QZ Serpentis: A Dwarf Nova with a 2-Hour Orbital Period and an Anomalously Hot, Bright Secondary Star

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ABSTRACT

We present spectroscopy and time-series photometry of the dwarf nova QZ Ser. The spectrum shows a rich absorption line spectrum of type K4±2. K-type secondary stars are generally seen in dwarf novae with orbital periods $P_{\text{orb}} \sim 6$ h, but in QZ Ser the absorption radial velocities show an obvious modulation (semi-amplitude $207(5)$ km s$^{-1}$) at $P_{\text{orb}} = 119.752(2)$ min, much shorter than typical for such a relatively warm and prominent secondary spectrum. The Hα emission-line velocity is modulated at the same period and roughly opposite phase. Time-series photometry shows flickering superposed on a modulation with two humps per orbit, consistent with ellipsoidal variation of the secondary’s light. QZ Ser is a second example of a relatively short-period dwarf nova with a surprisingly warm secondary. Model calculations suggest that the secondary is strongly enhanced in helium, and had already undergone significant nuclear evolution when mass transfer began. Several sodium absorption features in the secondary spectrum are unusually strong, which may indicate that the present-day surface was the site of CNO-cycle hydrogen burning in the past.

Subject headings: stars – individual; stars – binary; stars – variable.

1. Introduction

Cataclysmic variable stars (CVs) are close binary systems in which a low-mass secondary transfers mass onto a white dwarf; Warner (1995) wrote an excellent monograph on CVs.

The Roche geometry tightly constrains the secondary star’s mass at a given orbital period $P_{\text{orb}}$. Short-period systems have low-mass secondaries, so if the chemical composition is normal ($X \sim 0.7$), the secondary is a faint M dwarf or brown dwarf and contributes negligibly to the visible-
light spectrum (Fig. 4 of Patterson 2001); however, Thorstensen et al. (2002) found a K4 ± 2 secondary in the dwarf nova 1RXS J232953.9+062814 (hereafter RX 2329+06), which has $P_{\text{orb}} = 64$ min. They suggested that the secondary was somewhat evolved at the start of mass transfer, with its core substantially enhanced in helium. In this scenario the portion of the secondary remaining today corresponds to the core of the original star, and the enhanced helium greatly affects the mass-temperature relation.

Here we present new observations of the dwarf nova QZ Ser, which appears to be a close relative of RX 2329+06. QZ Ser was discovered by Katsumi Haseda in 1998 and designated as HadV04 in the discovery notification (vsnet-obs 18349)$^3$, in which T. Kato suggested an identification with the ROSAT WGA source 1WGAJ1556.9+2108 (White, Giommi, & Angelini 1994). The outbursting object was discovered on small-scale patrol films, and its quiescent counterpart was initially uncertain. On 2001 June 28 we obtained a spectrum of the star nearest the position, and it proved to be an ordinary late-type star. Returning to the field on 2002 January 20 we obtained a spectrum of a somewhat fainter star 11 arcsec to the northwest. This showed the distinctive broad Balmer emission characteristic of dwarf novae at minimum light, together with absorption features of a late-type star. On 2002 Feb 3.23 UT, P. Schmeer detected an outburst of QZ Ser (vsnet-campaign 1281), and an examination of an outburst image by H. Yamaoka (vsnet-alert 7172) confirmed that the outbursting object was on the position of the emission-line object, cementing the identification.

The position of QZ Ser, derived from a fit to 62 USNO A2.0 stars (Monet et al. 1996) on one of our 1.3m images (described below), is $\alpha_{\text{ICRS}} = 15^h 56^m 54.5^s.50$, $\delta_{\text{ICRS}} = +21^\circ 07' 19''.5$ ($\pm0''.3$ estimated uncertainty). Its position in the USNO A2.0 is not significantly different, which sets an upper limit on its proper motion $\mu < 0''.03$ yr$^{-1}$. The *Living Edition of the Catalog and Atlas of Cataclysmic Variables* (Downes et al. 2001) gives an up-to-date finding chart.

