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The only inflated brown dwarf in an eclipsing white dwarf–brown dwarf binary: WD1032+011B

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ABSTRACT

Due to their short orbital periods and relatively high-flux ratios, irradiated brown dwarfs in binaries with white dwarfs offer better opportunities to study irradiated atmospheres than hot Jupiters, which have lower planet-to-star flux ratios. WD1032+011 is an eclipsing, tidally locked white dwarf–brown dwarf binary with a 9950 K white dwarf orbited by a 69.7 M_{Jup} brown dwarf in a 0.09 d orbit. We present time-resolved *Hubble Space Telescope* Wide Field Camera 3 spectrophotometric data of WD1032+011. We isolate the phase-dependent spectra of WD1032+011B, finding a 210 K difference in brightness temperature between the dayside and nightside. The spectral type of the brown dwarf is identified as L1 peculiar, with atmospheric retrievals and comparison to field brown dwarfs showing evidence for a cloud-free atmosphere. The retrieved temperature of the dayside is 1748^{+66}_{-67} K, with a nightside temperature of 1555^{+76}_{-62} K, showing an irradiation-driven temperature contrast coupled with inefficient heat redistribution from the dayside to the nightside. The brown dwarf radius is inflated, likely due to the constant irradiation from the white dwarf, making it the only known inflated brown dwarf in an eclipsing white dwarf–brown dwarf binary.

Key words: binaries: eclipsing – brown dwarfs – white dwarfs.

1 INTRODUCTION

There is an observed scarcity of brown dwarfs orbiting main-sequence stars within 3 au, which is termed the ‘brown dwarf desert’ (Grether & Lineweaver 2006; Grieves et al. 2017). An analysis of the brown dwarf desert by Grether & Lineweaver (2006) found that in a sample of 514 stars with a companion object within 10 au, only two of these were brown dwarfs. As the main-sequence star in these systems evolves along the giant or asymptotic giant branch, it expands and fills out its Roche Lobe, leading to Roche Lobe overflow (Paczynski 1971). Brown dwarfs cannot accept the incoming material, and the red giant’s envelope engulfs the brown dwarf. A brief phase of binary evolution then occurs in a common envelope, where the brown dwarf does not have sufficient mass to force the envelope to co-rotate

(Ivanova et al. 2013). Friction causes the binary orbit to decay as the companion loses orbital angular momentum to the envelope which is then ejected (Izzard et al. 2012). The resultant system is a close, post-common envelope white dwarf–brown dwarf binary.

Since the brown dwarf must survive being engulfed by the white dwarf’s progenitor, these systems are rare, and only ~0.1–0.5 per cent of white dwarfs are predicted to have a brown dwarf companion (Farihi, Becklin & Zuckerman 2005; Steele et al. 2011; Rebassa-Mansergas et al. 2019). There are several all-sky surveys that have generated white dwarf catalogues (Girven et al. 2011; Gentile Fusillo et al. 2019); however, there are currently only 11 known close, detached white dwarf–brown dwarf binaries: GD1400 (WD+L6, $P = 9.98$ h; Farihi & Christopher 2004), WD0137–349 (WD+L6–L8, $P = 116$ min; Maxted et al. 2006), WD0837+185 (WD+T8, $P = 4.2$ h; Casewell et al. 2012), NLTT5306 (WD+L4–L7, $P = 101.88$ min; Steele et al. 2013), SDSS J141126.20+200911.1 (WD+T5, $P = 121.73$ min; Beuermann et al.

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2013), SDSS J155720.77+091624.6 (WD+L3–L5, $P = 2.27$ h; Farihi, Parsons & Gänsicke 2017), SDSS J1205–0242 (WD+L0, $P = 71.2$ min; Parsons et al. 2017), SDSS J1231+0041 (WD+M/L, $P = 72.5$ min; Parsons et al. 2017), EPIC212235321 (WD+L3, $P = 68.2$ min; Casewell et al. 2018), WD1032+011 (WD+L4–L6, $P = 2.20$ h; Casewell et al. 2020a), and ZTF J0038+2030 (WD+BD, $P = 10.4$ h; van Roestel et al. 2021). Additionally, recent analysis of eclipsing white dwarfs in the Zwicky Transient Facility Survey has identified several candidate eclipsing white dwarf–brown dwarf binaries (Keller et al. 2022; Kosakowski et al. 2022; Brown et al. 2023). The brown dwarfs in these systems are likely tidally locked, as hot Jupiters are, and the irradiation of the brown dwarf results in temperature differences between the ‘day’ and ‘night’ side of up to 500 K (Casewell et al. 2015). Eventually, the brown dwarf companion will lose sufficient orbital angular momentum such that mass transfer will begin, forming a cataclysmic variable with a sub-stellar donor (Meyer & Meyer-Hofmeister 1979; Warner 1995).

Despite their rarity, close white dwarf–brown dwarf binaries provide insights into sub-stellar object survival in common envelope evolution and an opportunity to study models of irradiated atmospheres (Casewell et al. 2015; Longstaff et al. 2017). Irradiated white dwarf–brown dwarf binaries bridge the gap between non-irradiated brown dwarfs and irradiated hot Jupiters. Some ultrahot brown dwarfs, such as EPIC2122B, have temperatures between that of the hottest hot Jupiter (KELT-9b, $T_{\text{eq}} = 4050$ K; Gaudi et al. 2017), and next hottest (TOI-2109b, $T_{\text{eq}} = 3646$ K; Wong et al. 2021; WASP-33b, $T_{\text{eq}} = 2800$ K; Collier Cameron et al. 2010), offering more objects to study in sparsely populated areas of the parameter space encompassing hot Jupiters. Hot Jupiters are a class of exoplanets which have masses $M \geq 0.25 M_{\text{Jup}}$, and orbit their host stars with periods of 10 d or less (Dawson & Johnson 2018). They comprise some of the most well-studied planetary-mass objects, with over 300 discovered to date (Akeson et al. 2013). They are tidally locked to their host stars, and receive significant irradiation on one hemisphere as a result (Guillot et al. 1996). It is difficult to characterize the atmospheres of hot Jupiters well due to the poor flux ratio between the planetary signal and the host star. However, the atmospheres of brown dwarfs have been well studied, and where the host star is a white dwarf, the contaminant flux in the infrared is minimal, leading to higher planet-to-star flux ratios. Irradiated brown dwarfs thus provide excellent proxies with which to study irradiated atmospheres and hot Jupiters.

Recent spectroscopic studies of hot Jupiters have revealed temperature differences between the dayside and nightside atmospheres on the order of a few hundred Kelvin (e.g. Arcangeli et al. 2019; Showman, Tan & Parmentier 2020) that can be as large as ~ 1000 K (Cho et al. 2003). These large temperature differences influence a range of atmospheric dynamics including atmospheric structure (Showman et al. 2020), jets (Amundsen et al. 2016), and turbulence (Youdin & Mitchell 2010). Heat transport between the dayside and nightside in hot Jupiters is mainly enabled by the presence of equatorial jets, and several recent works have investigated how parameters such as atmospheric composition and rotation rate influence this heat transport (e.g. Komacek et al. 2022; Tan et al. 2024).

3D circulation models that have been applied to irradiated brown dwarfs atmospheres show that the dayside hotspot does not undergo eastward-shifting, unlike those seen in hot Jupiters (Wong et al. 2016; Lee et al. 2020). The equatorial jets that are vital for heat redistribution are shrunk due to the fast rotation rates seen in brown dwarfs, thus suppressing the heat transfer from the dayside to the nightside (Tan & Showman 2020). Radiative transfer and chemical equilibrium modelling of the most highly irradiated brown dwarfs

has found that molecules at the upper atmosphere and photosphere of irradiated brown dwarfs are effectively dissociated, resulting in weak molecular absorption in the dayside atmosphere. Additionally, the atomic emission lines seen in ultrahot irradiated brown dwarf atmospheres could be due to a thermal inversion that is caused by the strong ultraviolet heating from the white dwarf (Lothringer & Casewell 2020). These temperature inversions and ionized hydrogen atoms arise because the upper atmosphere of the brown dwarf can absorb the short wavelength irradiation from the white dwarf more easily than deeper layers of the atmosphere (Zhou et al. 2022a).

Many hot Jupiters have been found to be inflated, that is to say that their radius is larger than what is predicted by planetary structure models considering their mass and equilibrium temperature (e.g. Stevens et al. 2017; Fortney, Dawson & Komacek 2021; Khandewal et al. 2022; Montalto et al. 2022). If a planet’s equilibrium temperature, T_{eq} , is greater than 1200 K, the difference between its model-predicted radius and the observed one increases as $R \propto T_{\text{eq}}^{1.4}$ (MolèLous & Miguel 2020). Thus, the greater the irradiation, the more inflated the radius of the planet. Irradiated brown dwarfs can also exhibit inflated radii similar to those seen in hot Jupiters; however, they do not follow the same linear trend with irradiation flux (e.g. Parsons et al. 2017; Casewell et al. 2020b).

Many of the well-studied white dwarf–brown dwarf binary systems are non-eclipsing, and physical parameters of the brown dwarf can therefore only be estimated from evolutionary models. If the orbital plane of white dwarf–brown dwarf binary is along our line of sight, then the brown dwarf will eclipse the white dwarf, and vice versa, during an orbit. White dwarfs have typical radii $10\times$ smaller than brown dwarfs, so the brown dwarf will completely occult the white dwarf as it passes in front of it. Since the brown dwarf is tidally locked, its nightside will be observed as it eclipses the white dwarf. Therefore, in eclipsing white dwarf–brown dwarf binaries, any spectra taken whilst the brown dwarf eclipses the white dwarf will be lone spectra of the brown dwarf, uncontaminated by any white dwarf flux. The dayside and nightside spectra of the brown dwarf can then be robustly extracted to investigate the atmospheric dynamics of the brown dwarf (e.g. Lew et al. 2022). Eclipsing close white dwarf–brown dwarf binaries thus make important benchmark systems which yield insights into irradiated brown dwarfs and exoplanet atmospheres.

To better understand the effect of irradiation on brown dwarfs and how this influences their atmospheric composition, we present *Hubble Space Telescope (HST)* Wide Field Camera 3 observations of WD1032+011, an eclipsing white dwarf–brown dwarf binary system. Our new observations allow the white dwarf and brown dwarf components to be separated from the combined spectroscopic observations. In Section 2, we discuss the target; in Section 3, we describe our observations, and our data reduction in described in Section 4. In Section 5.1, we generate and analyse the broad-band light curve; in Section 5.2, we present the phase-dependent spectra of the brown dwarf and compare these to models, and Section 5.3 investigates the brightness temperature of our spectra. In Section 6, we compare to field brown dwarfs; in Section 7.1, we compare to non-irradiated brown dwarf models; in Section 7.2 we run forward models, and in Section 7.3, we run atmospheric retrievals considering irradiated brown dwarf models. We discuss our results in Section 8.

