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FUSE Spectroscopy of the Accreting Hot Components in Symbiotic Variables

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Abstract

We have conducted a spectroscopic analysis of the far ultraviolet archival spectra of four symbiotic variables, EG And, AE Ara, CQ Dra and RW Hya. RW Hya and EG And have never had a recorded outburst while CQ Dra and AE Ara have outburst histories. We analyze these systems while they are in quiescence in order to help reveal the physical properties of their hot components via comparisons of the observations with optically thick accretion disk models and NLTE model white dwarf photospheres. We have extended the wavelength coverage down to the Lyman Limit with FUSE spectra. We find that the hot component in RW Hya is a low mass white dwarf with a surface temperature of 160,000K. We re-examine whether or not the symbiotic system CQ Dra is a triple system with a red giant transferring matter to a hot component made up of a cataclysmic variable in which the white dwarf has a surface temperature as low as $\sim 20,000$ K. The very small size of the hot component contributing to the shortest wavelengths of the FUSE spectrum of CQ Dra agrees with an optically thick and geometrically thin ($\sim 4\%$ of the WD surface) hot ($\sim 120,000$ K) boundary layer. Our analysis of EG And reveals that its hot component is a hot, bare, low mass white dwarf with a surface temperature of 80–95,000K, with a surface gravity $\log(g) = 7.5$. For AE Ara, we also find that a low gravity ($\log(g) \sim 6$) hot ($T \sim 130,000$ K) WD accounts for the hot component.

Graphical abstract

Subject headings

stars; binaries; stars; symbiotics; individuals; CQ Dra; RW Hya; EG And; AE Ara

1. Introduction

Up to now, virtually all of the temperatures and luminosities of symbiotic hot components have been derived using the modified Zanstra method to obtain radiation temperatures needed to account for photoionization of the observed emission lines (Muerse et al. 1991; Muerse & Nussbaumer 1994; Skopal 2005), or by simply assuming a photospheric temperature. This is understandable given the daunting complexity of symbiotic stars and the possible sources of FUV continuum radiation that may arise from that complexity. Nevertheless, many models have been proposed for the origin of the emission lines including the assumption that they all arise from photoionization. Moreover, the temperatures are derived for the most part from the He II (1640) recombination line and the H lines, but they yield different temperatures, with the temperature from the He II lines much higher than that from the H lines. The He II lines may arise from a wind or from wind collision shocks or coronae. Added to this uncertainty is the fact that for the very few systems analyzed up to now with actual NLTE photospheric models (mostly post-novae), the model-derived temperatures for hot accreting white dwarfs are a factor of two to three lower than the temperatures derived by Zanstra techniques.

An important archive of far ultraviolet spectra on symbiotic stars was obtained using the Far Ultraviolet Spectroscopic Explorer (FUSE) spacecraft. These spectra cover a wavelength range from 1180Å down to the Lyman Limit at 912Å. For observations of the hot accreting components of symbiotic stars, this offers a huge advantage because, unlike the IUE SWP spectral range, the FUSE spectra are unaffected by any UV contribution of the nebular continuum which arises from the photoionization of the red giant wind. In IUE and HST FOS, GHRS and STIS spectra, this nebular continuum tends to flatten their continuum slopes which, if not removed properly, leads to grossly underestimated effective temperatures and accretion rates.

Moreover, in the short wavelength part of the FUV, the hot boundary layer (BL) between the star and disk may contribute to the FUV. Luna et al. (2013) have shown that most of the symbiotic systems they observed in the X-ray domain with the SWIFT spacecraft appear to have optically thick boundary layers that emit strongly in the FUV. Given this empirical

result, it is clear that our modeling of the FUSE spectra should, when possible, take into account the boundary layer between the hot star and disk in symbiotic stars.

We have selected four systems with archival FUSE spectra for this study: CQ Dra, RW Hya, EG And and AE Arae. For CQ Dra and RW Hya we found, respectively, a matching IUE SWP spectrum and HST/GHRS spectrum to extend the spectral coverage. There is no evidence that the S-type symbiotics in this paper are metal poor, nor that their giant donor stars are s-process enhanced (Galan et al. 2016). This s-process enhancement is due to past mass transfer (when the present WD was on the AGB), and provides very strong indications that the WD mass should be at least $\sim 0.55 M_{\odot}$. CQ Dra has an outburst history and is clearly more interacting than RW Hya.

For those systems showing ellipsoidal light curves, especially in the red and near-IR range (where the red giant dominates the spectrum), it is very likely that the red giant is filling or nearly filling its Roche lobe. Therefore the mass transfer and accretion is mostly through L1, and hence an accretion disk may be present. Their mass transfer/accretion rates should also be relatively high, $\sim 10^{-7} M_{\odot}/\text{yr}$ as revealed by numerical hydrodynamic simulations of mass transfer in such systems. In relation to this mass transfer, Shagatova et al. (2016) have found, using SWIFT X-ray observations, that the wind from the giants in S-type symbiotic stars is not spherically symmetric but is enhanced or focused in the orbital plane which raises the accretion efficiency onto the hot component.

