The Amazing Old Nova Q Cygni: A Far-Ultraviolet Synthetic Spectral Analysis

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ABSTRACT. Q Cygni (Nova Cygni 1876) is the third-oldest old nova (after WY Sge and V841 Oph), with a long orbital period of 10.08 hr and spectroscopic peculiarities in the optical, including the presence of variable wind outflow revealed by optical P Cygni profiles in the He I lines and Hαβ. We have carried out a synthetic spectral analysis of a far-ultraviolet IUE archival spectrum of Q Cygni using our optically thick, steady state, accretion disk models and model white dwarf photospheres. We find that the accretion light of a luminous accretion disk dominates the FUV flux of the hot component with a rate of accretion of $2\sim3\times10^{-9} M_{\odot}$ yr$^{-1}$. We find that Q Cygni lies at a distance of $741\pm110$ pc. The implications of our results for theoretical predictions for old novae are presented.

1. INTRODUCTION

Q Cygni (Nova Cygni 1876) is one of the oldest old novae, with a long orbital period of 10.08 hr and spectroscopic peculiarities in the optical, including the presence of variable wind outflow revealed by optical P Cygni profiles in the He I lines and Hαβ (Kafka et al. 2003). Their time-resolved optical spectra revealed pronounced P Cygni profiles in the He I triplet lines at 5876 Å and 7065 Å and in Hα, indicating the presence of an outflow with velocity reaching 1500 km s$^{-1}$. The wind outflow is highly variable with time and with orbital phase. It is rare to find outflow signatures of cataclysmic variable winds in the optical.

Selvelli (2004) summarized the UV spectral properties of 18 old novae observed with IUE. He found that their reddened continuum energy distribution is well described by either a power-law distribution $F_{\lambda}\sim\lambda^{-\alpha}$ with $\alpha$ in the range 0.3 to 2.5 or by a single blackbody distribution with $T_{\star}$ in the range of 15,000–38,000 K. If one assume that the UV luminosities come entirely from an accretion disk, then one obtains that the “average” disk luminosity disk is about 20 $L_{\odot}$ and that the “average” accretion rate $\dot{M}$ is $\sim1\times10^{-8} M_{\odot}$ yr$^{-1}$. Much remains to be learned about old novae, including how well their optical and UV behavior as they enter quiescence agrees with predictions of hibernation theory. Q Cygni has been previously thought to be entering a state of hibernation, where the secondary star detaches from the Roche lobe. This has been supported from ground-based estimates that the accretion rate has been gradually declining since the 1876 outburst (Schafer 2010, private communication). For Q Cygni, there has not been a far-UV (FUV) synthetic spectroscopic analysis of this system using optically thick, steady state, accretion disk models and model white dwarf photospheres. We report the results of such a spectroscopic analysis and compare the physical parameters we derive with those of other old novae.

2. FAR-ULTRAVIOLET SPECTROSCOPIC OBSERVATIONS

The IUE spectroscopic observations of Q Cygni were carried out on 1989 January 1 starting at 10:51:36 UT. The spectrum SWP35239 had an exposure time of 14,160 s at low dispersion through the large aperture. An LWP spectrum (LWP14754) was also obtained, which is quite noisy, but indicates the expected absorption trough at 2200 Å due to interstellar absorption. The observed reddened spectrum has a well-exposed continuum, slightly rising with average flux level of $\sim7\times10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$ over the SWP wavelength range of 1170 Å to 2000 Å. There appear to be hints of emission features, but nothing that can be clearly identified, due to the low quality and signal-to-noise ratio of the spectrum. The Lyman $\alpha$ profile is filled in with emission due to geocoronal contamination of the large-aperture spectrum. What appears to be a broad absorption trough centered near 1500 Å could be pseudoabsorption due to two neighboring emission regions. There do appear to be absorption wings at Lyman $\alpha$. We reddened the spectrum with $E(B-V) = 0.20$, which is a reasonable value for its line of sight.

3. METHOD OF MODEL FITTING

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 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. For a given spectrum, we carry out fits for every combination of $\dot{M}$, inclination, and white dwarf mass in the
Wade & Hubeny (1998) library. The values of $i$ are 18, 41, 60, 75, and 81. The range of accretion rates covers $-10.5 < \log M < -8.0$ in steps of 0.5 in the log and five different values of the white dwarf mass, namely, 0.4, 0.55, 0.8, 1.0, and 1.2 $M_\odot$. The emission-line regions that were masked-out were 1195 Å–1245 Å, 1280 Å–1290 Å, and 1650 Å–1670 Å. For the disk models, we selected all models with inclination angle $i = 41$ and 18; $M_{\text{wd}} = 0.35, 0.55, 0.80, 1.03,$ and 1.21 $M_\odot$; and $-\log(M) = 8.0, 8.5, 9.0, 9.5, 10.0,$ and 10.5. The WD models used temperatures of 10,000 K to 80,000 K in steps of 1000 K and $\log g = 7.0, 7.5, 8.0, 8.5,$ and 9.0.

