The accreting white dwarfs in VY Scl nova-like variables

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Abstract. Accurate distances for nova-like variables offer the possibility of extracting information on nova-like accretion rates during high states of optical brightness and on their underlying accretion-heated white dwarfs during intermediate and low brightness states. The modeling technique which is employed is discussed and a representative example, the nova-like variable KR Aur, is presented. Although KR Aur was in a fainter high state when its far ultraviolet spectrum was obtained, roughly one-half of its FUV radiation is due to the light of an accretion disk and the other half is contributed by a hot white dwarf with $T_{\text{eff}} = 29,000 \pm 2,000$K. However, this best-fit solution corresponds to a distance of 180 pc which was an early distance estimate due to Patterson (1984).

1. Introduction
The nova-like variables are a non-magnetic subclass of CVs in which the mass-transfer rate tends to be high and the light of the system is typically dominated by a very bright accretion disk (Warner 1995). The spectra of nova-like variables resemble those of classical novae (CNe) that have settled back to quiescence. However, nova-like variables have never had a recorded CN outburst or any outburst. Hence their evolutionary status remains unknown. They could be close to having their next CN explosion, or they may have had an unrecorded explosion, in the recent past. Their distribution of orbital periods reveals a large concentration of systems in the range between three and four hours, the former period being the upper boundary of the CV period gap where very few CVs are found. Some nova-likes (classified as the VY Sculptoris systems) show the behavior of being in a high optical brightness state for most of the time, but then, for no apparent reason, plummeting into a deep low optical brightness state with little or no ongoing accretion. Then, just as unpredictably, their optical brightness returns to the high state (cf. Honeycutt & Kafka 2004 and references therein). These precipitous drops in brightness are possibly related to the cessation of mass transfer from the K-M dwarf secondary star either by starspots that drift into position under the inner Lagrangian point, L1 (Livio & Pringle 1998) or irradiation feedback in which an inflated outer disk can modulate the mass transfer from the secondary by blocking its irradiation by the hot inner accretion disk region (Wu et al. 1995). When VY Scl nova-likes drop into a deep low state, the underlying accretion heated white dwarf is exposed and its surface temperature can be determined with model photospheres.

Until recently, the accretion rates of nova-likes have been reported for only a few individual systems from a variety of model analyses of their optical, FUV spectra or X-ray spectra.
Optical determinations of the accretion rates in nova-likes are based upon estimates of their disk luminosity using distance estimates or clues (Patterson 1984). The absolute magnitudes of the accretion disks in nova-likes reveal that their accretion rates are similar to those derived for dwarf novae during their outbursts (Warner 1995). Unfortunately, the distances of nova-like variables remain uncertain due to the scarcity of trigonometric parallaxes and the absence of a reliable usable relation for nova-like variables between their absolute magnitude at maximum light versus orbital period similar to what exists for dwarf novae. A more systematic study of a larger number of systems is clearly needed in order to compare accretion rates among different subgroups of CVs. One recent statistical study explored how well current optically thick accretion disk models fit the FUV spectra of nova-likes and old novae in a sample of 33 nova-like and old novae by Puebla, Diaz & Hubeny (2007). The average value of $\dot{M}$ for nova-like systems was $\sim 9.3 \times 10^{-9} M_\odot \, \text{yr}^{-1}$. Interestingly, this study included an assessment of the contribution of an assumed 40,000 K white dwarf to the FUV spectra. The authors did not include the white dwarf flux contribution in each system explicitly as a free parameter in the fitting. Rather, they used a parameter defined as the ratio of the integrated spectral flux between 1500 Å and 3250 Å of the white dwarf model and disk model to estimate the flux contribution of the white dwarf. If this ratio was $< 0.1$, then the system was defined as disk-dominated. Indeed, the white dwarf contribution is expected to be minimal in these systems because their disks are thick and luminous and because at high inclination the inner disk, boundary layer and white dwarf should be significantly obscured by vertical structure in the disk. However, Puebla et al. (2007) found nine systems which according to the above criterion should have a considerable contribution from the accreting white dwarf. They are BK Lyn, V442 Oph, SW Sex, V1315 Aql, PX And, V794 Aql, LX Ser, KR Aur, and AC Cnc. Five of these nine nova-like variables have high orbital inclinations and undergo eclipses. Here we use the IUE archival spectra of KR Aur as an example of our approach to modeling nova-like variables.

