Spectroscopy of Four Cataclysmic Variables with Periods above 7 Hours

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ABSTRACT. We present spectroscopy of four cataclysmic variables. Using radial velocity measurements, we find orbital periods $P_{\text{orb}}$ for the first time: for GY Hya, $0.347230(9)$ days, for SDSS J204448$-$045929, $1.68(1)$ days, for V392 Hya, $0.324952(5)$ days, and for RX J1951.7$+$3716, $0.492(1)$ days. We also detect the spectra of the secondary stars, estimate their spectral types, and derive distances based on surface brightness and Roche lobe constraints.

1. INTRODUCTION

Cataclysmic variables (CVs) are close binary star systems composed of a white dwarf (the primary) that accretes matter from a less compact companion star (the secondary) in Roche lobe overflow. There exist many types of CVs, providing unique laboratories for studying various aspects of astrophysics. Warner (1995) gives an overview of the field.

The most fundamental characteristic of a CV is the period of its orbit, $P_{\text{orb}}$. When an eclipse is evident, the period is incontrovertible. In noneclipsing CVs, the period can be found using radial velocities. Often, a spectral contribution from the secondary star is present. This provides useful clues to the distance and the evolutionary state of the system.

In the current study, we discuss four CVs, GY Hya, SDSS J204448$-$045929, V392 Hya, and RX J1951.7$+$3716, none of which have extensive spectroscopic studies in the literature. We report their basic properties (period and spectral type of secondary) and infer distances. All four stars have periods above 7 hr, the longest period being that of SDSS J204448$-$045929, $1.68(1)$ days. As stated in Thorsten sen et al. (2004, hereafter TFT04), longer period systems provide information on CV evolution; in particular, many systems appear to have begun nuclear evolution prior to mass transfer (Baraffe & Kolb 2000). TFT04 provide a background in long-period CV analysis.

Section 2 describes the observations and analysis, and § 3 gives results. In § 4, we provide a brief discussion.

2. TECHNIQUES

Table 1 lists the observations, all of which were taken with the 2.4 m Hiltner Telescope at MDM Observatory in Kitt Peak, Arizona. We used the “modular” spectrograph, a 600 line mm$^{-1}$ grating, a 1” slit, and a SITe 2048$^2$ CCD detector yielding 2 Å pixel$^{-1}$ from 4210 to 7560 Å (vignetting severely toward the ends), and typical resolution of 3.5 Å FWHM. On most observing runs, spectra from comparison lamps were taken whenever the telescope was moved, to achieve accurate wavelength calibration. On some observing runs, comparison lamp spectra were not taken during the night, and the wavelength solution derived from lamps was shifted by an amount determined from the night-sky lines. For a detailed discussion of calibration procedures, see TFT04.

2.1. Period Determination

Our main objective was to find orbital periods. To this end, we measured radial velocities in the spectra, using both absorption and emission lines, when possible. The absorption lines originate in the atmosphere of the secondary star. Absorption-line velocities were found using the IRAF cross-correlation radial velocity package xcsao (Kurtz & Mink 1998). The routine was run on the wavelength range 6000 to 6500 Å. Uncertainties, based on the $R$-statistic of Tonry & Davis (1979), are typically less than 10 km s$^{-1}$. For a handful of low signal-to-noise ratio (S/N) exposures, the cross-correlations were not formally significant, leading to unphysical velocities that were excluded from further analyses.

Emission-line velocities were found by measuring the shift of Hα via the convolution technique of Schneider & Young (1980) and Shafter (1983). This method consists of convolving two antisymmetric Gaussians with the emission line, using an adjustable separation parameter and searching for the zero of the convolution. Typical values of $\alpha$ are 12–15 Å. The idea (valid or not) is that the two Gaussians measure the wings of the line, which may arise in a symmetrical portion of the accretion-disk emission close to the white dwarf. The best parameters for the convolution function are found by searching...
TABLE 1

