Far-Ultraviolet Spectroscopy of Three Long-Period Novalike Variables

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ABSTRACT. We have selected three novalike variables at the long-period extreme of novalike orbital periods: V363 Aur, RZ Gru, and AC Cnc, all with IUE archival far-ultraviolet spectra. All are UX UMa-type novalike variables and all have $P_{\text{orb}} > 7$ hr. V363 Aur is a bona fide SW Sex star, and AC Cnc is a probable one, while RZ Gru has not proven to be a member of the SW Sex subclass. We have carried out the first synthetic spectral analysis of far-ultraviolet spectra of the three systems using state-of-the-art models of both accretion disks and white dwarf photospheres. We find that the FUV spectral energy distribution of both V363 Aur and RZ Gru are in agreement with optically thick steady-state accretion disk models in which the luminous disk accounts for 100% of the FUV light. We present accretion rates and model-derived distances for V363 Aur and RZ Gru. For AC Cnc, we find that a hot accreting white dwarf accounts for $\sim 60\%$ of the FUV light, with an accretion disk providing the rest. We compare our accretion rates and model-derived distances with estimates in the literature.

Online material: color figures

1. INTRODUCTION

Novalike variables are a subset of cataclysmic variables (CVs), short-period binaries in which a late-type, Roche-lobe-filling main-sequence dwarf transfers gas through an accretion disk onto a rotating, accretion-heated white dwarf (WD). The spectra of novalike variables resemble those of classical novae (CNe) that have settled back to quiescence. However, they have never had a recorded CN outburst or any outburst. Hence, their evolutionary status is unclear: they could be close to having their next CN explosion, or they may have had an unrecorded explosion in the past, possibly hundreds or thousands of years ago. Or, quite possibly, they may not even have CN outbursts at all, in which case their WDs would be steadily increasing in mass to become the elusive progenitors of Type Ia supernovae.

A subset of novalike variables are those that remain in a high-brightness state, as though they are dwarf novae stuck in outburst. These novalike variables are part of the UX UMa subset. Complicating the picture of novalike variables further are the SW Sex-tantis subset. They display a multitude of observational characteristics: orbital periods between 3 and 4 hr; one-third of the systems are noneclipsing, while two-thirds show deep eclipses of the WD by the secondary (thus requiring high inclination angles); single-peaked emission lines despite the high inclination, and high-excitation spectral features, including He II (4686) emission and strong Balmer emission on a blue continuum; high-velocity emission S-waves with maximum blue-shift near phase $\sim 0.5$; delay of emission line radial velocities relative to the motion of the WD; and central absorption dips in the emission lines around phase $\sim 0.4-0.7$ (Rodriguez-Gil et al. 2007; Hoard et al. 2003). The white dwarfs in many, if not all, of these systems are suspected of being magnetic (Rodriguez-Gil et al. 2007), although this hypothesis remains unproven. Since SW Sex stars, as well as most of the UX UMa systems, are found near the upper boundary of the 2–3 hr period gap, a much better understanding of them is of critical importance to understanding CV evolution as they enter the period gap (Rodriguez-Gil et al. 2007), if indeed they even do enter the gap, since evolution across the gap has not yet been definitively proven.

Recent systematic studies of a larger number of novalike systems have been carried out by Puebla et al. (2007), Ballouz and Sion (2009), Zellem et al. (2009), and Misuzawa et al. (2010) with the aim of modeling their far-ultraviolet (FUV) spectra and comparing accretion rates among different subgroups of CVs as a function of orbital period. For this article, we have selected three novalike variables at the long-period extreme of novalike orbital periods: V363 Aur, RZ Gru, and AC Cnc, all of which are UX UMa-type novalike variables with orbital periods longer than 7 hr, well beyond the 3 to 4 hr range where most novalike variables are found. Lanning 10 (hereafter V363 Aur) is a bona fide SW Sex star, and AC Cnc is a probable one, while RZ Gru has not been proven to be an SW Sex star. All three are part of the UX UMa subset. In this article, our approach is to utilize grids of composite models (accretion disk plus white dwarf) for the first time on the IUE spectra of these three systems. The models are the same as used on dwarf novae in outburst
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2. IUE ARCHIVAL OBSERVATIONS

