SPECTROSCOPY OF NEW AND POORLY KNOWN CATACLYSMIC VARIABLES IN THE KEPLER FIELD

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ABSTRACT

The NASA Kepler mission has been in science operation since 2009 May and is providing high precision, high cadence light curves of over 150,000 targets. Prior to launch, nine cataclysmic variables were known to lie within Kepler's field of view. We present spectroscopy for seven systems, four of which were newly discovered since launch. All of the stars presented herein have been observed by, or are currently being observed by, the Kepler space telescope. Three historic systems and one new candidate could not be detected at their sky position and two candidates are called into question as to their true identity.

Key word: novae, cataclysmic variables

1. INTRODUCTION

Cataclysmic variables (CVs) are a well known group of interacting binary stars consisting of a white dwarf primary and a low-mass companion. The two stars are in a tight orbit having binary periods from about 60 minutes to 8 hr, and as such material flows from the low mass stars inner Lagrangian point toward the white dwarf. This material, the accretion stream, has orbital angular momentum and as such forms an accretion disk around the primary. Material within the disk is believed to pile up and reach a critical density, causing an increase in temperature and eventual hydrogen ionization. The resulting disk brightening, an outburst, lasts a few days to a week or so and increases the CV's light by a few to ∼6 mag. Short period CVs, having periods less than about 3 hr, show occasional larger (up to 9 mag) and longer (up to a month) eruptions termed superoutbursts. These systems comprise the subgroup of CVs called the SU UMa stars. CVs with orbital periods approximately in the 4–6 hr range generally have the highest mass transfer rates (see Howell et al. 2001) and show no outbursts. These binaries are believed to be in a state of constant outburst and are called nova-like variables. Warner (2003) provides a detailed description of all the types of CVs.

Photometric observations of CVs reveal not only the semi-periodic outbursts but a wide variety of other phenomena related to mass transfer and accretion processes. Understanding the physics behind the behavior of the accretion disk, the outbursts and the mass accretion process itself is often hampered by a lack of accurate or even well constrained values for the basic stellar properties such as mass and temperature. The NASA Kepler mission (Borucki et al. 2010) is providing nearly continuous photometric coverage of the stars discussed here and spectroscopic work, in particular phase-resolved spectroscopy, will yield good estimates for the stellar and binary properties. The Kepler light curves consist of long cadence (30 minutes) and short cadence (1 minute) photometry and are all publicly available at the MAST archive13 and at the NASA exoplanet archive.14

Scaringi et al. (2013) have reported on their initial discovery of 11 new CV candidates within the Kepler field of view based on blue + Hα color selection. None of their sources are the same as those included in this paper and, at present, none of their stars have Kepler observations. Additional CVs in the Kepler field, but not discussed in this paper, have had their Kepler light curves presented in Barclay et al. (2012), Fontaine et al. (2011), Ramsay et al. (2012), Ostensen et al. (2010), and Williams et al. (2010).

We report here on 11 CVs in the Kepler field for which light curves are in hand (public) or forthcoming. Some of the CVs are, at best, poorly studied, four new CV candidates are discussed, and two systems may not be CVs at all.

2. OBSERVATIONS

Nine CVs were known to reside in the Kepler field prior to the launch of this space telescope in 2009 March. Table 1 lists these nine historic systems as well as four new candidates. Eleven of these systems are discussed herein. We do not discuss MV Lyr (Linnell et al. 2005) or V447 Lyr (Ramsay et al. 2012) in this paper. The historic systems are cataloged in Downes & Shara (1993), Downes et al. (1997), and in the online version of their catalog.15 These catalogs will be referred to as DSW97. Our spectroscopic observations were obtained using the Kitt Peak National Observatory 4 m telescope and the Mount Palomar 200” telescope. We describe the instrumental setups used for our spectroscopy at the two telescopes below. Table 2 provides

13 http://archive.stsci.edu/
14 http://exoplanetarchive.ipac.caltech.edu/
15 http://archive.stsci.edu/preps/cvcat/
The slit width was set to 1′′.