2 WD1032+011

WD1032+011 was first identified as a DA white dwarf by Vennes et al. (2002), meaning its spectrum is dominated by hydrogen lines. Eisenstein et al. (2006) measured an effective temperature of $T_{\text{eff}} =$

Table 1. System parameters for the WD1032+011 binary system. Values are reproduced from table 4 in Casewell et al. (2020a). Equilibrium temperature is calculated here assuming a Bond albedo of zero. The numbers denoted in brackets represent the uncertainties for the period and ephemeris, which apply to the last two decimal places.

Parameter	Value
White dwarf T_{eff} (K)	9950 ± 150
White dwarf $\log g$	7.65 ± 0.13
White dwarf cooling age (Gyr)	0.455 ± 0.080
Period (d)	0.09155899610(45)
Ephemeris (BMJD)	58381.2439008(10)
White dwarf radius (R_{\odot})	0.0147 ± 0.0013
White dwarf mass (M_{\odot})	0.4052 ± 0.0500
Brown dwarf radius (R_{\odot})	0.1052 ± 0.0101
Brown dwarf radius (R_{Jup})	1.024 ± 0.098
Brown dwarf mass (M_{Jup})	69.7 ± 6.4
Brown dwarf T_{eq} (K)	1030 ± 50
Orbital separation (au)	0.00319 ± 0.00011
Inclination ($^{\circ}$)	87.5 ± 1.4

9904 ± 109 K and a surface gravity of $\log g = 8.13 \pm 0.15$ using the Sloan Digital Sky Survey (SDSS). Steele et al. (2011) found an infrared excess in the United Kingdom Infrared Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS) photometry. They suggested that this was due to an unresolved companion with a spectral type of $L5 \pm 1$ and a mass of $M = 55 \pm 4 M_{\text{Jup}}$ orbiting within 150 au.

Casewell et al. (2020a) used K2 photometry of WD1032+011 spanning across ≈ 81 d using long-cadence mode, and found a most likely period of ≈ 2.2 h using a Lomb–Scargle periodogram. Spectroscopy was taken using the Gemini Multiobject Spectrograph covering a wavelength range of 4600–6900 Å. After producing trailed spectra centred on the $H\beta$ line, they found a clear oscillation across a full orbit, corroborating the companion detection (fig. 2 in Casewell et al. 2020a). They calculated a radial velocity of $\gamma = 122.1 \pm 1.9$ km s^{-1} , and following the same kinematic analysis in Bensby, Feltzing & Oey (2014) determine that WD1032+011 is a likely member of the thick disc. They thus estimate the age as > 5 Gyr.

They also observed WD1032+011 with the Gemini Near-Infrared Spectrograph (GNIRS) across the entire spectrum of 0.8–2.5 μm with the 1 arcsec slit. They compared their GNIRS spectrum to composite DA white dwarf + brown dwarf models from the SpeX prism library (Burgasser 2014) and determined that a companion spectral type of L5 is most likely, in concurrence with Steele et al. (2011). Additionally, they compared the UKIDSS magnitudes of WD1032+011 to the absolute magnitudes of L3–L6 field brown dwarfs from Dupuy & Liu (2012), which also indicate a companion consistent with spectral types L4–L6.

A spectral energy distribution fit was performed using data from SDSS, Galaxy Evolution Explorer, and UKIDSS to estimate a white dwarf mass and determine the effective temperature. Three individual eclipses of WD1032+011 were observed using ultrafast, triple-beam CCD Camera (ULTRACAM), which simultaneously observes in three different filters. The system is eclipsing and the inclination was constrained to $87.5 \pm 1.4^{\circ}$, but no evidence of a secondary eclipse was found. Casewell et al. (2020a) normalized the ULTRACAM light curves and used an affine-invariant Markov chain Monte Carlo (MCMC) sampler to determine masses and radii for both the white dwarf and the brown dwarf. Table 1 lists the key parameters for WD1032+011, which is the only eclipsing white

dwarf–brown dwarf binary in which the brown dwarf is thought to be inflated.

3 OBSERVATIONS

We observed WD1032+011 with the *HST* Wide Field Camera, using the WFC3/IR/G141 grism. We observed across six consecutive orbits of *HST* on 2022 May 15, as a part of programme GO-16754 (PI: S. L. Casewell). In order to perform wavelength calibration, a direct image was taken at the beginning of each orbit using the F127M filter, with the GRISM256 aperture and a subarray setup of 256×256 . After these direct images, eight spectroscopic exposures were taken for each orbit. These spectra were taken in *staring mode* each with an exposure time of 313 s using the G141 grism, the GRISM256 aperture, and the same subarray setup as the direct images. This observing sequence has already been successfully conducted on over a dozen isolated brown dwarfs (e.g. Apai et al. 2013; Lew et al. 2016) and close white dwarf–brown dwarf binaries, offering spectra with a good signal-to-noise (Lew et al. 2022; Zhou et al. 2022a; Amaro et al. 2023). Our observations offer full phase coverage of WD1032+011 across the six *HST* orbits, allowing us to study any phase-dependent changes in its spectra.

4 DATA REDUCTION

We downloaded our `flt` file data from the Mikulski Archive for Space Telescopes (Marston et al. 2018) after they had been preprocessed by the `Ca1WFC3` pipeline (Ryan R. E. et al. 2016). The `Ca1WFC3` pipeline corrects for bias and dark current as well as flagging bad pixels and flat-fielding the image.¹

To extract the spectral data from the `flt` files, we utilized the established pipeline used by Amaro et al. (2023), which is the latest iteration of a pipeline developed and adapted by Buenzli et al. (2012) and Apai et al. (2013). This pipeline is an amalgamation of the AXE software designed for reducing *HST* WFC3 data (Kümmel et al. 2009) and a custom programme written in PYTHON. This pipeline has been shown to be successful in reducing white dwarf–brown dwarf binaries and extracting time-resolved observations from them (e.g. Lew et al. 2022; Zhou et al. 2022a; Amaro et al. 2023). Initially, the data is sorted into the individual *HST* orbits so that the direct image for each orbit, which is observed using the F127M filter, is with the relevant spectra which are observed with the G141 grism. Grouping the data in this way before reduction ensures that the correct direct images are used for wavelength calibration, and that the resulting calibration is precise.

Our data was taken using a 256×256 subarray, however AXE is unable to process subarrays properly. To use the AXE pipeline, we first had to pad our data into full-framed arrays which are 1014×1014 . To do this we padded the edges of the G141 files and the F127M direct images such that the data in our original subarray remains in the centre of the padded array. This allows AXE to use its standard full-frame calibration images during data reduction, and does not alter our actual data.

Any bad pixels in the data are flagged in the data quality extension after pre-processing through the `Ca1WFC3` pipeline. To correct for these bad pixels, we linearly interpolated neighbouring good pixels to fill in the gaps, using 4 pixels from either side of any bad pixels. We performed this interpolation in both the x -direction and the y -direction, using 16 pixels per interpolation. In addition, we had an

¹<https://hst-docs.stsci.edu/wfc3dhh>

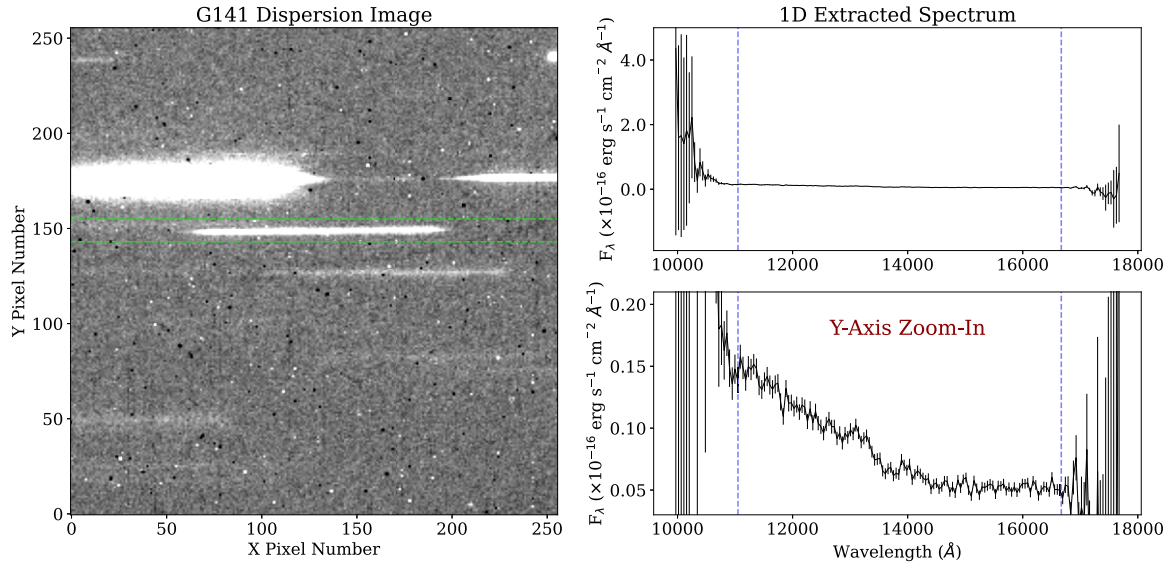


Figure 1. Full reduction performed on one frame of data. The left image is the G141 grism observation, with the grism spectrum of WD1032+011 highlighted between the green lines. This data is before correcting for cosmic rays and bad pixels. The plots on the right show the data after being passed through `axeprep` and extracted using `axecore`. This is the 1D spectrum of a single frame of data. The top right shows the full spectrum, with the blue lines denoting the wavelength range used for the science, spanning 1.1–1.66 μm . The bottom right graph shows a zoomed in view of this spectrum to highlight the actual shape of our data.

extra hot pixel just above the source which was interpolated in a similar way. However, for that hot pixel, we only interpolated in the horizontal direction to avoid accidentally using pixels from the target object in the interpolation. We ignore pixels flagged with cosmic ray hits and use our own cosmic ray detection algorithm which considers the change in count rate between two successive readouts at each pixel to identify cosmic rays. We use a 5σ threshold to identify cosmic ray hits which are then interpolated over. After cleaning them, we then performed precise source extraction on our direct images using `SourceExtractor` (Bertin & Arnouts 1996).

To prepare the data for extraction using AXE, we executed `axeprep` on our spectroscopic images. The master sky image `WFC3_IR.G141.sky.v1.0.fits` from Kümmel et al. (2011) is used to perform optimal background subtraction within the `axeprep` routine. We found that this background subtraction was not successful in processing our spectra, and produced unphysical results. This is likely due to large contaminant sources in the spectroscopic images of WD1032+011. Thus, we used a manual background subtraction method instead. We created a custom source mask that masked our target source as well as other contaminant sources in the spectroscopic images. After masking all the sources visible in our spectroscopic images, we calculated the median of the resulting background and subtracted that from the entire image. This yielded data with successful background subtraction, which was not affected by contaminant sources.

