**Kepler K2** and **TESS** observations of two magnetic cataclysmic variables: The new asynchronous polar SDSS J084617.11+245344.1 and Paloma

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**ABSTRACT**

There have been relatively few published long-duration, uninterrupted light curves of magnetic cataclysmic variable stars in which the accreting white dwarf’s rotational frequency is slightly desynchronized from the binary orbital frequency (asynchronous polars). We report **Kepler K2** and **TESS** observations of two such systems. The first, SDSS J084617.11+245344.1 was observed by the **Kepler** spacecraft for 80 days during Campaign 16 of the K2 mission, and we identify it as a new asynchronous polar with a likely 4.64-hour orbital period. This is significantly longer than any other asynchronous polar, as well as all but several synchronous polars. Its spin and orbital periods beat against each other to produce a conspicuous 6.77-day beat period, across which the system’s accretion geometry gradually changes. The second system in this study, Paloma, was observed by **TESS** for one sector and was already known to be asynchronous. Until now, there had been an ambiguity in its spin period, but the **TESS** power spectrum pinpoints a spin period of 2.27 h. During the resulting 0.7 d spin-orbit beat period, the light curve phased on the spin modulation alternates between being single- and double-humped. We explore two possible explanations for this behavior: the accretion flow being diverted from one of the poles for part of the beat cycle, or an eclipse of the emitting region responsible for the second hump.

1. **INTRODUCTION**

1.1. The three classes of magnetic cataclysmic variables

Cataclysmic variables (CVs) are interacting binaries in which a white dwarf (WD) accretes from a Roche-lobe-filling companion, usually an M-dwarf. If the WD possesses a significant magnetic field, the accretion flow from the donor star will be channeled onto the WD along its magnetic-field lines. The accreting matter produces a shock near the WD’s surface, and the post-shock material cools by emitting a combination of X-ray bremsstrahlung and optical/near-infrared cyclotron radiation (Cropper 1990).

Magnetic CVs (mCVs) are typically divided into three broad categories—polars, intermediate polars, and asynchronous polars—depending on the the difference between the spin period ($P_{\text{spin}}$) of the accreting WD and the binary orbital period ($P_{\text{orb}}$). In polars, the WD’s magnetic field is strong enough to synchronize $P_{\text{spin}}$ to $P_{\text{orb}}$, and no accretion disk forms (for a review, see Cropper 1990). Conversely, if $P_{\text{spin}}$ is significantly shorter than $P_{\text{orb}}$, the object is called an intermediate polar (IP; Patterson 1994). IPs tend to have accretion disks truncated by the WD’s magnetic field, but if the WD’s magnetosphere is large enough, it can prevent a disk from forming.
The third category of mCVs, the asynchronous polars (APs), is comprised of systems in which $P_{\text{spin}}$ and $P_{\text{orb}}$ differ by no more than several percent. As summarized in Table 1, only six confirmed APs have been previously reported, though the census could increase to seven, depending on how close $P_{\text{spin}}$ and $P_{\text{orb}}$ are required to be. APs are thought to be polars that have been temporarily desynchronized by nova eruptions. In their study of Nova Cygni 1975 (V1500 Cyg), Stockman et al. (1988) proposed that in the aftermath of the nova, the WD’s envelope encompassed the binary, resulting in a coupling between the secondary and WD. When the WD’s envelope subsequently shrank, the coupling ceased, which reduced the WD’s moment of inertia and caused it to spin up, leaving V1500 Cyg in its current asynchronous state. The short-lived nature of this differential rotation is supported by the observed period-derivative trend toward synchronous rotation in all APs with a sufficiently long observational baseline to detect a change in $P_{\text{spin}}$ (e.g., as in V1500 Cyg: Schmidt & Stockman 1991). The key observational distinction between IPs and APs is that in the former, asynchronous rotation is a stable equilibrium (King & Lasota 1991; King 1993; King & Wynn 1999), while in the latter, it is not.

Caused by the inequality of $P_{\text{spin}}$ and $P_{\text{orb}}$, the differential rotation of the WD produces a number of observable effects in both IPs and APs. The accretion flow in mCVs must become magnetically confined at some point after it leaves the secondary, and the relative orientation of the WD’s magnetic field will determine both its path through the magnetosphere and the region where it accretes onto the surface of the WD. In APs and diskless IPs, the magnetosphere rotates with respect to the ballistic accretion stream; this differential rotation causes the stream to gradually plow into different regions of the WD magnetosphere. The stream’s ballistic trajectory is stationary in the binary rest frame, so differential rotation occurs at the spin-orbit beat frequency of $\omega - \Omega$, where $\omega = P_{\text{spin}}^{-1}$ and $\Omega = P_{\text{orb}}^{-1}$; equivalently, $\omega - \Omega$ is the rotational frequency of the WD in the co-rotating binary rest frame.

The combination of potentially complex magnetic field structures and asynchronism has been modeled magneto-hydrodynamically (Zhilkin et al. 2012, 2016), which suggests that pole-switching may also accompany changes between one and two accretion pole configurations. However, establishing unique magnetic field configurations from observations remains difficult.

From an observational standpoint, the ever-changing accretion geometry of APs leads to several dramatic effects. For example, the accretion region on the WD will migrate across the WD’s surface, following the footprints of whichever magnetic field lines are capturing the accretion stream at that particular time (Geckeler & Staubert 1997). Likewise, the bulk of the accretion flow will travel to different accretion poles during different portions of the beat cycle, and when the accretion flow switches between poles, the light curve will show a discontinuity in phase (Mason et al. 1989).

