Observations of Outflows in Cataclysmic Variables

Cynthia S. Froning

Center for Astrophysics and Space Astronomy, University of Colorado, 593 UCB, Boulder, CO 80309, USA

Abstract. Outflows in the form of fast winds from the accretion disk appear in nearly all high accretion rate cataclysmic variables (CVs), both novalikes (NLs) and dwarf novae in outburst (DN). The primary signatures of CV winds are broad, blueshifted absorption features and P Cygni profiles that appear in the ionized metal lines of lower inclination systems and the broad emission lines that appear in eclipsing systems. Much progress has been made in our understanding of the structure and behavior of CV outflows based on data obtained with X-ray, EUV, and UV telescopes and the kinematical models developed to fit the observations. Our current picture of CV outflows is that they are bipolar, rotating winds driven off the accretion disk primarily by radiative line driving from disk, boundary layer, and white dwarf radiation. Other mechanical forces may play a role in the formation of CV winds. The winds are highly turbulent and show complex vertical and azimuthal structure. Future work will focus on determining the physical, thermal and ionization structure of the winds and probing the mechanisms that govern wind formation and behavior.

1. Background

1.1. The First Observations of CV Winds

The study of outflows in cataclysmic variables (CVs) was born in the IUE era. IUE ultraviolet spectra of luminous CVs — novalikes (NLs) and dwarf novae (DN) in outburst — showed high ionization UV transitions, particularly of CIV $\lambda\lambda 1548,1552$ Å, SiIV $\lambda\lambda 1393,1402$ Å and NV $\lambda\lambda 1238,1242$ Å, appearing with very broad, blueshifted absorption components and P Cygni profiles, shifting to pure emission in high orbital inclination systems (Heap et al. 1978; Krautter et al. 1981; Klare et al. 1982; Greenstein & Oke 1982; Szkody 1982; Córdova & Mason 1982; Hassall et al. 1983). Examples of wind-dominated FUV spectra of CVs at different inclinations are given in Figure 1, which shows observations taken from the Far Ultraviolet Spectroscopic Explorer (FUSE) data archive. It was immediately noted that the line profiles were similar to those seen in early-type and luminous stars such as O stars and Wolf-Rayet stars, in which the lines were (and are) believed to originate in expanding winds driven by radiation pressure (Conti 1978). As a result, a wind origin for the UV lines of high accretion rate CVs was adopted early on.

IUE spectroscopy revealed several properties of the CV winds. The maximum blue edge velocities of the absorption troughs ($\approx 5000$ km s$^{-1}$), which give a lower limit to the terminal velocity of the wind, were of order the escape velocity from the white dwarf (WD) accretor, suggesting that the outflows
Figure 1. Examples of CV FUV spectra for different system inclination angles. The spectra are time-averaged plots of observations in the FUSE data archive binned to 0.1 Å. The upper left panel shows the spectrum of the DN SS Cyg in outburst ($i = 30^\circ$). The upper right panel shows the spectrum of the NL IX Vel ($i = 60^\circ$). The lower left panel shows the spectrum of the NL, UX UMa ($i = 71^\circ$), and the lower right panel shows the spectrum of the DN, WZ Sge, at outburst peak ($i = 75^\circ$). Analysis of the UX UMa and WZ Sge observations can be found in Froning et al. 2003 and Long et al. 2003, respectively.

The deepest absorption in the lines occurred not at the blue edges of the lines, as is the case for early-type stars, but at lower velocities ($\approx 2000$ km s$^{-1}$), suggesting that the wind is more slowly accelerated in CVs than in luminous stars (Mauche & Raymond 1987). In eclipsing systems, the lines, unlike the continuum, were not occulted, indicating that the line-emitting region was extended relative to the bulk of the disk, with sizes of order the size of the occulting donor star (Holm, Panek, & Schiffer 1982; Mauche et al. 1994). A comparison of the strengths of the lines with model lines from spherically-symmetric, radiation pressure driven winds (designed for luminous stars) gave mass-loss rates in the wind from $10^{-11} - 10^{-12}$ M$_{\odot}$ yr$^{-1}$, or $10^{-2} - 10^{-4}$ of the mass accretion rate in the disk (Krautter et al. 1981; Klare et al. 1982; Greenstein & Oke 1982; Córdova & Mason 1982).
1.2. Early CV Wind Models

From the start, models for CV winds have been based on the wind models for luminous stars: resonant line scattering from absorption of photons from the central source transfers momentum to ions; as the wind expands outwards, the local resonance is redshifted, perpetuating the line scattering and the driving of the outflow. (For a more detailed discussion of the physics of CV wind models, see Proga, this volume.) The first models assumed a radial outflow with a constant ionization structure emerging from the center of the disk and the WD (Drew & Verbunt 1985; Drew 1987; Mauche & Raymond 1987). The models were used to compare theoretical line profiles to the observed lines, in particular CIV, the strongest wind feature in the UV spectrum.