Depending on the detector illumination history and the target fluence rates, data at the beginning of *HST* orbits can suffer from a ramp-like effect due to charge trapping and a delayed release. To correct for this possibility in our data, we use the RECTE model from Zhou et al. (2017) which is a physically motivated charge trap model, however we did not see a visible ramp effect. Fig. 1 depicts an extracted 1D spectrum from one frame of data in orbit 6. The left hand side shows the G141 spectroscopic image, with the target source highlighted in green, and the right hand side shows the 1D spectrum extracted from that image. This data reduction method was then

repeated for each of the 48 individual spectroscopic observations taken by *HST*. We made wavelength cuts where the flux density errors were over twice the average error between 13 000–15 000 \AA . Choosing these limits ensures a good signal-to-noise across the spectra, with our clipped data spanning 11 000–166 00 \AA for each spectrum.

5 RESULTS

5.1 Light curves

5.1.1 Creating light curves

To derive a light curve for WD1032+011 from our 48 spectra, we integrated the flux density of each spectrum between our wavelength limits. For each spectrum, the integral yields a singular flux point for the light curve, and we take the mid-exposure time of that observation as the corresponding time value. We then do this integration for each of the 48 spectra we have, yielding a light curve with 48 data points across the six consecutive *HST* orbits. Our light curve is shown in Fig. 2. It captures the eclipse as the brown dwarf fully occults the white dwarf, and we see the non-irradiated nightside of the brown dwarf.

To determine how the light curve of WD1032+011 changes throughout its orbit, we phasefold the light curve on its 0.09155899610 day period. Fig. 3 shows two complete orbits of WD1032+011, where the data points within the eclipses have been removed in the lower panel. The ephemeris of WD1032+011 has been included in the phasefolding such that the primary eclipse is at $\phi = 0$ in phase. The dashed grey lines in both panels show the predicted depth of the secondary eclipse based on the radii of the white dwarf and brown dwarf. We do not see a secondary eclipse at $\phi = 0.5$, where the white dwarf transits in front of the brown dwarf. As the predicted secondary eclipse depth is shallow, the inclination of 87.5° may be sufficient to suppress the eclipse such that it is not

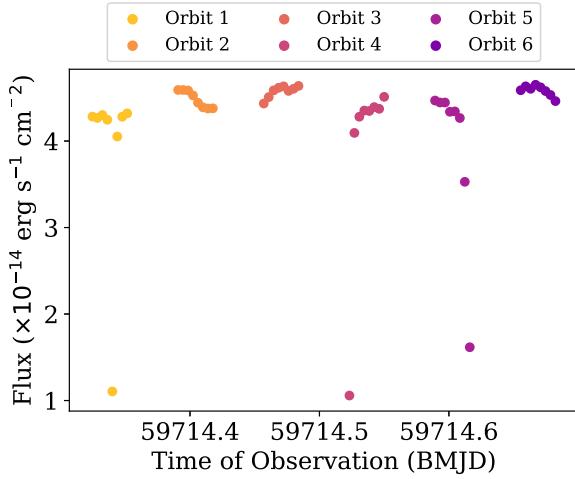


Figure 2. Broad-band light curve of WD1032+011 generated by integrating each individual spectroscopic observation between wavelength limits of 11 000–16 000 Å. The different colours correspond to each individual orbit of *HST* that our data spans, with orbits 1 to 6 shown left to right. The error bars are the same size as the points.

detectable outside of the scatter in the light curve. As the scatter is large at $\phi = 0.5$, it is not possible to definitively determine the presence of the secondary eclipse. However, since the scatter is larger at this phase than across the rest of the light curve, it is likely that the secondary eclipse is present but the inclination is reducing its depth such that it appears as an increase to the scatter rather than a distinct eclipse present below the noise.

There are two data points in our light curve that are in the eclipse, which has a duration of 16.6 min from the beginning of its ingress to the end of its egress. This is where the brown dwarf fully occults the white dwarf, and the non-irradiated nightside of the brown dwarf is visible. We can therefore expect the spectra of these two observations to be spectra of the nightside of the brown dwarf only, without any contamination flux from the white dwarf. We can then use these solo brown dwarf spectra to remove the white dwarf contribution from the rest of our spectra, which are combinations of the white dwarf and brown dwarf signals (see Section 5.2.1). For the out-of-eclipse light-curve data, the baseline is not flat and instead shows a sinusoidal shape, which is likely due to the reflection effect. The reflection effect occurs when the dayside atmosphere of the brown dwarf is irradiated by the white dwarf and heats up as a result, absorbing and re-radiating some of the incident flux. This leads to sinusoidal brightness variations when viewing the star at different orbital phases (Skopal 2001).

5.1.2 Light-curve fitting

To verify that the variation we see in the baseline of the light curve originates from WD1032+011AB and is not a data systematic, we fit a sinusoidal function to the light curve using an MCMC sampler (Goodman & Weare 2010). Since we are considering the baseline of the light curve and not the eclipse, we remove any point in the eclipse or its ingress and egress.

For our phasefolded light curve, we fit the following sinusoidal relationship using MCMC:

$$y(t) = F_0 + A \sin\left(\frac{2\pi(t - t_0)}{P} + \Phi_0\right), \quad (1)$$

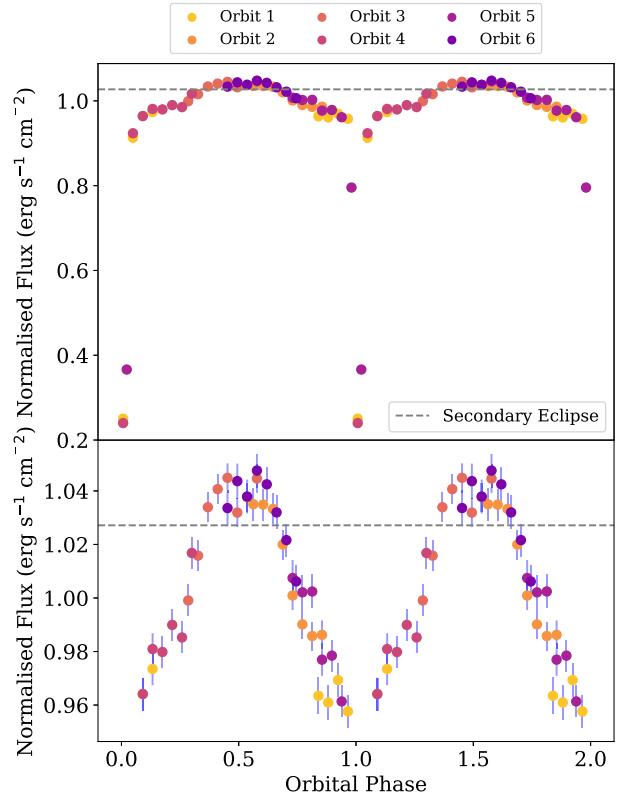


Figure 3. Broad-band light curve of WD1032+011 phasefolded on the 0.09155899610 day period to show the variation across the full phase of the orbit. Orbital phase is defined such that a phase of 0 occurs when the brown dwarf eclipses the white dwarf. The data has been repeated to show two orbits of WD1032+011. The upper panel includes the data points inside the eclipse, ingress and egress. The lower panel has these points removed. The colours correspond to each individual orbit of *HST* that our data spans. The dashed grey line is the depth at which the secondary eclipse should appear at a phase of 0.5, but this eclipse depth is not observed. The error bars in the upper panel are the same size as the points.

where $t_0 = 58381.2439008(10)$ d is the ephemeris and $P = 0.09155899610(45)$ d is the period, which are both from Casewell et al. (2020a). Here t is the time of observation, and F_0 , A , and Φ_0 are free parameters to be fit by the MCMC sampler, which correspond to flux offset, amplitude, and phase offset, respectively. This method of light-curve fitting has previously been utilized for fitting the light curves of white dwarf–brown dwarf binaries (Zhou et al. 2022a; Amaro et al. 2023).

For our MCMC models, we imposed uniform priors such that $A > 0$, $-\pi < \Phi_0 \leq \pi$, to cover one full phase with the phase offset. For F_0 , we used a Gaussian prior with a mean of 1. As the MCMC runs, each walker steps to a new position and calculates the model in equation (1) using the input parameters at that position. The MCMC sampler then computes the log *likelihood* at that grid position, which is calculated as:

$$\ln(\mathcal{L}) = -\frac{1}{2} \left(\frac{(y_{\text{data}} - y_{\text{model}})^2}{\sigma_{\text{data}}^2} - \ln\left(\sqrt{2\pi\sigma_{\text{data}}^2}\right) \right). \quad (2)$$

We use the PYTHONEMCEE package to perform our MCMC fitting (Foreman-Mackey et al. 2013), with a chain of $N_{\text{steps}} = 10000$, $N_{\text{walkers}} = 50$, and a burn-in of 1000. In Fig. 4, we present our light curve alongside our best-fitting model from our MCMC analysis,

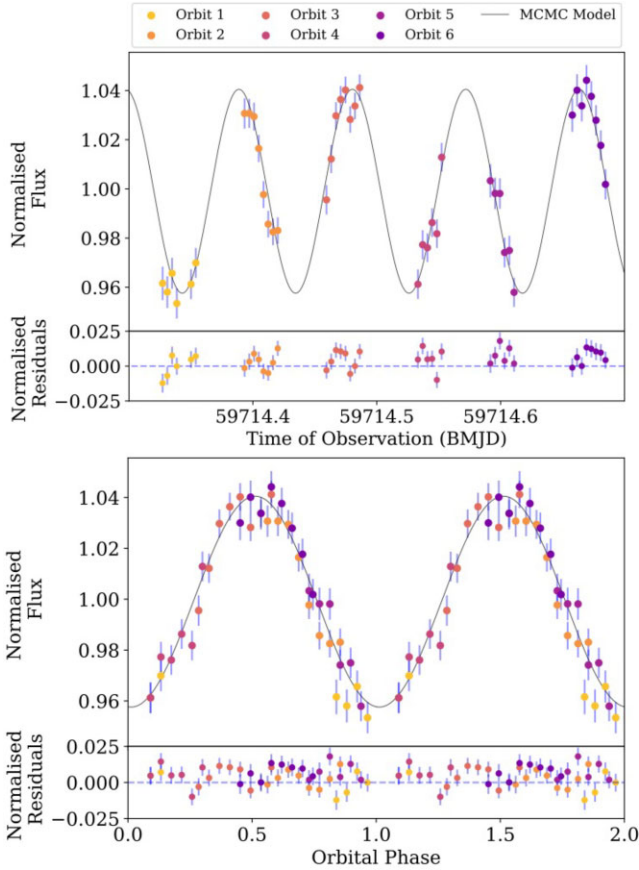


Figure 4. Broad-band light curve of WD1032+011 alongside our best-fitting MCMC parameters for the model in equation (1). Data points in the eclipse, ingress, or egress have been removed. The upper panel shows the full light curve with our MCMC model. The lower panel shows the phasefolded light curve with the same MCMC model, with the data repeated to show two orbits of the binary. The data has been normalized such that the median is at 1. Our data spans ~ 4.5 full orbits of WD1032+011.

for both our sequential and phasefolded data. The data points in the eclipse, ingress, and egress have been removed to properly study the variation in the baseline of the light curve.