$^3$The vsnet mailing list archives are available at http://vsnet.kusastro.kyoto-u.ac.jp/vsnet/index.html

2. Observations and Analysis

Our time-series photometry is from the 1.3 m Mcgraw-Hill telescope at MDM Observatory on Kitt Peak, during 2002 February. After bias subtraction and flat fielding our I-band CCD pictures, we measured instrumental magnitudes using aperture photometry, and differenced the program star against a nearby comparison object.

On 2002 January 21 we obtained UBVI exposures in photometric conditions with the 1.3 m telescope. We measured these with DAOPHOT and transformed to standard UBVI magnitudes using observations of Landolt (1992) standard stars. Our BV observations agreed within a few hundredths of a magnitude with photometry listed by Henden$^4$. QZ Ser had $V = 17.69, B - V = 0.72, U - B = -0.32$, and $V - I_{\text{Ko}} = 1.22$, rather redder than typical short-period dwarf novae at minimum light.

Table 1 gives a journal of our spectroscopy, all of which is from the 2.4 m Hiltner telescope at MDM Observatory on Kitt Peak. The procedures, instrumental setup and reduction were essentially as described in Thorstensen et al. (1998). Nearly all the exposures from the extensive 2002 February data set were 480 s, the total exposure in February being 38820 s. Because of the season, the February data span only 3.4 h of hour angle. Four 480-s spectra were taken in 2002 June, after this paper was first submitted, mostly to improve the ephemeris.

Fig. 1 shows the mean spectrum from February. The mean spectrum from January, before the outburst, appears somewhat similar, but with a flux level $\sim 30$ per cent lower in the $V$ band, a marginally redder continuum, and much weaker He I emission, and in June the spectrum resembled the one taken in January. Without simultaneous photometry it is difficult to be certain, but in February the star may have been slightly brighter than its minimum, perhaps because of the outburst earlier that month. Table 1 details the emission lines in the February spectrum. The lines appear double-peaked at the top, with separation $\sim 600$ km s$^{-1}$. Late-type absorption features are also present.

We measured absorption velocities by cross-
correlating our spectra against a rest-frame sum of late-type IAU velocity standards, using \textit{xsao} (Kurtz & Mink 1998). The 6000 to 6500 \text{ Å} region gave the best results, with mean formal uncertainty 10 km s\(^{-1}\). We discarded a few velocities with large formal errors, leaving four velocities from 2002 January and 69 from 2002 February. A least-squares period search (Thorstensen et al. 1996) showed a strong periodicity near two hours. Because the velocity uncertainties are small compared to the amplitude, the period is determined without ambiguity in the daily cycle count despite the relatively small hour-angle span of the data, and the cycle count between the January and February velocities is also secure. Table 3 gives sinusoidal fit parameters for the velocities, and Fig. 2 shows the velocities folded on the period. \textit{H}\textsubscript{o} emission-line velocities measured using a convolution method sensitive to the line wings (Schneider & Young 1980) gave noisier velocities (also in Fig. 2), but yielded a consistent period. A fit to the emission-line velocities with the period fixed at the more accurate absorption-line value gave parameters listed in Table 3. The phase of the emission line velocities lags the absorption lines by 0.58(2) cycles (formal error), whereas a lag of exactly 0.5 would be expected if the emission accurately traced the white-dwarf motion. We conclude that, as often is the case, the emission lines do not trace the white dwarf motion accurately. The equal periods and roughly opposing phases of the emission and absorption do confirm that they arise in the same system, and that the absorption features are from the secondary and not some interloper.