The published orbital and physical parameters of these four systems are given in Table 1 where we list, by row: (1) the system name; (2) the distance estimate in pc; (3) orbital period in days P_{orb} ; (4) the orbital inclination in degrees; (5) estimated mass of the hot component, M_{hot} ; (6) the color excess $E(B-V)$; and (7) the references for these parameters. These systems have been studied while in quiescence which optimizes the study of their hot components because their accretion rates and system luminosities tend to be lower. Our aim is to determine for the first time, with NLTE model accretion disks and model photospheres, the accretion rates, accretion efficiency and the temperatures and luminosities of the hot components and ascertain whether their FUV radiation is from accretion light or WD photospheric light or both.

In Sec.2 we present an observing log of the archival FUV spectra utilized in our study; in Sec.3 we describe our model accretion disks, high gravity photospheres and modeling analysis techniques; in Sec.4 we describe each system in greater depth and summarize our model fitting results; and in Sec.5 we draw our conclusions.

2. Archival Far Ultraviolet Spectroscopic Observations

In Table 2, we provide the observing log for all four systems where we list the observing details by row: (1) the system name; (2) the spectrum data identification number; the (3) date and (4) time of the observation; (5) the exposure time in seconds.

All of the FUSE spectra of the four systems were acquired through the LWRs aperture in TIME-TAG mode. Each exposure was made up of multiple subexposures. As pointed out by Godon et al. (2012), the FUSE reduction requires extensive post-processing of the data.

Details on the acquisition and processing of the FUSE data as well as the potential pitfalls (e.g. the ‘worm’, fixed-pattern noise, etc.) are discussed by Godon et al. (2012) and will not be repeated here. The co-added FUSE spectra of EG And, AE Arae, CQ Dra, and RW Hya are displayed in Figs. 1,2,3 and 4, respectively, where the strongest spectra line features are identified.

We also used an IUE SWP spectrum to extend the model fits to the FUSE spectrum of CQ Dra to $\sim 2000\text{\AA}$, and an HST/GHRS spectrum to extend the model fits to the FUSE spectrum of RW Hya to $\sim 1800\text{\AA}$, as listed in Table 2.

3. Model Accretion Disks and Model Photospheres

Model accretion disks from the optically thick disk model grid of Wade & Hubeny (1998) were utilized in this study. The outermost disk radius, R_{out} is chosen in such a way that the $T_{eff}(R_{out})$ of the outermost annulus is close to 10,000K. Disk annuli beyond this are so cool that they would contribute very little to the mid and far UV disk flux. For these steady state disks, by definition the mass transfer is assumed constant for all annuli.

Hence, the disk temperature as a function of radius is given by

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

where $x = r/R$ and $\sigma T_s^4 = 3GM_{wd}\dot{M}/8\pi R_{wd}^3$

These disk models include limb darkening which is incorporated using the methodology of Diaz et al. (1996). They use the Eddington-Barbier relation, the kinetic temperature increase with depth in the disk, and the temperature and wavelength dependence of the Planck function.

The database of disk models has the following combination of disk inclination angle $i = 18, 41, 60, 75, 81$ degrees, accreting WD mass $M_{wd} = 0.35, 0.55, 0.80, 1.03, \text{ and } 1.21 M_\odot$ and mass accretion rate $\text{Log}(\dot{M}) = -8.0, -8.5, -9.0, -9.5, -10.0, -10.5$ to fit the observed spectrum. When called for, we also constructed model disks outside of the parameter range of Wade & Hubeny (1998) in our search for the best fitting models.

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 then SYNSPEC version 48 (Hubeny & Lanz 1995) to construct synthetic spectra. We used our database of photospheric spectra covering the temperature range from $\sim 13,000\text{K}$ to $250,000\text{K}$ in increments of 500K (for low T_{wd}), 1000K (for intermediate T_{wd}), 5000K and $10,000\text{K}$ (for very large T_{wd}), and a surface gravity range, $\text{log}(g) = 7.0 - 9.0$, in increments of 0.2 and 0.5 in $\text{log}(g)$. When needed, we have also computed models outside this range of surface gravities in our search for better fitting solutions. The mass radius relation (from Hamada & Salpeter (1961); Wood (1995) or Panei et al. (2000) for different compositions and non-zero temperature WDs) is used to obtain the radius of the WD. When needed, we

also included a boundary layer by assuming that a fraction of the stellar surface (the equatorial region) has a higher temperature. Namely, we generated a two-temperature WD spectrum to include the boundary layer. The size and the temperature of the boundary layer were varied until a best-fit was found.

