FAR-ULTRAVIOLET SPECTROSCOPY OF OLD NOVAE. I. V603 AQUILA*

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Received 2015 January 12; accepted 2015 June 3; published 2015 July 7

ABSTRACT

We present the results of a synthetic spectral analysis of the far-ultraviolet archival International Ultraviolet Explorer, Hubble Space Telescope (HST), and FUSE observations of the fast old nova V603 Aql, obtained some 90 years after its 1918 nova outburst. Our analysis utilizes the new Hubble fine guidance sensor parallax distance for this nearly face-on old nova, a high white dwarf (WD) mass, and a low reddening. Our analysis includes non-truncated optically thick accretion disks since V603 Aql is neither a polar nor an intermediate polar. Our synthetic spectral modeling of the FUSE and HST spectra analyzed separately indicate a mass transfer rate of \( M = 1.5 - 2.2 \times 10^{-9} M_\odot \text{ yr}^{-1} \) for the FUSE and HST spectra, respectively, assuming a WD mass of 1.2 \( M_\odot \). The mass accretion rate also depends on the assumed WD mass and increases by a factor of two for a WD mass of 0.8\( M_\odot \). Combining the FUSE and HST spectra lead to the same results. Potential implications are discussed.

Key words: novae, cataclysmic variables – stars: individual (V603 Aquilae) – ultraviolet: stars

1. INTRODUCTION

There is much that we do not know about old novae (post-classical novae in or approaching quiescence). Do they become dwarf novae as their accretion rates drop? When does nuclear burning stop and hence the soft X-ray production stop following the dwarf novae as their accretion rates drop? When does nuclear burning cease? Do they become extinct forever? There have been 110 far-ultraviolet spectra obtained for V603 Aql with the short wavelength prime camera (SWP) on the IUE spacecraft. The IUE-SWP spectra cover the wavelength range

* Based on observations made with the NASA-CNES-CSA Far-Ultraviolet Spectroscopic Explorer (FUSE). FUSE was operated for NASA by the Johns Hopkins University under NASA contract NASS-32985.
1150–1978 Å, while the IUE long wavelength (LWP) spectra cover the 1885–3165 Å spectral range. However, because V603 Aql has very good and high signal-to-noise HST-GHRS archival spectra, we do not use the IUE spectra for the spectral fits. Instead we use IUE SWP+LWP spectra to assess the reddening $E(B-V)$ using the method of Verbunt (1987). Namely, we deredden a spectrum covering the 2175 Å “bump” for different values of $E(B-V)$ and then we inspect the resulting dereddened spectra. The dereddened spectrum for which the 2175 Å “bump” vanishes indicates the $E(B-V)$ value. In Figure 1 we show the actual dereddened spectra. We find a reddening of $E(B-V) = 0.10$, which we adopt in this work. Using the 2175 Å feature to estimate $E(B-V)$ introduces an error of up to 20% (Fitzpatrick 1997). Consequently we have $E(B-V) = 0.1 ± 0.02$. All of the HST and FUSE fluxes presented here were dereddened using the IUIERAF IDL routine, UNRED, with $E(B-V) = 0.10$. In Section 5 we evaluate the error on $M$ due to an error on $E(B-V)$.

An observing log of the HST GHRS and FUSE spectra is given in Table 2. V603 Aql was observed with FUSE over seven FUSE orbits in 2002 June. Since the inclination is low, we decided to combine the exposures without considering possible changes due to the orbital phase. Nonetheless, we checked the individual exposures (FUSE orbits) of the spectrum and found that the continuum flux level varies by no more than ~10% from one orbit to the other. The largest variation occurs near the O vi doublet and Lyβ region, possibly due to the combined effects of broad absorption and emission of these species. The change only mildly affects the absorption lines. We note, in passing, that IUE observations have shown (Borczyk et al. 2003) that both the continuum flux level and the emission lines (e.g., C iv, 1550 Å) fluctuate with time and the “scatter” is of the order of 100% in the 1992 IUE data (note that it is only ~30% in the 1989 IUE data).

