

Cataclysmic Variables

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Abstract This paper presents a concise summary of our current knowledge of cataclysmic variables, including definitions of types and the observational basis for classification, what we have been able to piece together about evolution, and discoveries from recent surveys. We provide a list of unanswered problems and questions and references for seeking additional information. The importance of AAVSO observations in the past and for the future is highlighted.

1. What we know about CVs

The basic definition of a cataclysmic variable (CV) is a mass-transferring close binary containing a white dwarf primary and a secondary that is usually a late-type main sequence star (although a few cases with giant or brown-dwarf secondaries exist). A good starting point for understanding the general properties of CVs is the book by Warner (1995) or by Hellier (2001). Various catalogs of CVs have been compiled over the years by Downes *et al.* (1997; on-line version frozen in 2006 at <http://archive.stsci.edu/prepds/cvcat/>), Ritter and Kolb (2003; current on-line version at <http://www.MPA-Garching.MPG.DE/RKcat/>), Drake *et al.* (2009; online at <http://nesssi.cacr.caltech.edu/catalina/AllCV.html>) and Szkody *et al.* (2011; online catalog at <http://www.astro.washington.edu/users/szkody/cvs>).

CVs are thought to form from wider binaries composed of two main sequence stars when the more massive star becomes a giant and forms a common envelope around the system. As the two stars orbit within this common envelope, their separation decreases and the orbital period shrinks from days to hours. Once the common envelope dissipates, the resulting white dwarf-main sequence binary system evolves without mass transfer, continually losing momentum through a braking wind from the secondary and decreasing its orbital period until the secondary fills its Roche lobe and begins to transfer mass to the white dwarf. At this point, it becomes a bona-fide CV. As the period continues to shrink to 3 hours, the secondary star structure changes, becoming completely convective, and at a period near 2 hours, gravity waves become the source of

momentum loss (resulting in low mass transfer rates) until a period minimum near 80 minutes is reached. After this point, the structure of the secondary again changes (becoming degenerate) and the orbital period increases.

A cataclysmic variable is usually identified by its variability on timescales of minutes (from flickering) to hours (from orbital variations) to weeks-years (from mass accretion variations), by its peculiar spectrum showing broad, usually doubled, Balmer emission lines, or by the detection of X-ray emission, which is generated by the material that accretes onto the white dwarf. The observational appearance of a CV depends primarily on two parameters: the amount of mass transfer, and the magnetic field strength of the white dwarf.

In a non-magnetic CV, where the white dwarf has no detectable field (typically much less than 1MG), the mass flow from the companion star builds up an accretion disk around the white dwarf. In these accretion disks, the material slowly spirals inwards towards the white dwarf. The rate at which the mass migrates through the disk depends on the viscosity of the material, as it is this “stickiness” that allows the exchange of angular momentum. There are two regimes in which accretion disks can be found, one of low viscosity, where the mass flow through the disk is slow, and one of high viscosity, where the mass flow is correspondingly much faster. In which of these states a CV is found depends on the rate at which the companion star supplies fresh material to the outer edge of the disk. For high mass transfer rates, the disk is in a stable state of high viscosity, hot, and the dominant source of light. These systems typically have orbital periods longer than 3 hours and are called nova-likes. They have no large-amplitude outbursts, and their spectra are often lacking the emission lines that are typical of most CVs, that is, they are rather inconspicuous. Thus, some of the brightest known CVs were found only very recently, and rather serendipitously, such as LSIV-08^o3 with $V=11.5$ (Stark *et al.* 2008).

For low mass transfer systems, the material in the accretion disk has a low viscosity and is cool. The rate at which material flows through the disk is actually lower than that provided by the companion star. Thus, the disk gradually grows in mass and heats up, until its temperature becomes sufficiently high to switch into the hot, high-viscosity state, where the accumulated mass is rapidly flushed onto the white dwarf. Systems that undergo these quasi-regular outbursts are called dwarf novae, and are the most common sub-class of CVs. The underlying physical mechanism of the accretion disk instability is important in a wide range of other astronomical objects; for example, it is thought that the protostellar accretion disks in T Tauri stars and the disks around supermassive black holes in the centers of galaxies also undergo outburst cycles.

Because of their short timescales, CVs are the best “laboratory” to study accretion disk physics. A particularly interesting sub-class among the non-magnetic CVs is the Z Cam type of system: here, the accretion rate is close to the borderline between hot, stable, and cool, unstable disks, and these systems can switch back and forth between being a dwarf nova and a novalike.