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| Date (UT) | N  | Start  | End  |
|-----------|----|--------|------|
| GY Hya    |    |        |      |
| 2004 Mar 7 | 8  | -2.05  | +1.36|
| 2004 Mar 9 | 9  | -0.33  | +1.29|
| 2004 Jun 22 | 3  | -0.15  | +2.21|
| 2004 Jun 25 | 2  | +0.02  | +0.15|
| 2004 Jun 26 | 1  | -0.06  | -0.06|
| 2004 Jul 1  | 2  | +0.18  | +0.35|
| SDSS 2044-04 | |        |      |
| 2004 Jun 22 | 2  | -1.58  | -1.47|
| 2004 Jun 23 | 3  | -1.24  | -1.05|
| 2004 Jun 24 | 4  | -0.39  | +1.14|
| 2004 Jun 25 | 3  | -2.13  | +0.43|
| 2004 Jun 26 | 5  | -3.08  | +0.30|
| 2004 Jun 27 | 2  | +0.55  | +1.07|
| 2004 Jun 28 | 6  | -2.19  | +1.20|
| 2004 Jun 29 | 2  | -3.41  | -3.29|
| 2004 Jun 30 | 1  | +1.33  | +1.33|
| 2004 Jul 1  | 2  | -3.02  | -2.49|
| V392 Hya   |    |        |      |
| 2002 Jan 22 | 2  | +0.07  | +0.18|
| 2003 Jan 31 | 1  | +0.17  | +0.17|
| 2003 Feb 1  | 3  | -1.21  | +2.42|
| 2003 Feb 2  | 2  | -0.10  | +1.11|
| 2003 Feb 3  | 5  | -2.44  | -1.07|
| 2004 Jan 13 | 1  | -1.23  | -1.23|
| 2004 Jan 16 | 1  | -0.58  | -0.58|
| 2004 Jan 17 | 1  | +2.12  | +2.12|
| 2004 Jan 18 | 1  | -0.47  | -0.47|
| 2004 Jan 19 | 1  | +2.47  | +2.47|
| 2004 Mar 7  | 1  | +1.58  | +1.58|
| RX 1951    |    |        |      |
| 2001 Jun 23 | 2  | +0.52  | +0.57|
| 2001 Jun 24 | 1  | +2.07  | +2.07|
| 2001 Jun 25 | 3  | -2.02  | +2.02|
| 2001 Jun 26 | 5  | -4.38  | +2.15|
| 2001 Jun 27 | 3  | -2.03  | +2.19|
| 2001 Jun 28 | 4  | -5.19  | +2.37|
| 2001 Jun 29 | 2  | -1.19  | +2.28|
| 2001 Jul 1  | 4  | -4.52  | +2.44|
| 2001 Jul 2  | 2  | +1.06  | +2.45|

Note.—Units of hour angle (H.A.) are hours and minutes.

for the largest value of $\alpha$ that yields reliable results. This was done for all stars, regardless of line profile (single- or double-peaked).

We ran a period-search algorithm that fit general least-squares sinusoids of the form

$$v(t) = A \cos(\omega t) + B \sin(\omega t) + C$$

to the time series with a range of equally spaced frequencies, $\omega$. Ideally, a periodogram of $1/\chi^2$ versus frequency shows a lone peak corresponding to the true frequency. Due to the uneven sampling of the time series, alias (false) periods often appear in the periodogram. We used a Monte Carlo algorithm developed by Thorstensen & Freed (1985) to assess confidence with which the highest peak in the periodogram can be identified with the true orbital frequency. Once the optimal period was found, we fit the time series with sinusoids of the form

$$v(t) = \gamma + K \sin[2\pi(t - T_0)/P]$$

using a hybrid linear least-squares algorithm. This procedure is described in detail in TFT04.

Figure 1 shows radial velocity curves that have been folded twice for continuity. When both absorption- and emission-line velocities are available, the radial velocity curves are folded.
using the weighted mean period. The parameters for the least-
squares best-fit curves are given in Table 4. The absorption-
and emission-line curves are very close to being \( \frac{1}{2} \) cycle out
of phase. If the curves are consistent with \( \Delta \phi = 0.5 \), the mass
ratio of the secondary to the primary can be estimated to be
\( q = M_s/M_1 = K_2/K_1 \). We caution the reader that the measured
values may misrepresent the orbital motion of the compo-
nents, especially \( K_2 \), which originates from the accretion disk.
Having the emission and absorption velocities \( \frac{1}{2} \) cycle out of
phase is a necessary but not sufficient condition for \( K_1 \) to re-
present the motion of the white dwarf.

