

An Update on the Periods and Period Changes of the Blazhko RR Lyrae Star XZ Cygni

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Abstract XZ Cygni is an RR Lyrae variable that underwent relatively large changes in its primary and Blazhko periods during the 20th century. Here we use AAVSO photometry obtained between 2001 and 2019 to extend previous studies of this star. Whereas XZ Cygni's fundamental mode and Blazhko periods changed dramatically between 1965 and 1979, those periods have been more stable since the 1980s, although the fundamental period has not been entirely constant. We compare the period change behavior of XZ Cygni with theoretical predictions of period change.

1. Introduction

XZ Cygni (HD 239124, BD +56 2257) was discovered in 1905 and found to be an ab-type RR Lyrae variable (RR0 star) with a period near 0.467 day. It exhibits the Blazhko effect, a periodic modulation in the shape of its light curve. The Blazhko effect is now known to be common among ab-type RR Lyrae stars, and less frequent but not rare among c-type (RR1) RR Lyrae stars (Smolec 2016; Skarka *et al.* 2020; Arellano Ferro *et al.* 2012).

The long term behavior of XZ Cyg was studied by Klepikova (1958), Baldwin (1973), Smith (1975), Pop (1975), Taylor (1975), Bezdenezhny (1988), Baldwin and Samolyk (2003), and LaCluyzé *et al.* (2004). These studies found that the fundamental mode period of XZ Cyg declined slowly in the first half of the 20th century falling from 0.4665878 d at its discovery to 0.4665790 d in 1964. Beginning in 1965, the decline in period became steeper, dropping in steps to reach a minimum of 0.4664464 d between 1974 and 1978 (Baldwin and Samolyk 2003). The direction of period change then suddenly reversed, with the period jumping upward in 1979 to a value near 0.4666938 d, before dropping once again to 0.4665934 d at the close of the 20th century.

As the primary (fundamental mode) period of XZ Cyg changed, so did its Blazhko period. Before 1965, the Blazhko period was about 57.4 days. When the primary period fell to its minimum, the Blazhko period increased to about 58.5 d. Following the 1979 increase in primary period, there was an interval when the Blazhko effect was weak. When it resumed, the Blazhko period was once more near 57.5 d.

Thus, between 1965 and 1979, there appear to have been changes in the structure of XZ Cyg that resulted in relatively large changes in both its fundamental mode and Blazhko periods. In this paper, we investigate the period behavior of XZ Cyg between 2001 and 2019. Has there been any repeat of the large period jumps seen half a century ago, or has XZ Cyg

maintained a more sedate rate of period change? How do the period changes of XZ Cyg match theoretical predictions?

2. Observations

During the interval spanned by this study, visual observations of XZ Cyg were supplanted by CCD photometry. Between 2001 and 2019, the AAVSO RR Lyrae star Legacy program received 911 visual observations of XZ Cyg and 86,926 CCD observations in the V band. These observations were downloaded from the AAVSO International Database (AID; Kafka 2020) for our investigation. Because about 98% of the CCD observations contributed to the AID were made with a Johnson V filter, only the V band CCD data were used in this study. These observations were reduced using multiple comparison stars (referred to as ensemble photometry). The comparison stars were chosen using the AAVSO Variable Star Plotter (VSP). The 100 (mag 10.005 V) and 106 (mag 10.579 V) were typically used and the 103 (mag 10.347 V) comparison star was also used when it fit into the field of view. The telescopes used ranged from 20 to 61 cm in aperture.

3. Changes in the primary period

The O–C diagram in Figure 1 indicates that XZ Cyg has not undergone any large change in its primary (fundamental mode) period since 2001. However, a closer look at the O–C diagram for the interval 2003–2019 indicates that a small change in period did occur around 2012 (Figure 2). Linear least squares fits to the O–C values yielded periods of 0.46659846 d \pm 0.00000038 d for the interval JD 2452771–2456062, and 0.46659753 d \pm 0.00000019 d for the interval JD 2456431–2458825. Figure 2 shows that a parabola also provides a satisfactory fit to the 2003–2019 observations. A parabola implies a constant rate of period change. Because the period change is small in this case, it is difficult to distinguish between

the shallow curve of the second order fit and the fit with two distinct but similar periods. In our Fourier analyses, we adopt the two-line model as a guide to how to divide the observations.

The PERIOD04 Fourier analysis program (Lenz and Breger 2005) was used to validate the fundamental periods within these two intervals. Using PERIOD04 we found the fundamental period in the first interval (9,443 CCD points) to be 0.4665976 ± 0.0000002 d, close to, but slightly smaller than, the result from the O–C diagram. In the second interval (77,483 points) PERIOD04 yielded a period of 0.4665973 ± 0.0000001 d, consistent with the O–C result to within the uncertainties.

