Continued Period Changes in BW Vulpeculae

David E. Cowall
Member, American Association of Variable Star Observers; 20361 Nanticoke Drive, Nanticoke, MD 21840; cowall@comcast.net

Brian A. Skiff
Research Assistant, Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001; bas@lowell.edu

Andrew P. Odell *(deceased May 2019)*
Emeritus Associate Professor of Physics and Astronomy, Northern Arizona University

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Abstract BW Vulpeculae (BW Vul) has the largest amplitude of the β Cephei stars. Over almost 80 years of observations, BW Vul has closely followed a parabolic ephemeris and possibly a light-travel-time effect. This parabola, with excursions on either side, also could be viewed as a sequence of straight lines (constant period) with abrupt period increases. This paradigm predicted a period increase around 2004, which did not occur. A recent observing campaign on this star using the AAVSOnet's Bright Star Monitor telescopes as well as the 0.7-m Lowell Observatory telescope has been undertaken. A period analysis of our data suggests that the period may have paradoxically decreased beginning around 2009. Further observations are necessary to confirm this analysis.

1. Introduction

β-Cephei stars (β Cep) are pulsating variables with periods of 0.1–0.3 day with masses 10–20 $M_{\odot}$. They exhibit large radial velocities but small visual amplitudes with the greatest flux and amplitude in the ultraviolet (UV). They have spectral types B0.5-B2. The largest amplitude β Cep star is the monoperiodic BW Vulpeculae (BW Vul) (aliases: HR 8007 and HD 199140; R.A. 20 54 22.4, Dec. +28 31 19). Its mass is ~15 $M_{\odot}$ and it is ~10^3 times more luminous than the Sun. The V band amplitude is 0.24, but almost 1 magnitude in UV (Percy 2007).

There has been extensive literature published regarding period increases in BW Vul. Based upon spectroscopy, Petrie (1954) first suggested a constant rate of period increase, dP/dt = +3.7 seconds/century. Cherewick and Young (1975) confirmed this with photometry, albeit with a rate approximately half as large. If due to the evolution of the star, then these large positive dP/dt would indicate that BW Vul is in the shell hydrogen burning phase. This contradicts evidence that β Cep stars in clusters are in the late core burning phase where the period change is well under one clock-second per century. This seemingly rules out the contraction phase where the period should decrease.

Another proposed interpretation of the data was a piecewise linear ephemeris with abrupt period changes, suggested by the following investigations: Tunca (1978) suggested a constant period with a dP/dt = +0.5 second/century in 1972. Chapellier (1985) offered a similar interpretation with abrupt period changes in 1931 and 1945 as well. Chapellier and Garrido (1990) documented another period increase around 1980–1981. An international campaign to monitor BW Vul during the 1982 observing season unfortunately yielded only one timing (Sterken *et al.* 1986). Chapellier and Garrido (1990) offered no physical explanation for the period changes but suggested that a convective process could be responsible. They posited that both the amplitude and timings became unstable for three years during the 1980–1981 change.

Odell (1984) noted an apparent periodic variation superimposed on the quadratic ephemeris and attributed it to the light-travel time effect (LTTE) of a small-mass companion, or to two pulsation modes beating with a period of about 25 years. Pigulski (1993) solved for this postulated binary orbit. With reasonable assumptions for the mass of the primary and the inclination of the orbit, the mass of the secondary should be less than 2.5 $M_{\odot}$, and therefore not detectable in extant observations. All this uncertainty surrounding BW Vul was mostly ignored due to the seemingly predictive power of LTTE and the case was considered settled (Horvath *et al.* 1998). Two excellent review papers, Zhou (1999) and Sterken (2005), both used BW Vul as the illustrative example of a star demonstrating LTTE. However, the LTTE model predicted a dP/dt = +0.5 second/century around 2002 which did not happen and thus appears to rule out this explanation for the period variation in this star (Odell 2012).

2. Methods

2.1. AAVSOnet

B-band and V-band images of BW Vul were obtained using the American Association of Variable Star Observers network (AAVSOnet) telescopes (Henden 2014) in Cambridge, Massachusetts (BSM-HQ), New Mexico (BSM-NM), and Hawaii (BSM-Hamren). All AAVSO images were calibrated each observing night using twilight flat-fields as well as bias and dark frames.

Ensemble photometry was done using comparison stars HD 199221 and HD 335322 and check star HD 199418 obtained from the AAVSO Comparison Star Database. Mathematical analyses were performed using VPHOT (AAVSO 2012), VSTAR (Benn 2013), and an EXCEL spreadsheet. Results were air mass corrected, transformed, and submitted to the AAVSO International Database (AID; Kafka 2015).