### 1.2. SDSS J084617.11+245344.1

The cataclysmic variable SDSS J084617.11+245344.1 (hereafter, J0846) has an exceedingly sparse observational history. Szkody et al. (2006) found that its Sloan Digital Sky Survey (SDSS) spectrum contains unusually prominent He II $\lambda4686$ emission, a common indicator of magnetic accretion. The same study was unable to detect circular polarization in the source in a single 6000-second exposure. J0846 is listed in the Catalina Survey Periodic Variable Star Catalog with a period of 0.1827862 d, with no uncertainty specified (Drake et al. 2014).

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**Table 1.** The confirmed asynchronous polars, J0846, and Paloma.

| Name              | $P_{\text{orb}}$ (h) | $P_{\text{spin}}/P_{\text{orb}}$ | $P_{\text{beat}}$ (d) | Distance (pc) | References                          |
|-------------------|----------------------|----------------------------------|-----------------------|---------------|-------------------------------------|
| IGR J19552-0044   | 1.39                 | 0.972                            | 2.04                  | 165.5$^{+1.9}_{-1.5}$ | Tovmassian et al. (2017)             |
| 1RXS J083842.1−282723 | 1.64               | 0.96                             | 1.8                   | 156.0$^{+1.9}_{-2.2}$ | Halpern et al. (2017)                |
| CD Ind            | 1.87                 | 0.989                            | 7.3                   | 235.3$^{+4.0}_{-3.2}$ | Littlefield et al. (2019)            |
| Paloma            | 2.62                 | 0.87                             | 0.71                  | 582$^{+28}_{-20}$   | this work                           |
| V1500 Cyg         | 3.351                | 0.986                            | 9.58                  | 1570$^{+270}_{-190}$ | Pavlenko et al. (2018)               |
| BY Cam            | 3.354                | 0.99                             | 15                    | 264.5$^{+1.9}_{-1.7}$ | Pavlenko et al. (2013)               |
| V1432 Aql         | 3.366                | 1.002                            | 62                    | 450. $^{+7}_{-7}$     | Littlefield et al. (2015)            |
| SDSS J084617.11+245344.1 | 4.64               | 0.972                            | 6.77                  | 1230$^{+800}_{-290}$ | this work                           |

Note—The listed distances are the geometric distances computed by Bailer-Jones et al. (2021) from Gaia EDR3 (Gaia Collaboration et al. 2021).
The Gaia EDR3 (Gaia Collaboration et al. 2016, 2021) distance to J0846 is $1230^{+800}_{-290}$ pc (Bailer-Jones et al. 2021). Its Galactic latitude of $+35.4^\circ$ therefore places it $710^{+460}_{-170}$ pc above the Galactic plane, which is significantly larger than nearly every polar (Beuermann et al. 2021).

1.3. **Paloma**

The second subject of the present study, Paloma$^1$ (= RX J0524+42), is a rare hybrid between IPs and APs. Schwarz et al. (2007) and Joshi et al. (2016) published in-depth photometric and X-ray studies, respectively, but Paloma has received scant attention otherwise. Schwarz et al. (2007) measured an orbital period of

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$^1$ Although CVs rarely have common names, Paloma (Spanish for “dove”) is an exception. It acquired its name because of its chance superposition next to an unrelated, dove-shaped supernova remnant (Schwarz et al. 2007).
Figure 2. Light curve and 2D power spectra for J0846. BKJD is defined as BJD-2454833. The middle and lower panels use different colormaps to reflect that they have different intensity cuts. The size of the sliding window is 0.5 d.

2.62 h and constrained the spin period to be either 2.27 h or 2.43 h. These differ from the orbital period by 13% and 7%, respectively, so the system could be plausibly classified as either a nearly synchronous IP or a highly asynchronous AP. Schwarz et al. (2007) also discuss the evolutionary implications of the unusual $P_{\text{spin}}/P_{\text{orb}}$ ratio, including the intriguing possibility that it is an IP evolving into a polar, a process envisioned by Chanmugam & Ray (1984). Power spectral analysis of the X-ray light curve suggests the absence of an accretion disk (Joshi et al. 2016).

The distance to Paloma based on Gaia EDR3 is $582^{+28}_{-20}$ pc (Bailer-Jones et al. 2021). Unlike J0846, it is situated very close to the Galactic plane, with a Galactic latitude of $+3.9^\circ$.

2. DATA

2.1. The K2 observation of J0846

The Kepler spacecraft observed J0846 during Campaign 16 of its K2 mission between 2017 December 7 and 2018 February 25. The observations utilized the long-cadence mode, so the integration time of each datum is 30 min.

We extracted the light curve of J0846 using lightkurve. To compensate for Kepler’s well-known pointing oscillations, we chose a sufficiently large extraction aperture to encompass the full range of J0846’s drift across the sensor. J0846 is situated in a sparse star field, and its signal does not suffer from serious blending.

2.2. The TESS observation of Paloma

The Transiting Exoplanet Survey Satellite (TESS) observed Paloma in its two-minute-cadence mode during Sector 19, between 2019 November 28 and 2019 December 23. The observations were uninterrupted with the exception of a day-long downlink gap in the middle of the sector. Because of the location of Paloma in a dense star field and the low angular resolution of TESS images, it is heavily blended with nearby sources.

