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Optical Photometry of Six Eclipsing Polars: DP Leo, J1312+1737, HS Cam, FL Cet, EP Dra, and CRTS 0350+3232.

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I present optical photometry obtained in order to address several long-standing problems in the field of magnetic cataclysmic variables (MCVs). Specifically, the important problems concerning, both long- and short-term evolution of the binary and the origin of the variable accretion rate in polars. Numerous high time-resolution light curves of eclipsing polars using the 2.1-m telescope of McDonald Observatory have been obtained in order to investigate potential period changes that may be due to one or more factors. Period changes on the time-scale of years to decades may originate due to changes in accretion rate, magnetic cycles of the donor, and long term secular evolution. By collecting many high-precision light curves, the effects due to binary evolution such as angular momentum loss by gravitational radiation and donor star winds may be studied. We present 1-5 second time resolution photometry of six polars and long-term (9 yr) photometric sampling by the Catalina Real-Time Transit Survey (CRTS) of the same binaries. Preliminary results in this regard are given, emphasizing a range of features seen in the light curves of the polars DP Leo, J1312+1737, HS Cam, FL Cet, EP Dra, and CRTS 0350+3232. Features such as pre-eclipse absorption dips, un-eclipsed accretion stream emission, and one vs. two spot accretion are observed from system to system and within single binaries as a function of accretion rate. The combination of high-speed photometry and long-term monitoring will aid in this effort.

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1. Introduction

Eclipse timing in polars, which are highly magnetic white dwarfs accreting from low-mass main sequence companions, is critical to theory in several ways. A single eclipse of the accretion region on the surface of the white dwarf can constrain the inclination and mass-ratio of the binary and the location of active accretion spot(s). Many eclipses obtained over years and decades may additionally constrain aspects of the orbital evolution of the binary. While mass is being transferred from the low-mass donor to the higher mass white dwarf, dynamics drive an increase in the orbital period and the stars would tend ro separate. However, angular momentum losses override and result in the reduction of stellar separation. Keep in mind that the donor remains in rotational synchronism with the binary, responding to changes on very short timescales. In particular, for polars, fundamental open questions include: Does the time rate-of-change of the orbital period, $\dot{P}$, suggest that period evolution occurs by emission of gravitational wave radiation (GWR) only, or do polar periods evolve as a result of both GWR and by angular momentum loss due to the donor's magnetized stellar wind (MSW)? The magnetized wind scenario is considered the dominant mechanism for driving angular momentum for long period CVs, both magnetic and non-magnetic types, because GWR is weak for long period binaries. However, the MSW angular momentum loss mechanism may be disrupted or even may not operate at all in shorter period polars [1].

So in brief, CVs evolve towards shorter periods determined by the mass transfer rate, GWR, and in some systems, MSW angular momentum loss. In addition, complicating effects like the Applegate mechanism [2] result in relatively periodic variations in the orbital period due to the putative magnetic cycle of the donor. Magnetic cycles may produce detectable O-C diagram peculiarities within 5 to 10 years. For additional details we refer the reader to the discussion by Robinson & Cordova [3] on DP Leo, a subject of the current paper, and references therein. Other complicating factors are introduced if circumbinary planets are present, notably a single giant planet has been proposed to explain timing variations in optical photometry of DP Leo [4]. The only way to disentangle all these possibilities and to learn something about evolutionary processes of Magnetic CVs is to obtain many eclipsing light curves over years and decades. This is the aim of the present work.

2. Optical Photometry

We obtained broad-band optical photometry at the McDonald Observatory 2.1-m Otto Struve telescope. A BVR filter was used with a ProEM, CCD camera. Continuous integrations ranged from 1 to 5 seconds depending on the brightness of the source. Images were flat fielded and dark subtracted using calibration frames in the usual way. Aperture photometry was performed using Pyraf and magnitudes were calculated relative to a comparison star in the field. Here we present example light curves of four binaries in Figure 1: DP Leo, J1312+1737, HS Cam, and FL Cet, each covering about 2 orbital cycles and of two binaries, EP Dra and CRTS 0350+3232 in Figure 2, each showing several luminosity states or equivalently several accretion rate states.