We extracted the archival spectra for each system from the Multi-Mission Archive at Space Telescope (MAST). An observing log is given in Table 2 for the IUE SWP spectra selected for our analysis. For the three systems, we list the following by row: (1) the SWP number, (2) the exposure time in seconds, (3) the spectral dispersion, (4) the aperture size, (5) the date and time of the start of the exposure, (6) the maximum continuum counts of each exposure, and (7) the background counts of each exposure.

All three systems were in their normal high-brightness state when the IUE spectra were obtained. We used IUERDAF software to process the spectra and the IDL routine UNRED to redden the spectra. The IUE SWP spectrum of V363 Aur reveals emission lines, of which the strongest are due to C iv and He ii, plus weaker emission features due to Si i, C i, Al ii, and C iii. The only absorption features evident in the spectrum are Si iv+ O i (1300) and C ii (1335). These features are labeled in Figure 1, which is discussed in §3. The spectrum of RZ Gru strongly resembles a UX UMa-type novalike system with strong P Cygni profiles at N v, Si iv, and C iv, revealing the presence of a hot, fast outflowing wind. These features are displayed in Figure 2, which is discussed in §3.

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 in, is fixed at a fractional white dwarf radius of x = R in/R wd = 1.05. The outermost disk radius, R out, was chosen so that T eff(R 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. Thus, the run of disk temperature with radius is taken to be

$$T_{\text{eff}}(r) = T_s x^{-3/4} (1 - x^{-3/2})^{1/4},$$

where x = r/R wd and σT^4 = 3GM wd M/8πR^3 wd.

Limb-darkening of the disk is fully taken into account in the manner described by Diaz et al. (1996) involving the Eddington-Barbier relation, the increase of kinetic temperature with depth in the disk, and the wavelength and temperature dependence of the Planck function. The boundary-layer contribution to the model flux is not included. However, the boundary layer is expected to

| Table 1 |
|----------|
| Parameters |
|----------|
| V363 Aur | RZ Gruis | AC Cancri |
| Subtype | UX,SW | UX | UX,SW |
| V | 14.2 | 12.3 | 13.5 |
| Period | 7 hr, 42 minutes (1) | 8 hr, 38 minutes to 9 hr, 48 minutes (3) | 7 hr, 12.6 minutes (8) |
| E(B − V) | 0.3 (1) | 0.03 (2) | 0.055 (9) |
| M wd | 0.86 M⊙ | ... | 0.76 ± 0.03 M⊙ (8) |
| M sd | 0.77 M⊙ (4) | ... | 1.02 ± 0.14 M⊙ (8) |
| Inclination | 73° (6) | 61° (7) | 75.6 ± 0.03° (8) |
| Distance | 530–1000 pc (6) | 440 ± 40 pc (5) | 550 (8) |

References.—(1) Szkody et al. 1981; (2) Bruch et al. 1994; (3) Tappert et al. 1998; (4) Schegel et al. 1986; (5) Stickland et al. 1984; (6) Rutten et al. 1992; (7) Kelly et al. 1981; (8) Thoroughgood et al. 2004; (9) GALEX archive.
contribute primarily in the extreme ultraviolet below the Lyman limit.

Theoretical, high-gravity, solar-composition photospheric spectra were computed by first using the code TLUSTY, version 200 (Hubeny 1988), to calculate the atmospheric structure and SYNSPEC, version 48 (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 1000 K, and a surface gravity range, log \( g \) = 7.0–9.0, in increments of 0.2 in log \( g \).

