Resynchronization of the Asynchronous Polar CD Ind

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Abstract

CD Ind is one of only four confirmed asynchronous polars (APs). APs are strongly magnetic cataclysmic variables of the AM Herculis subclass with the characteristic that their white dwarfs rotate a few percent out of synchronism with their binary orbit. Theory suggests that nova eruptions disrupt previously synchronized states. Following the eruption, the system is expected to rapidly resynchronize over a timescale of centuries. The other three asynchronous polars—V1432 Aql, BY Cam, and V1500 Cyg—have resynchronization time estimates ranging from 100 to more than 3500 years, with all but one being less than 1200 years. We report on the analysis of over 46,000 observations of CD Ind taken between 2007 and 2016, combined with previous observations from 1996, and estimate a CD Ind resynchronization time of 6400 ± 800 years. We also estimate an orbital period of 110.820(1) minutes and a current (2016.4) white dwarf spin period of 109.6564(1) minutes.

Key words: cataclysmic variables – novae – stars: individual (CD Ind – V1432 Aql – BY Cam – V1500 Cyg

1. Introduction

CD Ind was discovered during the EUVE all-sky survey (EUVE 2115-58.6: Bowyer et al. 1996) and the ROSAT all-sky survey (RX J2115-5840: Voges et al. 1996). Optical spectra (Craig 1996), spectroscopic observations (Vennes et al. 1996), and optical polarimetry (Schwope et al. 1997) confirmed CD Ind to be a member of the polar subclass of magnetic cataclysmic variables.

In polars, the white dwarf’s strong magnetic fields (typically > 10 MG) preclude the formation of an accretion disk. Instead, matter from the secondary star flows directly along the magnetic field lines onto one or both of the white dwarf’s magnetic poles. The strength of the magnetic fields of polars typically synchronizes the spin of the white dwarf with the orbital period of the binary system.

But asynchronous polars (APs)—a small subset of the polars—exhibit orbital periods near, but not equal to, the white dwarf spin. Optical polarimetry observations (Ramsay et al. 1999) confirmed CD Ind as a member of this rare subclass. CD Ind has a 1.2% difference between the white dwarf spin and binary orbital period.

Currently there are four confirmed asynchronous polars: V1432 Aql, BY Cam, V1500 Cyg, and CD Ind.11

The cause of their asynchronous behavior is theorized to be an eruption on the surface of the white dwarf disrupting a previously synchronized state. V1500 Cyg was the first detected AP showing the asynchronous condition following its 1975 nova eruption. The three other stars plausibly fit this scenario, but are more speculative since the nova event blamed for the asynchronism is only hypothesized, not actually observed. A recent attempt to estimate eruption dates of APs by searching for their nova shell remnants resulted in no shell detections (Pagnotta & Zurek 2016).

Following the nova disruptive event, it is theorized that resynchronization between the white dwarf and orbital period...
occurs rapidly (on the order of centuries).\footnote{This point is disputed by Harrison & Campbell (2016) who interpreted their 2014 observations to indicate V1500 Cyg has already synchronized: a mere 39 years after the nova. This point is important since V1500 Cyg is the only AP for which we know the actual date of the nova event. But CBA’s extensive photometry in 2014 shows an obvious detection of the spin period, free from aliases and shorter than $P_{\text{orb}}$ by 175 ± 1 s. This is consistent with the other photometrically derived timescales for synchronization in Table 1, as well as the timescale of 170 yr derived by Schmidt et al. (1995) from polarimetry. These CBA observations will be written up separately.} Table 1 shows current estimates for V1432 Aql, BY Cam, and V1500 Cyg resynchronization times ($t_{\text{sync}}$). The objective for this study is to determine CD Ind’s resynchronization time and compare it to the other three asynchronous polars.

## 2. Observations

More than 46,000 photometric observations taken over 1224 hours on 285 nights were submitted to the Center for Backyard Astrophysics (CBA) (www.cbastro.org) by eight observers between 2007 and 2016. Table 2 shows the spread of observations across those 10 years.

The CBA is a global network of small telescopes dedicated to photometry of cataclysmic variables. The observations were taken with telescopes located in South Africa, Chile, Australia, and New Zealand. This provides a good longitudinal spread significantly reducing aliases. Table 3 describes the telescopes used by the CBA observers.

