KIC 9406652: An unusual cataclysmic variable in the kepler field of view

Douglas R. Gies
Georgia State University

Zhao Guo
Georgia State University

Steve B. Howell
NASA Ames Research Center

Martin D. Still
NASA Ames Research Center

Tabetha S. Boyajian
Yale University

See next page for additional authors

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Authors
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KIC 9406652: AN UNUSUAL CATAclySMIC VARIABLE IN THE KEPLER FIELD OF VIEW

DOUGLAS R. GIES1, ZHAO GUO1, STEVE B. HOWELL2,7, MARTIN D. STILL3,4, TABETHA S. BOYAJIAN5, ABE J. HOEKSTRA6, KIAN J. JEK6, DARYLL LACOURSE6, and TROY WINARSKI6

1 Center for High Angular Resolution Astronomy and Department of Physics and Astronomy, Georgia State University, P.O. Box 5060, Atlanta, GA 30302-5060, USA; gies@chara.gsu.edu, guo@chara.gsu.edu
2 NASA Ames Research Center, P.O. Box 1, M/S 244-30, Moffett Field, CA 94035, USA; steve.b.howell@nasa.gov
3 NASA Ames Research Center, Moffett Field, CA 94035, USA; martin.still@nasa.gov
4 Bay Area Environmental Research Institute, Inc., 560 Third Street West, Sonoma, CA 95476, USA
5 Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101, USA; tabetha.boyajian@yale.edu
6 Planet Hunters Program, Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101, USA; abejhoekstra@hotmail.com, kianjin@gmail.com, daryll.lacourse@gmail.com, troywinarski@gmail.com

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ABSTRACT

KIC 9406652 is a remarkable variable star in the Kepler field of view that shows both very rapid oscillations and long term outbursts in its light curve. We present an analysis of the light curve over quarters 1–15 and new spectroscopy that indicates that the object is a cataclysmic variable with an orbital period of 6.108 hr. However, an even stronger signal appears in the light curve periodogram for a shorter period of 5.753 hr, and we argue that this corresponds to the modulation of flux from the hot spot region in a tilted, precessing disk surrounding the white dwarf star. We present a preliminary orbital solution from radial velocity measurements of features from the accretion disk and the photosphere of the companion. We use a Doppler tomography algorithm to reconstruct the disk and companion spectra, and we also consider how these components contribute to the object’s spectral energy distribution from ultraviolet to infrared wavelengths. This target offers us a remarkable opportunity to investigate disk processes during the high mass transfer stage of evolution in cataclysmic variables.

Key words: binaries: spectroscopic – circumstellar matter – novae, cataclysmic variables – stars: individual (KIC 9406652)

1. INTRODUCTION

Cataclysmic variable (CV) stars are evolved, interacting binary systems in which mass transfer from a cool, Roche-filling donor star feeds a dynamic accretion disk surrounding a white dwarf, gain star (Warner 1995; Hellier 2001). The physical processes of disk accretion can lead to flux variations over a wide variety of amplitudes and timescales (Honeycutt et al. 1998), and long term photometric monitoring is key to our understanding of the mass accretion and loss processes. The NASA Kepler mission is now providing us with a particularly rich data set to explore these variations in detail. Several dozen new CVs are now known in the Kepler field of view (Howell et al. 2013; Scaringi et al. 2013), and detailed investigations from Kepler of previously known CVs are available for V344 Lyr (Wood et al. 2011; Cannizzo et al. 2012), V447 Lyr (Ramsay et al. 2012), and V1504 Cyg (Cannizzo et al. 2012).

Here we report on the discovery of outbursts and fast variability in the Kepler light curve of the star KIC 9406652 (= TYC 3556-325-1) that were identified through the work of the citizen-scientist Planet Hunters program8 (Fischer et al. 2012). This is a relatively faint and blue star ( V = 12.5, B – V = +0.1; Everett et al. 2012), and its variable nature was first determined from quarter 1 data by Debosscher et al. (2011). The light curve shows evidence of both short period oscillations and quasi-monthly outbursts that bear some similarity to those observed in old novae and nova-like CVs (Honeycutt et al. 1998). We present a periodogram and wavelet analysis of the Kepler light curve in Section 2, and we discuss evidence for two key periodic signals in addition to the low frequency power related to the outbursts. In Section 3, we present new time series spectra from 2013 April that we use to measure radial velocities and derive preliminary orbital elements. We describe the nature of the spectra of the companion and accretion disk in Section 4. We discuss the rapid light curve variations in Section 5, and we argue that they result from the changes in disk flux that occur as the gas stream strikes a tilted, precessing disk (Wood & Burke 2007).

