Asynchronous polar V1500 Cyg: orbital, spin and beat periods

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ABSTRACT

The bright Nova Cygni 1975 is a rare nova on a magnetic white dwarf (WD). Later it was found to be an asynchronous polar, now called V1500 Cyg. Our multisite photometric campaign occurring 40 years post eruption covered 26-nights (2015-2017). The reflection effect from the heated donor has decreased, but still dominates the optical radiation with an amplitude \( \sim 1^{m}.5 \). The \( 0^{m}.3 \) residual reveals cyclotron emission and ellipsoidal variations. Mean brightness modulation from night-to-night is used to measure the 9.6-d spin-orbit beat period that is due to changing accretion geometry including magnetic pole-switching of the flow. By subtracting the orbital and beat frequencies, spin-phase dependent light curves are obtained. The amplitude and profile of the WD spin light curves track the cyclotron emitting accretion regions on the WD and they vary systematically with beat phase. A weak intermittent signal at 0.137613-d is likely the spin period, which is 1.73(1) min shorter than the orbital period. The O-C diagram of light curve maxima displays phase jumps every one-half beat period, a characteristic of asynchronous polars. The first jump we interpret as pole switching between regions separated by \( 180^\circ \). Then the spot drifts during \( \sim 0.1 \) beat phase before undergoing a second phase jump between spots separated by less than \( 180^\circ \). We trace the cooling of the still hot WD as revealed by the irradiated companion. The post nova evolution and spin-orbit asynchronism of V1500 Cyg continues to be a powerful laboratory for accretion flows onto magnetic white dwarfs.

Key words: stars: novae, cataclysmic variables – stars: magnetic field – stars: V1500 Cygni: individual

1 INTRODUCTION

Polars are interacting binaries consisting of a magnetic white dwarf (WD) accreting matter along field lines from a low mass main sequence secondary. The strong magnetic field of the WD prevents the formation of an accretion disk. The vast majority of polars are also synchronized, such that the spin of the WD becomes locked with the binary orbit due to the interaction of the magnetic field with the donor star, see Frank, King, and Raine (1992).

Nova Cygni 1975 reached 2nd magnitude and thus was one of the brightest novae of the 20th century (Honda 1975; Warner 2006). The nova occurred on the WD in the binary V1500 Cyg, later found to an asynchronous polar (Schmidt, et al. 1995). The three other confirmed asynchronous polars are BY Cam, V1432 Aql, and CD Ind. Of particular importance, V1500 Cyg is the site of a rare magnetic nova, along with GK Per and DQ Her. In the case...
of V1500 Cyg, it is assumed that the expanding nova shell slowed the orbit of the companion of a previously synchronized polar (Stockman et al. 1988). A strong irradiation of the secondary by the hot WD dominated the total radiation of this system for decades following the eruption.

While polarization was observed to track the WD spin, optical photometry gave information on two periods: 1) the orbital modulation caused by heating of the secondary component by irradiation from the WD (Schmidt, et al. 1995) that is still very hot, 40 years after the 1975 explosion and 2) the spin-orbital (syodic) beat period (Pavlenko and Pelt 1991). The orbital period has been detected every year of observation and its amplitude has varied from year to year (Pavlenko and Shugarov 2005a, b). The beat period has systematically increased with time. Using the spin-orbit beat period relation, orbital and beat periods were used for calculation of the current value of the WD spin period (Pavlenko and Shugarov 2005a) rather than direct measurements of the WD spin period which is possible only while the accretion flow is stable, between pole switchings, and is best done with polarimetric or X-ray observations.

Spin-orbit synchronization times of a hundreds to a few thousand years are expected from theory, see e.g. Andronov (1987). Campbell and Schwope (1999) show that a range of synchronization times are possible with the fastest being about 50 years and requiring an unusually low-mass primary of 0.5 M⊙. Such a low mass WD is unlikely given that evidence from the nova ejecta (Lance, McCall, and Uomoto 1988) indicate a high mass WD. Photometry over the intervening years indicated that the WD was undergoing fast and nonlinear synchronization from measurements by Katz (1991) with a rate of \( P = 1.8 \times 10^{-6} \) for 1977–1979, \( 2.7 \times 10^{-8} \) for 1979–1987, and \( 2.4 \times 10^{-8} \) for 2000–2003 (Pavlenko and Shugarov 2005a). Schmidt, et al. (1995) obtained \( \dot{P} = 3.86 \times 10^{-8} \) for 1987–1992 from polarimetry. The time of synchronization was estimated independently by Schmidt, et al. (1995) as \( \sim 170 \) years and by Pavlenko and Pelt (1991) as 150–200 years. Recently Harrison and Campbell (2016) suggest that V1500 Cyg is already synchronized. Armed with extensive beat-phased resolved photometry we find that to the contrary, V1500 Cyg is still an asynchronous polar.