Observations of CD Ind used exposure times between 30 and 120 sec and either no filter or Clear filters with a UV cutoff. All images were dark subtracted and flat fielded. Timings were adjusted to HJD and observations from different observers were adjusted to yield a common instrumental magnitude, with effective wavelength near 6000 A (“pink”). Observers used differential photometry using AAVSO and UCAC4 comp magnitudes. Overlap of observing runs between observers were used to develop constants for adjusting the magnitudes to a common baseline.

## 3. Results

### 3.1. White Dwarf Spin

#### 3.1.1. Analysis Based on CBA 2007–2016 Observations

Obtaining an accurate value of the spin period requires careful timing of a specific feature observed in each spin cycle. But the hump profiles in CD Ind vary considerably, often changing from night to night, and complicating the task of choosing a consistent marker.

In a fully synchronized polar, the accretion flow from the secondary follows a ballistic trajectory until captured by the magnetic field of the primary where it is directed above or below the orbital plane onto the surface of the white dwarf (WD). The relative position of the two stars remains fixed, because the WD spin and binary orbit period are locked. A more complex flow is expected to occur in APs because the accretion region on the surface of the white dwarf is not fixed, but changes periodically on the beat cycle (approximately 7.3 days for CD Ind as discussed and calculated in Section 3.3).

Like nearly all magnetic CVs, CD Ind sometimes dives into states of very low accretion. The exact cause is not known. This was observed twice during our observations (HJD 2455830.4 and 2457225.2).

The variation in the profile makes it difficult to obtain precise timing measurements of a consistent feature in each cycle. Figure 1 shows three examples of the changing profile probably caused by the ever-changing angle between the two magnetic fields (the white dwarf and the secondary).

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Table 1

| System      | $P_{\text{out}}$ (h) | $P_{\text{spin}}$ (h) | ($P_{\text{out}}/P_{\text{spin}}$) | $t_{\text{sync}}$ in years [source] |
|-------------|----------------------|------------------------|-----------------------------------|-------------------------------------|
| V1432 Aql   | 3.3655 [1]           | 3.7351 [2]             | ~0.0029                           | 110[1]; 199[3]; 96.7 [4]           |
| BY Cam      | 3.3544 [1]           | 3.3222 [2]             | 0.0096                            | 1200[5]; 1107[1]; >3500[6]; 250[7]  |
| V1500 Cyg   | 3.3507 [1]           | 3.2917 [2]             | 0.0176                            | 185[5]; 150[1]; 150–290 [7]; 39[9];| 170[10]                             |
| CD Ind      | 1.8467 [1]           | 1.8258 [2]             | 0.0113                            | 6400[8]                             |

Table 2

| Year | No. of Runs | No. of Observations | Duration of Observing Sessions (h) | Approximate Number of Spin Cycles Observed |
|------|-------------|---------------------|------------------------------------|------------------------------------------|
| 2007 | 31          | 8631                | 153                                | 83                                       |
| 2008 | 20          | 10273               | 103                                | 56                                       |
| 2011 | 53          | 13467               | 270                                | 148                                      |
| 2013 | 9           | 879                 | 27                                 | 14                                       |
| 2014 | 52          | 1923                | 163                                | 89                                       |
| 2015 | 76          | 7144                | 295                                | 161                                      |
| 2016 | 44          | 3771                | 213                                | 116                                      |
| Totals| 285         | 46088               | 1224                               | 667                                      |
To improve the accuracy of the timing of individual maxima, only cycles with light curves clearly showing a profile similar to Figure 1(a) were used. Of the approximate 667 spin cycles observed, 165 had this distinctive profile. Even with these light curves, there was no clear marker for precise timings. Many humps exhibit virtually flat profiles near their peak. Therefore, times of maximum light were determined by fitting a quadratic curve to the observed humps and recording the time of maximum light. Figure 2 shows the quadratic fits to three of the peaks observed using different scopes that used different image exposure times.

After we measured the timings on the 165 selected humps (Table 4), we generated ephemerides using linear and quadratic regressions on the times of maximum light as a function of associated cycle counts.