2. KEPLER LIGHT CURVE

The flux of the target KIC 9406652 was recorded in long cadence mode in each observing quarter, and we obtained the Presearch Data Conditioning version of the light curve from the data archive (almost identical to the Simple Aperture Photometry version of the light curve). The entire Kepler light curve from quarters 1 through 15 is shown in the lower panel of Figure 1 and a close up portion from quarter 7 is shown in Figure 2. We see that that are outbursts on timescales of weeks as well as rapid, smaller amplitude variations. The recurrence times for the outbursts vary from 27 to 84 days, and they are often (although not always) characterized by slow rise followed immediately by a sharp decline or dip. This is opposite to the fast rise and slower decline that is often observed in dwarf nova outbursts (Cannizzo et al. 2012). At peak outburst, the system is typically 0.7 mag brighter than average, while the dip minima are often 0.8 mag fainter than average. The outbursts usually have a duration of ≈7 days, although a much longer event was recorded around BJD 2,455,240. The fast variation...
The peaks nearest these mean frequencies are listed in Table 1 and plotted in Figure 3. The typical measurement uncertainties associated with the peak frequencies are 0.03 cycles day\(^{-1}\) for quarter 1 and 0.01 cycles day\(^{-1}\) for the subsequent quarters. We see that \(f_1\) and \(f_3\) grew significantly in strength up to quarter 7 while \(f_2\) and \(f_4\) remained approximately constant in amplitude.

In order to explore this change in the strength of the periodic signals over time, we also performed a wavelet analysis that is displayed in the central panel of Figure 1. We performed the wavelet analysis using the package of Torrence & Compo (1998).\(^9\) The wavelet amplitude of a discrete time series \(x_n\) with a sampling time \(\delta t\) is given by a convolution of \(x_n\) with a wavelet function \(\Psi((t' - t)/s)\),

\[
W_n(s) = \sum_{n=0}^{N-1} x_n^* \Psi^\star \left[ \frac{n' - n}{s} \delta t \right],
\]

where \(s\) is the wavelet scale, \(n\) is the index for the time variable, and the superscript \(\star\) indicates the complex conjugate. The wavelet function used in this paper is the Morlet function defined by

\[
\Psi(t/s) = \pi^{-\frac{1}{4}} \exp \left( \frac{i \omega t}{s} \right) \exp \left( -\frac{1}{2} \frac{t^2}{s^2} \right),
\]

where \(t\) is the time difference and \(\omega\) is a dimensionless oscillation frequency multiplier that sets the number of oscillations within the central part of the wavelet function. We adopted \(\omega = 10\) which gave better frequency resolution than the default value of \(\omega = 6\) in the Torrence and Compo wavelet package, but at the cost of somewhat worse temporal resolution (De Moortel et al. 2004). The wavelet scale sets the test frequency and the cost of somewhat worse temporal resolution (De Moortel et al. 2004). The wavelet analysis using the package of Torrence & Compo (1998).

The right-hand panel in Figure 1 illustrates the periodogram for the entire Kepler light curve from quarter 1 to 15. There is a broad distribution of low frequency power that corresponds to the cyclic (but not strictly periodic) outbursts. However, there are also four significant and narrow peaks that labeled in Figure 1 and that have frequencies (periods) of \(f_1 = 0.2421\) cycles day\(^{-1}\) (4.131 days), \(f_2 = 3.9291\) cycles day\(^{-1}\) (6.108 hr), \(f_3 = 4.1714\) cycles day\(^{-1}\) (5.753 hr), and \(f_4 = 7.8584\) cycles day\(^{-1}\) (3.054 hr). We also made periodograms of the light curve from each quarter separately, and the frequencies and amplitudes of

\[
\Psi^\star \left[ \frac{n' - n}{s} \delta t \right],
\]

the peaks nearest these mean frequencies are listed in Table 1 and plotted in Figure 3. The typical measurement uncertainties associated with the peak frequencies are 0.03 cycles day\(^{-1}\) for quarter 1 and 0.01 cycles day\(^{-1}\) for the subsequent quarters. We see that \(f_1\) and \(f_3\) grew significantly in strength up to quarter 7 while \(f_2\) and \(f_4\) remained approximately constant in amplitude.