The results revealed problems with the picture of a radial wind. In high inclination CVs, the blueshifted absorption component of the wind lines disappears as the disk becomes more edge-on, but the radial models continue to show absorption at high inclination. Drew (1987) cited this as evidence for bipolarity, rather than spherical symmetry, in the outflow, although it was noted by Mauche & Raymond (1987) that radial winds could still be present if the bipolarity was introduced by limb-darkening effects in the accretion disk. Mauche & Raymond pointed out another significant problem with radial CV winds, however: radial winds “see” so much of the continuum from the WD and boundary layer (BL) that the wind is ionized beyond CIV unless it is highly optically thick, which requires wind mass loss rates of \( \geq \frac{1}{3} \) of the mass accretion rate. Such a massive wind cannot be radiatively driven, produces UV line fluxes an order of magnitude larger than observed values, and would absorb the soft X-ray continuum from the BL, which is inconsistent with observed X-ray fluxes. On the basis of their models, the authors concluded that radial outflows were unlikely in CVs.

As a result, the next generation of CV wind models adopted biconical, axysymmetric wind structures, with the winds being launched from the accretion disk. Shlosman & Vitello (1993) developed a kinematical model of a rotating, biconical disk wind, taking into account radiation from the WD, the BL, and the accretion disk when calculating the local ionization structure of the (constant temperature) wind. Radiation transfer and line driving of the wind were treated using the standard wind modeling theory for luminous stars. By comparing theoretical line profiles from their models with those of radial winds, they showed that biconical disk winds provide a better match to the profiles of CIV wind lines at varying inclinations and do not suffer from the excessive absorption of BL photons and subsequent over-ionization of the wind as seen in radial wind models. Vitello & Shlosman (1993) compared the biconical disk model line profiles to observed IUE spectra of CVs. They were able to match the CIV profiles of the low inclination system, RW Sex, and the eclipsing NL, RW Tri, with wind mass-loss rates of order 1 – 15% of the mass accretion rate. Their models gave a typical scale for the CIV line of 50 – 100 \( R_{WD} \) in vertical height above the accretion disk. At this point, the theoretical and observational evidence both pointed to the presence of biconical accretion disk winds driven by radiation pressure in high accretion rate CVs.
2. Properties of Cataclysmic Variable Outflows

2.1. Wind Structure and Behavior

Much of the progress in understanding CV outflows continues to come from UV spectroscopic observations of luminous systems, although EUV and X-ray observations of CVs have also provided information on the properties of the winds. Winds have also been cited as possible sources for features in optical lines, particularly non-Keplerian emission in HeII $\lambda 4686$ Å, but the evidence for wind signatures at optical wavelengths is generally indirect (Honeycutt, Schlegel, & Kaitchuck 1986; Marsh & Horne 1990). One exception is the optical spectrum of BZ Cam, which shows intermittent P Cygni profiles in H$\alpha$ and HeI $\lambda 5876$ Å (Patterson et al. 1996; Ringwald & Naylor 1998). The optical lines are complex blends of emission from the wind and the disk, however, which limits analysis of the wind behavior based on optical emission. In the UV, the advent of sensitive, high time resolution UV spectrographs on HST and FUSE has allowed direct tests of the predictions of disk wind models. Below, we examine several properties of CV winds that have resulted from observations in the past decade.

