Spectroscopy of Nine Cataclysmic Variable Stars

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Received 2007 March 5; accepted 2007 April 5; published 2007 May 24

ABSTRACT. We present optical spectroscopy of nine cataclysmic binary stars, mostly dwarf novae, obtained primarily to determine orbital periods. The stars and their periods are LX And, 0.1509743(5) days; CZ Aql, P orb = 0.2005(6) days; LU Cam, 0.1499686(4) days; GZ Cnc, 0.0881(4) days; V632 Cyg, 0.06377(8) days; V1006 Cyg, 0.09903(9) days; BF Eri, 0.2708804(4) days; BI Ori, 0.1915(5) days; and FO Per, for which P orb is either 0.1467(4) or 0.1719(5) days. Several of the stars proved to be especially interesting. In BF Eri, we detect the absorption spectrum of a secondary star of spectral type K3 subclass, which leads to a distance estimate of ∼1 kpc. However, BF Eri has a large proper motion (∼100 mas yr⁻¹), and we have a preliminary parallax measurement that confirms the large proper motion and yields only an upper limit for the parallax. BF Eri’s space velocity is evidently large, and it appears to belong to the halo population. In CZ Aql, the emission lines have strong wings that move with large velocity amplitude, suggesting a magnetically channeled accretion flow. The orbital period of V1006 Cyg places it squarely within the 2 to 3 hr “gap” in the distribution of cataclysmic binary orbital periods.

Online material: extended table

1. INTRODUCTION

Cataclysmic variables (CVs) are binary star systems in which the secondary, usually a late-type main-sequence star, fills its Roche lobe and loses mass to the white dwarf primary (Warner 1995). CVs are long-lived systems that are stable against mass transfer, so the mass transfer must be driven by gradual changes in the orbit, or in the secondary star, or both. It is commonly believed that the evolution of most CVs is driven by the slow loss of angular momentum from the orbit, most likely through magnetic braking of the corotating secondary star, at least at longer orbital periods \( P_{\text{orb}} \), where gravitational radiation is ineffective (Andronov & Pinsonneault 2004 give a recent discussion). The loss of angular momentum constricts the Roche critical lobe around the secondary and causes the system to transfer mass as it evolves toward shorter \( P_{\text{orb}} \). In this scenario, \( P_{\text{orb}} \) serves as a proxy measurement for the system’s evolutionary state. Correct and complete orbital period measurements are fundamental to any accurate theory of CV evolution. Given the usefulness of \( P_{\text{orb}} \), it is fortunate that it can usually be measured accurately and precisely.

This paper presents optical spectroscopy of the nine CVs listed in Table 1. We took these observations mostly for the purpose of finding orbital periods using radial velocities (none of these systems are known to eclipse). The long cumulative exposures also allowed us to look for any unusual features. The Catalog and Atlas of Cataclysmic Variables, Archival Edition (Downes et al. 2001) lists seven of the stars as dwarf novae, one as either a dwarf nova or a DQ Her star, and one simply as a cataclysmic, possibly a dwarf nova similar to U Gem or SS Cygni (type UGSS). Except for CZ Aql, for which we confirm a 4.8 hr candidate period suggested by Cieśliński et al. (1998), all of these objects lacked published orbital periods when we began working on them. Subsequently, Tappert & Bianchini (2003) found \( P_{\text{orb}} = 0.0883 \) days for GZ Cancri; we had communicated our advance findings to these authors so they could disambiguate their period determination.

2. OBSERVATIONS, REDUCTIONS, AND ANALYSIS

2.1. Observations

All our spectra were taken at the MDM Observatory on Kitt Peak, Arizona, using either the 1.3 m McGraw-Hill Telescope or the 2.4 m Hiltner Telescope. The earliest observations were

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1 Based on observations obtained at the MDM Observatory, operated by Dartmouth College, Columbia University, Ohio State University, Ohio University, and the University of Michigan.

2 Available at http://archive.stsci.edu/prepds/cvcat/index.html; this had been called the “Living Edition” until its author retired and ceased updates.
The wavelength calibration was based on 2.2. Reductions for each nighttime exposure using the O pixel-to-wavelength relation, and set the zero point individually used lamp exposures taken in twilight to find the shape of the was moved. For the 2.4 m data from 2003 to the present, we took lamp exposures through the night and whenever the telescope was covered. For unknown reasons, the results were unsatisfactory. To salvage the Hα emission velocities from that run, we determined a correction by cross-correlating the night-sky emission features in the 6200–6625 Å range with a well-calibrated night-sky spectrum obtained with a similar instrument. The correction was calculated for each individual spectrum and then applied to each measured velocity, and it did reduce the scatter somewhat, evidently because the wavelength range used includes the Hα emission line for which we measured velocities.

On all our runs, we observed flux standards during twilight when the sky was clear, and applied the resulting calibration to the data. The reproducibility of these observations suggests that our fluxes are typically accurate to ±20%. We also took short exposures of bright O and B stars in twilight to map the telluric absorption features and divide them out approximately from our program object spectra. Before flux calibration, we divided our program star spectra by a mean hot-star continuum in order to remove the bulk of the response variation. Table 1 lists V magnitudes synthesized from our mean spectra, using the IRAF sbands task and the passband tabulated by Bessell (1990); clouds, losses at the slit, and calibration errors make these uncertain by a few tenths of a magnitude, but they do give a rough indication of the brightness of each system at the time of our observation.