### 2.2. Spectral Decomposition

For spectral decomposition, we prepared for each system an
average spectrum in which the individual exposures were
shifted to the absorption-line rest frame. We have a collection
of standard K and M stars obtained with the same instrumental
setup as the present data. These K and M stars were classified
by Keenan & McNeil (1989) and Boeshaar (1976), respectively.
The library of template spectra were scaled and subsequently
subtracted from the averaged spectra in order to eliminate the
absorption lines due to the secondary. We did not rotationally
broaden our template spectra prior to subtraction, because the
rotational broadening expected for the secondary stars is small
compared to our spectral resolution. We examined the residual
spectra by eye. In an ideal case, the absorption lines would
disappear entirely, leaving only the continuum and emission
lines, but in reality the subtractions were never perfect. None-
etheless, the subtractions were fairly good. In all the cases con-
ceived here, the spectral type of the secondary could be esti-
imated to \( \pm 1 \) subclass, and the secondary’s contribution to
the flux could be estimated to \( \pm 15\% \).

Using the known periods and spectral types, inferences about
the systems have been made, based on physical considerations
and empirical relations. We assumed that the secondaries fill
their Roche lobes and are undergoing mass transfer. Note care-
fully that we did not assume that the secondaries follow a main-
sequence spectral type versus absolute magnitude (SpT-Mx)
relationship. Instead, we used a relationship between the surface
brightness and the spectral type for normal stars derived by K.
Beuermann (2004, private communication). To convert the
surface brightness to \( M_V \), we of course need a secondary-star radius
\( R_2 \). This is strongly constrained by the Roche geometry and
the orbital period. To estimate \( R_2 \), we begin with an analytical
approximation of the Roche lobe radius, given by Beuermann
et al. (1998), which shows that at a given \( P_{\text{orb}} \), \( R_2 \) is almost
independent of the primary star mass \( M_1 \), and is dependent only
on the cube root of \( M_2 \). We have no direct measure of \( M_2 \), but
we can estimate a range of plausible values, using the evolu-
tionary scenarios of Baraffe & Kolb (2000) as a guideline, at
least for systems with \( P_{\text{orb}} < 10 \) hr. Armed with our estimate of
the secondary’s radius, we transformed the surface brightness
to \( M_V \). The synthetic apparent magnitude of the secondary, \( m_V \),
was found from the scaled template spectra used during spectral
decomposition by using the IRAF task \texttt{ebands} and the Bessell
(1990) tabulation of the \( V \) passband. Finally, visual extinction
values \( A_V \) were estimated from infrared dust maps of Schlegel
et al. (1998), and \( A_V \), \( m_V \), and \( M_V \) were combined to yield a
distance. The dust extinction estimate is imperfect, because
(1) the interstellar medium can be patchy on scales smaller than
the \( 3' \) resolution of the maps, and (2) the maps give estimates
of the total extinction to the edge of the Galaxy, rather than
to the star of interest. However, for three of the four objects
studied here, the Galactic latitudes are high enough that the
uncertain extinction should have a fairly minor effect on the
distance.

### 3. THE INDIVIDUAL STARS

Our results are summarized in the tables and figures. Table 2
shows measurements of spectral-line properties based on flux-
averaged spectra. All radial velocity measurements included in
the analysis are listed in Table 3. Table 4 lists parameters of
the best-fit sinusoids to the velocity time series. Table 5 shows
derived characteristics of the secondaries and the inferred dis-
tances. Figure 1 shows folded radial velocity curves, Figure 2
displays the spectrum of V392 Hya during two separate ob-
serving runs, and Figure 3 shows the flux-averaged spectra of
the four objects before and after spectral decomposition.

#### 3.1. GY Hya

Downes et al. (2001) list GY Hya as an unconfirmed U Gem
star, a subclass of dwarf nova (DN). Zwitter & Munari (1996)
obtained a spectrum in which strong emission from H\( \alpha \), H\( \beta \),
and He ii were present. Our spectroscopic observations span
a baseline of 111 days. Our spectrum (Fig. 3) shows weaker
emission features and strong absorption lines, indicating a sig-
nificant contribution from the secondary. The absorption-line
velocities have large amplitude (\( K_2 \sim 180 \text{ km s}^{-1} \)) and small
scatter about a best-fit sinusoid of period \( P_{\text{orb}} = 0.347230(9) \)
days, or 500 minutes. A Monte Carlo simulation yields a dis-
criminatory power of 98% for this \( P_{\text{orb}} \). Time-series photometry
from B. Monard (2005, private communication) shows an
eclipse with a period of \( P_{\text{orb}} = 0.347237(1) \) days; our period
is consistent with this. The emission lines were weak; thus, a
reliable fit to the H\( \alpha \) emission-line velocities could not be found
and was not included in Figure 1.