The TESS pipeline creates two versions of each two-minute-cadence light curve: simple-aperture photometry (SAP) and pre-conditioned simple-aperture photom-
that strongly disagreed with the trend in the SAP data. Arbitrarily removing this point resulted in $r^2_{\text{SAP}} = 0.29$, but there are no obvious indicators that that particular ZTF measurement is unreliable.

Therefore, on the basis of these comparisons, we elected to use the PDCSAP light curve. We stress that unlike TX Col, there are no astrophysically noteworthy differences between the SAP and PDCSAP light curves, so the choice between these two datasets does not significantly impact the results of our analysis. Since a few of the PDCSAP flux measurements are negative, we added an arbitrary constant offset to the PDCSAP flux.

2.3. Paloma spectra

On 2019 December 19, during the TESS observation of Paloma, we obtained time-resolved spectroscopy with the Large Binocular Telescope (LBT). From 8:06 UT until 10:30 UT, we obtained a series of 180 s exposures with the MODS spectrographs (Pogge et al. 2010), a 250 lines mm$^{-1}$ grating, and a 0.8 arcsec slit aligned to the parallactic angle. During this sequence, the air mass ranged from 1.05 to 1.36. All spectra were flux-calibrated and reduced using IRAF$^3$ standard procedures.

The LBT spectra are extremely complex and will be the subject of a dedicated spectroscopic paper. As a result, in this study, we rely upon them sparingly (primarily to establish an orbital ephemeris in order to phase the photometry to the binary orbit).

3. ANALYSIS OF THE NEW ASYNCHRONOUS POLAR J0846

3.1. Light curve

The top panels of Figs. 1 and 2 show a representative segment of the K2 light curve of J0846 and its full light curve, respectively. Despite the 30-min cadence of the observations, it is obvious that J0846 has large-amplitude variability on timescales shorter than the observational cadence. At times, the flux doubles in the span of several hours and is halved in even less

2 The LBT is an international collaboration among institutions in the United States, Italy and Germany. LBT Corporation partners are: The University of Arizona on behalf of the Arizona university system; Istituto Nazionale di Astrofisica, Italy; LBT Beteiligungsgesellschaft, Germany, representing the Max-Planck Society, the Astrophysical Institute Potsdam, and Heidelberg University; The Ohio State University, and The Research Corporation, on behalf of The University of Notre Dame, University of Minnesota and University of Virginia.

3 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.
time, giving the light curve a jagged appearance. The profiles of individual photometric maxima, with their large amplitudes and rapid changes, are typical for a polar. However, unlike normal polars, both the amplitude and shape of the maxima gradually evolve over a 6.7-d period before returning to their original appearance. This highly periodic and well-defined modulation of the short-term variability is the distinguishing property of J0846’s light curve and provides compelling evidence that it is an AP. As we explain in detail in Sec. 3.2.2, we identify the 6.7-d period in J0846 as the beat between its likely spin ($\omega = 5.32$ cycles d\(^{-1}\)) and orbital ($\Omega = 5.17$ cycles d\(^{-1}\)) frequencies.

The changes in the light curve across the beat period result in a rich power spectrum (Fig. 1, lower panels) containing $\omega$, $\Omega$, and numerous sidebands and harmonics thereof. The time-resolved power spectrum (Fig. 2) shows that the power spectrum varies cyclically at the beat period. Here again, this behavior is expected in an AP and has been observed in TESS observations of the AP CD Ind (Hakala et al. 2019; Littlefield et al. 2019; Mason et al. 2020).

Our classification of J0846 as an AP is supported by the previously reported observations of the system. As we noted earlier, an SDSS spectrum obtained in 2004 and published in Szkody et al. (2006) was consistent with J0846 being a polar. Fig. 3, which averages the previously reported SDSS spectrum with two additional spectra obtained in 2018 and 2019, confirms that He II $\lambda$4686Å is of comparable strength to H\(\beta\) and that the emission lines are single-peaked, properties that are commonly observed in polars.\(^4\) Although Szkody et al. (2006) did not detect circular polarization in a single 6000 s interval, this timespan covered significantly less than half of one cycle of the photometric variations in

\(^4\) To improve legibility, the individual spectra are not shown in Fig. 3, but except for changes in the strength of the He I emission, the three spectra were largely similar.
be 2 cause the dominant frequency in the power spectrum to that in X-ray light curves of IPs, pole switching could the power spectrum. Wynn & King (1992) predicted the movement of the accretion region wreaks havoc on the surface of the WD and even jumps between magnetic poles, making the photometric modulation of the accretion region an unreliable indicator of the spin period. Wynn & King (1992) predicted the accretion region an unreliable indicator of the spin period.

Poles, making the photometric modulation of the accretion region an unreliable indicator of the spin period. With synchronous polars, the accretion region is expected to be stationary at a fixed mass-transfer rate, so for purposes of measuring the WD’s spin period, it is often treated as a fiducial marker of the star’s rotation. In APs, however, the accretion region moves across the surface of the WD and even jumps between magnetic poles, making the photometric modulation of the accretion region an unreliable indicator of the spin period.