Mike Simonsen (2011) has initiated a dedicated project to obtain high-quality light curves for a large number of Z Cam stars. For orbital periods between 3 and 4 hours, a peculiar class of CVs exist called SW Sex stars (Thorstensen *et al.* 1991). These systems show single Balmer emission lines as well as a prominent HeII 4686 emission line, show transient absorption at some phases, and are often discovered as eclipsing systems. A list of SW Sex objects is provided by Hoard *et al.* (2003; an online updated list is at <http://www.dwhoard.com/home/biglist>). A few of these SW Sex stars show low circular polarization, indicating a relatively high magnetic field for the white dwarf (for example, Rodriguez-Gil *et al.* 2001). Some novalikes, including the SW Sex stars, occasionally fade by several magnitudes, for weeks to years. During these low states, the mass transfer from the secondary star is interrupted, and the accretion disk becomes very faint, or vanishes altogether. Consequently, the white dwarf and the secondary star can be observed directly. It appears that the white dwarfs in these systems are extremely hot, which suggests that the high accretion rates observed during the high states probably prevail for thousands of years.

A completely different picture is found among the magnetic CVs. If the white dwarf has a very high magnetic field (> 10 MG), the mass transfer stream impacts directly onto the white dwarf magnetic poles without forming a disk (King and Lasota 1993). In these systems (called Polars), the field locks the secondary and the white dwarf spin to the orbit so all variations are on the orbital timescale. The high field is identified from the presence of strong circular polarization or from Zeeman splitting. At very low accretion rates, broad cyclotron humps are prominent in the spectrum. Polars, just like the novalikes mentioned above, can cycle aperiodically between low and high states. This suggests that variations in the mass transfer rate from the companion star are inherent to all CVs, but that in dwarf novae, these variations are smoothed out by the accretion disk. For white dwarf fields of about 1–10 MG, an outer accretion disk forms but the inner disk is disrupted by the field so the material rains onto the white dwarf in broad accretion curtains. In these Intermediate Polars (IPs), the white dwarf spin is usually evident as a strong pulse visible in optical or X-ray at about one-tenth of the orbital period, even though the last years have seen the discovery of IPs with both much smaller and larger spin-to-orbital period ratios.

As CVs accrete from their companion stars, a layer of hydrogen-rich material builds up on the white dwarf, which will eventually ignite in a violent thermonuclear reaction, called a classical nova. All CVs should undergo many classical nova eruptions, with typical recurrence times of thousands of years. However, for high mass white dwarfs, this recurrence time can be as short as a few decades. A spectacular example is T Pyx, which showed regular nova eruptions every ~ 20 years until 1966, but then went unexpectedly quiet—until 2011, when it surprised astronomers who had already started to develop theories why it would not erupt any time soon. These recurrent novae may eventually explode as type Ia supernovae, if the white dwarf reaches the Chandrasekhar limit.

The realm of satellite observations in the last few decades enabled ultraviolet, X-ray, and IR observations of CVs that vastly contributed to our knowledge of the components within these binaries. In disk CVs, the accretion disk was shown to be a dominant source of UV light, especially during an outburst. The delay between the start of the outburst in optical vs UV light led to increased understanding of the way the outburst proceeds through the disk. In the systems where the white dwarf could be seen as well as the disk, studies throughout the outburst interval showed how the white dwarf was heated by the outburst and subsequently cooled over months to years. Determination of the temperatures of the white dwarfs at quiescence revealed the difference in heating efficiency between magnetic accretion onto a pole vs disk accretion onto a boundary layer, as the white dwarfs in Polars had lower temperatures than disk CVs (Sion 1991; Araujo-Betancor *et al.* 2005). X-ray observations also showed differences between disk and magnetic CVs. The IPs revealed the hardest, most absorbed X-ray spectra, leading to models of accretion curtains, while the Polars typically showed both soft and hard X-rays (the hard from the accretion column and the soft from the heating of the white dwarf surface by the x-rays from the column). Spitzer observations of disk CVs produced surprising results on dust rings within and around several CVs (Brinkworth *et al.* 2007; Hoard *et al.* 2009). Ground-based near-IR spectroscopy also revealed some surprises. When the secondary stars could be observed, the majority of those in disk CVs showed a depletion of CO and metals compared to normal main-sequence stars, whereas the secondaries in Polars do not show this effect (Howell *et al.* 2010). In some short period systems, no evidence of a secondary is seen, implying a very low mass, brown-dwarf type object (Patterson 2011).

