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QU CARINAE: ORBITAL PARAMETERS AND SPECTRA FOR A NOVA-LIKE VARIABLE

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ABSTRACT

High time resolution spectroscopy has been used to determine an orbital period of 10.9 hr for QU Carinae (= HDE 310376). The spectrum shows moderate He II λ4686 and C III–N III λλ4630–4660 emission with weak and variable Balmer-line absorption and emission. The λλ4630–4660 feature is centered at 4648 Å, which rules out Bowen fluorescence or dielectronic recombination of N III as the dominant production mechanism. The C III–N III feature most likely results from nonselective emission and may be indicative of high C and N abundances. The contributions of C and N to the λλ4630–4660 feature are 75% and 25%, respectively, with negligible O II contribution. Although QU Car has a relatively long orbital period of 10.9 hr determined from radial velocities of He II emission, no evidence of an absorption-line spectrum from an expected G–K spectral type secondary component is seen. A bolometric magnitude $M_{bol} \lesssim 2.2$ for the system is inferred from the lack of secondary lines. High-speed photometry confirms variations of 0.1–0.2 mag on time scales of minutes.

Subject headings: stars: binaries — stars: emission-line — stars: individual — stars: novae — stars: variables

I. INTRODUCTION

QU Carinae was reported as an emission-line object by Stephenson, Sanduleak, and Schild (1968), who suggested a similarity to Sco X-1. Schild (1969) presented high-speed photometric observations showing flickering or flare activity of up to 0.2 mag on a time scale of 90 s. Schild also presented low-temporal resolution spectra and suggested classification as an old nova—no periodicity suggestive of orbital changes was detected.

In an attempt to determine orbital characteristics for QU Car, we obtained spectra during three nights in 1979 March using the SIT-vidicon with Cassegrain spectrograph on the 1.5 m CTIO telescope. Analysis of these observations suggested an orbital period of ~11 hr from radial velocity variations of the λλ4630–4660 and He II λ4686 features. Since no orbital period had been suspected before these observations were obtained, the phasing was not optimal to prove the existence of an 11 hr variation. In order to verify the ~11 hr period, further spectra over four nights in 1980 March using the SIT-vidicon with Ritchey-Chrêtien spectrograph on the 4 m CTIO telescope were obtained by one of us (R. L. G.). The latter observations verified the suspected orbital variation. Photometry obtained in 1980 showed behavior similar to that reported by Schild (1969).

At $P_{orbit} = 10.9$ hr, QU Car has the fourth from longest orbital period out of a recent compilation of 55 accreting degenerate dwarfs with known periods (Córdova and Mason 1982). Failure to detect an absorption spectrum is unusual for a system with such a long period and suggests that the spectrum is dominated by light from the accretion disk or primary. This suggests a high rate of mass transfer and classification as an old nova or nova-like variable. (A secondary absorption spectrum is quite obvious in the long-period [$P = 14.67$ hr] dwarf nova BV Cen observed on the same nights; Gilliland 1982*a*.)

The λλ4630–4660 emission feature occurs in a wide variety of astrophysical systems including compact X-ray sources, novae, Wolf-Rayet C and N stars, planetary nebulae and gaseous nebulae, symbiotic stars, and Of, Be, and P Cygni stars (Meinel, Aveni, and Stockton 1969). Although ubiquitous in emission-line systems, the λλ4630–4660 feature is not well understood, largely because it can be attributed to several competing emission processes (Bowen fluorescence, dielectronic recombination, and nonselective emission) from several ionic

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species (N III, C III, and O II). The line is also observationally difficult, often occurring in intrinsically faint classes of objects (e.g., the X-ray bursters; see Canizares, McClintock, and Grindlay 1979), where the individual components of the line are Doppler broadened by orbital motion in excess of the interspecies wavelength separation, and the line strength is variable. In QU Car we have the opportunity of resolving the observational nature of the λλ4630–4660 emission since we have spectra of high signal-to-noise ratio (~100 to 1), the lines are fully resolved given their large intrinsic Doppler widths, averages over several orbital cycles are available, and we have excellent wavelength calibration. The optical spectrum of QU Car is quite similar to that of X-ray bursters in being dominated by λλ4630–4660 and λ4686 with occasional weak Balmer absorption and/or emission (Canizares, McClintock, and Grindlay 1979). We argue, however, that the λλ4630–4660 in QU Car is simply due to nonselective emission. See McClintock, Canizares, and Tarter (1975) for a thorough discussion of the diverse nature of λλ4630–4660 emission lines.