For each spectrum, we separately determined the best-fitting single-temperature white dwarf model and the best-fitting accretion disk-only model. Depending upon the success of these fits, we tested whether a combination of a disk plus a white dwarf significantly improved the fit. Using two \( \chi^2 \) minimization routines, either IUEFIT for disks alone and photospheres alone or DISKFIT for combining disks and photospheres or two-temperature white dwarfs, \( \chi^2 \) values and a scale factor were computed for each model or combination of models. The scale factor, \( S \), normalized to a kiloparsec and solar radius, can be related to the white dwarf radius \( R \) through \( F_{\lambda(\text{obs})} = S H_{\lambda(\text{model})} \), where \( S = 4\pi R^2 d^{-2} \), and \( d \) is the distance to the source. For the white dwarf radii, we use the mass-radius relation from the evolutionary model grid of Wood (1995) for C-O cores. The best-fitting model or combination of models was chosen based not only upon the minimum \( \chi^2 \) value achieved, but also on the goodness of fit of the continuum slope, the goodness of fit to the observed Ly\( \alpha \) region, and consistency of the scale factor-derived distance with other distance estimates in Table 1.

In Table 3, we list the best-fitting parameters of the three systems, where the entries by row are (1) the system name, (2) white dwarf mass, (3) inclination angle, (4) best-fitting model distance in pc, (5) scale factor, (6) \( \chi^2 \) value, and (7) \( \dot{M}_\odot \) yr\(^{-1} \).

V363 Aur is normally observed at \( V = 14.2 \), but has been observed to be as faint as \( V = 15 \). It has never been seen at a low-brightness state, thus suggesting its classification as a member of the UX UMa subclass. The FUV spectrum reveals a steeply rising continuum toward shorter wavelengths and a line spectrum dominated by strong emission features due to C\( \text{IV} \), and He\( \text{II} \). The He\( \text{II} \) strength is strong for a nonmagnetic nova-like, raising the possibility that the white dwarf could be magnetic. Absorption features due to Si\( \text{III} \) (1300), C\( \text{II} \) (1335), and O\( \text{V} \) (1371) are also seen, along with the C\( \text{IV} \) and He\( \text{II} \) emission. On the basis of V363 Aur having an optically thick, steady-state accretion disk, Hoare and Drew (1991) used the Zanstra method to determine a boundary-layer temperature of 70,000 K to 100,000 K using both the He\( \text{II} \) 1640 flux and the He\( \text{II} \) 4686 flux.

### Table 2

| IUE Observation Log | V363 Aur | RZ Gruis | AC Cnc |
|---------------------|----------|----------|--------|
| Spectra .............| SWP 35335| SWP 18138| SWP 18734|
| Exposure time ........| 9000s    | 2100s    | 6000s  |
| Dispersion ..........| Low      | Low      | Low    |
| Aperture ............| Large    | Large    | large  |
| Observation start time ..| 1985 Feb 28, 04:30:18 | 1982 Sep 27, 21:15:53 | 1982 Dec 5, 03:47:36 |
| Max continuum ..........| 75       | 150      | 51     |
| Background count ..........| 32       | 21       | 27     |

Fig. 1.—Flux vs. wavelength for the spectrum SWP 35335 of the UX UMa system V363 Aur. The solid curve is the best-fitting accretion disk model (see text for details). See the electronic edition of the PASP for a color version of this figure.

Fig. 2.—Flux vs. wavelength plot for the spectrum SWP 18138 of RZ Gru. The solid curve is the best-fitting accretion disk model (see text for details). See the electronic edition of the PASP for a color version of this figure.
For the model fitting to V363 Aur, we adopted a white dwarf mass $M_{\text{wd}} = 0.86 M_\odot$, inclination $i = 73^\circ$, and a reddening value of $E(B-V) = 0.3$ (see Table 1). We carried out model accretion disk fitting using optically thick, steady-state disk models. Our best-fitting accretion disk model to the dereddened spectrum SWP 25335 consisted of a white dwarf mass $M_{\text{wd}} = 0.8 M_\odot$ (log($g$) = 8.26), an inclination $i = 75^\circ$, and $\chi^2 = 2.24$, and it yielded an accretion rate $\dot{M} = 1 \times 10^{-9} M_\odot$ yr$^{-1}$. This best fit gave a distance of 134 pc for V363 Aur. This best-fitting accretion disk model is displayed in Figure 1.

