The first sub-70 min non-interacting WD–BD system: EPIC212235321

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Accepted 2018 January 23. Received 2018 January 23; in original form 2017 December 4

ABSTRACT
We present the discovery of the shortest period, non-interacting, white dwarf–brown dwarf post-common-envelope binary known. The K2 light curve shows the system, EPIC 212235321 has a period of 68.2 min and is not eclipsing, but does show a large reflection effect due to the irradiation of the brown dwarf by the white dwarf primary. Spectra show hydrogen, magnesium, and calcium emission features from the brown dwarf’s irradiated hemisphere, and the mass indicates the spectral type is likely to be L3. Despite having a period substantially lower than the cataclysmic variable period minimum, this system is likely a pre-cataclysmic binary, recently emerged from the common-envelope. These systems are rare, but provide limits on the lowest mass object that can survive common-envelope evolution, and information about the evolution of white dwarf progenitors, and post-common-envelope evolution.

Key words: brown dwarfs – white dwarfs.

1 INTRODUCTION
To date, there are only a handful of known close, detached, post-common-envelope systems containing a white dwarf with a brown dwarf companion. This is not surprising, as brown dwarf companions to main-sequence stars within 3 au are rare compared to planetary or stellar companions to main-sequence stars (Metchev & Hillenbrand 2004; Grether & Lineweaver 2006). For instance, the planetary or stellar companions to main-sequence stars (Metchev & Hillenbrand 2004; Grether & Lineweaver 2006). For instance, the SuperWASP survey (Pollacco et al. 2006) has discovered over 120 confirmed extrasolar planets, but only one brown dwarf, WASP-30b (Anderson et al. 2011), within the same parameter space, although this may be due to selective follow-up. Brown dwarf companions to white dwarf stars are even rarer with only 0.5 per cent of white dwarfs having a brown dwarf companion (Steele et al. 2011). Despite many candidate systems being discovered from all-sky surveys (e.g. Debes et al. 2011; Girven et al. 2011), only eight post-common-envelope systems have been confirmed: GD1400 (WD+L6, P = 9.98 h; Farihi & Christopher 2004; Dobbie et al. 2005; Burleigh et al. 2011), WD0137−349 (WD+L6−L8, P = 116 min; Burleigh et al. 2006a; Maxted et al. 2006), WD0837+185 (WD+T8, P = 4.2 h; Casewell et al. 2012), NLTT5306 (WD+L4−L7, P = 101.88 h); Steele et al. 2013), SDSS J155720.77+091624.6 (WD+L3−L5, P = 2.27 h); Farihi, Parsons & Gänsicke 2017, SDSS J1011−0916 (WD+T5, P = 121.73 min; Beuermann et al. 2013; Littlefair et al. 2014). All of these systems have survived a phase of common-envelope evolution, resulting in the close binary system. These systems are all detached, and the brown dwarf is likely tidally locked. Eventually, they will become cataclysmic variables (CVs), such as SDSS1433+1011 in which the substellar donor was recently detected (Hernández Santisteban et al. 2016).

Along with CVs containing a brown dwarf, these few systems represent the lowest mass objects that can survive common-envelope evolution, as well as informing us about the mass-loss processes as the giant evolves (e.g. Casewell et al. 2012; Rappaport et al. 2017). In the case of SDSS J155720.77+091624.6, there is not only a brown dwarf that has survived the common-envelope evolution, but also a dust disc that may represent the remnants of a planetary system (Farihi et al. 2017). Additionally, these systems can provide information on how substellar objects respond to heating. Spectra of WD0137−349B show emission lines consistent with the cloud composition of an L dwarf, suggesting that these objects can be used as directly detected proxies for exoplanets.

Here, we present the discovery of the shortest period, non-interacting, white dwarf–brown dwarf post-common-envelope binary known to date.

