PROCEEDINGS OF SCIENCE

Low States of Polars: Catalina (CRTS) Light Curves

Paul A. Mason[*†]
New Mexico State University, Las Cruces NM, USA
E-mail: pmason@nmsu.edu

Joshua B. Santana
New Mexico State University, Las Cruces NM, USA

We discuss an important outstanding problem in accretion astrophysics for the highest field magnetic cataclysmic variables (CVs) known as polars. Namely, what is the the origin of low accretion states in these disk-less CVs? A number of suggestions have been made to account for the often observed 3 mag drop in optical light. However, the long-term variability of polars is well observed in just a handful of cases. We broaden the study of long-term optical behavior by analyzing photometry from the Catalina Real-time Transit Survey (CRTS) from about 9 years of data. CRTS cadence depends on source location, so some data-sets are sparser than others. Here we examine a representative subset of well observed sources.

High to low brightness transitions corresponding to complete shutting off of accretion are observed only in a minority of cases. More commonly, polars drop to low brightness levels very briefly or not at all. However, there are also several low accretion rate polars (LARPS) constantly in low states. Some polars show dipping behavior, dropping to minimal levels only to quickly rise to intermediate or higher levels. Other polars very rarely drop to low states. A selection of 44 polars, with well sampled light CRTS light curves are shown to demonstrate representative behavior. Those with repeatable low states are AMHer, AR UMa, EF Eri, IWEri, CSS J1944-4202, ST LMi, MR Ser, and EV UMa. Eclipsing polars shown are DP Leo, J0227+1306, V1309 Ori, HS Cam, MN Hya, HU Aqr, EP Dra, HY Eri. LARPS includeWX LMi, MQ Dra, J1250+1549, SDSS J1514+0744, IL Leo, SDSS J0837+3850, HS0922+1333, and V379 Vir. Polars dipping to, but not remaining, in low states include EG Lyn, EK UMa, BM CrB, EQ Cet, V834 Cen, and CSS J0810+0024. Complex multi-state behavior is seen in FL Cet (also eclipsing), CE Gru, GG Leo, FR Lyn, SDSS J1530+2206, and EQ Cet. Other polars mostly remaining in high states are PW Aqr (also eclipsing), CSS J0810+0024, AN UMa, CP Tuc, EU Lyn, V1189 Her, AI Tri, and CD Ind.

The Golden Age of Cataclysmic Variables and Related Objects - III, Golden2015
7-12 September 2015
Palermo, Italy

[*]Speaker.
[†]Thanks to the Sloan Foundation: SDSS/FAST program

PoS(Golden2015)016

1. Introduction

Polars are a sub-class of cataclysmic variable (CV) binaries having accreting white dwarf (WD) primaries. They are at the upper-end (B > 5 MG) of the WD magnetic field distribution in binaries. While non-magnetic CVs, comprising 80-90% of all CVs, have an accretion disk, polars - characterized by polarized optical light - do not form an accretion disk. Rather, transferred plasma flows down to the WD surface following magnetic field lines [1]. Intermediate polars, or IPs, have an accretion disk that is disrupted at its inner edge by the WD magnetic field, forming a gap between the WD and the disk. Plasma flows across this gap by following magnetic field lines from the disk down to the WD [2].

AM Herculis is the original polar, as it was identified by its unprecedented polarized optical radiation [3]. Several others, AN UMa, VV Pup, EF Eri quickly followed. By 1990, just before the launch of Rosat, the number had grown to 18 with most discoveries made from optical follow-up of newly detected X-ray sources. The Rosat All Sky Survey (RASS) added 29 polars [4]. The Sloan Digital Sky Survey (SDSS) added even more polars [5]. Other polars have been more recently discovered using XMM, Swift, and CRTS. The current census is 125 confirmed polars.

The companion or donor is a lower mass main sequence star or in rare cases a brown dwarf, orbiting close enough to the WD to fill its Roche-lobe. The long-term average mass transfer rate is driven by the rate of change of angular momentum between the components of the binary. Since mass transfers from the lower mass companion to the higher mass WD, the exchange of angular momentum results in a decrease of the semi-major axis of the binary, reducing the orbital period and the size of the donor Roche-lobe. However, CVs reach a period minimum once the companion star reaches a low enough mass to become degenerate. Binaries that have evolved past this point are called period-bouncers as they then evolve to longer periods. These very low-mass degenerate stars expand as they lose mass. As a result they maintain contact with the Roche-lobe to continue mass loss, even as the period increases.

The magnetic field of the WD in polars is not only responsible for the lack of an accretion disk, but also provides a strong magnetic interaction with the companion star. The resulting torque acts to slow the WD spin while at the same time accretion may supply a spin-up torque on the binary. In all but a few polars this magnetic torque manages to synchronize the rotation of the WD with the binary orbit. The four or possibly five known exceptions are called the asynchronous polars (APs).