The FUSE observations were obtained on 2002 June 7 with the LWRS in TIMETAG mode with a total exposure time of 16,807 s. FUSE has a spectral range covering the higher order of the Lyman series, namely from ~905 to ~1185 Å. We combined these FUSE exposures and then extracted the co-added spectrum from the combined fits files. We followed the procedure described in Godon et al. (2012) to process the FUSE spectra. Because the SiC channels (1aSiC, 1bSiC, 2aSiC, 2bSiC) did not collect much data, the spectrum starts at 980 Å (instead of ~910 Å) and it has a gap around 1085 Å. The resulting combined FUSE spectrum is displayed in Figure 2 where the strongest absorption and emission features are identified. Some significant interstellar absorption (molecular hydrogen) affects the spectrum.

The HST-GHRS spectrum of V603 Aql we use here is the combination of the z37v0204t and z37v0205t exposures which were obtained on 1996 October 6 with the G140L/2.0 configuration. The first exposure covers the 1140–1435 Å spectral range, while the second exposure covers the 1367–1663 Å spectral range. These pipeline-processed spectra were downloaded (as ascii/vo tables) from the virtual observatory using VOSpec. In Figure 3, we display the HST-GHRS combined z37v0204t+z37v0205t spectrum as flux $F_\lambda$ versus wavelength $\lambda$ in Angstroms—Å, together covering the spectral region from 1140 to 1663 Å. Note the Lyα absorption line (which may have an interstellar contribution), steeply rising continuum, and strong emission lines due to C iii (1175, Si iv (1394, 1402), C iv (1548, 1551), and He ii (1640).
given WD mass (and therefore radius), the best-fitting accretion disk model is obtained simply by scaling the model to the distance published from the Hubble FGS trigonometric parallax, namely 249 pc $\pm$8/–9 pc. Since we feel secure with both the distance and the low inclination of V603 Aql, essentially two critical free parameters are tightly constrained. We present the results of our synthetic spectral fitting with disks and photospheres in Section 4 where we have modeled the FUSE spectrum alone, the HST spectrum alone, and finally, the combination of the FUSE + HST spectrum to attempt to consistently fit a broader wavelength baseline than with HST and FUSE individually.

4. SYNTHETIC SPECTRAL FITTING RESULTS

We started by fitting the FUSE spectrum alone for the combination of parameters in our disk and white dwarf model grids (see previous section) with the distance fixed at 249 pc, and for white dwarf masses of 0.8, 1.0, and 1.2 $M_\odot$. A single WD model, without a disk, could not fit the data. Namely, the white dwarf is relatively massive and has a small radius, and consequently its contribution to the overall flux was of the order of $\sim$1% and did not affect the results. Realistic best fits were obtained for disk models, and we included a moderately hot WD ($T_{\text{wd}} = 30,000$ K) for the sake of completeness even though the WD did not affect the results. The mass accretion rate $\dot{M}$ of the disk model fit depended mainly on the WD mass and we list $\dot{M}$ for each different value of $M_{\text{wd}}$ (0.8, 1.0, 1.2 $M_\odot$) in Table 3. We present the model fit for the $M_{\text{wd}} = 1M_\odot$ case in Figure 4. The model has $\dot{M} = 2.4 \times 10^{-9} M_\odot \text{ yr}^{-1}$, $i = 18^\circ$ (the lowest inclination in our disk model grid) and $d = 249$ pc. The model fit, as explained in the figure, was carried out between the continuum unaffected by ISM absorption (in red) and the synthetic spectrum (solid black line). Excess flux appears in all the fitting and indicates broad emission from N iii (990), H i (1026), O vi (1032), and C iv (1175) and possibly from Si iv (1173). The C iv and O vi emission were masked before the fitting as they were readily apparent while the other lines were not.

Next we fit the HST-GHRS spectrum alone, masking the emission lines and the bottom of the Ly$\alpha$ region. The model fit resulted in an accretion rate very similar to what we obtained by modeling the FUSE spectrum, as shown in Table 3 for the different WD masses assumed. The model fit to the HST-GHRS spectrum is shown in Figure 5 for $M_{\text{wd}} = 1M_\odot$. The model fit has the following parameters: $M_{\text{wd}} = 1.0M_\odot$, $i = 18^\circ$, and a corresponding accretion rate of $\dot{M} = 3 \times 10^{-9} M_\odot \text{ yr}^{-1}$. The overall slope of the observed spectrum is shallower than the slope of the synthetic spectrum, and this is apparent, especially at longer wavelengths. This might be due to the contribution of a colder component peaking into the NUV or optical, which we are not modeling (see Section 5), due to either the irradiated donor star or the hot spot at the outer rim of the accretion disk where the gas stream from the inner Lagrangian point impacts supersonically onto the disk.