RZ Gru is typically observed at $V = 12.3$, but has been observed as faint as 13.4. Thus, it is always in a high-brightness state, with excursions in brightness of a magnitude or less, which is also characteristic of the UX UMa subclass of novalike variables. The IUE spectrum reveals a strong continuum steeply rising toward shorter wavelengths, with deep absorption features due to C IV (blended 1548, 1550 components), Si IV (blended 1393, 1402 components), and N V (blended 1238, 1242 components). The N V, Si IV, and C IV resonance lines all have blueshifted absorption and weak, sharp P Cygni absorption flanking the short wavelength side of the profiles. These features may manifest a hot, outflowing wind arising from the inner accretion disk and boundary layer between the star and disk. The wind absorption at C IV and N V is very deep, as expected for a UX UMa system viewed at low inclination, where a larger disk surface area is emitting continuum photons that are absorbed by the outflowing wind.

Relatively little is known about RZ Gru. We adopted a reddening of $E(B-V) = 0.03$ (Bruch and Engel 1994) and adopted a nominal white dwarf mass of $0.6 M_\odot$ (log($g$) = 8) in the absence of any published value. From Table 1, the published orbital inclination is $61^\circ$. With these parameters, we carried out accretion disk model fitting to keep the accretion rate as a free parameter. Our best-fitting model accretion disk to SWP 18138 is displayed in Figure 2. The best-fit parameters are given in Table 3. The model accretion disk had $i = 60^\circ$, $M_{\text{wd}} = 0.55 M_\odot$ (log($g$) = 7.71), and $\chi^2 = 4.314$, and it yielded a distance of 116 pc and accretion rate $\dot{M} = 1 \times 10^{-9} M_\odot$ yr$^{-1}$. This optically thick, steady-state accretion disk accounts for essentially 100% of the FUV flux.

The observation of AC Cnc was obtained when its $V$ magnitude was 14.2, which is fainter by one magnitude than its normal brightness of 13.5. However, the system has been observed to be as faint as 15.4. Therefore, the IUE spectrum was taken during a fainter high state and not during its deep low state. The IUE spectrum is dominated by a strong C IV (1548, 1550) emission feature and weak emission lines of N V (1238, 1242), Si IV (1393, 1402), and He II (1640). While the high inclination of AC Cnc reduces the brightness of the disk, thus enhancing the possibility that the underlying white dwarf is exposed, the fact that the disk is viewed nearly edge-on raises the possibility that disk material and magnetic structures extending above and below the disk plane may complicate or obliterate the line spectrum and continuum exhibited by the exposed white dwarf’s photosphere.

We have adopted a reddening value, $E(B-V) = 0.055$ for AC Cnc, that we have obtained from the GALEX archive. Using this value, we dereddened the IUE spectrum and reanalyzed it with our grid of photosphere and accretion disk models. We carried out the model fitting in two ways: (1) taking the distance as a free parameter and (2) fixing the distance at values taken in the literature. Our model fitting of the dereddened spectrum of AC Cnc, treating the distance as a free parameter, and with $i = 75^\circ$ and $M_{\text{wd}} = 0.8 M_\odot$, resulted in the best-fitting model to the dereddened spectrum displayed in Figure 3. This model consists of an accretion disk with an accretion rate of $10^{-10} M_\odot$ yr$^{-1}$, a cool white dwarf contributing about 20% of the FUV flux, and a distance of 105 pc.

With a fixed distance of 450 pc (Thoroughgood et al. 2004), the best-fitting accretion disk model to the dereddened spectrum with $i = 75^\circ$ and $M_{\text{wd}} = 0.8 M_\odot$ yielded an accretion rate $\log(\dot{M}) = -9.0 M_\odot$ yr$^{-1}$. However, the fit is unsatisfactory. When we fit the original spectrum without dereddening but with the distance fixed at 450 pc, we obtained an accretion rate between $\log(\dot{M}) = -9.0$ and $-9.5 M_\odot$ yr$^{-1}$, closer to the value derived by Puebla et al. (2007).