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\[
s_j = s_0 2^{j\delta j}, \quad j = 0, 1, \ldots, J.
\]

We used twice the average time spacing of Kepler long cadence data for \(s_0\), and adopted \(\delta j = 0.25\) for a grid of values up to \(J = 50\). The wavelet analysis is done in a similar way to the

\[
\Psi^\star \left[ \frac{n' - n}{s} \delta t \right],
\]

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dimensions: 612.0 x 792.0

Figure 1. Grayscale image of the logarithm of the wavelet power as a function of time and frequency. The white dots at the bottom of the image indicate the end of each quarter (1–15), and the vertical white segments indicate gaps in the time series. The cross-hatched regions in lower left and right show the “cone of influence” where edge effects influence the wavelet power. The upper legend shows the relation between gray intensity and logarithm (base 10) of the square of the wavelet amplitude. The panel below shows the corresponding Kepler light curve with time in units of Barycentric Julian Date. The rotated panel to the right displays the amplitude of the full sample periodogram, and the four main signal frequencies are indicated to the right of the corresponding peaks.

Figure 2. Detailed view of an outburst and rapid variations in a portion of the light curve from quarter 7.

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Figure 3. Amplitudes of one low and three high frequency signals in the periodograms of the Kepler light curves plotted against observing quarter number. The symbols represent the amplitudes of the signals at \(f_1 = 1/4.131\) days, \(f_2 = 1/6.108\) hr, \(f_3 = 1/5.753\) hr, and \(f_4 = 1/3.054\) hr (see Table 1).
short-time Fourier transform (STFT) analysis, in the sense that the signal is multiplied with a wavelet function, similar to the window function in the STFT, and the transform is computed separately for different segments of the time-domain signal. The width of the window is changed as the transform is computed for every single spectral component, which is probably the most significant characteristic of the wavelet transform. Because the wavelet method is a multi-resolution analysis which was designed to overcome the resolution problem of STFT, it will give good time resolution and poor frequency resolution at high frequencies and bad time resolution and good frequency resolution at low frequencies. Furthermore, the edge effects introduced by the finite limits of the time series become progressively worse at low frequencies so that the derived wavelet power becomes unreliable within a “cone of influence” at the boundaries of the time series (Torrence & Compo 1998).

The wavelet power for the Kepler light curve is shown as a grayscale image in the central panel of Figure 1 as a function of both time and frequency. In the same way as the periodogram, most of the wavelet power occurs in the lower frequency part of the diagram, corresponding to the outbursts and dips. However, the periodic signals, \( f_1 \) to \( f_6 \), are also seen as the dark horizontal bands in the wavelet diagram. We see the same trends as documented in Figure 3, namely the near constancy of the signals \( f_2 = 3.9291 \text{ cycles day}^{-1} (6.108 \text{ hr}) \) and \( f_4 = 7.8584 \text{ cycles day}^{-1} (3.054 \text{ hr}) \) while the other signals \( f_1 = 0.2421 \text{ cycles day}^{-1} (4.131 \text{ days}) \) and \( f_3 = 4.1714 \text{ cycles day}^{-1} (5.753 \text{ hr}) \) grow from near invisibility to maxima around BJD 2,455,400.

These four frequencies are related in two ways. First, \( f_4 \) is the first harmonic of \( f_2 \) (\( f_4 = 2f_2 \)) indicating that the \( f_2 \) signal has a non-sinusoidal shape. This is seen in Figure 4 (upper panel), which shows the light curve rebinned according to phase in the \( f_2 \) period. It resembles that of a low amplitude ellipsoidal binary light curve with two unequal minima. On the other hand, the shape of the \( f_3 \) signal (Figure 4, lower panel) is approximately sinusoidal. The second relation is \( f_1 = f_3 - f_2 \). Both \( f_1 \) and \( f_3 \) share the increase in amplitude toward a maximum in quarter 7 (Figure 3). We argue below that the \( f_2 \) signal is probably the orbital frequency (Section 3) while the \( f_1 \) signal may correspond to the precessional frequency of a tilted accretion disk (Section 5).

<table>
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<th>Quarter Number</th>
<th>Mean Date (BJD−2,400,000)</th>
<th>( f_1 ) (cycles day(^{-1}))</th>
<th>( a_1 ) (e(^{-} \text{s}^{-1}))</th>
<th>( f_2 ) (cycles day(^{-1}))</th>
<th>( a_2 ) (e(^{-} \text{s}^{-1}))</th>
<th>( f_3 ) (cycles day(^{-1}))</th>
<th>( a_3 ) (e(^{-} \text{s}^{-1}))</th>
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Figure 4. Phase-binned light curves from quarters 1 to 4 for the \( f_2 \) signal (upper panel) and from quarters 5 to 15 for the \( f_3 \) signal (lower panel). The starting phase is arbitrary in both cases. Vertical lines indicate the square root of the variance of the mean within each bin.