II. SPECTROSCOPIC DATA

The 37 spectra obtained in 1979 March with the 1.5 m CTIO telescope had a dispersion of 1.1 Å per channel resulting in ~3 Å resolution and covered the wavelength range ~4300–4800 Å with an 8 minute temporal resolution. The 12 spectra obtained in 1980 March with the 4 m CTIO telescope had a dispersion of 0.95 Å per channel resulting in 2–3 Å resolution and covered the wavelength range ~4550–4920 Å with 3–5 minute (co-addition of 2 or 3 shorter scans) temporal resolution. All individual scans had exposures within ~50% of saturation for the continuum yielding a noise level of ~5% with the SIT-vidicon system. In Table 1 we present a journal of the observations with time of mid-exposure, phase with respect to the ephemeris (to be given in the next section), and radial velocity and equivalent width of He II λ4686.

III. RADIAL VELOCITY CURVE

For both the 1979 and 1980 spectroscopic data sets we have followed the procedure outlined in an earlier paper (Gilliland 1982*b*) to derive radial velocities for the emission lines. The procedure yields wavelength calibrations with a precision of ~3 km s^{-1} for the 1980 data and about half this precision for the 1979 data. The He II emission line was measured by fitting a Lorentzian profile to the wings within ±800 km s^{-1} of line center—points within ±200 km s^{-1} of the center were assigned zero weight. The C III–N III complex was also measured for radial velocities and yielded variations consistent with those from He II, but with larger formal errors. Hγ (for the 1979 data) and Hβ (1980 data) were measurable in fewer than half the scans.

TABLE 1

SPECTROSCOPIC OBSERVATIONS OF QU CARINAE

Epoch (HJD 2,440,000.+)	ϕ_o	Velocity He II (km s^{-1})	Weight	EW He II
3,961.517	0.824	−12.	0.3	3.10
3,961.525	0.842	−90.	0.3	2.23
3,961.532	0.857	−47.	0.3	2.73
3,961.539	0.873	28.	0.3	2.90
3,961.546	0.888	41.	0.3	2.53
3,961.553	0.904	21.	0.3	1.96
3,961.560	0.919	56.	0.3	2.86
3,961.567	0.935	100.	0.3	3.03
3,961.574	0.950	132.	0.3	2.91
3,961.582	0.968	40.	0.3	2.53
3,961.588	0.981	26.	0.3	0.91
3,961.595	0.996	15.	0.3	1.78
3,961.602	0.012	−1.	0.3	2.38
3,961.644	0.104	−83.	0.3	1.82
3,961.828	0.509	−176.	0.3	1.60
3,961.835	0.525	−237.	0.3	2.42
3,961.842	0.540	−264.	0.3	2.50
3,962.832	0.720	−107.	0.3	2.35
3,962.840	0.738	−78.	0.3	2.47
3,962.846	0.751	8.	0.3	2.54
3,962.853	0.767	−68.	0.3	2.70
3,963.499	0.189	−42.	0.3	2.43
3,963.505	0.203	−62.	0.3	2.45
3,963.512	0.218	−73.	0.3	2.41
3,963.519	0.233	−33.	0.3	2.48
3,963.526	0.249	−88.	0.3	3.06
3,963.532	0.262	−76.	0.3	2.26
3,963.539	0.277	−138.	0.3	2.07
3,963.550	0.302	−95.	0.3	2.47
3,963.592	0.394	−202.	0.3	2.62
3,963.598	0.407	−158.	0.3	2.66
3,963.605	0.423	−247.	0.3	1.88
3,963.637	0.493	−102.	0.3	2.08
3,963.644	0.509	−192.	0.3	1.82
3,963.787	0.824	−93.	0.3	2.21
3,963.794	0.839	−59.	0.3	2.67
3,963.801	0.854	14.	0.3	2.01
4,321.530	0.669	−190.	0.7	1.18
4,321.650	0.934	−58.	0.7	1.50
4,321.765	0.188	−115.	0.9	1.76
4,321.852	0.379	−159.	1.0	1.43
4,322.584	0.991	33.	1.0	2.07
4,322.865	0.610	−153.	1.0	1.76
4,323.547	0.111	59.	1.0	1.52
4,323.679	0.403	−166.	1.0	1.62
4,323.769	0.600	−166.	1.0	1.70
4,323.801	0.672	−104.	1.0	1.78
4,324.779	0.825	−3.	1.0	2.35
4,324.826	0.929	52.	1.0	1.46