Our long term objectives are: (1) to see if we can characterize or constrain the temperature of the white dwarf in nova-like variables using a different approach than Puebla et al. (2007) and (2) to carry out a systematic synthetic spectral analysis of IUE and HST archival spectra of nova-like variables based upon a uniformly applied new method of distance determination to obtain accretion rates from fitting the observed spectral slopes and Lyman alpha profiles.

2. Distances to nova-likes
There is only one nova-like, RW Tri, with a reliable trigonometric parallax measurement. Unlike dwarf novae where there exists a correlation between their absolute magnitude at maximum and their orbital period (Warner 1995), there is no such relation for the nova-likes. A new method (Knigge 2006) utilizing 2MASS $JHK$ photometry and the observed properties of CV donor stars has proven useful for constraining nova-like distances. At present, this may be the only reliable handle one has on nova-like distances. For each system, we obtained the $J$, $H$, $K$ apparent magnitudes from 2MASS. For a given orbital period, Knigge (2006) provides absolute $J$, $H$ and $K$ magnitudes based upon his semi-empirical donor sequence for CVs. If it is assumed that the donor provides 100% of the light in $J$, $H$ and $K$, then the distance is a strict lower limit. If the donor emits 33% of the light (the remainder being accretion light), then an approximate upper limit is obtained. The latter limit is a factor of 1.75 times the lower limit distance. These distances using IR photometry provide useful comparisons with distance estimates published by Patterson (1984) from the mean light levels in AAVSO light curves of nova-like variables on the assumption that the accretion disk provides 100% of the optical light.

3. Synthetic spectral fitting models
We adopted model accretion disks from the optically thick disk model grid of Wade & Hubeny (1998). In these accretion disk models, the innermost disk radius, $R_{\text{in}}$, is fixed at a fractional
Figure 1. The best-fitting combination accretion disk + white dwarf photosphere synthetic fluxes to the spectrum SWP27096 of the VY Scl-type nova-like variable KR Aur during an fainter high state. The accretion disk corresponds to $M = 3 \times 10^{-10} M_\odot \text{ yr}^{-1}$, $i = 41^\circ$, and $M_{\text{WD}} = 0.55 M_\odot$. The top solid curve is the best-fitting combination, the dotted curve is the contribution of the white dwarf alone and the dashed curve is the accretion disk synthetic spectrum alone. In this fit, the white dwarf with $T_{\text{eff}} = 29,000 \pm 2,000 K$, log $g = 8$ contributes 50% of the FUV light and the accretion disk contributes 50% of the far UV flux.

The white dwarf radius of $x = R_{\text{in}}/R_{\text{WD}} = 1.05$. The outermost disk radius, $R_{\text{out}}$, was chosen so that $T_{\text{eff}}(R_{\text{out}})$ is near 10,000 K since disk annuli beyond this point, which are cooler zones with larger radii, would provide only a very small contribution to the mid and far UV disk flux, particularly the SWP FUV bandpass. The mass transfer rate is assumed to be the same for all radii.

Theoretical, high gravity, photospheric spectra were computed by first using the code TLUSTY (Hubeny 1988) to calculate the atmospheric structure and SYNSPEC (Hubeny and Lanz 1995) to construct synthetic spectra. We compiled a library of photospheric spectra covering the temperature range from 15,000 K to 70,000 K in increments of 1,000 K, and a surface gravity range, log $g = 7.0 - 9.0$, in increments of 0.2 in log $g$.