3. SPECTROSCOPY AND ORBITAL ELEMENTS

We obtained 19 observations of KIC 9406652 with the KPNO 4 m Mayall telescope and Ritchey–Chrétien spectrograph with the T2KA CCD detector. They were made on three nights over a time span of eight days. Two lower resolving power (\( R = 1180 \)) spectra were made back to back on 2013 April 14, and these cover most of the optical spectrum (3410–8760 Å). The spectra from 2013 April 20 and 22 have higher resolving power (\( R = 1940 \)), KPC 17B grating), and these record the yellow–red region for the spectrum, while the second covers the yellow–red portion of the spectrum (4380–7830 Å). Exposure times ranged from 100 to 600 s. The observations were reduced and spectra extracted using standard methods in IRAF\(^{10}\) to create wavelength and flux calibrated spectra. These were rectified to a unit continuum by fitting the line-free regions, and then the spectra were transformed into two matrices on a uniform log \( \lambda \) wavelength grid (heliocentric frame). The first of these contains only the first two spectra that record the blue part of the spectrum, while the second covers the yellow–red region for all 19 spectra.

\(^{10}\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
from Earth’s atmosphere (Hinkle et al. 2003). The interstellar lines, such as those of peculiar He-strong star). The interstellar lines, such as Ca $\lambda$3933 and the diffuse interstellar band at 4428 Å, are weak or absent, suggesting there is little extinction along the line of sight to this star.

Figure 6 shows the yellow–red spectrum from the average for all 19 spectra. The hydrogen Balmer lines of H$\beta$ $\lambda$4861 and H$\alpha$ $\lambda$6563 both show emission, and the absorption part of the profile is absent in H$\alpha$. Emission is also present in He $\lambda$ 5876, 6678, 7065, with absorption wings present in He $\lambda$ 5876. There are also a number of strong telluric and molecular bands from Earth’s atmosphere that can be identified from the atmospheric transmission spectrum shown in the lower part of Figure 6 (from Hinkle et al. 2003\textsuperscript{11}). We checked the wavelength zero-point of each spectrum by cross-correlating the atmospheric transmission spectrum with each observation (in the topocentric frame).

The basic appearance of the spectrum is similar to that of the CV RW Sextantis (Beuermann et al. 1992), and hence suggestive that KIC 9406652 is also a CV. In the spectrum of RW Sex, the absorption wings form in the accretion disk, and the hydrogen Balmer emission lines have two components: a broad base that forms in the accretion disk and a narrow peak that originates in the hemisphere of the cool star that faces the disk and white dwarf. All these components display Doppler shifts related to orbital motion. Consequently, an important first step is to search for evidence of the orbital modulation of the spectral lines of KIC 9406652.

The spectral measurements are summarized in Table 2. The first column lists the Heliocentric Julian Date of mid-observation. The second column gives the equivalent width of the strongest emission line, H$\alpha$, which was measured by numerical integration between 6531 and 6592 Å. Columns 3–9 list various radial velocity measurements of the three strongest features, H$\alpha$, H$\beta$, and He $\lambda$ 5876. The three kinds of radial velocity measurements are illustrated for one H$\beta$ profile (from HJD 2,456,404.9342) in Figure 7. The first type of measurement was a simple parabolic fit to the upper quarter of the emission peak, and these are listed under the symbol $V_p$ for each line. Note that the emission displayed two close peaks in the last three spectra (for H$\beta$ and the He $\lambda$ lines but not H$\alpha$), so there are two entries for $V_p$ in Table 2 for the blue and red peaks. The spectral evolution of the profiles on the third night is shown in Figure 8, where each subsequent spectrum is offset downward by an amount equal to five times the elapsed time in days. The other two measurements are bisectors of the line wings from Gaussian sampling (Shafter et al. 1986). The line wings form in the fastest moving gas, which is located close to the white dwarf if the emission forms in an accretion disk. The columns for $V_w$ give the emission line wing bisector velocities for H$\alpha$ and H$\beta$ (from positions at $\pm$500 km s$^{-1}$), while $V_a$ lists the bisector velocities for the extreme absorption wings of H$\beta$ (at $\pm$1400 km s$^{-1}$) and He $\lambda$ 5876 (at $\pm$1300 km s$^{-1}$).

\textsuperscript{11} ftp://ftp.noao.edu/catalogs/atmospheric_transmission/
Figure 8. Montage of the line profiles of Hα, Hβ, and He I λ5876 observed on the third night. The continua of each spectrum are offset downward from the first spectrum (top) by an amount equal to five times the elapsed time in days.

