THE CHANGING BLAZHKO EFFECT OF XZ CYGNI

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ABSTRACT

New CCD photometry has been obtained for the RR Lyrae variable star XZ Cygni. An analysis of old and new photometry confirms earlier results that XZ Cyg exhibits the Blazhko effect and that its Blazhko period has changed over time. These changes in the Blazhko period are anticorrelated with observed changes in the primary period of XZ Cyg. During the first half of the 20th century, XZ Cyg had a Blazhko period of approximately 57.4 days. Beginning in 1965, its primary period underwent a steep decline in several steps. Coincidentally, its Blazhko period increased to about 58.5 days. In 1979, the primary period suddenly increased again. After an interval in which the Blazhko effect was small, the Blazhko effect reestablished itself, with a period of approximately 57.5 days. When its Blazhko period is near 57.5 days, XZ Cyg has also shown a tertiary period of 41.6 days. We confirm that there is evidence for a longer 3540 day period in photometry obtained during the first half of the 20th century. XZ Cyg is compared with three other RR Lyrae stars that also appear to show changing Blazhko periods. The observed changes in the length of the Blazhko period of XZ Cyg constrain possible explanations for the Blazhko effect. In particular, they argue against any theoretical explanation that requires that the Blazhko period be exactly equal, or directly proportional, to the rotation period of the star.

Key words: RR Lyrae variable

On-line material: machine-readable tables

1. INTRODUCTION

Blazhko (1907) discovered a periodic oscillation in the times of maximum light of the RR Lyrae variable RW Dra. Shapley (1916) found that the light-curve shape of RR Lyrae itself changed with a secondary period of approximately 40 days. Subsequently, long-term secondary modulations in light curves have been identified for a number of well-observed RR Lyrae variables. These secondary modulations are now usually referred to as the Blazhko effect, although Szeidl & Kolláth (2000) have suggested that the name Blazhko-Shapley effect might be appropriate in recognition of Shapley’s role in their discovery. In the Milky Way, about 20%–30% of RR Lyrae variables of Bailey type ab (RRab, also termed RR0) show the Blazhko effect (Moskalik & Poretti 2003; Szeidl 1988). In the Large Magellanic Cloud, the percentage of RRab stars that show the Blazhko effect is smaller, about 12%–15% (Alcock et al. 2003; Soszyński et al. 2003). Periods of reported secondary modulations of classical Blazhko effect RRab stars in the Milky Way range from 11 to 533 days. More recently, secondary modulations similar or identical to the Blazhko effect have also been discovered for a small percentage of the RR Lyrae stars of Bailey type c (RRc or RR1). Reviews of the Blazhko effect have been given by Szeidl (1976), Szeidl (1988), Smith (1995), and Kovács (2001). As we discuss in §7, several explanations have been advanced, but there is still no consensus on the mechanism underlying the Blazhko phenomenon (Cousens 1983; Shibahashi 2000; Kovács 2001).

Many RR Lyrae stars are known to have undergone changes in the length of their primary pulsation cycle (Smith 1995). However, significant changes in the length of the Blazhko period appear to have been reported for only four stars (Jurcsik, Benko, & Szeidl 2002): XZ Dra, RV UMa, RW Dra, and the subject of this study, XZ Cyg (HD 239124, BD +56°2257). RR Lyrae stars with changing Blazhko periods are of particular interest, because they may shed light on the cause of the Blazhko effect.

The variability of XZ Cygni was discovered in 1905 by L. Cerasi. Subsequent investigations have made XZ Cyg one of the best studied RRab stars. Blazhko (1922) established that XZ Cygni displays the Blazhko effect, finding the Blazhko period to be approximately 57.4 days. For the next half-century, investigations of XZ Cyg confirmed the existence of a Blazhko period near 57.4 days, although some indicated the possibility of a 41.6 day tertiary period as well (Klepikova 1958; Muller 1953). In the 1960s, however, XZ Cyg underwent striking changes. Baldwin (1973), Smith (1975), Pop (1975), and Taylor (1975) reported that the Blazhko period of XZ Cyg abruptly lengthened to about 58.4 days in the mid-1960s. This change in the Blazhko period coincided with a sharp decrease in the primary pulsation period, which took
place in several steps (Bezdenezhny 1988; Baldwin & Samolyk 2003). More recently, the primary period has increased once more, rising to a value close to the one it had before its sudden decline (Baldwin & Samolyk 2003).

In this paper, we investigate the behavior of XZ Cyg between its discovery and 2002. We present new CCD photometry of XZ Cyg and analyze old and new observations of the star. Our intent is to verify that the Blazhko period of XZ Cyg has indeed changed and to understand how any changes in the Blazhko period are related to changes in the primary period. Finally, we consider how observed changes in the Blazhko period might constrain theoretical models of the Blazhko phenomenon.