When available, we adopted published E(B-V) values to de-redden the spectra. We took the published parameters for the four systems to use as initial estimates in our model fitting. The emission line and ISM absorption line regions were masked out in the model fitting. We carried out a range of disk and photosphere model fits to derive accretion rates, possibly estimate hot component temperatures, masses, orbital inclinations, and to compare model-derived distances with distance estimates published in the literature. Our main focus is to determine whether an accretion disk is present, estimate the temperature of the white dwarf, estimate the accretion rate, and gain possible insights into the underlying mechanism of their outbursts. The underlying, accreting white dwarf could be hidden from us by the accretion disk (if a disk can form in a wind-accreting system) or by the nebula and red giant's wind. It is because of the multi-component flux contributions of these emitting sources that actual model fitting analyses of the hot components have been very few and daunting. For both of these two types of models, we determined whether an improved fit resulted from a combination of a disk plus a white dwarf model. We employ a chi square minimization routine FIT, to find the lowest reduced χ^2_ν (χ^2 per degrees of freedom ν) values model (best-fit). The scale factor, S , normalized to a kiloparsec and solar radius, is defined in terms of the white dwarf radius R as

$$F_{\lambda}(\text{obs}) = S H_{\lambda}(\text{model}),$$

where $S = 4\pi R^2 d^{-2}$, and d is the distance to the source. For the range of white dwarf masses, we adopted the mass-radius relation from the evolutionary model grid of Wood (1995) for C-O cores. The best-fitting model or combination of models were selected on the basis of the minimum χ^2_ν value achieved. However, we required additional fitting criteria: the goodness of fit to the continuum slope, the goodness of fit to the observed Lyman series (when not contaminated with emission) and the requirement that the scale factor-derived distance agrees with published distance estimates in Table 1.

4. System by System Discussion and Modeling Results

The best fitting results are recapitulated in Table 3 where for each system, by row, we list the log of the WD surface gravity, the WD effective surface temperature, the WD radius in solar radii, the WD luminosity in solar units, the boundary layer temperature (if the BL was included in the best fit model), the boundary layer luminosity (if the BL was included in the best fit model), and the mass accretion rate of the accretion disk (if a disk was included in the best fit model).

4.1. CQ Dra

CQ Dra was originally thought to be a cataclysmic variable in binary orbit with a red giant (Reimers et al. 1988), but was later re-classified as a symbiotic variable. However, as

discussed below, the cataclysmic variable interpretation of the hot component may be correct after all. CQ Dra has a reliable HIPPARCOS parallax $\pi = 5.25 \pm 0.48 \text{ mas}$ (van Leeuwen 2007). The orbital period for CQ Dra was determined to be 1703 days by Eggleton et al. (1989) from radial velocity periodicity searches. This is the longest orbital period of the four systems discussed in this work.

We found a usable FUSE spectrum of CQ Dra in the MAST archive driving our investigation in the following direction. The FUSE spectrum has much lower continuum flux level than the IUE spectra and was obtained in a state of relative low luminosity. Curiously, the Lyman (series) profiles of H are not clearly seen, making it more difficult to identify a disk versus a WD. The spectrum does not show signs of interstellar absorption as seen in the FUSE spectra of the other 3 systems in this work, except for atomic H (sharp Lyman series towards the shortest wavelengths). Some of the sharp emission lines are probably due to terrestrial airglow and sunlight reflected in the telescope, and some of the sharp, weak absorptions may also be either terrestrial (e.g. N I 1135) or interstellar (e.g. Fe II 1145).

While identifying lines in the FUSE range via comparison with FUSE spectra of other systems with accreting white dwarfs, we found that the FUSE spectrum of the hot white dwarf in the dwarf nova RU Peg during quiescence, is very similar to the FUSE spectrum of CQ Dra, as clearly shown in Fig.5. There is also a similarity between the IUE spectra (e.g. SWP28355) of the two systems as displayed in Fig. 6. At first glance, these similarities would seem to add support the possibility that the hot component in CQ Dra may indeed be a cataclysmic variable as Reimers et al. (1988) originally claimed, thus identifying CQ Dra as a triple system.

For the modeling of the FUSE spectrum, we assume a WD mass of $0.8 M_{\odot}$. Some parts of the FUSE spectrum show better agreement with a WD at $T_{wd} = 30,000 \text{ K}$ while at the shortest wavelengths in the FUSE spectrum, there is better agreement with a WD surface temperature higher than $50,000 \text{ K}$. However, such a high temperature lead to an unacceptably large distance. When we fit the FUSE spectrum with an accretion disk model, then for a distance of 100 pc (the Reimers et al. (1988) distance), we obtain $\dot{M} = 10^{-9.5} M_{\odot}/\text{yr}$ for disk inclinations of 40 to 60 degrees. If $\dot{M} = 10^{-9} M_{\odot}/\text{yr}$, the distance is of order 250 pc and the fit is poor. The only decent accretion disk fit to the FUSE spectrum of CQ Dra requires $\dot{M} = 1 \times 10^{-8} M_{\odot}/\text{yr}$ and corresponds to a distance of $\sim 950 \text{ pc}$.