Spectral decomposition of our flux-averaged spectrum shows
a secondary of type K4 or K5. The synthetic \( V \) magnitude of the
secondary is 16.7 \( \pm 0.2 \), based on the decomposition. This
includes the uncertainties in both the spectral type and the
factors used to multiply the template spectra. The \( P_{\text{orb}} \) falls
within the range of evolutionary scenarios considered by Bar-
affe & Kolb (2000), so for the purpose of defining the Roche
lobe, we estimate \( M_2 = 0.65 \pm 0.10 M_\odot \). This corresponds to
\( R_2 = 0.84 \pm 0.05 R_\odot \) at this \( P_{\text{orb}} \), which, using surface bright-
nesses from K. Beuermann (2004, private communication), in turn

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for example, with \( q \leq 1 \) and \( M_s = 0.65 \pm 0.10 \, M_\odot \), there is a comfortable fit with \( i = 80^\circ \) at \( M_i = 0.7 \, M_\odot \) and \( M_s = 0.65 \, M_\odot \).

### 3.2. SDSS J204448–045929

The subclass of SDSS J204448–045929 (SDSS 2044, for brevity) is unknown, as it was recently discovered as a CV in the Sloan Digital Sky Survey (SDSS; Szkody et al. 2003). Our data span 10 days and had high S/Ns. The spectra showed intrinsically strong and narrow emission lines, most notably H\( \alpha \). Both the absorption- and emission-line velocities are measurable, although amplitudes are low. The orbital period, \( P_{\text{orb}} = 1.68(1) \) days, is unusually long for a CV. According to the Catalog and Atlas of CVs (the Living Edition; Downes et al. 2001), only 7% of CVs with known periods (440 total, including SDSS 2044) have periods above 9 hr. However, a 97% Monte Carlo discriminatory power shows that our preferred period is very likely to be correct.

We find that the absorption- and emission-line radial velocity curves in Figure 1 are consistent with \( \Delta \phi = 0.5 \). This allows us to estimate a mass ratio \( q = 0.36^{+0.13}_{-0.12} \). Given that the mass of the white dwarf needs to be less than the Chandrasekhar limit of \( 1.4 \, M_\odot \), this requires that the secondary have a mass \( \leq 0.7 \, M_\odot \). The period of SDSS 2044 (~40 hr) is well above the 10.0 hr upper limit of the evolutionary scenarios of Baraffe & Kolb (2000), so we could not use their results. Given the above mass ratio constraints, we adopt a conservative range of mass for the secondary, \( M_s = 0.4 \pm 0.3 \, M_\odot \). The secondary’s radius is dependent on the cube root of the mass, so although the uncertainty in the mass is large, that of the radius is not: \( R_s = 1.9 \pm 0.5 \, R_\odot \) at \( P_{\text{orb}} = 1.68(1) \) days. Given the range in \( q \) and a conservative range in white dwarf mass of \( M_i = 0.9 \pm 0.4 \, M_\odot \), the inclination is within \( 45^\circ \pm 10^\circ \).

A clean spectral decomposition gives a secondary spectral type of K4 or K5, with corresponding synthetic \( V \) apparent magnitude of \( 18.4 \pm 0.2 \). Using the radius for the secondary, the surface brightness is transformed into an absolute magnitude of \( M_V = 7.5 \pm 0.7 \). With an extinction of \( A_V = 0.2 \), we find a distance of \( 1380^{+380}_{-530} \) pc.

### 3.3. V392 Hya

Similar to GY Hya, V392 Hya is also listed by Downes et al. (2001) as an unconfirmed U Gem star (DN). V392 Hya, or EC 10565–2858, was discovered in the Edinburgh-Cape Blue Object Survey. Chen et al. (2001) show a spectrum that spans 3800–5000 Å; our spectral range is 4210–7560 Å. Therefore, comparison is limited; the only spectral feature in common is H\( \beta \) emission. Chen et al. (2001) report two periods, \( \sim 8 \) and \( \sim 12 \) hr, derived from time-resolved spectroscopy. Due to gaps in their time series, they were unable to distinguish between the two periods. Our time series comprises a lone observation in 2002, followed a year later by four consecutive nights, and finally six nights scattered through 2004.
### TABLE 3