The orbital parameters resulting from analysis of the radial velocity data are presented in Table 2. The results for the 1979 and 1980 data sets obtained with different telescopes and spectrographs show quite good consistency and yield $K_1=115\pm13$ km s^{-1}, $\gamma=-84\pm20$ km s^{-1} for the He II λ4686 line. The radial velocities

TABLE 2
RADIAL VELOCITY FITS[a] FOR QU CARINAE

Line	T_o (HJD 2,440,000.+)	P (days)	K_1 (km s^{-1})	γ (km s^{-1})	σ_{SD} (km s^{-1})	No. of Scans
1979 He II	3,960.660	0.459	120.±18.	−87.	47.	37
1980 He II	4,320.332	0.451	110.±30.	−83.	46.	12
1979 C−N	3,960.729	0.462	118.±33.	...	88.	37
1980 C−N	4,320.276	0.463	119.±34.	...	53.	12
1979 Hγ	3,960.60	0.454[b]	167.±40.	−70.	72.	18
1980 Hβ	4,320.20	0.454	167.±70.	−114.	64.	6
Combined He II ...	3,960.683±0.03	0.454±0.014	115.±13.	−84.±20.	30.	49

[a]We have assumed $\varepsilon=\omega=0$. Epochs are time of maximum redshift.
[b]Period fixed at 0.454 days for the Balmer-line fits.

and best fit orbital solution to the combined data sets ($\varepsilon=\omega=0$ assumed) are shown in Figure 1.

The mass function for the adopted radial velocity curve is $f(M)=0.07$ with $a \sin i = 7.2\times10^5$ km. The lack of orbital modulation in the light curve (Schild 1969; this paper) suggests a small inclination angle $i \lesssim 60°$. The relatively narrow emission features (half-width at zero intensity of λ4686 is ~800 km s^{-1}, see Fig. 2) for cataclysmic variables are consistent with a small inclination angle. The presence of doubled emission lines suggests $i \gtrsim 30°$.

The assumption that the secondary is on the zero-age main sequence yields a secondary mass of $M_2=1.3\ M_\odot$ based on the mass-radius relation of Lacy (1977) and the usual period–mean density relation (see, e.g., Robinson 1976). Given the lack of detectable absorption lines and the possibility that the secondary could be significantly evolved, this is not a reliable mass estimate. Considering the relatively imprecise K_1, lack of confidence in M_2, and lack of knowledge of i, an estimate of M_1 would not be useful.

IV. PHOTOMETRY

We obtained photometric observations of QU Car in white light with a single-channel photometer on the CTIO 60 cm telescope in 1980 March. Figure 3 shows reduced photometry (sky subtracted and corrected for

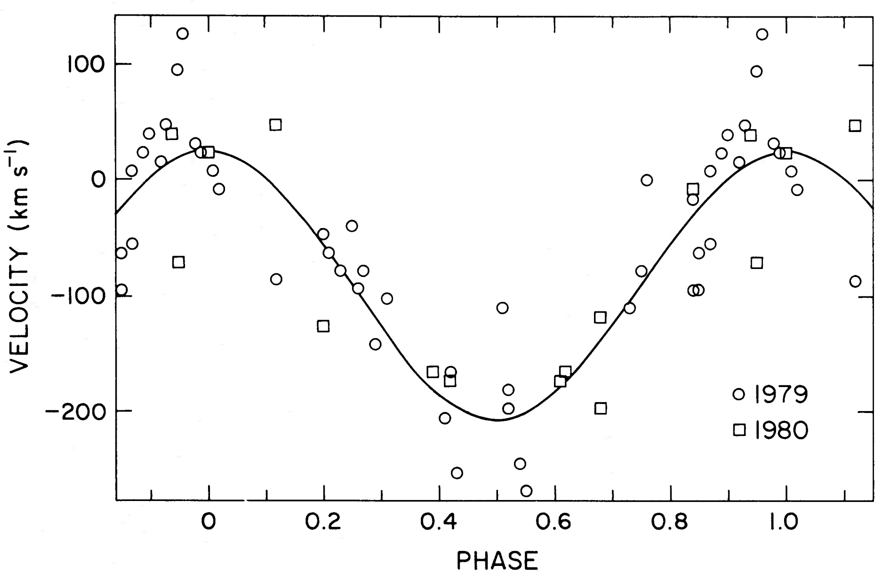

FIG. 1.—Radial velocity curve for QU Car. The continuous curve represents an orbital fit ($\varepsilon=\omega=0$ assumed) to the combined 1979 and 1980 He II velocities with weights as given in Table 1.