4. DISCUSSION

It is interesting to compare our results for V363 Aur, RZ Gru, and AC Cnc with a statistical study by Puebla et al. (2007), which utilized a multiparametric optimization model fitting method, and explored how well current optically thick accretion disk models fit the FUV spectra of novalike variables and old novae in a sample of 33 novalike and old novae. This study included an assessment of the contribution of an assumed 40,000 K white dwarf to the FUV spectra, but did not include the white dwarf.

| Table 3: Synthetic Spectral Fitting |
|-----------------------------------|
| V363 Aur | RZ Gruis | AC Cnc |
| $M_{\text{wd}}$ | $0.80 M_\odot$ | $0.55 M_\odot$ | $0.80 M_\odot$ |
| Inclination | $75^\circ$ | $60^\circ$ | $75^\circ$ |
| Distance | 134 pc | 116 pc | 105 pc |
| $\chi^2$ | 2.24 | 4.31 | 1.88 |
| $\dot{M}$ | $1 \times 10^{-9} M_\odot$ yr$^{-1}$ | $1 \times 10^{-8} M_\odot$ yr$^{-1}$ | $1 \times 10^{-10} M_\odot$ yr$^{-1}$ |
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 40,000 K white dwarf model and disk model to estimate the flux contribution of the white dwarf. If this ratio was less than 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 inclinations the inner disk, boundary layer, and white dwarf should be significantly obscured by vertical structure in the disk. These authors adopted distances in the literature, while in our model fitting, we kept the distance, the white dwarf temperature, and the orbital inclination as free parameters.

For V363 Aur, the range of parameters in the Puebla et al. (2007) statistical fitting was an inclination range of 60 to 35°, white dwarf mass range of 0.7 to 1.1 \( M_\odot \), and an adopted distance of 550 pc, for which their best-fitting solution was an accretion disk with an accretion rate of \( 4.6 \times 10^{-9} M_\odot \text{yr}^{-1} \). Their derived value of the accretion rate is a factor of 5 larger than our derived accretion rate. We find that the major cause of the distance difference arises from the adoption of the reddening. Our adopted reddening, \( E(B-V) = 0.3 \) is taken from Szkody and Crosa (1981), and we consider it to be the most reliable value. Rutten et al. (1992) adopted \( E(B-V) = 0.1 \) following Schlegel et al. (1986). The difference in reddening itself generates a large difference in the distance. The galactic reddening is extremely large in the line of sight to V363 Aur, as large as 1.5, so if V363 Aur were very distant (say, 500–1000 pc), then it would have an even larger reddening.

For RZ Gru, Puebla et al. (2007) explored inclinations in the range of 10 to 35° and white dwarf masses in the range of 0.8 to 1.2 \( M_\odot \) and adopted a distance of 440 pc. Their best-fitting solution was an accretion disk with an accretion rate of \( 2 \times 10^{-9} M_\odot \text{yr}^{-1} \). Thus, their derived value of \( \dot{M} \) is a factor of 5 smaller than the value that we derive for RZ Gru. Stickland et al. (1984) derived an upper-limit distance to RZ Gru of 440 pc. Moreover, their result used an exceedingly crude fit to the spectral energy distribution, ignoring the inclination angle of the disk. Their disk has \( T_{\text{max}} = 39,000 \text{ K} \) and an inner radius of 9000 km. From the far more sophisticated published grid of Wade and Hubeny (1998) and from standard accretion disk theory, this corresponds to a WD mass of about \( \sim 0.55 M_\odot \) (perhaps slightly smaller), and the corresponding disk (for that WD mass with a disk having \( T_{\text{max}} = 39,000 \text{ K} \)) has a mass accretion rate of \( 10^{-8.5} M_\odot \text{yr}^{-1} \). Such a disk with a low inclination gives a distance of 400 pc, but gives a very bad fit (the slope does not fit properly). However, with an inclination of 60°, that same disk gives a slightly better fit and a distance of 230 pc. We note that the best fit to the IUE SWP data is obtained assuming \( i = 60 \text{ deg} \) with a mass accretion rate of \( 10^{-9.0} M_\odot \text{yr}^{-1} \) for \( M_{\text{wd}} = 0.55 M_\odot \). This gives a distance of 117 pc.