2. Low States of Polars

One of the longer lasting unsolved problems in polar astrophysics concerns the occurrence of variations in mass transfer from the Roche-lobe filling companion to the WD. Since no accretion disk is formed, the start of mass transfer or its secession are immediately followed by accretion onto or the halting of accretion onto the WD, respectively. There is no accretion disk to buffer the flow. The accretion flow may be detected by optical and UV emission lines; the Balmer sequence, He I, He II, N V for example, and in the X-ray flux from the stream impact point on the WD.

The majority of optical and IR emission during high accretion states originates in a cyclotron emission region surrounding the denser X-ray emitting post-shock region. As the flow is collimated by the magnetic field just above the surface of the white dwarf electrons spiral down the magnetic field lines, cooling the plasma flow by cyclotron emission. This radiation is detected as broad overlapping features in the optical and IR spectrum. Known as cyclotron humps, these features allow for the measurement of magnetic fields within accretion regions. In addition to hard X-rays resulting from a post-shock region just above the accreting pole, softer X-rays and broad-band UV is emitted from a hot photospheric polar cap. During low accretion states, Zeeman spectroscopy may be used to measure magnetic field strengths effectively averaging the atomic splitting of spectral lines over the WD photosphere.

Quite a few low accretion rate polars (LARPs) are known including several from the the SDSS [5]. These binaries have not been observed to go into high states and were thus not detected by X-ray surveys. They are likely the result of a temporary detached stage or a yet to be semi-detached stage in the coupled stellar plus binary evolution. Their magnetic field strengths are likely similar to other polars and low level accretion may still occur due to the wind from the companion. However, emission of gravitational radiation inevitably will reduce the binary separation and hence the size of the donor Roche-lobe eventually resulting in mass transfer.

AM Herculis has very long history of observation and while it usually alternates between high and low states it has also remained at intermediate levels [6]. Irradiation of the companion star by the accretion radiation has been proposed as a mechanism for restricting the accretion flow from the L1 point [7]. It has also been suggested that low states in the prototype polar AM Her are the direct result of star-spots at the inner Lagrangian point, [8] [9]. Wu and Kiss [10] argue that the strength of the WD magnetic field plays a critical role. An argument in support of the latter is the fact that low states are only rarely observed in IPs [11], which have weaker magnetic fields. The star-spot mechanism is attributed in a few other polars as well [12].

Because of tidal forces of the WD on the ellipsoidal companion, the rotation rate of the donor is synchronized with the binary period, which ranges from 78 min to 8 hrs. These rotation rates are much faster than those of single main sequence stars, which only rotate fast when they are young. So, the fast rotating secondaries of polars and indeed of all CVs with short periods and convective donors are expected to have strong magnetic fields. This lends support for the star-spot model. However, observational constraints on low state models are still weak as they require long-term light curves for many binaries. Knowledge of the long-term light curve variability and the proper identification of accretion states aids this effort.

3. Catalina Real-time Transit Survey Light Curves

In this paper we examine V-band light curves from the Catalina Real-time Transit Survey (CRTS), see e.g. Drake [13] for observing details. The focus of this short report is on the identification of brightness states, especially low states, in multi-year light curves of polars. These data allow one to identify states that can be reliably attributed to cessation of Roche-lobe filling accretion flow.

Often, accretion rates drop without being completely shut off. It is important to distinguish low levels of accretion with periods of no Roche-lobe overflow. If Roche-lobe overflow stops then there may be continued wind accretion. However, the dominant light from the binary will be the WD photosphere at high energies (UV and blue) and the low mass companion photosphere at lower energies (red and IR). Spectral fits to determine temperatures and to look for indications of residual accretion may be obtained during low states. At longer wavelengths ellipsoidal variations may be observed allowing constraints to be placed on inclination and stellar masses. For any of these studies it is critical to determine if the observed low state actually represents no Roche-lobe overflow, with possible wind accretion, or to simply, a lower-level of Roche-lobe overflow.

Specifically our approach is to see if the V-band CRTS light curve repeatedly reaches the same minimum magnitude; then it likely corresponds to accretion shut-off or wind accretion only. The CRTS light curves of many polars have sufficient cadence over ~9 years to reveal true off accretion states seen in some light curves, as opposed to the variable low levels of accretion activity interspersed between high states seen in other polars. In other words, some polars accrete at low levels without stopping accretion except possibly for very short intervals. Relatively few polars remain in high accretion states on the decade long time-scale examined here.

The duty cycle, defined here as the relative amount of time spent above median V-magnitude to the total time has important implications for CV evolution models and estimates of the space density of polars as well as the related search for the so-called missing polars. Namely those that have so far escaped detection by surveys because they were in low states at the time of the survey observations. If some polars have a low duty cycle and thus remain unknown, then space density estimates will be under estimated. The low luminosity LARPs represent some of this population.

