancewicz and Dworak (1980) using an iterative method which indicated a semi-detached configuration. XZ Per is also included in a catalogue of 411 Algol-type binary stars (Budding et al. 2004). This catalogue gives an orbital inclination of 88°, a mass ratio of 0.69, a distance of 250 pc, and spectral types for the primary and secondary stars of G1+K1 IV. In a spectroscopic survey of late F-K eclipsing binaries, Popper (1996) found the primary star’s spectral type to be F2-5. Many primary minima timings have been published going back to 1927. Several period studies have been completed on this system (Whitney 1959; Szafraniec 1960; Wood and Forbes 1963; Kreiner 1971; Mallama 1980; Qian 2001a). It has also been surveyed for a gaseous disk using time-resolved spectroscopy (Kaitchuck and Honeycutt 1982; Kaitchuck et al. 1985).

In this paper a photometric study of XZ Per is presented. The paper is organized into sections. The first complete set of multi-wavelength photometric observations for this star is presented in section 2. Orbital period changes are investigated in section 3, a light curve analysis is presented in section 4, results from the period study and light curve analysis are discussed in section 5, and conclusions are stated in section 6.

2. Observations

XZ Per was observed photometrically with the 0.31-m Ritchey-Chrétien telescope located at the Waffelow Creek Observatory (http://obs ejmj.net/index.php). Images were acquired with a SBIG-STXL camera equipped with a KAF-6303E CCD (9μm pixels). Two complete data sets were collected. Images that comprise Data Set 1 (DS1) were taken in the Sloan g’, r’, and i’ passbands on fifteen nights in January and February 2016. Data Set 2 (DS2) images were acquired in the Johnson B and V passbands on eight nights in September and October 2016. A total of 7,226 images were acquired, 4,648 in the Sloan passbands and 2,578 in the Johnson passbands. All the images were calibrated with bias, dark, and flat field frames taken before and after each night’s observing run. MIRASO software was used for calibration and ensemble differential aperture photometry of the light images (Mirametrics 2015). The instrumental magnitudes of XZ Per were converted to standard magnitudes using comparison star magnitudes taken from the AAVSO Photometric All-Sky Survey (APASS; Henden et al. 2014). The comparison and check stars used in this study are shown in Table 1. The finder chart in Figure 1 shows a nearby field star 8.1” to the ENE of XZ Per. The light contribution from this star was easily removed by proper sizing of the rings when performing the aperture photometry. After converting the Heliocentric Julian Day (HJD) of each observation to orbital phase the folded light curves were plotted (see Figure 2). All light curves in this paper are plotted from phase ~0.6 to 0.6, with negative phase defined as φ = −1. The check star’s V passband observations are shown in the bottom panel of Figure 2 with the standard deviations shown in Table 1. The check star magnitudes were inspected each night and no significant variability was found. The observations have been archived and are accessible from the AAVSO International Database (Kafka 2015).

3. Analysis

3.1. Period study and ephemerides

The most recent study of orbital period changes for XZ Per was done by Qian (2001a). Since that study, many additional minimum timings have become available and were used in the present analysis. From the literature, 488 minima were found spanning the years 1927–2016. From the observations in this study, an additional seven new primary minima were obtained (Table 2). Using the linear ephemeris of Mallama (1980),

\[ \text{HJD Min I} = 2443507.47742 + 1.15163412 \times E, \tag{1} \]

the (O–C) values were computed. All the minima timings and (O–C) values are listed in Tables 2 and 3. The ephemeris diagram is shown in Figure 3. From the full set of minima, fifteen timings identified in Table 3 showed significant deviations from the
Table 1. Variable (V), comparison (C), and check (K) stars in this study.

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APASS comparison and check star magnitudes and errors. The observed check star magnitudes are the averages over all nights for each passband.

Table 2. New times of minima for XZ Per.

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Figure 1. Finder chart for XZ Per (V), comparison (C1–C9), and check (K) stars.