2.2. Lowell Observatory

Images of BW Vul were obtained using the 0.7-m robotic telescope at Lowell Observatory's Anderson Mesa Station. The CCD field is 15' × 15' with image-scale 0.46"/pixel. Because of the star's brightness, data were taken with narrowband filters approximating the B, V, R wavelengths. These were centered at 4450 Å, 5260 Å, and 7128 Å, and all about 60 Å width. These filters are normally used to subtract out continuum flux from other filters used to measure emission bands in comets. They have the additional use of allowing bright stars to be observed with the telescope in reasonable exposure times. Twilight flat-field and bias frames were obtained each observing night. The CCD camera is cooled using a CryoTiger chiller to –110° C, so dark frames are not required for calibration.

Similar frames of the B-giant HD 198820 = HR 7996 (B3III), 4 degrees north of BW Vul, were interleaved with the variable to serve as the sole comparison star. This procedure worked only on bona-fide photometric (cloud-free) nights. More recently the BW Vul field center has been adjusted to include three rather faint on-chip comparison stars, so that useful data could be obtained when the sky was unexpectedly "cirrus-y."

Seasonal observations continue using the on-chip comparisons, omitting the red filter, but substituting a narrow-band filter in the far-red (8900 Å), near the center of the Sloan z filter passband.

The data prior to Andy Odell's death were analyzed by him using IRAF scripts. We do not know the details of those reductions. However, we know that he necessarily needed to be a finicky photometrist in order to seek the subtle effects in the stars on which he worked.

3. Results

Observed Timings (T_o) of maximum/minimum light were determined using the parabolic method. To for the AAVSO data represent the mean of the B-band and V-band data. Calculated Timings (T_c) are from Sterken's (1993) equation:

$$T_c = 28802.5487 + (0.201038)(\text{Cycle\#}) \qquad (1)$$

These data are included in the ephemerides of Table 1 (AAVSO) and Table 2 (Lowell). To are reported in the columns labeled HJD in days. Cycle numbers ending in .45 represent minima. (O–C)s are the residuals to a linear fit of data and are in clock-minutes.

The BW Vul B-band phase plot from the AAVSO data is shown in Figure 1. Mean scatter on the fit is ~0.05 mag.

A residuals plot combining our data with historical results dating back to 1982 is shown in Figure 2 showing best linear fits.

4. Discussion

Over almost 80 years of observations, BW Vul has closely followed a parabolic ephemeris (period increasing by 2.4 seconds/century) with perhaps LTTE induced by a hypothetical companion. This parabola with excursions on either side also could be viewed as a sequence of straight lines (constant period) with abrupt period increases. This paradigm predicted a necessary period increase around 2004, which did not occur. To the contrary, our data, as seen graphically in the Figure 2 residuals plot, suggest that the period may have paradoxically decreased around 2009 by ~0.0006%. There are insufficient data at present to determine if this proposed period change is real, or if this assumed change is linear plus/minus a sine wave accounting for LTTE. Therefore, both the AAVSOnet and the Lowell Observatory have committed to further observations of this star.

Table 1. BW Vul timings, AAVSO.

Cycle	*HJD (2450000+)*	*(O–C)*
134114.45	5764.8898	–0.6
142048.45	7359.9608	–7.8
143727.45	7697.524	9.2
143772.45	7706.553	–16.6
144500.45	7852.927	4.4
144530.45	7858.954	–1.8
144535.45	7859.948	–17.9
144540.45	7860.962	–5.3
144644.45	7881.8682	–8.6
144659.45	7884.8877	–3
144667.45	7886.4961	–2.9
144684.45	7889.9154	–0.7
144694.45	7891.9294	4.5
144704.45	7893.9389	3.1

Table 2. BW Vul timings, Lowel Observatory.