In the last decade, the Hamburg Quasar Survey (HQS) and the Sloan Digital Sky Survey (SDSS) produced many new CV candidates. Followup photometry and spectroscopy confirmed several new IPs and SW Sex stars from the brighter objects found by HQS (Rodriguez-Gil *et al.* 2007), and more than 200 CVs from the SDSS which could reach to fainter magnitudes (Szkody *et al.* 2011). Determination of the orbital periods of over 100 of the CVs from the SDSS revealed a period distribution that was much closer to that predicted by population models, with the majority of objects having periods less than 2 hours (Gaensicke *et al.* 2009). However, the minimum period where most of the CVs appear occurs at a slightly larger value (80 minutes) than the 70 minutes predicted by population models (Kolb and Baraffe 1999). These results confirm the basic picture of angular momentum losses via magnetic braking at periods longer than 3 hours and via gravitational radiation at periods under 2 hours, but will require some tweaking of these parameters along with the structure of the stars to obtain a perfect match (Knigge *et al.* 2011). Many new eclipsing CVs are found among the SDSS systems, in which accurate masses and radii can be measured (Littlefair *et al.* 2006). These studies led to the puzzling fact that the white dwarfs in CVs are on average much more massive compared to both

single white dwarfs and those in pre-CVs (Zorotovic *et al.* 2011). The only two answers to this discrepancy are that either the white dwarfs in CVs grow in mass, or that the current-day CV population descends from progenitors that are different from the pre-CVs we have found so far.

Other results from SDSS included the discoveries that there are significant populations of Polars with mass transfer rates three orders of magnitude lower than typical Polars (Low Accretion Rate Polars or LARPs; Schwope *et al.* 2002; Schmidt *et al.* 2005), and there are many CVs containing accreting, pulsating white dwarfs (Szkody *et al.* 2010). The LARPs provide a means to study wind loss from a low mass star, as the low accretion rates preclude the existence of an accretion shock above the white dwarf surface and the visible cyclotron radiation likely stems from the concentration of the wind from the secondary by the interaction of the fields of the two stars. This magnetic interaction has been explored by Kafka *et al.* (2010) for a variety of systems, demonstrating that magnetic prominences occur in many systems other than solar-type stars.

The pulsating white dwarfs have also led to probes of the instability region of white dwarfs. Asteroseismology of white dwarfs has shown their importance for the determination of stellar parameters of mass, age, spin, core composition, magnetic field strength, and distance (Winget and Kepler 2008). The white dwarf pulsators in CVs have the added advantage of undergoing accretion, which heats the white dwarf and changes the composition and rotation, allowing the study of how these parameters affect the instability strip. In addition, the presence of outbursts allows the unique advantage of observing a white dwarf move out of the instability strip (when its heated by the outburst) and then moving back in (as it cools to its quiescent temperature), changes which take millions of years for single white dwarf but only a few years for CVs.

2, Open questions

While the general evolutionary picture and the characteristics of the types of CVs are known at some level, there are major unsolved questions which remain. These include:

- 1) What is the actual number density and distribution of CVs in the Galaxy? As future surveys push to fainter limits and sample the disk as well as the halo, we can finally determine the real population of CVs in the Milky Way.
- 2) What happens to CVs once they reach the period minimum? Theory predicts that they evolve back to longer periods, and that ~70% of all CVs should have evolved to that state. Yet, among more than a thousand CVs, at best a handful of those “period bouncers” are known. Does this imply that these highly evolved CVs look very different from the CVs we know now, and we have so far simply not been able to identify them? Or are the models fundamentally flawed?

3) What are the detailed physics occurring in the common envelope? So far, many of the theoretical models of cataclysmic variable evolution rely on rather crude parametrization of the complex processes in the common envelope, but with the large samples found by Sloan, it will become possible to provide some observational constraints for these parameters.

4) What is the correct physics to describe viscosity in accretion disks? Magnetic turbulence is generally accepted to be the most important effect, yet, no model of this magneto-rotational instability can so far reproduce the observed characteristics of dwarf nova outbursts. Will we finally be able to determine the spectral energy distribution (SED) of a low mass accretion rate disk?

5) What is the correct angular momentum prescription below the gap (besides gravitational radiation) that can account for the observed period minimum spike and the exact period distribution? Is it related to some residual magnetic braking?

