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Abstract

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Full Text

Preamble

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Abstract

We present spectroscopy of stars in the immediate vicinity of the dwarf nova (DN) KZ Gem to confirm its identification, which had been ambiguous in the literature. Analysis of 73 radial velocities spanning from 2014 to 2019 provides a high-precision orbital period of 0.2224628(2) d (5.34 hr) and shows KZ Gem to be a double-lined DN. Time series photometry taken from 2016 to 2018 reveals a variable double-hump modulation with a full amplitude of 0.3 mag, along with five Gaussian-like transient events lasting 30 min or more. Using the light curve code XRBinary and nonlinear fitting code NMfit, we obtain an optimized binary model from time series photometry consisting of a Roche-lobe-filling K-type dwarf with a mass transfer rate of 2.7-7.9×10^{1} M yr^{1} to a large, cool, and thick disk surrounding a white dwarf, in an orbit with an inclination of 51.6°(±1.4°). Two hotspots on the disk are demonstrated to cause the observed variations in the ellipsoidal modulations from the secondary star. This physical model is compatible with the Gaia distance of KZ Gem.

Keywords: Stars: binaries: close; Stars: cataclysmic variables; Stars: individual (KZ Gem)

1. Introduction

KZ Gem was first discovered as a variable star a half-century ago by Hoffmeister (1966) and Kukarkin et al. (1968). It is listed in various catalogs of cataclysmic variables (CVs; e.g., Downes & Shara 1993; Downes et al. 1997, 2001; Ritter & Kolb 2003) as a dwarf nova (DN). Since KZ Gem falls within the field of view of the K2 Campaign 0 (K2-C0), it was proposed as a CV target and observed in long cadence (30 min sampling) mode. In the K2 variable catalog, KZ Gem was listed as OTHPER (i.e., other periodic and quasi-periodic variables; Armstrong et al. 2015, 2016). The "self-flat-fielding" (SFF) corrected light curve of KZ Gem

(Vanderburg & Johnson 2014; Vanderburg 2014) shows an ellipsoidal-like effect. Dai et al. (2017) applied a phase-correction method to these data to show that the orbital period is 0.22242 d, almost exactly twice the orbital period of 0.11122 d listed in RKcat (Edition 7.24; Ritter & Kolb 2003). A DN outburst of KZ Gem was detected in 2015 January by Lange (2016), but without a published spectrum, KZ Gem remained poorly understood.

The coordinates for KZ Gem given in RKcat and the VSX (Variable Star Index) databases of the AAVSO differ by 9 from those in SDSS, SIMBAD, and K2. Because the field of KZ Gem is crowded, a difference of 9 is large enough to cause incorrect identification. Figure 1 [Figure 1: see original paper] shows six stars within 15 of KZ Gem; Table 1 lists the SDSS coordinates of these stars. The two different coordinates listed for KZ Gem correspond to stars S1 and S3, which are marked by blue rectangles in Figure 1. The crowding in the field also leaves open the possibility that the ellipsoidal modulation found by Dai et al. (2017) in the K2 light curve might arise from a neighboring star rather than KZ Gem.

This paper presents ground-based spectroscopy of four nearby stars (S1, S2, S3, and S4) and photometry of S3. In Section 2, we confirm the identification of S3 with KZ Gem, and in Section 3 we obtain a high-precision orbital period from radial velocities. Folding with this period, the light-curve morphology, models, and five transient events are discussed. Table 2 provides a journal of the observations.

2.1. Spectroscopy

Our spectra were obtained from four different instruments on three telescopes: (1) With the Double Imaging Spectrograph (DIS) on the Apache Point Observatory (APO) 3.5m telescope, we obtained spectra on five nights using the blue and red channels simultaneously. Gratings B1200/R1200 provided a dispersion of 0.6 Å pixel ^{1}. (2) With the Beijing Faint Object Spectrograph (BFOSC) and grating G4 on the Xinglong Observatory (XLO) 2.16m telescope, we obtained spectra on three nights with a resolution of 2000 (2.97 Å pixel ^{1}). (3) With the modspec spectrograph on the Hiltner 2.4m telescope at Michigan-Dartmouth-MIT (MDM) Observatory in Kitt Peak, Arizona, we obtained spectra on 12 nights spread across four observing runs (2014 December, 2016 January, 2016 February, and 2018 November). A 600 line mm ^{1} grating provided 3.5 Å resolution from 4310 to 7500 Å, with vignetting toward the ends of the range. (4) Also with the 2.4m MDM telescope, we used the Ohio State Multi-Object Spectrograph (OSMOS) on six additional nights in 2018 December and 2019 January to disambiguate the long-term velocity cycle count. These spectra covered 3970 to 6870 Å with a resolution of 3 Å FWHM. Flux standards were observed when appropriate, and comparison lamps were observed to maintain accurate wavelength calibration. All spectra were reduced using IRAF.