There are about 125 known polars, a few more if pre-polars and candidate polars are included. Most of these have been observed as part of the Catalina Real-Time Transient Survey. From these we select 44 of the better sampled light curves in order to examine representative behavior. Cumulative histograms of magnitudes are calculated and displayed along with the light curves in Figures 1-6.

In Figure 1, polars with distinctive repeatable low states are shown. These are AM Her, AR UMa, EF Eri, IW Eri, CSS J1944-4202, ST LMi, MR Ser, and EV UMa. Eclipsing polar light curves are shown in Figure 2, namely DP Leo, J0227+1306, V1309 Ori, HS Cam, MN Hya, HU Aqr, EP Dra, HY Eri. The following LARPS are shown in Figure 3, WX LMi, MQ Dra, J1250+1549, SDSS J1514+0744, IL Leo, SDSS J0837+3850, HS0922+1333, and V379 Vir. Figure 4 shows polars dipping to, but not remaining in low states; EG Lyn, EK UMa, BM CrB, EQ Cet, V834 Cen and CSS J0810+0024. Several polars showing quite complex multi-state behavior are shown in Figure 5; FL Cet (also eclipsing), CE Gru, GG Leo, FR Lyn, SDSS J1530+2206, and EQ Cet. Finally, in Figure 6 additional polars are shown, mostly remaining in high states; PW Aqr (also eclipsing), CSS J0810+0024, AN UMa, CP Tuc, EU Lyn, V1189 Her, AI Tri, and CD Ind.

Many of the other polars observed by CRTS show similar behavior to the selection shown here, some are poorly sampled. Models for the origin of polar low states must take into account the variation seen in these and similar light curves. Continued long-term monitoring of polars will aid in the characterization of members of this important class of binaries. Many more discoveries are expected in the coming years and the improved sample size will allow improved constraints on accretion state transition mechanisms.

We thank Paula Szkody and Paul Barrett for discussions, the Sloan Foundation for funding support of the SDSS/FAST program, the SDSS Collaboration, and especially Kelly Holley-Bockelmann for her support.

References

[1] G. Chanmugam and R. L. Wagner, *The remarkable system AM Herculis/3U 1809 + 50*, *ApJL*, 1977, **213**, L13.

[2] P. Ghosh, C. J. Pethick, and F. K. Lamb, *Accretion by rotating magnetic neutron stars. I - Flow of matter inside the magnetosphere and its implications for spin-up and spin-down of the star*, *ApJ*, 1977, **217**, 578.

[3] S. Tapia, *Discovery of a magnetic compact star in the AM Herculis/3U 1809+50 system*, *ApJ*, 1977, **212**, 125L.

[4] K. Beuermann and V. Burwitz, *AM Herculis Binaries in the ROSAT ERA* in Magnetic Cataclysmic Variables ,ed. D. A. H. Buckley and B. Warner, *ASP Conf. Ser.*, 1995, **85**, 99.

[5] P. Szkody et al., *Cataclysmic Variables from the Sloan Digital Sky Survey. VIII. The Final Year (2007-2008)*, *AJ*, 2011, **142**, 181.

[6] S. Kafka, and D. W. Hoard, *Discovery of an Unusual High State in the Long-Term Light Curve of AM Herculis*. *PASP*, 2009, **121**, 1352.

[7] A. R. King, *Irradiation of the companion star in cataclysmic variables*. *MNRAS*, 1989, **241**, 365.

[8] F. V Hessman, B. T. Gänsicke, and J. A. Mattei, *The history and source of mass-transfer variations in AM Herculis*, *A & A*, 2000, **361**, 952.

[9] V. Łimon, *Short and long time-scale variability in magnetic cataclysmic variables: long-term monitoring of polars*, *MNRAS*, 2012, **422**, 1601.

[10] K. Wu and L. L. Kiss, *High and low states of the system AM Herculis*. *A & A*, 2008, **481**, 433.

[11] P. Garnavich and P. Szkody, *Observed low states in DQ Herculis systems*, *PASP*, 1988, **100**, 1522.

[12] B. Kalomeni, *Short and long time-scale variability in magnetic cataclysmic variables: long-term monitoring of polars*. *MNRAS*, 2012, **422**, 1601.

[13] Drake, A. J. et al., *Cataclysmic variables from the Catalina Real-time Transient Survey*. *MNRAS*, 2014, **441**, 1186.