4. The Blazhko effect

As noted above, XZ Cyg has long been known to exhibit the Blazhko effect. The recent continuation of this phenomenon is illustrated in Figure 3, which plots data from the AID for 2015. To further investigate the Blazhko effect in XZ Cyg, we used PERIOD04 to pre-whiten the two CCD photometric datasets to remove the fundamental frequency and its six higher harmonics (f_0 , $2f_0$, $3f_0$, ... $7f_0$). In doing this, we divided the data into the two time intervals noted above, 2003 to 2012, and 2012 to 2019. PERIOD04 was then employed to conduct a Fourier analysis of the residuals for each of these two time intervals. In such an analysis the Blazhko effect shows itself as peaks on one or both sides of the fundamental frequency and its lower harmonics (e.g. LaCluyz e *et al.* 2004). Those side-peak frequencies are equal to the fundamental frequency or the harmonic frequency plus or minus the frequency of the Blazhko effect (f_{BI}). We found this pattern of side-peaks to be present in the analyses of the XZ Cyg data, permitting us to determine the length of the Blazhko period. These side-peaks are shown in Figure 4 for the earlier and smaller dataset and in Figures 5 and 6 for the later and larger dataset.

Table 1 shows the strongest side-peak frequencies for JD 2452771–2456062 after removing the primary frequency $f_0 = 2.1431745$ and its harmonics. For the smaller of our two photometric datasets we list only the stronger peaks on the long frequency sides of f_0 and $2f_0$. Table 2 shows similar results for data in the interval JD 2456431–2458825, after removal of $f_0 = 2.1431756$ and its harmonics. In this case, the Fourier diagram was less noisy and both higher and lower side-peak frequencies are listed.

For JD 2452771–2456062, we determined an average Blazhko period of 57.85 days. The formal uncertainties for the two side-peak frequencies are correlated so that the agreement of the two Blazhko periods likely underestimates the actual uncertainty. An uncertainty of about 0.2 d for the Blazhko period is probably more realistic. For JD 2456431–2458825, we determined an average Blazhko period of 57.55 ± 0.03 , where the uncertainty is the standard deviation of the mean. An uncertainty of 0.1 d may be more realistic. The difference in the two Blazhko periods, while possibly real, is not highly significant.

Some previous studies of XZ Cyg found evidence for a second Blazhko period, which we call the tertiary period. Muller (1953) found a tertiary period of either 41.7 or 44 days. LaCluyz e *et al.* (2004) found a tertiary period of 41.6 days.

Table 1. PERIOD04 results for the JD 2452771–2456062 data.

Frequency (1/days)	Notation	Blazhko Period (days)
2.160446	$f_0 + f_{BI}$	57.9
4.303648	$2f_0 + f_{BI}$	57.8

Table 2. PERIOD04 results for the JD 2456431–2458825 data.

Frequency (1/days)	Notation	Blazhko Period (days)
2.16052541	$f_0 + f_{BI}$	57.64
2.12577107	$f_0 - f_{BI}$	57.46
4.26897525	$2f_0 - f_{BI}$	57.55
6.44687866	$3f_0 + f_{BI}$	57.63
6.41212833	$3f_0 - f_{BI}$	57.48

Table 3. Frequencies found in the search for a tertiary period.

Frequency (1/days)	Notation	Tertiary Period (days)
2.16717158	$f_0 + f_{ter}$	41.67
2.11915428	$f_0 - f_{ter}$	41.63
4.31037577	$2f_0 + f_{ter}$	41.62
4.26230936	$2f_0 - f_{ter}$	41.59
6.45353686	$3f_0 + f_{ter}$	41.65
6.40549183	$3f_0 - f_{ter}$	41.61

Only our larger JD 2456431–2458825 dataset is adequate for searching for the tertiary period. To search for a tertiary period, we removed not only f_0 , $2f_0$, ... $7f_0$ but also the f_{BI} side-frequencies, assuming a Blazhko period of 57.55 d. We did indeed find evidence for a tertiary period, with a value of 41.63 ± 0.01 d, where again the standard deviation of the mean underestimates the true uncertainty (see Figure 7). The beat period of a 41.63- and a 57.55-day period is about 150 days. The annual intervals of observation of XZ Cyg are typically longer than this, but there is usually some annual gap in the observations. Observations extending over as much of the year as possible will help the study of these two periods.

After removing the main frequency, its harmonics, and the side-peaks of the 41.63- and 57.55-day periods, the Fourier spectrum of the residuals shows no clear evidence of an additional period (Figure 8).