2.3. Analysis

Except for a few spectra taken in outburst (which show weak emission or absorption on a strong continuum), all of the stars show the prominent emission lines. Figures 1 and 2 show averaged spectra, and Table 3 gives the equivalent width and FWHM of each line measured for each star from its averaged spectrum.

Two stars, BF Eri and BI Ori, showed the spectral features of a late-type star. To quantify the secondary contribution in

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3 IRAF is distributed by the National Optical Astronomy Observatories.
these objects, we began by preparing averaged flux-calibrated spectra (in BF Eri’s case, the secondary’s radial velocity curve was measurable, so we shifted the individual spectra to the secondary’s rest frame before averaging). Over time we have used the 2.4 m and modular spectrograph to collect spectra of K and M stars classified by Keenan & McNeil (1989) or Boe-shaar (1976). The wavelength coverage and spectral resolution of these data are similar to the 1.3 m data. We applied a range of scaling factors to the library spectra, subtracted them from the averaged spectra, and examined the results by eye to estimate a range of spectral types and scaling factors giving acceptable cancellation of the late-type features.

We use the spectral type and secondary flux to estimate the distance in the following manner. We begin by finding the surface brightness of the secondary star in $V$, on the assumption that the surface brightness is similar to that of main-sequence stars of the same spectral type; the Barnes-Evans relation for late-type stars is discussed by Beuermann (2006). Combining the known $P_{\text{orb}}$ with the assumption that the secondary fills its Roche critical lobe yields the secondary’s radius $R_2$ as a function of its mass, $M_2$. In the relevant range of mass ratio, $R_2 \propto M_2^{1/3}$, approximately, and the dependence on $M_1$ is weak enough to ignore. We generally do not know $M_2$, so we guess at a generous allowable range for this parameter using evolutionary simulations by Baraffe & Kolb (2000) as a guideline; the weakness of the dependence of $R_2$ on $M_2$ means that this (rather questionable) step does not dominate the error budget. Combining the surface brightness with $R_2$ yields the absolute magnitude $M_V$. Subtracting this from the apparent magnitude measured for the secondary star gives a distance modulus. The reddening maps of Schlegel et al. (1998) can then be used to estimate the extinction. Note carefully that we do not assume that the secondary is a “normal” main-sequence star; we assume only that the secondary’s surface brightness is similar to field stars of the same spectral type. The normalization of the secondary’s contribution also depends on the assumption that the spectral features used to judge the subtraction are similar in strength to those of a normal star.

As noted earlier, the immediate aim of our observations was to find orbital periods from radial velocity time-series data. The Hα emission line is usually the strongest feature, and it generally gives good results in dwarf novae. All the emission-line velocities reported here are of Hα.

We measured radial velocities of Hα emission using convolution methods described by Schneider & Young (1980) and Shafter (1983). In this technique, one convolves an antisymmetric function with the line profile and takes the zero of the convolution (where the two sides of the line contribute equally) as the line center. For the antisymmetric function with which the spectrum is convolved, we used either the derivative of a Gaussian with adjustable width, or positive and negative Gaussians of adjustable width offset from each other by an adjustable separation. Uncertainties in the convolution velocities are estimated by propagating forward the counting-statistics errors.
in the individual data channels; in practice, these are lower limits to the true uncertainties, since the line profile can vary in ways unrelated to the orbital modulation. The choice of convolution parameters is dictated by the shape and width of the line, and in practice the parameters are adjusted to give the best detection of the orbit. The physical interpretation of CV emission lines is complicated and controversial (see, e.g., Shafter 1983; Marsh 1988; Robinson 1992), but in almost all cases the emission-line periodicity accurately reflects $P_{\text{orb}}$ (although Araujo-Betancor et al. [2005] describe a noteworthy exception to this rule). A sample of the radial velocities for each object are listed in Table 4, while the full tables can be found online.

One of our systems, BF Eri, has a K-type absorption component in its spectrum. We measured its velocities with the cross-correlation radial velocity package described by Kurtz & Mink (1998), using the region from 5000 to 6500 Å and excluding the region containing the He $\lambda$ 5876 emission line and the Na D absorption complex. For a cross-correlation template spectrum, we used a velocity-compensated sum of many observations of IAU velocity standards taken with the same instrument, as described in Thorstensen et al. (2004).

We searched for periods in all the velocity time series using the “residualgram” method (Thorstensen et al. 1996); the resulting periodograms are given in Figures 3 and 4. At the best candidate periods, we fitted least-squares sinusoids of the form $v(t) = \gamma + K \sin [2\pi(t - \tau)/P]$. Figure 5 shows the velocities folded on the best-fitting periods, and Table 5 gives the parameters of these fits. Because of limitations of the sampling (e.g., the need to observe only at night from a single site), a single periodicity generally manifests as a number of alias frequencies. To assess the confidence with which we could assert that the strongest alias is the true period, we used a Monte Carlo test described by Thorstensen & Freed (1985).

