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Accretion States in Magnetic CVs: TESS and ground-based photometry

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Recent work on magnetic CVs is presented, with a focus on accretion states observed in TESS photometry. TESS data consists of red/IR photometry consisting of a continuous data stream with 2 minute cadence. When possible the TESS data is supplemented by high-speed (1-5 sec cadence) photometry using the 2.1-m telescope of the McDonald Observatory. Asynchronous polars (AP) and intermediate polars (IPs) with slowing rotating white dwarfs, hereafter slowly rotating IPs, are especially useful targets for TESS studies. This is because APs and slowly rotating IPs have beat periods that last from days to weeks. TESS provides continuous coverage across the beat cycle for these binaries. In addition, since the TESS exposure time of 2-min is long compared to the spin periods of the rapidly rotating IPs, TESS is better suited to the study of IPs with longer white dwarf spin periods. In the Interactive Magnetic Value Model proposed to explain mass transfer variations in APs, the strong magnetic field of the white dwarf interacts with the moderate magnetic field of the rapidly spinning donor star. The superposition of the fields of both stars at the inner Lagrangian point (L1) may either inhibit or enhance mass transfer through L1, depending on the orientation of the resultant field. Rapid accretion rate variations are observed in polars, initiating high or low accretion states, and in some IPs, and may be explained by rapid changes in the magnetic field at L1 affecting the mass-transfer rate. A combination of published and new results on the following magnetic CVs are presented: BY Cam, CD Ind, V1500 Cyg, SDSS J134441.83+204408.3, Paloma, and J084617.11+245344.1.

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I review a few things concerning recent results on magnetic cataclysmic variables (mCVs) highlighting changes in accretion states or accretion geometry in polars, especially asynchronous polars and their somewhat related cousins the slowly rotating intermediate polars (IPs). I discuss other recent work on the magnetic field interactions of APs and IPs. The analysis presented here were performed using mostly TESS and ZTF photometry often combined with McDonald Observatory 2.1-m telescope high-speed photometry.

1. Asynchronous Polars and Slowly Rotating Intermediate Polars

Asynchronous Polars (APs) are just like ordinary synchronous polars except that there is a small, less than ∼10%, difference between the white dwarf spin period and the binary orbital period. Because of this difference, APs exhibit a beat cycle between the white dwarf spin and the binary orbital frequencies. In all but one of the APs, the white dwarf spins a bit faster than the binary orbit, such that $P_{spin} > P_{orb}$. The exception is the AP, V1432 Aql, which is the only magnetic CV discovered to be over-synchronous; with a white dwarf spin period that is 0.2% longer than the orbital period.

APs cannot be easily distinguished from synchronous polars from a single observation of a few hours as their multi-wavelength observations appear as an ordinary synchronous polar on short time scales. The difficulty in AP identification depends on the degree of asynchronism. However, when observed on longer time scales the light curve changes. This is because, due to asynchronism, the accretion flow is continuously redirected as the binary progresses through its spin-orbit beat cycle.

A possible evolutionary link between intermediate polars (IPs) and polars is illustrated using the spin-orbit diagram for magnetic CVs given in Figure 1. Polars are shown as a horizontal sequence on this semi-log plot, with the asynchronous polars (APs) slightly off the horizontal synchronous polar line. IPs have typically $P_{spin}/P_{orb} \sim 0.1$ and the slowly rotating IPs are shown as the vertical sequence at short periods. See the discussion [1] on the highly asynchronous AP (or slowly rotating IP) SDSS J134441.83+204408.3 (hereafter J1344), see the green star in Figure 1. The difference between an AP and a synchronous polar can be determined from photometry by measuring the beat period between the white dwarf spin and the binary orbit. Spectroscopic observations often unambiguously track the orbital period in APs [e.g. 2] just as they do for normal polars. Switching between accretion regions, known as pole switching [3], occurs around the beat cycle and results in accretion geometry changes as evidenced by light curve differences as a function of beat phase. Looking at Figure 1, we see that the slowly rotating IPs are shown as the vertical sequence at short periods and may be the evolutionary sequence predicted in 1984 by Chanmugam and Ray [4] when EX Hyd was the only known slowly rotating IP.

1.1 SDSS J1344 and V1432 Aql

TESS observations have provided an unprecedented view of both APs and slowly rotating IPs, because continuous photometric coverage around the beat cycle of magnetic CVs is possible. The most useful data results when TESS observes a source during multiple sectors, each covering about 28 days. So far, only one sector of data is available for SDSS J134441.83+204408.3 (hereafter J1344 [1]) and V1432 Aql. In Figure 2, the results of the phase dispersion minimization analysis (PDM) of SDSS J1344 from TESS Sector 50 is shown in the left panel. The right panel shows