2. CCD OBSERVATIONS

Differential \( V \) band photometry of XZ Cyg was obtained with the 60 cm telescope of the Michigan State University Observatory between JD 2,451,338 and 2,452,506 (1999 June 8 through 2002 August 19). Until JD 2,452,202, observations were obtained with an Apogee Ap7 CCD camera. After that date, an Apogee Ap47p camera was used instead. The star TYC 3929-1703-1 was adopted as a primary comparison star, and TYC 3929-1811-1 was used as a check star. Transforming the Tycho catalog \( V_T \) and \( B_T \) magnitudes to the Johnson system using the prescription of Bessell (2000), one obtains \( V = 9.97 \pm 0.04 \) and \( B-V = 1.31 \pm 0.08 \) for TYC 3929-1703-1. Differential \( V \)-band photometry for XZ Cyg is listed in Table 1. Differential magnitudes are given in \( V(XZ \text{ Cyg}) - V \) (comparison star). The typical uncertainty in a measurement of \( \Delta V \) is 0.01 mag. A total of 7738 observations of \( \Delta V \) were obtained.

The comparison star is redder than XZ Cyg itself, for which \( B-V \) varies between 0.2 and 0.01739, reduced the residuals with a standard deviation of 0.079 mag. The Blazhko effect reveals itself in two different types of frequency structure. Some Blazhko variables show frequency triplets with peaks at frequencies \( f_0 \pm k_f \), where \( j = 0, 2, 3, \ldots, k = 0 \) or 1, and \( f_0 \) is the frequency of the Blazhko period. Other Blazhko variables show only frequency doublets (see, e.g., Alcock et al. 2003). Our observations of XZ Cygni indicate the presence of frequency triplets, although the presence of frequency aliases complicates the Fourier spectrum. A portion of the Fourier spectrum around the frequency of the primary period is shown in Figure 3 for the prewhitened data. The peaks at frequencies of 2.12577 and 2.16054 cycles day\(^{-1}\) would beat with the primary frequency at periods of 57.45 and 57.59 days, respectively. Similarly spaced peaks are evident in the Fourier spectrum near frequency \( 2f_0 \). Overall, the peaks identified in the CLEANest and Period98 power spectra indicate the presence of a Blazhko period of 57.5 ± 0.2 days. Subtraction of frequencies \( f_0 \pm f_0 \), where \( j = 1, 2, \ldots, 10 \) and \( f_0 = 0.01739 \), reduced the residuals to 0.042 mag, still significantly larger than the expected observational uncertainty.

With the data prewhitened to remove the primary and Blazhko periods, a further search was conducted for peaks in the Fourier spectrum that might represent a tertiary period. A portion of the resulting Fourier spectrum is shown in Figure 4.

### Table 1

| 
| HJD \( - 2,450,000 \) | \( \Delta V \) |
|---|---|
| 1338.6430 | -0.004 |
| 1338.6452 | -0.027 |
| 1338.6470 | -0.028 |
| 1338.6487 | -0.019 |

**Note.**—Table [1] is presented in its entirely in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.

### Table 2

| 
| HJD \( - 2,450,000 \) | \( \Delta V \) |
|---|---|
| 2210.49663 | -0.675 |
| 2210.49810 | -0.693 |
| 2210.49957 | -0.721 |
| 2210.50103 | -0.735 |

**Note.**—Table [1] is presented in its entirely in the electronic edition of the Astronomical Journal. A portion is shown here for guidance regarding its form and content.
The highest peaks occur at frequencies of 2.1191 and 2.1698 cycles day\(^{-1}\), which would beat with the primary frequency at intervals of 41.6 and 37.5 days, respectively. A lesser peak is evident at a frequency of 2.1671 cycles day\(^{-1}\), which would beat with the primary frequency at an interval of 41.8 cycles day\(^{-1}\). Note that the frequency at 2.1698 cycles day\(^{-1}\) can be interpreted as a 1 yr alias of the frequency at 2.1671 cycles day\(^{-1}\). The Fourier spectrum around the location of 2\(f_0\) shows peaks at frequencies of 4.2623 and 4.3104 cycles day\(^{-1}\), which would indicate a beat period of length 41.6 days. A peak is also evident at a frequency of 4.2596 cycles day\(^{-1}\), which is, however, interpretable as a 1 yr alias of the peak at 4.2623 cycles day\(^{-1}\). We thus conclude that the CCD photometry indicates the existence of a tertiary period of length 41.6 days with an uncertainty of about ±0.2 days. As we discuss later, this period is close to the tertiary periods found by Muller (1953) and Klepikova (1958).