Indeed, by causing large phase shifts in the light curve, the movement of the accretion region wreaks havoc on the power spectrum. Wynn & King (1992) predicted that in X-ray light curves of IPs, pole switching could cause the dominant frequency in the power spectrum to be $2\omega - \Omega$, even if the light curve is modulated at $\omega$ between the pole switches (Mason et al. 2020). The widely-used Lomb-Scargle periodogram (Lomb 1976; Scargle 1982), along with other common period-finding algorithms, presume that a signal does not experience these large, regular phase jumps, and if pole switching is present in a light curve, these algorithms will be biased towards the identification of a period that forces a signal to remain as in-phase as possible (Sec. 4.1 in Littlefield et al. 2019).

Mason et al. (1995) and Mason et al. (1998) extended the rationale of Wynn & King (1992) to optical observations of APs and identified the $2\omega - \Omega$ sideband as the strongest signal in the power spectrum of BY Cam. In a similar vein, Littlefield et al. (2019) concluded from the TESS light curve of CD Ind that the long-accepted identification of the spin frequency in that system is actually $2\omega - \Omega$ (although this proposal awaits independent spectroscopic confirmation).

There is yet another complication: even between pole switches, the accretion region is expected to move longitudinally across the surface of the WD (Geckeler & Staubert 1997). The asynchronous rotation of the WD, with respect to the binary, causes the accretion stream to thread onto a continuously changing ensemble of magnetic field lines, each of which channels material onto different points along the WD’s surface. Consequently, in an AP, the interval between the accretion region’s crossings of the WD’s meridian can differ by several percent from the true WD rotational period (Geckeler & Staubert 1997).

Although accurately identifying $\omega$ and $\Omega$ from photometry alone is therefore a challenging affair, it is comparatively easy to identify their beat frequency ($\omega - \Omega$). Even if $\omega - \Omega$ is not directly visible in the power spectrum, it will be observable as the spacing between sideband frequencies of $\omega$ and $\Omega$.

### 3.2.2. Frequency identifications in J0846

With these considerations in mind, we turn to the power spectrum of J0846 and examine two sets of possible frequency identifications in the observed power spectrum of J0846.

The unusually rich power spectrum of J0846 (bottom panels of Fig. 1) bears many similarities with the TESS power spectrum of CD Ind and is consistent with J0846 being an AP. The major signals in the power spectrum are clustered in three groups, and the signal with the most power occurs at a frequency of 5.47 cycles d$^{-1}$. This is the same frequency measured by the Drake et al. (2014) pipeline from survey photometry. Nearby at 5.32 cycles d$^{-1}$ is another major signal. At lower frequencies, there is a family of six harmonically related signals, with the fundamental being 0.15 cycles d$^{-1}$; this is also the spacing between the frequencies in the other two clusters of signals.

The power spectrum is amenable to two sets of frequency identifications, and while both agree that the beat frequency ($\omega - \Omega$) is 0.15 cycles d$^{-1}$, they diverge on the correct identifications of $\omega$ and $\Omega$. Following Mason et al. (1995) and Mason et al. (1998), we propose that the highest-amplitude signal (5.47 cycles d$^{-1}$) is the $2\omega - \Omega$ sideband. In this scenario, which we shall refer to as Case 1, $P_{\text{spin}}=5.32$ cycles d$^{-1}$ and $P_{\text{orb}}=5.17$ cycles d$^{-1}$. The phased light curves based on the Case 1 identifications are presented in Fig. 4. The $2\omega - \Omega$ sideband profile shows the behavior qualitatively explained by Littlefield et al. (2019) for CD Ind; when phased to this frequency, the pulses remain comparatively in phase.
Figure 5. **Top:** The *TESS* light curve of Paloma. BTJD is defined as BJD - 2457000. **Middle:** Two-dimensional power spectrum with a 0.25-d sliding window, with linear intensity scaling. Across the 0.7-d beat cycle, the light curve alternates between a single- and double-humped profile, causing power to shift cyclically between $\omega$ and $2\omega$. **Bottom:** Two-dimensional power spectrum with a 2-d sliding window and logarithmic scaling. The larger window size offers improved frequency resolution at the expense of completely concealing the changes evident in the middle panel.

throughout the observation. Littlefield et al. (2019) contended that this is due to a bias of frequency-analysis algorithms. The spin-phased profiles, conversely, show evidence of discrete, variable accretion regions on opposite sides of the WD.

There is an additional set of plausible frequency identifications in which the dominant signal in the power spectrum would be the spin frequency, such that $\omega = 5.47$ cycles d$^{-1}$. In this scenario, which we call Case 2, $\Omega = 5.32$ cycles d$^{-1}$. Returning to the phased light curves in Fig. 4, the nominal sideband-phased and spin-phased light curves from Case 1 would actually be the spin-phased and orbit-phased light curves, respectively, in Case 2.

We summarize both sets of frequency identifications in Table 2. While we favor Case 1, the proper identification of the orbital period can be conclusively ascertained with time-series spectroscopy of the secondary. An undisputed orbital period, in combination with the 6.7 d beat period, would also eliminate any remaining ambiguity surrounding the spin period.

In either set of frequency identifications, J0846 would have an unusually long orbital period for a polar. At the time of writing, the International Variable Star Index (VSX) catalog contains 145 confirmed or candidate polars; if the orbital period of J0846 is 4.64 h, as we have argued, only three systems (V895 Cen, V1309 Ori, and V479 And) would have longer orbital periods. That census would increase to only four polars (with AI Tri being the fourth) if J0846’s orbital period is instead 4.51 h, as

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5 We exclude the object CG X-1 from this group. CG X-1 was formerly considered a candidate polar and remains identified as such in the VSX at the time of writing. However, Esposito et al. (2015) and Qiu et al. (2019) reclassified it as an extragalactic high-mass X-ray binary.
it would be in the second, disfavored set of frequency identifications.