Wind Rotation

One observational signature of line-driven disk winds is that they rotate and that the winds preserve angular momentum as they leave the disk. This is in contrast to hydromagnetically-driven winds, such as those seen in YSOs, which maintain a constant angular velocity out to the Alfvén radius and perhaps beyond. In at least two CVs, the observational evidence favors a rotating wind that conserves angular momentum. Shlosman, Vitello, & Mauche (1996) compared the out of eclipse and mid-eclipse UV line profiles in IUE observations of the nearly edge-on NL, V347 Pup. They showed that the CIV wind line narrows in eclipse when the region of the wind near the disk surface that is responsible for the most of the rotational broadening of the line is occulted. They demonstrated that the line profile variations during eclipse are consistent with the biconical disk wind model of Shlosman & Vitello (1993) when only orbital phase changes are invoked. The CIV emission line also narrows during eclipse in UX UMa and a rotational signature can be seen in the eclipse light curves of different velocities in the line: the eclipse appears in the blue wing of the line before it appears in the red wing, and the eclipse is most shallow at the line center (Mason et al. 1995; Baptista et al. 1995). Knigge & Drew (1997) modeled the UX UMa data — high spectral resolution, time-resolved HST/GHRS observations of CIV — with a biconical disk wind model and were able to reproduce the pre- and mid-eclipse spectra and the velocity-resolved eclipse light curves with moderately collimated ($65^\circ$ opening angle), rotating disk wind.

Wind Vertical Structure

Observations of eclipsing systems have also been instrumental in probing the vertical structure of the winds as they are launched from the disk. The HST observations of the CIV line in UX UMa, in addition to exhibiting a rotational disturbance, show narrow, low-velocity absorption components that are occulted during eclipse. The same narrow absorption components are observed in numerous other lines in the HST spectral range and also appear in phase-resolved FUSE spectra of UX UMa (Froning et al. 2003). The eclipse behavior of the UV spectrum of UX UMa is shown in Figure 2. Outside
of eclipse, the spectrum is a complex blend of line emission, with no discernable continuum. At mid-eclipse, the spectrum is much cleaner, and is characterized by a flat continuum and strong, broad line emission from the unocculted portion of the wind. The difference spectrum, which is the spectrum of the eclipsed light, shows that the eclipsed parts of the wind lines are narrow (≃ 500 – 1000 km s\(^{-1}\)) absorption components centered on the rest wavelengths of the lines. Knigge & Drew (1997) showed that to successfully model these absorption dips and their disappearance during eclipse requires the presence of a dense, low outflow velocity transition region between the bulk of the accretion disk and the fast wind. The transition region, or disk chromosphere, may be part of the wind itself: the hydrodynamical disk wind models of Proga, Stone, & Drew (1998) show that when the line driving is dominated by radiation from the disk (over that from the WD and BL), the wind has both a fast outflow component and a dense, low outflow velocity region near the disk surface.

Figure 2. HST/GHRS FUV spectra of UX UMa. The upper panel shows the out of eclipse spectrum of UX UMa. The middle panel shows the spectrum at mid-eclipse, and the lower panel shows the difference spectrum, which is the spectrum of the eclipsed light. Dotted lines indicate the rest wavelengths of the observed spectral features. (Figure from Froning et al. 2003. See also Mason, Drew, & Knigge 1997 for a discussion of pre-eclipse light curve dips in these observations.)

**Orbital Variability** Recent observations also point to azimuthal structural variations in the disk winds. Time-resolved FUSE spectra of RW Sex show that
the FUV wind lines are modulated on the orbital period \cite{Prinja2003}. Over the orbit, all of the wind lines in the FUV spectrum — ranging from lower-ionization transitions of CIII and NIII to PV, SVI, and OVI — show the same behavior: a single-humped modulation in which the velocity of the deepest absorption of each line moves to the red, accompanied by an increase in the absorption depth, and a shift back. The authors speculate on the source of the orbital phase modulation, which they link to an asymmetry in the structure of the disk. Orbital-phased modulations in wind lines have also been observed in the NLs V795 Her and V592 Cas \cite{Rosen1998,Prinja2004}.

The source of the orbital changes in the wind lines remains unknown. Prinja et al. (2003) suggest that a disk tilt or warp could account for the modulation in RW Sex, but this explanation is not favored for V592 Cas, as the wind variations are modulated on the orbital period, but not on the known superhump period of the system. Orbital changes in the UV continuum and (non-wind) line spectra, particularly associated with the phases before eclipse, have also been seen in NLs and DN in outburst \cite{Mason1997,Froning2001}. The orbital effects are believed to be caused by interactions between the disk and the mass accretion stream from the donor star, resulting in a bulge in the outer disk or in stream overflow, similar to the source of X-ray dips in some X-ray binaries \cite{White1995}. Azimuthal variations in CV winds may be tied to the disk-stream interaction region, but the explicit link between outer disk and wind asymmetries has not yet been discovered.