**Radial Velocities**

| Modified JD | $v_{ds}$ | $\sigma_{ds}$ | $v_{cm}$ | $\sigma_{cm}$ | Modified JD | $v_{ds}$ | $\sigma_{ds}$ | $v_{cm}$ | $\sigma_{cm}$ | Modified JD | $v_{ds}$ | $\sigma_{ds}$ | $v_{cm}$ | $\sigma_{cm}$ |
|-------------|---------|-------------|---------|-------------|-------------|---------|-------------|---------|-------------|-------------|---------|-------------|---------|-------------|
| GY Hy | V392 Hy | SDSS 2044 | RX 1951 |
|-------------|---------|-------------|---------|-------------|-------------|---------|-------------|---------|-------------|-------------|---------|-------------|---------|-------------|
| 53,071.8712 | 51 10 | ... | ... | 52,296.9372 | 108 16 | 78 18 | 53,071.8802 | 70 10 | ... | ... | 52,296.9448 | 113 14 | 44 11 | 53,071.9361 | 175 9 | ... | ... | 52,670.9208 | 179 18 | 130 20 | 53,071.9450 | 171 9 | ... | ... | 52,671.8506 | 107 14 | 15 10 | 53,071.9539 | 175 10 | ... | ... | 52,671.9360 | 133 13 | 18 10 | 53,071.9628 | 160 9 | ... | ... | 52,672.0186 | 101 12 | 65 11 | 53,072.0064 | 120 10 | ... | ... | 52,672.8971 | 138 13 | 38 13 | 53,072.0243 | 42 10 | ... | ... | 52,672.9531 | 35 20 | ... | 53,073.9296 | 24 8 | ... | ... | 52,673.0392 | 136 22 | 53,073.9408 | 11 6 | ... | ... | 52,673.7875 | 75 29 | ... | 53,073.9559 | 48 11 | ... | ... | 52,673.8185 | 122 24 | ... | 53,073.9644 | 65 8 | ... | ... | 52,673.8330 | 86 18 | 75 22 | 53,073.9734 | 109 7 | ... | ... | 52,673.8473 | 163 14 | 57 24 | 53,073.9823 | 115 9 | ... | ... | 52,673.8548 | 154 20 | 29 21 | 53,073.9965 | 133 9 | ... | ... | 53,017.8900 | ... | ... | 53,074.0054 | 166 9 | ... | ... | 53,017.8999 | 5 20 | 9 15 | 53,074.0143 | 147 10 | ... | ... | 53,020.9094 | 116 13 | 106 13 | 53,178.6563 | 87 5 | ... | ... | 53,022.0388 | 132 18 | 102 16 | 53,178.6653 | 115 7 | ... | ... | 53,022.9115 | 60 20 | 4 14 | 53,178.7645 | 118 6 | ... | ... | 53,024.0574 | 23 31 | 3 7 | 53,181.6594 | 177 9 | ... | ... | 53,070.9123 | ... | ... | 53,181.6683 | 171 9 | ... | ... | 53,071.8322 | ... | ... | 53,182.6514 | 79 7 | ... | ... | 53,071.8947 | 127 20 | 27 12 | 53,187.6536 | 48 7 | ... | ... | 53,073.7569 | ... | ... | 53,187.6655 | 16 9 | ... | ... | 53,073.7679 | ... | ... | 53,187.8876 | 116 13 | ... | ... | 53,085.9276 | 49 10 | ... | 53,180.8940 | 62 10 | 70 5 | ... | 53,085.9650 | 52 14 | 67 7 | 53,180.9015 | 49 10 | ... | ... | 53,086.6848 | 102 8 | 19 4 | 53,180.9645 | 84 10 | 50 5 | ... | 53,086.7143 | 129 14 | 29 4 | 53,180.9720 | 96 8 | 54 5 | ... | 53,086.8356 | 12 13 | 34 6 | 53,181.8260 | 99 7 | 38 5 | ... | 53,086.9013 | 35 14 | 63 5 | 53,181.8934 | 50 7 | 41 5 | ... | 53,086.9710 | 38 11 | 93 3 | 53,181.9477 | 58 5 | 32 5 | ... | 53,087.7898 | 54 9 | 6 4 | 53,182.7852 | 79 11 | 25 6 | ... | 53,087.8954 | 70 12 | 60 5 | 53,182.7928 | 57 14 | 32 6 | ... | 53,087.9710 | 35 10 | 55 4 | 53,182.8285 | 55 11 | 36 6 | ... | 53,088.6510 | 109 19 | 29 9 | 53,182.8330 | 28 13 | 47 7 | ... | 53,088.7348 | 85 11 | 29 4 | 53,182.9364 | 4 9 | 10 5 | ... | 53,088.9537 | 55 14 | 85 4 | 53,183.9507 | 13 6 | 37 5 | ... | 53,088.9807 | 53 9 | 43 4 | 53,183.9596 | 26 9 | 48 5 | ... | 53,089.8151 | 15 7 | 49 3 | 53,184.8143 | 54 10 | 22 5 | ... | 53,089.9722 | 28 12 | 87 4 | 53,184.8232 | 57 10 | 9 6 | ... | 53,091.6617 | 88 19 | 25 7 | 53,184.9419 | 82 9 | 12 6 | ... | 53,091.8416 | 57 12 | 73 6 | 53,184.9495 | 104 11 | 5 6 | ... | 53,091.9143 | 24 8 | 95 3 | 53,184.9569 | 108 12 | ... | ... | 53,091.9780 | ... | ... | 53,184.9656 | 87 12 | ... | ... | 53,092.9073 | 57 10 | 87 5 | 53,185.7547 | 52 10 | 51 6 | ... | 53,092.9760 | 14 12 | 36 7 | 53,185.7628 | 42 16 | 45 6 | ... | 53,186.9690 | 77 5 | 4 5 | 53,187.7761 | 85 8 | 22 5 | ... | 53,187.7850 | 67 8 | 24 5 |
Figure 2 shows V392 Hya in two different states during 2004 January and 2003 February. This is evident from the continua. The mean flux level differs by a factor of \( \sim 4 \). Differences in spectral features are evident, most notably the strength of H\(\alpha\) emission and the structure of the H\(\beta\) line. As shown in Table 2 and Figure 2, the H\(\alpha\) line becomes thinner and stronger by a factor of \( \sim 2 \) in outburst. The H\(\beta\) line changes from emission superposed on flat continuum during the lower state to emission superposed on a wider absorption line during the higher state. This is commonly thought to be due to the optically thick accretion disk.