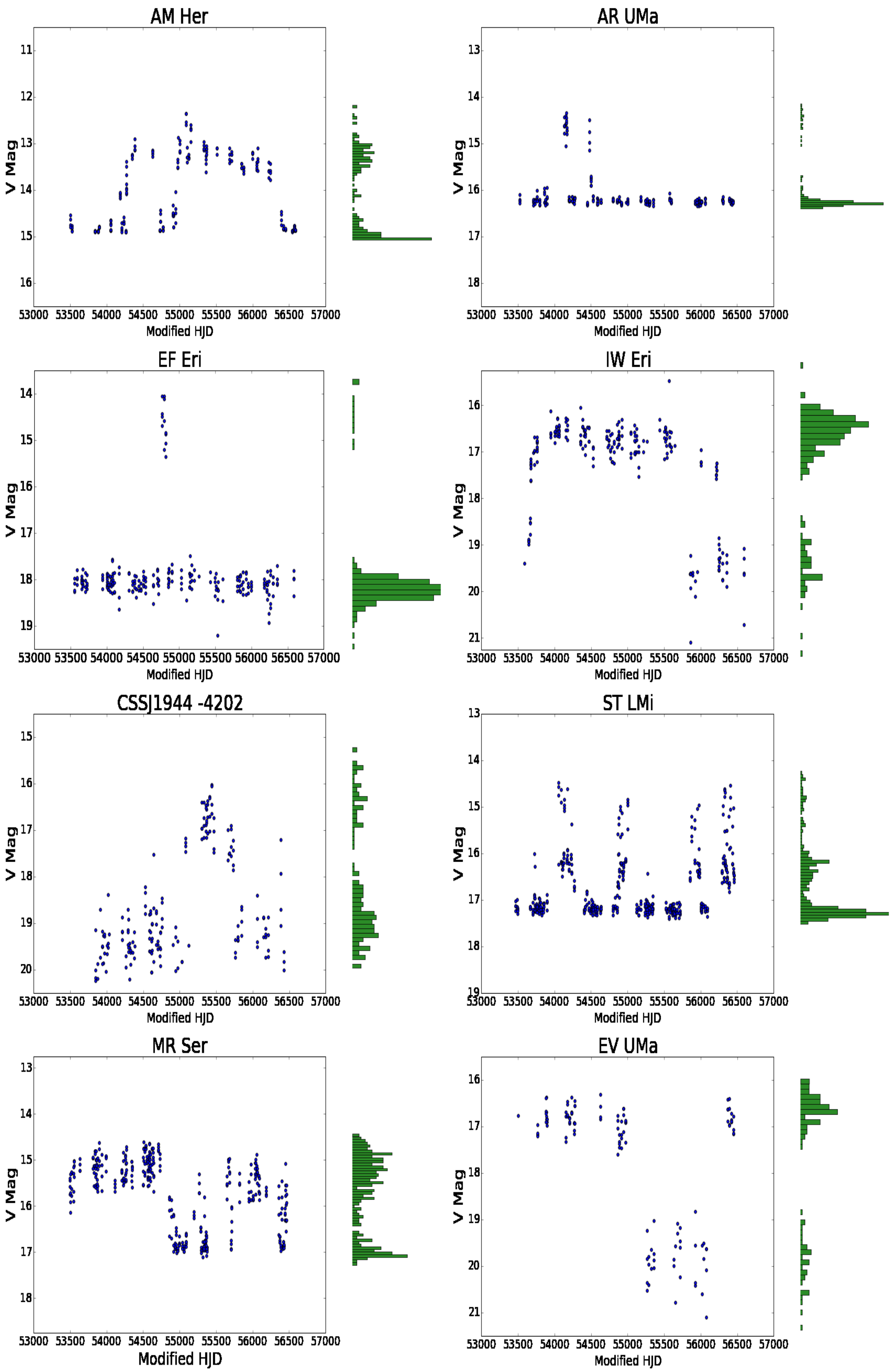

Figure 1: Polars with repeating low states: Catalina Real-Time Transit Survey (CRTS) light curves (left) and magnitude histograms (right).