The linear regression of the measured times of maximum light versus cycle count yields the following ephemeris with an O-C standard deviation of .0038 d:

\[
\text{HJD of mid–humps} = 2454332.2616(38) + 0.07614973(9) \, E, \tag{1}
\]

where \( E \) is the cycle number. The O-C residuals using Equation (1) are shown in Figure 3. A quadratic regression to these residuals yields the curve shown indicating a changing white dwarf spin period.

The quadratic regression of the measured times of maximum light versus cycle count yields the following ephemeris with an O-C standard deviation of 0.0034 d:

\[
\text{HJD of mid–humps} = 2454332.2637(34) + 0.07614926(8) \, E + 1.10(18) \times 10^{-11} \, E^2. \tag{2}
\]

3.1.2. Incorporation of Schwope et al. Data from 1996

In addition to the 165 timings measured using the CBA data, four timings of mid-hump peaks observed in 1996 were available from Schwope et al. (1997). Because of the uncertainty about exactly how the measurements were made —and the fact there is an 11-year gap with the CBA data— analysis was first performed on only the CBA data. Then the effect of including Schwope’s additional four earlier measurements was evaluated.

Schwope et al. (1997) contains four mid-hump timings “...derived for far-pole accretion” so it appears measurements were made on light curve profiles similar to those used in analyzing CBA data.

A quadratic regression to the combined data yields the following ephemeris with an O-C standard deviation of 0.0034 d:

\[
\text{HJD of mid–humps} = 2454332.2641(34) + 0.07614917(8) \, E + 1.32(18) \times 10^{-11} \, E^2. \tag{3}
\]

The O-C residuals incorporating the Schwope data are shown in Figure 4. From the second-order coefficient in Equation (3), we infer a value of \( \Delta P_{\text{spin}} / \Delta t = 3.5(4) \times 10^{-10} \). Because of the consistency of the results when incorporating the Schwope data and the fact that with these data, we have a 20-year observation baseline, Equation (3) is adopted as the best ephemeris. Based on this ephemeris the white dwarf spin period increases from 109.6528(1) to 109.6564(1) min across the 20 years of observation. This period is consistent with the lower of the two estimates (109.84 or 109.65 minutes) from Schwope et al. (1997), which were based on photometric measurements.

To be conservative with our error estimates, we used the 42752 cycle count from the CBA data rather than the full 95251 cycles starting with Schwope’s 1996 observations.

3.2. Orbital Period

We analyzed all the CBA data using the Period04 package (Lenz & Breger 2005) based on the discrete Fourier transform method. Based on existing information we limited the period search to the interval 12.5 to 13.5 cycles/d to include both the orbital and spin periods. We show the corresponding power

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### Table 3

CBA Telescopes Used to Observe CD Ind from 2007 to 2016

| Observer   | Observatory Location          | Telescope                  | CCD               | Number of Measured Maxima |
|------------|--------------------------------|----------------------------|-------------------|---------------------------|
| Hambsch    | San Pedro de Atacama, Chile    | Orion Optics ODK 400 mm    | FLI w/Kodak 16803 | 64                        |
| Myers      | Coonabarabran, Australia       | Planewave CDK 410 mm       | FLI PL4710        | 48                        |
| Rea        | Nelson, New Zealand           | 2007/2008—Celestron C11    | SBIG ST-402       | 5                         |
|            |                                | 2007/2008—Celestron C14    | SBIG ST-9         | 15                        |
|            |                                | 2011—CDK20                 | SBIG ST-9         | 5                         |
| McCormick  | Auckland, New Zealand         | Meade LX200R—360 mm        | SBIG ST-8XME      | 3                         |
| Monard     | Pretoria, South Africa        | 2007/2008—Meade RCX400—300 mm | SBIG ST-7XME   | 18                        |
|            | Calitzdorp, South Africa      | 2010—Meade RCX400—350 mm   | SBIG ST-8XME      | 3                         |
| Bolt       | Perth, Australia              | Meade LX200—254 mm         | SBIG ST-7         | 3                         |
| Allen      | Blenheim, New Zealand         | Classical Cassegrain—400 mm | SBIG STL-1001E   | 1                         |

To be conservative with our error estimates, we used the 42752 cycle count from the CBA data rather than the full 95251 cycles starting with Schwope’s 1996 observations.
spectrogram in Figure 5. The spectrum is dominated by a peak centered at $13.1320(14)$ cycles/d, a value fully consistent with our previous estimate of the spin period.