3.3. Accretion geometry

Assuming that Case 1 correctly identifies the spin period, the profile of the spin pulse across the beat cycle is extremely intricate. The spin profile often resembles that of a synchronous polar across short intervals of the beat cycle, particularly during beat phases 0.0-0.25 (where $T_{0,\text{beat}}$ is arbitrarily defined as BJD=2458095.4882). During the next quarter of the beat cycle, the profile develops a plateau, while its peak becomes sharp and narrow, with a conspicuous dip after the pulse maximum. For much of the remainder of the beat cycle, the pulse profile becomes comparatively ill-defined, particularly at beat phase 0.8. Nevertheless, the main accretion region appears to be active for well over half of the beat cycle.

These behaviors are difficult to reconcile with a centered, dipolar field. Such a configuration would be expected to result in diametrically opposed accretion regions on opposite sides of the WD, with each pole accreting during opposite halves of the beat cycle. There is very clearly a dominant accretion region near spin phase 0.5, but there is also a signal near spin phase 1.0 at two different points in the beat cycle. Due to the 30-min cadence of the observations, we cannot confidently discern whether this is a second accretion spot or simply an evolution of the photometric profile of the main accretion spot. The latter might occur as a result of the migration of the accretion region, both in longitude and latitude, across the beat cycle, as first described by Geckeler & Staubert (1997) in a different AP, V1432 Aql.

Pole-switching in J0846 is much less pronounced than it is in the first TESS observation of CD Ind (Hakala et al. 2019; Littlefield et al. 2019; Mason et al. 2020). In the CD Ind light curve, there was a conspicuous jump in phase, as well as a change in the pulse profile, whenever the accretion flow switched between magnetic poles (Littlefield et al. 2019). In J0846, the pulse profile of the main accretion region experiences obvious changes, but it never switches off in the same manner as CD Ind. However, the poor phase resolution of the K2 light curve means that any single rotational cycle is sampled fewer than 10 times, whereas CD Ind’s spin profile was much more favorably sampled by TESS.

3.4. Comparing J0846 to other APs

As summarized in Table 1, J0846 is either the seventh or the eighth AP (depending on whether Paloma is also classified as such) and it joins six other APs for which the condition $|P_{\text{spin}} - P_{\text{orb}}|/P_{\text{orb}} \lesssim 4\%$ holds true. Only Paloma, for which $|P_{\text{spin}} - P_{\text{orb}}|/P_{\text{orb}} = 0.13$, fails to satisfy this requirement; its comparatively high level of desychronization makes its inclusion in Table 1 debatable. Regardless of Paloma’s classification, J0846 has by far the longest orbital period of the systems listed in Table 1.

Of these systems, V1432 Aql is a clear outlier, based on its very small level of asynchronism, its eclipsing nature, and the fact that it alone has $P_{\text{spin}} > P_{\text{orb}}$. On that final point, however, Wang et al. (2020) used a
Figure 7. Interdependence of Paloma’s spin and orbital profiles across the beat cycle (relative to \( T_0, \text{beat}[BJD] = 2458836.1495 \)). Panels A-C share the same x-axis (spin phase relative to \( T_0, \text{spin}[BJD] = 2458836.9065 \)), while panels D and E show the orbital phase on a common x axis. Panels A and D present six-harmonic Fourier-series representations of the average spin and orbital profiles across the entire TESS observation. Horizontal slices through panels B and C yield the spin profile that would be observed if the beat and orbital phases, respectively, could be held constant, and Panel C shows that the secondary spin maximum disappears at inferior conjunction. Similarly, panel E shows the evolution of the orbital profile across the beat cycle. Panel C establishes that the spin profile changes significantly near inferior conjunction.

new power-spectral modeling technique to propose new identifications of the orbital frequencies of CD Ind and BY Cam, and they argued that \( P_{\text{spin}} > P_{\text{orb}} \) in these two systems, too.\(^6\) The Wang et al. (2020) proposal can be tested conclusively by measuring \( P_{\text{orb}} \) from the radial-velocity variations of the donor star in each system; unlike the complex photometric variations, the orbital motion of the secondary must, by definition, occur at \( P_{\text{orb}} \).

4. PALOMA
4.1. Frequency identifications

\(^6\) The final paragraph in Sec. 4.2 of Littlefield et al. (2019) discusses circumstantial evidence against this particular re-identification for CD Ind.

Paloma is a faint and blended source in the TESS data, but its complex variability is visible in Fig. 5. The sliding-window size of 6 h in the two-dimensional power spectrum in the middle panel of Fig. 5 captures the cyclical transfer of power between \( \omega \) and \( 2\omega \) across the 0.7-d beat cycle.

The power spectrum for the full dataset (Fig. 6) provides an opportunity to resolve the long-standing ambiguity concerning the correct identification of the spin period. Schwarz et al. (2007) proposed and carefully justified two possible sets of frequency identifications, and with the TESS light curve, we can determine which is correct. Since the spectroscopic orbital frequency is unambiguously \( \Omega = 9.1 \text{ cycles d}^{-1} \) (Schwarz et al. 2007), there are only two plausible identifications of Paloma’s signal at 10.5 cycles d\(^{-1}\): the \( 2\omega - \Omega \) sideband or the
spin frequency $\omega$. Schwarz et al. (2007) refer to these two scenarios as Case A and Case B, respectively. The X-ray study presented by Joshi et al. (2016) argued for Case B, and we concur.