Fig. 3 shows a greyscale representation of the February spectra arranged as a function of phase (Taylor et al. 1998). The sharp absorption features and their modulation are obvious. The HeI \(\lambda\) 5876 line shows evidence of an \textit{S}-wave, i.e., an emission component apparently arising from the hot spot where the accretion stream strikes the disk. A phase-dependent absorption around \(\lambda\)5910, with \(~ 20 \text{ Å FWHM}\) is also clearly visible. We measured the feature’s equivalent width in the original spectra, and while these measures were noisy they showed a smooth and persistent modulation with binary phase (Fig. 2, lower panel). A sine fit gave a mean EW of 3.8 \text{ Å}, with a half-amplitude of 2.2 \text{ Å}. The feature reaches maximum strength around the time of maximum radial velocity of the secondary. It seems likely that this feature is due to sodium, but we have been unable to explain it further. Its diffuseness suggests a velocity spread characteristic of the accretion structures rather than the stellar photosphere. Although phase-dependent absorption calls to mind the superficially similar phenomenon in SW Sex stars, the morphology and phasing of this feature in the single-trailed spectrum is quite different from typical SW Sex absorption events (see e.g. Taylor et al. 1998).

To estimate the secondary’s spectral type, we used spectra (obtained with the same instrumental setup) of stars classified by Keenan & McNeil (1989). Using two temperature-sensitive line ratios appropriate for our spectral resolution and coverage, we found K4 ± 2 subclasses for QZ Ser’s secondary. Most of the absorption features appeared similar to the spectral type standards, but the standards do not show the broad \(\lambda\)5910 feature noted above. A pair of absorption lines at \(\lambda\)5683, 5688 also appears unusually strong, with equivalent widths of 0.9 and 1.2 \text{ Å} respectively. These are evidently a Na I triplet at \(\lambda\lambda\) 5682.63, 5688.19, and 5688.21.

The strength of these lines prompted us to search for other sodium features. The NaD lines are unsuitable because of saturation and confusion with \(\lambda\)5876 (they may also be responsible for the unusual \(\lambda\)5910 feature), but a search of the NIST atomic line database \(^5\) yields other features. One, near at \(\lambda\)6154.225, appears enhanced in equivalent width by a factor of about three compared to our K star standards; a neighboring sodium line at \(\lambda\)6160.747 is unfortunately blended with a strong Ca I line at our resolution. In several other features (a blend of \(\lambda\lambda\)4978.5 and 4982.8, and one at \(\lambda\lambda\)4664.8 and 4668.6) the enhancement is not enough to be significant, though the features are clearly detected. All the sodium features considered here arise from the 3p level, further corroborating the line identification. These sodium features move with the secondary’s spectrum, so we conclude that there is circumstantial evidence for an enhanced sodium abundance in the secondary’s photosphere.

Because the spectrum does not appear perfectly normal, we cannot put a strong constraint on the

\(^5\)http://physics.nist.gov/cgi-bin/AtData/main
fraction of the light contributed by the secondary, but it is clearly very substantial. From systematically subtracting the library spectra from the average spectrum, we estimate that the secondary contributes \(70 \pm 20\) percent of the light in the 5500 – 6500 \(\AA\) range. On face value, our \(V\) magnitude then implies \(V = 18.1 \pm 0.4\) for the secondary alone. Because the secondary’s fractional contribution was probably a little higher in January (when the photometry was taken) than in February (when the secondary contribution was measured), our best estimate for the secondary’s magnitude is \(V = 17.9 \pm 0.4\).

The lower panel of Fig. 2 shows averaged, mean-subtracted, differential \(I\)-band magnitudes as a function of orbital phase. The time averaging suppresses considerable flickering present in the original time series. The light curve shows two humps per orbit, with mean full amplitude 0.076(9) mag. The minima appear to be asymmetric, differing by \(\Delta A = 0.012(7)\) mag. This is the waveform characteristic of tidally distorted secondaries within a Roche lobe, as calculated for example by Bochkarev et al. (1979) (hereafter BKS).