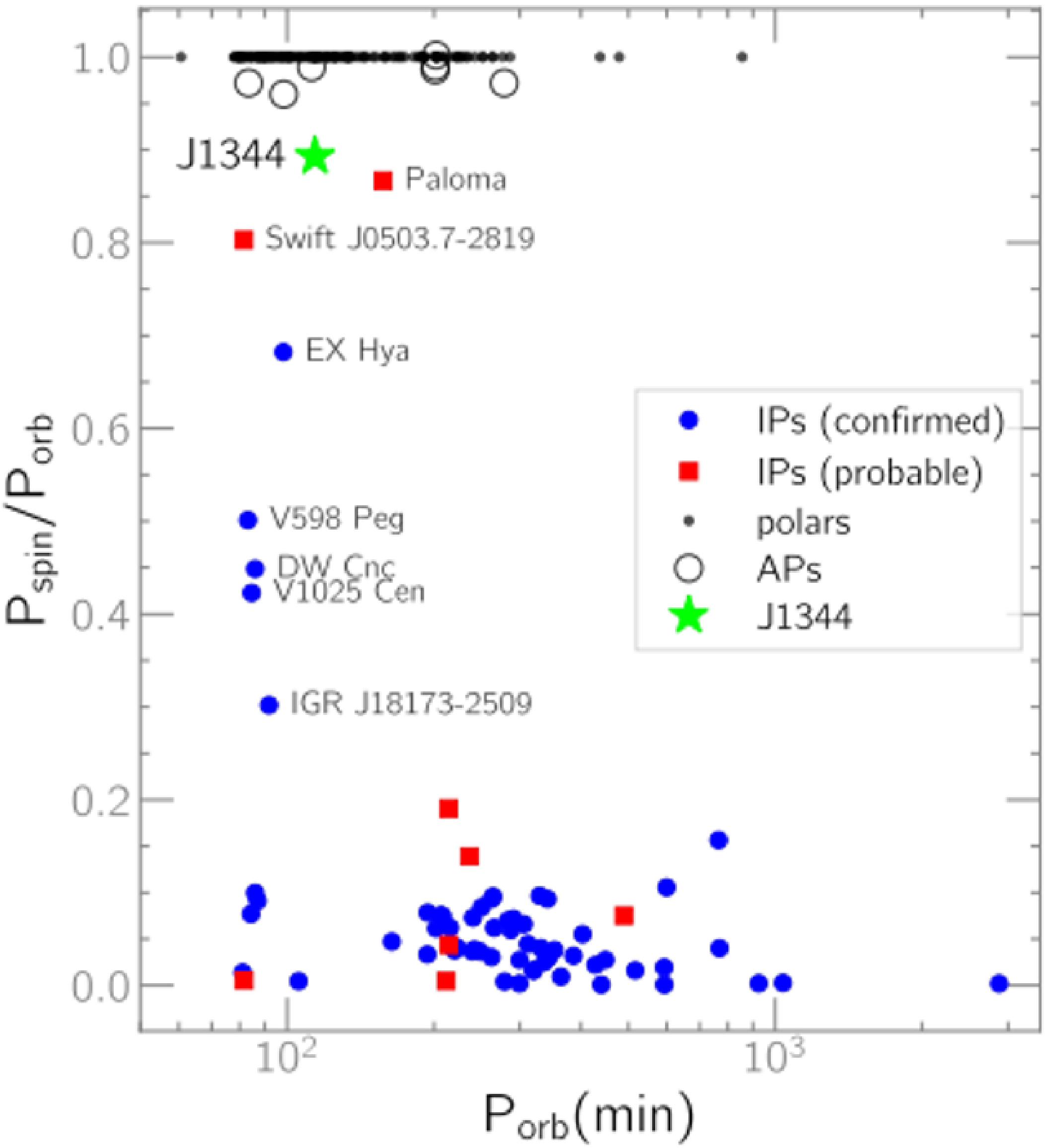

Figure 1: The spin-orbit diagram of magnetic CVs includes polars, asynchronous polars (APs), and intermediate polars (IPs). The slowly rotating IPs are shown as the vertical sequence at short periods and may be the evolutionary sequence predicted by Chanmugam and Ray [4]. Credit: Figure 5 from Littlefield et al., 2023. [1]

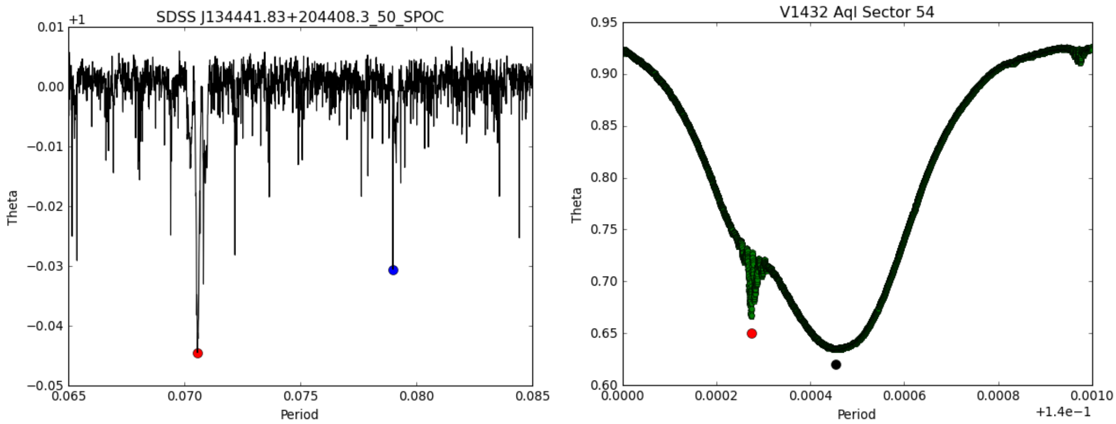

Figure 2: Phase dispersion minimization analysis (PDM) of SDSS J1344 from TESS Sector 50 is shown in the left panel. The side-band (red dot) and orbital (blue dot) periods are identified. The right panel shows the Sector 54 PDM of the AP, V1432 Aql. The orbital (red dot) and spin (black dot) periods are identified.

the (Sector 54) PDM of the AP, V1432 Aql. Simply described the PDM finds that the most likely periods are those showing a minimum in the phase dispersion of data folded on a series of trial periods.

