The Light Curve and Period of MT696

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Abstract We have obtained four-year narrowband light curves at 645 nm and 656 nm of the massive eclipsing binary star #696 in the Massey and Thompson (1991) study of massive stars in the Cygnus OB2 association. MT696 is a near-contact binary with components of near-equal temperature. We refine its orbital period to 1.46919 ± 0.00006 days. There is no convincing evidence of a change in period, and the 645-nm and 656-nm light curves are indistinguishable.

1. Introduction

The Cygnus OB2 Association (Cyg OB2) is home to an extraordinary number of massive stars (Massey and Thompson 1991; Camerón and Pasquali 2012), a high proportion of which are multiple (Kiminki *et al.* 2007; Kiminki *et al.* 2012). Massey and Thompson (1991) identified star #696 in their enumeration (hereafter "MT696"), also known as star No. 27 in Schulte (1956), as an O9.5V star. Rios and DeGioia-Eastwood (2004) found this star to be a double-lined spectroscopic and eclipsing binary, consisting of late O and early B components and having an orbital period of 1.46 days. Kiminki *et al.* (2007) spectroscopically determined a mass ratio of 0.7 and deduced a B1-B2V type for the secondary. Kiminki (2010) then found a spectroscopic period of 1.4694 ± 0.002 days, later refined to 1.4692 ± 0.0005 days and a mass ratio of 0.85 by Kiminki *et al.* (2012). Further, they observe no Balmer emission, which along with early spectral types and a period > 1 day leads them to suggest that it may be of β Lyr rather than W UMa type.

2. Observations and reduction

Since 2010 we have been monitoring Hα emission variability in massive stars in open clusters (Souza *et al.* 2011, Souza *et al.* 2013) via imaging through

Table 1. Identifications and basic observational data for MT696. Identifications and positions are from VizieR (Ochsenbein *et al.* 2000); magnitudes are from NOMAD (Zacharias *et al.* 2004) as accessed through VizieR.

Parameter	*Value*
USNO B1.0 identifier	1312-0390508
NOMAD identifier	1312-0408466
GSC 2.3 identifier	N31A000744
2MASS identifier	20335952+4117354
UCAC4 identifier	657-088171
R.A. (J2000)	$20^h 33^m 59.513^s$
Dec. (J2000)	+41° 17' 35.63"
B	13.18
V	12.38
R	10.61

5 nm-wide filters centered on continuum (645 nm) and Hα (656 nm) at the 0.6-m DFM Engineering telescope at Williams College. In the course of this work we have accumulated 106 pairs of observations of the central 20 × 20 arc minutes of Cyg OB2 during the 2010, 2011, 2012, and 2013 Cygnus observing seasons. Observing methods and reductions are as described in Souza *et al.* (2013) and Souza (2013), except that during the 2010, 2011, and 2012 seasons we used our original (Astrodon Imaging) filter pair, while during the 2012 and 2013 seasons we used a new filter pair from Custom Scientific, with parallel observations during the 2012 season for continuity. The new filters have similar bandpasses but better uniformity than the original set. Basic observational data for MT696, including alternate identifications, are shown in Table 1. A finding chart for MT696, including the star BD+40 4227 for reference, is shown in Figure 1.

The extraction of light curves from these less-than-homogeneous data is facilitated by inhomogeneous ensemble photometry (IEP; Honeycutt 1992; Bhatti *et al.* 2010; Richmond 2012) to correct for seeing, transparency, and airmass variations by using nearly all non-variable stars in the field as references. The IEP solution is a set of internally normalized time series, one per star. Putting these measurements on a standard magnitude scale requires comparison with at least several non-variable stars in the field, but this was not done because a) it is not needed for the desired orbital period estimate and normalized light curve, and b) these narrowband data are not readily comparable to the broadband magnitudes in the literature. Fortunately, in testing we found that IEP is effective in compensating for the slightly different characteristics of the two filter pairs, so all observations at each wavelength were combined for IEP solution.

Fourier-based period finding software such as VSTAR (Benn 2012) can have difficulty with eclipsing binaries, which proved to be the case for MT696. We

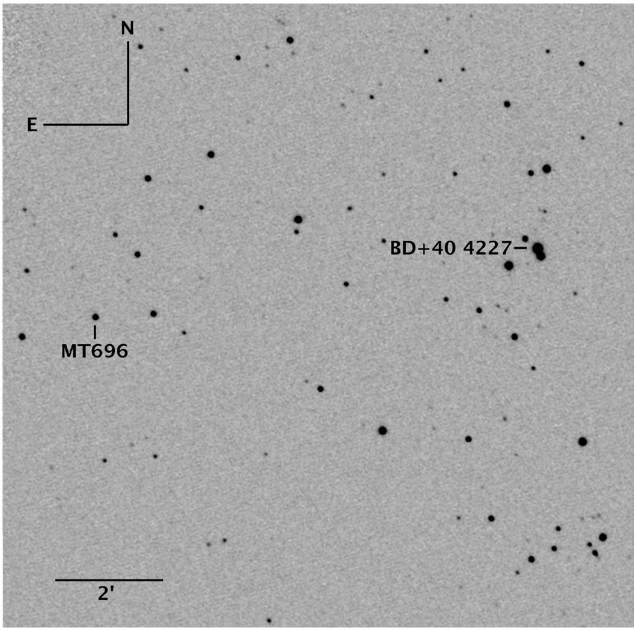

Figure 1. A portion of the Cyg OB2 field, from a 645-nm image taken on 2012 August 18. The position of MT696 is indicated, as is BD+40 4227 (the nominal center of Cyg OB2) for reference.