3. Inferences

**Distance.** The secondary spectrum and period constrain the distance. Assuming the secondary fills its Roche lobe, we have \(R_2/R_\odot = 0.234 f(q)P_{\text{orb}}^{2/3}(M_2/M_\odot)^{1/3}\) (Beuermann et al. 1998), where \(f(q)\) is very close to unity over the range of interest. Evolutionary models suggest \(M_2 = 0.125\ M_\odot\) (see below), and because this enters weakly in the present calculation we take this as a guide, assuming an uncertainty of \(\pm 0.025\ M_\odot\), which yields \(R_2 = 0.185 \pm 0.013\ R_\odot\). K-star surface brightnesses inferred from Table 3 of Beuermann et al. (1999) then imply that the secondary has \(M_V = 9.4 \pm 0.4\), where nearly all the uncertainty arises from the spectral type. Our photometry and estimated secondary-star contribution then gives \(m - M = 8.5 \pm 0.6\). QZ Ser lies at \(b = +47^\circ\), and Schlegel, Finkbeiner, & Davis (1998) estimate \(E(B - V) = 0.05\) in this location from IRAS 100-micron maps, or \(A_V = 0.17\). Accounting for this yields a distance around 460 (+150, -110) pc. At 460 pc, \(\mu < 0.03\) yr\(^{-1}\) corresponds to \(v_T < 65\) km s\(^{-1}\), which is not unlikely.

**Orbital Parameters and Masses.** After correcting for the estimated blue-star contamination in the \(I\) band, the ellipsoidal light curve has \(A = 0.098(14)\) mag and \(\Delta A = 0.015(9)\) mag. To reproduce these numbers, we interpolated and extrapolated from Table I of BKS, adopting plausible values of limb- and gravity-darkening for a cool star (respectively \(u = 0.8\) and \(\beta = 0.6\), but the results are not sensitive to these choices). With mass ratios in the range 0.1-0.4, we obtained the measured \(A\) for inclination \(i = 33 \pm 4\) degrees (at such low inclinations, \(A\) depends mainly on \(i\)). In principle we could use the measured \(\Delta A\) to constrain \(q(i)\) further, but our measurement is too crude, and cataclysmic variables can easily produce signals at \(P_{\text{orb}}\) from effects unrelated to ellipsoidal distortion.

The secondary’s velocity amplitude gives a mass function of 0.075(5) \(M_\odot\). This may be distorted by illumination effects, but we see no evidence of variation of the line features with orbital phase. If we assume for a moment that \(M_2 = 0.125\ M_\odot\) and a broadly typical white dwarf mass \(M_1 = 0.7\ M_\odot\), the mass function implies \(i = 32^\circ\), essentially identical to the inclination derived from the ellipsoidal variations. We emphasize that we have not measured these masses, but we use them only to show that the data are consistent with our scenario without assuming an unusual mass for the white dwarf. As noted earlier, we believe that the apparent emission line radial velocities do not indicate the white dwarf motion with any interesting accuracy.

4. Discussion

QZ Ser is only the second short-period dwarf nova to show a K-star secondary. In all other dwarf novae with \(P_{\text{orb}} < 2\) hr, save for a handful of helium systems, the secondaries are late M dwarfs which contribute a small fraction of the visible light. How are we to account for this unusual object? As with RX 2329+06 (Thorstensen et al. 2002), we suggest that the secondary evolved significantly on the main sequence prior to mass transfer, enhancing the core with enough helium to greatly affect the mass-\(T_{\text{eff}}\) relation. The small, hot secondary we see is the remnant of a once more massive secondary.

For illustration, we computed some evolutionary models in the framework of the standard
disrupted magnetic braking scenario (see Baraffe & Kolb 2000 and references therein). At the ~2 hr orbital period of QZ Ser, a donor which started mass transfer on the zero-age main sequence (ZAMS) would have spectral type M4-M5 and mass $M_2 \approx 0.2 M_\odot$. Such a “standard” sequence, based on the models of Baraffe & Kolb (2000), is displayed in Fig. 4 by the solid curve. Also shown in Fig. 4 are some test calculations in which mass transfer begins near the end of central H burning. The tracks shown represent several choices of initial secondary masses $M_2 \gtrsim 1 M_\odot$, constant mass loss rates $\dot{M} \sim 10^{-9} - 10^{-8} M_\odot$ yr$^{-1}$, and different levels of nuclear evolution $X_c < 0.1$. As Fig. 4 shows, these naturally reproduce the observed properties of QZ Ser and RX 2329+06. The choice of our parameters seems reasonable and we do not require particularly extreme assumptions on our evolutionary scenarios to fit these objects\(^6\).