Long-term light curves from the ongoing Catalina Real-Time Transit Survey (CRTS) [5] were gathered from the online database and are shown in Figure 3 for all six of the polars shown in Figures 1 and 2. All data presented here used the Catalina Sky Survey 0.7-m Schmidt telescope

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near Tucson, Arizona. 30-second integrations using a V filter were taken seasonally from 2005 to 2014. The limiting magnitude for this telescope is V $\sim$ 20 mag.

3. Results

Figure 1 shows two consecutive orbital cycles of four eclipsing polars. From top, DP Leo, to bottom, FL Cet, these light curves show increasingly complex behavior. DP Leo displays the standard trapezoidal eclipse profile. J1312+1737 shows an extended ingress most likely due to the magnetically collimated stream not being completely eclipsed by the secondary until well after the spot eclipse begins. The HS Cam light curve is similar, but it also displays a small pre-eclipse dip. Such dips are likely due to the eclipse of the accretion spot on the white dwarf by the stream. The optical depth of the absorbing stream may be calculated from the depth in magnitude of the pre-eclipse dip feature. See our recent work [6] for an example of this calculation in the case of CRTS 0350+3232. In FL Cet, there is a deep pre-eclipse dip, stream emission seen during eclipse, as well as a two-step eclipse involving two spots on the same hemisphere of the white dwarf [7].

Polars display significant changes in their light curves as a function of the mass transfer rate from the companion. In Figure 2, McDonald 2.1-m photometry of EP Dra and CRTS 0350+3232 are shown over a range of accretion states. We find that at the highest mass transfer rates, pre-eclipse absorption dips are seen in both binaries. In addition, un-eclipsed stream emission is seen at high and intermediate accretion rates. These are seen as the extended ingress into totality for these light curves, and for those in Figure 1. During the lowest states, only the eclipse of the white dwarf is seen in Figure 2.

The CRTS (9-year) light curves of the six polars from Figures 1 and 2 are shown Figure 3. These polars display a wide variety of long-term photometric behavior. FL Cet, as an extreme example, likely has three luminosity levels corresponding to 2-pole, 1-pole, and no-accretion states, see also ODonoghue et al. [7] for a detailed study of FL Cet. Polars may remain either in high or low accretion states for years, or they may switch back and forth rapidly. Transitions between high and low states in polars appear to be system dependent [8].

4. Summary

I present motivation and very preliminary results for the investigation of light curves of polars and their changes. Example light curves of six eclipsing polars are presented using both high time-resolution photometry at a 2.1-m telescope of the McDonald Observatory as well as long term monitoring by the CRTS program. These observations will eventually allow us to distinguish between the effects of different models for changes in orbital periods from O-C diagram analysis. These studies will have important consequences for determining the period evolution of polars in terms of finding out if their period evolution is determined by emission of gravitational wave radiation (GWR) only, or possibly as a result of both GWR and angular momentum loss due to a magnetized stellar wind (MSW) from the companion. Complicating magnetic cycle effects must also be considered. Recent examples of our work have been published for the non-eclipsing asynchronous polar V1500 Cyg [9] and the newly discovered polar CRTS 0350+3232 [6].