The general (O–C) trend indicates the orbital period appears to be slowly decreasing with embedded sudden alternating period jumps. This behavior was first noted by Qian (2001a), who found the period variation to consist of a secular period decrease with two superposed period jumps. Since that study, it appears several additional period jumps have occurred (see Figure 3). Assuming the (O–C) data trend has a parabolic variation that is not a part of a longer repeating cycle, a weighted least-squares solution was used to fit a new ephemeris.

Using the (O–C) residuals from Equation 1, a new linear ephemeris was computed by weighted least-squares solution. A weight of 1 was applied to visual and photographic timings, and 10 to PE and CCD observations. The new linear ephemeris is given by

$$HJD\text{ Min I} = 2457689.78840(8) + 1.15163048(9) E,$$

and is shown overlaid on the O–C data in Figure 3 (dashed line). The behavior was first noted by Qian (2001a), who found the period variation to consist of a secular period decrease with two superposed period jumps. Since that study, it appears several additional period jumps have occurred (see Figure 3). Assuming the (O–C) data trend has a parabolic variation that is not a part of a longer repeating cycle, a weighted least-squares solution was used to fit a new ephemeris.

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Figure 2. Folded light curves for each observed passband. The differential magnitudes of the variable were converted to standard magnitudes using the calibrated magnitudes of the comparison stars. From top to bottom the light curve passbands are Sloan i', Sloan r', Johnson V, Sloan g', and Johnson B. The bottom curve shows the standard Johnson V magnitudes of the check star (offset +2.0 magnitude). The standard deviations of the check star magnitudes are shown in Table 1. Error bars are not shown for clarity.

Figure 3. \((O-C)\) residuals from the linear ephemeris of Equation 1. The dashed line is the new linear fit of Equation 2 and the solid line the quadratic fit of Equation 3. Circles refer to visual and photographic data and triangles the PE and CCD data.

Figure 4. \((O-C)_{\text{res}}\) residuals from the quadratic ephemeris fit. The line segments are several linear ephemerides that were fit to the residuals. Circles refer to visual and photographic data and triangles the PE and CCD data.
solution yields the following quadratic ephemeris:

\[
\text{HJD Min I = 2457689.7909(7) + 1.15162587(6) E - 3.48(12) \times 10^{-10} E^2. (3)}
\]

The quadratic fit to the \((O-C)\) observations is shown in Figure 3 (solid line) and the \((O-C)_{e}\) residuals from the quadratic ephemeris are presented in Figure 4.

The \((O-C)_{o}\) residuals clearly show the decreasing period is not smooth but punctuated by several alternating period changes. It is assumed that between the period jumps the orbital period is undergoing a steady decrease. From inspection of Figure 4, there appear to be 8 period jumps. To better characterize the period jumps, the \((O-C)_{o}\) residuals were divided into nine segments (see Figure 4). Using the method of least-squares, a linear function given by

\[
(O-C)_{o} = \Delta T + \Delta PE , \quad (4)
\]

was found for each segment to obtain the best fit to the \((O-C)_{o}\) values. The computed \(\Delta T\) and \(\Delta P\) values for each segment are listed in Table 4. For any cycle \(E\) the orbital period, \(P(E)\), can be computed by summing the ephemeris period \(P_{E}\) (1.15163412 days), the period jump for the segment in which the cycle is located \(\Delta T\), and the contribution from the secular period decrease using \(dP/dt\) in units of days/day \((dP/dt = -3.48 \times 10^{-10} \text{ d d}^{-1})\). Using the following equation,

\[
P(E) = P_{E} + \Delta P + \frac{dP}{dt} EP , \quad (5)
\]

the differences between the actual period \(P(E)\) and the ephemeris period \(P_{E}\) for each segment were computed and the results plotted in Figure 5. It is possible some of the early jumps located between cycles \(-16,000\) and \(-6,000\) are not real. This cycle interval has fewer observations, the visual minima have a large amount of scatter, and a large data gap exists for the years 1938–1945. More precise CCD minima timings became available beginning about the year 1999 (cycle count 7,000). Between cycles 7,000 and 15,000 a few sudden period changes are well documented by these precision timings, leaving little doubt that period jumps are occurring in this system.