Period98 was used to fit the data with a set of frequencies of the form \(jf_0, jf_0 \pm f_3, \) and \(jf_0 \pm f_3\), where \(f_3\) is the frequency of a 41.6 days tertiary period, 0.02404 cycles day\(^{-1}\). The resulting fit left residuals of 0.029 mag, still somewhat larger than expected from observational error alone. A search for additional periodicities did not lead to clear evidence that any exist. A portion of the Fourier spectrum around the primary frequency after removal of a 0.466598 day primary period, the 57.5 day secondary period, and the 41.6 day tertiary period is shown in Figure 5. The frequencies, amplitudes, and phases of the components of this fit are listed in Table 3.

The period search procedure was repeated incorporating just the Michigan State University Observations. The results, as might be expected, are very similar. The residuals in the final fit to the Michigan State University observations were slightly smaller, ±0.026 mag.

The effects of the secondary and tertiary periods have been removed from the light curve by subtracting the sidelobe components of the 57.5 day and 41.6 day periodicities. The
resulting light curves, phased as in Figures 1 and 2, are shown in Figures 6 and 7.

4. XZ CYGNI BEFORE 1965

The most extensive studies of the behavior of XZ Cyg before the changes in primary period that began about 1965 are those of Muller (1953) and Klepikova (1958). Muller obtained the first detailed photoelectric observations of XZ Cyg, monitoring the star from 1948 until 1952 November. Muller confirmed the existence of the secondary period reported by Blazhko (1922), finding the period to be approximately 57.4 days. However, Muller found that the observations were better described if, in addition to this secondary period, there existed a tertiary period with a length of either 89.34 or 94.31 times the primary period, 41.7 or 44.0 days, respectively, were better described if, in addition to this secondary period, there existed a tertiary period with a length of either 89.34 or 94.31 times the primary period, 41.7 or 44.0 days, respectively, assuming a primary period of 0.4665839 days.

Klepikova (1958) attempted, insofar as was possible, to put all existing observations of the maximum brightness of XZ Cyg on a consistent photometric system. She then used the times and brightnesses of maxima obtained between JD 2,417,017 and 2,434,946 to study the long-term behavior of XZ Cyg and found evidence for a slow decline in the primary period of the variable during this time span, described by the ephemeris for the times of maximum light

\[
\begin{align*}
\text{Max}_\text{a} &= \text{HJD} 2,417,201.241 + 0.4665878E \\
& \quad - 0.000107E^2 \times 10^{-6},
\end{align*}
\]

where \(E\) is the number of cycles elapsed since the start date. Thus, the period would have decreased from 0.4665878 days in 1905 to 0.466584 days in 1954. Bezdenzhny (1988) provided a slightly different interpretation of the period changes of XZ Cyg during this interval, finding that the primary period decreased stepwise from 0.4665861 days during JD 2,417,000–2,424,800 to 0.466579 days during the interval JD 2,434,600–2,438,700 (ending in 1964). Whichever description one accepts for the period changes, it is clear that the primary pulsation period of XZ Cyg was relatively stable between 1905 and 1965.

Klepikova (1958) confirmed the existence of a Blazhko period of 123.040 times the primary period (giving \(P_{\text{Bl}} = 57.4\) days). She also confirmed the existence of a tertiary period of 89.23 times the primary period \((P_3 = 41.6\) days). Thus, 3 times the secondary period would be approximately (but not exactly) 4 times the tertiary period, as Klepikova noticed. Klepikova also identified a superimposed, longer quaternary variation with a period of about 3460 days, during which there is a long-term change in the mean magnitude at maximum light. This can be seen in Figure 8, which plots the magnitude at maximum light versus Julian Date for the maxima in Table 10 of Klepikova. Not plotted in Figure 8 are the later maxima listed by Kanishcheva & Sakharov (1965),