The alias problem can be particularly irksome over longer timescales; in this case, the uncertain number of cycles that have elapsed between observing runs causes fine-scale “ringing” in the periodogram. The individual periods have tiny error bars because of the large time span covered, but the ambiguity in period means that a realistic error bar—one that covers the range of possibilities—is much larger. In those cases, the period uncertainties given in Table 5 are estimated by analyzing data from the individual observing runs separately. When only two observing runs are available, the allowable fine-scale frequencies are well described by a fitting formula

$$P_{\text{orb}} = (t_2 - t_1)/n,$$

where $t_1$ and $t_2$ are the epochs of blue-to-red velocity crossing observed on the two runs, and $n$ is the integer number of cycles that have passed between $t_1$ and $t_2$. The allowed range of $n$ is determined from the weighted average of the periods derived from separate fits to the two runs’ data. When more than two observing runs are available, the situation becomes more complex. In some happy cases, there are enough overlapping con-
constraints that only a single, very precise period remains tenable. We were able to find such precise periods for LX And, LU Cam, and BF Eri.

3. NOTES ON INDIVIDUAL OBJECTS
We discuss the stars in alphabetical order by constellation.

3.1. LX Andromedae
LX And was first identified as a variable star (RR V-3) in the Lick RR Lyrae search (Kinman et al. 1982). It was classified incorrectly as an RV Tauri star, and its dwarf nova nature was unrecognized until the photometric study by Uemura et al. (2000). Morales-Rueda & Marsh (2002) obtained spectra of...
The broad components around Hβ phase 0 corresponds to the blue-to-red crossing of the line core. With those of Hα/H11002 have been shifted into a rest frame before averaging and do not include the 2006 March or 2007 January data.

LX And as part of their study of dwarf novae in outburst and determined the equivalent widths and FWHMs of the Balmer and He ii lines. Our mean spectrum appears typical for a dwarf nova at minimum light.

Because of the large hour-angle span, the radial velocity time series leaves no doubt about the daily cycle count, which is near 6.6 cycles day⁻¹. The several observing runs constrain the fine-scale period in a more complicated way, but the Monte Carlo test indicates that a precise period of 0.1509743(5) days is preferred, with about 98% confidence. Two other candidate periods separated from this by 1 cycle per 53.2 days in frequency are much less likely.

3.2. CZ Aquilae

Very little has been published on CZ Aql, which is listed in the Archival Edition as a U Gem dwarf nova. Cieslinski et al. (1998) included the star in their spectroscopic study of irregular variables and noted a probable 4.8 hr period and emission lines typical of dwarf novae. Our velocities confirm the suggested 4.8 hr period, but we cannot determine a unique cycle count between our observing runs.

While the spectrum superficially resembles that of a dwarf nova, a closer look reveals interesting behavior. Figure 6, constructed using methods described by Taylor et al. (1999), presents our spectra as a phase-averaged gray-scale image. There is a striking broad component in the stronger Balmer and He i lines that shows a large velocity excursion, with the red wing of Hα reaching to +3100 km s⁻¹ at phase 0.3 (where phase 0 corresponds to the blue-to-red crossing of the line core). The broad components around Hβ and λ6678 move in phase with those of Hα and range from 900 to 2600 and -2500 to -900 km s⁻¹ and 700 to 2100 and -1000 to -600 km s⁻¹.

![Graph](Image)

**Fig. 2.**—Plot of the averaged spectrum of BF Eri (top) and the spectrum after a scaled late-type (K3 V) star has been subtracted (bottom). The spectra have been shifted into a rest frame before averaging and do not include the 2006 March or 2007 January data.

SPECTROSCOPY OF NINE CVs

### Table 3

| Feature | EW (Å) | Flux (10⁻¹⁶ ergs cm⁻² s⁻¹) | FWHM (Å) |
|---------|--------|-----------------------------|----------|
| Hβ      | 45     | 690                         | 18       |
| He i λ4921 | 4     | 60                          | 25       |
| He i λ5015 | 3     | 50                          | 20       |
| Fe i λ5169 | 2     | 20                          | 14       |
| He i λ5876 | 11    | 120                         | 19       |
| Hα      | 54     | 560                         | 17       |
| He i λ6678 | 4     | 40                          | 19       |

**CZ Aql**

| Feature | EW (Å) | Flux (10⁻¹⁶ ergs cm⁻² s⁻¹) |
|---------|--------|---------------------------|
| Hβ      | 21     | 670                       |
| He i λ4921 | 1     | 40                        |
| He i λ5015 | 2     | 50                        |
| He i λ5876 | 7     | 160                       |
| Na D    | -1    | -16                       |
| Hα      | 61     | 1250                       |
| He i λ6678 | 5     | 90                        |