Lastly, we fit the FUSE+HRS combined spectrum, to increase the wavelength range. For this purpose we had to scale the spectra to each other and multiplied the GHRS spectrum by a factor of 0.80. As before, we fixed the distance to 249 pc and obtained results almost identical to the FUSE spectral fit results. In Table 3, we summarize the accretion rates derived from the fitting. In Figure 6, we display the fit for the $M_{\text{wd}} = 1M_\odot$ model. For clarity we have intentionally removed the ISM molecular hydrogen modeling in the shorter wavelengths, but we kept it in the Ly$\alpha$ region. Here too we see that in the longer wavelengths the observed spectrum has extra flux, indicating the possible presence of a colder component.

Overall, however, we are satisfied that we have achieved a robust value of the accretion rate of V603 Aql.
For our accretion rate, and with the assumption that compressional heating alone is operating, we transform our rate of accretion to a white dwarf effective temperature. This yields $T_{\text{eff}} = 30,000$ K. The accreting white dwarf in the system contributes only about $\sim 1\%$ of the FUV flux.

### 5. DISCUSSION

It is not surprising that the FUV spectrum of the old Nova V603 Aql is dominated by accretion light from its optically thick accretion disk since old novae generally appear to sustain high accretion rates due most likely to the heating and irradiation effects of the nova outburst on the secondary star. The FUV spectra we used were obtained in 1996 and 2002, 78 and 84 years after the 1918 nova explosion. It is therefore not unusual to have an accretion rate as high as the one we have derived. Puebla et al. (2007) found an accretion rate of $1.4 \times 10^{-9} M_\odot$ yr$^{-1}$, using a different model-fitting method (statistical optimization) than ours.

Since our model fitting depends sensitively on the observed continuum level and slope and there is an error range of reddening values $E(B-V)$, namely $0.10 \pm 0.02$, it is of interest to explore how the corrected fluxes are affected, and hence the derived accretion rate. The range of error in $E(B-V)$ (0.02) affects the corrected flux by a factor of 0.85, such that for $E(B-V) = 0.08$, the flux is decreased to 0.85, the value it has for $E(B-V) = 0.10$, and for $E(B-V) = 0.12$ the flux is increased to 1.17. To a first order estimate, the mass accretion itself is directly proportional to the flux, such that the error on $M_\dot{\theta}$, due to the reddening error, is $-15\%$ and $+17\%$.

As stated in Section 2, we used the IUERDAF script “unred” (IDL routine) which by default uses the reddening law of Savage & Mathis (1979) assuming $R = 3.1$. This option gives the same results as the reddening law by Seaton (1979) and uses the same value of $R$, 3.1, which is an average of the Galactic (Milky Way) reddening. Ideally the value of $R$ has to be known in the direction of the object as it varies in the Galaxy by more than a factor of 2, from about 2.2 to 5.5 (Fitzpatrick 1999). The reddening itself, $E(B-V)$, varies as $1/R$, and consequently the possible error

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**Figure 2.** FUSE spectrum of V603 Aql has been dereddened assuming $E(B-V) = 0.10$ and is shown with line identifications. The spectrum is strongly affected by sharp absorption lines. The prominent molecular hydrogen lines are identified with vertical tick marks without a label at $5 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. Some low ionization species, such as, e.g., Fe ii, are also identified. The sharp absorption lines could be due to ISM absorption, or to the surrounding material ejected during previous eruptions, or to a combination of both. The Si ii and O vi lines around 1030–1032 Å are probably from V603 Aql itself, as is the C iii (1175) multiplet which appears as a broad and shallow emission feature. Known FUSE fixed pattern noises are marked "FPN." Because of the failure of one of the FUSE channels there is detector gap in the spectrum around 1085 Å. The sharp H i (1025) emission lines are due to airglow.
There is little doubt that in V603 Aql, there is enhanced mass transfer from the donor to bloat and/or driving a wind off of the donor star to relax into thermal equilibrium again, eventually detaching from its Roche lobe and hence entering hibernation. Since the white dwarf reduces the irradiation thus allowing the donor to cool, the irradiation would be back at its law of 0.44 mag per century. The gradual cooling of the inner disk region still irradiated by the heated central white dwarf.