5. Conclusions

In the four decades since 1979, changes in both the primary and Blazhko periods of XZ Cyg have been relatively small. There has been no repeat of the episode of large period changes following 1965. In addition to the 57.5-day Blazhko period, the 41.6-day tertiary period found in some previous studies is still present in recent photometry. Interestingly, XZ Cyg showed a slow period decline before the acceleration of that decline in 1965. Since 1979, XZ Cyg has resumed a slow decrease in period. Nonetheless, the recent period of XZ Cyg, 0.4665974 d, is slightly greater than Klepikova’s (1958) value for the early 20th century. Thus, despite decades of slow period decrease,

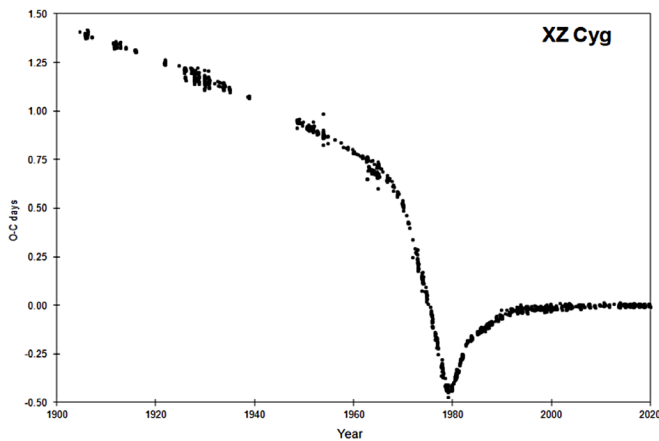


Figure 1. O–C diagram for XZ Cyg for times of maxima from 1900 to 2020. This plot is based on the period of 0.46659753 day. In addition to the AAVSO data, this plot includes times of maxima from the GEOS database.

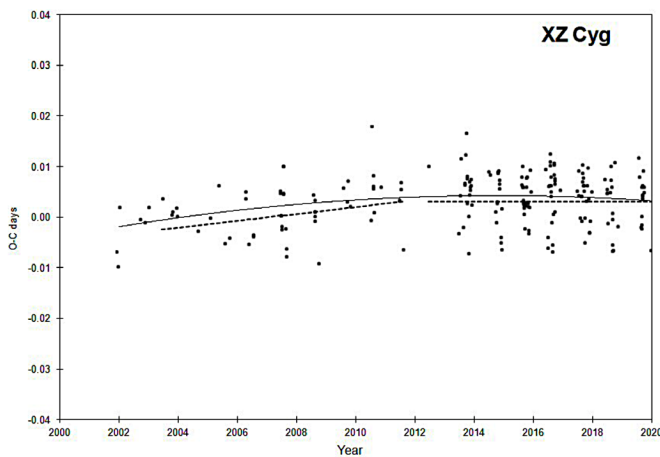


Figure 2. O–C diagram for XZ Cyg for times of maxima from 2002 to 2019. The left dashed line is based on the period of 0.46659846 day. The right dashed line is based on the period of 0.46659753 day. The solid line is a parabolic fit to the 2002–2019 O–C data.

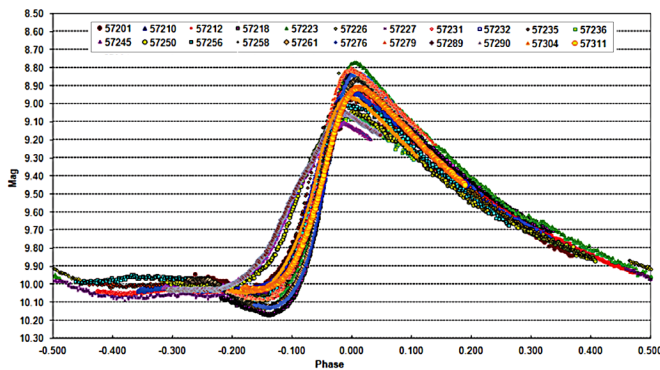


Figure 3. A phase plot of V-band observations made during the 2015 observing season. This plot is based on a period of 0.4665992 d.

the large increase in period around 1979 leaves the period today higher than it was soon after the discovery of XZ Cygni.