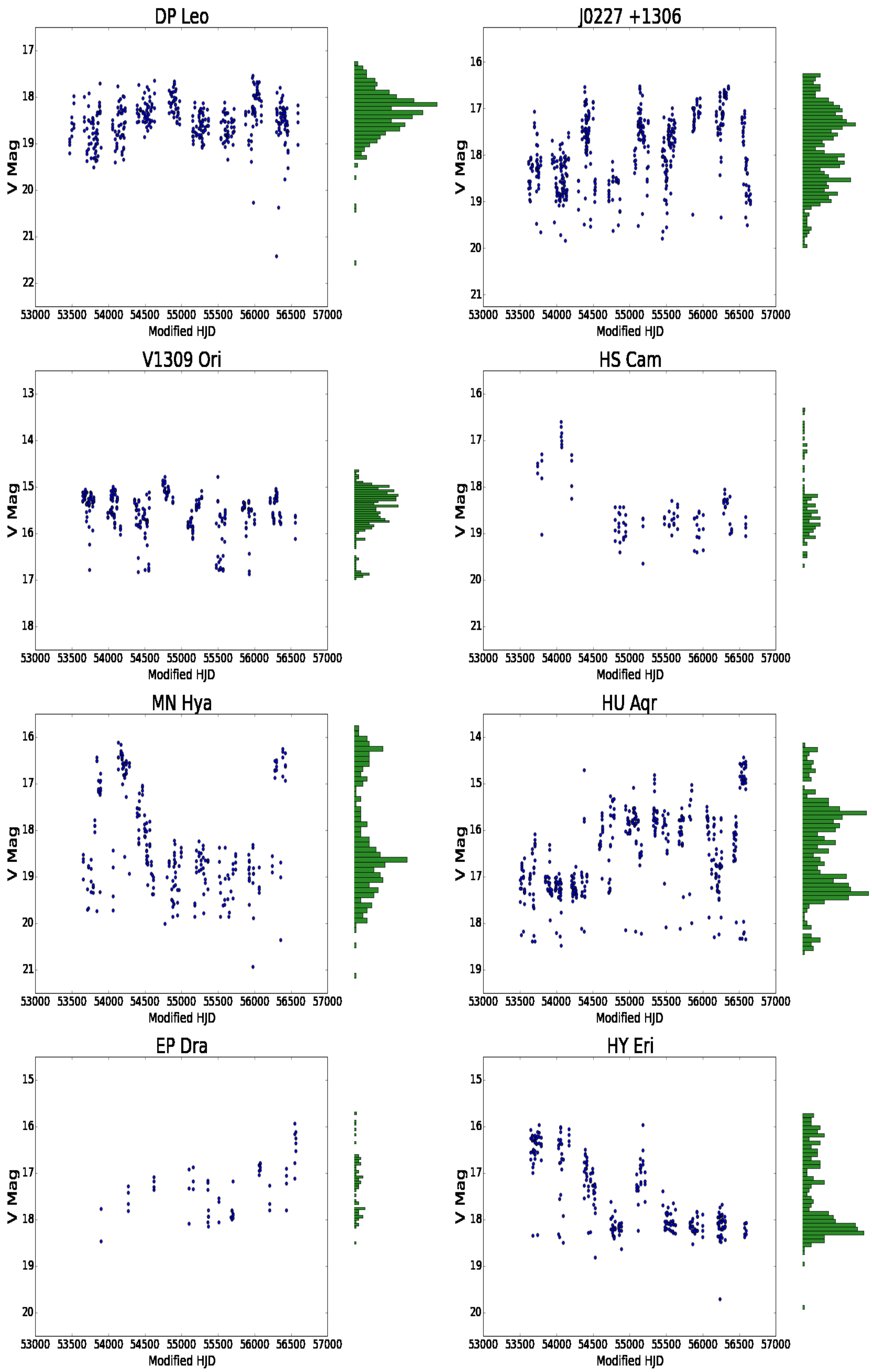

Figure 2: Eclipsing Polars: Catalina Real-Time Transit Survey (CRTS) light curves (left) and magnitude histograms (right).