As shown below, the spectrum of the star we identify with KZ Gem shows a contribution from a late-type secondary star. We measured absorption velocities in the MDM spectra by cross-correlating against a composite template spectrum originally composed by taking 76 spectra of late-type velocity standard stars, shifting them to zero velocity, and averaging. The cross-correlation was performed using either the rvsao package (Kurtz & Mink 1998), which implements the algorithm developed by Tonry & Davis (1979), or the fxcor task in the IRAF rv package.

To estimate the secondary star' s spectral type and contribution, we shifted the individual MDM 2.4m exposures to the secondary' s rest frame and averaged the shifted spectra. We have a collection of archival spectra of K- and M-type main sequence stars classified by Boeshaar (1976) and Keenan & McNeil (1989), taken with the same instrument setup as our KZ Gem spectra and also shifted to zero radial velocity. We estimated the secondary' s spectral type and its fractional contribution by scaling these main sequence spectra and subtracting them from the KZ Gem spectrum, interactively trying different spectral types and scaling factors until the secondary-star absorption lines were cancelled as well as possible.

2.2. Identification of KZ Gem

Inspection of Figure 1 indicates that spectra of stars S1, S2, and S4 can be taken simultaneously using a wide slit along the north-south direction, which was accomplished on 2017 January 22. Since S1 is faint, all spectra of S1 were smoothed by a running boxcar of 5 and 3 pixels for the APO and XLO spectra, respectively. Despite the low S/N, both APO and XLO spectra of S1 (shown in the three panels of Figure 2 [Figure 2: see original paper] and panel a of Figure 3 [Figure 3: see original paper]) display similar features: a sloping linear continuum from blue to red with shallow and marginal H and H absorption lines and a lack of emission lines. Note that the H absorption line shown in the blue APO spectrum taken on 2016 December 05 is undetected in the subsequent two APO spectra and the XLO spectrum. The spectra of S1 are atypical for a quiescent DN. The simultaneous spectra of the other two targets, S2 and S4 (shown in panels b and c of Figure 3, respectively), also show only absorption rather than emission lines; S2 appears to be an early M-type star, and S4 is consistent with a G-type star. There is therefore no indication that S1, S2, and S4 are dwarf novae.

In contrast, the two XLO spectra of S3 taken on January 9 and 10, 2018 (Figure 4 [Figure 4: see original paper]) clearly show broad H emission superimposed on the continuum, along with a higher blue flux level. He I emission lines are marginally visible at 5876, 6678, and 7065. These features confirm that S3 is the DN, validating the coordinates listed in RKcat, VSX, and Gaia. In both spectra, the He I 5876 emission line is blended with weak NaD absorption (as in the DN SDSS J063213.1+253623, or J0632+2536; Dai et al. 2016), and the He I 5876 emission observed on 2018 January 09 appears doubled. The averaged blue and red high-resolution APO spectra are shown in Figure 5 [Figure 5: see original paper]. H , H , and H are visible in emission in the spectra taken on 2018 January 17, and the lower two panels of Figure 5 clearly show neutral He emission at 4471, 6678, and 7065. Despite the low S/N of the spectra taken on 2018 January 19 (due to weather and poor seeing), H is visible in the bottom right panel of Figure 5. Table 3 lists the emission equivalent widths of H and H . The upper panel of Figure 6 [Figure 6: see original paper] shows the mean MDM spectrum of S3, which appears similar to the two XLO spectra. All the XLO, APO, and MDM spectra have similar continuum flux and moderate Balmer emission lines, indicating KZ Gem was in a similar accretion state during the observations.