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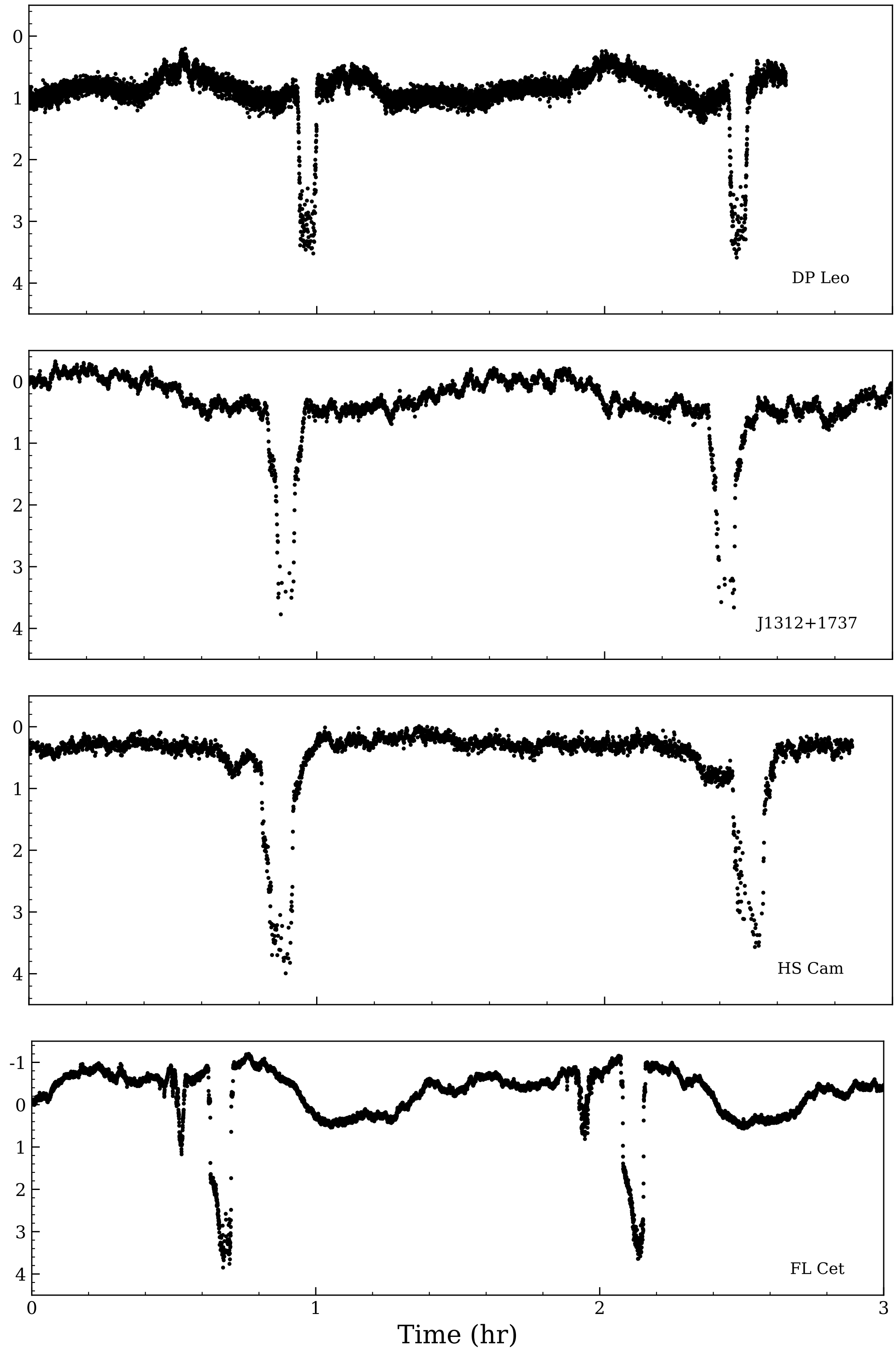

Figure 1: Light curves of 4 eclipsing polars from the McDonald 2.1-m. The vertical axis gives magnitude relative to a comparison star. Pre-eclipse dips, un-eclipsed stream emission, and both one- and two-spot eclipses, are seen. Zero points are as follows: J1312 2458633.6702664, HS Cam 2458162.6080385, DP Leo 2458578.6722941, and FL Cet 2455828.8125000