We confirm the finding by Puebla et al. (2007) that the white dwarf component in AC Cnc is a nonnegligible contributor to the FUV flux. However, the accretion rate that we obtained is nearly a factor of 10 lower than the rate determined by Puebla et al. (2007). We now have a reddening value, \( E(B-V) = 0.055 \) for AC Cnc, that we have obtained from the GALEX archive. Using this value, we dereddened the IUE spectrum and reanalyzed it with our grid of photosphere and accretion disk models. The fit with the distance kept fixed at 450 pc is unsatisfactory. When we fit the original spectrum without dereddening, we obtained an accretion rate between log(\( \dot{M} \)) = −9.0 and −9.5 \( M_\odot \text{yr}^{-1} \), closer to the value derived by Puebla et al. (2007).

Our model-derived distances are considerably lower than the distances cited for AC Cnc and V363 Aur in the published literature. For example, for AC Cnc, Shugarov (1981), Patterson (1984), Zhang (1987), Warner (1987), and Thoroughgood et al. (2004) obtained distances between 400 and 800 pc. For V363 Aur, Szkody & Crosa (1981), Berriman (1987), Rutten et al. (1992), and Thoroughgood et al. (2004) obtained distances between 450 and 1300 pc. Moreover, distances from an absolute magnitude calibration using infrared 2MASS magnitudes were derived by Ak et al. (2007). They found 704 + 161 / −208 pc for AC Cnc and 790 + 187 / −245 pc for V363 Aur. This IR calibration agrees with CV distances measured from trigonometric parallaxes (Gariety & Ringwald 2012). Furthermore, the very similar novalike BT Monocerotis (\( P_{\text{orb}} = 8.01 \text{ hr} \)) is measured to be at \( d = 1700 \pm 300 \text{ pc} \) (Smith et al. 1998), although a closer distance of 972 + 286 / −406 pc is reported by Ak et al. (2007). However, since nearly all of the published distances were derived in some degree from assumed and measured properties of the Roche-lobe-filling donor star, which is
not only evolved, but also irradiated (Thoroughgood et al. 2004), then it is possible that the uncertainties in the distances may be larger than what is estimated. Of the four distances in the literature, Patterson’s (1984) distance is based upon a relationship between the Hα equivalent width—$M_v$ relationship plus “properties” of the secondary (which is probably evolved) to obtain his distance. Given the difficulty of determining the correct spectral type and luminosity class (V or IV) of the secondaries in AC Cnc and V363 Aur, we believe a shorter distance to the two objects cannot be definitively ruled out.

It is obvious that the IUE spectra are not high-quality data, especially at the shorter wavelengths of the IUE SWP spectra. The Lyα region is strongly contaminated with airglow emission, and the continuum level across the spectrum is difficult to identify, as there are absorption lines and emission lines seen across the spectrum. Some of these features in both eclipsing systems may be due to magnetic structures or gas above the disk midplane. It is also possible that the continuum slope of the observed FUV spectra are affected by additional reddening (circumbinary?). Clearly, higher-quality, phase-resolved FUV spectra are needed to confirm (or deny) our results.

At their respective orbital periods, the secondaries of V363 Aur and AC Cnc should be G7 ±2 and K2 ±1, respectively, while the uncertainty in the orbital period of RZ Gru complicates a spectral type assignment. However, Stickland et al. (1984) estimated the secondary in RZ Gru to be an F5 dwarf. The secondaries in the three systems may be similar to each other in their degree of magnetic activity. Their convection zones and expected slower rotation may imply a lower level of magnetic activity. Since all three systems are novalike variables of the UX UM type and have similar periods, their accretion rates should be similar. This suggests the possibility that the white dwarf temperature may be the key factor that differentiates the observed behavior and accretion rates of the three systems. Further investigations of the long-period systems are clearly warranted.

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