Cycle	*HJD (2450000+)*	*(O-C)*
142056.45	7361.5800	10.1
142948.45	7540.9025	-1.3
143028	7556.9002	4.6
143166.45	7584.7314	0
143167	7584.8436	2.3
143171.45	7585.7355	-1.6
143172	7585.8468	-0.6
143311	7613.7982	8.6
143519.45	7655.7021	3.5
143623.45	7676.6111	4.3
143624	7676.7239	7.5
143772.45	7706.5655	2.8
143773	7706.6729	-1.8
143777.45	7707.5730	6.1
143778	7707.6872	11.3
144674	7887.8166	3.9
144674.45	7887.9027	-2.5
144679	7888.8262	10.1
144679.45	7888.9116	2.8
144793.45	7911.8321	5.1
144794	7911.9437	6.6
144798.45	7912.8384	6.6
144799	7912.9480	5.2
145354.45	8024.6133	0.2
145355	8024.7316	10.5

5. Acknowledgements

The impetus for this paper comes, in large part, from the passion that Andy Odell had for BW Vul. Unfortunately, he passed away suddenly from a heart attack in May of 2019. He was convinced that this star had much more to teach us and that new surprises awaited us if we continued to observe it. When he was asked what he thought those surprises might

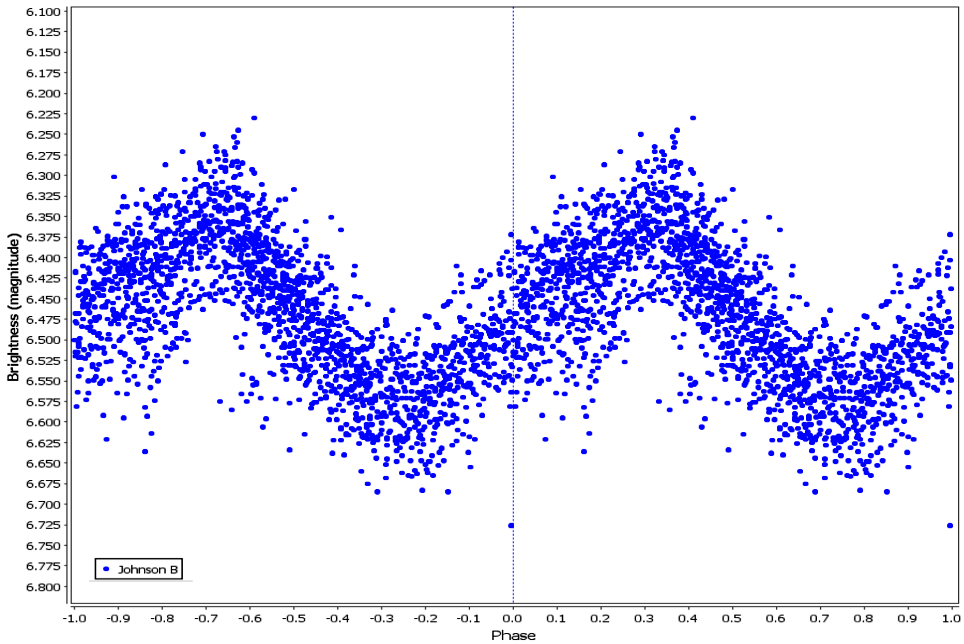

Figure 1. BW Vul B-band phase plot from the AAVSO data.

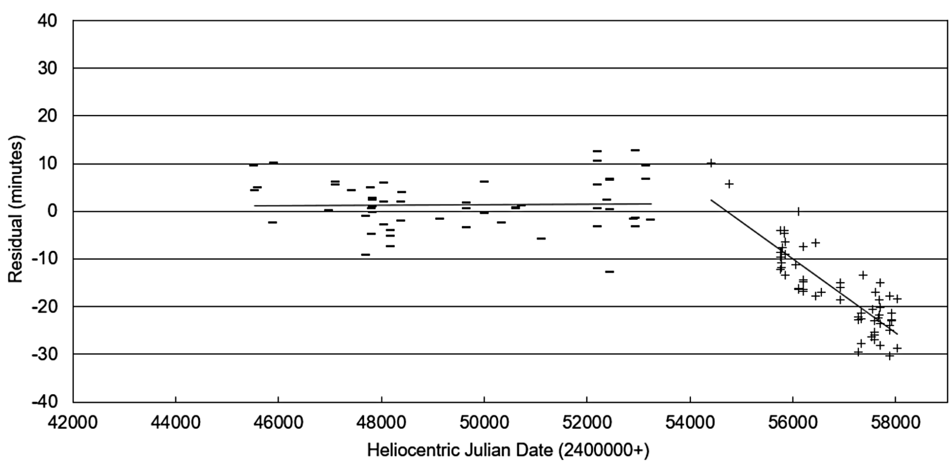

Figure 2. BW Vul O–C HJD (2400000+). "-": 1982–2004 (historical); "+": 2007–2017 (AAVSO and Lowell).

be he said, "Ask me again in 50 years." Rest in peace, Andy, amongst the stars. We acknowledge with thanks the variable star observations from the AAVSO International Database contributed by observers worldwide and used in this research.

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