Are these period changes consistent with those expected from stellar evolution theory? Periods of pulsating stars obey the pulsation equation $P\sqrt{\rho} = Q$, where P is the pulsation period, ρ is the density of the star, and Q is the pulsation constant. In the long term we expect the observed rate of period change to reflect the slow changes in the size and structure of the star as nuclear burning on the horizontal branch moves the star through the H-R diagram. However, the existence of erratic period changes in some RR Lyrae stars has long been known (e.g. Sweigart and Renzini 1979). Le Borgne *et al.* (2007) investigated the period changes of a large number of field RRab stars using the GEOS database (GEOS 2000–2017). They concluded that, while many RR Lyrae variables showed small rates of period change consistent with the predictions of stellar evolution, others showed large period changes and complicated O–C diagrams requiring other phenomena to be at work.

XZ Cyg clearly falls into the group of RR Lyrae variables with large and erratic period changes. Sweigart and Renzini (1979) proposed that discrete mixing events in the semi-convective zone within RR Lyrae stars could produce abrupt period changes, which could both increase and decrease the period of an RR Lyrae depending upon the exact nature of the mixing. Possibly, mixing events associated with instabilities in the semi-convective zone of XZ Cyg produced the large period changes of 1965–1979.

Taken at face value, the increase in the period of XZ Cyg between 1905 and 1919 implies that its density has decreased. That would be consistent with redward evolution in the H-R diagram, assuming an unchanged pulsation constant. However, the slow period decline over much of that timespan indicates long intervals of increasing density. That would be consistent with blueward evolution. Thus, after more than a century of observation, it is not clear which direction nuclear burning is carrying XZ Cyg through the H-R diagram.

As noted by LaCluyz e *et al.* (2004), the observed changes in the Blazhko period of XZ Cyg argue against any theory which requires that the Blazhko period be exactly equal to, or directly proportional to, the rotation period of the star. To conserve angular momentum, a longer Blazhko period would require a bigger stellar radius, were the Blazhko period directly correlated with the rotation period. However, a larger radius would mean a lower stellar density and a longer fundamental period by the pulsation equation. That is not what has been seen in XZ Cyg.

Finally, we note that Gaia has found evidence that XZ Cyg is a member of a binary star system, though it is not a tight binary (Kervella *et al.* 2019). The orbital period of XZ Cyg is not well-defined, but, if XZ Cyg and its companion are indeed bound, any period is likely in the hundreds or thousands of years (Table A.6 of Kervella *et al.*). It cannot yet be excluded that changing light travel time because of an orbit could produce a very small apparent change in the primary period of XZ Cyg. Any such change would not, however, produce the large and abrupt period changes of the 1960s–1970s.

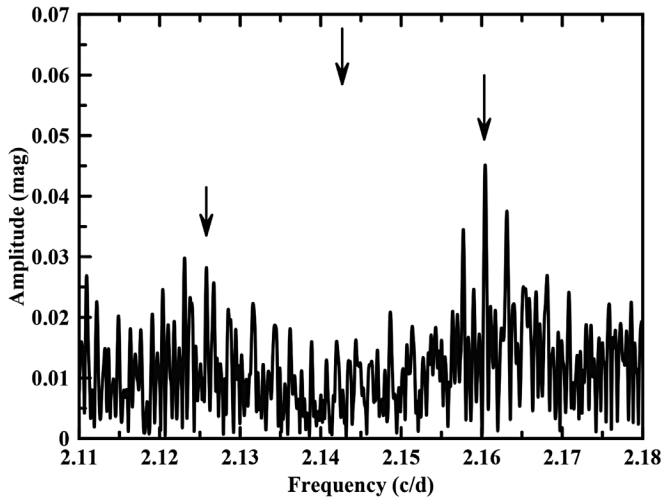


Figure 4. A portion of the Fourier spectrum of XZ Cyg based on the JD 2452771–2456062 photometry, after removal of the main frequency and its harmonics. Peaks due to the 57.85-day Blazhko effect are marked, though only the peak on the long frequency side is strongly significant. Annual alias peaks of these frequencies are also present. The location of the subtracted frequency f_0 is also indicated.

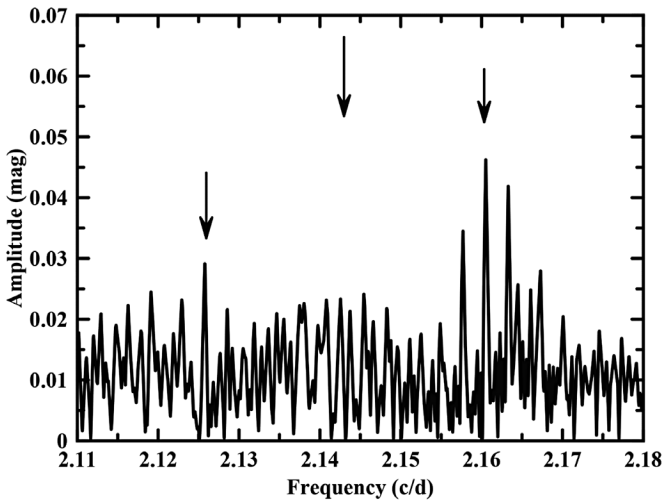


Figure 5. This figure is similar to Figure 4, but is based on photometry from JD 2456431–2458825. In this larger dataset, side-peaks both higher and lower than f_0 reveal the presence of a 57.55-day Blazhko period. Annual alias peaks are also present.