The difference between APs and slowly rotating IPs is further blurred with the help of a new asynchronous polar J1344, recall Figure 1, which is just less than 10% asynchronous. J1344 in particular, challenges conventional theory concerning asynchronism. It seems to be too asynchronous to have had synchronism disrupted by a single nova and because it has such a short period, likely P = 102 min, and a strong magnetic field of B = 56 MG, the expected time scale for synchronization of J1344 to become a polar must be quite short. Its origin is a bit mysterious and will require follow-up observations to determine the synchronization time scale. One possibility is that the white dwarf in J1344 has a high mass [1]. It is important to note that the synchronization time scale for an IP to become a polar is significantly increased for a high-mass white dwarf, because of the small white dwarf radius associated with the high mass [1].

The spin-orbit diagram of Figure 1 now focused only on the polars is shown as Figure 3, including the asynchronous polars (APs), shown this time with linear axes. The magnetic field of the accreting white dwarf in a mCV will cause synchronization of the rotation of the white dwarf to the binary orbital period if the field strength is above ∼10 MG. The APs have such strong fields that some of them have already been determined to be synchronizing on short time scales [5-8].

1.2 CD Ind

Three Sectors, 1, 27, and 67 of TESS photometry of CD Ind are shown in Figure 4. The time resolution is 2-min and the data span about 28 days for each sector. In the top (Sector 1) and bottom (Sector 67) plots the 7 or 14 day beat cycle is clearly seen. Detailed analysis of TESS Sector 1 have been published elsewhere [9,10,11]. In addition, it was hypothesized [11] that a hidden pole accretes material during part of the 7.3-day (or 14.6-day) beat cycle in CD Ind. While details cannot be resolved on this scale, notice that the individual spin pulses are superimposed on a continuous

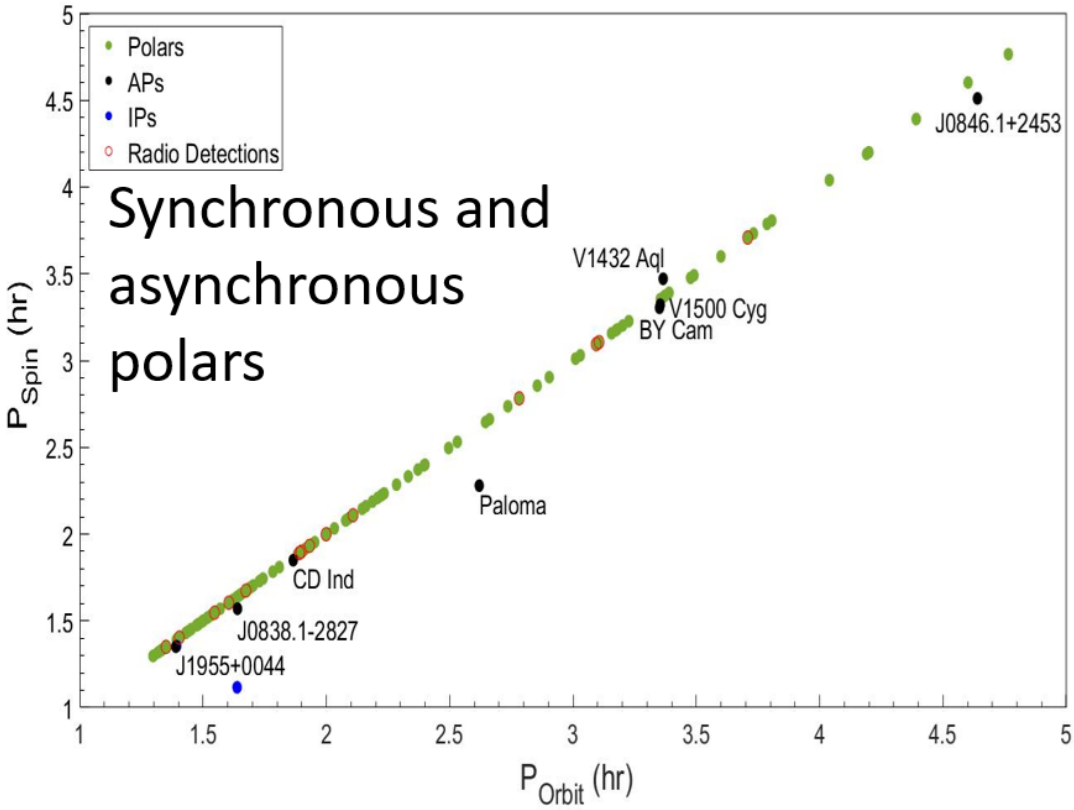

Figure 3: The spin-orbit diagram of the polars, including the asynchronous polars (APs), is shown.

brightness variation (seen as a dark band) modulated at the beat cycle.