This work aims to unravel the combination of several sources contributing to the optical radiation of V1500 Cyg \( \sim 40 \) years after the 1975 nova explosion and to establish the current status of V1500 Cyg in terms of synchronization and accretion geometry. First, one would expect a reduction of the reflection effect from cooling of the hot WD, Second, with reduced heating comes the appearance of significant, and recently detected, optical cyclotron radiation from accretion columns (Harrison and Campbell 2018). Third, ellipsoidal variations due to the aspherical Roche-lobe filling companion may be observed. In particular, the test for asynchronism is accomplished by examination of the variable orientation of the WD magnetic field with respect to the secondary component. In other words, asynchronous polars display light curves which vary according to the beat phase between the binary orbit and the WD spin and is confirmed by the detection of these periods.

2 OBSERVATIONS

CCD-photometry of V1500 Cyg was obtained during 25 nights within a 54-day interval in 2015, with a follow-up observation in 2017. Observations were carried out using five telescopes located at four observatories. See the journal of observations given in Table 1. Exposure times varied from 10-s with no significant dead-time between exposures using the Otto Struve 2.1 m telescope at McDonald Observatory to 60-180 s at the Crimean Astrophysical Observatory (CrAO) 1.25 m and Shajn 2.6 m telescopes as well as the Terskol 60 cm telescope and Sternberg Astronomical Institute 1.25 m. All of the images were unfiltered and fielded in the usual manner. The comparison star USNO B1 1381-0460911 (Monet 2003) which has B=19.05(5) and V=17.83(5) was used for absolute calibration while the stars C2 and C3 (Kaluzhny and Semeniuk 1987) were used for differential photometry in 2015 and for B photometry in 2017. During the time of these observations the brightness of V1500 Cyg varied between \( V = 19^m \) and \( V = 21^m \). Photometric uncertainties varied depended on the size of telescope, the brightness level, and weather conditions. The maximum uncertainty was \( \sim 0.1 \). All of the data were converted to Heliocentric Julian Day (HJD) for further analysis.
In order to extract weaker signals in the ephemeris of longer than the predicted value of 9.1 - 9.3 d according to minimum at a 9.58(3)-d period that is just a few percent changes in our view of the accretion flow geometry which depends on the spin-orbit beat phase.

Examples of nightly light curves are presented in Fig. 3 RESULTS from the observed light curve and constructed a periodogram In order to investigate possible spin-orbital beat modulation.

The periodogram in the range of the expected beat period is shown as Fig. 2. The most significant feature is the minimum at a 9.58(3)-d period that is just a few percent longer than the predicted value of 9.1 - 9.3 d according to the ephemeris of Schmidt, et al. (1995), using polarimetry to track the spin of the WD and photometry for the orbital variability. The mean light curve has an amplitude of about 0.5 mag. So, the appearance of rapidly evolving light curves along with the determination of a putative beat period is strong evidence of spin-orbital asynchronism, still in 2015.

### 3.2 Orbital period: the reflection and possible ellipsoidal effects

As we noticed that the dominant modulation is still caused by a strong reflection component, see top panels of Fig. 3, our data reveled a period of 0.139617(6)-d that within errors coincides with the orbital period measurement of 0.139613-d (Semeniuk et al. 1995). In order to extract weaker signals in the light curve we construct a periodogram of the residuals of all data after both the beat and orbital modulation (which we fit using a one-humped wave) were removed, see bottom panels of Fig. 3. The result reveled some excess at the orbital period in the form of a two-humped curve with near-equal maxima (amplitude of 0.35 mag). We suggest this is a light curve produced by the ellipsoidal shape of the secondary component in a field of high-mass white dwarf. However the true ellipsoidal profile will show a small difference from the one obtained due to some difference of a best-fitted curve from a properly modeled curve at a precise orbital inclination. Likely, the observed profile of the orbital modulation results from a superposition of reflection and ellipsoidal effects.

### 3.3 Spin period

Inspection of the periodogram of the beat and orbital reflection subtracted light curve, see Fig. 4, reveals no prominent signal at the WD spin period, see arrows in left panels. Rather a residual signal is seen at the orbital period of 0.139617(6)-d. This signal is interpreted as the ellipsoidal modulation, an orbital variation due to the changing view of the aspherical Roche-lobe filling companion, as discussed in the previous subsection. After the ellipsoidal modulation is subtracted, a weak WD spin signal at 0.137613(7)-d remains (see Fig. 4). As expected, the spin signal is strongly diluted by changes in the accretion flow geometry likely including pole switching. The marginally detected WD spin period is