2.3. Photometry

Our differential time-series photometry was obtained using: (1) the K FlareCam with 1.3 pixel^{1} when binned 2×2, mounted on the APO 0.5m Astrophysical Research Consortium Small Aperture Telescope (ARCSAT); and (2) Andor CCD cameras on the XLO 0.85m and MDM McGraw-Hill 1.3m telescopes. We obtained 14 light curves spanning almost three years. For the XLO and ARCSAT data, we used star C1 (Figure 1) as the comparison star, while for the MDM data we used S4, which was well-resolved from the DN. The MDM 1.3m data from 2016 February 13, 14, and 15 were obtained with a GG420 filter (hereafter GG420-band), and no filter was used in four XLO observations with the 0.85m and 2.16m telescopes. The XLO and ARCSAT data were reduced using the Point Source Function (PSF) in IRAF standard routines due to contamination from the two nearby objects S2 and S4. Five light curves were also obtained with Johnson-Cousins V filters (hereafter V-band) on the APO 0.5m and MDM 1.3m telescopes. The ARCSAT data taken on 2016 November 29 represent the only light curve obtained in an SDSS g filter.

3.1. Period Analysis

Since the K2 data are defocused and KZ Gem is located in a crowded field, the wide aperture shown in the K2 image plot of KZ Gem in the Mikulski Archive for Space Telescopes (MAST) indicates that the SFF-corrected light curve includes flux from several nearby stars. Consequently, the orbital period of 0.22242 d (5.34 hr) derived by Dai et al. (2017) from the blended K2 data required further verification.

We successfully measured cross-correlation velocities of the secondary star in 55 of our MDM 2.4m spectra (the APO spectra did not yield cross-correlation velocities). We excluded the NaD 5893 blended absorption feature from the correlation region due to possible confusion with nearby He I 5876 emission. To search for periods, we constructed least-squares sinusoidal fits on a sufficiently dense grid of trial frequencies over the range of typical CV periods. Only a single period, corresponding to a single choice of cycle count between observing runs, yielded an acceptable result. A sinusoidal fit to the velocities of the form V (t)

= + K sin[2 (t - T)/P b] produced the parameters listed in Table 4 , where T is the time when the secondary star passes from blue to red through the mean velocity (i.e., the inferior conjunction of the secondary star). The orbital period found in the search, refined using Equation 1, is P b = 0.2224628(2) d, near 5.34 hr, in excellent agreement with the period derived from K2 photometry. The uncertainty is small because the cycle count is unambiguous over more than four years.

To further verify this derived period, we constructed an absorption velocity periodogram shown in Figure 7 [Figure 7: see original paper] using the "residual-gram"method described by Thorstensen et al. (1996). A significant peak appears at a frequency of 4.4951 d ^{1}, coincident with P b. Although the APO spectra could not contribute to the absorption line fit, the 18 APO H emission line velocities obtained over a 46 hr time base corroborate the result, giving P b = 0.225(3) d, consistent with the absorption-line result. Fixing the period of the emission-line fit to that derived from the absorption lines produces a scatter (44 km s ^{1}) larger than typically found. The best-fitting emission velocity curves shown in Figure 8 [Figure 8: see original paper] display large deviations around phase 0.75–1.0, when a hotspot would have maximum contribution, suggesting these deviations may be caused by a hotspot.

The ephemeris for the inferior conjunction of the normal star, T f, derived from the absorption line velocities is: T f = BJD 2457434.9280(7) + 0.2224628(2) E where E is the cycle number and the time base is UTC.

Using this ephemeris, we phased and stacked the 2019 January and February MDM modspec data to create a phase-resolved greyscale image (lower panel of Figure 6). Before averaging, we rectified the spectra and edited out cosmic rays and other artifacts. The many absorption features of the late-type secondary are seen Doppler-shifting back and forth with phase, while the H emission line moves in anti-phase to the absorption lines, consistent with an origin in the disk/hotspot surrounding a white dwarf. Assuming that the motion of the emission lines traces the motion of the white dwarf (as in the long-period DN TT Crt; Szkody et al. 1992), the mass ratio of the two component stars may be roughly estimated as 0.81 using the relationship between the amplitudes of the best-fitting radial velocity curves derived from emission and absorption lines. A range of q = 0.74–0.88 is derived by considering the 2 errors of K and K b listed in Table 4, though larger systematic errors are possible.