The light curve obtained during Sector 27, see the middle panel of figure 4, is very different from the other two sectors and indicates a change in accretion structure or geometry.

1.3 J0846 and Paloma

The newly discovered AP, SDSS J084617.11+245344.1 (hereafter J0846) , was observed by the Kepler spacecraft for 80 days during Campaign 16 of the K2 mission. J0846, has a likely 6.77-day beat cycle resulting from a 4.64-hour orbital period from its 2.8% asynchronism [12]. This degree of asynchronism is in line with the previously discovered asynchronous polars IGR J19552+0044 at 2.8%, and IRSX J083842.1-282723 which is about 4% asynchronous. However, J0846 poses an interesting challenge to synchronization theory and would benefit from future observations. Notice that J0846 lies at the long period end of the spin-orbit diagram of Figure 3.

An interesting case is Paloma, which is usually classified as an AP, which is about 13% asynchronous. TESS observations resolved the ambiguity in the white dwarf spin period [12] Using TESS we find a white dwarf spin period of 2.27 hr. Paloma has a short 0.7-day beat period compared to other APs because of its high degree of asynchronism. Here again we have (at least) two possibilities. Either J0846 and/or Paloma were previously synchronized polars that have been desynchronized by one or more recent novae or they are slowly rotating IP on the verge of synchronizing for the first time.

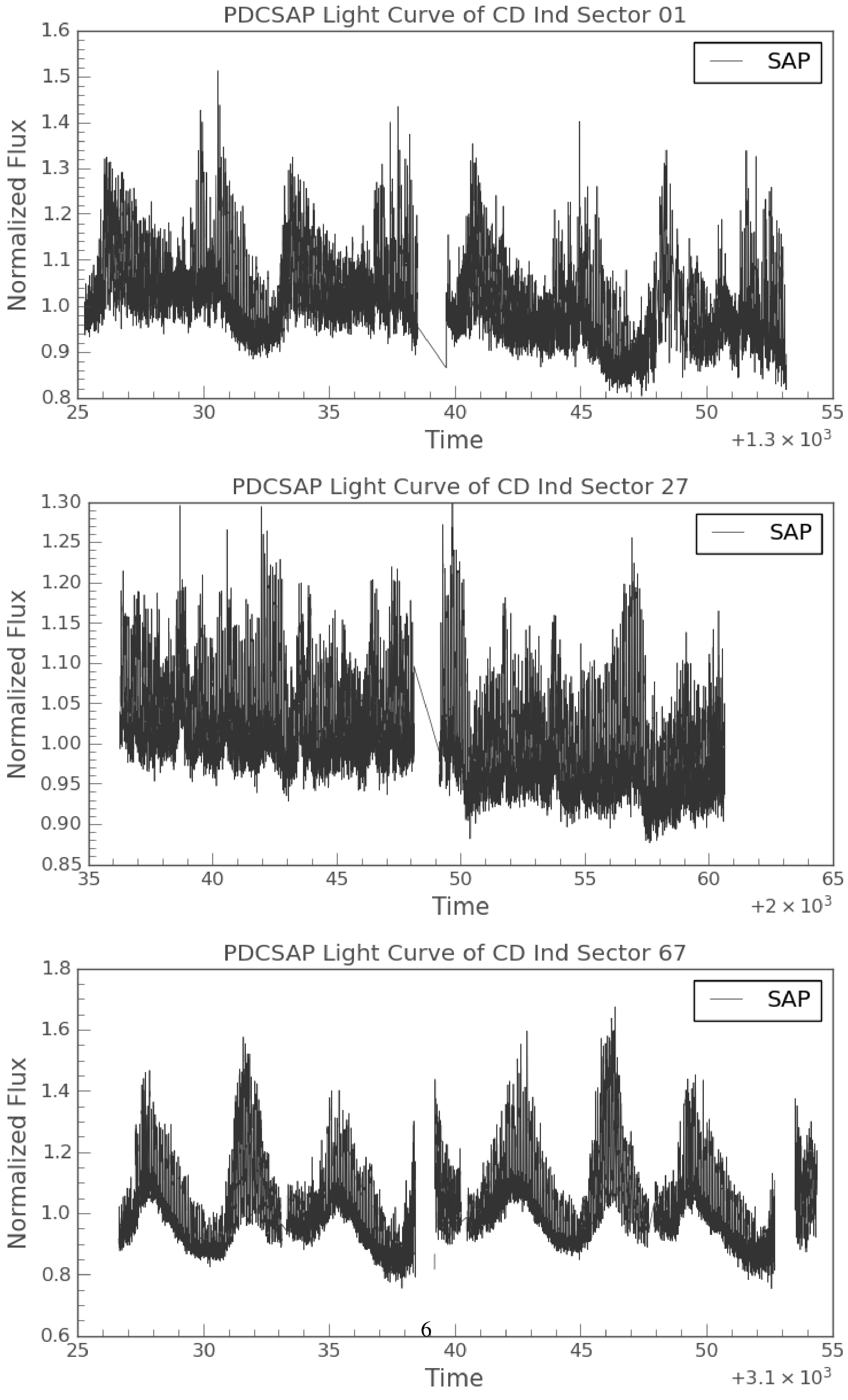

Figure 4: Three Sectors, 1, 27, and 67 of TESS photometry of CD Ind are shown.