Table 2
Spectroscopic Measurements

<table>
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<tr>
<th>HJD (−2,456,000)</th>
<th>−W₁ (Hα) (Å)</th>
<th>Vp (Hα) (km s⁻¹)</th>
<th>Vw (Hα) (km s⁻¹)</th>
<th>Vp (Hβ) (km s⁻¹)</th>
<th>Vw (Hβ) (km s⁻¹)</th>
<th>Vp (He i) (km s⁻¹)</th>
<th>Vw (He i) (km s⁻¹)</th>
<th>Vc (Å)</th>
<th>σ(Vc) (Å)</th>
<th>Vccf (km s⁻¹)</th>
<th>σ(Vccf) (km s⁻¹)</th>
</tr>
</thead>
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All these velocity measurements show similar trends, and we averaged the five measurements for the emission components (see Table 2, Columns 10 and 11 for the mean and standard deviation of the mean). We did not include the absorption wing velocities because they have a large scatter and possible systematic differences.

If KIC 9406652 is a CV, then we would expect that the companion is a cool star. The optical spectra of K- and M-dwarfs
are dominated by broad molecular bands (Gray & Corbally 2009), but it is difficult to search for such broad features in the rectified versions of our spectra because the rectification process tends to remove low frequency patterns. However, we were able to identify a significant depression in the average spectrum in the region of 5200 Å (see Figure 6) that resembles the MgH and Mg I b blend found in cool star spectra (see Figure 8.1 of Gray & Corbally 2009). We measured the radial velocity of this complex through cross-correlation with a model spectrum from the BT-Settl PHOENIX grid from Rajpurohit et al. (2013).12 We selected a model with \( T_{\text{eff}} = 3900 \) K, \( \log g = 5.0 \), and solar metallicity, parameters appropriate for a M0 V dwarf star (however, this choice is not critical because we show below in Figure 11 that a model for hotter \( T_{\text{eff}} = 4500 \) K star shows a very similar spectral morphology and would presumably give nearly identical radial velocity measurements). We then rebinned and rectified the model spectrum in the same way as done for the observed spectra (see Figure 11 below). We cross-correlated each observed spectrum with a flux diluted version of the model spectrum over the wavelength range between 5013 and 6221 Å (omitting the region around He I \( \lambda 5876 \)). The resulting cross-correlation peaks were well-defined in all but the results for first two low dispersion spectra, and the corresponding cross-correlation function (ccf) radial velocities and their uncertainties (Zucker 2003) are listed in Columns 12 and 13 of Table 2, respectively.

Both the emission and absorption feature radial velocities show large excursions over the course of the second and third nights, so we searched for a periodic signal by calculating the discrete Fourier transform of each velocity set (Roberts et al. 1987). The resulting periodograms, shown in Figure 9, have a large but mutually consistent set of peaks due to the many possible alias frequencies consistent with our limited spectroscopic time series. The two similar signal frequencies from the analysis of the Kepler light curve (Section 2), \( f_2 \) and \( f_3 \), are also indicated in Figure 9, and only \( f_2 \) is consistent with the variations in the radial velocities.

We made several estimates of the orbital elements using the nonlinear least squares fitting program of Morbey & Brosterhus (1974), and these are summarized in Table 3. We assumed circular orbits given the short orbital period, and we made solutions for both the emission and absorption radial velocities with the period free and fixed to the mean for \( f_2 \) from Table 1, \( P = 0.25440 \pm 0.00008 \) days. The solutions for the emission line measurements are given under the columns labeled Emission, and those for the absorption line ccf velocities under columns labeled Absorption. The rows list the orbital period \( P \), the epoch of cool star inferior conjunction \( T_1 \), the semiamplitude \( K \), the systemic velocity \( \gamma \), and the root mean square of the residuals from the fit. The radial velocity curves for the period-free solutions are illustrated in Figure 10. This plot depicts the mean emission line velocity measurements as open circles and the absorption line ccf measurements as filled circles. The results are generally consistent between the period free and fixed solutions. The systemic velocities for the emission and absorption line systems are significantly different, but this is not surprising given the differences in the nature of the measurements. The emission lines, for example, may have subtle blue absorption components if a disk wind exists, and this would tend to yield emission measurements biased to more positive values. Furthermore, small differences between the cool star’s spectrum and the adopted model would also produce a net velocity difference from the true systemic velocity. Finally, we caution that the hemisphere of the companion facing the hot white dwarf may be significantly heated by the flux of the white dwarf and disk. This would shift the center of light of the companion flux away from the star’s center of mass toward the white dwarf, and this would cause us to underestimate the true semiamplitude of the companion’s radial velocity curve.

We estimate that minimum light for \( f_2 \) occurred in the quarter 15 Kepler light curve at BJD 2,456,286.646 ± 0.005 (based upon an \( f_2 \) phase-binned light curve for that quarter), and the epoch of cool star inferior conjunction in our radial velocity data occurred after an elapsed time of 118.324 ± 0.006 days. This corresponds to a duration of 456.10 ± 0.14 orbital cycles, where the large uncertainty is derived from the number of cycles and uncertainty in \( P \). This near integer relation suggests that minimum light in the \( f_2 \) cycle occurs at cool star inferior conjunction.