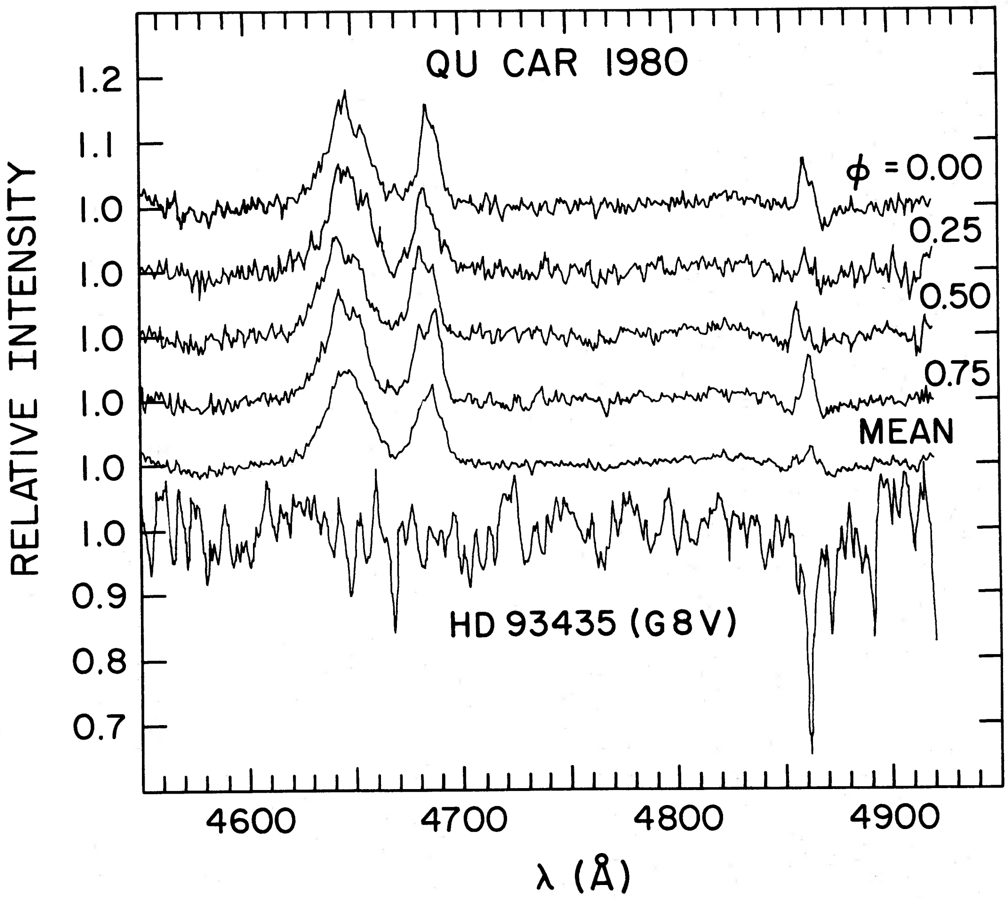

FIG. 2.—From the top, the scans represent means for the 1980 QU Car data at the four phases centered at 0.0, 0.25, 0.5, and 0.75 and over the full orbit. The full orbit mean represents a co-addition to the rest frame of the secondary, assuming a mass ratio of unity. For comparison, the spectrum of a G8 dwarf (HD 93435) is shown at the bottom. The continua have been flattened and normalized to unity.