4. KR Aur

This nova-like system is classified as a VY Scl subtype with high states at magnitude 12.7 and the deepest low state being 17.9. The system underwent a deep minimum during 1994–95 when optical spectra revealed emission lines possibly indicative of a disk still being present (Antov et al. 1996). The minimum lasted eight months. However, usually the system brightness is
magnitude 12 to 14 with 13.5 being the most typical brightness. KR Aur is one of six out of 23 VY Scl nova-likes which have negative superhumps. Negative superhumps may arise when a disk becomes tilted due to intense radiation from every hot white dwarf and thus could be an indirect indicator of nuclear burning (Kozhevnikov 2007). The other systems with negative superhumps are V442 Oph, DW UMa, TT Ari and V751 Cyg. The orbital inclination is low with an upper limit of 38 degrees and a lower limit of 10 degrees (Ritter & Kolb 2003). The orbital period is 0.1628 days. The white dwarf mass has been estimated to be in the range of 0.59 to 0.17 $M_\odot$. Its two far UV spectra were obtained during a fainter high state and are dominated by absorption features due to metals with the strongest features due to N V (1240), Si III (1300), C II (1335), Si IV (1400). Of the two SWP spectra, SWP 13584 has a slightly higher flux level and a better signal to noise. There are no P Cygni profiles evident indicating wind outflow. KR Aur has a reddening value, $E(B-V) = 0.05$ (Bruch & Engel 1994).

The white dwarf contribution is expected to be minimal in these systems because their disks are thick and luminous and because at high inclination the inner disk, boundary layer and white dwarf should be significantly obscured by vertical structure in the disk. For KR Aur, Puebla et al. (2007) explored a range of white dwarf masses $0.4 - 0.8 M_\odot$, inclinations $i = 30^\circ - 50^\circ$ and an adopted Patterson (1984) distance of $d = 180$ pc. They found an accretion rate $\dot{M} = 4.5 \times 10^{-10} M_\odot$/yr which is atypically low for a VY Scl nova-like variable in its high state. Moreover, Puebla et al. (2007) found that KR Aur should have a significant flux contribution of a hot white dwarf in addition to an accretion disk.

Using our different modeling approach to KR Aur, we found that neither an accretion disk alone nor a white dwarf photosphere alone provided a satisfactory fit to the observed continuum slope and absorption spectrum of KR Aur. However, we found that a statistically significant improvement (lower $\chi^2$) in the fitting was evident when we combined an accretion disk model with a white dwarf model. We find that the optimal combination for KR Aur at the Patterson (1984) distance of 180 pc consists of an accretion disk model with a white dwarf mass of $0.55 M_\odot$, an inclination angle $i = 41^\circ$ and an accretion rate of $3 \times 10^{-10} M_\odot$/yr together with a white dwarf photosphere model with $T_{\text{eff}} = 29,000 \pm 2,000$ K, $\log g = 8$. This best combination fit to the IUE spectrum of KR Aur is displayed in Fig. 1. In this fit, the accretion disk provides 50% of the FUV flux and the white dwarf contributes 50% of the flux.

5. Conclusion
For the VY Scl nova-like variable KR Aur, we find that a combination of models consisting of a hot white dwarf and an optically thick steady state accretion disk provides a significantly improved model fit to its FUV spectrum. The best-fitting model is a combination of a white dwarf with $T_{\text{eff}} = 29,000 \pm 2,000$ K, $\log g = 8$, contributing 50% of the FUV flux and an accretion disk with accretion rate $\dot{M} = 3 \times 10^{-10} M_\odot$/yr at an inclination of 41 degrees, contributing 50%. This fitting solution was achieved for a fixed distance of 180 pc which was the early distance estimate by Patterson (1984). However, the distance implied by this combination fit is at odds with the Knigge (2006) distance. This difference is explored elsewhere (Mizusawa et al. 2009).

Acknowledgments
This work is supported by NSF grant AST-0807892 to Villanova University and by the Delaware Space Grant Consortium.

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