therefore used the NASA Exoplanet Archive Periodogram Service (Akeson *et al.* 2013) to determine the period and to phase the light curve. We selected the Plavchan *et al.* (2008) algorithm with a fixed period step of 0.00001 day, which is well suited to close eclipsing binaries. The uncertainty in the period was estimated from the half-width of the resulting periodogram peak.

3. Results and discussion

The orbital period of MT696 was derived from these data, grouped several ways (Table 2). The first (global) solution includes all the data from both filters combined, and should be considered our best estimate: 1.46919 ± 0.00006 days, which is in good agreement with but roughly an order of magnitude more precise than the best previously published estimate of 1.4692 ± 0.0005 days by Kiminki *et al.* (2012).

The resulting light curve is shown in Figure 2, plotted with mid-eclipse of the spectroscopic primary (Kiminki *et al.* 2012) at zero phase (epoch HJD 2456162.634). Data for the light curve are shown in Table 3, and are made available through the AAVSO ftp site at ftp:ftp.aavso.org/public/datasets/ssouzj421.txt. The shape of the light curve supports the identification of MT696 as a near-contact β Lyr type system, similar to BF Aur (Kallrath and

Table 2. Orbital period estimates for the MT696 system, derived from these data.

Data Grouping	*Period (days)*
All data	1.46919 ± 0.00006
645-nm only	1.46920 ± 0.00009
656-nm only	1.46920 ± 0.00006
2010–2011 only	1.46917 ± 0.00007
2012–2013 only	1.46920 ± 0.00009

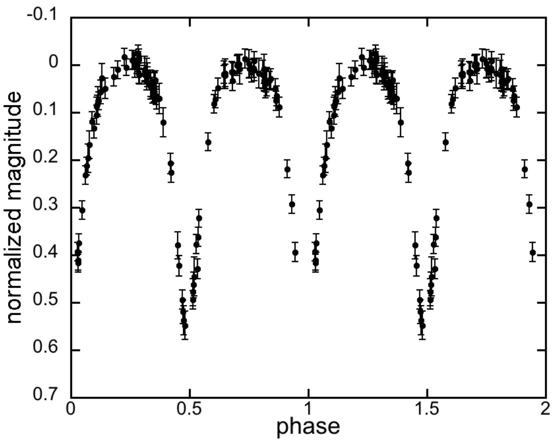

Figure 2. The phased light curve for MT696, using all 645-nm and 656-nm data. The magnitude is set to zero out of eclipse. The solution yields a period of 1.46919 ± 0.00006 days, plotted at an epoch of HJD2456162.634 to center on mid-eclipse of the spectroscopic primary.

Strassmeier 2000). From the nearly equal eclipses we deduce nearly equal surface temperatures, as expected. Correspondingly, the maximum eclipse depth of ~0.6 magnitude roughly corresponds to a minimum inclination of ~60 degrees, consistent with the estimate of 80 degrees by Kiminki *et al.* (2012) based on assumed stellar masses.

To check for filter dependence we computed separate period solutions for 645-nm and 656-nm data. They are consistent with one another and with the global solution, and their corresponding light curves are indistinguishable, as expected for a pair of hot main sequence stars with no Balmer emission.

Finally, we divided the combined data from both filters into early (2010–2011: 46 observations) and late (2012–2013: 50 observations) groups, effectively providing a two-year baseline. Though the later group gives a slightly longer period corresponding to a change of order 10^{-5}/yr, the periods agree to well within the stated uncertainty. However, the internal consistency of these solutions may indicate that our uncertainties are overestimated. If the actual uncertainty was

Table 3. Data for the MT696 light curve shown in Figure 2. Relative magnitude and magnitude uncertainty are from the IEP solution for all the data from both filters combined. Phase is from the NASA Exoplanet Archive Periodogram Service solution, adjusted for mid-eclipse of the spectroscopic primary (Kiminki *et al.* 2012) at zero phase.