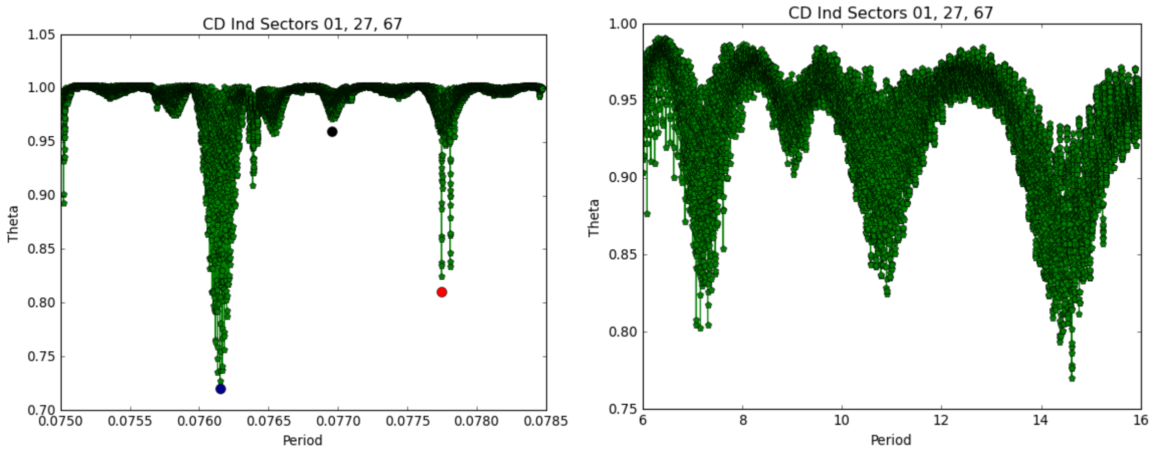

Figure 5: Period analysis of CD Ind from TESS Sectors 1, 27, and 67. In the top panel the side-band (blue dot), spin (black dot), and orbital (red dot) periods [9,10] are shown. Super-orbital periods were found at 7.162-day, 10.894-day, and the most significant detection is the probable beat period of P = 14.616-day.

1.4 V1500 Cyg - Nova Cygni (1975)

Nova Cygni 1975, also known as the polar V1500 Cygni, is undergoing post-nova synchronization on a time scale of a few hundred years [7]. It was also found that the white dwarf in V1500 Cygni is still cooling 40 years after the nova [8]. So it is very likely that the 1975 nova eruption caused V1500 Cygni to become an asynchronous polar. The original APs, V1500 Cygni [7,8] and BY Cam [2,3] are each about 1% asynchronous, although V1500 Cygni was about 2% asynchronous after the 1975 nova was discovered to be an AP in 1991 [7].

TESS has observed V1500 Cyg extensively with a total of 5 sectors. In Figure 6 three sectors of high cadance data are shown. Figure gives 7 the period analysis of V1500 Cyg from TESS Sectors 15 and 16 (left) and Sectors 15, 16, 55, 75, and 76 (right). The red and blue dots correspond to the orbital and spin periods respectively of V1500 Cyg obtained using ground based data and presented by Pavlenko et. al. [8].