3.2. Temperature, spectral type

Popper (1996) obtained three high-resolution spectra of XZ Per and found a spectral type of F2.5. The spectral lines of only the primary star were seen. For light curve modeling an effective temperature for the primary was selected midway between the spectral types F2 and F5 with an error estimate taken from that range. Using Table 5 of Pecaut and Mamajek (2013) gives an effective temperature for the primary star of \(T_{\text{eff}} = 6680 \pm 170 K\) and a color index of \(B-V = 0.40 \pm 0.05\). To measure the changing color of XZ Per over its entire phase range, the Johnson \(V\) and \(B\) passband observations were binned with a phase width of 0.005. Both phase and magnitude were averaged in each bin interval. Figure 6 shows the binned \(V\) magnitude light curve and in the bottom panel the \((B-V)\) color index. The significant reddening of the light at primary eclipse indicates a large temperature difference between the primary and secondary stars. The observed color over the entire phase range may also be reddened due to interstellar dust. XZ Per is located 3° south of the galactic equator, therefore a significant amount of interstellar extinction is possible. Extinction will be discussed further in section 4.

3.3. Synthetic light curve modeling

Photometric models of XZ Per were obtained for each of the two sets of data, DS1 \((g', r', i'\) observations) and DS2 \((B\) and \(V\) observations). The observations were binned in both phase and magnitude with a phase interval of 0.005. The average number of observations per bin was eight for DS1 and six for DS2. The binned magnitudes were converted to relative flux for modeling. Preliminary fits to each light curve were made using the binary maker 3.0 program (BM3; Bradstreet and Steelman 2002). The initial mass ratio for this modeling was taken from a catalogue of eclipsing binary parameters (Branczewicz and Dworak 1980); standard convective parameters were used for both stars and limb darkening coefficients were from Van Hamme’s (1993) tabular values. The resulting BM3 synthetic light curves for each color fit the observations well and were consistent for each data set. The stellar parameters from the light curve fits were independently averaged for each model, DS1 and DS2. These values were used as the initial input parameters for computation of simultaneous three-color (DS1) and two-color (DS2) light curve solutions with the 2013 version of the Wilson-Devinney program (WD; Wilson and Devinney 1971; Van Hamme and Wilson 1998). There are two mass ratios published for this system, 0.69 (Branczewicz and Dworak 1980) and 0.50 (Malkov et al. 2006). A derived mass ratio from a WD solution would only have reasonable accuracy if the eclipses are total (Wilson 1978; Terrell and Wilson 2005). The eclipses of XZ Per are not total, and combined with the inconsistent published mass ratios, a q-search would be required. For fixed inputs, the effective temperature of the primary was set to \(T_{1} = 6680 \text{ K} \) (see section 3.2) and standard convective values for gravity darkening and albedo, \(g_{1} = g_{2} = 0.32\) (Lucy 1968) and \(A_{1} = A_{2} = 0.5\) (Rucinski 1969), respectively. The logarithmic limb darkening coefficients were interpolated from tabulated values using the method of Van Hamme (1993). The Kurucz (1993) stellar atmosphere model was applied and detailed reflection was utilized in modeling. The adjustable parameters include the inclination (i), mass ratio (\(q = M_{2}/M_{1}\)), potential (\(\Omega\)), temperature of the secondary star (\(T_{2}\)), the normalized flux for each wavelength (L), and third light (\(f\)).

Mode 2 (detached configuration) was used initially but every solution attempt converged quickly to a semi-detached configuration. This indicates the secondary star fills its Roche lobe. Mode 5 (semi-detached configuration) was therefore used on subsequent iterations and the final solutions. Using the DS1 light curves, a series of solutions were made using fixed mass ratios from 0.30 to 1.00 with a step of 0.05. This q-search had minimum residual value at about \(q = 0.64\) (see Figure 7) and was used as the initial mass ratio for the final solution attempts for each data set. With the mass ratio as a free parameter, the resulting best-fit final solution parameters are shown in columns
Table 3. Available times of minima and O–C residuals from Equation 1.