4. MODEL-FITTING RESULTS

In preparation for the model fitting we masked-out possible emission-line regions at 1195 Å–1245 Å, 1280 Å–1290 Å, and 1650 Å–1670 Å. Our fitting procedure to the dereddened IUE spectrum, using our $\chi^2$ minimization routine called IUEFIT, which consisted of first using models of hot white dwarfs only, then fitting the spectrum with accretion disk models only, and finally fitting combinations of white dwarf and accretion models, if a statistically significant improvement resulted. We combined white dwarf models and accretion disk models using a $\chi^2$ minimization routine called DISKFIT. Using these routines, the best-fitting WD-only, disk-only, and composite white dwarf plus disk models are determined based upon the minimum $\chi^2$ value achieved, visual inspection ($\chi$, by eye) of the model, consistency with the continuum slope and Ly$\alpha$ region, and the consistency of the scale-factor-derived distance with published distance estimates or trigonometric parallax distance.

The results of our fitting are given in Table 1, where we list the following: type of model used (col. [1]), $T_{\text{eff}}$ of the WD model (col. [2]), accretion rate (col. [3]), inclination (col. [4]), WD mass of the model (col. [5]), $\chi^2$ value (col. [6]), scale factor of the fit (col. [7]), and distance implied by the model fit (col. [8]).

![Fig. 1.—Flux vs. wavelength plot for the spectrum SWP35239 of the old nova Q Cygni. The solid curve is the best-fitting white dwarf model (see text for details).](image1)

![Fig. 2.—Flux vs. wavelength plot for the spectrum SWP35239 of the Q Cygni. The solid curve is the best-fitting accretion disk model (see text for details).](image2)
the FUV flux and the disk contributing 90%. This combination fit is shown in Fig. 3. Since there was no statistically significant improvement over the fit with an accretion disk alone, we rejected this combination and adopted the accretion-disk-only fit as the most reasonable solution for Q Cygni.

5. SUMMARY

The accretion rate that we derive for Q Cygni, \(3 \times 10^{-9} \, M_\odot \, \text{yr}^{-1}\), is below the average accretion rate derived in the FUV for old novae, but still considerably higher than the theoretically expected low accretion rates needed to power a strong nova explosion.

Our distance of 741 pc is much closer than the distance used by Kafka et al. (2003), which was based upon the Na D absorption lines in their optical spectra and yielded a distance of the order of 3 kpc, about a factor of 4 further than our model-derived distance. On the other hand, the distance to Q Cygni using the \(t_3\) method of Duerbeck (1981) with \(t_3 = 11\) days (a very fast nova) yields a distance \(d = 1.9\) kpc. For an old nova at a distance of 750 pc, with \(V\) magnitude \(\sim 15\) (from the photometry of Kafka et al. 2003), and a visual absorption \(A_v = 0.8\) mag, the resulting absolute magnitude is 4.85. This is in very good agreement with the absolute magnitude of classical novae in quiescence, which was about 4.2 (see Patterson 1984). A 3 kpc distance measurement yields an absolute magnitude of 1.8, which would make Q Cygni a superluminous old nova, and a correspondingly much higher accretion rate.

In summary, the hot component is overwhelmingly dominated by accretion light from a luminous disk surrounding the white dwarf. The distance that we derived from the modeling (740 pc) is not unreasonable, and the accretion rate we derive (2–3 \(\times 10^{-9} \, M_\odot \, \text{yr}^{-1}\)) in the FUV indicates that the mass transfer rate is still fairly high 112 yr after the nova explosion in 1876.

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REFERENCES

Bruch, A., & Engel, A. 1994, A&AS, 104, 79
Duerbeck, H. 1981, PASP, 93, 165
Kafka, S., et al. 2003, AJ, 126, 1422
Patterson, J. 1984, ApJS, 54, 443
Selvelli, P. 2004, Baltic Astron., 13, 93
Wade, R. A, & Hubeny, I. 1998, ApJ, 509, 350