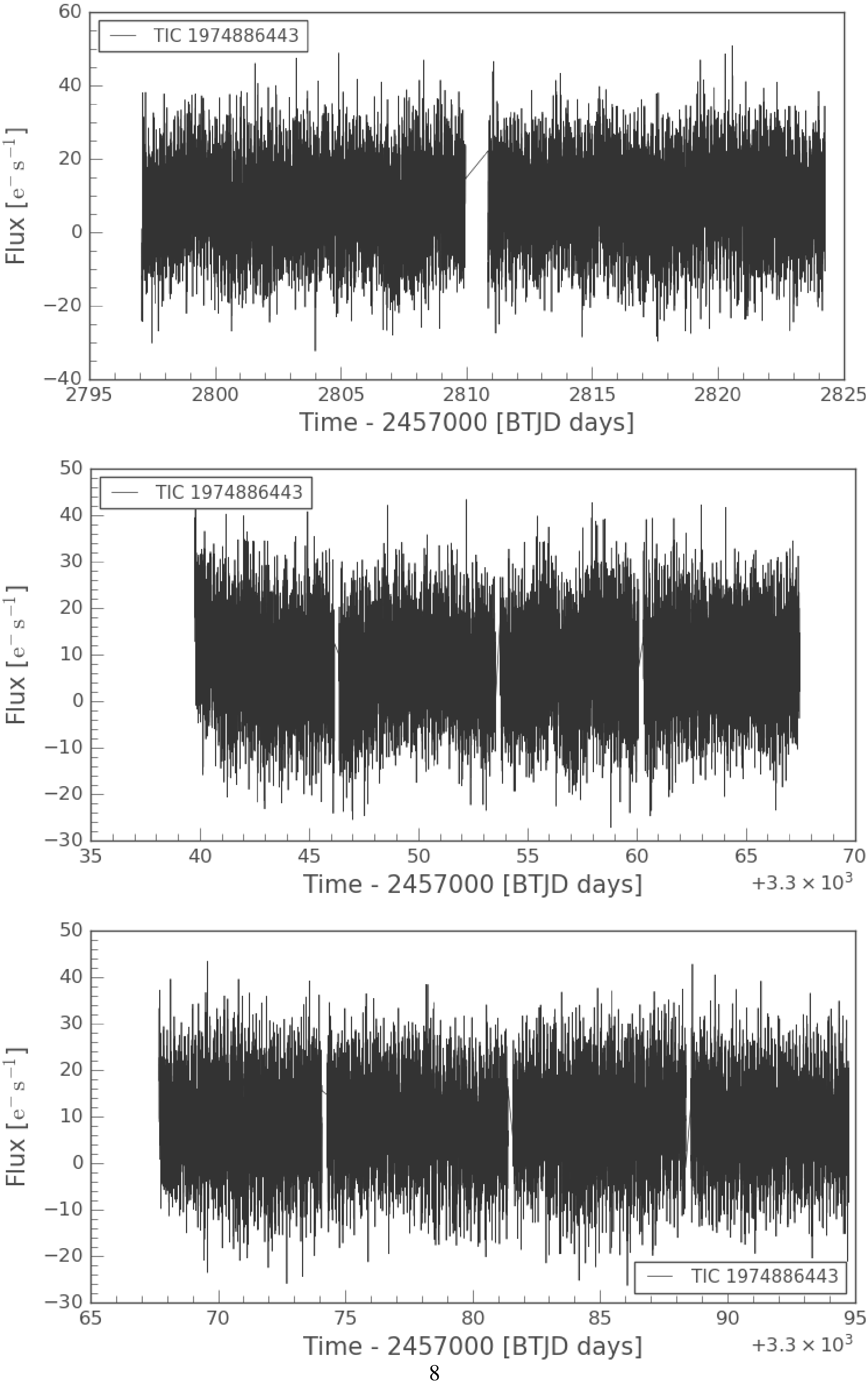

Figure 6: Two Sectors, 55, 75, and 76 of TESS photometry of V1500 Cyg are shown.

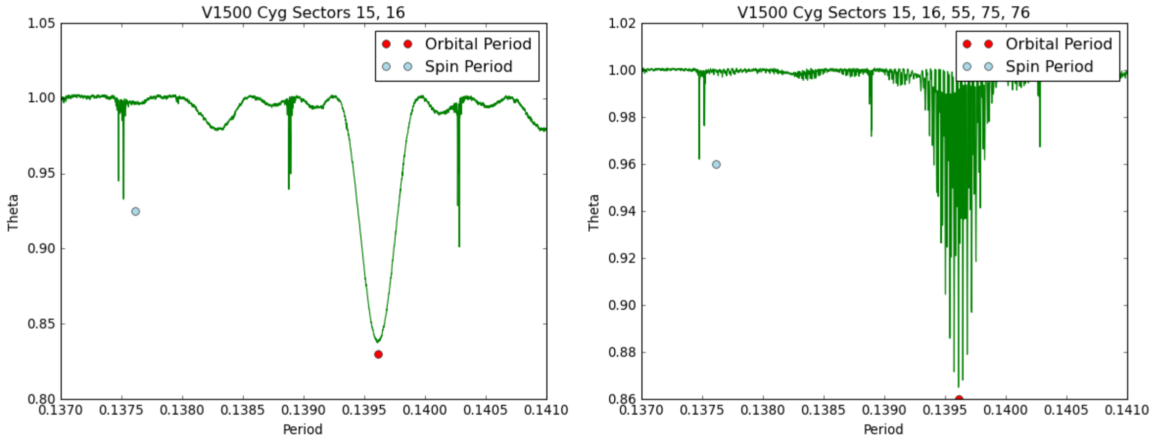

Figure 7: Period analysis of V1500 Cyg from TESS Sectors 15 and 16 (left) and Sectors 15, 16, 55, 75, and 76 (right). The red and blue dots correspond to the orbital and spin periods of V1500 Cyg obtained by Pavlenko et. al. [7].

2. Interactive Magnetic Valve Model

An Interactive Magnetic Valve Model for mass transfer in polars, capable of modulating mass transfer over the beat cycle in the typical AP, BY Cam, was proposed [13]. The two sectors of TESS photometry of BY Cam are shown in Figure 8. Essentially the same model is used to explain the high and low accretion states of synchronous polars [14] and in a joint study of TESS observations involving a comparison of the low-field polar AM Her and the canonical high-field polar AR UMa [15]. At much lower magnetic field strength of IPs, accretion rarely if ever stops as it does frequently in most polars [16]. The IP, YY Dra often known as DO Dra, was found to undergo occasional and very brief low accretion states due to a cessation of mass transfer [17]. The Interactive Magnetic Valve Model may also explain these short-term events.