Kepler data archive at MAST.

our spectroscopic observing log. Kepler light curves used herein are the public, standard products and were obtained from the Kepler data archive at MAST.

2.1. Mount Palomar 200′ Hale Telescope

At Mt. Palomar, we used the double beam spectrograph (DBSP) attached to the 200′ telescope. The dichroic filter D-55 was used to split light between the blue and red arms. The blue arm used a 1200 l mm\(^{-1}\) grating providing \( R \sim 7700 \) and covered 1500 Å of spectrum. The red arm used a 1200 l mm\(^{-1}\) grating providing \( R \sim 10,000 \) and covered only 670 Å. The slit width was set to 1′′ and the usual procedures of observing spectrophotometric stars and arc lamps were adhered to. Red spectra were wavelength calibrated with a HeNeAr lamp while the blue arm used a FeAr lamp. The nights were clear and provided stable seeing near 1′′. Data reduction was done using IRAF two- and one-dimensional routines for spectroscopic data and produced a final one-dimensional spectrum for each observation. The Palomar instrument has a CCD acquisition camera which can be used to take timed exposures of the local field of view as well as help to find and place faint sources on the slit. Integrations with this camera allowed us to see point sources near the slit down to \( V \sim 22 \).

2.2. Kitt Peak 4 m Telescope

Observations were obtained with the Ritchey–Chrétien (RC) spectrograph using grating KPC-22b in first (red) and second (blue) order. The blue spectral resolution for the setup used is \( \sim 5000 \), providing a wavelength coverage of 3700–5100 Å with a dispersion on the CCD detector of 0.72 Å pixel\(^{-1}\). The red setup yielded 1.42 Å pixel\(^{-1}\) and covered 6200–6800 Å. The slit was set to 1′′ and used in an east–west (90°) orientation for all observations. The weather was clear each night with stable 1·2 seeing. Observations of spectrophotometric standard stars were obtained near in time to the target stars and used to provide relative flux values. FeAr, HeNeAr, or ThAr lamp exposures, obtained directly before or after each spectrum, were used to set the wavelength scale. Data reduction was done using IRAF two- and one-dimensional routines for spectroscopic data and produced a final one-dimensional spectrum for each observation.

3. DISCUSSION

The stars are presented by their variable star name, for those which have one, otherwise we use their Kepler input catalog (KIC) identification. The KIC in discussed in Brown et al. (2011) and can be accessed at the MAST archive.\(^{16}\) We note here that Kepler can successfully perform photometric observations for sources near \( R \sim 21–22 \) mag, with some dependence on the variability amplitude of the source in question (e.g., deep eclipses or outbursts).

3.1. V344 Lyr

The Kepler light curve of V344 Lyr was presented in Still et al. (2010) and Wood et al. (2011) where the star was shown to be a SU-UMa-type CV with a photometrically determined orbital period of 2.11 hr. We report here on phase-resolved spectroscopy of the star obtained over the time period of 6:01 to 9:39 UT on 2011 June 5. This time period covers 1.7 orbital cycles of V344 Lyr. Figure 1 shows one of the 12 time-resolved blue and red spectral pairs that we obtained for V344 Lyr.

References. 
1. Wood et al. 2011; (2) Still et al. 2010; (3) Cannizzo et al. 2012; (4) Feldmeier et al. 2011; (5) this paper.

\(^{16}\) http://archive.stsci.edu/kepler/kepler_fov/search.php
No significant differences are seen in any of the spectra or their emission line shapes over the 3 hr 40 minutes time span. The smooth and narrow emission line profiles seen in V344 Lyr suggest that this binary has a low orbital inclination.

Measurements of the equivalent width of H\(\alpha\) and H\(\beta\) during the 1.7 orbital cycles show nearly constant values of \(-32.5 \pm 2\) Å and \(-22 \pm 2\) Å, respectively. Fitting a Gaussian profile to these emission lines in each spectrum, we found that the measured velocities show a low amplitude modulation (\(K \sim 10\) km s\(^{-1}\)) consistent with a low orbital inclination (Figure 2). Higher order Balmer lines have a similar velocity appearance to that of H\(\beta\).