**TABLE 3**

| Frequency (day\(^{-1}\)) | Amplitude (mag) | Phase (cycles) | ID |
|--------------------------|-----------------|----------------|----|
| 2.14317                   | 0.447           | 0.090          | f_0 |
| 2.16056                   | 0.031           | 0.708          | f_0 + f_8 |
| 2.12578                   | 0.027           | 0.267          | f_0 - f_8 |
| 2.16721                   | 0.026           | 0.824          | f_0 + f_3 |
| 2.11913                   | 0.027           | 0.613          | f_0 - f_3 |
| 4.28634                   | 0.186           | 0.632          | 2f_0 |
| 4.30374                   | 0.022           | 0.242          | 2f_0 + f_0 |
| 4.26895                   | 0.012           | 0.656          | 2f_0 - f_0 |
| 4.31058                   | 0.013           | 0.795          | 2f_0 + f_3 |
| 4.26231                   | 0.015           | 0.233          | 2f_0 - f_3 |
| 6.42952                   | 0.126           | 0.172          | 3f_0 |
| 6.44691                   | 0.017           | 0.906          | 3f_0 + f_0 |
| 6.41213                   | 0.019           | 0.394          | 3f_0 - f_0 |
| 6.45356                   | 0.009           | 0.697          | 3f_0 + f_3 |
| 6.40548                   | 0.020           | 0.679          | 3f_0 - f_3 |
| 8.57269                   | 0.070           | 0.626          | 4f_0 |
| 8.59008                   | 0.020           | 0.161          | 4f_0 + f_0 |
| 8.55530                   | 0.015           | 0.483          | 4f_0 - f_0 |
| 8.59673                   | 0.014           | 0.119          | 4f_0 + f_3 |
| 8.54865                   | 0.016           | 0.867          | 4f_0 - f_3 |
| 10.71586                  | 0.037           | 0.292          | 5f_0 |
| 10.73325                  | 0.009           | 0.845          | 5f_0 + f_0 |
| 10.69847                  | 0.008           | 0.099          | 5f_0 + f_8 |
| 10.73990                  | 0.009           | 0.852          | 5f_0 + f_3 |
| 10.69182                  | 0.012           | 0.742          | 5f_0 - f_0 |
| 12.85904                  | 0.027           | 0.533          | 6f_0 |
| 12.87643                  | 0.010           | 0.136          | 6f_0 + f_0 |
| 12.84164                  | 0.008           | 0.359          | 6f_0 - f_0 |
| 12.88307                  | 0.009           | 0.297          | 6f_0 + f_3 |
| 12.83500                  | 0.008           | 0.072          | 6f_0 - f_3 |
| 15.00221                  | 0.015           | 0.170          | 7f_0 |
| 15.01960                  | 0.007           | 0.758          | 7f_0 + f_0 |
| 14.98482                  | 0.005           | 0.653          | 7f_0 + f_8 |
| 15.02625                  | 0.003           | 0.312          | 7f_0 + f_3 |
| 14.97817                  | 0.004           | 0.542          | 7f_0 - f_0 |
| 17.14538                  | 0.011           | 0.981          | 8f_0 |
| 17.16277                  | 0.005           | 0.082          | 8f_0 + f_0 |
| 17.12799                  | 0.006           | 0.261          | 8f_0 + f_8 |
| 17.16942                  | 0.001           | 0.397          | 8f_0 + f_3 |
| 17.12134                  | 0.003           | 0.914          | 8f_0 - f_0 |
| 19.28855                  | 0.010           | 0.927          | 9f_0 |
| 19.20592                  | 0.007           | 0.567          | 9f_0 + f_0 |
| 19.28855                  | 0.004           | 0.853          | 9f_0 + f_8 |
| 19.31259                  | 0.002           | 0.468          | 9f_0 + f_3 |
| 19.26451                  | 0.003           | 0.569          | 9f_0 - f_0 |
| 21.43137                  | 0.004           | 0.307          | 10f_0 |
| 21.44876                  | 0.005           | 0.795          | 10f_0 + f_0 |
| 21.41398                  | 0.002           | 0.806          | 10f_0 - f_0 |
| 21.45576                  | 0.002           | 0.619          | 10f_0 + f_3 |
| 21.40767                  | 0.004           | 0.933          | 10f_0 - f_3 |

**Fig. 5.**—Fourier spectrum of the CCD observations after subtraction of the frequency components of the primary period, a 57.5 day period, and a 41.6 day period.
which are approximately on the system of Klepikova but which may not be exactly comparable.

Long-term periodicities have been reported for a few other Blazhko effect stars, most notably RR Lyrae itself (Detre & Szeidl 1973). In addition to its 41 day Blazhko period, RR Lyrae exhibits a 4 yr periodicity. The amplitude of the Blazhko effect varies during this longer cycle, and the phase of the Blazhko cycle shifts when one 4-yr cycle ends and the next begins.

The data accumulated by Klepikova (1958) indicate that the amplitude of the Blazhko effect in XZ Cyg changed over time, but they are not sufficient to let us decide whether the 3460 day period is exactly analogous to RR Lyrae's 4 yr period. Detre (1956) reported that J. Balazs had identified a 153.8 day tertiary period for XZ Cyg, which, however, might also be interpreted as the beat interval between periods of approximately 57.4 and 41.6 days.