**LU Cam**

| Feature | EW (Å) | Flux (10⁻¹⁶ ergs cm⁻² s⁻¹) |
|---------|--------|---------------------------|
| Hβ      | 10     | 170                       |
| He i λ4471 | 2     | 30                        |
| Hβ      | 14     | 190                       |
| He i λ4921 | 1     | 20                        |
| He i λ5015 | 2     | 20                        |
| Fe i λ5169 | 1     | 10                        |
| He i λ5876 | 4     | 50                        |
| Hα      | 27     | 240                       |
| He i λ6678 | 3     | 20                        |
| He i λ7067 | 3     | 20                        |

**GZ Cnc**

| Feature | EW (Å) | Flux (10⁻¹⁶ ergs cm⁻² s⁻¹) |
|---------|--------|---------------------------|
| Hβ      | 26     | 940                       |
| He i λ4471 | 8     | 260                       |
| He ii λ4686 | 5     | 140                       |
| Hβ      | 36     | 1040                      |
| He i λ4921 | 5     | 140                       |
| He i λ5015 | 4     | 100                       |
| Fe i λ5169 | 2     | 60                        |
| He i λ5876 | 9     | 200                       |
| Hα      | 38     | 790                       |
| He i λ6678 | 4     | 90                        |
| He i λ7067 | 3     | 60                        |

**V632 Cyg**

| Feature | EW (Å) | Flux (10⁻¹⁶ ergs cm⁻² s⁻¹) |
|---------|--------|---------------------------|
| Hβ      | 80     | 260                       |
| He i λ4921 | 6     | 20                        |
| He i λ5015 | 8     | 20                        |
| Fe i λ5169 | 5     | 10                        |
| He i λ5876 | 28    | 70                        |
| Hα      | 113    | 260                       |
| He i λ6678 | 15    | 30                        |

**V1006 Cyg**

| Feature | EW (Å) | Flux (10⁻¹⁶ ergs cm⁻² s⁻¹) |
|---------|--------|---------------------------|
| Hβ      | 74     | 250                       |
| He i λ4921 | 8     | 30                        |
| He i λ5015 | 8     | 30                        |
| Fe i λ5169 | 8     | 30                        |
| He i λ5876 | 26    | 70                        |
| Hα      | 108    | 250                       |
| He i λ6678 | 11    | 30                        |

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lies along the line of sight, and that the luminosity is relatively high.

High-velocity wings reminiscent of the ones seen here have been seen in V795 Her (Casares et al. 1996; Dickinson et al. 1997), LS Peg (Taylor et al. 1999), V533 Her (Thorstensen & Taylor 2000), and RX J1643+34 (Patterson et al. 2002), all of which are SW Sex stars. We do not, however, detect another SW Sex characteristic, namely phase-dependent absorption in the \( \text{He} \dagger \) lines (Thorstensen et al. 1991). The orbital periods of most SW Sex stars are shorter than 4 hr, so CZ Aql’s 4.8 hr period would be unusually long for an SW Sex star.

3.3. LU Camelopardalis

Jiang et al. (2000) obtained the first spectrum of this dwarf nova in a follow-up study of CV candidates from the ROSAT All-Sky Survey. We found no other published spectroscopic studies. Our velocities constrain the period to a unique value, 0.1499685(7) days. The averaged spectrum shows a rather strong, blue continuum, which may indicate a state somewhat above true minimum.

3.4. GZ Cancri

Jiang et al. (2000) confirmed the cataclysmic nature of GZ Cnc by obtaining the first spectrum of the object. Kato et al. (2002) suggested that this star, originally labeled as a dwarf nova, could possibly be an intermediate polar (DQ Her star), based on similarities in its long-term photometric behavior to that of other intermediate polars. Tappert & Bianchini (2003) conducted a photometric and spectroscopic study of the system. Using advance results from the present study to help decide the daily cycle count, they found \( P_{\text{orb}} = 0.08825(28) \) days, or 2.118(07) hr, placing the system near the lower edge of the so-called gap in the \( \text{CV} \) period distribution—an dearth of systems in the period range from roughly 2 to 3 hr. Tappert & Bianchini (2003) also saw characteristics that could indicate an intermediate polar classification but did not claim their evidence was definitive on this point.

Almost all our observations come from two observing runs a year apart. The full set of velocities strongly indicates an orbital frequency near 11.4 cycles day\(^{-1}\), with the Monte Carlo test giving a discriminatory power greater than 0.99 for the choice of daily cycle count. However, the number of cycles between the two observing runs is not determined. Precise periods that fit the combined data set are given by \( P = \frac{349.785(3) \text{ days}}{n} \), where \( n \) is the integer number of cycle counts; \( n = 3972 \pm 8 \) corresponds to roughly 1 standard deviation. While our period agrees well with that of Tappert & Bianchini (2003), our data neither support nor disprove the claim that GZ Cnc may be an intermediate polar.