As already mentioned in Thorstensen et al. (2002), the models predict altered surface abundances. Fig. 4 displays the surface enrichment of $^{14}$N processed by the CNO cycle in the deeper layers and mixed up to the surface. The surface helium abundance increases also, reaching mass fraction $\sim 0.6$ at $P_{\text{orb}} \sim 2$h. In RX 2329+06 the strengths of H$\alpha$ and HeI $\lambda5876$ are in the ratio 3.6:1, whereas this ratio is typically 6 and above in SU UMa stars (Thorstensen et al. 2002); in the 2002 February spectra of QZ Ser, the ratio is 5:1, which may indicate some enhancement of He. As noted earlier, though, He features were nearly absent in the 2002 January pre-outburst spectra, so the He:H line ratio is evidently not a consistent measure of abundance in this object.

The sodium enhancement noted earlier (if real) may provide an important window on the secondary’s nuclear processing history. The temperatures reached in the deepest layers of stars with masses $\gtrsim 1.2 M_\odot$ near the end of central H burning are high enough to allow the production of $^{23}$Na via the $^{22}$Ne$(p, \gamma)^{23}$Na reaction. During mass transfer, the convective envelope proceeds inward and may reach the Na-enriched layers. At the 2-hour period of QZ Ser, the bottom of the secondary’s convective envelope should reach into layers which have attained temperatures of $1.5 - 2 \times 10^7$ K during prior evolution. Based on the recent NACRE reaction rates (Angulo et al. 1999), this is hot enough to destroy $^{22}$Ne by proton capture, but it is not hot enough for the Na-Ne cycle to contribute significant Na enhancement (Weiss, Denissenkov, & Charbonnel 2000). A combination of deep mixing and Ne-Na cycling has been considered as an explanation for anomalous Na abundance in globular cluster giants (Denissenko & Denisenkova 1990; Kraft et al. 1997; Weiss, Denissenkov, & Charbonnel 2000). The nuclear reaction networks presently implemented in our models unfortunately do not produce a quantitative estimate the sodium enhancement, but work is in progress to remedy this. At present, we can only point to the strong Na lines as a clue that the surface material was processed at relatively high temperatures, mixed upward, and exposed as mass transfer stripped away the overlying layers.

The origin of the Na enhancements in the globular cluster stars is uncertain, and as in that case, it is possible that QZ Ser’s sodium was already present in the gas from which the system formed. It would therefore be desirable to detect the primary products of CNO processing – He and N enrichment, and C and O depletion. Unfortunately, test model atmospheres with $T_{\text{eff}} = 4300$ K and log $g = 5.5$, kindly computed by F. Allard (private communication) showed essentially no observable effect when He was enhanced to 50% in mass fraction and the CNO abundances were altered as expected. More noticeable effects should appear in models at cooler temperatures ($T_{\text{eff}} < 4000$ K), where molecules involving C or O form.

If our interpretation based on nuclearily evolved donors is correct, we may expect that a non-negligible number of short period CVs with anomalously hot secondaries will be discovered. As already emphasized by Beuermann et al. (1998) and Baraffe & Kolb (2000), such evolved sequences can indeed explain a substantial fraction of the observed CVs with late spectral types and orbital periods $P \gtrsim 6$ h. As shown in Fig. 4, the most evolved sequences which provide an explanation for such systems predict as well the existence of early spectral types at shorter periods. The late spectral type systems with $P \gtrsim 6$ h represent a non-negligible fraction of systems in the sample of

\(^6\)With our assumptions, the system in principle should have initially transferred mass on a thermal timescale, until $M_2$ became small enough for the system to reappear as a standard CV (see Baraffe & Kolb 2000 for a discussion).
Beuermann et al. (1998). Baraffe & Kolb (2000) were thus concerned by the fact that such evolved sequences may remain active in the 2-3 h period gap, since such extreme secondaries never become fully convective. In order to prevent populating the period gap and predicting too early spectral types at shorter periods, (Baraffe & Kolb 2000, see their §4) suggested an increase of the mean mass transfer rate during the secular evolution of such evolved donors. However, the existence of QZ Ser at $P_{\text{orb}} = 2.0$ h now supports the idea that evolved sequences may remain active in the gap.