V603 Aql was observed with ASCA, and a mass accretion rate of only $1.6 \times 10^{-10} M_\odot$ yr$^{-1}$ was derived by Mukai & Orio (2005). This is much smaller than the value we derived here, however, most CVs at high mass accretion rates usually exhibit an X-ray-derived mass accretion rate much smaller than that derived from UV spectral analysis. A possible explanation for this is that the boundary layer is optically thin (Popham & Narayan 1995) and cannot radiate efficiently. Its energy is advected into the outer layer of the accreting white dwarf, thereby increasing its temperature. The $HST$-GHRS observations of Friedjung et al. (1997) reveal the presence of a chromosphere-corona that surrounds the accretion disk and rotates with it; they associate this with the emission lines which are rotationally broadened. The blueshifted absorption is the result of the wind outflow photo-ionized by the hot innermost disk/boundary layer. The inference of a disk corona in the rest frame of Friedjung et al. (2013) suggests that the X-rays may arise from the inner disk region still irradiated by the heated central white dwarf.

Figure 3. $HST$-GHRS G140L spectrum of V603 Aql has been dereddened assuming $E(B - V) = 0.10$. We identify all the lines as marked. The NV doublet ($\sim 1240$ Å) has been marked at its expected (rest frame) position but is not detected. The C IV (1175), Si IV (1400), C IV (1550), He II (1640), and possibly C II (1335) lines are all in emission. Note the double absorption in the bottom of the Lyα, with a shift of $\pm 3$ Å corresponding to a projected velocity of $\sim \pm 750$ km s$^{-1}$, or a rotational velocity of 2900 km s$^{-1}$ for $i = 14^\circ$ and 3330 km s$^{-1}$ for $i = 13^\circ$.

| $M_{red}$ (M$_\odot$) | $M$ (M$_\odot$ yr$^{-1}$) | $M$ (M$_\odot$ yr$^{-1}$) | $M$ (M$_\odot$ yr$^{-1}$) |
|-----------------------|--------------------------|--------------------------|--------------------------|
| 0.8                   | 3.2 $\times$ 10$^{-9}$   | 4.0 $\times$ 10$^{-9}$   | 3.3 $\times$ 10$^{-9}$   |
| 1.0                   | 2.4 $\times$ 10$^{-9}$   | 3.0 $\times$ 10$^{-9}$   | 2.6 $\times$ 10$^{-9}$   |
| 1.2                   | 1.5 $\times$ 10$^{-9}$   | 2.2 $\times$ 10$^{-9}$   | 1.5 $\times$ 10$^{-9}$   |

Table 3.

The $FUSE$ and $HST$ spectra is due to an actual decrease of the mass accretion rate (about 8%). However, based on the $IUE$ data, it is very likely that the change in the continuum flux level between the $HST$ data and the $FUSE$ data is solely due to the fluctuations of the UV source as described by Borczyk et al. (2001).

Recent work by Johnson et al. (2014) has shown that V603 Aql returned to deep quiescence by 1938 and is fading in the optical at a rate of 0.44±0.02 mag per century. The hibernation model of Shara et al. (1986) predicts that old novae should fade by roughly one magnitude per century. The gradual cooling of the white dwarf reduces the irradiation thus allowing the donor star to relax into thermal equilibrium again, eventually detaching from its Roche lobe and hence entering hibernation. There is little doubt that in V603 Aql, there is enhanced mass transfer due to irradiation of the secondary donor star (causing the donor to bloat and/or driving a wind off of the donor star) by the hot white dwarf and/or hot accretion disk. Since the $FUSE$ spectrum was taken 6 years after the $HST$ spectrum, it is tempting to speculate the difference in mass accretion rate obtained from fitting the $FUSE$ and $HST$ spectra is due to an actual decrease of the mass accretion rate (about 8%). However, based on the $IUE$ data, it is very likely that the change in the continuum flux level between the $HST$ data and the $FUSE$ data is solely due to the fluctuations of the UV source as described by Borczyk et al. (2001).