Hence the very hot component of the system contributing flux to the shortest wavelengths of FUSE must have a very small size, smaller than the inner disk and smaller than the WD. We, therefore, decide to include the contribution of a boundary layer in our modeling.

The BL is included either as a direct optically thick component (at high mass accretion rate the boundary layer forms a hot equatorial spread layer on the WD surface (Inogamov & Sunyaev 1999; Piro & Bildsten 2004)), or as an optically thin hot component (at low mass accretion rate (Narayan & Popham 1993)) heating up the equatorial region of the WD through advection of energy (Abramowicz et al. 1995). Consequently, in either cases, we assume, that the WD equatorial region has an elevated temperature, and we model the WD as a two-temperature component. The WD itself has a temperature that is moderate ($T < 30$,

000 K, so as to not contribute all of the flux) and the boundary layer has a temperature of the order of 100,000 K. If the visible part of the BL has a fractional area f , then the visible part of the WD has an area $1 - f$. To this two-temperature WD we add an accretion disk.

We obtain that the best fit to the continuum and within a reasonable (scaled) distance is for a WD with a temperature $T_{\text{wd}} \approx 20,000 \pm 3000$ K, a boundary layer of size $4 \pm 1\%$ and temperature $120,000 \pm 20,000$ K, and a disk with $\dot{M} \approx 10^{-10} M_{\odot}/\text{yr}$, $i \approx 40 - 50^\circ$. Most of the solutions were obtained for $\dot{M} = 10^{-10} M_{\odot}/\text{yr}$, but some solutions were also obtained for $\dot{M} = 10^{-10.5} M_{\odot}/\text{yr}$ and $\dot{M} = 10^{-9.5} M_{\odot}/\text{yr}$, therefore adding an error bar to the mass accretion rate $\log(\dot{M}) = -10.0 \pm 0.5 (< M_{\odot}/\text{yr})$. We present such a best fit to the FUSE spectrum of CQ Dra in Fig.7. We note that such a mass accretion rate is consistent with the low brightness state during which the FUSE spectrum was obtained.

We also retrieved an IUE SWP spectrum (33521) of CQ Dra in the low state with a continuum flux matching the FUSE spectrum (in the spectral region where they overlap), and decided to model the combined FUSE + IUE spectrum. We found that the IUE spectrum agrees well with our FUSE best-fit model, as shown in Fig.8, an indication that CQ Dra consistently comes back into the same low state.

4.2. RW Hya

The S-type symbiotic system RW Hydrae (=HD 117970) has a primary component classified as a M2 III red giant. The inclination of RW Hya is high, just sufficient for the system to undergo eclipses while the orbital period is 370.2 days (Merrill 1950; Kenyon & Mikolajewska 1995). Published estimates of the white dwarf mass range extend from 0.3 to $0.6 M_{\odot}$. The red giant mass is between 0.5 and $2 M_{\odot}$ (Schild et al. 1996; Kenyon & Mikolajewska 1995). We take the distance to the system, based upon the corotation of the red giant as found by Schild et al. (1996) of 670 ± 100 pc. The total luminosity of the system at this distance is $\sim 700 L_{\odot}$. RW Hya exhibits ellipsoidal variability (Rutkowski et al. 2007) based upon the observed light curve. The distance set by the Roche lobe geometry, which requires a filling factor above 0.9, is then 1.7 kpc.

A noteworthy aspect of RW Hya for studies of the hot component is that there is little or no evidence for an accretion From the disk. Its multi-wavelength data was analyzed most recently by Skopal (2005) who dismissed an accretion disk but fit the FUV data with a hot black body SED at $T_{\text{eff}} = 10^5$ K.

To our delight, we found a good FUSE spectrum of RW Hya in the MAST archive which had never been analyzed and allowed us to sample the FUV flux down to the Lyman Limit. The FUSE spectrum of RW Hya, with its flat continuum increasing towards shorter wavelengths, indicates that the hot component has a very high temperature, but the Lyman series is affected by ISM atomic H absorption lines.

Single disk models require a very high mass accretion rate to fit the relatively flat continuum and yield a ridiculously short distance. We therefore conclude that the disk does not

significantly contribute to the FUV spectrum, and that the surface area of the hot component is much smaller than that of an accretion disk.