In the Schwarz et al. (2007) Case A, the identification of the $2\omega - \Omega$ sideband would require the true spin frequency $\omega$ to be equidistant between $\Omega = 9.1$ cycles d$^{-1}$ and $2\omega - \Omega = 10.5$ cycles d$^{-1}$. Although there is a signal near this frequency in the Schwarz et al. (2007) power spectra, there is none in either the TESS or Joshi et al. (2016) power spectra. Case A further demands a beat frequency of $0.7$ cycles d$^{-1}$. The TESS power spectrum shows no significant power at this frequency. Moreover, for Case A to be correct, all power at the fundamental spin and beat frequencies would need to be shifted into harmonics, a scenario that is unlikely.

Conversely, in the Schwarz et al. (2007) Case B identifications, the frequency at $10.5$ cycles d$^{-1}$ is $\omega$, resulting in a beat frequency $\omega - \Omega$ of $1.4$ cycles d$^{-1}$. The TESS power spectrum shows no significant power at this frequency. Moreover, for Case B to be correct, all power at the fundamental spin and beat frequencies would need to be shifted into harmonics, a scenario that is unlikely.

4.2. The orbital-phase dependence of the spin pulse

The unbinned light curve of Paloma is rather noisy, but because the spin and orbital frequencies are known, we can phase-average the light curve to improve the signal-to-noise ratio. Fig. 7 reveals the complex interplay between the spin and orbital profiles throughout
the TESS observation. The spin profile shows two distinct maxima, separated in phase by 0.5 rotational cycles. Interestingly, the secondary maximum, which occurs at spin phase 0.5, is present for only part of the beat cycle and is not visible when it coincides with the secondary’s inferior conjunction (the epoch of which is measured in Sec. 4.3). In contrast, the primary spin maximum (spin phase 0.0) is present throughout the light curve and shows very little dependence on the orbital or spin phases. Because the amplitude of the secondary spin pulse is so strongly modulated across the beat cycle, we define a reference epoch ($T_0$, $beat[BJD] = 2458836.1495$) such that the secondary maximum attains its maximum amplitude at beat phase 0.0, and we use this definition when phase-folding data in Fig. 7.

While the orbital profile (Fig. 7, panel E) is not nearly as intricate as the spin profile, it shows a wide dip at inferior conjunction. The structure of this profile suggests that the secondary’s inner hemisphere contributes significantly to the TESS light curve and that the dip occurs when the inner hemisphere is mostly blocked by the secondary’s cool backside.

There are two scenarios that could account for the behavior in Fig. 7: pole switching and a grazing eclipse of one of the emitting regions. We shall consider the strengths and weaknesses of each hypothesis separately.

4.2.1. Scenario 1: pole switching

In the pole switching scenario, accretion onto one of the poles ceases for half of the beat cycle, while the other pole accretes continuously. The preference for accretion onto one of the poles would require the magnetic-field topology to be more complex than a simple, centered dipole. One strength of this explanation is that it is consistent with the power spectral evidence (both here and in Joshi et al. 2016) that Paloma is a diskless IP. In the absence of a disk, one or more magnetic poles can be temporarily and periodically starved of a matter supply. Conversely, in a disk-fed IP, the inner rim of the disk provides a reservoir of material for both accretion regions, independent of the WD’s rotation.

4.2.2. Scenario 2: a grazing eclipse

An alternative explanation is that the spin pulse is intrinsically the same across the observations but is intrinsically altered by an eclipse. Figure 7 establishes that the pulse from the second pole disappears when it coincides with the secondary’s inferior conjunction. This phasing is exactly what is expected of a grazing eclipse by the donor star.

The chief difficulty with this scenario, however, is the absence of eclipses in the Joshi et al. (2016) X-ray observations, which covered a full beat cycle. X-rays in IPs are emitted from a post-shock region just above the WD’s photosphere, so an eclipse of the WD will produce sharp, energy-independent dips every orbital cycle. Thus, the non-detection of such a feature is very strong evidence that the WD itself is not eclipsed by the secondary. However, the eclipse interpretation of Fig. 7 nevertheless remains tenable. This is because the optical spin pulse might be produced in extended accretion curtains away from the WD, as has been observed for, e.g., FO Aqr (Beardmore et al. 1998). If one of these curtains is blocked by the secondary at inferior conjunction, it could easily explain the disappearance of one of the maxima of the spin profile in Fig. 7 without a corresponding eclipse at X-ray energies.

The available evidence does not offer an obvious answer as to which scenario (if either) is correct. However, it is difficult to dismiss as a coincidence the fact that one of the spin maxima disappears only when it is observed at inferior conjunction, and it is this factor that leads us to tentatively favor the eclipse interpretation. Spectroscopic observations of the eclipse-like feature might offer a more definitive answer, as the eclipse of an accretion curtain should produce a concomitant weakening of the high-velocity components of the H and He emission lines.