3.5. V632 Cygni

Liu et al. (1999) offer the only published spectrum of this dwarf nova. They measured the equivalent widths and inte-
Fig. 3.—Periodigrams for most of the stars studied here. The vertical axis in each case is the inverse of $\chi^2$ for the least-squares best-fitting sinusoid at each trial frequency. When data from more than one observing run are combined, the periodigram can require hundreds of thousands of points to resolve the fine-scale ringing; in those cases, the curve shown is formed by connecting local maxima of the periodogram with straight lines. In those cases, the right-hand panel gives a close-up view of the region around the highest peak, revealing the alias structure resulting from different choices of cycle count between the observing runs. The periodogram of BF Eri is for the absorption-line velocities.
Fig. 4.—Periodigrams for the remainder of the stars, plotted in the same manner as the previous figure. Because the choice of daily cycle count for FO Per remains ambiguous, we have not chosen to enlarge either peak region.

grated line fluxes of the Balmer, He i, and He ii emission lines and suggested that the orbital period is likely short, based on the very strong Balmer emission. Our spectrum appears similar to theirs, and our measured flux level is also nearly the same. The periodogram in Figure 3 clearly favors an orbital frequency near 15.7 cycles day$^{-1}$, with a discriminatory power of 95% and a correctness likelihood near unity. This confirms the suggestion of Liu et al. (1999) that the period is rather short and suggests that it is an SU UMa–type dwarf nova.

3.6. V1006 Cygni

Bruch & Schimpke (1992) present the only published spectrum we know of and characterized it as a “textbook example” of a dwarf nova spectrum. They noted a slightly blue continuum with strong Balmer and He i emission, as well as clear He ii λ4686 and Fe ii emission. Our spectrum (Fig. 1) is similar to theirs in both appearance and normalization, and our line measurements (Table 3) are also comparable.

The periodogram (Fig. 4) indicates a frequency near 10.1 cycles day$^{-1}$, and the Monte Carlo test confirms that the daily cycle count is securely determined. Most of our data are from 2004 June, but we returned in 2005 June/July to confirm the unusual period indicated in the earlier data. The periods found by analyzing the two runs separately are consistent within their uncertainties. As with GZ Cnc, there are multiple choices for the cycle count between the two observing runs; the best-fitting periods are given by $P = (369.006(4)$ days)/$n$, where $n = 3726 \pm 4$ corresponds to 1 standard deviation. Including a few velocities from other observing runs suggests that $n$ is slightly larger, perhaps 3728. In any case, the period amounts to 2.38 hr, which places V1006 Cyg firmly in the period gap (Warner 1995), where there is apparently a true scarcity of dwarf novae (Hellier & Naylor 1998).

3.7. BF Eri

The first evidence that BF Eridani was a cataclysmic variable came when an Einstein X-ray source, 1ES 0437–046, was matched to the variable (Elvis et al. 1992). Schachter et al. (1996) confirmed this match and presented an optical spectrum. Kato (1999) and the Variable Star Observers League in Japan (VSOLJ) found photometric variability characteristic of a dwarf nova.

The spectrum of BF Eri (Fig. 2) shows a significant contribution from a K star, along with the usual dwarf-nova emission lines. Normally, this suggests that $P_{\text{orb}} > 6$ hr. Nearly all our spectra yielded good cross-correlation radial velocity measurements as well as emission-line velocities. The absorption- and emission-line velocities independently give a period near 6.50 hr (Table 5), in accordance with expectation based on the spectrum. There is no ambiguity in cycle count over the 5 yr span of the observations, so the period is precise to a few parts per million. Figure 6 shows a phase-resolved average of the BF Eri spectra, with the absorption spectrum shifting in antiphase to the emission lines.

If the emission-line velocities faithfully trace the primary’s center-of-mass motion, and the absorption-line velocities also trace the secondary’s motion, then the two velocity curves should be exactly one-half cycle out of phase. In BF Eri, we
Fig. 5.—Radial velocities plotted as a function of phase using the adopted orbital periods. For CZ Aql, GZ Cnc, and V1006 Cyg, the number of cycle counts between observing runs is unknown, and the exact period chosen to fold the velocities is one of a number of possibilities. The two plots for FO Per are for different choices of the daily cycle count, and each of these in turn is also an arbitrary choice among many finely spaced periods. In BF Eri, both emission and absorption velocities are plotted; the absorption velocities are shown with error bars.
find a shift of 0.515 ± 0.007 cycles between the two curves, consistent with 0.5 cycles, so we feel emboldened to explore the system dynamics.

Masses can only be derived when the orbital inclination is known, as in eclipsing systems. To see if BF Eri might eclipse, we derived differential magnitudes from images that were taken for astrometry (discussed below) and plotted them as a function of orbital phase. Some images were taken at the phase at which an eclipse would appear, but no evidence for an eclipse was found. Limits on the depth and duration of the eclipse are difficult to quantify, because the data were taken in short bursts in the presence of strong intrinsic variability, so a weak eclipse cannot be ruled out, but the photometry does suggest that the inclination is not close to edge-on.

Because the system apparently does not eclipse, we cannot derive masses; rather, we find broad constraints on the inclination by assuming astrophysically reasonable masses for the components. Taken at face value, the velocity amplitudes \( K \) imply a mass ratio \( q = M_2/M_1 = 0.60 ± 0.03 \). If we arbitrarily choose a white dwarf mass \( M_1 = 0.9 M_\odot \) (so that \( M_2 = 0.53 M_\odot \)), the observed \( K \) velocities imply \( i = 50^\circ \). To find a rough lower limit on the inclination, we consider a massive white dwarf (\( M_1 = 1.2 M_\odot \)) and, ignoring the constraint on \( q \) for the moment, take \( M_2 = 0.4 M_\odot \); this yields \( i = 40^\circ \). For a rough upper limit, we assume \( M_1 = 0.6 M_\odot \) and \( M_2 = 0.4 M_\odot \), which gives \( i = 67^\circ \).