We find that the first order model in equation (1) fits our data well. The corner plot is shown in Fig. A1. Although we are only able to achieve residuals of ~ 5 percent, we find that adding higher order terms, or adding a cosine term worsens the quality of the fit. This sinusoidal variation in the light curve is likely due to the reflection effect, and not other variability. Our best-fitting model parameters are $F_0 = (4.442 \pm 0.004) \times 10^{-14}$, $A = (1.84 \pm 0.06) \times 10^{-15}$, and $\Phi_0 = -1.58 \pm 0.03$. Notably, our value for the phase offset, Φ_0 is well within 1σ of $\pi/2$. This is expected because we define the eclipse as being at phase $\phi = 0$, and the maximum flux observed is at $\phi = 0.5$, which is where the dayside of the brown dwarf is visible and the white dwarf only blocks a small portion of the brown dwarf flux. As we are fitting a sine function, the maximum would be at an argument of $\pi/2$ but since we define $\phi = 0.5$ as our maximum flux, this would correspond to an argument of π in the sine function. Hence, there is a $\pi/2$ offset in the phase, supporting that this variation is due to the reflection effect. This phase offset is consistent with other light curves of irradiated brown dwarfs obtained via *HST* observations (e.g. Lew et al. 2022; Zhou et al. 2022a).

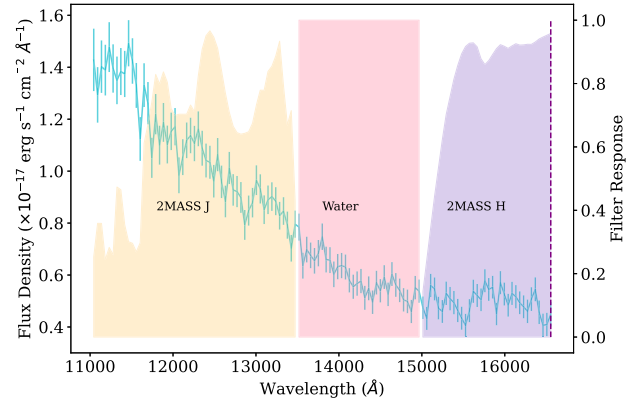


Figure 5. Spectrum of WD1032+011 after data reduction. The filter transmission profiles for 2MASS *J*, water, and 2MASS *K* filters used to create the sub-band light curves are shown in yellow, pink, and purple, respectively from left to right. The filter profiles were resampled to match the resolution of our data before multiplying them with our spectrum.

5.1.3 Sub-band light curves

The varying dust and gas opacities within brown dwarf and exoplanet atmospheres cause different wavelengths to probe different pressure regions within the atmosphere (Buenzli et al. 2012; Lew et al. 2022). Analysing light curves in individual *J*-, water and *H*-wavebands has previously identified wavelength-dependent intensity changes in brown dwarfs, indicating the presence of atmospheric structure and dynamics which are pressure-dependent (e.g. Apai et al. 2013; Amaro et al. 2023). To identify any wavelength-dependent changes in intensity in our light curve, we generate sub-band light curves from our observations. By comparing any changes in flux across different wavelength regions, we can quantify any differences that would indicate pressure-dependent behaviour in the atmosphere. We derive three separate sub-band light curves for different sections of our wavelength range, spanning a *J* filter, a water filter, and a modified *H* filter. These filter choices have previously recovered wavelength-dependent intensity variations in the atmospheres of brown dwarfs. Fig. 5 depicts our overall combined spectrum for WD1032+011 with the filters we use to generate these sub-band light curves overlaid.

To create a light curve in the *J* band, we used the filter transmission from the Two-Micron All Sky Survey (2MASS) *J* filter (Skrutskie et al. 2006), and multiplied this with our spectra between 11 000 and 13 500 Å. We then integrated the resulting spectrum between these wavelengths to obtain a single flux point. Similarly for the *H* band, we multiplied our spectrum with the filter transmission for the 2MASS *H* filter beginning at 14 500 Å, and then integrated. Since the 2MASS *H* filter extends beyond our quality data at 16 600 Å, we modified this *H* filter to end at the same point as our data. Water absorption is an important feature in the atmospheres of brown dwarfs, so we created a top hat-shaped water filter spanning 13 500–14 500 Å. We then integrated between these wavelengths to create a water-band light curve. After applying this methodology to each of our 48 individual spectra, we normalized the median of each light curve to 1 to obtain the sub-band light curves depicted in Fig. 6.

Unlike those seen in NLTT5306B (Amaro et al. 2023), we do not find any significant differences between the sub-band light curves in different bands, indicating that there is no evidence of a pressure-dependent dayside–nightside temperature contrast or dynamics in

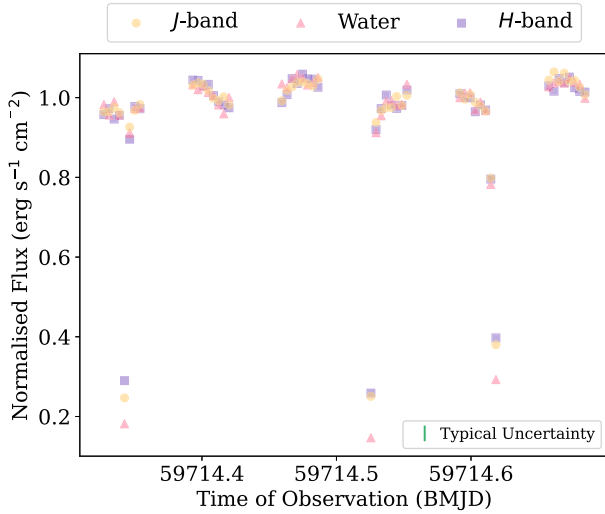


Figure 6. Normalized sub-band light curves of WD1032+011 generated using the 2MASS *J*, water and 2MASS *H* bands by integrating spectra between 11 000–13 500, 13 500–14 500, and 14 500–16 600 Å, respectively. The yellow circles, pink triangles, and purple squares correspond to the 2MASS *J*, water, and 2MASS *H* bands, respectively. The typical uncertainty size is shown in the lower right corner.

the atmosphere of WD1032+011B. The only difference present is that the eclipses in our light curve are deeper in the water band. This is not unexpected as the thermal structures on the nightside of the brown dwarf are such that temperature decreases with decreasing pressure. The water band then probes the cooler upper layers in the nightside of the brown dwarf. The apparent strength of the water absorption features in the system are also greater in the eclipse when the brown dwarf occults the white dwarf.

To fit the baseline of our *J*-, water, and *H*-band light curves, we followed the same procedure described in Section 5.1.2 for each individual light curve. We find that all of the *J*-, water, and *H*-band light curves are well-fit with the first order MCMC model we use. The MCMC fitting for our phasefolded sub-band light curves is shown in Fig. 7. We note that the flux uncertainties are larger for our sub-band light curves compared to our broad-band light curve, which is due to the smaller samples of data used to calculate each light-curve point. We do not see any significant differences in the peak-to-peak amplitude or phase offset between the MCMC fitting for each wavelength band. With the eclipse points removed, the peak-to-peak amplitude of each sub-band light curve are within 0.4σ of each other, where σ is the average flux uncertainty for each band. Additionally, there is only a minimal phase offset present between the best-fitting models for the *J*-, water, and *H*-band light curves, and these offsets are within the resolution of the intervals in orbital phase, which is ~ 0.04 . There are no significant amplitude variations or phase offsets between the wavebands. The consistent phase offsets between the bands indicates the absence of jets which enable efficient heat redistribution from the dayside to the nightside. As such, the poor heat redistribution would lead to an observed temperature contrast between the two hemispheres. This also indicates that the observed reflection effect is not dependent on the pressure in the atmosphere. It is therefore likely that the irradiation the brown dwarf receives from the white dwarf is equally penetrating the entire atmosphere, as opposed to only affecting certain depths.

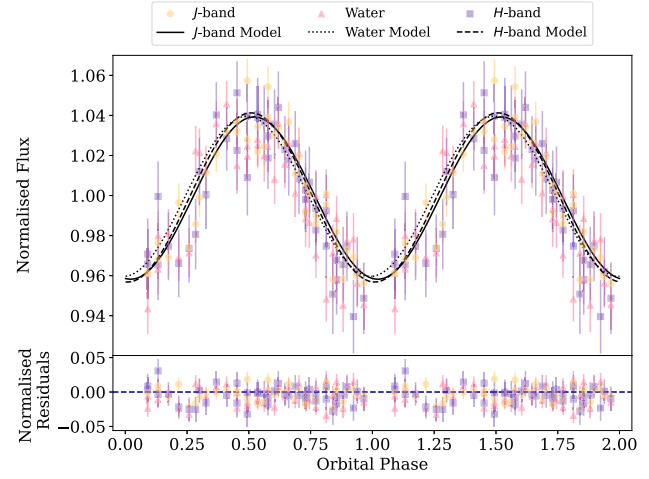


Figure 7. Phasefolded light curves in the *J*, water, and *H* bands alongside the best-fitting models from our MCMC analysis, following Amaro et al. (2023). The data has been normalized such that the median is at 1. The *J* band is depicted with yellow circles and a solid line, the water band has pink triangles with a dotted line, and the *H* band is shown with purple squares and a dashed line. The data has been repeated to show two orbits of WD1032+011.

There is an apparent scatter in the eclipse depths at different observation times seen in Fig. 6. Considering the two light-curve points in the centre of the eclipse, where the nightside of the brown dwarf is observed, rather than its ingress or egress, this variation in the eclipse depth is only marginally higher than the average scatter of the light curves. The maximum orbit-to-orbit eclipse depth variation is seen in the water band, with a difference of 1.19σ , where σ is the average scatter between the data and the best-fitting MCMC model of the reflection effect. As this remaining variation is so small, it is unlikely that there is any inherent variability present within WD1032+011B.

5.2 Spectra

We combined our 48 individual spectra first for each orbit, and then we combined all orbits together. Fig. 8 shows our average spectrum across all six orbits in the upper panel. During this process, we identified two frames that were significantly different to the rest, which are shown in the lower panel of Fig. 8. These different spectra are the two data points within the eclipse in our broad-band light curves, when we are only observing the nightside of the brown dwarf, hence their lower flux density and different spectral features. These two spectra were excluded from the combining, and instead we created a combined in-eclipse spectrum using them, so that we have an in-eclipse spectrum, and an out-of-eclipse spectrum. The in-eclipse spectra were obtained entirely in the eclipse and do not contain any data taken in the ingress or egress. The in-eclipse spectra span phases of 0.961–1.0 and 0.0–0.0006, with the primary eclipse of the binary spanning phases of 0.9–1.0 and 0.0–0.1 from the K2 light curve presented in Casewell et al. (2020a).