4.3. Orbital ephemeris from LBT spectroscopy

The LBT spectra enable us to phase Paloma’s TESS light curve to the binary orbit because several features from the donor star are present. In particular, there is significant emission at the Ca II λλ8498, 8542, 8662 Å triplet from the secondary’s inner hemisphere, and the Na I λλ8183, 8195 Å absorption doublet is weakly present. In addition to the Ca II triplet, Paloma’s spectrum contains a large number of narrow, weak metal lines that are visible when the secondary’s irradiated inner hemisphere is viewed preferentially (Fig. 8).

The Ca II emission and the Na I absorption move in phase with each other, and since the signal-to-noise ratio of the Ca II lines is significantly higher, we measure their motion to obtain a radial velocity curve (Fig. 9). The blue-to-red crossing of the Ca II lines yields the time of the donor’s inferior conjunction, for which we provide an ephemeris of:

$$T_{conj}[BJD] = 2458836.9131(2) + 0.10914(12) \times E.$$  (1)

Since the spectra were obtained during the TESS observation, the relative imprecision of the orbital period results in negligible phasing errors across the month-long TESS light curve.

Given the complexity of the LBT spectra, it is beyond the scope of this paper to analyze them comprehensively,
and we will do so in a separate paper. However, an initial analysis of the spectra does not offer a clear-cut explanation of the variable secondary spin maximum discussed earlier. The observations were obtained between beat phases 0.98-1.12, which is outside the interval during which the secondary maximum vanishes at inferior conjunction (Fig. 7). The spectra do provide evidence of a moderately high orbital inclination, as evidenced by the precipitous decline of the secondary’s metal emission lines hemisphere near inferior conjunction. This behavior, which is the reason for the lack of measured radial velocities for the Ca II triplet near inferior conjunction in Fig. 9, is likely the result of the secondary’s irradiated inner hemisphere being hidden by its backside. However, there is no evidence of an eclipse of the accretion flow in either the He II or Hβ lines in Fig. 9.

4.4. The spin period derivative of Paloma

With a sufficiently long (~decades) observational baseline, we would expect Paloma to show a spin-period derivative (\(\dot{P}\)), as has been observed in all APs with such baselines (for a recent summary, see Table 1 in Myers et al. 2017). These systems have a characteristic synchronization timescale \(\tau = |(P_{\text{orb}} - P_{\text{spin}})|/\dot{P}\).

We measure a spin period of 0.09460(10) d at Julian year epoch 2019.94, compared to a period of 0.094622(3) d in observations between 1992 and 2002 (Schwarz et al. 2007). Because the Schwarz et al. (2007) value falls within our 1σ uncertainty for the spin period, we do not detect evidence of a statistically significant \(\dot{P}\). This non-detection is subject to an important caveat: the Schwarz et al. (2007) period suffers from a cycle-count ambiguity.

Although the non-detection of \(\dot{P}\) is disappointing, it is not unexpected, given the relatively large uncertainty of the TESS spin period. The maximum observed \(\dot{P}\) in FO Aqr, an IP famous for its rapidly varying spin period, is \(|\dot{P}| = 8 \times 10^{-10}\) (Littlefield et al. 2020). If the Schwarz et al. (2007) period were either increasing or decreasing at that rate, the change in period would be indiscernible a quarter-century later at the precision of the TESS spin period. Without long-term, highly precise measurements of the spin period, it will be challenging to convincingly detect \(\dot{P}\) in Paloma.

5. CONCLUSION

We have used a long-cadence K2 light curve to show that J0846 is a new asynchronous polar with a significantly longer orbital period than any other AP. Our analysis of the TESS light curve of another nearly synchronous magnetic CV, Paloma, eliminates the long-standing ambiguity surrounding the proper identification of its spin frequency. Both targets warrant long-term monitoring so that their spin-period derivatives can be measured.

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Facility: Large Binocular Telescope

Software: astropy (Astropy Collaboration et al. 2013), lightkurve (Lightkurve Collaboration et al. 2018)

REFERENCES

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33, doi: 10.1051/0004-6361/201322068

Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Dennefeld, M., & Andrae, R. 2021, AJ, 161, 147, doi: 10.3847/1538-3881/abd806

Beardmore, A. P., Mukai, K., Norton, A. J., Osborne, J. P., & Hellier, C. 1998, MNRAS, 297, 337, doi: 10.1046/j.1365-8711.1998.01382.x

Bellm, E. C., Kulkarni, S. R., Graham, M. J., et al. 2019, PASP, 131, 018002, doi: 10.1088/1538-3873/aaeche

Beuermann, K., Burwitz, V., Reinsch, K., Schwope, A., & Thomas, H. C. 2021, A&A, 645, A56, doi: 10.1051/0004-6361/202038598

Channuggam, G., & Ray, A. 1984, ApJ, 285, 252, doi: 10.1086/162499

Cropper, M. 1990, SSRv, 54, 195, doi: 10.1007/BF00177799

Drake, A. J., Graham, M. J., Djorgovski, S. G., et al. 2014, ApJS, 213, 9, doi: 10.1088/0067-0049/213/1/9

Esposito, P., Israel, G. L., Milisavljevic, D., et al. 2015, MNRAS, 452, 1112, doi: 10.1093/mnras/stv1379

Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1, doi: 10.1051/0004-6361/201629272

Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2021, A&A, 649, A1, doi: 10.1051/0004-6361/202039657

Geckeler, R. D., & Staubert, R. 1997, A&A, 325, 1070

Hakala, P., Ramsay, G., Potter, S. B., et al. 2019, MNRAS, 486, 2549, doi: 10.1093/mnras/stz992