\textit{Stochastic Variability} While some CV winds show orbital modulation, others are dominated by secular variability. Oddly, there is little overlap between these two sets of systems.) Prinja et al. (2000) studied high time resolution HST/GHRS spectra of the NL, BZ Cam. The spectra show strong and continuous variability in the absorption troughs, but not the emission components, of the P Cygni lines of CII $\lambda$1334 Å, CIII $\lambda$1175 Å, Si III $\lambda$1300 Å, SiIV, NV, and CIV. The lines vary together and can show optical depth changes of a factor of 5 over 1000 – 3000 km s$^{-1}$ of the absorption troughs on 100 sec time scales. Since all lines vary together, the variability is likely tied to density fluctuations in the wind rather than changes in the ionization state. In BZ Cam, then, the picture is that of a turbulent, stochastic wind, a contrast to the more stable winds from luminous stars. The outflows in CVs are much more compact than those from stars — Prinja et al. note that a wind travelling at 3000 km s$^{-1}$ can traverse the binary separation ($\sim$50$R_{WD}$) in 2 – 3 min — and may therefore reflect underlying disk fluctuations on short time scales. This chaotic, unsteady outflow is also consistent with the behavior of the wind in the models of Proga, Stone, & Drew (1998), although in other hydrodynamic models, a more steady outflow is seen \cite{Pereyra1997}.

\textit{Narrow Absorption Dips} Some CVs do not show the short time scale variability exhibited by BZ Cam, but do show variable line profiles in the form of narrow absorption components to the lines. In the NLs IX Vel and V388 Sgr, very narrow ($< 100$ km s$^{-1}$), blueshifted ($-900$ km s$^{-1}$) absorption dips appear in the absorption troughs of several of the wind lines at times of strongest wind activity \cite{Mauche1991,Hartley2002}. Similar dips appear intermittently in the profiles of the OVI $\lambda\lambda$1032,1038 Å doublet lines of U Gem in outburst
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(Froning et al. 2001). In U Gem, the lines (located at \(\sim -500 \text{ km s}^{-1}\)) appear erratically and are not correlated with orbital phase; sometimes, two dips appear in each of the doublet transitions. The features are analogous to the discrete absorption components (DACs) seen in luminous star winds, although the CV absorption dips remain at constant velocity, while the DACs are observed to move slowly outward with time. Because the dips in the CV lines do not move, many of the models invoked to explain DACs will not apply for the CV dips. A possible source for the dips is the formation of localized plateaus in the outflow velocity law, leading to pileup of ions.

High Ionization Wind Lines

Determining the formation mechanisms of winds in high accretion rate CVs also depends on understanding cases in which the “standard” UV wind features do not appear. One example is U Gem in outburst: with the exception of the aforementioned absorption dips in OVI and perhaps a weak P Cygni profile in the same, there is no sign of an outflow in the FUV spectra of U Gem; instead, the lines are generally narrow, low-velocity absorption features and sometimes are absent altogether (Sion et al. 1997; Froning et al. 2001). One possibility is that the BL luminosity plays a role in the structure of the wind. U Gem is one of the few CVs that shows evidence for a luminous BL in outburst: EUV spectra show a hot (140,000 K) blackbody component whose luminosity, consistent with classical accretion disk theory, is comparable to that of the accretion disk (Long et al. 1996). The same EUV observations show highly ionized resonant line transitions in emission. The lines that appear are consistent with an origin in gas photoionized by the BL and are likely formed in a highly ionized wind.

Further understanding of the ionization structure of winds will require comparisons of UV, EUV, and X-ray spectra in different systems. The lower inclination DN, SS Cyg, has a low-luminosity BL, for example, and shows wind features in both X-ray and FUV spectra, but no EUV wind lines (Mauche 2004; Long et al. 2004, in preparation). Good fits to the X-ray spectrum can be obtained with a wind model, but only if the individual ionization fractions of the lines are allowed to vary arbitrarily. In the DN OY Car in superoutburst, the EUV spectrum shows strong wind emission in resonant transitions of several ions (Mauche & Raymond 2000). Mauche & Raymond note, however, that the radiation pressure required to drive the wind in OY Car cannot be met by current wind models, a point that is discussed further below.