2 KEPLER OBSERVATIONS
The Kepler 2 (K2) mission (Howell et al. 2014) has observed hundreds of spectroscopically and photometrically identified white dwarfs – white dwarfs.
dwarfs. EPIC212235321 was identified as a photometric candidate white dwarf from the SuperCosmos Sky Survey (Hambly et al. 2001a,c; Hambly, Irwin & MacGillivray 2001b) and was proposed as a target by PI Kilic in Campaign 3 field (RA 22:26:40, Dec. −11:05:48). See Table 1 for the photometric parameters. EPIC212235321 was observed by K2 for \( \approx 69 \) d between 2014 Nov 15 and 2015 Jan 23 in long cadence mode. Our analysis used the K2 Guest Observer Office (Van Cleve et al. 2016) light curve obtained through the Mikulski Archive for Space Telescopes (MAST). The light curve was normalized and flagged points (such as those affected by cosmic ray hits) were removed resulting in a light curve with 3151 data points. We searched for periodicity in the light curve using Lomb–Scargle (Lomb 1976; Scargle 1982) periodogram software packages VARTOOLS (Hartman & Bakos 2016) and PERIOD04 (Lenz & Breger 2005). These identified a most likely period, show no eclipses, which would have been detected with the cadence of the observations. If present, these should have been identified within the K2 data, however, there is a chance that the long cadence of the data means a short eclipse was missed. The identified within the K2 data, however, there is a chance that the long cadence of the data means a short eclipse was missed. The

Figure 1. Phase folded K2 long cadence data light curve for EPIC2122353521 binned over 50 equally spaced bins. The red line shows the sinusoidal fit to the light curve.

3 OPTICAL PHOTOMETRY

We observed EPIC212235321 using the Sutherland High-speed Optical Camera (SHOC; Coppejans et al. 2013) camera on the South African Astronomical Observatory (SAAO) 1.0 m telescope. The first observations were conducted in white light on the night of the 2016 July 11, with subsequent observations conducted again on the 2016 November 24–27 in the g- and i-band filters, respectively (Table 2). Observing conditions were affected by some scattered high cloud during the beginning of the night on the July 11 which may have affected the white light observations.

The data were reduced using the standard procedure with sky flats and bias frames taken during the observing run. We used the STARLINK package AUTOPHOTOM to perform the photometry of the target and comparison stars. The aperture was fixed for the data and was set to be two times the mean seeing (full width at half-maximum; Naylor 1998). This aperture size limited the impact of the background noise in the aperture. The sky background level was determined using the clipped mean of the pixel value in an annulus around the stars and the measurement errors were estimated from the sky variance. To remove atmospheric fluctuations, the light curve was divided by the light curve of one of the comparison stars.

The g- and i-band light curves in Fig. 2, folded on the 68.21 min period, show no eclipses, which would have been detected with the cadence of the observations. If present, these should have been identified within the K2 data, however, there is a chance that the long cadence of the data means a short eclipse was missed. The light curves have been fitted with a sine curve, and have slightly different \( T_0 \), indicative of a phase shift between the two bands, similar to that seen in WD0137−349 by Casewell et al. (2015). The difference is only 2.1 min, however, this is slightly less than twice the maximum error derived for the \( T_0 \). The semi-amplitudes were 0.028 ± 0.003 mag in the g band and 0.170 ± 0.008 in the i band. The K2 band (4200–9000 Å) semi-amplitude is 0.056 ± 0.00009, indicating that the reflection effect due to the irradiation of the brown

Table 1. Photometry for EPIC212235321.

| Property | Value | Info |
|----------|-------|------|
| Ra       | 22:03:40.61 | K2   |
| Dec.     | −12:15:10.8 | K2   |
| K2       | 17.6     |      |
| Fuv      | 16.573 ± 0.030 | Galex |
| Nuv      | 16.866 ± 0.022 | Galex |
| u        | 17.122 ± 0.007 | VST ATLAS |
| g        | 17.386 ± 0.004 | VST ATLAS |
| r        | 17.649 ± 0.004 | VST ATLAS |
| i        | 18.104 ± 0.010 | VST ATLAS |
| z        | 18.299 ± 0.021 | VST ATLAS |
| Y        | 17.542 ± 0.017 | VISTA VHS |
| J        | 17.512 ± 0.027 | VISTA VHS |
| K_s      | 17.594 ± 0.130 | VISTA VHS |

Table 2. Observations taken at the SAAO of EPIC212235321. The \( T_0 \) determined in each waveband is also given. The \( i \)-band data were combined to calculate one value for the waveband.