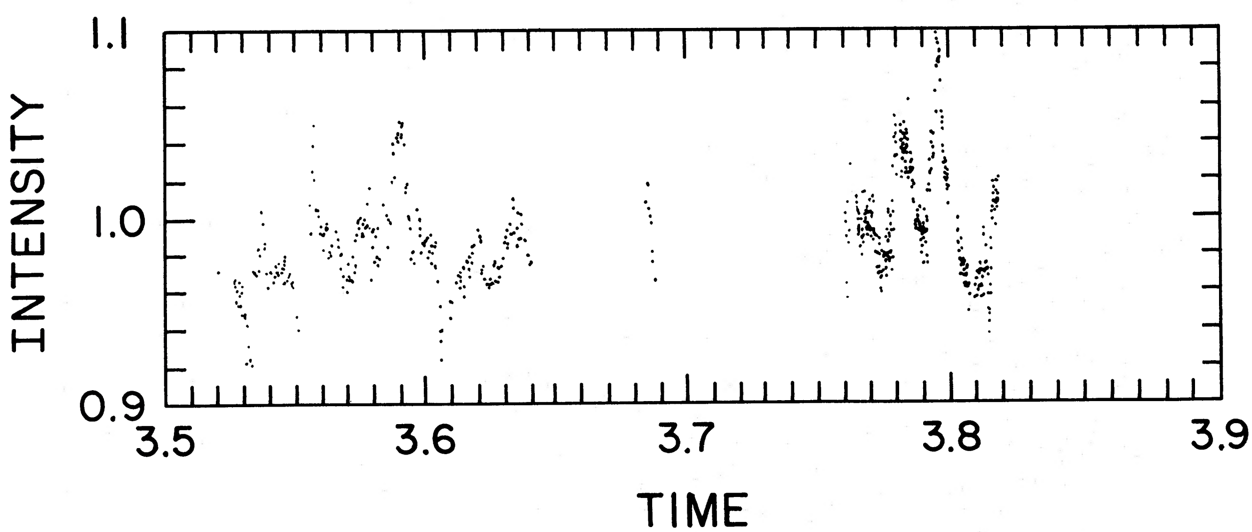

FIG. 3.—Reduced photometry from 1980 March plotted vs. time (HJD 2,444,320.+). Initial points are 30 s integrations with 10 s integrations used for the last block. The normalization is 158,887 counts per 10 s integration.

variable extinction) covering over 4 hr on one night. The photometry shows erratic variations of 0.1–0.2 mag on time scales of a few minutes, which agrees with Schild (1969). The orbital phase covered in Figure 3 with respect to the ephemeris of the emission lines is 0.06–0.72. No orbital variation is apparent, but the phase coverage is not sufficient to rule such out.

Schild (1969) suggested that emission lines are weakest and absorption strongest during times of maximum photometric flickering activity. The relative brightness of QU Car ($m_B \approx 11.2$) and length of the flickering activity (1–10 minutes) should make it possible to look for spectral changes of He II during well-defined heating or cooling episodes (assumed to arise from variable impact rates in the hot-spot region). We have a spectrum at time $=3.8$ of Figure 3 (rapid-decline stage of a flicker), which does not appear significantly different from a time-averaged spectrum. We, however, lack sufficiently dense simultaneous spectroscopic and photometric coverage to adequately test for spectroscopic variations as a function of phase with respect to the 0.1–0.2 mag flickers.

V. LINE PROFILES AND EQUIVALENT WIDTHS

In Figure 2 we show mean scans at the four quadrature phases and an overall mean (scans co-added to expected rest frame of the secondary, assuming a mass ratio of unity, for the overall mean) for the 1980 data. Each mean at a specific phase represents the sum of six to nine scans each of 60–90 s duration. The resulting noise level is $\lesssim 2\%$. The continuum has been flattened by fitting a fourth-order polynomial over the 500 channel range. The most pronounced variation occurs in Hβ, which varies from relatively strong and easily measured (for radial velocities) over phases ~ 0.7–0.2 to usually undetectable in individual scans over phases 0.2–0.7. (Hence results the large uncertainty concerning orbital radial velocity curves for the Balmer lines. Hγ in the 1979 data behaved in a similar way.) The equivalent width of Hβ varies from 0 to ~ 3 Å. A broad Balmer absorption feature is also evident. The He II $\lambda 4686$ profile has an apparent "s-wave" component varying from violet peaked near maximum recessional velocity to red peaked half a cycle later. At phases 0.5 and 0.75 an apparent doubling of the He II emission with full width of ~ 500 km s^{-1} is present. From comparison of the variable component of He II and the Hβ profile, it seems possible that they arise in the same physical location. (Note the similar He II and Hβ profiles for the 1980 data in Fig. 4 after co-addition to the emission-line rest frame.) The formal radial velocity fits given in Table 2 suggest that the Balmer-line velocity phases trail the adopted velocity curve by about 90°. (Lack of Balmer lines over a substantial part of the cycle makes this claim questionable.)