3.2. Secondary Spectrum

We used the parameters in Table 4 to shift the MDM 2.4m spectra to the rest frame of the secondary star as described in Section 2.1. The Green et al. (2018) three-dimensional reddening maps show little extinction in this direction out to 2 kpc, so we applied no reddening correction before decomposition. The decomposition process yielded acceptable results for spectral types K0 through K5, suggesting that approximately half the light in the 5000–6500 Å region arises from the secondary star. Figure 6 shows one of the most successful decompositions, for a K2V star (HD109011) scaled to a flux equivalent to V = 17.9. The flux calibration is typically accurate to 0.2 mag, limited by clouds and losses at the 1.1 spectrograph slit.

3.3. Light-Curve Morphology

3.3.1. The Variable Orbital Modulation

Compared with the high-precision orbital period derived from velocities, a periodogram from our differential time-series photometry (based on the Lomb-Scargle method; Lomb 1976; Scargle 1982) shows a notable period of 0.484 d—almost twice P b. Although a trivial peak at 0.221 d can also be found, a large discrepancy of 2 min from P b implies that the orbital modulation of KZ Gem is complex and noisy.

Figure 9 [Figure 9: see original paper] shows the 14 light curves in four bands (GG420, SDSS g, no-filter, and V) spanning 2016–2018, phased using the spectroscopic ephemeris (Equation 2). All display variable double-hump modulations with a full amplitude of 0.3 mag, compatible with pure ellipsoidal modulation (e.g., 0.2–0.3 mag; Bochkarov et al. 1979; McClintock et al. 1983). The consistent amplitude implies the source was quiescent for all observations. However, our observations from different filters and nights differ in detail. For brevity, we refer to phases 0.0, 0.25, 0.5, and 0.75 as the secondary dip, secondary hump, primary dip, and primary hump, respectively.

Table 5 lists minimum and maximum times with their corresponding phases, derived using parabolic fits to the light curves with uncertainties estimated via bootstrap methods. Although most phases are close to 0.0, 0.25, 0.5, or 0.75, the largest O–C deviation of the primary hump (observed on 2018 November 07) is 26 min from its typical phase of 0.75, while the following secondary hump shows only a small deviation of 6 min from phase 0.25. Due to these variations, O–C values of light minima or maxima cannot be used to determine orbital period variations, as commonly done for many eclipsing DN (e.g., Z Cha; Dai & Qian 2009; V2051 Oph; Qian et al. 2015).

The double-hump modulation is less distinct in the single SDSS g-band light curve observed on 2016 November 29 due to large scatter and relatively short duration. Figure 10 shows normalized and phased light curves in the other three bands, demonstrating variations in orbital modulation across filters. The three sequential days of GG420-band light curves show more typical double-hump modulations with a higher-level primary hump (0.75) and lower-level primary dip (0.5), similar to other dwarf novae (e.g., J0632+2536 and TW Vir; Dai et al. 2018). However, three no-filter-band light curves obtained on 2017 December 25, 2018 November 01, and December 31 display two humps at the same flux level and much deeper primary dips (0.1 mag), resembling pure ellipsoidal modulation with equal maxima and deepest minimum around phase 0.5 caused by tidal distortion of the Roche-lobe-filling secondary star (Bochkarov et al. 1979).

For KZ Gem, the amplitude of the V-band ellipsoidal variation is larger than that of the long-period DN TT Crt (<0.2 mag) derived by Szkody et al. (1992).

Panel d of Figure 9 shows that the lower-level secondary hump (0.25) detected on 2018 March 08 can rise to the level of the primary hump within eight months. Compared with the no-filter-band ellipsoidal modulation on 2018 December 31, the light curve observed three days earlier with the same filter and telescope (XLO 2.16m) clearly shows typical double-hump modulation. Although three V-band light curves display ellipsoidal modulation similar to no-filter-band curves, their individual descending branches around phases 0.25–0.5 show slight variations in the primary dip or secondary hump. The long-duration V-band light curve (6.22 hr) taken on 2018 November 07 presents atypical modulation where the primary hump is lower than the secondary hump, similar to the long-period CV CXOGBS J174444.7-260330 (Ratti et al. 2013). Normalized V-band light curves superposed in the bottom panel of Figure 10 [Figure 10: see original paper] confirm this atypical double-hump modulation, opposite to modulations in GG420 and no-filter bands. In summary, the orbital modulation of KZ Gem sometimes appears as pure ellipsoidal modulation and sometimes switches to typical DN double-hump modulation.