| Date       | Filter   | Exp time (s) | Total time (h) | \( T_0 \) (HJD)          |
|------------|----------|--------------|----------------|--------------------------|
| 20160711   | White light | 5            | 4.92           | 2457581.60276 ± 0.00013  |
| 20161124   | i        | 60           | 0.85           | –                        |
| 20161125   | i        | 30           | 1.36           | –                        |
| 20161126   | g        | 30           | 2.01           | 2457581.60225 ± 0.00085  |
| 20161127   | i        | 30           | 1.64           | 2457581.60371 ± 0.00032  |
The first sub-70 min detached WD-BD

Figure 2. g (blue) and i (red) band light curves for EPIC21223535321. The semi-amplitudes were $0.028 \pm 0.003$ mag in the g band and $0.170 \pm 0.008$ in the i band. The photometry has been binned into 25 equal bins. The light curves have been duplicated over two periods for display purposes.

dwarf is increasing as we move to longer wavelengths. There is a discrepancy of $\approx 52$ s between the i band and K2 $T_0$ derived from the i-band filter when compared to the K2 pass band, however this is within a $1 \sigma$ error in the period over the $\sim 12,000$ cycles between the two $T_0$ values.

4 ISIS SPECTROSCOPY

To confirm the nature of the primary star, we observed EPIC212235321 on the night of 20150909 with ISIS on the William Herschel Telescope (WHT) on La Palma. We used the 1 arcsec slit with the R600B grating in the blue arm and the GG495 filter with the R600R grating in the red arm. We took four exposures of 900 s, at an airmass of $\sim 1.5$ and seeing between 0.8 and 1.5 arcsec. We also observed arc lamps and flux standards to calibrate the data. The data were reduced using IRAF routines for long slit spectroscopy as in Dobbie et al. (2006).

The spectra confirm that the target is indeed a white dwarf. We determined the effective temperature ($T_{\text{eff}}$) and surface gravity ($\log g$) of the white dwarf, from the Balmer absorption lines (omitting H$\alpha$ and H$\beta$ as they are affected by emission features) by comparing to the predictions of white dwarf model atmospheres using the spectral fitting program \textsc{fitsb2} (v2.24; Napiwotzki et al. 2004).

We generated pure hydrogen DA models with mixing length $\text{ML}_2/\alpha = 0.8$ (Koester 2010) and Balmer/Lyman lines calculated with the modified Stark broadening profiles of Tremblay, Bergeron & Dupuis (2009). We then generated a model grid from 6000 to 80,000 K in 1000 K steps with $\log g$ ranging from 6.5 to 9.5 in 0.25 dex steps. We used \textsc{fitsb2} to fit our grid of model spectra to the six Balmer absorption lines ranging from H$\delta$ to H10 in each exposure. In addition, points in the observed data lying more than 3$\sigma$ from the model were clipped from subsequent iterations of the fitting process. The best-fitting values were $T_{\text{eff}} = 24,490 \pm 150$ K, and $\log g = 7.63 \pm 0.02$ (Table 3, Fig. 3).

5 SOAR SPECTRA

We obtained 20 higher signal-to-noise spectra using the Goodman spectrograph on the 4.1 m SOAR telescope (Clemens, Crain & Anderson 2004). These spectra, had 480 s exposures taken consecutively on 2016 August 15, cover H$\alpha$ using the R1200 grating, and a range from roughly 6000 to 7300 Å with a dispersion of roughly 0.3 Å pixel$^{-1}$. We used a 1 arcsec slit, and the seeing was 0.9 arcsec. The data were reduced in the same manner as the WHT spectra, with additional wavelength calibration performed using the skylines present in the spectra.