We searched for absorption features by shifting and co-adding (following the techniques outlined in Stover *et al.* 1980) the scans into various assumed rest frames for the secondary. In Figure 2 the mean spectrum of QU Car shifted to the assumed secondary rest frame is plotted above the spectrum of HD 93435 (G8 V). Absorption features are not discernible in the spectrum of QU Car. We can set a limit of $\sim 1\%$ on the depth of any consistent absorption features in QU Car. With G–K standards showing absorption features to $\sim 10\%$ depth, we infer that $\lesssim 10\%$ of the light in QU Car can come from the secondary component. Since the secondary is likely to have a mass $\gtrsim 1.0\ M_\odot$, the disk and primary components in QU Car must be radiating at $\gtrsim 10\ L_\odot$ ($M_{\rm bol} \lesssim 2.2$) in the visual. (A significantly evolved secondary with mass less than 1.0 $M_\odot$ is possible, but an evolved secondary would have relatively stronger absorption features tending to support the claimed luminosity limit.) At $m_B = 11.2$, this sets a lower limit to the distance of $\gtrsim 500$ pc using standard assumptions for interstellar absorption.

From 1979 to 1980 the mean EW of He II changed from 2.36 ± 0.08 to 1.66 ± 0.09 Å, while the C–N complex changed insignificantly from 3.59 ± 0.10 to 3.52 ± 0.16 Å. Measured absolute fluxes for the continuum at 4600 Å were 1.20 and 1.17×10^{-24} ergs s^{-1} cm^{-2} Hz^{-1} for 1979 and 1980, respectively. The difference is not significant and is within the range of normal short time scale variations and expected measurement errors. (These fluxes correspond to a B magnitude of 11.2, which is the same as that found by Schild in 1968.) Thus, based on the decreased He II EW, some change in the physical state of the line-emitting region over the course of 1 year is probable. Since the He II is formed at a higher excitation potential than the C III–N III, a decrease of temperature in the line-emitting regions is probable. Neither the C–N complex nor He II EWs show significant variation with orbital phase.

The $\lambda\lambda 4630$–4660 feature ranges from 50% stronger than He II $\lambda 4686$ in 1979 to more than a factor of 2 stronger in the 1980 spectra. The $\lambda\lambda 4630$–4660 emission feature is a hallmark of X-ray sources in which Bowen fluorescence is often indicated as an important source of N III $\lambda\lambda 4634$–4641 emission (McClintock, Canizares, and Tarter 1975; Canizares, McClintock, and Grindlay 1979). Gallagher and Starrfield (1978) in a recent review of the theory and observations of classical novae indicate that "the N III $\lambda 4640$ blend is the hallmark of [quiescent] novae." QU Car has not been detected in hard X-rays (90% upper limit of 10^{-11} ergs cm^{-2} s^{-1} for energies greater than 2 keV) or soft X-rays (Swank 1982), which would likely be present if Bowen fluorescence were important. Moreover, N III cannot be the dominant source of the $\lambda\lambda 4630$–4660 feature in QU Car since the line centroid is at 4648 ± 1 Å in both the 1979 and 1980 data sets (see Fig. 4). This