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<td>0.03004</td>
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<td>4827.0</td>
<td>0.01360</td>
<td>BAV Lichten. DB</td>
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</table>

**Table continued on next page**
passband, overlaid by the synthetic solution curves, are shown both small and negative. The normalized light curves for each very small, while the longer wavelengths, r', i', and V, were seen in the lights. The values for the g' and B passbands were 2 and 3 of Table 5. No appreciable third light contribution was

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Interval</th>
<th>AT (days)</th>
<th>AP (10^6 s)</th>
<th>AP (seconds)</th>
</tr>
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<td></td>
<td>-10000 to -9900</td>
<td>-0.1163 ± 0.0106</td>
<td>-0.80 ± 0.07</td>
<td>-0.69 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>-9900 to -7200</td>
<td>-0.0422 ± 0.0152</td>
<td>0.64 ± 0.18</td>
<td>0.56 ± 0.15</td>
</tr>
<tr>
<td></td>
<td>-7200 to -6400</td>
<td>0.0641 ± 0.0087</td>
<td>-0.72 ± 0.13</td>
<td>-0.62 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>-6400 to 2600</td>
<td>-0.0063 ± 0.0003</td>
<td>0.38 ± 0.01</td>
<td>0.33 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>2600 to 6700</td>
<td>0.0332 ± 0.0018</td>
<td>-0.70 ± 0.04</td>
<td>-0.60 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>6700 to 8600</td>
<td>-0.0087 ± 0.0005</td>
<td>-0.02 ± 0.07</td>
<td>-0.02 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>8600 to 10100</td>
<td>-0.1055 ± 0.0044</td>
<td>1.10 ± 0.05</td>
<td>0.95 ± 0.04</td>
</tr>
<tr>
<td></td>
<td>10100 to 11500</td>
<td>0.0704 ± 0.0080</td>
<td>-0.62 ± 0.08</td>
<td>-0.54 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>11500 to 12400</td>
<td>-0.0632 ± 0.0044</td>
<td>0.54 ± 0.04</td>
<td>0.46 ± 0.03</td>
</tr>
</tbody>
</table>

The asymmetries in the light curves seen in Figures 8 and 9 are usually attributed to cool spots, hot regions such as faculae, or gas streams that impact one of the stars. At orbital phase 0.9 there is an excess of light seen in all the light curves. The residuals in Figure 9 show a sharp cutoff in this excess light when the stars approach primary eclipse. This feature is most likely caused by a hot spot on the primary star. Mass transferred from the Roche lobe filling secondary star would impact the primary star on its trailing side close to the equator (Zhang et al. 2014). An additional feature seen in the light curve residuals of Figure 9 is a light loss centered between orbital phase 0.3 to 0.4 for the DS1 observations. This indicates an under luminous region (cool spot) on the larger secondary star at the time the DS1 observations were acquired. This feature is not apparent in the DS2 data that were obtained six months later. Using WS3, a hot and cool spot were modeled for the DS1 observations and a single hot spot for DS2. The spot parameter’s latitude,
4. Discussion

The \textit{wd} solutions indicate XZ Per is an evolved semi-detached system with the less massive secondary star filling its Roche lobe. Figure 13 compares the mass and radius of both stars with 61 semi-detached systems with well determined absolute parameters (Ibanoğlu \textit{et al.} 2006). The primary star of XZ Per is close to the ZAMS like most of the other primaries in this group. The secondary along with all the other secondary stars in the sample are located on or above the TAM line. The absolute stellar parameters of XZ Per can now be estimated. A main-sequence star with an effective temperature of 6680 K gives a mass of $1.41 \pm 0.08 \text{M}_\odot$ (Pecaut and Mamajek 2013). Using the mass ratio from the \textit{wd} solution gives the secondary star’s mass as $0.92 \pm 0.06 \text{M}_\odot$ and applying Kepler’s Third Law gives a distance between the mass centers of $6.125 \pm 0.005 \text{R}_\odot$. The mean stellar densities, $\bar{\rho}_1 = 0.39 \pm 0.01 \text{g cm}^{-3}$ and $\bar{\rho}_2 = 0.14 \pm 0.03 \text{g cm}^{-3}$, were found using Mochnacki’s (1981) empirical relationship