We carried out single temperature hot WD model fits for a low mass WD to the FUSE spectrum of RW Hya and found a best fit corresponding to a white dwarf with a surface temperature of 160,000K with $\log(g) = 6.5$. The temperature and gravity are dictated by the shape of the wings of the Lyman series (where possible) and continuum. Assuming a mass of $0.4M_{\odot}$ and radius of $0.065R_{\odot}$ yields a scale factor-derived distance of 811 pc confirming that a low mass white dwarf with its larger radius, and a very high temperature gives a distance to RW Hya which is within the error bars of the original Schild et al. distance. This best-fitting NLTE WD model atmosphere fit to the FUSE spectrum is shown in Fig.9. While we calculate a luminosity of 2 to $3,000L_{\odot}$ as listed in Table 3, a luminosity of $700L_{\odot}$ results if one assumes a $\log(g)=6.8-7.0$, instead of 6.5.

While a low mass (large radius) hot component seems consistent, it cannot be ruled out that the WD is undergoing hydrogen shell burning, has a higher mass but an extended atmosphere whose radius is larger than that given by the WD mass-radius relation.

We found a HST GHRS spectrum of RW Hya in the MAST archive that has a similar flux level to the FUSE spectrum. In this way, we extended the wavelength coverage from 1700Å down to the Lyman Limit. After dereddening the spectra with $E(B-V)=0.10$, we found basically the same solution for the combined spectrum (FUSE+GHRS) that we found for FUSE alone, namely a very hot and very small mass WD can provide the flux needed. This single temperature white dwarf fit is displayed in Fig.10. When compared to the model, the HST GHRS spectrum has a flux slightly lower.

An accreting white dwarf at this very high temperature almost certainly sustains thermonuclear burning of the accreted hydrogen and should be a supersoft X-ray source. The absorbing column of the ionized red giant wind in a symbiotic system is nominally more than sufficient to obscure X-ray emission from an accreting white dwarf with shell burning. Thus, the absence of X-ray emission does not rule out the presence of thermonuclear shell burning in the hot component.

4.3. EG And

Observations of EG And suggest the wind from the giant is focused toward the orbital plane thus raising the accretion efficiency and rate of accretion onto the WD (Shagatova et al. 2016). The mass loss rate from the giant is estimated to be a few times $10^{-6}M_{\odot}/\text{yr}$ with an inclination of $i = 80$ degrees. The interstellar reddening is $E(B-V) = 0.05$ (Kenyon & Garcia 2016). The temperature ($\sim 75,000\text{K}$) and luminosity of the hot component in EG And were estimated using a modified Zanstra method while the orbital period, $P_{\text{orb}} = 482.6$ days was re-determined by Fekel et al. (1992) who also determined a distance of 568 pc. van Leeuwen (2007) presented a distance of 513 ± 169 pc based upon a Hipparcos parallax. The mass of the hot component $M_{\text{wd}} = 0.35 \pm 0.1M_{\odot}$ Kenyon & Garcia (2016).

We carried out a synthetic spectral analysis of the FUSE spectrum alone. We assumed a distance of 400–700pc, a low white dwarf mass between 0.35 and $0.6M_{\odot}$ and orbital

inclination of $i = 60, 75$, and 81 degrees, and an interstellar reddening value of $E(B-V) = 0.05$. Our first fitting attempt involved a steady state, optically thick accretion disk. However, our accretion disk fitting met with limited success. The disk fits are poor toward the short wavelength (Lyman Limit) end of the FUSE wavelength range. Moreover, the distance implied by the disk fits, the scale-factor derived distance is far too close, even for $\dot{M} = 10^{-8} M_{\odot}/\text{yr}$, $i = 60$ degrees and 75 degrees. At a high mass accretion rate, the disk becomes rather thick and with an inclination of 80 degrees, we expect the boundary layer near the equatorial region of the star to be masked by the disk. We are thus forced to conclude that a standard accretion disk cannot account for the FUSE spectrum of EG And.

Next, we tried fitting hot NLTE white dwarf photospheres to the FUSE data of EG And. The best fit that we obtained is for $\text{Log}(g) = 7.5$ and $T_{\text{wd}} \sim 80\text{--}95,000$ K. If $\log(g) < 7.5$, then the best-fitting temperature becomes lower. When we combine an optically thick disk with the WD model, there is an improvement over a disk-only fit but the WD +disk fit is clearly inferior to the WD-only model. The addition of a hot boundary layer to the WD (i.e. a two-temperature WD) introduces a degeneracy to the solution in that the contribution of small surface area BL with $T \sim 10^5$ K BL does not produce a noticeable change in the spectrum given that the WD itself has already a temperature close to $100,000$ K (producing a flat spectrum). Also because of the high inclination, the contribution from a BL would be minimal. Thus, for EG And, it appears that the hot component can be identified with a hot, bare white dwarf having a surface temperature of $80\text{--}95,000$ K and $\text{Log } g = 7.5$. These derived parameters using synthetic spectral fitting are in good agreement with the results of Kenyon & Garcia (2016). This best-fitting solution is displayed in Fig. 11.