Despite the different states, the absorption-line velocities from the late-type secondary are measurable in all our data and yield a best-fit period of \( P_{\text{ orb}} = 0.324952(5) \) days, or 468 minutes. A Monte Carlo simulation to discriminate between alias periods returns a confidence level of \( \sim 90\% \). This radius translated the surface-brightness calculation of K. Beuermann (2004, private communication) into an absolute magnitude of \( M_V = 6.0 \pm 0.2 \), which, when combined with an extinction of 0.2 mag and \( m_V \), gave an inferred distance of \( 3470^{+510}_{-440} \) pc.

**TABLE 5**

**Inferences from Secondary Stars**

| Star     | Type     | \( m_V \) (mag) | \( M_V \) a (\( M_\odot \)) | \( R_2 \) a (\( R_\odot \)) | \( M_2 \) b (mag) | \( A_p \) (mag) | Distance (pc) |
|----------|----------|------------------|-----------------------------|-----------------------------|------------------|----------------|---------------|
| GY Hya   | K4 or K5 | 16.7 ± 0.2       | 0.65 ± 0.10                 | 0.84 ± 0.05                 | 5.9 ± 0.2        | 0.3            | 1260 ± 160    |
| SDSS 2044| K4 or K5 | 18.4 ± 0.2       | 0.4 ± 0.3                   | 1.9 ± 0.5                   | 7.5 ± 0.7        | 0.2            | 1380 ± 730    |
| V392 Hya | K5 or K6 | 18.9 ± 0.2       | 0.60 ± 0.05                 | 0.78 ± 0.03                 | 6.0 ± 0.2        | 0.2            | 3470 ± 450    |
| RX 1951  | K7.5 or M0.5 | 17.6 ± 0.2 | 0.6 ± 0.3 | 0.99 ± 0.18 | 7.4 ± 0.6 | 0.8 | 760 ± 240 |

a Note that these masses are not measured, but are estimates guided by the models of Baraffe & Kolb (2000). They are used only to constrain \( R_2 \), which depends only on the cube root of \( M_V \), so this does not contribute substantially to the error budget.

b Absolute visual magnitude inferred for the secondary alone, on the basis of surface brightness and Roche lobe size (see text).

c The period is above the limit of evolutionary scenarios computed by Baraffe & Kolb (2000), so a conservative estimate of the mass is made.
Fig. 2.—Mean spectra of V392 Hya in different states. Top and bottom spectra were taken in 2004 and 2003, respectively. Note the differences in mean flux level, continuum shape, and line strength.