The SOAR spectra were normalized to 1 and phase-binned on the ephemeris using Tom Marsh’s \textsc{molly}\footnote{http://deneb.astro.warwick.ac.uk/phsaap/software/molly/html/INDEX.html} software. There is clearly an emission feature in the centre of the H$\alpha$ line that moves in antiphase with the H$\alpha$ absorption features from the white dwarf. To model these absorption and emission features, we used the technique in Parsons et al. (2017), using three Gaussian profiles to model the absorption from the white dwarf that change position.

| Property | Value | Units |
|----------|-------|-------|
| K2 P | $0.047369569 \pm 0.000000056$ | days |
| K2 $T_0$ | $2457011.65566 \pm 0.000013$ | HJD |
| $T_{\text{eff}}$ | $24,490 \pm 194$ | K |
| $\log g$ | $7.63 \pm 0.02$ | |
| $\gamma_{\text{g}}$ | $41 \pm 2$ | km s$^{-1}$ |
| $\gamma_{\text{i}}$ | $47.5 \pm 1.6$ | km s$^{-1}$ |
| $R_1$ | $0.017 \pm 0.005$ | R$_\odot$ |
| $\gamma_{\text{em}}$ | $308 \pm 5$ | km s$^{-1}$ |
| $\gamma_{\text{em}}$ | $35 \pm 5$ | km s$^{-1}$ |
| $R_{\text{em}}$ | $0.0973$ | R$_\odot$ |
| $a$ | $0.44$ | |

Figure 3. ISIS spectrum of EPIC212235321 with the best-fitting model $T_{\text{eff}} = 24,490 \pm 150$ K, $\log g = 7.63 \pm 0.02$ overplotted. H$\alpha$ and H$\beta$ have been omitted as they are the most affected by the emission features.
according to $\gamma_1 + K_1 \sin(2\pi f)\phi$, where $\phi$ is the orbital phase, and two Gaussian components to model the Hα emission from the companion star that change position according to $\gamma_\text{em} + K_\text{em} \sin(2\pi f)\phi$, and vary in strength according to $(1 - \cos \phi)/2$. We also allowed an offset to be fit to take into account the error on the period. The errors on the radial velocity parameters were determined as in Casewell et al. (2015), with 1 km s$^{-1}$ added in quadrature in order to achieve a reduced chi-squared with $\chi^2 \sim 1$. The final velocities were $K_1 = 42 \pm 4$ km s$^{-1}$ and $K_\text{em} = 305 \pm 7$ km s$^{-1}$ with $\gamma_1 = 30 \pm 2$ km s$^{-1}$ and $\gamma_\text{em} = -4 \pm 6$ km s$^{-1}$. There is a notable difference in the gamma velocities indicative of the low resolution of the spectrograph and suggesting there are systematic errors that have not been accounted for.

6 XSHOOTER SPECTRA

We also observed EPIC212235321 with the medium-resolution echelle spectrograph XSHOOTER (Vernet et al. 2011), mounted on VLT-UT2 at Paranal, Chile. XSHOOTER covers the spectral range from the atmospherically cut-off in the UV to the near-infrared K band in three separate arms, known as the UVB (0.30–0.36 µm), VIS (0.56–1.01 µm), and NIR (1.01–2.40 µm). We observed with XSHOOTER on the VLT on the night of 2017 August 31 and obtained 10 spectra in the UVB and VIS arms with exposure times of 330 s each. The data were taken in a stare mode, and so the NIR arm data is dominated by the sky background and is not used. The data were reduced using the standard pipeline release of the XSHOOTER Common Pipeline Library (CPL) recipes (version 2.6.8) within ESOfit, the ESO Recipe Execution Tool. The accuracy of the wavelength calibration of XSHOOTER data from the pipeline reduction is 0.03 nm in the UVB and 0.02 nm in the VIS arm, corresponding to a velocity precision of $\sim 10$ km s$^{-1}$ at Hα. The data were analysed in the same manner as the SOAR data, although the data were of better quality, and so four Gaussians were used, two for the emission and two for the absorption (Fig. 4). The fit parameters can be seen in Table 3. The XSHOOTER data have a resolution $R \sim 7500$, higher than the $R \sim 5000$ for the SOAR data, hence the errors are much smaller. These are the parameters that are therefore used within the rest of this paper. We tested the discrepancy between the $\gamma$ values in the XSHOOTER and SOAR data by fixing them to the XSHOOTER values and refitting the SOAR data. The fits then agree to within 1 per cent, indicating our assumption about the underestimated errors on the SOAR data was correct.