As a check on the conclusions of Klepikova (1958) and Muller (1953), the CLEANest routine was used to search for periodicities in the magnitudes of maximum reported by Klepikova. Applied to the entire data range from JD 2,417,017 to 2,434,946, the CLEANest routine did identify periods of 57.41 ± 0.02, 41.61 ± 0.04, and 3540 ± 100 days. Thus, we broadly confirm Klepikova's results. Nonetheless, it is also evident that these three periodicities are not able to explain much of the scatter in the data. The standard deviation of the maximum magnitudes about the mean was initially 0.113 mag. Removing these three periods and their harmonics from the data reduced that value only slightly, to 0.086 mag. It is possible that instead of being 3540 days long, the actual longest period could be twice that value. When the data are phased with a circa 7000 days period, there are large gaps in the phase coverage that make it difficult to fully test that possibility. In Figure 9, we plot the residuals of maximum magnitudes from Klepikova after removal of the 57.4, 41.6, and 3540 day periodicities.

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Fig. 6.—V light curve of all CCD observations with the sidelobes of the frequency triplets removed.

Fig. 7.—V light curve of Michigan State University CCD observations with the sidelobes of the frequency triplets removed.

Fig. 8.—Magnitude of XZ Cyg at maximum light vs. Julian Date for maxima listed by Klepikova (1958).

Fig. 9.—Residuals of the magnitudes of XZ Cyg at maximum light listed by Klepikova (1958) after removal of the 57.4, 41.6, and 3540 day periodicities.
collected by Klepikova. There is, for example, little evidence for a ~57 day period in the observations made from JD 2,417,017 to 2,417,538. A period near 57.34 days is, however, present in the observations made between JD 2,424,370 and 2,427,750 (Fig. 10). Such variability in the Blazhko effect would, of course, not be unique to XZ Cyg, as it is also well observed in RR Lyrae itself, for example. In addition, despite the efforts by Klepikova to place all observations on a consistent system, the heterogeneity of the observations makes it difficult to compare results over the entire time interval for which Klepikova tabulated maxima.

For the interval spanned by the observations of Muller (1953) and the data compiled by Klepikova (1958), one can conclude that the primary period of XZ Cyg decreased slightly but was relatively stable, and that additional periods of length about 41.6, 57.4, and 3540 days were present. The durability of the 3540 day period is uncertain, since it could be followed for only a few cycles, and, as we have noted, the possibility that the longest period is 7000 days rather than 3540 days cannot be entirely excluded. Moreover, it appears likely that the amplitudes of the 41.6 and 57.4 day periodicities were not constant throughout that time interval. Nonetheless, our check confirms prior studies of the behavior of XZ Cyg before 1965.

5. THE BEHAVIOR OF XZ CYGNI SINCE 1965

Beginning about JD 2,438,800 (1965), the primary period of XZ Cyg began a steep decline in several steps (Bezdenezhny 1988; Baldwin & Samolyk 2003). The primary period fell to a minimum of 0.4664464 days during the interval JD 2,442,050 to 2,443,740, 1974 to 1978 (Baldwin & Samolyk 2003). In 1979, the primary period sharply increased, rising to values slightly greater than those observed before the steep decline. Changes in the primary period of XZ Cyg since 1965 are listed in Table 4, which follows Baldwin & Samolyk. The periods reported in Baldwin & Samolyk are similar to those reported by Bezdenezhny for time intervals covered in both studies.

Shortly after the decline in the primary period of XZ Cyg, observers began to report a coincident increase in its 57.4 days Blazhko period (Baldwin 1973; Pop 1975; Kunchev 1975; Smith 1975). These indicated that, at about the time that the primary period of XZ Cyg fell to its minimum, the Blazhko period of XZ Cyg increased to about 58.4 days, or perhaps slightly more. An O–C (observed minus calculated times of maximum light) diagram illustrating this change in the Blazhko period is included in Smith (1975). As a check and an extension of these earlier results, we have analyzed observations of XZ Cyg reported since 1965 to the RR Lyrae Committee of the American Association of Variable Star Observers (AAVSO).