5.2.1 Removing the white dwarf contribution

Since our observations are combined spectra of the white dwarf and the brown dwarf, we need to isolate the brown dwarf signal in order to study its phase-resolved spectra. As WD1032+011AB is eclipsing and we have identified two spectra that are in the eclipse, we already have spectra of the nightside of the brown dwarf alone. If we consider

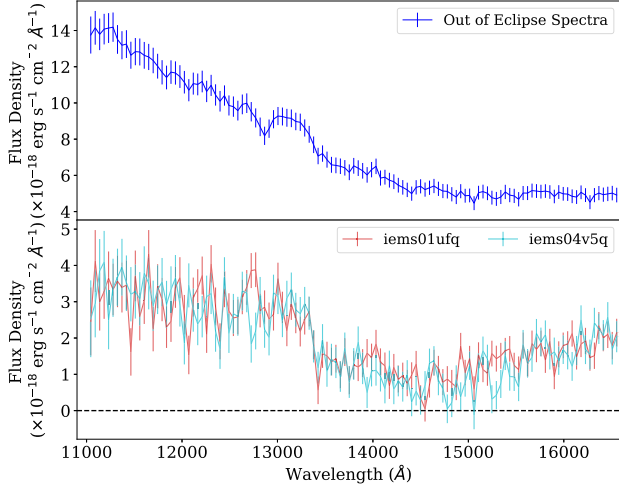


Figure 8. WFC3 spectra of WD1032+011 showing spectra in and outside the eclipse. The upper panel shows the combined out of eclipse spectra, which is a combination of the contributions from both the white dwarf and the brown dwarf. The lower panel shows the two spectra within the eclipse, which are the nightside of the brown dwarf alone.

the night phase of WD1032+011AB where the brown dwarf eclipses the white dwarf, at orbital phases surrounding $\phi = 0$ such that the white dwarf is not fully occulted, the flux received from the system is

$$F_{\text{night}} = F_{\text{WD}} + F_{\text{nightBD}}, \quad (3)$$

where F_{night} is the total flux observed from WD1032+011AB during the night phase, F_{WD} is the flux emitted from the white dwarf, and F_{nightBD} is the flux emitted by the nightside of the brown dwarf. Since the eclipse spectrum of the brown dwarf is equivalent to its nightside emission, we can calculate the flux from the white dwarf only as

$$F_{\text{WD}} = F_{\text{night}} - F_{\text{eclipseBD}}. \quad (4)$$

To extract the spectrum of the white dwarf from our combined white dwarf–brown dwarf spectra, we defined a series of phase windows for the four quarters of our full orbital phase. The phase windows are defined as eclipse: $\phi = 0.00\text{--}0.01$, and $\phi = 0.99\text{--}1.00$, midnight, that is the rest of the night phase which includes the ingress and egress but does not include the eclipse: $\phi = 0.89\text{--}0.99$ and $\phi = 0.01\text{--}0.11$, noon, when the white dwarf eclipses the brown dwarf: $\phi = 0.40\text{--}0.60$, morning: $\phi = 0.15\text{--}0.35$, and evening: $\phi = 0.65\text{--}0.85$. In the morning and evening phases, the white dwarf and the brown dwarf are both side on with respect to the observer. Fig. 9 shows the normalized, phasefolded light curve for WD1032+011 alongside these phase windows.

For each phase window, we combined the spectra within that window to create single averaged spectra for each of eclipse, midnight, morning, noon, and evening. We then subtracted our combined eclipse spectrum from our midnight spectrum following equation (4) to obtain our spectrum of the white dwarf alone.

We also modelled the spectrum of the white dwarf in WD1032+011 using the Koester (2010) DA white dwarf models. From this model grid which uses T_{eff} and $\log g$ as free parameters, we bi-linearly interpolate along both axes in the grid to create a model for our parameters of WD1032+011A, $T_{\text{eff}} = 9950 \pm 150$ K and $\log g = 7.65 \pm 0.13$.

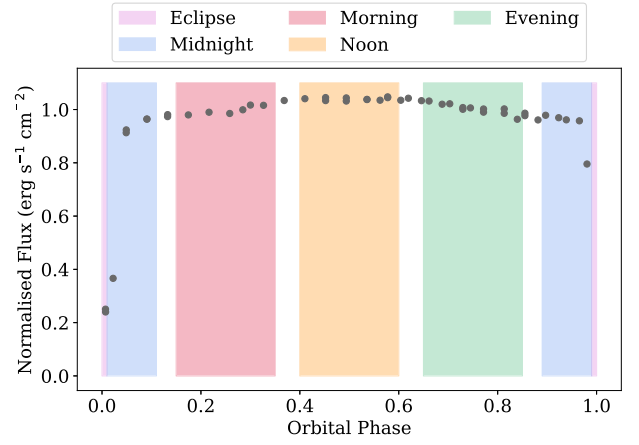


Figure 9. Phasefolded light curve of WD1032+011 showing a single orbit with phase windows overplotted. The phase windows are defined as eclipse: $\phi = 0.00\text{--}0.01$, and $\phi = 0.99\text{--}1.00$, midnight: $\phi = 0.89\text{--}0.99$, and $\phi = 0.01\text{--}0.11$, morning: $\phi = 0.15\text{--}0.35$, noon: $\phi = 0.40\text{--}0.60$, evening: $\phi = 0.65\text{--}0.85$. These windows are shown in pink, blue, red, yellow, and green, respectively from left to right.

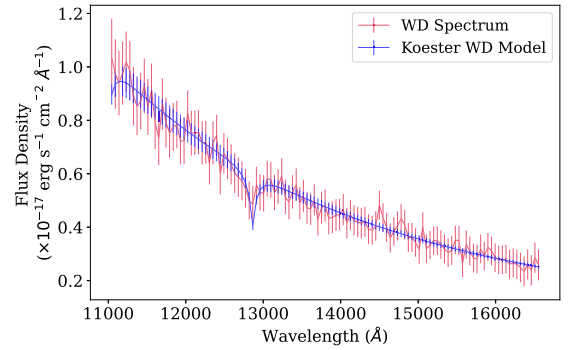


Figure 10. Comparison of our extracted white dwarf spectrum in red with our white dwarf Koester model in blue, with flux uncertainties determined using our Gaussian methodology. The Koester model has been scaled to our derived white dwarf spectrum.

To account for the uncertainties in our values of T_{eff} and $\log g$, we generated flux uncertainties for our bi-linearly interpolated Koester model using a series of Gaussians. We first created Gaussian distributions centred on the measured values of $T_{\text{eff}} = 9950$ K and $\log g = 7.65$ using their uncertainties, 150 K and 0.13, as the respective standard deviations. We sampled 10 000 unique parameter pairs of $(T_{\text{eff}}, \log g)$ from these distributions and then generated 10 000 white dwarf models via bi-linear interpolation of the Koester model grid.

To determine the flux uncertainties of our white dwarf model, we calculated the full width half-maximum of the Gaussian formed by the fluxes from our 10 000 models at each wavelength point. To scale our white dwarf model to the white dwarf spectrum we have extracted, we multiply by the scale factor $\left(\frac{R_{\text{WD}}}{D}\right)^2$, where the white dwarf radius, R_{WD} , and distance, D , are those from Casewell et al. (2020a). We find a constant 10 per cent flux offset between our white dwarf spectrum and our scaled Koester model, but this is well within the 24 per cent uncertainty in the scale factor, which is dominated by the uncertainty in the *Gaia* DR3 distance to WD1032+011. Fig. 10 compares the white dwarf spectrum we extracted from our

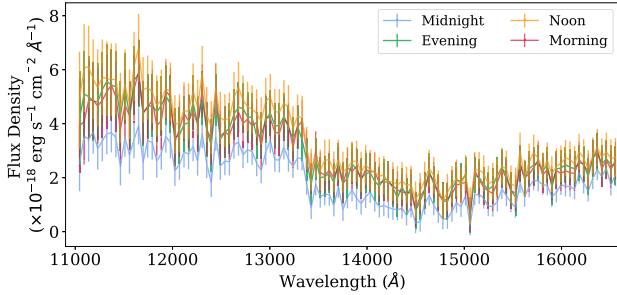


Figure 11. Phase-resolved spectra of the brown dwarf in WD1032+011. The phases considered are the midnight phase (blue), morning (red), noon (orange), and evening (green). Here the midnight spectrum is the nightside of the brown dwarf, and the noon spectrum is its dayside.

observations with our Koester model that has been scaled by the scale factor, and additionally scaled to correct for the 10 per cent flux offset. Our rescaled Koester model and white dwarf spectrum are very well-aligned with each other, with the initial flux offset well within the uncertainty in our scale factor, indicating that we have successfully extracted the white dwarf spectrum, and our data is consistent with the white dwarf radius and distance presented in Casewell et al. (2020a).

5.2.2 Phase resolved brown dwarf spectra

We subtracted our isolated spectrum of the white dwarf from the combined white dwarf + brown dwarf spectra we had in each phase window of midnight, morning, noon, and evening. Our phase-resolved spectra of the brown dwarf are depicted in Fig. 11, with the midnight spectrum hereafter corresponding to the eclipse spectrum of the nightside of the brown dwarf, observed at $\phi = 0$. The large feature in all of the spectra at $\sim 13\,500\text{ \AA}$ is due to water absorption in the brown dwarf atmosphere. The eclipse (midnight) spectrum is the faintest, which is expected due to only the nightside of the brown dwarf being visible. Similarly, the noon spectrum is the brightest as this is when the irradiated dayside of the brown dwarf is visible. We have corrected our noon spectrum to account for the small fraction of flux that is blocked as the white dwarf transits the brown dwarf. The morning and evening spectra are in-between these two extremes and are incredibly similar to each other. This is expected as at morning and evening the brown dwarf appears half-irradiated and half-non-irradiated to the observer. We find that on average, our dayside (noon) spectrum is 81 per cent brighter than our nightside (midnight) spectrum. This indicates a high level of irradiation from the white dwarf primary coupled with poor heat redistribution between the irradiated and non-irradiated hemispheres of the brown dwarf (Perna, Heng & Pont 2012).

5.3 Brightness temperature

The thermal structure of the atmosphere of WD1032+011B will be influenced by the differing opacities within the atmosphere, the internal heat flux, and the absorbed flux due to irradiation from the white dwarf (Marley & Robinson 2015). To identify potential differences between the thermal structure of the dayside and nightside hemispheres of WD1032+011B, we investigated its brightness temperature. The brightness temperature is the temperature a blackbody of the same radius would be at to emit the flux that we observe.

We calculate the brightness temperature using Planck’s law of radiation for a blackbody with our observed flux, the distance

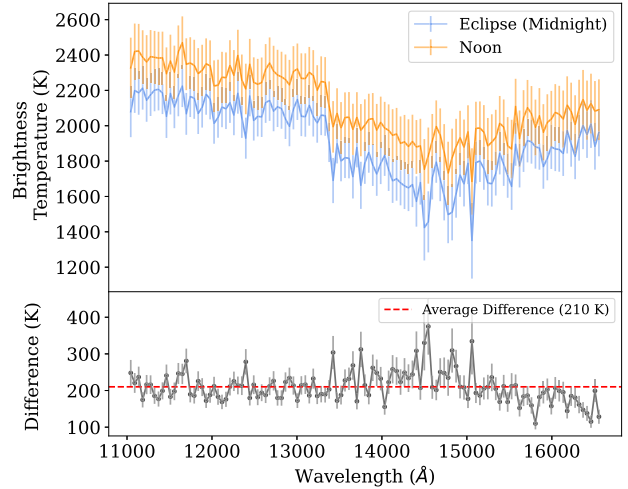


Figure 12. Brightness temperature of WD1032+011B for both the dayside and nightside, determined by calculating the blackbody temperature from the Planck equation for each wavelength. The difference between the nightside and the dayside is near-constant across the entire spectral range at 210 K.

of 313 pc to WD1032+011, and the radius of the brown dwarf, which is $1.024 R_{\text{Jup}}$. We calculate the brightness temperature at each wavelength point for both our dayside and nightside spectra, which is shown in Fig. 12.