\begin{equation}
\frac{\bar{\rho}_1}{\bar{\rho}_2} = \frac{0.0189}{r_1^3(1 + q)} P^2 \quad \text{and} \quad \frac{\bar{\rho}_1}{\bar{\rho}_2} = \frac{0.0189q}{r_2^3(1 + q) P^2},
\end{equation}

where the stellar radius is normalized to the semi-major axis and $P$ is in days. The visual luminosities, $L_{1V} = 5.87 \pm 0.56 \text{L}_\odot$ and $L_{2V} = 1.20 \pm 0.30 \text{L}_\odot$, were calculated using the bolometric magnitudes from the \textit{wd} light curve program (\textit{lc}) and bolometric corrections (Pecaut and Mamajek 2013). The \textit{lc} output also provided the stellar radii and surface gravities of each star. All the estimated stellar parameters have been collected in Table 6.

The distance to this system was determined from the precision parallax measurements of the Gaia spacecraft (Gaia 2016). The measured parallax is $p = 0.00234 \pm 0.00023$, which gives a distance of $d = 427 \pm 48 \text{pc}$. Assuming no interstellar extinction, this distance combined with the apparent V magnitude at orbital phase 0.25 gives an absolute magnitude of $M_V = 2.73 \pm 0.05$. This value compares well with the absolute magnitudes from the DS1 and DS2 model solutions, $M_V = 2.74 \pm 0.10$ and $M_V = 2.77 \pm 0.10$, respectively. If the spectroscopically determined effective temperature for the primary star is accurate, these values indicate the interstellar extinction is likely small (a few hundredths of a magnitude). A higher temperature primary, on the other hand, would point to a larger extinction value. A precision spectroscopic study would be necessary to confirm the temperature of the primary star as well as provide direct determination of the stellar masses.

Mass transfer can occur in semi-detached systems when the secondary star fills its Roche lobe. The main-sequence primary is on the receiving end of the matter stream. Given the short orbital period of XZ Per, the distance between the two stars is small compared to their radii. The mass stream would likely be narrow and would directly impact the primary star near its equator, creating a small hot spot due to impact heating (Zhang \textit{et al.} 2014; Ibanoğlu \textit{et al.} 2006). The locations and sizes of the hot spots modeled in both \textit{wd} solutions are consistent with an active mass stream from the secondary to the primary star. Additional small distortions in the light
Table 5. XZ Per synthetic light curve solutions.