5.1. AAVSO Visual Observations

AAVSO observers have accumulated a large number of visual observations of XZ Cyg since 1965. These data mainly consist of observations obtained near the time of maximum light, rather than throughout the entire light curve. We begin by considering M. Baldwin’s observations of the magnitude attained by XZ Cyg at maximum light (Baldwin & Samolyk 2002). In Figure 11, we plot the magnitude of maximum light versus Julian Date. It is apparent that the scatter in the maxima was relatively large around JD 2,443,000 but diminished after JD 2,444,000. This change is also evident in the plots of O–C in Baldwin & Samolyk (2003), which are corrected for the observed changes in the primary period of the star. The diminution in the scatter was noticed by Taylor (1980), who further noted that it was approximately

### Table 4

| Julian Date | Primary Period (days) |
|-------------|-----------------------|
| 2,438,880–2,440,520 | 0.4665454 |
| 2,440,520–2,442,050 | 0.4664750 |
| 2,442,050–2,443,740 | 0.4664464 |
| 2,444,050–2,445,270 | 0.4666938 |
| 2,445,270–2,446,440 | 0.4666263 |
| 2,446,440–2,448,570 | 0.4661795 |
| 2,448,570–2,452,618 | 0.4659934 |

7 This data is unpublished and available in the AAVSO archives.
coincident with the abrupt large increase in the primary period of XZ Cyg that took place near JD 2,444,000. Subsequent to JD 2,449,000, there is some evidence for another increase in the size of the scatter of the maximum magnitudes, but not to the level observed near JD 2,443,000.

We have made two new analyses of the AAVSO observations to determine the length and amplitude of the Blazhko cycle during the time interval covered by the AAVSO observations. We first searched for a periodicity in the magnitude reached at maximum light using CLEANest, limiting ourselves to the maxima observed by M. Baldwin to reduce the possibility of systematic errors among different visual observers. Results from this analysis are listed in Table 5. We also searched for periodicities in the O–C values provided by Baldwin & Samolyk (2003). In this case, we analyzed all the O–C values reported by AAVSO observers. Results from a period search using CLEANest are listed in Table 6. For comparison, in Table 7 we list a number of determinations of the Blazhko period of XZ Cyg from the literature.

These analyses confirm that, in the interval from about JD 2,439,000 to 2,444,000, the Blazhko period was indeed about a day longer than it had been in the time intervals studied by Muller (1953) and Klepikova (1958). The Blazhko amplitude was particularly large around JD 2,443,000, when the primary period of XZ Cyg was near its minimum. The Blazhko periodicity was apparently suppressed for a while when the primary period abruptly increased near JD 2,444,050, before gradually starting to reassert itself. The renewed Blazhko period is shorter again. However, the evidence for the current length of the Blazhko period is stronger in the CCD observations than in the AAVSO visual data.

It would be very interesting to know whether the 41.6 day tertiary period was still present when the secondary period was near 58.5 days. To investigate this, we analyzed AAVSO data obtained between JD 2,438,882 and 2,443,800. Figure 12 shows the Fourier spectrum for the 109 maximum magnitudes observed by Baldwin during this time interval. A strong peak is evident at a frequency of 0.01709 cycles day$^{-1}$, which corresponds to a period of 58.5 days. Figure 13 plots the maximum magnitudes phased with the 58.5 day period. For comparison, the same maxima phased with a 57.4 day period are plotted in Figure 14. Figure 15 shows the Fourier spectrum of the data after the magnitudes at maximum have been prewhitened to remove the 58.5 day periodicity and its four highest harmonics. No clear peak is evident near a frequency of 0.024 cycles day$^{-1}$, which corresponds to a periodicity of 41.6 days. The two highest peaks occur at frequencies of 0.019377 and 0.016345 cycles day$^{-1}$, corresponding to periods of 51.6 and 61.2 days, respectively. These periods would beat against a 58.5 day period in about 440 and 1300 days, respectively. They are, however, much weaker than the 58.5 days Blazhko period, and it is doubtful whether they correspond to physically real periodicities.

A similar analysis was performed on 182 O–C values observed during the same interval, excluding two values that were very deviant from the trend of the other observations. The Fourier spectrum for these observations (Fig. 16) shows a peak at 0.01706 cycles day$^{-1}$, corresponding to a period of 58.6 days, which is consistent within the uncertainties with the value seen in Figure 12. The O–C values are phased with a 58.5 day period in Figure 17, which shows considerably more scatter than in the corresponding diagram for magnitude at maximum light. For comparison, Figure 18 shows the O–C values phased with a 57.4 day period. Prewhitening to remove the 0.01706 cycles day$^{-1}$ frequency again left no clearly significant peaks in the Fourier spectrum. Thus, while we find a Blazhko period of approximately 58.5 days in both the times and brightnesses of maximum light during this interval, we find no evidence for a tertiary period. Any tertiary periodicity present at this time must have had an amplitude less than about one-third that of the 58.5 day Blazhko cycle. In contrast, Figure 19 shows the Fourier spectrum for O–C observations obtained between JD 2,448,570 and 2,452,618. The peaks at frequencies of 0.01736 and 0.02404 cycles day$^{-1}$ indicate the existence of 57.6 and 41.6 day periods. A peak is also evident at a frequency of 0.0146 cycles day$^{-1}$, which corresponds to a period of 68.5 days. That, however, is the 1 yr alias of the 57.6 day period.