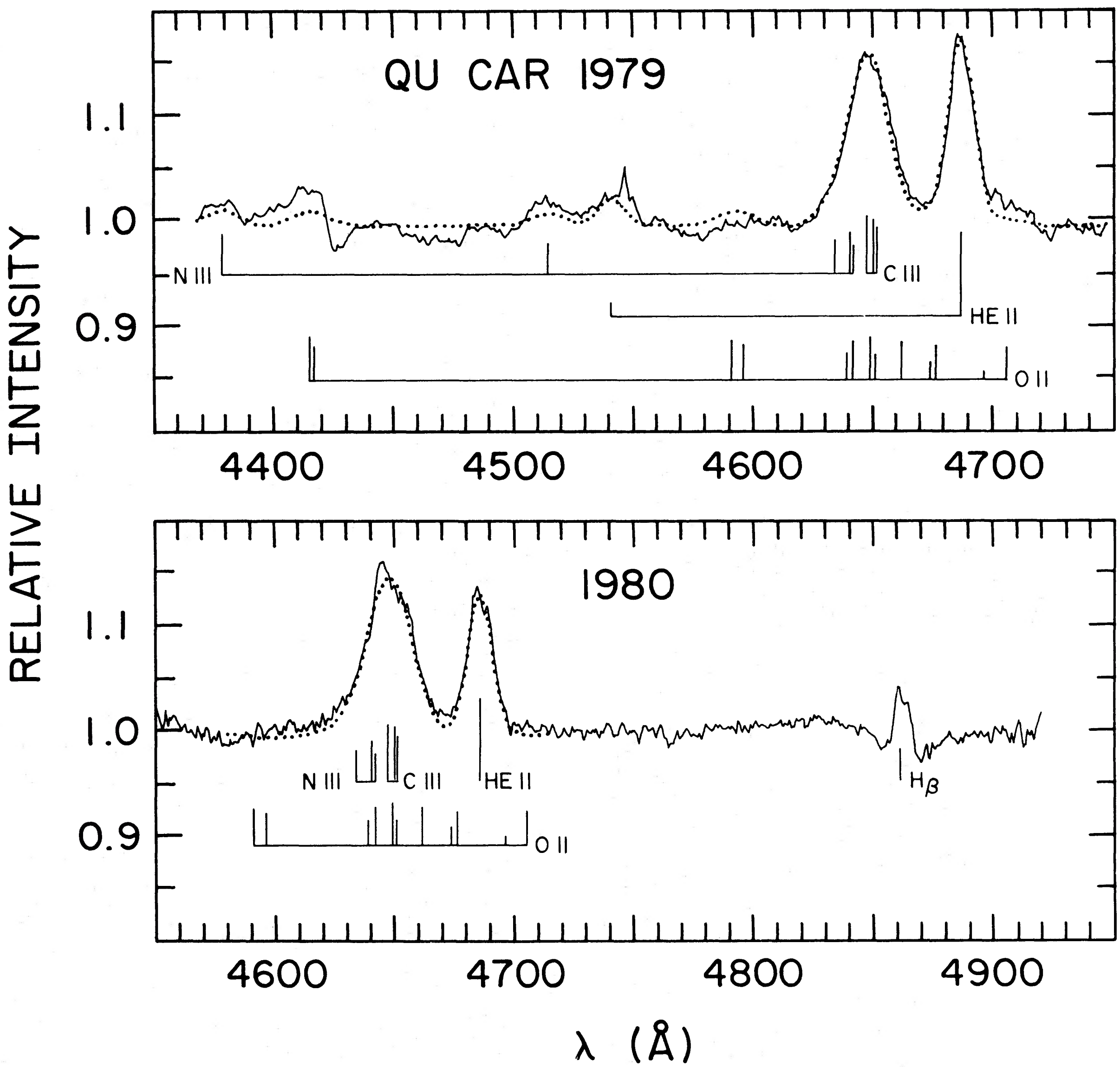

FIG. 4.—Summed spectra of QU Car for 1979 (4.9 hr total integration time) and 1980 (36 minutes) co-added to the rest frame of the emission lines. Continua have been flattened and normalized to unity. Positions and line strengths are indicated by vertical bars for the C III, N III, and O II lines as given in McClintock, Canizares, and Tarter (1975). Line profile fits as discussed in § V are indicated by solid dots.

also rules out the selective enhancement of N III by dielectronic recombination (Mihalas and Hummer 1973) as the dominant contributor to the λλ4630–4660 feature. Hence, the C III triplet at λλ4647–4652, which is not readily excited by such selective processes, is likely to be the dominant source of λλ4630–4660 emission in QU Car. In Figure 4 we have plotted the mean spectra of QU Car for 1979 and 1980 co-added to the emission-line rest frame. The positions and relative laboratory emission strengths for C III, N III, and O II (as taken from Table 4 of McClintock, Canizares, and Tarter 1975) are indicated by vertical lines in Figure 4. From the 1980 spectrum it is evident from lack of features at λλ4593 and 4705 that O II can contribute only slightly (less than 10%) to the λλ4630–4660 feature, but it might have been weakly present in the 1979 spectrum, which may show weak O II features at λλ4416, 4593, and 4705. The 1979 data suggests the presence of N III lines at λλ4379 and 4515, which would arise from a nonselective emission process.