This model argues that the 10-235 MG magnetic field of the white dwarf interacts with the few kG magnetic field of the donor star to either cut off or enhance the plasma flow from the inner Lagrangian point on the donor [13-17]. A high-speed photometric flickering analysis of TESS observations of polars [18] and magnetic gating reported in the IP, TX Col [19], are likely both indicative of magnetically influenced accretion flows as is the presence of occasionally accreting polars in the 2-3 hr CV period gap [e.g. 20]. A schematic magnetic valve model for BY Cam is shown in Figure 9. These spot positions compare favorably with the emission line spectroscopy of BY Cam [e.g. 21] and MHD calculations [22,23].

3. New Magnetic CVs

Finally, I highlight several results often including McDonald Observatory 2.1-m photometry combined with larger multi-wavelength campaigns. ASASSN-18fk was discovered as a dwarf nova and was followed up with an extensive multi-site observing campaign [24]. ASASSN-18fk was determined to be a WZ Sge-type dwarf nova. It underwent multiple rebrightenings and displays an 86.4-min superhump period over all stages of the super-outburst. A 22-min modulation is

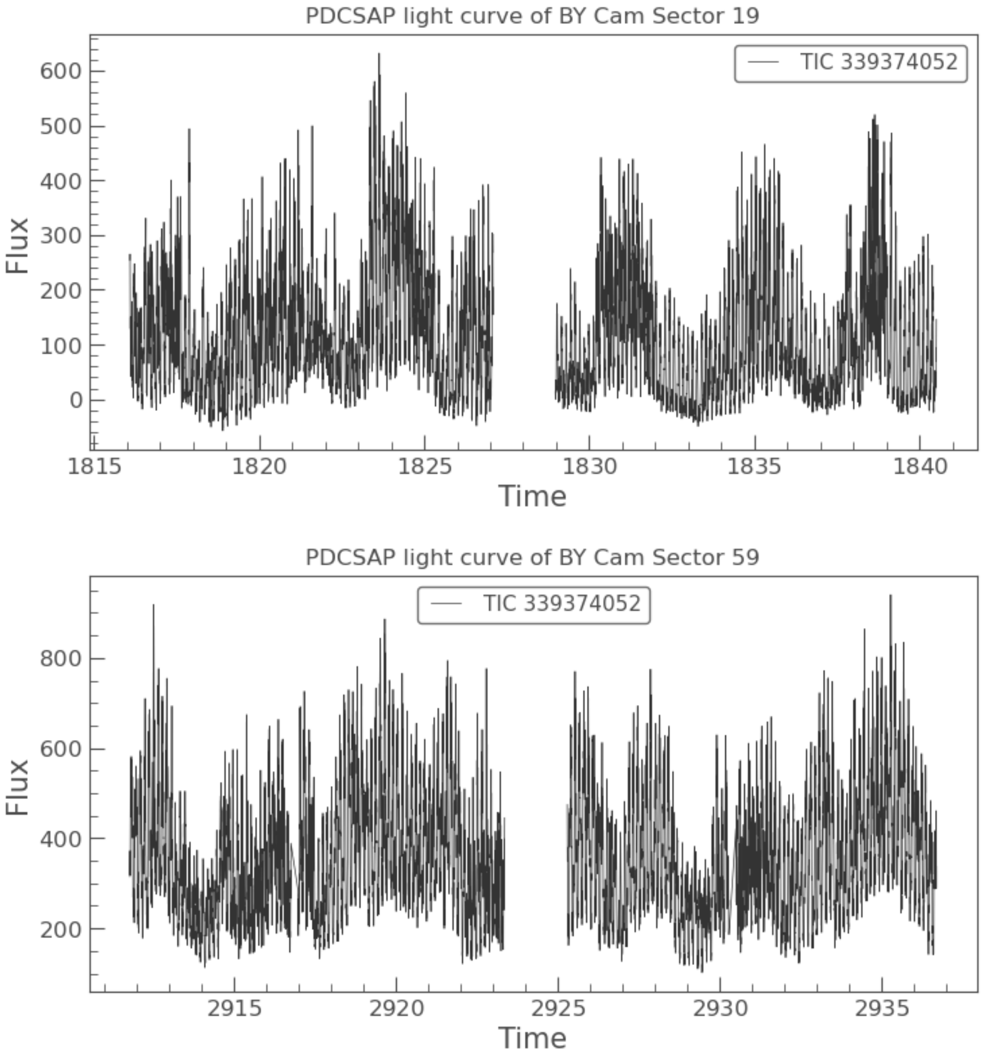

Figure 8: Two sectors, 19 and 59, of TESS photometry of BY Cam are shown. A beat period of about 15 days is apparent in both light curves. However, there are variations between different beat cycles. Details of the analysis of TESS Sector 19 are presented elsewhere [13].

interpreted as the spin period of the white dwarf and suggests that ASASSN-18fk is a good IP candidate. Characteristics of the permanent superhumps in V533 Herculis were investigated [25]. Szkody et al. [26] presented spectroscopic Follow-up of several likely magnetic CVs. And recently, a new candidate circumbinary planet in an eccentric orbit around the polar V808 Aur was found [27].