4.4. AE Arae

On the basis of IR spectroscopy, Fekel et al. (2010) found an orbital period of 803 days. There is no evidence of eclipses in AE Ara. Fekel et al. (2010) estimated an orbital inclination of 51 degrees and a distance range of 2.3 to 3.2 kpc. More recently, Galan et al. (2016) revealed that AE Ara shows metallicity closer to solar by ~ 0.2 dex. The presence of enriched ^{14}N isotope found in AE Ara reveals that the giant donor has gone through the first dredge-up.

If we assume that the WD mass has to be somewhere between 0.35 and 0.6 , and that the distance is estimated to be around 2.3 kpc to 3.5 kpc, with an inclination of 60 deg and reddening of $E(B-V) = 0.25$, we find that an accretion disk cannot contribute to the flux even with $\dot{M} = 1 \times 10^{-8} M_{\odot}/\text{yr}$. Such a disk would imply an extremely short distance and would not produce the increase of flux observed in the short FUSE wavelengths.

Here too, it is apparent that the hot component in AE Arae is not an accretion disk. In order to generate such a large FUV flux, a WD has to be hot and its radius has to be extended (it cannot be the boundary layer neither). We found that fitting solutions with M_{wd} as specified above and the distance as indicated, must have a gravity as low as $\log(g) = 6.0$ or even lower.

The best fitting results at $\log(g) = 6$ are as follows. For a distance $d = 2.3$ kpc (lower limit), the WD temperature ranges between $100,000$ K and $160,000$ K, where the lower temperature

is obtained for $R_{wd} = 0.134R_{\odot}$ ($M_{wd} = 0.65M_{\odot}$), and the higher temperature is obtained for $R_{wd} = 0.100R_{\odot}$ ($M_{wd} = 0.36M_{\odot}$). For a distance $d = 3.5\text{kpc}$, the only fitting solution is for a larger mass, hotter WD with $M_{wd} = 0.62M_{\odot}$, $R_{wd} = 0.131R_{\odot}$ and $T_{wd} = 160,000\text{K}$. An intermediate best fitting solution is displayed in Fig.12. We found that lower gravity WDs fit better than higher gravity WDs. Hence, with the larger radius of lower mass WDs, the calculated luminosity is higher and is consistent when scaling the model using the radius and distance.

5. Discussion

The four S-Type symbiotic binaries that we chose for this study were selected for their relative "simplicity" compared with symbiotics containing Mira variables with their high wind mass loss rates, more complex nebulae and associated dust. Our approach was to confront their FUV spectra with NLTE accretion disk models and hot white dwarf model photospheres, thereby probing the nature of the hot component, testing temperatures derived from modified Zanstra techniques, and achieving our key objectives; the accretion rate, accretion efficiency, and the photospheric temperatures of the hot components in S-type systems. These parameters are crucial for understanding the evolution of symbiotic stars, including whether accretion disks form and dominate the FUV light, and whether the relationship between the long term time-averaged accretion rate and the surface temperature of the accretors via compressional heating (Sion 1995; Townsley & Bildsten 2003), also holds for symbiotic hot components.

For most symbiotics, including the "simpler S-Types", the FUV spectra obtained with IUE (SWP), and HST (FOS, GHRS, STIS) of the hot components cannot be successfully modeled. The chief problem is that the observed FUV continuum slopes are less steep due to the inclusion of flux contributions principally from the nebular continuum produced by the photoionized red giant wind. Hence, the hot components mimic a much cooler white dwarf or cooler accretion disk thereby lowering the derived temperature or accretion rate, while the true continuum slope of the hot component alone is much steeper Skopal (2005). In addition, while 3D numerical simulations (Mohamed & Podsiadlowski 2007; de Val-Borro et al. 2014) show that the accretion disks in symbiotics resemble optically thick, steady state disks, the scale of the symbiotic systems is vastly different from cataclysmics, and the accretion flows are more complex.

However, our investigation underscores the critical importance of extending the FUV coverage of accreting white dwarfs in interacting binary systems down to the Lyman Limit. This FUSE coverage was key to our understanding of the nature of the hot components in CQ Dra, RW Hydrae, EG And and AE Ara.

A number of studies of symbiotic stars with X-ray observations by Luna & Sokoloski (2007); Kennea et al. (2009); Luna et al. (2013); Nunez et al. (2016) offer important insights into our FUSE FUV observations, that those systems with hard X-ray emission ($E > \text{several keV}$) reveal the presence of an accretion-disk boundary layer. If the boundary layer is optically thin, most of the radiated energy (equal to half of the accretion luminosity) is emitted in the X-ray domain, while an optically thick boundary layer emits most of its

radiation in the EUV/FUV domain, with much less emitted in X-rays. For symbiotics without shell burning, the hard X-ray emission can provide an estimate of the accretion rate and the mass of the accreting WD. Luna et al. (2013) have also found that systems in which the symbiotic phenomenon is powered by accretion alone (as opposed to shell burning + accretion) tend to show large-amplitude, stochastic, UV variability.