Fig. 3.—Montage of spectra. The vertical scale in each plot is in units of $10^{-15}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$, subject to calibration uncertainties of some tens of percent. The lower trace in each panel shows the data after a scaled late-type star has been subtracted away (see text and Table 5). In all cases, the original spectra are shifted into the rest frame of the secondary star before averaging.

3.4. RX J1951.7+3716

Motch et al. (1998) classify RX J1951.7+3716 (RX 1951 hereafter) as a CV, with no specified subclass. Our data span 10 days in 2001, with coverage over an 8 hr range in hour angle to discriminate the daily cycle alias. The mean flux level for the spectra is ≥2.5 times higher than that of the other three objects in this paper. In Figure 3, the small difference between the upper and lower spectra shows the weak, but present, contribution from the secondary.

The emission lines (particularly Hα and Hβ) are strong and narrow, yielding only a small uncertainty in emission-line velocities (see Table 3.). Despite the weakness of the secondary contribution, absorption-line velocities are measurable. The weighted mean period found is $P_{orb} = 0.492(1)$ days. Monte Carlo simulations rule out other alias periods, with a discriminatory power of ≥90%. With a small $K_2$ of $81 \pm 7$ km s$^{-1}$, the inclination is expected to be low. We find that for a white dwarf mass range of $0.9 \pm 0.4 M_\odot$ and $q \leq 1$, $i = 25^\circ \pm 10^\circ$.

The spectral type of the secondary is estimated to be K7.5 or M0.5; the lower spectrum in the top panel of Figure 3 shows the results after an M0.5 star has been subtracted. The synthetic magnitude calculated for the secondary star is $m_v = 17.6 \pm 0.2$. A secondary mass of $0.6 \pm 0.3 M_\odot$ is extrapolated from Baraffe & Kolb (2000), since the period lies slightly above the cutoff of 10.0 hr. At $P_{orb} = 0.492(1)$ days, this mass range corresponds to a radius of $R_2 = 0.99 \pm 0.18 R_\odot$. Surface brightnesses found by K. Beuermann (2004, private communication) were converted into an absolute magnitude of $M_v = 7.4 \pm 0.6$. The extinction value used is large ($A_V = 0.8$), due to the fact that RX 1951 is only ∼5° from the Galactic plane. We find RX 1951 to be at a distance of $240^{+240}_{-180}$ pc. Because of its greater apparent brightness, it is not surprising to find that this source is closer than the other three.

4. DISCUSSION

We find orbital periods for these four systems to be above 7 hr; the period of SDSS 2044, $P_{orb} = 1.68(1)$ days, is notably long for a CV. In longer period systems, the secondaries are usually cooler than expected for main-sequence stars filling their Roche lobes at the observed period (Beuermann et al. 1998). Referring to the plot of spectral type versus period in Baraffe & Kolb (2000), it is clear that the four secondary stars
in this paper do not lie on zero-age main-sequence (ZAMS) evolutionary tracks, but rather are significantly cooler, most likely due to commencement of nuclear evolution prior to the onset of mass transfer (Baraffe & Kolb 2000). Although the models of Baraffe & Kolb (2000) do not apply to periods above 10 hr, and thus may not be directly applied to SDSS 2044 and RX 1951, these two systems are the furthest from the ZAMS.

The systems in this paper have been selected based on their longer periods. Therefore, they do not represent the full range in CV periods. For example, dwarf novae with hydrogen-rich secondaries have periods as short as 75 minutes. One goal of CV studies is to obtain an accurate catalog of their population. To do so, different methods of CV discovery are essential, as is evident from the subset presently studied. V392 Hya was identified in the Edinburgh-Cape Blue Object Survey, while SDSS 2044 and RX 1951 were discovered by SDSS and Röntgensatellit (ROSAT), respectively. The wide range in techniques and energies is beneficial for finding these systems.

We find distances to the CVs via spectroscopic parallax. This method relies on surface-brightness calculations of the secondary star filling its Roche lobe, but more importantly, on an accurate identification of the secondary’s spectral type. We are able to detect and deduce the spectral type (via spectral decomposition) of the secondary star, to within one subclass. This is sufficient to yield distances with 15% uncertainty in favorable cases.

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