### Table 1. Journal of observations.

| HJD 2457000+ (start - end) | Observatory/telescope | CCD | N |
|-----------------------------|-----------------------|-----|---|
| 211.407 - 211.564           | CrAO/2.6m             | APOGEE E47 | 105 |
| 212.405 - 212.555           | CrAO/2.6m             | APOGEE E47 | 94  |
| 221.420 - 221.560           | CrAO/2.6m             | APOGEE E47 | 95  |
| 223.263 - 223.546           | CrAO/2.6m             | APOGEE E47 | 247 |
| 225.380 - 225.553           | SAI/1.25m             | VersArray-1300s | 186 |
| 226.379 - 226.557           | SAI/1.25m             | VersArray-1300s | 233 |
| 245.280 - 245.557           | CrAO/2.6m             | APOGEE E47 | 341 |
| 270.228 - 270.386           | CrAO/2.6m             | APOGEE E47 | 199 |
| 271.264 - 271.584           | CrAO/2.6m             | APOGEE E47 | 392 |
| 272.225 - 272.479           | CrAO/2.6m             | APOGEE E47 | 300 |
| 274.221 - 274.378           | Terskol/60cm           | SBIG STL 1001 | 138 |
| 278.264 - 278.421           | Terskol/60cm           | SBIG STL 1001 | 100 |
| 281.266 - 281.493           | Terskol/60cm           | SBIG STL 1001 | 135 |
| 284.266 - 284.475           | Terskol/60cm           | SBIG STL 1001 | 124 |
| 295.302 - 295.437           | Terskol/60cm           | SBIG STL 1001 | 87  |
| 300.241 - 300.377           | CrAO/1.25m            | ProLine PL23042 | 65  |
| 301.231 - 301.419           | CrAO/1.25m            | ProLine PL23042 | 69  |
| 311.191 - 311.350           | CrAO/1.25m            | ProLine PL23042 | 74  |
| 326.188 - 326.374           | CrAO/1.25m            | ProLine PL23042 | 73  |
| 331.176 - 331.324           | CrAO/1.25m            | ProLine PL23042 | 70  |
| 332.196 - 332.348           | CrAO/1.25m            | ProLine PL23042 | 70  |
| 341.131 - 341.208           | SAI/1.25m             | VersArray-1300s | 56  |
| 344.133 - 344.344           | SAI/1.25m             | VersArray-1300s | 146 |
| 344.161 - 344.316           | CrAO/1.25m            | ProLine PL23042 | 71  |
| 367.559 - 367.637           | McDonald/2.1m         | ProEM | 659 |
| 368.565 - 368.664           | McDonald/2.1m         | ProEM | 804 |
| 1013.389 - 1013.594         | CrAO/2.6m             | APOGEE E47 | 127 |

Figure 2. Left: periodogram for all of the data after orbital modulation is subtracted. Right: residuals (gray points) folded on the 9.58-d period. The mean per night values are marked by black squares. The zero phase corresponds to the start of observations (HJD =2457300.24118). For clarity the data are reproduced twice.
consistently with the calculated spin period $P_{\text{spin}}$ according to equation (1), namely,

$$p^{-1}_{\text{beat}} = \frac{1}{p^{-1}_{\text{spin}} + p^{-1}_{\text{orb}}}$$

where the observed orbital period is $P_{\text{orb}} = 0.139617$-d and beat period is $P_{\text{beat}} = 9.58$-d. The dilemma in measuring the spin period directly is that one must either do so in less than one-half of a beat cycle or face significant signal dilution due to accretion pole switching. The WD spin period predicted using equation (1) is $P_{\text{spin}} = 0.137611$-d.

It is not so obvious that we must detect the signal at the spin period. Its detectability probably depends on the accretion geometry in the V1500 Cyg system and uniformity of the data distribution. If the accretion stream switches from one magnetic pole to the other and back during the beat cycle and if data are distributed uniformly in all beat phases, we would expect to see no spin period. On the other hand, in the case of no pole switching the spin signal must be strong enough to be detected. As expected, the cooling of the WD in Fig. 3) remains as other signals have weakened. This dilution of the spin signal is due to pole switching of the magnetically channeled accretion flow.

2015 its spin period was 173(1)-s or 0.88% shorter than its orbital period.

### 3.4 Accretion geometry

The residuals (after the beat and orbital modulations were subtracted) are folded on the suggested WD spin period of 0.137613-d and are presented in Fig. 5 for each night. The corresponding phases of the 9.58-d beat period are indicated. It is seen that the residual light curves still have a variable amplitude and profile. Several morphological structures are observed, including one-, two-, or even three-humped structures. The shape of light curve even changes from cycle-to-cycle on some occasions (JD 221, JD 270). Sometimes, a high-amplitude QPO-like structure is seen (JD 221, JD 270) superposed on some humps. The phases of highest maxima and deepest minima also change. Such a diversity of profiles could be explained by a complex structure of the WD magnetic field. Such a complex accretion geometry as has been proposed for the asynchronous polar BY Cam (Mason et al. 1998).