Figure 20 plots the Blazhko period versus the fundamental mode period for XZ Cyg. Here we have used our results for the length of the Blazhko period and have adopted the results of Baldwin & Samolyk (2003) for the length of the primary period. For the earlier maxima listed by Klepikova (1958), we...
have adopted an average primary period of 0.466584 days. Note that, while the Blazhko period clearly is correlated with the fundamental mode period, the exact form of that correlation is not clear. There might be a linear correlation, with $dP_{\text{Bl}}/dP_0 = -8 \pm 1 \times 10^{-3}$. On the other hand, the Blazhko period might have jumped discretely from a value near 57.4 days when $P_0$ was near 0.4666 days to a value near 58.5 days when $P_0$ was smaller than 0.46655 days.

6. COMPARISON WITH OTHER RR LYRAE STARS HAVING CHANGING BLAZHKO PERIODS

As noted in § 1, changes in the Blazhko period have been reported for three RR Lyrae stars in addition to XZ Cyg (Jurcsik et al. 2002). In all four reported cases, the change in the Blazhko period coincides with changes in the primary pulsation period. However, the ratios of the changes in the Blazhko period to those of the primary period, as well as the sign of those ratios, differ from star to star. In the case of XZ Dra (Jurcsik et al. 2002), the primary period and the Blazhko period change with the same sign. In the other three cases, RV UMa (Kanyó 1976), RW Dra (Firmanyuk 1978), and XZ Cyg, the reported changes of the Blazhko period have a sign opposite that of the changes in the primary period. Of the four stars, XZ Cygni has undergone the largest changes in its primary period. Observed ratios of $dP_{\text{Bl}}/dP_0$ are listed in Table 8. For the purposes of this table, we have assumed a linear dependence of the change in the Blazhko period on the

Fig. 12.—Fourier spectrum for maximum magnitudes observed by M. Baldwin between JD 2,438,882 and 2,443,800. The strong peak at frequency 0.01709 cycles day$^{-1}$ corresponds to a period of 58.5 days.

Fig. 13.—Magnitudes of XZ Cyg at maximum light observed by M. Baldwin between JD 2,438,882 and 2,443,800, folded with a 58.5 day period. More scatter is seen than in Fig. 13.

Fig. 14.—Magnitudes of XZ Cyg at maximum light observed by M. Baldwin between JD 2,438,882 and 2,443,800, folded with a 57.4 day period.
change of the primary (fundamental mode) period. Such a linear dependency is consistent with the observations, but, as we have noted above, other dependencies are also possible. In the case of RW Dra, the changes in period have been estimated from the $O-C$ diagram of Firmanyuk (1978). As is the case for XZ Cyg, very long additional periods have been reported for two of the remaining three stars. Jurcsik et al. (2002) identified a 7200 day tertiary period in XZ Dra, while Kanyó (1976) reported that RV UMa also shows a long-term cycle of 2000 to 3000 days.

7. CONSTRAINTS ON THE NATURE OF THE BLAZHKO PHENOMENON

As noted in § 1, there is as yet no completely satisfactory explanation for the Blazhko phenomenon. Proposed explanations can be broadly divided into two groups: (1) magnetic models in which Blazhko variables have a magnetic field with an axis tilted obliquely with respect to their axis of rotation and (2) resonance models in which there is a nonlinear resonance between the dominant radial mode and a nonradial pulsation mode. Oblique magnetic rotator models (Cousens 1983; Shibahashi 2000) generally require that the Blazhko period and the rotation period of the star are equal. Babcock (1958) and Romanov, Udovichenko, & Frolov (1994) reported the presence of a magnetic field in the photosphere of the brightest Blazhko variable, RR Lyrae itself. However, Preston (1967) and Chadid-Vernin (2003) have not detected any strong magnetic field in RR Lyrae. The recent results by Chadid-Vernin (2003) have not yet been published in full detail, but if the preliminary results are confirmed, they would provide perhaps the strongest argument against any oblique

Fig. 16.—Fourier spectrum of $O-C$ values for the time of maximum light, from observations obtained between JD 2,438,882 and 2,443,800. The peak at 0.01706 cycles day$^{-1}$ corresponds to a period of 58.6 days.

Fig. 17.—$O-C$ values obtained from observations made between JD 2,438,882 and 2,443,800 and folded with a period of 58.5 days.

Fig. 18.—$O-C$ values obtained from observations made between JD 2,438,882 and 2,443,800 and folded with a period of 57.4 days.