3.3.2. Transient Events

Although transient events have been detected in many low-state magnetic CVs (e.g., Kafka & Hoard 2009; Araujo-Betancor et al. 2005), similar reports for quiescent dwarf novae are rare. Inspection of Figure 11 [Figure 11: see original paper] reveals five transient events with nearly symmetric profiles (i.e., equal rise and fall) rather than the exponential profiles typical of X-ray/optical flares in polars (e.g., Dai et al. 2013; Terada et al. 2010). Since two of the five events are dips rather than brightenings, a simple parabolic function may be more appropriate than a Gaussian. Table 6 details these events, showing they last longer and have smaller amplitudes than those detected in the low-state polar AM Her (Dai et al. 2013).

The g-band light curve in the top panel of Figure 11 displays two sequential brightening events with nearly equal timescales of 30 min. The first peak occurs near the light minimum of the primary dip, while the second has smaller amplitude, resembling two R-band brightening events with similar amplitudes and durations at the beginning of the low-to-high state transition in the prototype polar AM Her (Dai et al. 2013). Since most brightening events (flares) in cool stars show typical exponential profiles in red bands with amplitudes of 0.02–0.3 mag (e.g., Qian et al. 2012; Zhang et al. 2010), the twin brightenings in the blue SDSS g-band likely originate from the white dwarf or inner disk rather than the secondary star. The three brightenings in KZ Gem have shorter durations, smaller amplitudes, and more symmetric profiles than quasi-periodic mini-outbursts detected in Kepler observations of two other DN (V1504 Cyg; Osaki & Kato 2014, and CRTS J035905.9+175034; Littlefield et al. 2018), which lasted 2 d with amplitudes of 0.5 mag and irregular morphologies. This suggests different origins for these events.

In the bottom panel of Figure 11, a no-filter-band brightening at phase 0.04 (near the secondary dip minimum) has the longest duration (64 min) and smallest amplitude (0.093 mag). Two significant no-filter-band dips with similar amplitude and duration observed on 2018 March 08 and November 01 appear in the middle panels. The former occurs at the primary hump peak (0.75), while the latter is slightly asymmetric and appears 20 min before phase 0.75 (i.e., on the egress branch of the V-shaped primary hump). In the no-filter-band light curve from 2018 December 31, a less distinct dip with short duration (9 min) and small amplitude (0.05 mag) appears at phase 0.74. Thus, the detected brightenings and dips in quiescent KZ Gem appear related to secondary light minima and primary light maxima, respectively.

3.4. Synthetic Analysis

Dai et al. (2018) proposed a phenomenological model to reproduce double-hump light curves of low-inclination DN and successfully obtained photometric solutions for three DN using the light curve code XRBinary (developed by E. L. Robinson) and the nonlinear fitting code NMfit, demonstrating the reliability of this approach. We applied this model to perform a complete synthetic analysis of KZ Gem based on our ground-based light curves spanning 3 years.

All 13 light curves in GG420, no-filter, and V bands were separated into three types. Since no-filter and V-band light curves consist of data from many different telescopes on several nights, they show larger scatter than the three-day sequential GG420-band light curves with 4000 data points. Due to higher orbital phase resolution and smaller scatter, we derived a light curve model for KZ Gem from the overlapped GG420-band light curve shown in the top panel of Figure 10. Before running XRBinary, the light curve was binned with phase resolution 0.01. Since the main feature is variable ellipsoidal modulation, the two stellar components dominate flux contributions, as in DN TT Crt (Szkody et al. 1992) and J0632+2536 (Dai et al. 2018). At times, one or more disk hotspots may change the orbital modulation from pure ellipsoidal to typical DN double-hump modulation. The amplitude of H emission variation in the greyscale plot (bottom panel of Figure 6) shows an S-wave indicating hotspot motion on the disk, similar to trailed spectra of DN SDSS J0116+09 (Szkody et al. 2018). Therefore, we investigated two models: model-1 (no surface hotspot) and model-2 (with a surface hotspot).

3.4.1. System Parameters for KZ Gem

Based on RKcat and other literature, the averaged white dwarf masses for three grades (A: well-measured; B: less-well-measured; C: without error bars) are 0.82 M , 0.78 M , and 0.74 M , respectively, similar to the previous prediction of 0.83±0.23 M for average CVs (Zorotovic et al. 2011). Since the white dwarf mass of KZ Gem is not accurately determined, we preset the initial M_wd to

0.83 M as a starting point rather than a fixed parameter. Because the derived orbital period is above the period gap, we assumed an average CV white dwarf temperature of 25,793 K (Sion 1999; Urban & Sion 2006) as the initial T_wd. The NaD absorption line in the two XLO and mean MDM spectra (Figures 4 and 6) implies a late K star in KZ Gem. We assumed initial temperature and mass for the secondary star (T_rd and M_rd) of 4410 K and 0.67 M , respectively. A preparatory accretion disk model with fixed masses and temperatures implied the disk extends nearly to the white dwarf surface, so R_in was always equal to R_wd during iterations.