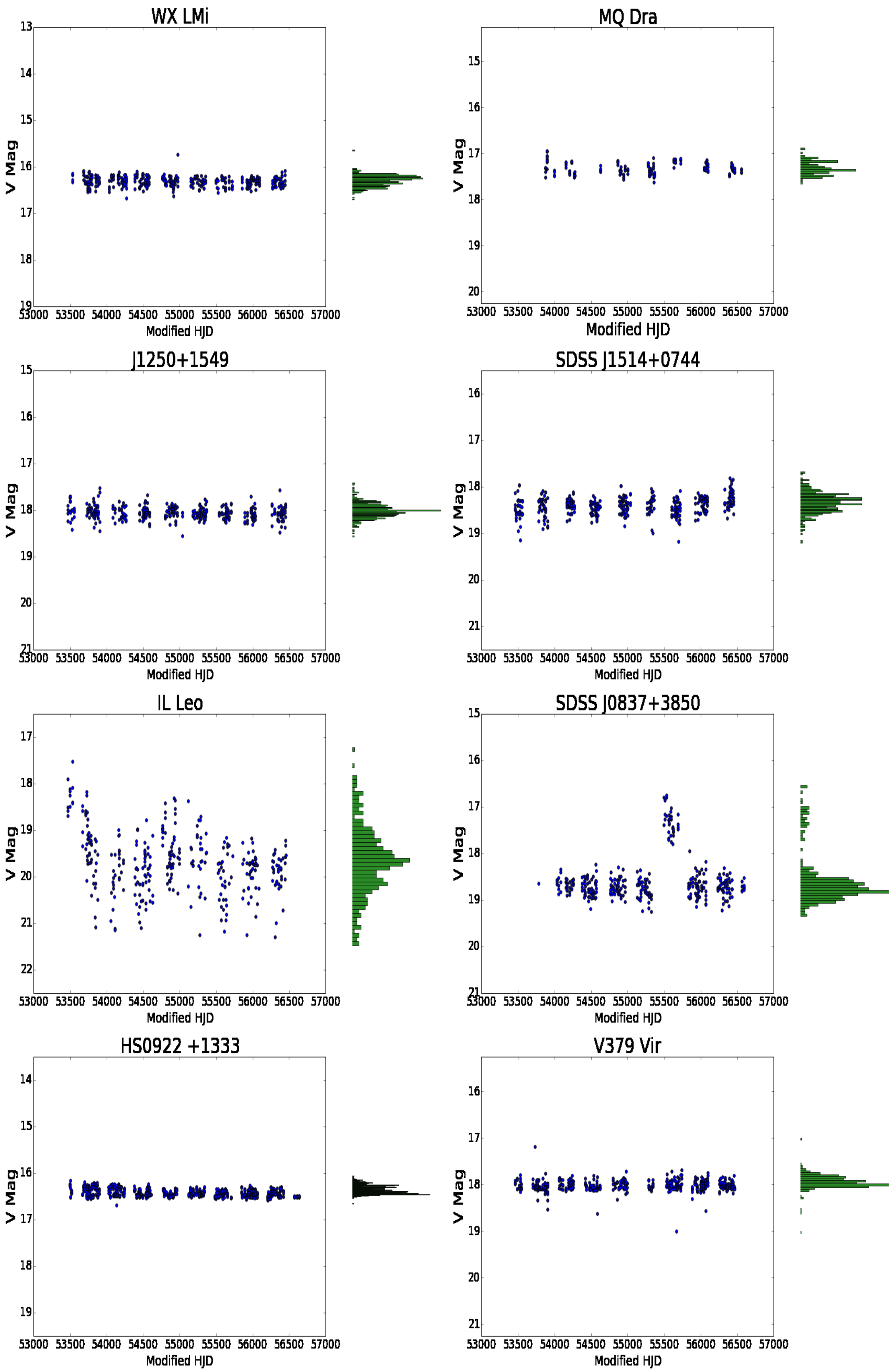

Figure 3: Low Accretion Rate Polars (LARPs): Catalina Real-Time Transit Survey (CRTS) light curves (left) and magnitude histograms (right).