The brightness temperatures range between ~ 1400 and 2500 K , and show a strong wavelength dependence in both the dayside and nightside hemispheres. The lowest brightness temperatures for both the dayside and the nightside are at $\sim 13\,500\text{--}14\,500\text{ \AA}$, which is the water absorption band. Our brightness temperatures show a temperature difference of 210 K between the dayside and nightside of the brown dwarf across the full spectral range. Comparing the brightness temperatures on the dayside and nightside, the vast majority have a difference within 2σ of the overall 210 K temperature contrast, with only a few deviations concentrated around the water absorption feature. As our temperature difference is nearly constant, it is likely that the atmosphere in both hemispheres has the same composition and opacity sources. However, there are small changes in the shape of the brightness temperature between the different hemispheres, such as the nightside exhibiting deeper features around $14\,500\text{--}15\,000\text{ \AA}$, which could result from the dissociation of atmospheric molecules in the dayside of the brown dwarf due to the irradiation it receives, and indicate that the response time is of a similar order to the orbital period.

6 COMPARISON TO FIELD BROWN DWARFS

To identify the spectral type of the brown dwarf companion in WD1032+011, we compare our nightside spectrum to spectral libraries of non-irradiated field brown dwarfs. We used two different data bases for this, the SpeX Prism data base (Burgasser 2014), and the Cloud Atlas spectral library (Manjavacas et al. 2019). The SpeX prism library comprises 234 L, T, and Y dwarf spectra with available data, all observed using SpeX, which is a ground-based spectrograph. The Cloud Atlas library contains 53 usable L, T, and Y dwarf spectra that have been observed with the *HST* WFC3 instrument. To scale our spectrum of WD1032+011B to the same flux as the field brown dwarfs, we normalize the flux at $13\,000\text{ \AA}$ to 1. This wavelength probes high-pressure areas in the atmosphere and should thus be less affected by irradiation (Amaro et al. 2023). To determine which

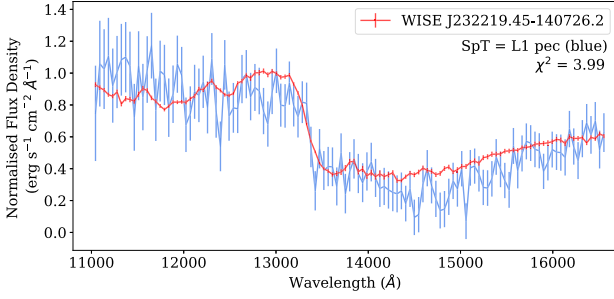


Figure 13. Comparison of the nightside spectrum of the brown dwarf with field brown dwarfs using χ^2 fitting. The red line shows the best-fitting object for the SpeX library, WISE J232219.45–140726.2 which is an L1 pec spectral type with a χ^2 of 3.99. Our nightside spectrum is shown in blue.

field brown dwarf spectrum best matches our nightside spectrum, we resample the field spectra to the same resolution as our data, and calculate the χ^2 value between our data and each field brown dwarf spectrum. Fig. 13 shows the best-fitting field brown dwarf from the SpeX and Cloud Atlas sources.

We note that the χ^2 values were consistently lower for the SpeX template spectra than for the Cloud Atlas ones. Additionally, although the Cloud Atlas library is *HST* WFC3 data, it only starts at a spectral type of L4.5, whereas the SpeX library starts at L0. WD1032+011B is outside of the spectral type coverage of the Cloud Atlas Library, but it is included in the coverage of the SpeX data base. Our best-fitting spectrum is WISE J232219.45–140726.2 from the SpeX prism library, which is an L1 pec spectral type brown dwarf. L1 peculiar brown dwarfs tend to have deeper water absorption and a bluer slope longwards of 13 000 Å compared to their L1 counterparts (Luhman & Sheppard 2014). A spectral type of L1 pec is also consistent with our average nightside brightness temperature of 1909 K.

7 ATMOSPHERIC MODELS

7.1 Non-irradiated brown dwarf models

We compare our nightside and irradiated dayside spectra of WD1032+011B to the ATMO 2020 suite of non-irradiated atmosphere models, which do not include cloud opacity, designed for brown dwarfs and giant exoplanets from Phillips et al. (2020). The models have a solar metallicity and vary through $\log g = 2.5$ – 5.5 in steps of 0.5, and $T_{\text{eff}} = 200$ – 3000 K, with steps of 50 and 100 K Kelvin lower and higher than $T_{\text{eff}} = 600$ K, respectively. The models are generated by the ATMO code which solves the pressure-temperature structure of an atmosphere following a radiative-convective equilibrium model. Since these models do not consider irradiation, the effective temperature is equivalent to the internal heat flux. There are three model grids, one for equilibrium chemistry, and two for disequilibrium chemistry with different strengths of vertical mixing, which is characterized by the K_{zz} parameter.

To find the best-fitting model for both our nightside and dayside brown dwarf spectra, we multiply the ATMO 2020 models by the scale factor $\left(\frac{R_{\text{BD}}}{D}\right)^2$, where the brown dwarf radius, R_{BD} , and distance, D , are those from Casewell et al. (2020a). We then perform a χ^2 fitting between the model and our data, as we did in Section 6. We take the smallest χ^2 value to be our best-fitting model. For the chemical equilibrium grid, the best-fitting models are shown in upper and lower panels of Fig. 14 for the dayside and nightside of

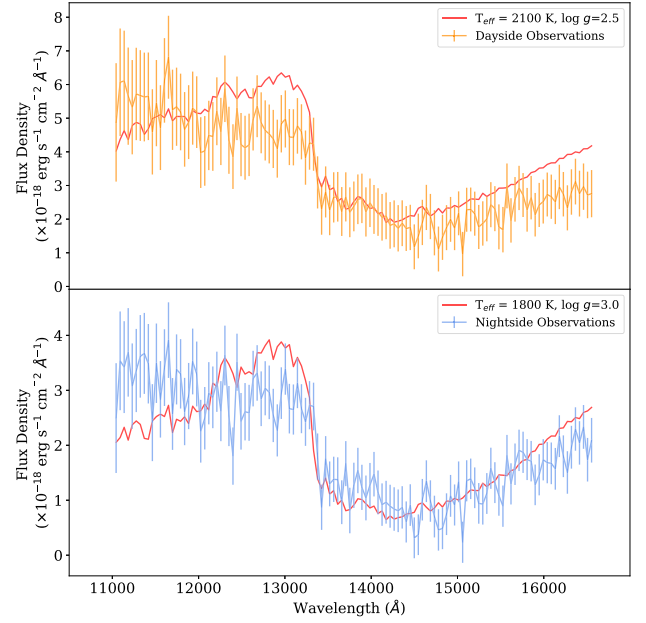


Figure 14. Comparison of our spectra of WD1032+011B with chemical equilibrium ATMO 2020 models using χ^2 fitting. The upper panel shows our dayside spectrum in orange, with the red line depicting the best-fitting ATMO model which has $T_{\text{eff}} = 2100$ K and $\log g = 2.5$. The lower panel shows our nightside spectrum in light blue, with the red line depicting the best-fitting ATMO model which has $T_{\text{eff}} = 1800$ K and $\log g = 3.0$.

WD1032+011B, respectively.

For the nightside of WD1032+011B, the best-fitting ATMO 2020 model has $T_{\text{eff}} = 1800$ K and $\log g = 3.0$ compared to $T_{\text{eff}} = 2100$ K and $\log g = 2.5$ for the best-fitting dayside model. These results are consistent with our brightness temperature calculations. They also imply a potential low gravity for WD1032+011B. To evaluate the surface gravity of our brown dwarf, we calculated the gravity indices from Allers & Liu (2013), however these were inconclusive due to the limited wavelength range of our data. We calculate the surface gravity of WD1032+011 from its mass and radius, derived by Casewell et al. (2020a) via radial velocity and eclipse photometry respectively, as $\log g = 5.21 \pm 0.09$, meaning that the ATMO models fit uncharacteristically low-surface gravities. It should be noted that the disequilibrium grid of ATMO models produce a more reasonable surface gravity of $\log g = 5.5$ for the dayside of the brown dwarf, however they do not fit the spectral features, and still underestimate the nightside as $\log g = 3.0$, which is unphysical given the mass and radius of WD1032+011B. Additionally, even if we fix the surface gravity to only vary between 5.0–5.5, the best-fitting ATMO models do not fit the water absorption feature or the rest of the spectra morphology well for either the dayside or the nightside.

We also fit the Sonora suite of models, which are designed for non-irradiated sub-stellar objects, to our dayside and nightside spectra Marley et al. (2021). We find that they give similar results to the ATMO models, however they produce more realistic surface gravity estimates of $\log g = 5.5$. Additionally, the low metallicity grid of Sonora models provides the best fits to our data, particularly on the dayside, indicating that WD1032+011B may be metal-poor. Overall, the ATMO models fit our data better despite not matching the surface gravity, with χ^2 values consistently less than half of those produced by the Sonora models, which is likely a consequence of better matching the pressure-temperature profile, the cloud parameters, and

chemical abundances. Both the ATMO and Sonora models do not fit the water absorption feature or the slope shortwards of 13 000 Å particularly well, indicating that these non-irradiated models do not adequately describe our observations, proving the effects of irradiation need to be included.

7.2 Forward models

We run a small grid of 1D radiative-convective equilibrium models using EGP (Marley et al. 1999; Ackerman & Marley 2001). The grid spans the following parameters: age = 1, 1.5, and 2 Gyr, metallicity = $-1\times$, $-0.5\times$, and $0\times$ solar, and the cloud cases of cloud free, cloudy with sedimentation efficiency, $f_{\text{sed}} = 3.0$ or 5.0 (Ackerman & Marley 2001). Available clouds for condensation include KCl, ZnS, Na₂S, MnS, Cr, MgSiO₃, Fe, and Al₂O₃.

By varying the recirculation factor, which parametrizes the redistribution of incident energy across the atmosphere, we can model both the day and nightsides. The age is used to set the internal heat flux, T_{int} , from the Marley et al. (2018) evolution grid. These models assume chemical equilibrium. We do not include TiO and VO opacity in the atmosphere. Given the hot temperature of the white dwarf, we employ the same methodology as Amaro et al. (2023) and Lew et al. (2022), where we increase the irradiation in the first few wavelength bins to account for the flux at wavelengths shorter than the modelling grid, essentially assuming that the opacities are constant through the ultraviolet where opacities are not available.