The velocities vary with a roughly 2 hr period, more obvious in the H\(\beta\) velocities, a time period consistent with the well measured photometric period for this star. However, due to the narrow lines, their small \(K\) amplitude, our uncertainties of \(\sim 6\) km s\(^{-1}\) per point, and long (20 minutes) integrations, a robust sinusoidal (orbital) fit to the measurements was not possible.

While the photometric analysis presented in Wood et al. (2011) can only limit the inclination of V344 Lyr to between 0° and 60°, the small velocity variation observed most likely suggests that V344 Lyr has a very low inclination, near 5°–10°.

### 3.2. V358 Lyr

The magnitude range ascribed to this star in DWS97 is \(V = 16\) to fainter than 20. Their associated finder chart shows only an empty circle at the star’s position. Antipin et al. (2004) provide a discussion of the star’s history, including its faint limit being below \(V = 21\) and some confusion as to the maximum magnitude reached during outburst. They conclude that V358 Lyr is a CV with rare and apparently large outbursts. DWS97, in agreement with Antipin’s findings, list V358 Lyr as a nova or possibly a TOAD (Tremendous Outburst Amplitude Dwarf nova; Howell et al. 1995). Our examination of the field using the Palomar 200″ acquisition CCD camera revealed no source at the stars position down to 21.5–22 visual magnitude. This star had an outburst in 2008 (Kato et al. 2009) reaching a peak magnitude of 16.1 and revealing a superhump period of 0.0556 days. Putting all of this information together, suggest that V358 Lyr has a short orbital period and an outburst amplitude of >6 mag, it is likely to be a TOAD.

### 3.3. V452 Lyr

V452 Lyr is a suspected dwarf nova with a minimum magnitude of \(V > 18.5\). We estimate that V452 Lyr was near \(V \approx 20.5\) when we obtained our spectrum being nearly equal in brightness to its close neighbor sitting \(\sim 5\)″ to the southeast (see finding chart in DWS97).

Our spectrum (Figure 3), obtained presumably near minimum light, shows a red source not a blue one. While of low signal-to-noise ratio (S/N), the blue spectrum appears almost featureless and without a rising blue continuum, the usual tell-tale sign of an accretion disk system. The red spectral appearance and light curve behavior of the target we observed places doubt on the true identify of this variable star but it seems unlikely to be a CV.

### 3.4. V585 Lyr

This star has a minimum magnitude listed as fainter than \(V \sim 21.5\) in DWS97. The 200″ telescope CCD acquisition camera image revealed a very faint source near the position of
Figure 2. Velocity measurements for Hα (top) and Hβ (bottom) for V354 Lyr. Each point has a formal error of ±6 km s\(^{-1}\). The time coverage is 1.7 orbital cycles and the data show a low amplitude modulation, \(K \sim 10\) km s\(^{-1}\), that appears to repeat approximately at 2 hr. This period is consistent with the well defined photometric period of 2.11 hr, but due to the low \(K\) amplitude, our spectral resolution, and the long (20 minutes) integrations, a robust RV fit was not possible.

Figure 3. Simultaneous red (smoothed by seven points) and blue spectra of V452 Lyr. The general spectral appearance does not look like a typical CV. The rising red continuum in the blue spectrum would be unusual for a CV. While of relatively low S/N, the spectra do not provide much evidence that V452 Lyr is indeed a CV. The y-axis is flux in units of erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\).
Figure 4. Kepler long cadence (30 minute sample) light curve of V523 Lyr covering Quarters 6–8. The top plot shows the full light curve while the bottom plots show detail at three interesting times.

the star but with a magnitude estimated to be near 22. If the point source was V585 Lyr, it was too faint to obtain a spectrum as a part of this survey program and thus we cannot confirm the source or its CV nature.