<table>
<thead>
<tr>
<th>parameter</th>
<th>DS1–g', r', i' no spots</th>
<th>DS1–g', r', i' with spots</th>
<th>DS2–B,V no spots</th>
<th>DS2–B,V with spots</th>
</tr>
</thead>
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<tr>
<td>i (°)</td>
<td>85.05 ± 0.42</td>
<td>84.97 ± 0.08</td>
<td>85.15 ± 0.11</td>
<td>85.03 ± 0.05</td>
</tr>
<tr>
<td>T1 (K)</td>
<td>16680</td>
<td>16680</td>
<td>16680</td>
<td>16680</td>
</tr>
<tr>
<td>T2 (K)</td>
<td>4624 ± 7</td>
<td>4636 ± 8</td>
<td>4628 ± 11</td>
<td>4636 ± 5</td>
</tr>
<tr>
<td>q(M2/M1)</td>
<td>0.638 ± 0.013</td>
<td>0.647 ± 0.005</td>
<td>0.637 ± 0.003</td>
<td></td>
</tr>
<tr>
<td>Ω1</td>
<td>4.195 ± 0.038</td>
<td>4.195 ± 0.013</td>
<td>4.247 ± 0.012</td>
<td></td>
</tr>
<tr>
<td>L1/(L1+L2) (B)</td>
<td>—</td>
<td>0.8906 ± 0.0002</td>
<td>—</td>
<td>0.8949 ± 0.0002</td>
</tr>
<tr>
<td>L1/(L1+L2) (V)</td>
<td>—</td>
<td>0.8185 ± 0.0005</td>
<td>—</td>
<td>0.8244 ± 0.0003</td>
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<tr>
<td>L1/(L1+L2) (g')</td>
<td>0.8650 ± 0.0023</td>
<td>0.8644 ± 0.0004</td>
<td>—</td>
<td></td>
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<tr>
<td>L1/(L1+L2) (r')</td>
<td>0.7802 ± 0.0035</td>
<td>0.7788 ± 0.0007</td>
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<tr>
<td>L1/(L1+L2) (i')</td>
<td>0.7337 ± 0.0041</td>
<td>0.7318 ± 0.0008</td>
<td>—</td>
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<td>r1 pole</td>
<td>0.2703 ± 0.0020</td>
<td>0.2724 ± 0.0013</td>
<td>0.2818 ± 0.0011</td>
<td>0.2779 ± 0.0010</td>
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<tr>
<td>r1 point</td>
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<td>0.2848 ± 0.0016</td>
<td>0.2964 ± 0.0014</td>
<td>0.2918 ± 0.0012</td>
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<td>r1 side</td>
<td>0.2747 ± 0.0021</td>
<td>0.2771 ± 0.0014</td>
<td>0.2872 ± 0.0012</td>
<td>0.2831 ± 0.0011</td>
</tr>
<tr>
<td>r1 back</td>
<td>0.2790 ± 0.0022</td>
<td>0.2821 ± 0.0015</td>
<td>0.2930 ± 0.0013</td>
<td>0.2887 ± 0.0012</td>
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<tr>
<td>r1 pole</td>
<td>0.3095 ± 0.0019</td>
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<td>0.3185 ± 0.0006</td>
<td>0.3198 ± 0.0004</td>
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<tr>
<td>r1 side</td>
<td>0.3234 ± 0.0020</td>
<td>0.3324 ± 0.0006</td>
<td>0.3330 ± 0.0007</td>
<td>0.3344 ± 0.0004</td>
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<tr>
<td>r1 back</td>
<td>0.3557 ± 0.0020</td>
<td>0.3646 ± 0.0006</td>
<td>0.3651 ± 0.0006</td>
<td>0.3665 ± 0.0004</td>
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<tr>
<td>Σres^2</td>
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<th>Star 1-Hot Spot</th>
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<td>colatitude (°)</td>
<td>—</td>
<td>90 ± 14</td>
</tr>
<tr>
<td>longitude (°)</td>
<td>—</td>
<td>21 ± 3</td>
</tr>
<tr>
<td>spot radius (°)</td>
<td>—</td>
<td>10 ± 3</td>
</tr>
<tr>
<td>temp.-factor</td>
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<table>
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</tr>
</thead>
<tbody>
<tr>
<td>colatitude (°)</td>
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<tr>
<td>spot radius (°)</td>
</tr>
<tr>
<td>temp.-factor</td>
</tr>
</tbody>
</table>

^1 Assumed.

Note: The errors in the stellar parameters result from the least–squares fit to the model. The actual uncertainties of the parameters are considerably larger (ex. T1 and T2 have uncertainties of about ±180K).

Figure 7. Results of the q-search showing the relation between the sum of the residuals squared and the mass ratio q.

Curves at other orbital phases may also be effects of the impact heating, as diffusion and convection transport energy beyond the impact region.