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4. SPECTRAL PROPERTIES OF THE COMPONENTS

We used a Doppler tomography algorithm (Bagutinu et al. 1994) to reconstruct the individual spectra of the disk and companion. The algorithm performs the spectral reconstructions using the calculated radial velocity curves (from the solutions where the period was fit) and an estimate of the flux ratio $F_2/F_1$, where $F_2$ and $F_1$ are the fluxes of the secondary and disk, respectively. The method assumes for simplicity that this monochromatic flux ratio is constant across the spectrum and at all orbital phases, and both of these assumptions are suspect in this case. Nevertheless, the reconstruction is acceptable over a limited spectral range (in particular omitting those regions with terrestrial atmospheric lines that do not share in the orbital motion of either component), and we show the reconstructed spectrum of the companion in Figure 11. Also shown are model spectra from the grid of Rajpurohit et al. (2013) for solar abundance atmospheres with $T_{\text{eff}}$ = 4500 K and $\log g$ = 4.5 (above) and with $T_{\text{eff}}$ = 3900 K and $\log g$ = 5.0 (below; used as the ccf template in Section 3). Both model spectra were transformed to the observed wavelength grid using the observed spectral resolution and were rectified to a unit continuum in the same way as was done for the observed spectra. A good match of the line depths in the reconstructed spectrum with those in the models was made by adopting a flux ratio of $F_2/F_1 = 0.04 \pm 0.01$ (for a central wavelength of 5400 Å). The agreement between the observed and model spectra is satisfactory over this wavelength range, but because the relative line depths change only modestly between the temperatures of the models, it is difficult to estimate the effective temperature of the companion from the features in this part of the spectrum.

Figure 12 shows the reconstructed spectrum of the hot source that follows the emission line radial velocities. This appears similar to the average spectrum (Figure 6) because most of the flux in this region originates in the accretion disk surrounding the white dwarf. One interesting difference, however, is seen in the appearance of the He $\lambda$5876 line, which shows absorption wings that are similar in shape to those of Hβ. The stronger red wing of the He $\lambda$5876 line in the average spectrum is due to blending with the strong Na I D $\lambda\lambda$5890, 5896 feature in the spectrum of the cool companion. There are a number of similarities in the reconstructed spectrum of the disk with that of RW Sex (Beuermann et al. 1992; see their Figure 2) including the presence of emission in the C ii/N iii complex near 4650 Å and in He ii $\lambda$4686, which probably form in the hotter, inner part of the disk close to the white dwarf.

We show a representation of the spectral energy distribution (SED) in Figure 13. The small plus signs show the flux in 200 Å bins from one spectrum on each of the three nights of observation, and the spread in these is consistent with the amplitude of the short term photometric variability and the observational errors in the flux. The larger plus signs represent flux measurements from broad band photometry: a Galaxy Evolution Explorer FUV magnitude ($\lambda_{\text{eff}}$ = 1516 Å; Morrissey et al. 2005), Johnson UBV photometry (Everett et al. 2012), Two Micron All Sky Survey JHK photometry (Skrutskie et al. 2006), and Wide-field Infrared Survey Explorer (WISE) 3.35, 4.6, and 11.6 μm photometry (Jarrett et al. 2011).
appropriate for this direction in the Galaxy, to represent the disk flux contribution, and the dotted and dashed curves show possible companion fluxes for $T_{\text{eff}} = 3900$ K and 4500 K, respectively (normalized to the observed fluxes at 5400 Å). All these are transformed for interstellar extinction assuming $E(B-V) = 0.07$ mag. The upper and lower solid lines show the sum of the Planck and companion fluxes for $T_{\text{eff}} = 3900$ K and 4500 K, respectively.

Figure 13. Spectral energy distribution of KIC 9406652. The large plus signs indicate multi-wavelength photometric measurements (described in the text) while the small plus signs show our spectrophotometric results for each of the three nights. The dash-dotted line shows a Planck curve for $T_{\text{eff}} = 17,450$ K to represent the disk flux contribution, and the dotted and dashed curves show possible companion fluxes for $T_{\text{eff}} = 3900$ K and 4500 K, respectively (normalized to the observed fluxes at 5400 Å). All these are transformed for interstellar extinction assuming $E(B-V) = 0.07$ mag. The upper and lower solid lines show the sum of the Planck and companion fluxes for $T_{\text{eff}} = 3900$ K and 4500 K, respectively.