We have further analyzed the source of the λλ4630–4660 emission feature by least squares fitting Gaussian profiles for C III, N III, and O II utilizing relative laboratory line strengths and wavelengths for the indi-

TABLE 3

EMISSION-LINE ANALYSES[a]

Spectral Region	He II Height	Gaussian Width (Å)	C III Height (%)	Gaussian Width	N III Height (%)	O II Height (%)
λλ4580–4715 (1980) ...	1.63	5.3	0.89(76)	8.6	0.36(27)	−0.03(−3)
λλ4580–4715 (1979) ...	2.12	5.2	0.95(77)	8.0	0.28(20)	0.03(3)
λλ4370–4745 (1979) ...	2.12	5.2	0.84(58)	7.0	0.38(24)	0.21(18)

[a]Heights are with respect to the relative laboratory intensities of individual lines as extracted from McClintock, Canizares, and Tarter 1975 and as indicated in Fig. 4 by vertical bars. Percentages are total elemental contributions of C, N, and O to the λλ4630–4660 emission feature obtained by summing over contributions of individual lines. Estimated 1 σ errors are ~10% for the first two entries and 20% for the extended 1979 fit.

vidual components. The fitted profile (dots in Fig. 4) represents a six parameter least squares fit comprised of the four Gaussian heights for He II, C III, N III, and O II and two Gaussian width parameters for He II and the CNO lines. The heights and wavelengths for individual Gaussians within an element are fixed at the relative laboratory values (McClintock, Canizares, and Tarter 1975). The results of this procedure are given in Table 3 and show C III and N III contributing in a ratio of about 3 to 1 with negligible O II for the 1980 data over the range λλ4580–4715. The fit shown in the upper panel of Figure 4 for the 1979 spectrum includes contributions from additional lines as indicated. All results are consistent with C III being the dominant source of λλ4630–4660 emission with a smaller contribution from N III also present and O II small or negligible.

Also present in the emission spectrum is He II λ4542 at about a factor of 10 weaker than He II λ4686. (The sharp feature at λ4547 in the 1979 spectrum is a vidicon readout glitch.) He I lines at λλ4387, 4471, and 4713 are not present in either emission or absorption. The strong He II and lack of He I suggest a temperature in the line-emitting region in excess of 20,000 K to maintain ionization of He. Such a high temperature could explain the relative weakness of the Balmer features, but these could also be explained by a large He/H ratio as has been suggested for cataclysmic variables (Williams and Ferguson 1981). The relative strength of the nonselective C III–N III and He II features may be indicative of enhanced C and N abundances. High CNO abundances have been invoked by Starrfield, Sparks and Truran (1974) to theoretically model nova eruptions. The shells ejected by classical novae have been shown to have anomalously high CNO abundances by one to two orders of magnitude (Robinson 1976). The relative brightness ($m_B = 11.2$) and strength of the C–N features make QU Car a good candidate for a detailed observational and theoretical modeling effort to determine CNO abundances (before nuclear processing in a nova outburst) in the accretion disk of a cataclysmic variable—a study which has not been reliably done to date (Gallagher and Starrfield 1978). It is usually thought that high CNO abundances in the preoutburst accreted mass result from surface mixing of carbon- and oxygen-rich white dwarf material. The possibility that CNO enriched material may be transferred to the white dwarf should be further tested.

VI. CONCLUSIONS

QU Car has been found to be a binary with a period of about 10.9 hr. The period coupled with the spectral properties (moderate C III–N III and He II and weak, variable Balmer lines) are consistent with classification as an old (classical) nova or a nova-like variable. The lack of clearly detectable absorption features in such a long-period system suggests that the light is dominated by the accretion disk and primary. The relative weakness of the Balmer lines with respect to He II and the C III–N III complex suggests either a low H abundance or a very hot disk—quite possibly both.

We thank the staff of CTIO for providing competent and timely support of this study, for which a new observing mode on the 4 m telescope was encoded. The excellent assistance of Mr. Leonardo Alvay made simultaneous photometry possible. Dr. J. Baldwin obtained fluxed, low-resolution scans for us on 1979 April 3.

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