At first glance, changes in the nightly light curves appear chaotic. A more attenitive procedure was performed in order to confirm or refute this suggestion. We determined times of the highest maxima (see Table 2) assuming that they originate from the more intense accretion spot on the WD and calculated a O-C diagram using the ephemeris:

$$HJD_{\text{max}} = 2457211.40731 + 0.137613E.$$
of the O-C values situated at beat phases 0.5 – 1.0 imply that the accretion spot period is longer than the WD spin period, but shorter than orbital period, during that time. There are two jumps occurring at beat phases 0.0 and 0.5 suggesting that the accretion stream switches between accretion spots at those phases. Further, during beat phases ~ 0.5-0.62 the accretion spot drifts in the opposite direction to the WD rotation with a period close to the orbital one. At later phases it probably remains relatively constant and close to the spin period. Finally, at beat phase 1.0 the accretion stream switches to the second region separated from the first accretion spot by less than 180°. Unfortunately, a lack of data does not allow complete coverage between beat phases 0.8 and 1.0.

4 DISCUSSION

In order to further investigate the cooling time-scale for the WD in V1500 Cyg, we gathered all of the data on the amplitude of B-band photometry to follow the decrease in emission from the heated companion in the same manner as Somers and Naylor (1999). We included data from their Table 1 along with data from Litvinchova, Pavlenko and Shugarov (2011) and Harrison and Campbell (2016) and plotted them in Fig. 7. As it turns out, the new data lie on the extension of the previous relation confirming that the orbital amplitude decrease is indeed in accordance with theoretical predictions for post-nova cooling. The best-fit power low index is $\eta = 1.13$, which is remarkably consistent with the purely theoret-
Figure 7. Cooling of the white dwarf. The log of the amplitude, $A$, of the reflection modulation is shown as a function of the log of the time $T$ since the nova eruption in 1975. Data is collected from the similar plot of Somers and Naylor (1999), see note in text, (black points) and more recent measurements of Litvinchova, Pavlenko and Shugarov (2011) and our new B-band light curve (pink points) and those of Harrison and Campbell (2016) (blue points). Scatter is indicative of amplitude variation as a function of beat phase. The best-fit matches the theoretical prediction for WD cooling of Prialnik (1986).

dipole spot and an equatorial one, with some drift of an accretion spot in the opposite direction to the WD spin. MHD calculations around the beat cycle were also performed demonstrating the main effects of pole switching in the case of a complex magnetic field structure (Zhilkin et al. 2012).

The profiles of the 2015 spin light curves of V1500 Cyg are reminiscent of those of BY Cam in a high accretion state. Here for V1500 Cyg we find both the pole switching and a similar accretion spot drift as that observed in BY Cam. The major difference being, in V1500 Cyg, the domination of the optical light is from the hot WD irradiating the companion producing a strong reflection effect.

5 CONCLUSIONS

We have carried out a photometric investigation of the asynchronous polar and post-nova V1500 Cyg ∼40 years after its 1975 eruption. Our extensive dataset consists of photometric observations obtained during 25 nights within a 54-day interval in 2015 and during one night in 2017 at four observatories. Several key features in the light curve argue for continued asynchronous spin-orbital motion of the the binary. These are the existence of nightly variations in the orbital light curve following the 9.6-d spin-orbital beat cycle, the enigmatic appearance of the 0.137613-d spin period which is only seen during some beat phases, and ultimately evidence of accretion stream flow switching between magnetic poles.

Earlier it was suggested (Litvinchova, Pavlenko and Shugarov 2011) that the beat modulation in V1500 Cyg is caused by a periodic shading of the heated side of the secondary by an accretion ring around the WD. This explanation is in agreement with the interpretation of Schmidt, et al. (1995) of "relatively broad optically thick accretion columns with lumps of dense gas, and/or orbiting debris in a disk-like geometry". We can not distinguish between these possibilities, but we can say that such a structure would be a long-lived one, existing for the last 40 years. More high density observations covering the complete beat cycle are needed to monitor the path towards synchronism and to further investigate the beat phase dependent peculiarities in accretion geometry of V1500 Cyg.

An important question remains. Why is the WD in V1500 Cyg still so hot? After 40 years it remains hot enough for the irradiated secondary to dominate the optical flux, yet it CONTINUES TO FOLLOW THE THEORETICAL COOLING LAW. The nova eruption was among the most luminous ever recorded and apparently heated the WD to a higher temperature than is typical. Other magnetic CVs have also had luminous novae, namely GK Per and DQ Her, suggesting that magnetic novae may be more luminous as a sub-class. Further work is needed to properly address this question.

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