A peak at a frequency of $12.994939(5)$ cycles/d, or a periodicity of $110.82005(4)$ min, is also apparent in the spectrum. This is similar to previous reports of the orbital period of 110.889 minutes from Ramsay et al. (1999) based on polarimetry data and 110.756 minutes from Vennes et al. (1996) based on spectroscopy data. Thus, we interpret this detection as a footprint of the orbital motion. The error estimates were obtained using Period04’s Monte Carlo simulation.

### 3.3. Beat Period

Based on the WD 2015 spin frequency ($f_{\text{spin}}$) of $13.1324$ c/d and orbital frequency ($f_{\text{orb}}$) of $12.9949$ c/d, the 2015 beat frequency of $0.137$ c/d, which equates to a period of $7.299$ d. Because the beat period represents the time taken by the
Figure 1. Several nightly light curves of CD Ind, illustrating the variety. We interpret type (a) as signifying accretion onto one magnetic pole and type (b) as possibly signifying two pole accretion. Type (c) probably arises from one main pole accreting with a changing perspective angle during the white dwarf spin cycle. With this variety, we choose only to use type (a) for our period study.
secondary to orbit the white dwarf in the frame of the rotating white dwarf, a clear beat period profile was expected. For unknown reasons, the strength of the appearance of the beat period varies considerably during different years. The observing year with the most runs—2015 with 76 runs—shows the most distinctive beat period pattern. Figure 6 shows the light curve folded on the beat period of 7.299 d. The beat period assumes the white dwarf spin is prograde (i.e., the beat frequency is \( f_{\text{spin}} - f_{\text{orbit}} = 0.137 \) c/d). If the motion were retrograde, the beat frequency would be \( f_{\text{spin}} + f_{\text{orbit}} = 26.127 \) c/d. Spectral signals were detected at both frequencies with the 0.137 c/d signal having a power amplitude of 0.35 compared with a power amplitude of 0.078 for the 26.127 c/d signal. The significantly higher strength of the 0.137 c/d signal supports the assumption of prograde motion, consistent with the current theory of AP formation.

4. Conclusion: Resynchronization Projection

A resynchronization time estimate was made by dividing the current difference between the WD spin and orbital spin periods \( (P_{\text{spin}} - P_{\text{orb}}) \) by the white dwarf spin change rate \( dP_{\text{spin}}/dt = 3.5(4) \times 10^{-10} \). This assumes that the spin change

**Figure 2.** For all profiles of type (a), we determine the time of maximum light by fitting a quadratic. The three plots show different image exposure times used by different observers: 60, 120, and 30 seconds.
rate is constant over time and yields a resynchronization time of 6400 ± 800 years.

This predicted resynchronization time is longer than estimates for the other three APs shown in Table 1. The exact reason is not known. One possibility is that the resynchronization rates may not be constant; they may vary over time, e.g., they could decay exponentially as the systems approach synchronism.

Another potential cause relates to the strength of the CD Ind’s relatively low magnetic field strength (for a polar). Polars field strength is typically 7–230 MG (Ferrario et al. 2015). Estimates
for CD Ind’s field are 11 ± 2 MG (Schwope et al. 1997) and <20 MG (Vennes et al. 1996). Campbell & Schwope (1999) indicate the resynchronization time is inversely proportional to the square of the magnetic field strength. This may be a contributing factor but additional research is required.

Separate from the analysis of the resynchronization time estimate, the question of whether CD Ind’s WD spin is prograde or retrograde was examined. The Fourier power spectrum at the two potential interaction frequencies (f_{\text{spin}} + f_{\text{orb}} and f_{\text{spin}} - f_{\text{orb}}) was examined. Based on the strength of the signals, CD Ind exhibits prograde motion which is consistent with the current theory of AP evolution.

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Figure 6. 2015 folded light curve based on a beat period of 7.299 d.