6) What causes the period gap? The classic idea is that magnetic braking becomes inefficient, however, recent studies of single M-dwarfs suggest that the reality may be more complex.

7) How do Polars form and why are no magnetic white dwarfs in wide binaries observed? Are LARPS the progenitors of polars? Is there a difference in the emergence of systems containing magnetic white dwarfs versus non-magnetic?

8) What causes Polars, as well as the novalike disk systems with orbital periods between 3 and 4 hours, to cease mass transfer and enter low states? Are the associated mass transfer variations of the companion stars a general phenomenon among all CVs?

9) Can the white dwarfs in CVs grow in mass? Current classical nova models seem to categorically rule out this possibility, yet, observations show that the average mass in CVs is much higher than among pre-CVs.

10) What are the secondaries like in period-bouncers?

11) Do CVs contain exoplanets? Long-term studies of the ephemeris of eclipsing CVs reveal variations of the mid-eclipse times, which can be explained by a third, unseen body tugging on the CV binary. However, many other effects can result in the observed variations, and a much longer baseline of eclipse time monitoring will be necessary to unambiguously confirm or refute the presence of circumbinary planets.

3. The importance of the AAVSO for CVs

Since the very early days of CV research, the AAVSO has played a vital part in obtaining the data on which discoveries and resulting breakthroughs in understanding are based. The long term light curves of the dwarf novae SS Cyg and U Gem, spanning more than a century, provided the impetus for the modeling of dwarf novae outbursts (Cannizzo and Mattei 1998). Observations of the onset of outbursts that triggered UV and satellite observations revealed a delay between the optical and UV light that led to further understanding of the outburst scenario (Cannizzo 2001). The simultaneous monitoring of SS Cyg by the AAVSO observers and the EUVE and RXTE satellites revealed a strong anti-correlation between the soft and hard X-rays during an outburst, providing new insight into the processes at the boundary between the white dwarf and the accretion disk (Wheatley *et al.* 2003). After Polars were found, the long term records of the AAVSO showed the various high and low states of accretion and helped reveal that Polars spend most of their time in low states. Combined with multi-epoch X-ray observations, Hessman *et al.* (2000) used twenty years' worth of AAVSO observations to accurately measure the accretion rate in AM Her, the prototypical polar, and to estimate the fraction of the companion that is covered by star spots. Most recently, HST observations on CVs have required a ground based optical measurement within twenty-four hours of the scheduled HST time to confirm the objects at quiescence. Due to vagaries of weather at any one site, this requirement has led to a vital need for AAVSO monitoring prior to and during observation. The AAVSO CV Section page handled by Mike Simonsen provides campaigns and highlights requests to promote the best interaction between observers and scientists. The Z CamPaIn is one productive example of an ongoing campaign that is unique to AAVSO. No single individual or professional could accomplish the concentrated observations that recently produced new scientific results on the number of Z Cam systems and some unique members (Simonsen 2011). The installation of AAVSONet, providing robotic telescope access at a variety of sites, has been used in these campaigns and other programs, enabling productive observations at both hemispheres and at good weather sites. The archive provided by all of these observations is used by scientists around the world.

The future is moving toward large surveys and large satellites. If funding is realized, PanSTARRS and LSST will provide constant monitoring of the southern and northern skies by the next decade. These surveys will change the landscape for some AAVSO programs, eliminating the need for monitoring of some stars, but enhancing the need in many other areas. The proposed surveys saturate at fairly bright limits of 16–18 magnitudes. This means that there will continue to be a need to continue the long term archive of brighter CVs that is the fodder for theorists. While the surveys will sample some timescales, the coverage is not ideal for CVs with orbital periods of hours, not days, and outbursts that can

rise within one night. The survey filters are mostly concentrated toward the red, while CVs have more activity levels in the blue than the red. The survey telescopes are pre-programmed to move around the sky for a certain pattern so observations that are simultaneous with satellites will still be in demand. Another major mission to be launched next year is GAIA, which will observe the entire sky for at least five years, measuring distances to about a billion stars. Given its location above the Earth's atmosphere, GAIA's scanning pattern is not affected by bad weather, and the mission's first data to become available will be alerts of variable objects identified during the repeated observations. Ground-based confirmation and time-series follow-up will be a key area where AAVSO observers can play a very important role. The surveys will expose a huge number of variables at all magnitudes. The bright end will be a bonanza for AAVSO to scavenge and determine types of objects and behavior at times when the survey is not looking. The era of new opportunities in the field of CVs is just beginning.

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