3.5. V516 Lyr

This star is one of two CVs in the Kepler field of view which may be a member of the open cluster NGC 6791; V523 Lyr is the other (see below). While a faint source, near 22, is shown on the DWS97 finder chart, our CCD acquisition image at Palomar revealed no source present down to \(\sim 22\). Therefore, no spectrum was obtained and thus we cannot confirm the source or its CV nature.

3.6. V523 Lyr

V523 Lyr is located on the outskirts of the core of the open cluster NGC 6791, thus its membership in that cluster has long been suspected. Listed as a VY Scl or Z Cam star, this object has a historic magnitude range quoted in DWS97 as 17.7 to 20.2. Figure 4 presents the Quarters 6–8 long cadence Kepler light curve of V523 Lyr. The light curve of this star was normalized using the tools available at the NASA Exoplanet archive and shows clear indications of dwarf nova outbursts as well as one superoutburst occurring near the end of the data set, starting about day 760. The light curve covers \(\sim 250\) days and contains ten normal outbursts that occur almost periodically at \(\sim 18\) day intervals, each lasting about 4 days. We see that the outbursts grow in amplitude as they approach the superoutburst, but in a nonlinear step-wise fashion. The first normal outburst in the Kepler light curve, shown in the lower left of Figure 4, as well as the second outburst, appear to be two outbursts occurring in close succession. We also note (bottom right of Figure 4) that directly after the superoutburst, some small amplitude, shorter duration (\(\sim 1\) day) outbursts occur. The entire set of Kepler long and short cadence light curves of V523 Lyr will be the subject of an upcoming detailed light curve study by our group.

In between the outbursts, as easily seen in the top and bottom middle plots of Figure 4, is a periodic modulation in the light curve. A period search, with the outbursts removed, identifies this period as \(0.087478\) days (\(2.1\) hr), and we present a phase-binned light curve of V523 Lyr at minimum light in Figure 5. Whether this period is the true orbital period of V523 Lyr will be one of the findings of our upcoming study. The light curve, showing a superoutburst, and the (orbital) period of V523 Lyr suggest that it is an SU-UMa-type CV.

The spectrum of V523 Lyr is shown in Figure 6. The blue spectrum rises to the shorter wavelengths and shows \(\text{H}_\beta\) to be in weak emission while the higher Balmer lines appear in
absorption. The red spectrum shows a narrow Hα emission line sitting on an otherwise featureless continuum. These spectral features are not typical of a low state SU UMa star. We note, however, that our spectrum was taken on JD 2455719, two days into a normal outburst of V523 Lyr that started on day 885. Thus, our Palomar spectrum was obtained during an outburst which would explain its non-typical SU UMa minimum light appearance.

Being a relatively bright CV, even at minimum light, V1504 Cyg has been studied in some detail with recent photometric papers being Pavlenko et al. (2002) and Cannizzo et al. (2012). DWS97 lists V1504 Cyg as an SU-UMa-type CV ranging from $V = 13.5$ to 17.4 in magnitude and Cannizzo et al. (2012) provide a detailed study of the Kepler light curve of this star, confirming its period at 1.67 hr as well as its SU UMa status.

Our Kitt Peak 4 m blue observation (Figure 7) shows a classic dwarf nova spectrum with double peaked emission in the

![Figure 6. Simultaneous red and blue spectra of V523 Lyr. Hα and Hβ are in emission while the rest of the Balmer series is in absorption. This spectrum was obtained during an outburst (see text). The y-axis is flux in units of erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$.](image1)

![Figure 7. Kitt Peak 4 m blue spectrum of V1504 Cyg. The spectrum is a very classic high inclination CV showing double-peaked Balmer emission lines from the accretion disk. The y-axis is flux in units of erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$.](image2)

### 3.7. V1504 Cyg

3.7. V1504 Cyg
Figure 8. *Kepler* short cadence (1 minute time samples) light curve of KIC 9778689 covering Quarters 6–8. The light curve shows essentially no modulation except for occasional, small flare like events (see bottom zoomed plots). This source is not likely to be a CV.