Based on the phased and binned GG420-band light curve, all 17 parameters (13 for model-1) were set as adjustable. Model-1 showed large deviations from the observed light curve at phases 0.0–0.25, but these were eliminated using model-2. A much smaller ^{2} indicates that model-2 with default limits R_in=R_wd and 0.74 q 0.88 provides a better fit than model-1. The best-fitting parameters and uncertainties were estimated by NMfit, with the modeled GG420-band light curve plotted in the top left panel of Figure 12 [Figure 12: see original paper].

For KZ Gem, XRBinary does not calculate irradiation effects as L_rd > L_wd + L_d. Although accurate white dwarf mass cannot be obtained from our light curves due to nearly constant flux contributions from the white dwarf (4%), appropriate physical parameters can be roughly constrained within a small q range. A search over white dwarf masses from 0.6–1.1 M shows ^{2} only varies from 14 to 17, with the minimum at 0.86 M , consistent with the average CV mass from Zorotovic et al. (2011). Based on MK spectral classes (Cox 2000), a normal K0V star corresponds to T_rd = 5120(±110) K. The derived M_rd 0.7(±0.2) M indicates a later K-type dwarf.

Our light curve model demonstrates that KZ Gem' s secondary is an early K-type dwarf, consistent with observed spectra. Like other long-period DN TW Vir and J0632+2536 (Dai et al. 2018), M_rd and R_rd of KZ Gem are basically consistent with the semi-empirical mass-radius relation of CV donor sequences (Knigge 2006; Knigge et al. 2011) and CV mass/radius-period relations (Warner 2003; Smith & Dhillon 1998) shown in the bottom left and two right panels of Figure 13 [Figure 13: see original paper]. To verify the secondary mass, further high-resolution observations are needed. The top left panel of Figure 13 indicates T_rd of KZ Gem is 900 K higher than predicted by the semi-empirical CV donor sequence, implying the secondary has undergone some nuclear evolution. The other three DN investigated by Dai et al. (2018) may also have evolved donors similar to KZ Gem. Thus, these four DN appear to be Peculiar Cataclysmic Variables (PCVs) containing evolved donors (Rebassa-Mansergas et al. 2014; Ren et al. 2018).

3.4.2. Disk Models in Three Bands

Five best-fitting system parameters (q, i, M_wd, T_wd, and T_rd) derived from the GG420-band light curve were fixed to model the 12 disk parameters in three bands. The derived parameters listed in Table 7 visualize a system configuration of KZ Gem using Phoebe 2.0. All three 2D CV configurations at phase 0.75 shown in the middle panels of Figure 12 indicate a consistent disk model: a large, cool, thick disk with flat temperature distribution surrounding a 0.86(±0.09) M white dwarf, and two hotspots (one at the vertical edge of the disk, called hotspote, and one on the disk surface, called hotspotss). The hotspote luminosity is given by L_acc = GM_wdM/R_out. From this, we estimate a mass transfer rate range of 2.7-7.9×10^{1} M yr^{1} due to different L_acc in different bands. This corresponds to a mass loss timescale _M   M_rd/M of 0.9–2.5×10 yr, far exceeding the thermal (Kelvin-Helmholtz) timescale of the secondary star (_kh 9×10 yr), as is generally the case for CV secondaries (Patterson 1984). The secondary star is somewhat smaller in radius than an isolated main sequence star of the same mass, which may imply an overestimated M. Therefore, mass transfer via the L1 point should be much slower, and the secondary can maintain thermal equilibrium.