Fig. 19.—Fourier spectrum of $O-C$ values for the time of maximum light, from observations obtained between JD 2,448,570 and 2,452,618. Peaks at frequencies 0.01736 and 0.02404 cycles day$^{-1}$ correspond to periods of 57.6 and 41.6 days.
Changes in the Blazhko period have been observed for at least four RR Lyrae variables, as noted above. In the case of XZ Cyg, the length of the Blazhko period increased by about 2% before returning to something close to its original value. An increase and later decrease in the rotation period of XZ Cyg by as much as 2% is physically implausible. Moreover, while a large increase in the radius of XZ Cyg around 1965 might produce a longer rotation period, the pulsation equation, \( P(\rho)^{1/2} = Q \), would then indicate that the primary period should have increased, not decreased, at that time. We would therefore argue that the Blazhko period of XZ Cyg is unlikely to be equal to or directly proportional with its period of rotation. That is another argument against simple oblique magnetic rotator models. It may also be an argument against the nonradial excitation models of Nowakowski & Dziembowski (2001) and Nowakowski (2002), although there the argument is not so clear. If the rotationally split \( m = \pm 1 \) modes could manage to maintain a relatively constant frequency when the frequency of the fundamental radial mode changed, then it is possible for the beat period of the radial and nonradial modes to change, producing the observed changes in the Blazhko period.

In the case of XZ Cyg, there are additional observations that any complete theory must explain. First is the existence of a 41.6 day tertiary period at the same time as that of the main 57.5 day Blazhko period. It might be explained through the excitation of an additional nonradial mode. That mode may not have been excited during the interval when the Blazhko period of XZ Cyg was near 58.5 days. Second, we have the coincidence in the changes of the Blazhko period and of the period of the fundamental radial mode. Third, the Blazhko effect in XZ Cyg continued to be strong after the decline in the fundamental mode period of the star, but seems to have diminished when the fundamental period increased again. One might imagine that the Blazhko effect was somehow turned off when the primary period increased, taking some years to become reestablished. The possibility that this simultaneous change in the Blazhko amplitude and the primary period was coincidental seems unlikely but cannot be entirely excluded. The Blazhko effect in XZ Cyg and other RR Lyrae stars has undergone changes in amplitude even when the primary period of the star has been relatively stable. How the multiyear periods seen in XZ Cyg and other RR Lyrae stars are related to the Blazhko phenomenon also remains unclear.

It is interesting that XZ Cyg seems to have returned to something close to the state it had during the first half of the 20th century following several decades of large period changes. It has long been known that evolution cannot account for all of the observed changes in the primary periods of RR Lyrae variable stars (see the review in Smith 1995). Some sort of period change noise appears to overlie any evolutionary period changes in these stars. It has been suggested that this noise might be related to discrete mixing events associated with the semiconvective zone of the stellar core (Sweigart & Renzini 1979). Whatever is responsible for the period change noise, in XZ Cyg that mechanism can reverse its behavior in such a way that it seems to have returned the structure of the star to something close to the state it had half a century before.

### TABLE 8

| Star   | \( \Delta P_{\text{Blazhko}}/P_0 \) |
|--------|------------------------------------|
| XZ Cyg | \(-8 \pm 1 \times 10^3\)            |
| XZ Dra | \(+7.7 \pm 1.1 \times 10^4\)        |
| RV UMa | \(-1 \times 10^6\)                 |
| RW Dra | \(-7 \times 10^3\)                 |

8. CONCLUSIONS

We confirm that the Blazhko period of XZ Cyg increased sharply from about 57.4 to 58.5 days at the same time that its primary pulsation period underwent a sharp decline. Subsequently, when the primary pulsation period increased again, the
Blazhko period decreased. During the intervals when XZ Cyg has had a Blazhko period near 57.4 days, it has also shown a tertiary period of 41.6 days. When the Blazhko period was near 58.5 days, the 41.6 day tertiary period either was not present or had an amplitude much smaller than that of the 58.5 day periodicity. The amplitude as well as the period of the Blazhko effect in XZ Cyg has changed over time. We particularly note the disappearance or diminution of the Blazhko effect around JD 2,444,000, which is about when the primary period jumped from 0.4664464 to 0.4666938 days. The Blazhko effect is evident again after about JD 2,448,570, when the primary period had decreased to 0.466599 days. During the first half of the 20th century, photometry of XZ Cyg also showed evidence for a fourth period, in this case almost 10 yr in length. The observed changes in the Blazhko period of XZ Cyg and a few other Blazhko stars argue that the Blazhko period is not exactly equal or directly proportional to the rotation period of the star, as required by some theoretical models.

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