2.2. Limitations of the Pure Line Driving Model

Using time-tagged HST/STIS observations of the NLs IX Vel and V3885 Sgr, Hartley et al. (2002) tested radiatively-driven wind models by comparing luminosity variations in the UV continuum and in the wind lines. For a purely radiative wind, the strength of the wind lines should be directly correlated with the strength of the photoionizing continuum, but they found no such correlation in either system: while both the continuum and the lines varied with time, the wind had often weakened when the continuum was higher, and two epochs with the same continuum level in IX Vel showed strong wind features and little to no wind emission at all, respectively. Hartley et al. (2002) concluded that the ob-
servations provided a serious challenge to the model of purely radiatively-driven disk winds.

The result was not entirely surprising, as there have been other indications that line-driving may not be the sole wind-formation mechanism at work in CVs. One problem that continues to plague hydrodynamic wind models is an inability to match the observed strengths of the wind lines. [Drew & Proga (2000)] showed that when current determinations of mass accretion rates in luminous CVs are assumed, the hydrodynamic models underpredict the strength of the wind by an order of magnitude. As a result, additional mechanical wind drivers may be present in luminous CVs. The possible role of centrifugal forces in driving disk winds was considered at an early date by [Cannizzo & Pudritz (1988)], who also noted that hydromagnetically-driven outflows would strongly influence binary secular evolution as sinks of angular momentum. In addition, [Mauche & Raymond (1987)] showed that the presence of shocks in the wind can cause local density enhancements that lower the overall wind mass loss rate required to match observed wind line strengths. Work on incorporating non-radiative forces into CV wind models is only beginning (see Proga, this volume), but represent an important avenue for future studies of disk winds.

2.3. Future Work

Most of the modeling of CV winds has concentrated on one transition, CIV λλ1548,1552 Å. As a result, our understanding of the thermal and ionization structure of disk winds remains limited. The next steps in understanding the formation and behavior of CV disk winds will depend on simultaneously modeling the broad range of species and ionization levels that appear in X-ray and UV spectra of CV winds. To this end, [Long & Knigge (2002)] developed a Monte Carlo radiative transfer program that, given an input WD and accretion continuum spectrum, self-consistently calculates the thermal and ionization structure of the wind and generates synthetic spectra at every viewing inclination. An example of the types of fit possible with their program is shown in Figure 3, which shows a disk and wind model fit to the outburst spectrum of Z Cam, obtained with the Hopkins Ultraviolet Telescope. A qualitatively good fit to the observed spectrum can be obtained with a model in which the disk has a mass accretion rate of $6 \times 10^{-9} \, M_\odot \, \text{yr}^{-1}$ and the mass loss rate in the wind is $1 \times 10^{-10} \, M_\odot \, \text{yr}^{-1}$.

In the case of relatively simple spectrum, such as the FUV spectrum of SS Cyg in outburst, which is dominated by OVI (see Figure 1), a good model fit can be achieved assuming a steady-state accretion disk and a disk wind carrying away $10^{-2}$ of the accreted mass [Froning et al (2002)]. The wind mass loss rate obtained from the model fit ($4 \times 10^{-11} \, M_\odot \, \text{yr}^{-1}$) is also within a factor of a few of the mass loss rate determined from Chandra observations of SS Cyg in outburst [Mauche (2004)]. Once the spectrum becomes more complex, however, with wind signatures appearing in many lines, as in the case of Z Cam above, fitting the entire spectrum and determining uniqueness of the fit parameters becomes challenging. CV spectra are extremely complex and can contain emission from multiple components in the system, parameters for some of which remain poorly constrained. Nevertheless, the combination of high quality observations
and sophisticated models offer a promising opportunity to quantify the structure and behavior of disk winds in CV systems.

3. Conclusions

Outflows, in the form of moderately collimated winds, are closely tied to disk accretion in luminous CVs. A combination of observations and modeling have shown that CV winds are bipolar, highly turbulent, and structurally complex. Radiative line-driving models for the source of the wind explain many of the observations, but additional, mechanical mechanisms may play a role in the structure and formation of the wind. Future observations and modeling will concentrate on determining the vertical and azimuthal distribution of the wind, its thermal and ionization structure, and the mechanisms that influence wind formation and behavior.

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