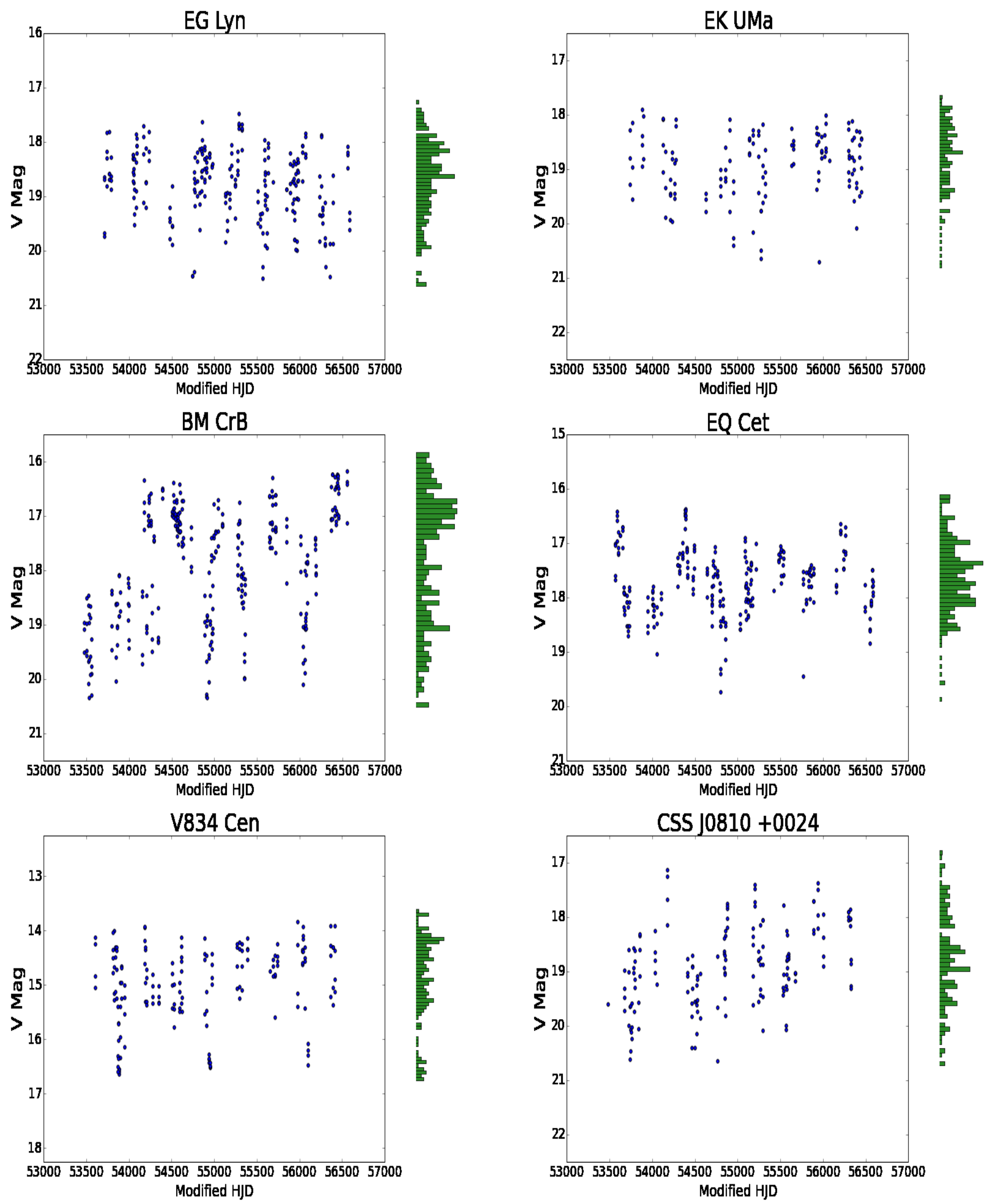

Figure 4: Dipping Polars, not remaining in low state: Catalina Real-Time Transit Survey (CRTS) light curves (left) and magnitude histograms (right).