Note that we omitted the WISE 22.1 μm measurement because no uncertainty estimate was listed. Also shown are several model flux distributions that are all modified for interstellar extinction (Fitzpatrick 1999) assuming a value of reddening appropriate for this direction in the Galaxy, $E(B-V) = 0.07$ mag (Schlafly & Finkbeiner 2011; Gontcharov 2012). These model flux curves are all normalized to the observed flux at 5400 Å (interpolated between $B$ and $V$ from Everett et al. 2012) with each component’s contribution set by the observed flux ratio at that wavelength, $F_{\lambda}/F_{1} = 0.04$. The dash-dotted line shows a Planck curve for $T_{\text{eff}} = 17,450$ K as a representation of the disk flux contribution, and the dotted and dashed curves show companion fluxes (from Rajpurohit et al. 2013) for $T_{\text{eff}} = 3900$ K and 4500 K, respectively. The solid lines show the sum of the fluxes of the disk and companion, and the model with a cooler companion ($T_{\text{eff}} = 3900$ K; upper curve) shows a somewhat better match to the infrared (IR) photometry. We caution, however, that the photometry was gathered over a long time span and that intrinsic variability of the source will influence the appearance of the SED. For example, if the models were normalized at 5400 Å to the brighter phase recorded in our spectrophotometry, then the model with a $T_{\text{eff}} = 4500$ K companion would probably fit the IR photometry as well.

5. DISCUSSION

The spectra of KIC 9406652 show clearly that the object is a CV. We observe the spectral components of both the accretion disk and cool donor star, and the orbital velocity variations indicate that the 6.108 hr periodicity in the light curve is the orbital period of the binary. The object is apparently not an X-ray source (A. Smale, 2013, private communication), so we expect that the mass gainer is a white dwarf as found in other CVs. However, the light curve is remarkable for its recurrent outbursts that although bright are not as large as those observed in dwarf novae. The light properties resemble those of a group of old novae and nova-like CVs identified by Honeycutt et al. (1998) that display unusual “stunted” outbursts. These objects experience quasi-periodic outbursts that are often accompanied by fadings or “dips” in the light curve. One of the objects in this group is RW Sex (Beuermann et al. 1992), which has a similar orbital period ($P = 5.88$ hr) and shares a number of spectral similarities with KIC 9406652. Thus, the Kepler light curve of KIC 9406652 provides us with a key opportunity to study the processes that lead to “stunted” outbursts in such CVs.

We can use the preliminary orbital elements to estimate the physical properties of the binary system. If we tentatively adopt the fixed P elements (Table 3), then the mass ratio is $q = M_{2}/M_{1} = 0.83 \pm 0.07$, the projected semimajor axis is $a \sin i = 1.54 \pm 0.06 R_{\odot}$, and the mass products are $M_{1} \sin^{2} i = 0.41 \pm 0.04 M_{\odot}$ and $M_{2} \sin^{2} i = 0.34 \pm 0.04 M_{\odot}$. The long term evolution of CVs depends on the properties of the donor star, and given a mass–radius relation for such low mass stars, there exists a relationship between the orbital period and donor mass (Patterson 1984; Howell et al. 2001; Knigge 2006; Knigge et al. 2011). Based upon the semi-empirical relations with orbital period given by Knigge (2006) and Knigge et al. (2011), a CV with an orbital period of 6.108 hr has a donor of mass $M_{2} = 0.75 M_{\odot}$, radius $R_{2} = 0.72 R_{\odot}$, an effective temperature $T_{\text{eff}} = 4390$ K, and K-band absolute magnitude $K = 4.38$ (assuming that the donor is not in a state of advanced evolution). This effective temperature is consistent with the appearance of the donor’s spectrum (Figure 11). Furthermore, the model evolutionary tracks from Knigge et al. (2011) predict that the white dwarf will be hot ($T_{\text{eff}} = 40–50$ KK), which is consistent with the presence of the He I $\lambda 4686$ emission feature in the spectrum associated with the disk (Figure 12). If we adopt the mass estimate for the donor from the orbital period–mass relationship, then the mass of the white dwarf (mass gainer) star is $M_{1} \approx 0.9 M_{\odot}$ and the inclination is $i \approx 50^\circ$. The distance derived from the estimated absolute magnitude of the donor and its relative flux contribution in the SED at the K-band wavelength is in the range of 340 pc (3900 K model) to 400 pc (4500 K model).