Based upon the present data, we do not know how close V603 Aql is to the termination of its irradiation-induced, enhanced mass transfer (cf. Tappert et al. 2013). Since V603 Aql has been shown to be essentially non-magnetic (Borczyk et al. 2003; Mukai & Orio 2005), then the strong persistent He II (1640) emission line may originate in the hot inner disk region still irradiated by the heated central white dwarf.

in $R$ introduces an additional error of +41% (3.1/2.2−1.0) and −44% (3.1/5.5−1.0) in the value of the reddening and in its law (this is assuming that $R$ could be as low as 2.1 or as high as 5.5). We cannot rule out that the discrepancy between the observed spectrum and the model is due to the reddening law we are using. Since $R$ is unknown, however, it is standard practice to use the 3.1 value and the reddening law we are using. Since the optical at a rate of 0.44$\pm$0.02 mag per century. The hibernation model of Shara et al. (1986) predicts that old novae should fade by roughly one magnitude per century. The gradual cooling of the white dwarf reduces the irradiation thus allowing the donor star to relax into thermal equilibrium again, eventually detaching from its Roche lobe and hence entering hibernation. There is little doubt that in V603 Aql, there is enhanced mass transfer due to irradiation of the secondary donor star (causing the donor to bloat and/or driving a wind off of the donor star) by the hot white dwarf and/or hot accretion disk. Since the $FUSE$ spectrum was taken 6 years after the $HST$ spectrum, it is tempting to speculate the difference in mass accretion rate obtained from fitting the $FUSE$ and $HST$ spectra is due to an actual decrease of the mass accretion rate (about 8%). However, based on the $IUE$ data, it is very likely that the change in the continuum flux level between the $HST$ data and the $FUSE$ data is solely due to the fluctuations of the UV source as described by Borczyk et al. (2003).

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Figure 4. Best fitting disk model for the FUSE spectrum of V603 Aql assuming $M_{\text{wd}} = 1.0 M_\odot$, $d = 250$ pc, and $i = 18^\circ$. The observed FUSE spectrum is in red and blue; the model is represented with the solid black line. Fitting is performed between the red line and the solid black line; the portions of the spectrum masked before the fitting are shown in blue. The model consists of an accretion disk with $M = 2.4 \times 10^{-9} M_\odot$ yr$^{-1}$. All the sharp absorption lines, believed to be due to the ISM, have been masked out and are colored in blue. While the obvious OVI ($1031.9$ Å) and CII ($1075$ Å) lines were masked before the fitting, the non-obvious NIII ($990$ Å) and SIV ($1073$ Å) lines were not masked and became apparent only in the fitting. The modeling includes an elementary ISM model that reproduces the ISM absorption. The model is also shown without the ISM absorption (dashed black line). The inclusion of a WD model in the fitting did not produce a significant change in the fitting as it contributed to only $\sim1\%$ of the flux.

Figure 5. Best fitting disk model for the HST-GHRS spectrum of V603 Aql. This model is for a WD with a mass $M_{\text{wd}} = 1 M_\odot$, an inclination $i = 18^\circ$, and a mass accretion rate $M = 3.0 \times 10^{-9} M_\odot$ yr$^{-1}$. The distance is 250 pc. The dashed line shows the Ly$\alpha$ region without the ISM modeling. The regions that have been masked (and that are not modeled) for the fitting are in blue.
This work is supported by NASA grants NNX13AF12G and NNX13AF11G to Villanova University. We are grateful to an anonymous referee whose helpful comments have improved our paper. P.G. is thankful to William P. Blair for his kind hospitality at the Henry A. Rowland Department of Physics and Astronomy at Johns Hopkins University, Baltimore, MD.

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Figure 6. Best fitting disk model for the FUSE + GHRS wavelength range of V603 Aql. This model is for a WD with a mass $M_{\text{wd}} = 1 M_\odot$, an inclination $i = 18^\circ$, and a mass accretion rate $dot{M} = 2.6 \times 10^{-9} M_\odot \text{yr}^{-1}$. The GHRS spectrum has been scaled to the FUSE spectrum using a factor of 0.80. The distance is 250 pc. For clarity, the ISM model has been omitted from the FUSE spectral range but it has been kept for the Ly$\alpha$ region. The dashed line shows that region without the ISM modeling. The regions that have been masked (and that are not modeled) for the fitting are in blue.