Our proposed scenario would be supported if QZ Ser and RX 2329+06 were found to have enhanced CNO-process abundances at their surfaces, and a more quantitative study of the abundances of Na, Al, and other light metals may provide this evidence despite the low $T_{\text{eff}}$. In the models we have computed to date, the secondaries in longer-period systems are significantly less massive than in ‘standard’ systems. If this tendency proves robust, accurate measures of donor masses in long-period systems could identify systems destined to evolve into stars like RX 2329+06 and QZ Ser in our scenario. Finally, if our interpretation is correct, one should find similar systems in the period gap.

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White, N. E., Giommi, P., & Angelini, L. 1994, IAU Circ., No. 6100
### Table 1

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<sup>a</sup>Number of spectra.

### Table 2

**Emission Features**

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<sup>a</sup>Emission equivalent widths are counted as positive.

<sup>b</sup>Absolute line fluxes are uncertain by a factor of about 2, but relative fluxes of strong lines are estimated accurate to ∼ 10 per cent.

<sup>c</sup>From Gaussian fits.
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$^a$Fits are of the form $v(t) = \gamma + K \sin[2\pi(t - T_0)/P]$. The number of points used is $N$ and $\sigma$ is the standard deviation from the best fit.

$^b$Blue-to-red crossing, HJD $-2450000$. 
Fig. 1.— Mean flux-calibrated spectrum. In the upper trace, the individual exposures have been shifted into the absorption rest frame and the trace has been shifted upward.

Fig. 2.— Data folded on the binary period. All points are shown twice for continuity. *Upper panel*: Radial velocities with best-fitting sinusoids. Emission velocities are shown as round dots; absorption velocities are as follows: 2002 January = open squares, 2002 February = filled squares, and 2002 June = open triangles. *Middle panel*: Phase-averaged, mean-subtracted, $I$-band differential magnitudes. *Lower Panel*: Equivalent widths of the diffuse $\lambda$5910 absorption feature.

Fig. 3.— Spectra near $\lambda$5900 rectified and shown as greyscale against phase. All data are shown twice for continuity. The emission feature to the left is HeI $\lambda$5876. Note the doppler motion of the sharp absorption features, and the diffuse absorption feature around $\lambda$5910. (Included as a separate jpg file in astro-ph preprint. The white horizontal line is an artifact of the ps to jpg conversion.)
Fig. 4.— Spectral type, mass, effective temperature and surface $^{14}\!\!N$ abundance (normalized to the solar abundance) of the secondary versus orbital period. The solid curve corresponds to a "standard" sequence with an initially unevolved donor, in the framework of the disrupted magnetic braking model (reproducing the 2-3h period gap). The other curves correspond to evolutionary sequences starting mass transfer near the end of H burning, at a central H mass fraction $X_c$. Long-dashed curve: $M_2 = 1.2 \, M_\odot$, $\dot{M} = 1.5 \times 10^{-9} \, M_\odot \, \text{yr}^{-1}$, $X_c = 4 \times 10^{-4}$. Dash-dotted curve: $M_2 = 1.3 \, M_\odot$, $\dot{M} = 1.5 \times 10^{-9} \, M_\odot \, \text{yr}^{-1}$, $X_c = 5 \times 10^{-2}$. Short-dashed curve: $M_2 = 1.5 \, M_\odot$, $\dot{M} = 10^{-8} \, M_\odot \, \text{yr}^{-1}$, $X_c = 1.7 \times 10^{-2}$. The locations of QZ Ser (present work, filled triangle) and RX 2329 (Thorstensen et al. 2002), filled square) are indicated. The filled circles are observations from Beuermann et al. (1998).