The orbital period determined from spectroscopy is consistent with the $f_{2}$ signal from the Kepler light curve (Section 2). The fact that the orbital phased light curve displays a minimum around the time of donor inferior conjunction suggests that the orbital part of the light curve variations is associated with a reflection effect, i.e., the hemisphere of the donor facing the white dwarf appears brighter. The stronger $f_{2}$ signal indicates the presence of a periodic variation that is somewhat shorter than the orbital period. Such near orbital period variations are known in many CVs through the presence of “superhumps” in the light curve, and in some cases they appear at shorter periods (see the case of TV Col; Retter et al. 2003). Wood & Burke (2007) argue that these “negative superhumps” are caused by variations in the flux from the hot spot where the mass transfer stream strikes the accretion disk. They show how the orientation of a tilted and precessing accretion disk in a CV results in a hot spot location that changes through the orbital and precession cycle. When the mass stream encounters the nodal line of the disk, the hot spot occurs at a relatively large radial distance from the white dwarf. Then, as the companion progresses around the orbit, the stream will travel over the equatorial plane to arrive at a position closer to the white dwarf where the gas is denser, so that the hot spot flux increases. However, instead of seeing two maxima per orbit if the disk were transparent, the final result is that an external observer outside of the disk plane will witness one variation per orbit because the hot spot will occur below
the optically thick disk in the second half of the cycle. The “negative superhump” objects have a shorter superhump period because the disk precession is retrograde to the orbit, so that the line of the nodes is seen earlier each orbit. Thus, in this model, the difference between the superhump and orbital frequencies is equal to the disk precessional frequency.

We suggest that this retrograde precessing disk model applies to the case of KIC 9406652. The difference frequency, superhump $f_3$ minus orbital $f_2$, is also observed in the periodogram as $f_1$, which would correspond to the precessional frequency. This signal with a period of 4.13 days is clearly seen in the light curve at various times (see Figure 2) and it probably results from changes in the projected size of the disk with the precessional cycle. Thus, the higher frequency signals in the light curve appear to be related to two primary “clocks,” the binary orbital and disk precessional periods. Larwood (1998) showed that the ratio between the orbital period and forced precession period is

$$\frac{P}{P_0} = \frac{3}{7} \left(1 + \frac{\mu}{2}\right) \beta^{3/2} R^{3/2} \cos \delta,$$

where $\mu = M_2/M_1$ is the mass ratio, $\beta$ is the ratio of disk outer radius to Roche radius of the white dwarf, $R$ is the ratio of white dwarf Roche radius to the binary semimajor axis, and $\delta$ is the disk inclination angle relative to the orbital plane. If we assume $\mu = 0.83$, $\beta = 1$, $R = 0.40$ (from the mass ratio and the formula from Eggleton 1983), and $\delta = 10^\circ$ (a representative small disk tilt), then the predicted ratio of $P/P_0 = 0.064$ is the same within uncertainties as the observed ratio of $P/P_0 = 0.062$.

The lower frequency signals in the periodogram of the light curve are related to the outbursts and dips that occur on a ~30 day timescale (Figure 1). These generally take the form of an outburst followed immediately by a dip. One exception was observed near BJD 2,455,190 where a strong dip occurred before an outburst. Curiously, the next outburst that occurred near BJD 2,455,240 was also exceptional in its duration. Both of these events happened just prior to the appearance of the $f_1$ and $f_3$ signals in the periodogram (see Figure 1), which marks the beginning of the disk precession phase in these observations.

The cause of the stunted outbursts in this system is unknown, but they may be related to cycles of changing disk mass. Mennickent et al. (2003) have discovered a class of double periodic variables among binaries containing massive stars in interacting binaries. They argue that the mass gainers have reached critical rotation and can no longer easily accrete additional mass from the donor. Consequently, the transferred mass builds up in a thick accretion torus surrounding the companion, until it is finally released into an expanding circumbinary disk. The cycle of growth and dissipation of the disk gas is observed as the longer periodicity in the light curves of these systems. It is possible that a similar process is occurring in CVs like KIC 9406652. Models suggest that the mass transfer rate is relatively large in longer period CVs (Kniege et al. 2011). The incoming gas from the donor may become trapped in the disk because direct accretion is inhibited by the rapid rotation and/or magnetic field of the white dwarf gainer. If this is the case with respect to KIC 9406652, then the outburst and dip would be related to the growth in physical size and subsequent ejection of disk gas from the system (possibly causing some obscuration). We speculate that such gas ejection events may provide the torque required to cause a disk warp and promote disk precession (as occurs, for example, by the action of a disk coronal wind in the X-ray binary Her X-1; Schandl & Meyer 1994).

The remarkable richness of the Kepler light curve of KIC 9406652 provides us with the opportunity to explore disk physical processes with unprecedented temporal coverage. This is especially important for this CV where the short and long period variations appear to be related in a fundamental way. If the outbursts are caused by relatively low energy mass ejections, then the system may be surrounded by a circumbinary disk of large dimension, and high angular resolution observations may provide the means to detect and map such an outflow.

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Facilities: Kepler, Mayall

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