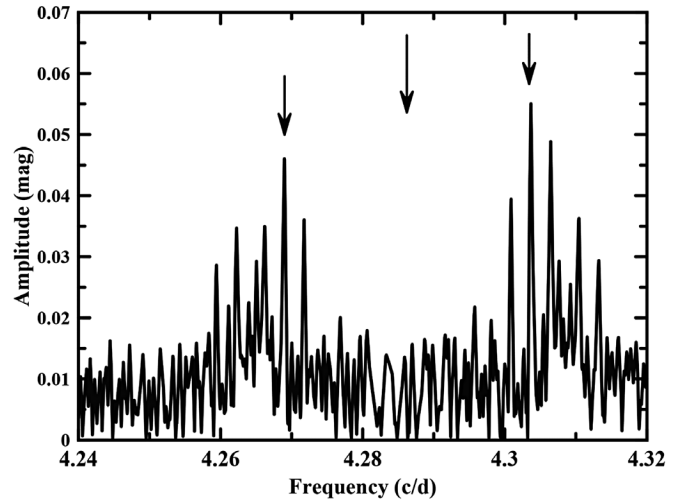


Figure 6. This figure is similar to Figure 5, but for the vicinity of $2f_0$. Side-peaks due to the 57.55-day Blazhko period are marked, as is the subtracted $2f_0$ frequency. One cycle per year annual aliases of the Blazhko peaks are evident.

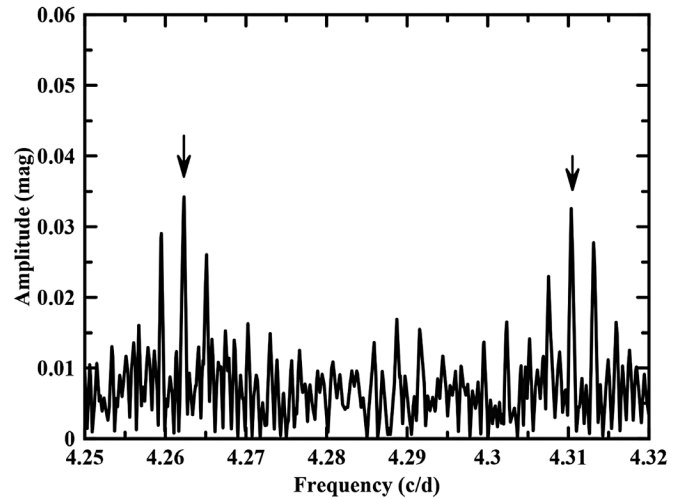


Figure 7. After subtraction of f_0 , harmonics of f_0 , and the side-peaks of the 57.55-day Blazhko period, the side-peaks of the 41.63-day period are revealed. Their annual alias peaks are also present. Here we show the peaks around the $2f_0$ frequency.

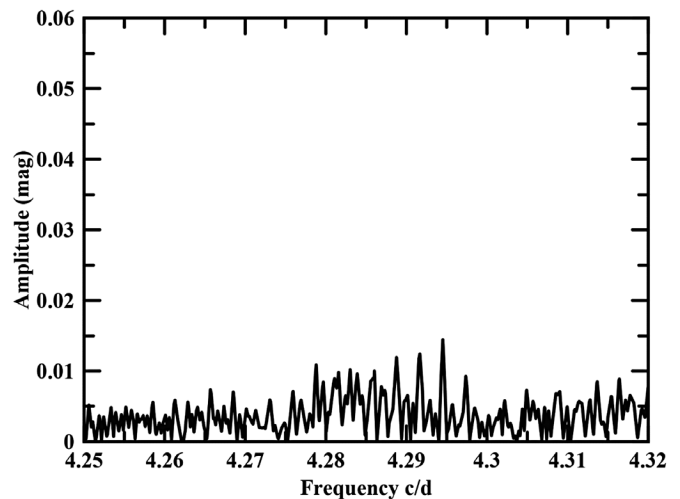


Figure 8. The Fourier spectrum around $2f_0$ after removal of the main frequency, its harmonics, and the 41.63- and 57.55-day side-peak frequencies. Based on photometry from JD 2456431 to 2458825.

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