Figure 9. Typical spectrum of KIC 11390659 obtained at the Kitt Peak 4 m telescope. The y-axis is flux in units of erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$.

higher Balmer series lines. He I (4471 Å) is also present in emission. The general spectral appearance, showing double-peaked Balmer emission lines, argues for a moderate to relatively high orbital inclination (perhaps 40°–60°). We note that the spectrum presents a mostly flat Balmer decrement. This is a typical spectral appearance of a short period, low mass transfer CV.

3.8. KIC 9778689 = BOKS CV

Feldmeier et al. (2011) discovered this variable blue source in a pre-launch survey of the *Kepler* field of view. They present a finding chart and a light curve suggesting a minimum magnitude near $V = 20$ and an apparent dwarf nova type outburst rising to $\sim 17$ and lasting $\sim 5$ days. Thus, KIC 9778689 was suspected of
Figure 10. Typical red and blue spectrum of KIC 11390659 obtained at the Mt. Palomar 200\" telescope. The y-axis is flux in units of erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$.

Table 3

| Obs    | Line | $P$ (minutes) | $e^a$ (km s$^{-1}$) | $K$ (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) |
|--------|------|---------------|---------------------|-------------------|------------------------|
| Palomar| H$\alpha$ | 103 | $-37 \pm 2$ | $82 \pm 9$ | 19 |
| Palomar| H$\beta$ | 107 | $-22 \pm 1$ | $99 \pm 6$ | 13 |
| KPNO   | H$\beta$ | 107 (fixed) | $-3 \pm 2$ | $89 \pm 14$ | 32 |
| Palomar| H$\gamma$ | 106 | $-35 \pm 1$ | $114 \pm 7$ | 15 |
| KPNO   | H$\gamma$ | 107 (fixed) | $-43 \pm 1$ | $90 \pm 9$ | 23 |
| Palomar| H$\delta$ | 109 | $-10 \pm 1$ | $110 \pm 6$ | 12 |

Note. $^a$ No attempt was made to produce an absolute $\gamma$ velocity consistent across the different telescopes and nights listed here.

KIC 11390659 was observed with the KPNO 4 m telescope and RC spectrograph on 2010 September 12 from 2:50–4:54 UT. On 2011 June 7, 11 additional spectra were obtained from 8:18 to 10:28 UT at the Palomar 200\" telescope using the Double Imaging Spectrograph. In each case, the spectra were wavelength and flux calibrated with IRAF routines and the line velocities were measured with the “e” (centroid) and “g” (Gaussian) routines within the splot package. A typical spectrum from each run is shown in Figures 9 and 10. These spectra are usual for a short period CV, with strong Balmer emission lines and a steep blue continuum. The Palomar data reveal a narrow peak in the lines, which shifts back and forth, typical of a hot spot on an accretion disk. In addition, the strong blue continuum shortward of 4000 Å is indicative of the contribution of a hot white dwarf or boundary layer.

Figure 11. Kepler light curve for KIC11390659 covering Quarters 6–7. The data show a rapid flare-like structure, each brightening lasting for a few days, and a sine-like modulation possibly revealing a long term periodic structure. A power spectrum of this light curve showed no significant periods including any near 107 minutes.
Figure 12. Velocity curves for the four brightest Balmer lines in KIC 11390659. Each point has a formal $1\sigma$ velocity error of $\sim 6$ km s$^{-1}$. The best fit velocity curves as derived from the different emission line data give values for the period and phase which are consistent.

Figure 13. Spectra of a newly discovered CV candidate. The top plot shows a blue spectrum of KIC 3426313 (Blue 10) while the bottom covers the red spectral region for the star, observed four months later. KIC 3426313 shows very narrow Balmer emission in the blue with odd broad continuum features. The red spectrum shows a weak, narrow H$\alpha$ emission line. The spectra are not corrected for telluric features and the y-axis is flux in units of erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$.