The XSHOOTER spectra show evidence of the Ca ii triplet at 8498.02, 8542.09, 8662.14 Å and Mg i at 8806.76 Å in emission within our spectra. We did not detect any Na i in emission, but we do detect interstellar Na i in absorption at 5889.95 and 5895.92 Å. We also do not detect Fe i, Fe ii, Ti i, or K i in emission, as are seen in WD0137–349B (Longstaff et al. 2017). There are also no Mg ii or Ca ii absorption features which could be attributed to accretion from a dust disc as are seen in SDSS1557 (Farihi et al. 2017). SDSS1557 has a similar effective temperature to EPIC212235321, however it only shows Balmer line emission features from the brown dwarf, and not emission from other atoms within the brown dwarf atmosphere.

7 DISCUSSION

The log $g$ and $T_{\text{eff}}$ of the white dwarf mean that it falls in a mass range between two types of white dwarf models; the He core and C/O core models. Using the C/O core models of Fontaine, Brassard & Bergeron (2001), the white dwarf mass is $0.47 \pm 0.01$ M$\odot$. The He core models of Panei et al. (2007) and Panei, Althaus & Benvenuto (2000) give masses of 0.46 and 0.48 M$\odot$ depending on the model grid used. These He core grids are quite coarsely spaced, and the uncertainties due to $T_{\text{eff}}$ and log $g$ are much smaller than the difference in mass determined between the grids. As both sets of models give consistent results, we take the mass of the white dwarf to be $0.47 \pm 0.01$ M$\odot$. The radius determined from the Fontaine et al. (2001) models is $0.017 \pm 0.005$ R$\odot$.

The difference in the $\gamma$ velocities is $13 \pm 6$ km s$^{-1}$. This value is consistent with the gravitational redshift of the white dwarf calculated using the mass and radius which is $16.4 \pm 0.5$ km s$^{-1}$, serving as an independent check.

The mass ratio of the binary taken from the $K$ velocities is $q = M_2/M_1 = 0.135$. Assuming a white dwarf mass of $0.47$ M$\odot$ gives a companion mass of 0.063 M$\odot$, or 66.4 M$\oplus$. However, $K_\text{em}$ only represents the emission from the heated hemisphere of the brown dwarf, not the true centre of mass velocity of the secondary but a lower limit, and hence an upper limit on the mass determination. This means that the secondary is definitely a brown dwarf, not the true centre of mass velocity of the secondary. Using this brown dwarf radius allows us to determine the Roche lobe for a range of secondary masses. We then compared these predictions on the size of the Roche lobe with the upper limit on the mass determination 66.4 M$\oplus$, and radii predicted by the BTCond models (Allard, Homeier & Freytag 2012). The size of the Roche lobe is $0.0988 \pm 0.007$ R$\odot$, and as there are no signs of accretion within this system, this is the maximum size possible for the secondary. Using this brown dwarf radius allows us to determine that the inclination of the system is likely to be greater than 48°, which when combined with the $K$-correction gives a mass range for the secondary of $47 < M_2 < 65$ M$\oplus$. If we assume the emission feature is due to uniform emission from the heated hemisphere of
the brown dwarf, then the inclination of the system is 56°, and the brown dwarf mass is 58 M_Jup. In the following discussions, this is taken to be the mass of the brown dwarf. Fig. 5 is a diagram of the system showing both binary constituents and their Roche lobes.

The BT-COND evolutionary models of brown dwarfs indicate that in order for the brown dwarf to not fill its Roche lobe at this orbital period, it must be older than 700 Myr with a radius of 0.0973 R_⊙. Such a brown dwarf has T_{eff} \sim 2000 K, which gives an estimated spectral type of L3, around L3 (Golimowski et al. 2004). If the brown dwarf is older, the effective temperature is likely to be cooler. The cooling age of the white dwarf was estimated using the white dwarf models, resulting in 18 ± 1 Myr from the C/O core models and 14 ± 8 Myr from the He core models. Clearly, while the white dwarf is relatively newly formed, the system itself is much older.