Using PICASO (Batalha et al. 2019), we compute the resultant spectra and select the best-fits to the data based on the chi-squared metric. The best-fitting forward models for the data are shown in Fig. 15, with the dayside shown in the upper panel and the nightside shown in the lower panel. These models include the reflected flux for the dayside. The best-fitting model has an age of 1.5 Gyr, which corresponds to an internal heat flux of ~ 1775 K, with $\text{Fe}/\text{H} = -1.0$ and $f_{\text{sed}} = 5.0$. Without the effects of irradiation the model fits poorly, showing that irradiation is present in the atmosphere and needs to be considered. The associated pressure-temperature profiles are shown in Fig. 16. These pressure-temperature profiles do not show a temperature inversion on either the dayside or the nightside. The models predict a Na and K feature in the 1.1–1.2 μm wavelength region which is not supported by the data. Thus with the removal of those features, better fits are achieved overall but the models still struggle to reproduce the slope in the blue end of the spectrum.

7.3 Atmospheric retrievals

To fit the phase-resolved dayside and nightside spectra with more flexibility than the self-consistent grids, we also used the PETRA retrieval framework (Lothringer & Barman 2020), which uses the PHOENIX atmosphere model (Hauschildt, Allard & Baron 1999; Barman, Hauschildt & Allard 2001) as the forward model in a differential evolution MCMC statistical framework (Ter Braak 2006). The retrievals were run on a 64-layer pressure grid varying the surface gravity, the pressure-level and opacity of a grey cloud-deck, and the temperature structure. To parametrize the temperature structure, we used the 5-parameter Parmentier & Guillot (2014) parametrization, with the internal temperature as an additional free parameter. The composition was kept at solar metallicity, with the most important opacity sources being H₂O (Barber et al. 2006), H (John 1988), and H₂-H₂, and H₂-He collision induced absorption (Borysow, Frommhold & Moraldi 1989; Borysow & Frommhold 1990).

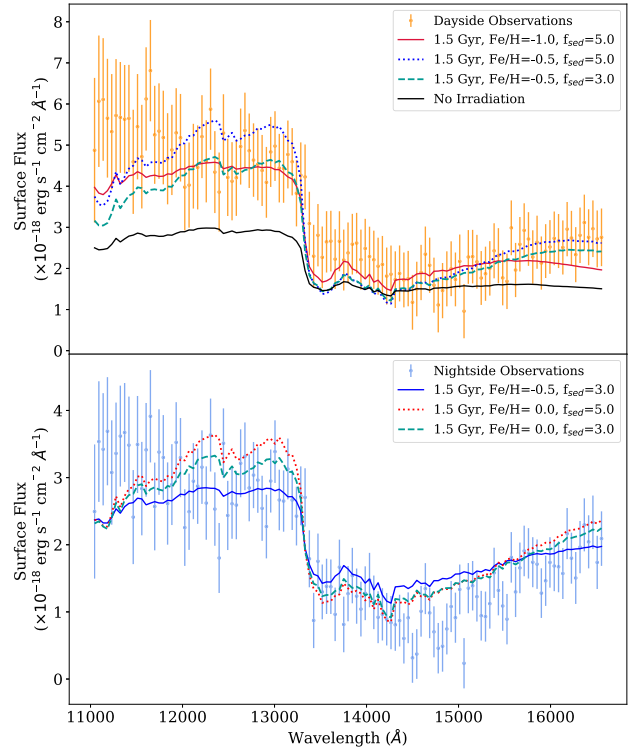


Figure 15. Best-fitting forward models of WD1032+011B. The dayside spectrum is shown in orange with the three best-fitting models depicted by a red solid line, a blue dotted line, and a green dashed line, respectively. The black solid line shows the best-fitting model with the effects of irradiation removed. The nightside spectrum is shown in light blue with the three best-fitting models depicted by a blue solid line, red dotted line, and green dashed line, respectively. The age, metallicity, and cloud parameter of each model are shown in the legend. An age of 1.5 Gyr corresponds to an internal heat flux of ~ 1775 K.

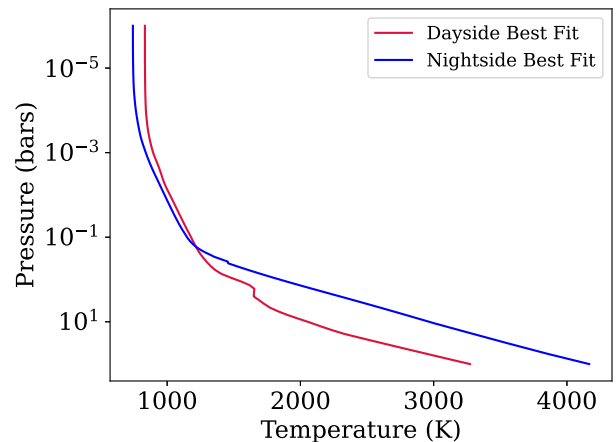


Figure 16. Pressure-temperature profiles of the best-fitting PICASO forward models of WD1032+011B. The dayside pressure-temperature profile is shown in red, and the nightside pressure-temperature profile is shown in blue.

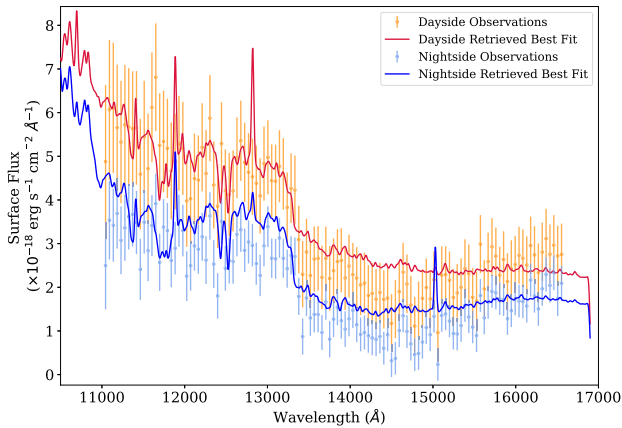


Figure 17. Best-fitting retrieved spectra of WD1032+011B using PETRA. The dayside observations are shown in orange with the fit overlaid in red. The nightside observations are shown in light blue with the fit overlaid in dark blue.

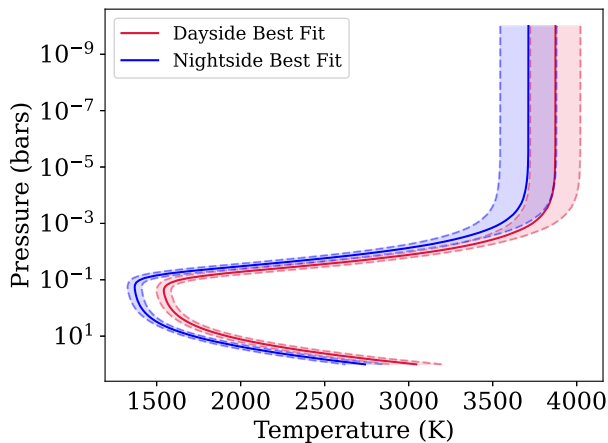


Figure 18. Pressure-temperature profiles of the best-fitting retrieved spectra of WD1032+011B using PETRA. The dayside pressure-temperature profile is shown in red, and the nightside pressure-temperature profile is shown in blue. The filled regions between the dashed lines indicate 1σ confidence limits, in red and blue for the dayside and nightside, respectively.

Fig. 17 shows the best-fitting dayside and nightside spectra. The associated pressure-temperature profiles are shown in Fig. 18. Both the dayside and nightside retrievals preferred a strongly inverted atmosphere. An irradiation-driven temperature inversion could be expected on the dayside, as seen in other irradiated brown dwarfs (e.g. WD0137B; Lee et al. 2020). However, such an inversion would not be expected to be retained on the nightside, as the photosphere would have more than enough time to have radiatively cooled to a non-inverted profile. At a pressure of 1 bar, the radiative time-scale in the photosphere is 0.183 h, which is equal to 8.3 per cent of a full orbit of WD1032+011AB. This time-scale decreases at lower pressures, so the atmosphere will have cooled to a non-inverted profile well within the 1.1 h between our observations of the dayside and nightside.

Fig. 19 shows the dayside best-fitting spectra with and without the inversion, as well as without the irradiation (i.e. just T_{int} determining the temperature structure in the Parmentier & Guillot parametrization). As can be seen, the retrieval adds the inversion to increase the flux between 1.1 and 1.3 μm , while sacrificing the fit

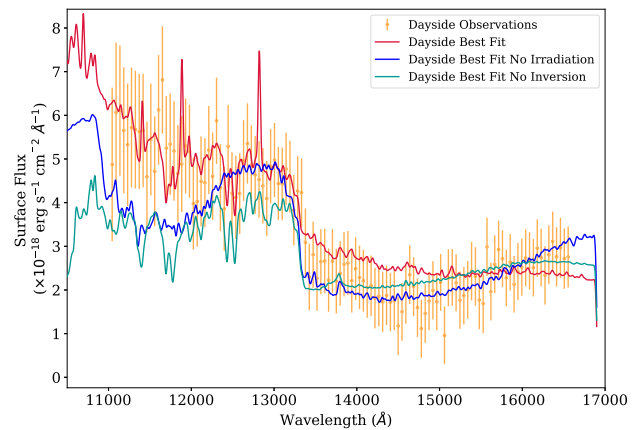


Figure 19. Best-fitting retrieved spectra of the dayside of WD1032+011B considering the effects of irradiation and inversion. The dayside spectrum is shown in orange. The red line shows the best fit, which includes both irradiation and a temperature inversion. The blue line is the best fit without irradiation, and the green line is the best fit without a temperature inversion. The red, blue, and green lines are shown from top to bottom, respectively, at the short wavelength end.

longward of 1.4 μm . Without either the inversion or irradiation, the retrieval struggles to match the short-wavelength data.

While the nightside temperature inversion is likely unphysical as it is driven by irradiation, both retrievals find a reasonable surface gravity, retrieving $\log_{10}(g_{\text{cgs}}) = 5.57 \pm 0.22$ and 5.22 ± 0.22 from the dayside and nightside, respectively. The retrieved temperatures are 1748^{+76}_{-62} and 1555^{+66}_{-67} K, respectively. The true internal temperature is expected to be the same between the dayside and nightside, so the increased temperature on the dayside represents the contribution from the irradiation that makes it to the deep atmosphere. Neither the dayside nor the nightside retrieved a cloud at observable photospheric pressures, though the PICASO forward models indicate that clouds may help fit the short wavelength observations more physically than a temperature inversion. Since the irradiated forward model is not showing such a large inversion, the processes responsible for the retrieved inversion need to be further explored. Absorption by unmodelled photochemical products including disequilibrium gases and hazes as well as energy transport by atmospheric waves are among the possibilities (e.g. Rajpurohit et al. 2020).

8 DISCUSSION

With comprehensive system parameters from Casewell et al. (2020a; see Table 1) resulting from high-resolution photometry and multiple spectroscopic observations, we do not recalculate those system parameters in this paper. When conducting our MCMC analysis on the broad-band and sub-band light curves we derived for WD1032+011, we treated the period in equation (1) as a fixed parameter with a value of $P = 0.09155899610$ d. Fixing the period to this value yielded excellent agreement between our data and the best-fitting MCMC model. We note that when the period was allowed to vary as a free parameter in our analysis, the true period was successfully recovered within 1σ . In addition, when the period was allowed to vary whilst fitting the MCMC model to our sub-band light curves, the individual periods for the J -, water, and H -band data were all within 1σ of the true period and each other.