Halpern, J. P., Bogdanov, S., & Thorstensen, J. R. 2017, ApJ, 838, 124, doi: 10.3847/1538-4357/838/2/124

Hill, K. L., Littlefield, C., Garnavich, P., et al. 2022, arXiv e-prints, arXiv:2203.00221. https://arxiv.org/abs/2203.00221

Joshi, A., Pandey, J. C., Singh, K. P., & Agrawal, P. C. 2016, ApJ, 830, 56, doi: 10.3847/0004-637X/830/2/56

King, A. R. 1993, MNRAS, 261, 144, doi: 10.1093/mnras/261.1.144

King, A. R., & Lasota, J.-P. 1991, ApJ, 378, 674, doi: 10.1086/170467

King, A. R., & Wynn, G. A. 1999, MNRAS, 310, 203, doi: 10.1046/j.1365-8711.1999.02974.x

Littlefield, C., Scaringi, S., Garnavich, P., et al. 2021, AJ, 162, 49, doi: 10.3847/1538-3881/ac062b

Littlefield, C., Garnavich, P., Mukai, K., et al. 2020, arXiv e-prints, arXiv:2004.08923. https://arxiv.org/abs/2004.08923

Littlefield, C., Garnavich, P., Szkody, P., et al. 2020, arXiv e-prints, arXiv:2004.08923

Lomb, N. R. 1976, Ap&SS, 39, 447, doi: 10.1007/BF00177799

Myers, G., Patterson, J., de Miguel, E., et al. 2017, PASP, 129, 044204, doi: 10.1088/1538-3873/aa54a8

Patterson, J. 1994, PASP, 106, 209, doi: 10.1086/133375

Pavlenko, E., Andreev, M., Babina, Y., & Malanushenko, V. 2013, in Astronomical Society of the Pacific Conference Series, Vol. 469, Magnetic Cataclysmic Variables, ed. D. A. H. Buckley & B. Warner, 496

Pavlenko, E. P., Mason, P. A., Kolesnikov, S. V., Pavlenko, E. P., & Shakovskoy, M. 1995, in Astronomical Society of the Pacific Conference Series, Vol. 85, Magnetic Cataclysmic Variables, ed. D. A. H. Buckley & B. Warner, 496

Pavlenko, E. P., Mason, P. A., Sosnovskij, A. A., et al. 2018, MNRAS, 479, 341, doi: 10.1093/mnras/sty1494
Pogge, R. W., Atwood, B., Brewer, D. F., et al. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7735, 77350A

Qiu, Y., Soria, R., Wang, S., et al. 2019, ApJ, 877, 57, doi: 10.3847/1538-4357/ab16e7

Rawat, N., Pandey, J. C., & Joshi, A. 2021, ApJ, 912, 78, doi: 10.3847/1538-4357/abedae

Scargle, J. D. 1982, ApJ, 263, 835, doi: 10.1086/160554

Schmidt, G. D., & Stockman, H. S. 1991, ApJ, 371, 749, doi: 10.1086/169939

Schwarz, R., Schwope, A. D., Staude, A., et al. 2007, A&A, 473, 511, doi: 10.1051/0004-6361:20077684

Stockman, H. S., Schmidt, G. D., & Lamb, D. Q. 1988, ApJ, 332, 282, doi: 10.1086/166652

Szkody, P., Henden, A., Agüeros, M., et al. 2006, AJ, 131, 973, doi: 10.1086/499308

Tovmassian, G., González-Buitrago, D., Thorstensen, J., et al. 2017, A&A, 608, A36, doi: 10.1051/0004-6361/201731323

Wang, Q., Qian, S., Han, Z., et al. 2020, ApJ, 892, 38, doi: 10.3847/1538-4357/ab7759

Wynn, G. A., & King, A. R. 1992, MNRAS, 255, 83, doi: 10.1093/mnras/255.1.83

Zhilkin, A. G., Bisikalo, D. V., & Mason, P. A. 2012, Astronomy Reports, 56, 257, doi: 10.1134/S1063772912040087

Zhilkin, A. G., Bisikalo, D. V., & Mason, P. A. 2016, in American Institute of Physics Conference Series, Vol. 1714, Space Plasma Physics, 020002, doi: 10.1063/1.4942564
APPENDIX

A. BEAT-PHASE RESOLVED SPIN PROFILES OF J0846 AND PALOMA

The $K2$ and $TESS$ data showcase the gradual evolution of the spin profiles of both J0846 and Paloma across their respective beat cycles. Figs. 4 and 7 used two-dimensional light curves to illustrate this behavior.

Here, we present one-dimensional light curves of the spin profiles of both J0846 and Paloma to enable a more careful inspection than is possible in their two-dimensional counterparts. Because the resulting figures are awkwardly large, we present them separately from the main text in Figs. 10 and 11 for J0846 and Paloma, respectively.
Figure 10. Binned spin profiles of J0846 in twenty non-overlapping portions of the 6.7 d beat cycle. The top of each panel indicates which beat phases were used to construct each spin profile. The data are repeated along the x axis for clarity. The pole near spin phase 0.5 has an associated photometric maximum for most of the beat cycle, but it becomes indistinct near beat phase 0.8.
Figure 11. Evolution of Paloma’s spin profile across the beat cycle. Beat phase 0.0 occurs when the primary spin maximum coincides with inferior conjunction of the secondary star (i.e., when the spin and orbital phases are both 0.0).