The decomposition procedure described earlier yielded a spectral type K3 ± 1 subclass; the result of the subtraction is shown in Figure 2. Using the \( V \) passband tabulated by Bessell (1990) and the IRAF task \texttt{sbands}, we find a synthetic \( V = 16.9 ± 0.3 \) for the K star’s contribution. Taking the range of plausible secondary star masses to be 0.4–0.8 \( M_\odot \), which yields \( R_2 = 0.7 ± 0.1 R_\odot \) at this \( P \). Combining this with the surface brightness expected at this spectral type yields \( M_2 = 6.8 ± 0.4 \) for the secondary. If there is no significant interstellar extinction, we have \( m - M = 10.1 ± 0.5 \), or a distance of approximately 1100 ± 300 pc. The dust maps of Schlegel et al. (1998) give a total \( E(B-V) = 0.062 \) in this direction. Assuming that BF Eri is beyond the Galactic dust, and taking \( A_V/E(B-V) = 3.3 \), gives an extinction-corrected \( m - M_0 = 9.9 \) and a distance estimate of 950^{+250}_{-200} \, pc.

We can also estimate a distance using the relation found by Warner (1987) between \( P \), and the absolute magnitude at maximum light, \( M_V \). Using our inclination constraints, the Warner relation predicts \( M_V \) at this orbital period. The General Catalog of Variable Stars (GCVS) lists \( m_p = 13.2 \) at maximum light; taking this to be similar to \( V_\text{mean} \), yields \( m - M = 9.3 \), or 9.1 corrected for extinction, which corresponds to 660 pc.

\begin{table}[h]
\centering
\caption{Fits to Radial Velocities}
\begin{tabular}{lcccccc}
\hline
Star & Algorithm & \( T_\text{ref} \) & \( P \) & \( K \) & \( \gamma \) & \( \sigma \) \\
& & & (days) & (km s\(^{-1}\)) & (km s\(^{-1}\)) & (km s\(^{-1}\)) \\
\hline
LX And & G2.21.7 & 53,754.6861(12) & 0.1509743(5) & 81(4) & -48(3) & 87 & 15 \\
CZ Aql & G2.18.8 & 53,557.802(3) & 0.2005(6) & 193(15) & 5(10) & 89 & 61 \\
LU Cam & D,15 & 52,327.742(14) & 0.1499686(4) & 57(4) & 44(3) & 66 & 14 \\
GZ Cnc & G2.15.9 & 51,992.8928(13) & 0.0881(4) & 79(7) & 22(5) & 71 & 26 \\
V632 Cyg & D,28 & 53,560.9748(13) & 0.06377(8) & 62(8) & -49(5) & 51 & 28 \\
V1006 Cyg & G2.20.9 & 53,187.9091(16) & 0.09904(9) & 89(8) & -11(6) & 120 & 44 \\
BF Eri & G2.21.7 & 52,574.0027(18) & 0.2708804(4) & 182(4) & -72(3) & 117 & 20 \\
BF Eri & ... & 52,573.8632(9) & 0.2708805(4) & ... & ... & ... & ... \\
BF Eri & G2.35.9 & 53,756.5413(1) & 0.1015(5) & 131(13) & 24(9) & 60 & 44 \\
FO Per (shorter) & D,11 & 52,261.872(3) & 0.1467(4) & 27(3) & -49(2) & 131 & 17 \\
FO Per (longer) & D,11 & 52,261.893(3) & 0.1719(5) & 27(3) & -45(2) & 131 & 17 \\
\hline
\end{tabular}
\end{table}

Notes.—Parameters of sinusoidal least-squares fits to the velocity time series, of the form \( r(t) = \gamma + K \sin [2\pi(t - T_\text{ref})/P] \). The quoted parameter uncertainties are based on the assumption that the scatter of the data around the best fit is a realistic estimate of the velocity uncertainty (Cash 1979). In practice, this is more conservative than assuming that counting statistics uncertainties are realistic.

\(^{a}\) Code for the convolution function used to derive emission-line velocities; \( D \) is a derivative of a Gaussian, \( G2 \) is double-Gaussian function (see text). For the \( D \) algorithm, the number that follows gives the line FWHM, in \( \text{Å} \), for which the function is optimized; for the \( G2 \) algorithm, the two numbers are respectively the separation of the two Gaussians and their individual FWHMs, again in \( \text{Å} \).

\(^{b}\) Heliocentric Julian Date minus 2,400,000. The epoch is chosen to be near the center of the time interval covered by the data and within one cycle of an actual observation.

\(^{c}\) Rms residual of the fit.