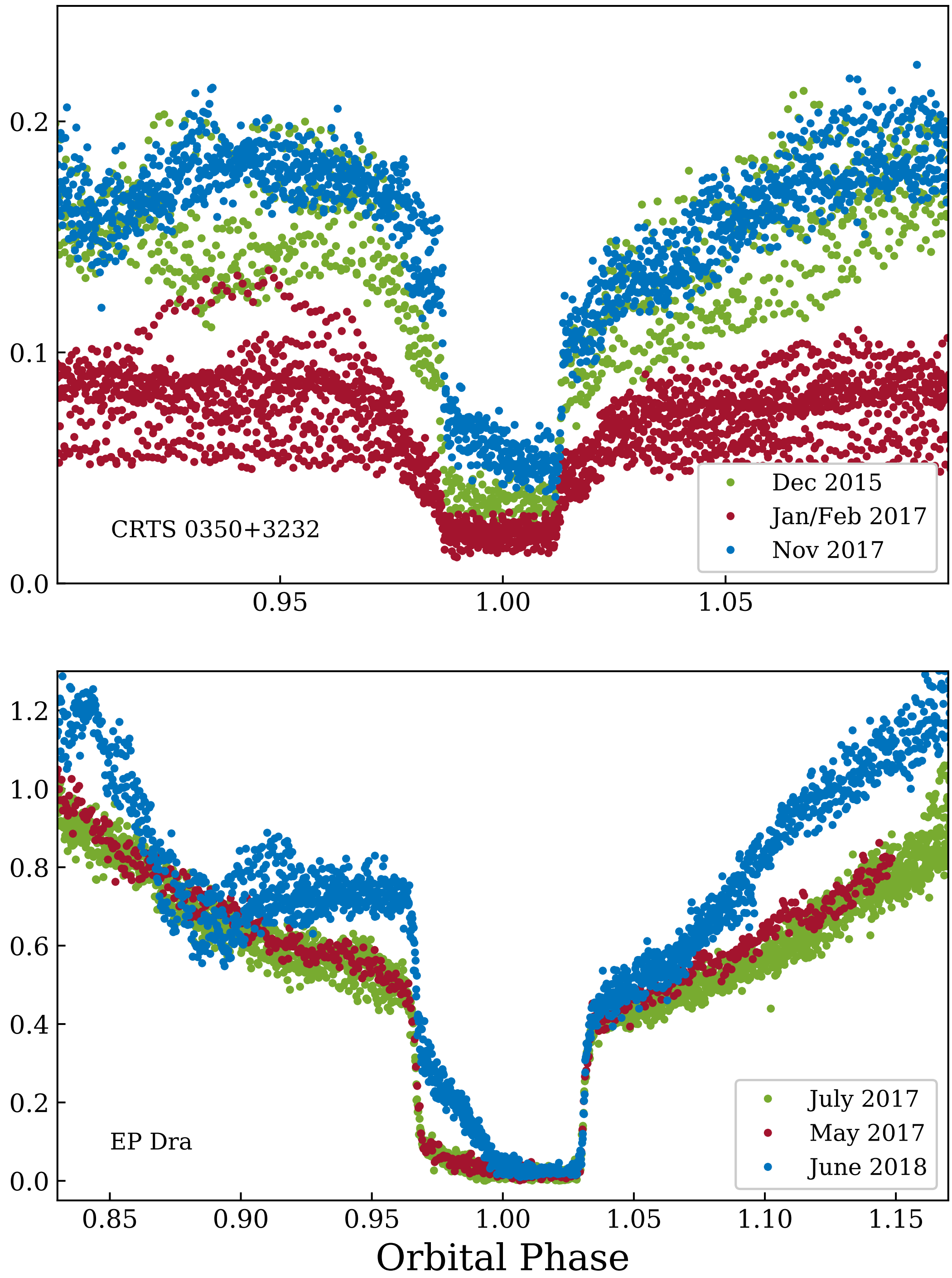

Figure 2: Top: Light curves of CRTS 0350+3232 at different accretion rates: (Credit: Mason et al. 2019). **Bottom:** Light curves of EP Dra at different accretion rates. The vertical axis gives magnitude relative to a nearby comparison star. In both polars, high accretion rates (blue data points) are associated with the appearance of both pre-eclipse dips and stream emission during eclipse.