In the present work on the four symbiotics observed with FUSE, the X-ray observations of EG And by Luna et al. (2013) offer an important comparison with our FUSE analysis. Luna et al. (2013) classifies the X-ray spectrum of EG And as Type β which is defined as a Soft X-ray source with most of the photons having energy less than 2.4 keV, the maximum energy detectable with ROSAT. Our analysis of the FUSE data indicates that EG And's hot component is a bare accreting white dwarf (no appreciable disk present) which may emit a hot wind. Such a wind would interact with the cold, slow wind of the giant donor. A collision of winds from the white dwarf with those from the red giant (Muerse et al. 1991) is the scenario which underlies the β classification of the X-ray spectra of symbiotics.

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Fig. 1.

The FUSE spectrum (flux versus wavelength) of EG And is shown with line identification. The spectrum has not been dereddened. All the sharp absorption lines are possibly from the interstellar medium (ISM). ISM hydrogen molecular lines are identified by their band (Werner or Lyman), upper vibrational level (here 1 to 13), and rotational transition (R, P, or Q with lower rotational state $J=1-3$). The (ISM) hydrogen Lyman series is identified under each panel. Additional ISM lines, such as O I, Fe II, Ar I and so on, are also identified. Some broad absorption lines from the sources are present, and consist of highly ionized species. These are the N IV (~ 923), S VI (~ 933 & 944), & O VI (~ 1032 & 1037) lines. Some of the sharp emission lines are also from the sources, such as the C III (977 and 1175), S IV (1073) lines and the two P V (1118 & 1128) lines. Other sharp emissions lines are known air-glow lines and are marked with an “earth” symbol. The nitrogen lines (~ 1185 & 1135) are also terrestrial in origin. The feature around $1152\text{\AA}$ is a known instrument fixed pattern noise (FPN).

Fig. 2.

The FUSE spectrum of AE Ara is shown with line identification. The spectrum has not been dereddened. Like the spectrum of EG And, the spectrum of AE Ara is heavily affected by ISM absorption lines, including molecular and atomic hydrogen lines, and low ionization species such as Fe II, Ar I, O I, S I, & Si II. The source itself present blue-shifted broad absorption lines from higher ionization species such as N IV (923), S VI (933 & 943), and O VI (1029 & 1036) as well as emission lines from S VI (934 & 945), C III (977 & 1075), the O VI doublet, S IV (1073), Si III (113), and P V (1118 & 1128). The very sharp emission lines of the hydrogen Lyman series and O I are most probably geo- and helio-coronal in origin, contamination of sunlight reflected in the SiC channels (e.g., C III 977). We note that the S VI (933, 944) and the Oxygen doublet appear to have two components: the first is in emission at about the rest wavelength, and the second is in absorption with a blueshift of at least $2\text{\AA}$.

Fig. 3.

The FUSE spectrum of CQ Dra is shown with line identification. The spectrum has not been dereddened. The spectrum presents little ISM contamination, except possibly for some absorption lines from low ionization species such as Fe II. The source presents broad emission lines from the O VI doublet and the two C III lines (977 & 1175) all superposed with sharper absorption lines.

Fig. 4.

The FUSE spectrum of RW Hya is shown with line identification. The spectrum has not been dereddened. The spectrum is moderately affected by ISM lines. The absorption lines we identify from the source are the O VI doublet lines, the P V (1118 & 1128) lines and the C III (1175) line. The O VI doublet seems to be made of a sharp (a few Å) component superposed onto a much broader ($\sim 10\text{Å}$) component. Weak sharp red-shifted emission lines are identified from higher ionization species as follows: S VI (934 & 945), C III (977), O VI (1034), He II (1085) and P V (1118 & 1128).

Fig. 5.
The FUSE spectrum of the hot white dwarf in the dwarf nova RU Peg during quiescence, shown in comparison with the (dereddened) FUSE spectrum of CQ Dra.

IUE SWP Spectra

Fig. 6.

A comparison of the IUE spectrum (SWP28355) of CQ Dra and the white dwarf in the dwarf nova RU Peg during quiescence. For clarity the IUE spectrum of CQ Dra has not been dereddened here. The IUE SWP spectra of CQ Dra in the archive are dominated by strong emission lines of C III (1175), weak N V (1240) emission, weak Si IV (1398) emission, very strong C IV (1550) emission, with He II (1640) being notably absent.

Fig. 7.