HJD	*Relative Magnitude*	*Uncertainty*	*Phase*	*HJD*	*Relative Magnitude*	*Uncertainty*	*Phase*
2455403.726	0.379	0.028	0.451	2455823.709	0.021	0.020	0.312
2455404.649	0.168	0.029	0.079	2455843.641	0.089	0.021	0.878
2455404.703	0.075	0.018	0.116	2455844.614	0.323	0.019	0.540
2455405.653	0.016	0.020	0.763	2455871.533	0.049	0.020	0.862
2455405.694	0.018	0.031	0.791	2455872.524	0.362	0.020	0.537
2455407.631	0.088	0.020	0.109	2455878.560	0.021	0.030	0.645
2455407.683	0.049	0.022	0.144	2455906.484	0.018	0.031	0.652
2455408.669	0.033	0.021	0.815	2455907.497	0.048	0.022	0.342
2455416.629	0.005	0.018	0.234	2455909.463	0.016	0.023	0.679
2455416.683	0.000	0.026	0.270	2455914.484	0.134	0.021	0.097
2455437.611	0.495	0.019	0.515	2456118.721	0.084	0.020	0.110
2455438.613	0.010	0.019	0.197	2456118.727	0.077	0.031	0.114
2455472.608	0.041	0.030	0.336	2456147.703	0.034	0.019	0.837
2455472.687	0.121	0.031	0.389	2456147.708	0.029	0.021	0.841
2455477.720	0.034	0.021	0.815	2456148.641	0.538	0.030	0.476
2455480.595	0.011	0.023	0.771	2456148.647	0.548	0.030	0.480
2455482.664	0.025	0.020	0.180	2456158.643	–0.006	0.021	0.283
2455503.463	0.046	0.021	0.337	2456158.648	–0.013	0.020	0.287
2455503.640	0.423	0.022	0.457	2456158.697	0.035	0.018	0.320
2455512.676	0.072	0.018	0.607	2456158.703	0.016	0.021	0.324
2455514.620	0.293	0.019	0.931	2456158.754	0.065	0.019	0.359
2455514.639	0.394	0.020	0.944	2456158.760	0.072	0.021	0.363
2455733.675	0.412	0.021	0.030	2456161.585	0.020	0.018	0.286
2455743.660	0.036	0.030	0.826	2456161.591	0.021	0.019	0.290
2455743.722	0.065	0.021	0.868	2456162.675	0.393	0.019	0.028
2455744.672	0.478	0.029	0.515	2456162.681	0.417	0.019	0.032
2455748.733	–0.003	0.021	0.279	2456166.600	0.001	0.021	0.699
2455757.657	0.037	0.021	0.354	2456166.606	–0.002	0.020	0.703
2455758.698	0.232	0.019	0.062	2456173.609	0.494	0.020	0.470
2455759.687	–0.013	0.021	0.735	2456173.615	0.519	0.025	0.474
2455775.679	0.049	0.021	0.620	2456182.682	0.020	0.019	0.645
2455776.695	0.010	0.027	0.311	2456182.688	0.023	0.023	0.649
2455782.661	0.071	0.032	0.372	2456183.619	–0.022	0.020	0.283
2455797.691	0.082	0.020	0.602	2456183.625	–0.012	0.022	0.287
2455804.612	0.015	0.018	0.313	2456183.672	0.019	0.033	0.319
2455823.583	–0.016	0.018	0.226	2456183.678	0.025	0.021	0.323

Table continued on next page

Table 3. Data for the MT696 light curve shown in Figure 2, cont.

HJD	*Relative Magnitude*	*Uncertainty*	*Phase*	*HJD*	*Relative Magnitude*	*Uncertainty*	*Phase*
2456183.719	0.046	0.031	0.351	2456249.502	0.057	0.025	0.126
2456183.724	0.032	0.019	0.355	2456249.507	0.028	0.030	0.130
2456194.618	0.007	0.020	0.769	2456250.505	0.021	0.030	0.809
2456194.623	–0.008	0.021	0.773	2456250.513	0.008	0.030	0.814
2456212.638	0.375	0.020	0.035	2456275.497	0.041	0.029	0.820
2456213.586	0.033	0.021	0.680	2456275.503	0.034	0.023	0.824
2456213.591	0.016	0.021	0.683	2456463.690	0.219	0.019	0.912
2456213.628	–0.001	0.019	0.709	2456490.653	–0.011	0.020	0.265
2456213.634	0.009	0.031	0.713	2456500.681	0.119	0.021	0.090
2456213.689	–0.003	0.030	0.750	2456508.672	0.377	0.021	0.529
2456213.695	0.008	0.018	0.754	2456510.634	0.075	0.021	0.865
2456223.629	0.463	0.027	0.516	2456511.615	0.430	0.021	0.532
2456223.634	0.446	0.041	0.519	2456528.621	0.105	0.020	0.108
2456246.479	0.213	0.019	0.068	2456562.635	–0.010	0.020	0.259
2456246.484	0.196	0.030	0.072	2456564.573	0.162	0.019	0.578
2456248.463	0.207	0.021	0.419	2456600.521	0.306	0.020	0.046
2456248.469	0.227	0.020	0.423	2456621.529	0.057	0.024	0.345

about half that stated, these solutions would be marginally consistent with a period increase, but higher quality data over a longer baseline are needed.

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2012); ENSEMBLE 0.7 (Richmond 2012); NOMAD, U.S. Naval Observatory (http://www.nofs.navy.mil/nomad); VizieR catalog access tool, CDS, Strasbourg, France (http://vizier.u-strasbg.fr); NASA Exoplanet Archive Periodogram Service (http://exoplanetarchive.ipac.caltech.edu/cgi-bin/Periodogram/nph-simpleupload).

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