The conservative mass transfer supported by the impact heating on the primary star would result in the widening of the orbit and an increasing period (Huang 1963). The least-squares solution for the quadratic ephemeris (section 3) gives a secular period decrease of dP/dt = −1.27 × 10^{-7} d yr^-1. This observed period decrease indicates the mass and angular momentum for the two stars is not conserved. Magnetic braking, which requires a stellar wind and a stellar magnetic field, is a possible cause of the angular momentum loss. XZ Per has a late-type secondary (spectral type K4) with a deep convective envelope. This convection combined with its rapid rotation should make the star magnetically active. The dark spot modeled on the secondary star and the changes in spot configuration between the two observational data sets is a good indication of magnetic activity. This could be the mechanism causing the mass and angular momentum loss and the resulting decrease in the orbital period (Hall 1989). There are a number of other Algols that have decreasing orbital periods with comparable dP/dt values (21 in Table 6 of Yang and Wei 2009). In addition, a
Figure 8. The \( w_0 \) model fit without spots (solid curve) to the observed normalized flux curves for each passband. From top to bottom the passbands are Sloan \( i' \), Sloan \( r' \), Sloan \( g' \), Johnson V, and Johnson B. Each curve is offset by 0.2 for this combined plot. The best-fit parameters are given in columns 2 and 3 of Table 5. Error bars are omitted from the points for clarity.

Figure 9. The residuals for the best-fit \( w_0 \) model without spots. Error bars are omitted from the points for clarity.

Figure 10. The \( w_0 \) model fit with spots (solid curve) to the observed normalized flux curves for each passband. From top to bottom the passbands are Sloan \( i' \), Sloan \( r' \), Sloan \( g' \), Johnson V, and Johnson B. Each curve is offset by 0.2 for this combined plot. The best-fit parameters are given in columns 4 and 5 of Table 5. Error bars are omitted from the points for clarity.

Figure 11. The residuals for the best-fit \( w_0 \) models with spots. Error bars are omitted from the points for clarity.
number of Algol systems (RW CrB, TU Her, BO Mon, Y Psc, AY Gem, UU And, TY Peg, X Tri, and Z Per) also show sudden period jumps superimposed on secular decreasing periods that are similar to XZ Per (Qian 2000a, 2000b, 2001a, 2001b, 2002). The possible mechanism for the observed alternating period changes in semi-detached binaries was discussed by van ’T Veer (1993) and investigated by Qian (2002), who finds both the secular period decrease and the irregular period jumps can be explained by the variable interplay between magnetic coupling and spin orbit coupling. A secular period decrease could also result from a small fraction of the transferred mass forming a circumbinary disk (Chen et al. 2006). Detailed calculations indicate the orbital angular momentum can be efficiently removed by a thin disk surrounding both stars, but observations of XZ Per with time-resolved spectroscopy found no evidence of emission from a gaseous disk (Kaitchuck and Honeycutt 1982).