While the object is a known ROSAT source (1RXSJ1858311.1+491434) with an X-ray count rate of $0.19 \pm 0.02$ c s$^{-1}$ obtained during 731 s of observation, the absence of strong He II emission likely means it does not contain a highly magnetic white dwarf. The Kepler public long cadence light curve (Figure 11), covers Quarters 6 and 7 (about 150 days), and shows high amplitude variability on timescales of days and flare-like structures but no periodicity was detected such as that which would be expected from an active accretion spot on a polar or a white dwarf spin from an intermediate polar.

A least-squares fit of the line velocities to a sine-curve was used to determine $\gamma$ (systemic velocity), $K$ (semi-amplitude), and $P$ (orbital period). The errors on $\gamma$ and $K$ as well as the standard deviation ($\sigma$) of the fit to the data points were determined from a Monte Carlo method. Due to the short length of the data sets, the periods are not well established but the
common solution for all three lines from the blue channel in the Palomar data are in the range of 106–109 minutes and both data sets are consistent with an orbital period in this range. Due to the larger errors on the KPNO data, the period was fixed at 107 minutes to provide a better constraint on the $K$ amplitude. The radial velocity solutions are given in Table 3 and a plot of the data and the sine fits for the Palomar data is shown in Figure 12. The $K$ amplitudes and line widths are all consistent with a dwarf nova with a moderate inclination.

3.10. KIC 3426313 = Blue 10

KIC 3426313 is a newly discovered blue variable based on an optical spectroscopic search for UV bright sources. Using the Howell–Everett $UBV$ catalog of the Kepler field (available at the MAST archive; Everett et al. 2012), and selecting sources with extremely blue $U - B$ colors ($U - B = -0.666$ mag, $B - V = 0.356$ mag) this source was identified as a UV bright object. Based on its spectroscopic appearance (Figure 13), this star is likely a new CV in the Kepler field of view. The blue spectrum shows very narrow Balmer emission lines along with broad absorption troughs in the continuum. The red spectrum shows weaker Hα emission, likely indicating emission line variability as the two spectra were obtained four months apart. Further study will be required to confirm the true nature of this star.

3.11. KIC 8490027 = Blue 19

This star was selected in the same manner as described for KIC 3426313 and is also a newly discovered CV candidate. KIC 8490027 appears to possibly be a nova-like type (Figure 14) showing Balmer absorption profiles from a nearly edge-on thick accretion disk or the underlying white dwarf. The red spectrum shows a weak Hα line now not centered in its absorption trough, indicative of velocity motion differences between the two non-contemporaneous spectra. The emission lines are narrow in this source, perhaps pointing to a low orbital inclination.

4. CONCLUSION

We have provided information on 11 CVs residing within the Kepler field of view. These stars have all been or soon will be observed by Kepler and their light curve observations are or will be public. Seven of the stars were previously known. New spectroscopy is presented for seven sources while no source could be confirmed for three of the stars. We presented the previously unpublished Kepler light curves for three of the sources, one of which, V523 Lyr, is a possible member of the open cluster NGC 6791. Evidence provided by a spectrum or Kepler light curve observation calls two candidates into question as being CVs; V452 Lyr and KIC 9778689 (BOKS CV). Given that the Kepler mission has and will continue to provide nearly continuous photometric coverage for the majority of these stars, detailed phase-resolved spectroscopy will be important to allow their stellar and orbital parameters to be determined. However, such study will require large telescopes for the systems that are fainter than $V \sim 20$ magnitude. CVs located within the Kepler field have a large potential to allow the first detailed view of the systems as a whole. The photometric coverage of the stars is unprecedented and will not likely occur again for decades to come. Studies of the accretion process, stellar variations, and details of short term and long term effects, aided by spectroscopic work, can turn this set of stars into a Rosetta Stone for CV research.

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Facilities: Mayall (RCSPEC), Hale (DBSP), Kepler

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