The best fit theoretical Disk + white dwarf + boundary layer spectrum (in black) to the dereddened FUSE spectrum of CQ Dra (in red). The WD has a mass of $0.8M_{\odot}$ and a relatively low temperature of 20,000K, with 120,000K boundary layer covering 4% of the WD surface. The disk has an accretion rate of $\dot{M}=10^{-10}M_{\odot}/\text{yr}$, and an inclination of 60° . The disk (dashed line) contributes 18% of the flux and the WD+BL (dotted line) contribute the remaining 82%. The distance obtained from the fit is 164pc. The known emission lines regions have been masked (in blue) are not modeled.

Fig. 8.

The same model shown in Fig.7 is shown here, but now it fits the combined FUSE + IUE SWP (33521) spectrum fo CQ Dra. The fit to the continuum is relatively good all the way down to $\sim 1,800\text{\AA}$.

Fig. 9.

A single temperature hot NLTE WD model fit for a low mass WD to the dereddened FUSE spectrum of RW Hya with a best fit corresponding to a white dwarf with a surface temperature of 160,000K and $\log(g) = 6.5$. Assuming a mass of $0.4M_{\odot}$ with a radius of $0.065R_{\odot}$ yields a scale factor-derived distance of 811 pc, confirming that a low mass white dwarf with its larger radius, and a very high temperature gives a distance to RW Hya which is within the error bars of the original Schild et al. distance.

Fig. 10.

The combined dereddened FUSE+ HST GHRS spectrum of RW Hya is modelled as in the previous figure. A very hot and very small mass WD provides the required flux. The fit reveals an accreting white dwarf with $T_{wd} = 160,000\text{K}$, $\log(g) = 6.5$. The two spectra were obtained at different epochs and with different instruments and the HST spectrum has a flux slightly lower than in the FUSE spectrum.

Fig. 11.

The best-fitting model solution for the dereddened FUSE spectrum of EG And. The hot component is revealed to be a hot, bare white dwarf with a surface temperature of 90,000K and $\log(g) = 7.5$.

Fig. 12.

The dereddened FUSE spectrum of AE Ara has been fitted with a single WD model with $\log(g) = 6$ and $T_{\text{eff}} = 130,000$ K.

Table 1

Physical and Orbital Parameters

System Name	Distance <pc>	P_{orb} <days>	Inclination <deg>	$M_{hot} M_{\odot}$	E(B-V)	Ref.
EG And	400 – 700	482.6	60	0.4 – 0.6	0.05	(1,2,3)
AE Arae	2.3k–3.5k	812	51	0.35–0.67	0.25	(4,5,6)
CQ Dra	178	1703	–	–	0.10	(7,8)
RW Hya	820	370.2	> 70	0.5	0.10	(9,10,11)

¹Muerstet et al. (1991)

²Fekel et al. (2000)

³Kenyon & Garcia (2016)

⁴Mikolajewska et al. (1997)

⁵Mikolajewska et al. (2003)

⁶Fekel et al. (2010)

⁷Reimers et al. (1988)

⁸Perryman et al. (1997)

⁹Merrill (1950)

¹¹Kenyon & Mikolajewska (1995)

¹⁰Schild et al. (1996)

Table 2

Observation Log

System	Data ID Obs.	Date Obs.	Time (UT)	Exp. Time(s)
EG And	FUSE C1690190	2003-12-01	01:20:46	9026
AE Ara	FUSE D1460201	2004-05-18	17:41:56	9831
CQ Dra	FUSE D9050401	2004-01-09	21:24:59	36719
	IUE SWP33521	1988-05-13	15:55:08	1800
RW Hya	FUSE E1460103	2004-06-14	06:07:21	6043
	GHRS z2xh0105t	1996-03-05	18:44:20	218
	GHRS z2xh0106t	1996-03-05	18:49:48	218

Table 3

Multi-Component Model Fitting Results

Parameters	CQ Dra	RW Hya	EG And	AE Ara
$\log(g) <\text{cgs}>$	8.4	6.5	7.5	6.0
$T_{\text{wd}}/10^3\text{K}$	20 ± 3	160 ± 10	80–95	130 ± 30
$(R_{\text{wd}}/R_{\odot})\times10^{-2}$	0.94	6.6	1.9–2.3	10–13.4
$L_{\text{wd}}/L_{\odot}$	$(6.6\text{--}22)\times10^{-3}$	$(2\text{--}3.3)\times10^3$	12.9–38.4	$(1.6\text{--}10.1)\times10^3$
$T_{\text{BL}}/10^3\text{K}$	120 ± 20	—	—	—
$L_{\text{BL}}/L_{\odot}$	0.316–1.215	—	—	—
$\log(\dot{M}/M_{\odot}/\text{yr})$	-10 ± 0.5	—	—	—