\(^{d}\) The period determination in this case is complicated by unknown numbers of cycles between observing runs; the uncertainty given here is an estimate based on fits to individual runs. Only certain values within the period range given here are allowed; see text for details.
Fig. 6.—Phase-averaged spectra of CZ Aql (top two panels) and BF Eri (bottom two panels), presented as a gray scale. The scale is inverted so that emission is represented by darker shades. The two CZ Aql spectra are scaled differently to show the line cores (top) and the extent of the line wings. Note the Na D lines in CZ Aql remain stationary, indicating an interstellar origin. The feature at 6280 Å is telluric. BF Eri’s spectrum is plotted in two overlapping sections; the K-star’s orbital motion is plainly visible.
Given these distance estimates, it is surprising that BF Eri has a very substantial proper motion. The Lick proper motion survey (Hanson et al. 2004) gives $(\mu_x, \mu_y) = (+34, -97)$ mas yr$^{-1}$. We have begun a series of parallax observations with the Hiltner 2.4 m telescope, using the protocols described by Thorstensen (2003); so far, we have five epochs from 2005 November and 2007 January. The proper motion related to the background stars is $(\mu_x, \mu_y) = (32, -111)$ mas yr$^{-1}$, and the parallax is not detected, with a nominal value of 1 $\pm$ 2 mas. The parallax determination is very preliminary, but given the data so far, we estimate the lower limit on the distance based on the astrometry alone to be $\sim 200$ pc.

At the nominal 950 pc distance derived from the secondary star, a 100 mas yr$^{-1}$ proper motion corresponds to a transverse velocity $v_T = 451$ km s$^{-1}$. This is implausibly large, so we are left wondering how we might have overestimated the distance. One effect might be as follows. Our distance is based on the secondary’s apparent brightness, and we estimate the secondary’s contribution to the total light by searching for the best cancellation of its features. If the secondary’s absorption lines are weaker than those in the spectral-type standards, we would underestimate the secondary’s contribution. In our best decomposition, the secondary is about 2.2 mag fainter than the total light in $V$. Assuming (unrealistically) that all the light is from the secondary would therefore decrease the distance modulus by 2.2 mag, to a distance of 340 pc.

We do not yet have enough information to resolve the cocoon of the secondary star, and to put it in something like 400–500 pc, with an underluminous, low-metallicity secondary. The cross-correlation velocities of the secondary have a zero point determined to be $V = 20.0 \pm 0.4$. Assuming that the secondary’s mass lies in the broad range from 0.2 to 0.6 $M_\odot$, its radius at this $P_{\text{orb}}$ would be 0.35–0.6 $R_\odot$. Combining this with the surface brightness derived from the spectral types gives an absolute magnitude $M_V = 10.2 \pm 1.0$. The distance modulus, corrected for extinction, is therefore $m - M = +9.8 \pm 1.1$, corresponding to 910$^{+660}_{-300}$ pc. Schlegel et al. (1998) estimate a total reddening $E(B - V) = 0.11$ in this direction; assuming that BI Ori lies beyond all the dust, and taking $A_V/E(B - V) = 3.3$, reduces the distance to $\sim 770$ pc. At maximum light, BI Ori has $m_\nu = 13.2$ (GCVS). Assuming the color is neutral, we find $M_V = 3.4 \pm 1.1$ at maximum. At BI Ori’s period, the Warner (1987) relation predicts $M_P > 3.6$ (with the brightness value corresponding to $i = 0$). This agrees broadly with our nominal value based on the secondary star’s distance, but is a little fainter, suggesting that BI Ori is not too far from face-on, or a little closer than our nominal distance, or both.

### 3.9. FO Per

FO Persei was apparently discovered by Morgenroth (1939), but its cataclysmic nature was not immediately recognized. Bruch (1989) obtained spectra and gave equivalent widths for the Balmer lines for two different nights of observations, between which the continuum changed from relatively flat to inclined toward the red.

The emission lines in FO Per are rather narrow (Fig. 1, Table 3). This is often taken to indicate a low orbital inclination. The velocity amplitude $K$ is small, so that $K/\sigma \approx 1.6$ for the best fits (Table 5). Because of this, the daily cycle count remains ambiguous; the orbital frequency is either 5.8 or 6.8 cycles day$^{-1}$, corresponding to $P_{\text{orb}}$ of 3.52 or 4.13 hr. CVs with periods in the 3–4 hr range tend to be nova-like variables (Shafter 1992), whereas FO Per is a dwarf nova; thus, the 4.13 hr period is more likely a priori.

### 4. SUMMARY

We have determined the orbital periods of eight CVs without significant daily cycle count ambiguity; for FO Per, the period is narrowed to two choices. For three of the systems, we find high-precision periods by establishing secure cycle counts over long baselines.

While most of these objects are similar to others already known, three stand out as especially interesting. CZ Aql shows asymmetric, high-velocity wings around the Balmer and He I $\lambda\lambda$5876 and 6678 lines, possibly indicating a magnetic system. BF Eri’s proper motion of $\sim 100$ mas yr$^{-1}$ is surprising in view of the large distance indicated by its secondary spectrum and by the Warner relation; even if it is somewhat nearer than these indicators suggest, its kinematics are not typical of disk stars.
Finally, the orbital period of V1006 Cyg places it squarely in the middle of the so-called period gap between 2 and 3 hr.