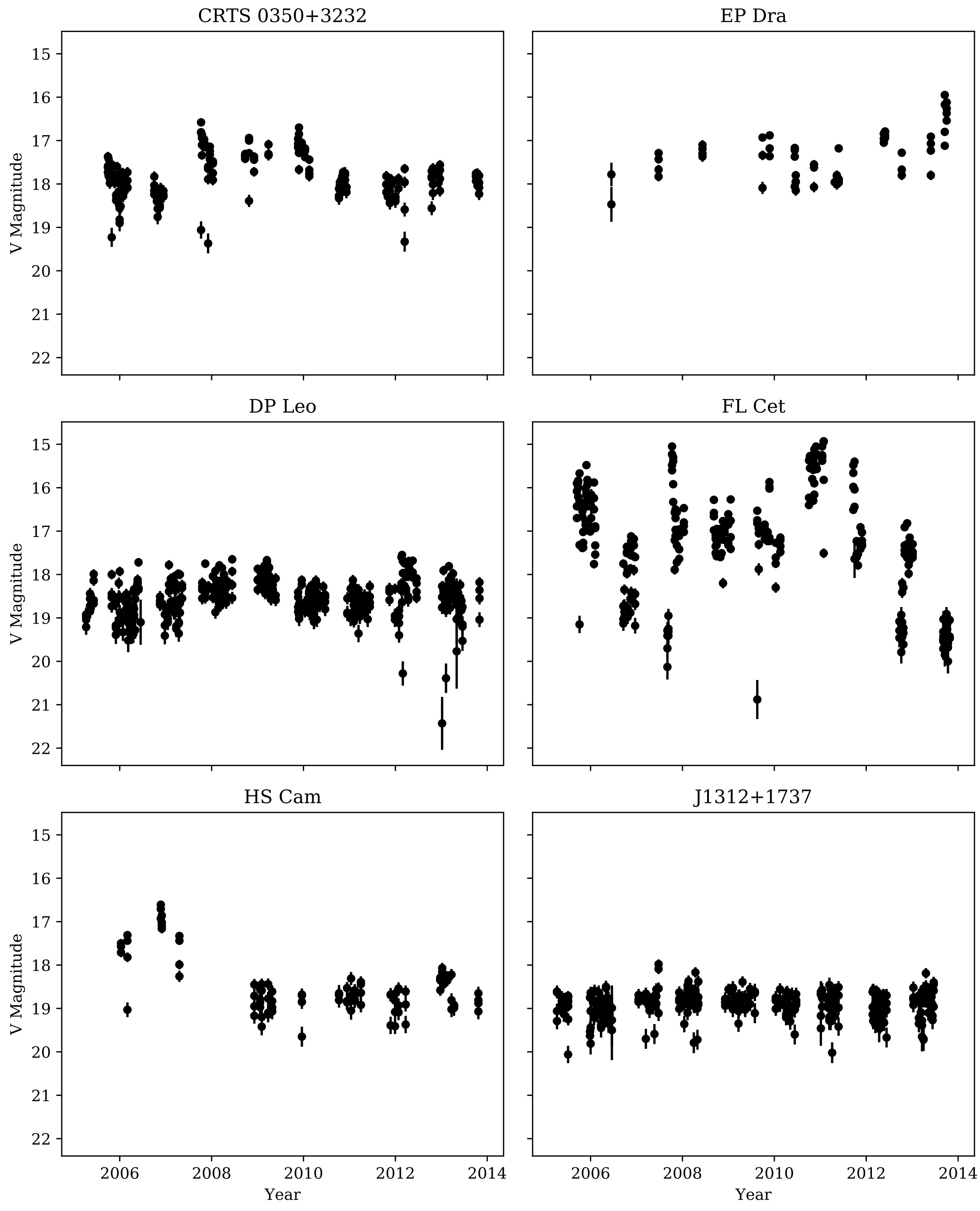

Figure 3: CRTS light curves of eclipsing polars. In most cases, high and low accretion states are seen to change on the timescale of months to years. FL Cet may be more highly variable because it has a 2-pole high state, a 1-pole medium state, and a non-accreting low state.