The right panel of Figure 12 shows relative flux contributions (in percentage) from different model components calculated by XRBinary. Disk size is similar across bands, while the thickest disk appears in V-band. Note that L_d in the no-filter band is only 30% of that in GG420 and V bands due to the cooler disk and smaller hotspote. The zero points of relative flux contributions listed in Table 8 indicate that two stellar components showing pure ellipsoidal modulation dominate system light in the no-filter band (maximal percentage 95%). Despite this, a weak hotspote at phase 0.72(±0.03) distorts the pure ellipsoidal modulation into typical double-hump modulation. However, the averaged orbital modulation in V-band (with relative flux contributions from the two stellar components similar to GG420-band) shows almost pure ellipsoidal modulation rather than typical double-hump modulation. Investigation of the middle panels of Figure 12 indicates that the hotspote in GG420-band is larger than in V-band, while the hotspotss in V-band with similar size is located ahead of the one in GG420-band. Moreover, hotspote and hotspotss in V-band have roughly equal contributions to primary and secondary humps, explaining the nearly equal maxima described by pure ellipsoidal modulation. Thus, the geometric sizes, positions, and intensities of the two hotspots are key parameters distorting the light curve from pure ellipsoidal modulation. All three models demonstrate that ellipsoidal modulation from a K-type dwarf dominates KZ Gem' s orbital modulation, with variations in the two humps resulting mainly from the two hotspots.

3.4.3. Comparison with Gaia Data

According to Equation (1) of Dai et al. (2018), a V-band magnitude of KZ Gem can be estimated from three parameters: the Gaia distance D_g, system luminosity L_all = L_rd + L_wd + L_d, and model-dependent bolometric correction BC_v, for comparison with Gaia mission results (Gaia et al. 2016).

The Gaia parallax implies a distance D_g = 1293 ± 149 pc (Luri et al. 2018).

Since BC_v values from three tabulations (Flower 1996; Bessell et al. 1998; Casagrande & VandenBerg 2014) are almost identical for T_rd > 4000 K, we set BC_v = -0.22(±0.03), interpolated from the updated table of Casagrande & VandenBerg (2014). The three disk models show different L_d, but estimate a small magnitude range of 16.70–16.87 mag for KZ Gem from L_all = 1.11-1.29×10^{33} erg s ^{1}, dominated by L_rd = 1.0×10^{33} erg s ^{1} (>75% of system light).

Although the apparent visual magnitude of KZ Gem (S3) is not listed in SIMBAD, the estimated V-band magnitude is close to B = 16.8 mag in RKcat and SDSS g = 16.74 mag and r = 16.43 mag. Thus, the synthetic model is compatible with the Gaia distance.

Like two other DN (J0632+2536 and TW Vir; Dai et al. 2018), the T_eff of KZ Gem in the Gaia catalog is higher than the derived T_rd = 5120(±110) K listed in Table 7. This confirms the speculation by Dai et al. (2018) that higher T_eff derived by Gaia is common for DN due to contributions from hotter components (e.g., white dwarf and disk). Note that Gaia temperatures are determined from three broad bandpasses (Andrae et al. 2018), and the DR2 release notes urge caution in their use.

4. Conclusions

Cross-checking several CV databases revealed a 9 coordinate discrepancy for the DN KZ Gem. Spectra of four nearby targets confirm that the correct identification is a star matching coordinates listed by RKcat and VSX. Absorption-line radial velocities from 2014–2019 improve the orbital period to 0.2224628(2) d. Light curves show variable double-hump modulation with typical amplitude 0.3 mag and night-to-night variations. We also detected three brightening and two dipping transient events with nearly symmetric rises and declines around orbital minima and maxima. The phased light curves are consistent with the high-precision spectral ephemeris.

Analysis of the binned and normalized GG420-band light curve using XRBinary and NMfit indicates that KZ Gem comprises a primary white dwarf (0.86(±0.16) M) and a Roche-lobe-filling K-type dwarf (0.7(±0.2) M) with higher effective temperature (5120(±110) K) than typical CV secondaries at this orbital period (Knigge 2006; Knigge et al. 2011), orbiting with inclination 51.6°(±1.4°). The hotter secondary suggests KZ Gem may be a new PCV candidate. Fixing system parameters yields a consistent disk model: a large, cool, thick disk with flat temperature distribution and two hotspots near phase 0.75, valid for all three bands. We estimate M = 2.7-7.9×10^{1} M yr ^{1}. All derived models agree with Gaia DR2 results and indicate that pure ellipsoidal modulation from a K-type dwarf dominates the orbital modulation.

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Software: IRAF (Tody 1986, 1993), XRBinary (v2.4; Dai et al. 2018), NMfit (v2.0; Dai et al. 2018), Phoebe (v2.0; Prša et al. 2016)

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