The observed light curves and photometric solutions of XZ Per look very similar to EP Cas, AK CMi, FG Gem, and DF Pup, which were classified as near contact binaries (NCB) (Yang et al. 2013) where the secondary star fills the Roche lobe and the primary is inside one. Yakut and Eggleton (2005) compiled a list of 25 NCBs with well determined parameters. Figure 14 shows a mass luminosity diagram (M-L) of the components of these binaries with XZ Per included. The primary star of XZ Per (open triangle in Figure 14) lies about midway between the zero-age main-sequence (ZAMS) line and the terminal-age main-sequence (TAMS), as do most of the other NCB primary stars. XZ Per’s secondary star (filled diamond in Figure 14) lies close to the TAMS, indicating it has evolved. Most of the other secondary stars in this NCB sample are at a similar point in their evolution.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stellar masses</td>
<td>( M_1 ) (( M_\odot ))</td>
<td>1.41 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>( M_2 ) (( M_\odot ))</td>
<td>0.91 ± 0.06</td>
</tr>
<tr>
<td>Semi-major axis</td>
<td>( a ) (( R_\odot ))</td>
<td>6.120 ± 0.005</td>
</tr>
<tr>
<td>Stellar radii</td>
<td>( R_1 ) (( R_\odot ))</td>
<td>1.75 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>( R_2 ) (( R_\odot ))</td>
<td>2.09 ± 0.12</td>
</tr>
<tr>
<td>Surface gravity</td>
<td>( \log g_1 ) (cgs)</td>
<td>4.10 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>( \log g_2 ) (cgs)</td>
<td>3.76 ± 0.04</td>
</tr>
<tr>
<td>Mean density</td>
<td>( \bar{\rho}_1 ) (g cm(^{-3}))</td>
<td>0.37 ± 0.01</td>
</tr>
<tr>
<td></td>
<td>( \bar{\rho}_2 ) (g cm(^{-3}))</td>
<td>0.14 ± 0.03</td>
</tr>
<tr>
<td>Stellar luminosity</td>
<td>( L_{1V} ) (( L_\odot ))</td>
<td>5.9 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>( L_{2V} ) (( L_\odot ))</td>
<td>1.2 ± 0.3</td>
</tr>
<tr>
<td>Bolometric magnitude</td>
<td>( M_{bol,1} )</td>
<td>2.9 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>( M_{bol,2} )</td>
<td>4.1 ± 0.2</td>
</tr>
</tbody>
</table>

Values in this table are provisional. Radial velocity observations are necessary for direct determination of \( M_1 \), \( M_2 \), and \( a \).
of the primary star and $R_\text{L}$ is the volume radius of the Roche lobe. Eggleton's (1983) formula gives $R_\text{L}/a$ as a function of mass ratio ($q$),

$$\frac{R_\text{L}}{a} = \frac{0.49q^{-3}}{0.6q^{-3} + \ln(1 + q^{1/3})},$$

where $a$ is the separation between the star's mass centers. Using the photometric solution from DS1 gives a value of $f_1 = 84\%$, which is higher than many semi-detached binaries that show a secular period decrease (Yang and Wei 2009). XZ Per appears to be at an intermediate evolutionary state, beginning life as a close detached binary and eventually, with additional mass and angular momentum loss, becoming a W UMa contact binary (Yakut and Eggleton 2005). Model calculations indicate XZ Per should start its contact phase 4–5 Gyr after its formation with the two stars ultimately coalescing into a single star (Gazeas and Stepień 2008).

5. Conclusions

Two new sets of photometric observations of XZ Per resulted in five complete light curves that were used for investigation of this system. Based on these observations, photometric solutions were obtained for both data sets. The results of a detailed analysis of the DS1 observations and the period study gave the following results:

1. XZ Per is a semi-detached Algol-type eclipsing binary with a mass ratio of $q = 0.647$ and an orbital inclination of $i = 85.2^\circ$. The effective temperature of the primary star is $T_1 = 6680\, K$, and the secondary $T_2 = 4628\, K$. The primary is a F3 main-sequence star and the secondary an evolved K4 star (possibly a subgiant). No third light was found in the system but a hot spot was modeled on the primary star and a large cool spot on the secondary. Mass transferred from the secondary star is the likely cause of the hot spot on the primary. The cool spot was not necessary for the DS2 solution, indicating a changing spot configuration and therefore a magnetically active secondary star.

2. The period study found a secular decrease in the orbital period at a rate of $dP/dt = -1.27 \times 10^{-7}\, \text{d yr}^{-1}$. Magnetic braking is likely the mechanism causing mass and angular momentum loss. In addition, the $(O-C)$ data displayed several alternating period jumps superimposed on the secular decrease. The fill-out of 84% for the primary star indicates a near contact configuration. With additional angular momentum and mass loss, the fill-out of the primary star will continue to increase as the orbital period decreases until it eventually fills its Roche lobe.

Future spectroscopic and precision photometric observations would be important in monitoring orbital period changes and would allow determination of absolute parameters.

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