While we cannot use an initial–final mass relationship for white dwarfs (e.g. Caswell et al. 2009) to determine the mass of the white dwarf progenitor, it is possible to use main-sequence models to determine the maximum progenitor mass. We have ignored the cooling time and the time for the common-envelope phase as they are so short in comparison to the lifetime of the system (see Parsons et al. 2017, for a more detailed description of the common-envelope phase), and have assumed that the total system age is equal to the main-sequence lifetime. The Marigo et al. (2017) PARSEC-COLIBRI models predict that at 700 Myr, the minimum age permitted, the maximum progenitor mass is 2.60 M_⊙, at 4 Gyr, the maximum progenitor mass is 1.35 M_⊙, while if the system is older, say 10 Gyr, this drops to 1.04 M_⊙. The initial–final mass relation for white dwarfs (e.g. Caswell et al. 2009) predicts that a 1 M_⊙ star should produce a white dwarf with mass near to the average white dwarf mass of \sim 0.6 M_⊙, indicating that the evolution of the white dwarf progenitor has been truncated by the common-envelope phase.

The period of this system is very short, \sim 3 min shorter than that of the two newly discovered K2 systems presented in Parsons et al. (2017), and so for further discussion of how these systems will evolve into a CV, we refer to these two papers.

Although this system is not eclipsing, and so we have no direct measurement of the radius of the brown dwarf, we were able to independently investigate the possible spectral type of the secondary by using Spectral energy distribution (SED) fitting. EPIC212235321 is in both the VST ATLAS DR3 (Shanks et al. 2015) and VISTA VHS DR4 catalogues providing ugrizYJHK\_AB magnitudes, and the Galex AB magnitudes shown in Table 1 into flux in mJy using the relevant zero-points. We also adjusted the GALEX magnitudes using the non-linearity transformations presented in Camarota & Holberg (2014). These fluxes were then compared to a white dwarf model of the primary star, as well as combined white dwarf–brown dwarf/M dwarf templates of spectral type M8 (VB10; Burgasser et al. 2004), L0 (2MASP J03454321254023; Burgasser & McElwain 2006), and L3 (2MASSW J1146345; Bur- gasser et al. 2010). Fig. 6 shows that there is clearly an excess in the near-IR wavelengths. However, the excess is indicative of spectral type earlier than M8 in the Y and J bands, and allows as late as spectral type of L3 in the K_s bands. At the estimated age of the brown dwarf, the masses indicate the effective temperatures should be \sim 2000 K depending on the mass of the secondary and the age. This effective temperature is consistent with a spectral type of L3 (Golimowski et al. 2004).

We used the Jura (2003) disc model to determine if it is possible some of the excess seen is due to a circumbinary dust disc as for J155720.77+091624.6 (Farihi et al. 2017). We used the parameters given in Debes et al. (2011) for the outer and inner disc radius. These parameters, when combined with the white dwarf parameters, give an outer disc temperature of 600 K, and an inner temperature of \sim 1500 K, close to the sublimation temperature. Such a disc however only begins to make a noticeable contribution within the SED of the combined system in the K_s band – the flux is negligible in YJ. When we combine this with the fact that we see no pollution in the XSHOOTER spectrum indicative of the white dwarf being a DAZ, we can discount the presence of a dust disc in the system.
It is possible that the majority of the ‘excess’ seen is due to a large reflection effect. The VISTA data were taken at phases 0.46 in \( Y \), 0.55 in \( J \), and 0.65 in \( K_s \), meaning that the \( Y \) photometry was observed as the hot side of the brown dwarf comes into view, and the \( J \) band was observed just past the peak emission from the brown dwarf at phase 0.5. In order for the excess seen to be due to the reflection effect in the system, we would have to have variations with semi-amplitudes of \( \sim 0.25–0.3 \) mag in the \( Y \) and \( J \) bands. For comparison, the light curve of WD0137−349 AB varies by \( \sim 15 \) per cent in the \( K_s \) band. EPIC212235321 shows this level of variability in the \( i \) band, due to its much shorter period, and hotter white dwarf. Thus, we expect large variability at longer wavelengths (e.g. in the mid-IR) from this system. Indeed, JWST will provide an excellent suite of instruments with which to study these shorter period, highly irradiated brown dwarfs in more detail.

8 CONCLUSIONS

We have discovered EPIC212235321, the first sub-70 min non-interacting WD+BD binary known. The light curves of this system show a significant reflection effect, which is supported by a large near-IR excess when the VISTA magnitudes are compared to tem show a significant reflection effect, which is supported by a large near-IR excess when the VISTA magnitudes are compared to...