We are most grateful for support from the National Science Foundation through grants AST 99-87334 and AST 03-07413. Bill Fenton took most of the spectra of GZ Cnc, and J. Cameron Brueckner assisted with the BF Eri spectroscopy. Some of the astrometric images of BF Eri were obtained by Sébastien Lépine and Michael Shara of the American Museum of Natural History. We would like to thank the MDM Observatory staff for their skillful and conscientious support. Finally, we are grateful to the Tohono O’odham for leasing us their mountain for a while, so that we may study the glorious universe in which we all live.

REFERENCES

Andronov, N., & Pinsonneault, M. H. 2004, ApJ, 614, 326
Araujo-Betancor, S., et al. 2005, A& A, 430, 629
Baraffe, I., & Kolb, U. 2000, MNRAS, 318, 354
Bessell, M. S. 1990, PASP, 102, 1181
Beuermann, K. 2006, A&A, 460, 783
Boeshaar, P. 1976, Ph. D. thesis, Ohio State Univ.
Bruch, A. 1989, A& AS, 78, 145
Bruch, A., & Schimpke, T. 1992, A&A, 93, 419
Casares, J., Martinez-Pais, I. G., Marsh, T. R., Charles, P. A., & Lazaro, C. 1996, MNRAS, 278, 219
Cash, W. 1979, ApJ, 228, 939
Cieslinski, D., Steiner, J. E., & Jablonski, F. J. 1998, A& AS, 131, 119
Dickinson, R. J., Prinja, R. K., Rosen, S. R., King, A. R., Hellier, C., & Horne, K. 1997, MNRAS, 286, 447
Downes, R. A., Webbink, R. F., Shara, M. M., Ritter, H., Kolb, U., & Duerrbeck, H. W. 2001, PASP, 113, 764
Elvis, M., Plummer, D., Schachts, J., & Fabbiani, G. 1992, ApJS, 80, 257
Hanson, R. B., Klemola, A. R., Jones, B. F., & Monet, D. G. 2004, AJ, 128, 1430
Hellier, C., & Naylor, T. 1998, MNRAS, 295, L50
Jenniskens, P., & Desert, F.-X. 1994, A& AS, 106, 39
Jiang, X. J., Engels, D., Wei, J. Y., Tesch, F., & Hu, J. Y. 2000, A& A, 362, 263
Kato, T. 1999, Inf. Bull. Variable Stars, 4745, 1
Kato, T., et al. 2002, A&A, 396, 929
Keenan, P. C., & McNeil, R. C. 1989, ApJS, 71, 245
Kinman, T. D., Mahaffey, C. T., & Wirtanen, C. A. 1982, AJ, 87, 314
Kurtz, M. J., & Mink, D. J. 1998, PASP, 110, 934
Liu, W., Hu, J. Y., Zhu, X. H., & Li, Z. Y. 1999, ApJS, 122, 243
Marsh, T. R. 1988, MNRAS, 231, 1117
Monet, D., et al. 1996, USNO-A2.0 Catalog (Washington: US Naval Obs.)
Morales-Rueda, L., & Marsh, T. R. 2002, MNRAS, 332, 814
Morgernroth, O. 1939, Astron. Nachr., 268, 273
Patterson, J., et al. 2002, PASP, 114, 1364
Robinson, E. L. 1992, in ASP Conf. Ser. 29, Cataclysmic Variable Stars, ed. N. Vogt (San Francisco: ASP), 29, 3
Schacht, J. F., Remillard, R., Saar, S. H., Favata, F., Sciortino, S., & Barbera, M. 1996, ApJ, 463, 747
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Schneider, D. P., & Young, P. 1980, ApJ, 238, 946
Shafer, A. W. 1983, ApJ, 267, 222
———. 1992, ApJ, 394, 268
Szkody, P. 1987, ApJS, 63, 685
Tappert, C., & Bianchini, A. 2003, A&A, 401, 1101
Taylor, C. J., Thorstensen, J. R., & Patterson, J. 1999, PASP, 111, 184
Thorstensen, J. R. 2003, AJ, 126, 3017
Thorstensen, J. R., Fenton, W. H., & Taylor, C. J. 2004, PASP, 116, 300
Thorstensen, J. R., & Freed, I. W. 1985, AJ, 90, 2082
Thorstensen, J. R., Patterson, J. O., Shambrook, A., & Thomas, G. 1996, PASP, 108, 73
Thorstensen, J. R., Ringwald, F. A., Wade, R. A., Schmidt, G. D., & Norrisworthy, J. E. 1991, AJ, 102, 272
Thorstensen, J. R., & Taylor, C. J. 2000, MNRAS, 312, 629
Uemura, M., Kato, T., & Watanabe, M. 2000, Inf. Bull. Variable Stars, 4831, 1
Warner, B. 1987, MNRAS, 227, 23
———. 1995, Cambridge Astrophysics Series (Cambridge: Cambridge Univ. Press)
Zacharias, N., Urban, S. E., Zacharias, M. I., Wycoff, G. L., Hall, D. M., Monet, D. G., & Raftery, T. J. 2004, AJ, 127, 3043