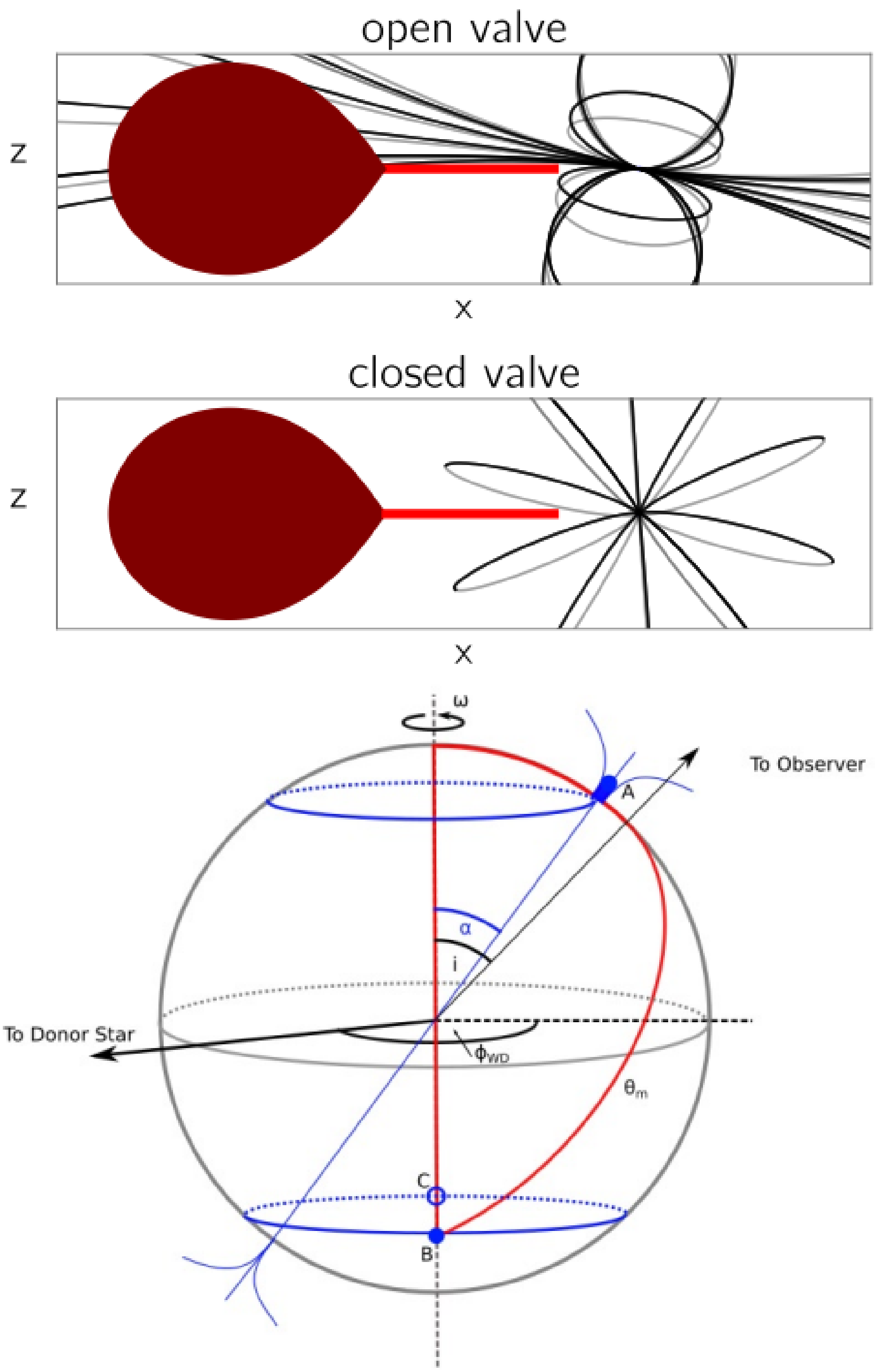

Figure 9: An Interactive Magnetic Valve model for polars. **Top:** The system is viewed at orbital phase 0.75 with two snapshots separated by 0.25 beat cycles. The white dwarf magnetic field allows the flow when parallel **(top)** and is a barrier to mass transfer through L1 when the flow is perpendicular **(middle)** to the magnetic field. **Bottom:** Schematic diagram showing the best-effort determination of spot positions for BY Cam [13]. Accretion region A, at the upper magnetic pole, remains in view as the WD spins. Regions B and C are self-eclipsing and alternate in activity around the beat cycle. Figure Credit: Mason et al. (2022) [13].

4. Conclusions

Several of the magnetic CV blur the line between APs and slowly rotating IPs. The term slowly rotating IPs should be reserved for those IPs that are either maintaining asynchronism or becoming synchronous for the first time. While APs are previous polars that have been knocked out of synchronism by, for example, one or more novae, like V1500 Cyg. It is important to consider the time-scales. It is possible that a once synchronous polar could have had a nova eruption before fully re-synchronizing from a prior nova eruption, thereby pushing it further away from synchronism with each nova. This effect is most likely to occur for APs with high mass CVs as they are expected to have a shorter nova recurrence time.

A key science problem for APs is the origin of their asynchronism and to differentiate between true APs and slowly rotating IPs. The discovery of several new mCVs that blur the line between APs and IPs is providing constraints for which synchronization theory in the realm of magnetically channeled flows by accreting white dwarfs may be tested and further developed.

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