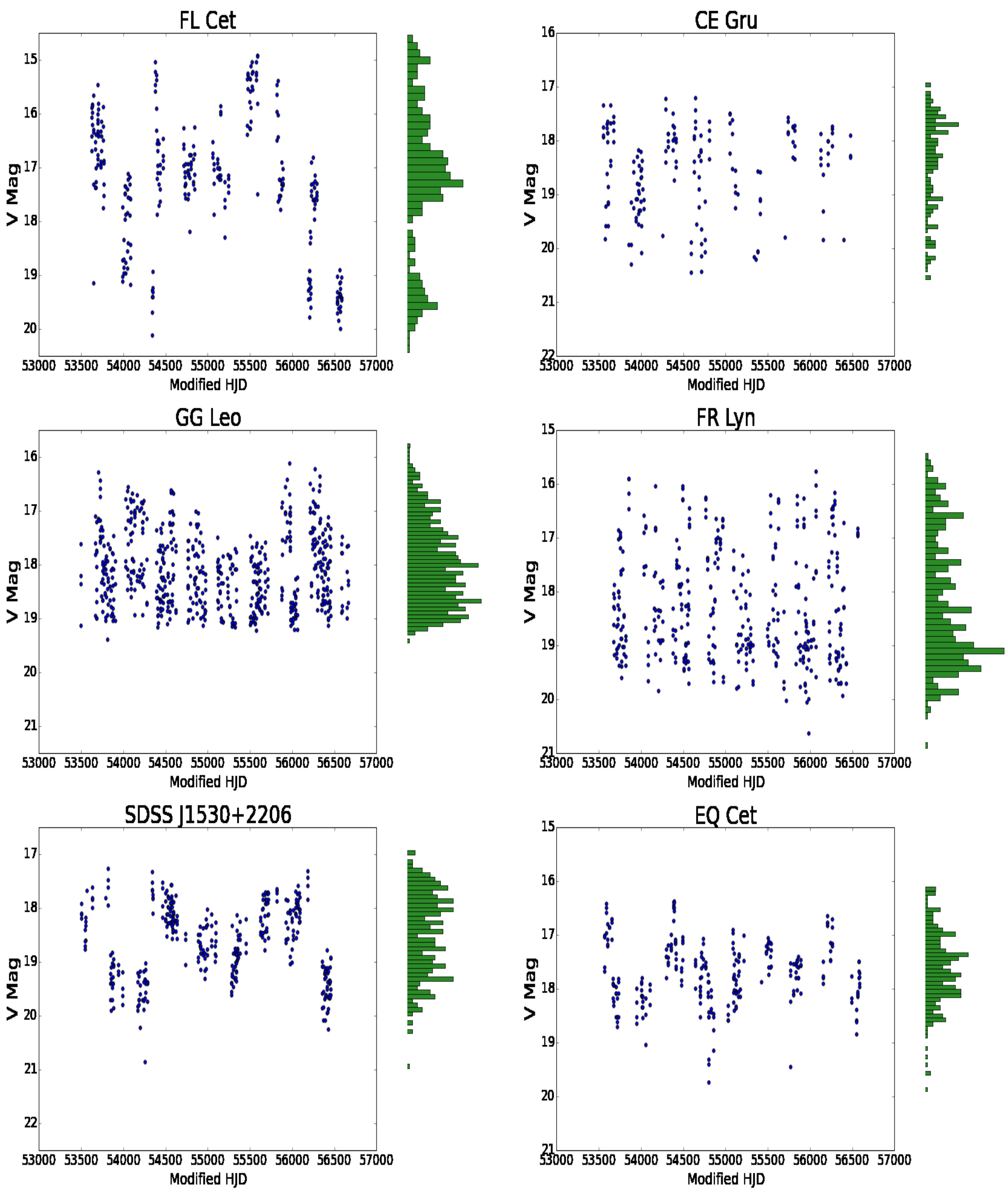

Figure 5: Polars with complex, multi-state light curves: Catalina Real-Time Transit Survey (CRTS) light curves (left) and magnitude histograms (right).

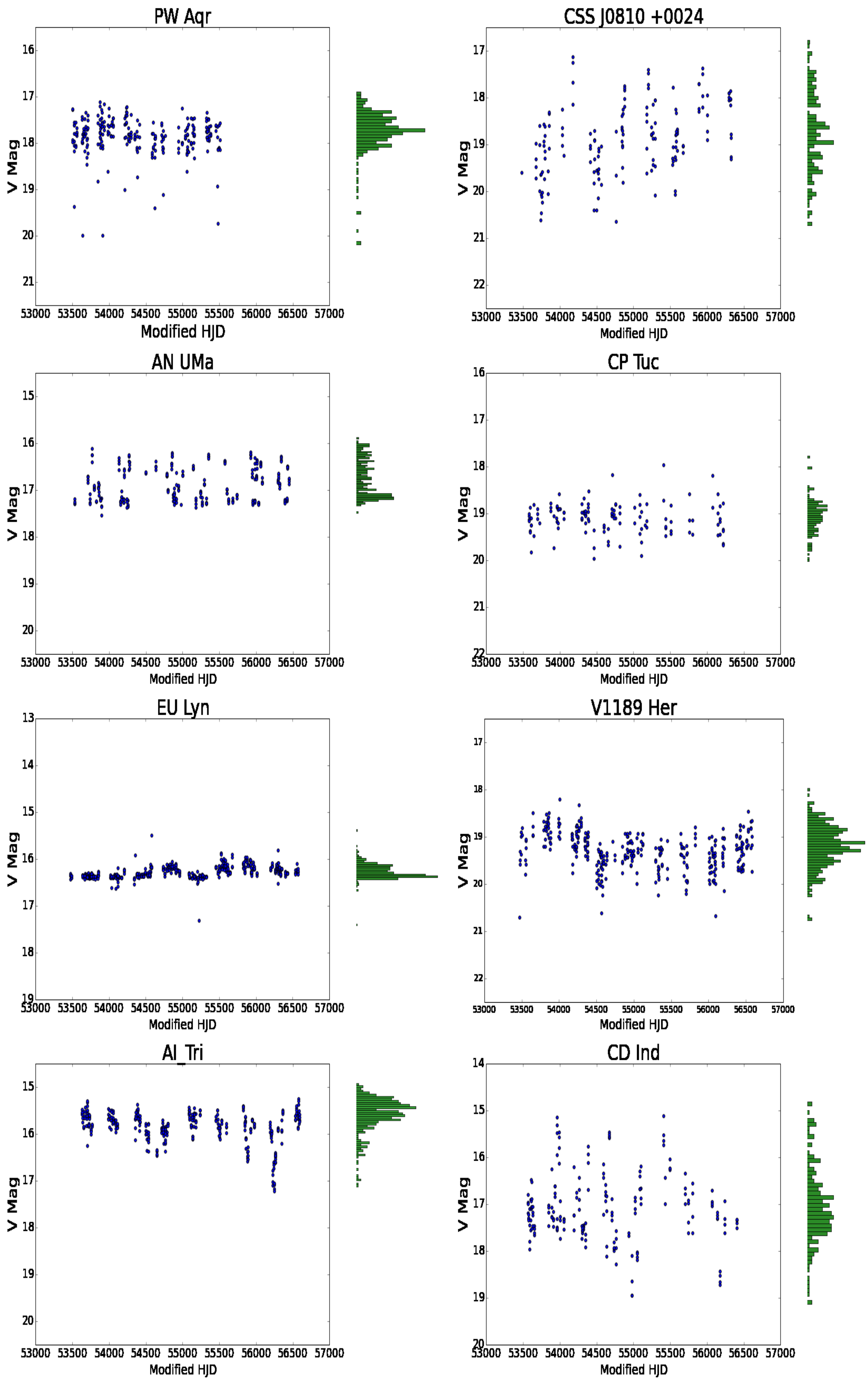

Figure 6: Other selected polars, mostly remaining in high accretion states: Catalina Real-Time Transit Survey (CRTS) light curves (left) and magnitude histograms (right).