8.1 Comparison to field brown dwarfs

To evaluate the effects that the external irradiation from the white dwarf has on the spectrum of the irradiated brown dwarf, we compare the dayside and nightside spectra of WD1032+011B to field brown dwarfs. Most field brown dwarfs exhibit rotational modulations in their emission spectra (Buenzli et al. 2014; Metchev et al. 2015). These flux variations arise from the cloud thickness variations in the atmosphere of the brown dwarfs (Apai et al. 2013; Lew et al. 2020). The cloud structure visible to external observers changes dramatically at the L/T spectral type transition (Radigan et al. 2012). At these temperatures, the cloud top is modulated by zonal circulation and atmospheric waves (Apai et al. 2017; Apai, Nardiello & Bedin 2021; Zhou et al. 2022b; Fuda et al. 2024; Plummer et al. 2024). At temperatures below, the cloud top is thought to sink below the photosphere and thus is no longer visible to the observer (Skemer et al. 2014). In irradiated and tidally locked brown dwarfs, rotational phase-dependent changes in flux can arise from the constant irradiation on the dayside and atmospheric circulation from the dayside to the nightside.

We searched the SpeX prism and Cloud Atlas data bases which contain spectra of L, T, and Y dwarfs for the field brown dwarf that best-matched WD1032+011B. We normalized the spectra such that the flux at 13 000 Å is at a value of 1. We find that the Cloud Atlas spectral library does not extend to early enough spectral types, whereas the SpeX prism spectral library contains numerous early L-dwarfs. Our nightside spectrum is best fit by L1 peculiar brown dwarfs, which exhibit deeper water absorption and a bluer slope longwards of 13 000 Å compared to their L1 counterparts (Luhman & Sheppard 2014). Peculiar brown dwarfs often exhibit higher or lower metallicities than field brown dwarfs (Marocco et al. 2015), and the differences in their spectra may result from changes in cloud structure and opacity alongside atmospheric changes. A spectral type of L1 pec is also consistent with our average nightside brightness temperature of 1909 K. We note that WD1032+011B was originally posited as an L5 spectral type by Casewell et al. (2020a), however the GNIRS spectrum they analysed was normalized to photometry that was taken at different points in orbital phase. The UKIDSS *Y* and *J* photometry was taken separately to the *H* and *K* photometry. If the *H* and *K* photometry were taken during or close to the eclipse, then their relative magnitude is lower than it should be compared to the *Y* and *J* photometry. This would then result in a later spectral type being identified as the best fit, where an earlier spectral type is actually more appropriate.

The dayside of WD1032+011B however, is instead best fit by a subdwarf sdL0 object, WISE J04592121+1540592 (Kirkpatrick et al. 2014). Subdwarfs describe metal-poor objects with subsolar abundances that often exhibit blue colours in the near-infrared and enhanced absorption bands for metal hydrides, but otherwise resemble the morphology of M, L, T, and Y dwarf spectra (Burgasser et al. 2009; Kirkpatrick et al. 2010). The kinematics of the white dwarf correspond to a thick disc membership, meaning that WD1032+011B could be metal-poor due to its age (Casewell et al. 2020a). However, the subdwarf field brown dwarf spectra do not fit the shape of the water absorption feature centred on $\sim 14\,000$ Å well. Subdwarfs tend to be less cloudy or completely cloud-free due to the reduction of condensates in their atmospheres, which causes their low metallicity (Gonzales et al. 2021). Clouds are typically expected in early L-type brown dwarfs as this is before the L/T transition where condensate clouds sink below the photosphere (Burgasser et al. 2002). As the dayside of WD1032+011B is best-matched by subdwarf spectra, which appear flatter in the *J* band, it is likely

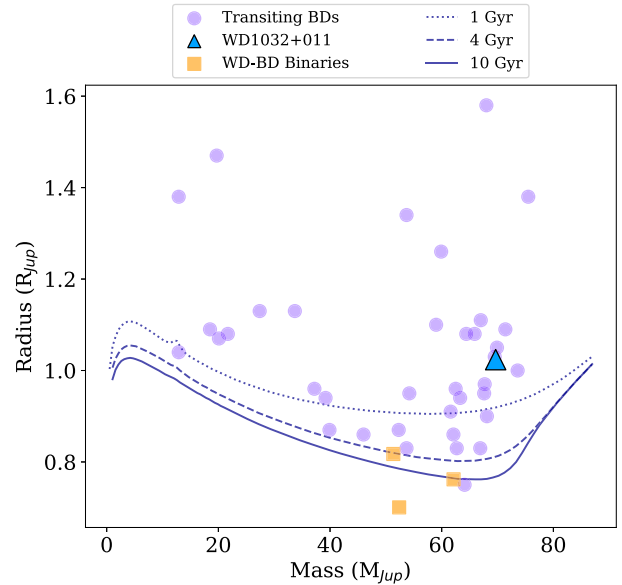


Figure 20. Known transiting brown dwarfs in the mass–radius parameter space, represented by purple circles alongside eclipsing brown dwarf companions to white dwarfs represented by orange squares. WD1032+011B is shown with an outlined blue triangle. The dotted, dashed and solid navy lines are Sonora brown dwarf evolution models for 1, 4, and 10 Gyr, respectively. The sample of transiting brown dwarfs is taken from Henderson et al. (2024). The transiting exoplanets are taken from the NASA Exoplanet Archive.

that the irradiation from the white dwarf is affecting the condensate clouds in such a way that the atmosphere of the brown dwarf is appearing more metal-poor. This suggests that the strong irradiation of the dayside is either dissipating some of the cloud coverage due to the increased heat, pushing silicate clouds below the photosphere, or circulating clouds towards the nightside, so that the dayside is silicate cloud-free (Burrows et al. 2001). This causes a heterogeneous atmospheric structure that is observed in the phase-dependent spectra of the brown dwarf (Mollière et al. 2015).

Since WD1032+011 is an eclipsing system, WD1032+011B belongs in the small population of transiting brown dwarfs that have been discovered. We compare WD1032+011B to this population of transiting brown dwarfs around main-sequence stars, which was most recently updated by Henderson et al. (2024). We also consider the other three known eclipsing close white dwarf–brown dwarf binaries, SDSS J1411+2009 (hereafter SDSS1411; Lew et al. 2022), SDSS J1205–0242 (Parsons et al. 2017), and ZTF J0038+2030 (van Roestel et al. 2021). In Fig. 20, we place WD1032+011B in the mass–radius parameter space of known transiting brown dwarfs. The purple circles show the transiting brown dwarfs around main-sequence stars, the orange squares correspond to eclipsing brown dwarfs orbiting white dwarfs, and WD1032+011B is represented by the outlined blue triangle. As can be seen, the brown dwarfs in eclipsing white dwarf–brown dwarf binaries fit well within the population of higher mass transiting brown dwarfs, alongside the other brown dwarfs orbiting white dwarfs. SDSS1411B has a radius slightly lower than the majority of the transiting brown dwarfs due to it being a later spectral type of T5, with brown dwarfs continuing to contract whilst they age and cool (Lew et al. 2022). The other brown dwarf companions to white dwarfs are well-aligned in the parameter space, with masses and radii consistent with the expectations from brown dwarf evolutionary models. However, WD1032+011B has a higher radius than expected compared to both the Sonora evolution

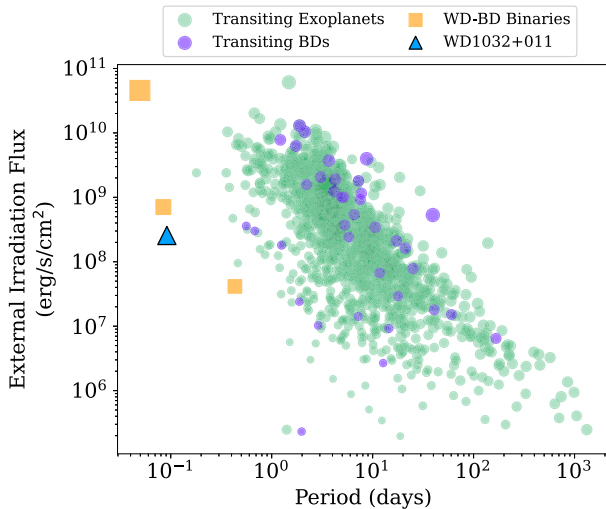


Figure 21. Variation of external irradiation flux received by brown dwarfs and exoplanets with orbital period. The purple circles correspond to transiting brown dwarfs and the green circles are transiting exoplanets. The orange squares show eclipsing brown dwarf companions to white dwarfs. WD1032+011B is represented by the outlined blue triangle. The size of the points corresponds to the effective temperature of the host star. The sample of transiting brown dwarfs is taken from Henderson et al. (2024). The transiting exoplanets are taken from the NASA Exoplanet Archive.

models and the other eclipsing brown dwarf companions to white dwarfs, verifying that it is inflated.

In Fig. 21, we investigate the variation of external irradiation flux with period for transiting brown dwarfs and exoplanets, alongside the population of brown dwarfs in close orbits around white dwarfs. Although WD1032+011B and the other brown dwarfs irradiated by white dwarfs follow the general trend of the transiting brown dwarfs, they should have an increased external irradiation flux considering their periods to continue the same linear trend seen in the non-irradiated transiting brown dwarfs.

Since white dwarfs are much smaller than main-sequence stars, their brown dwarf companions would receive a lower external irradiation flux than if they were orbiting a main-sequence star at the same temperature, as the decreased radius of the white dwarf decreases its surface area and thus the external irradiation flux received by the brown dwarf (Langer & Kudritzki 2014). Additionally, as the white dwarfs are already evolved, the orbits of the brown dwarfs have shrunk during this evolution, allowing them to occupy orbits much closer to their primary stars than the brown dwarfs transiting main-sequence stars. This discrepancy leads to two distinct populations in Fig. 21, separating the highly irradiated brown dwarfs from the other transiting brown dwarfs. Both of these populations follow slightly different linear trends as decreasing the orbital period increases the irradiation flux received by the brown dwarf.

8.2 Brown dwarf atmosphere models

To quantify the differences between the dayside and nightside of WD1032+011B and the effects of irradiation on the atmosphere, we analysed one dimensional atmospheric models for both hemispheres. We compared our derived dayside and nightside spectra to the ATMO 2020 atmospheric models which are non-irradiated, generated PICASO forward models which consider irradiation, and ran retrievals using PHOENIX atmosphere models with PETRA. From all of these models, we found that there is a consistent temperature

contrast between the dayside and nightside of WD1032+011B, which is due to irradiation coupled with a poor heat redistribution between the hemispheres. The best-fitting ATMO models for both the dayside and the nightside have effective temperatures that agree with our brightness temperatures (Fig. 12), and they have low gravities of $\log g = 2.5\text{--}3.0$. However, given the mass and radius of WD1032+011B, we calculate its surface gravity as $\log g = 5.21$. The uncharacteristically low gravity identified by fitting to the ATMO models is likely because they are non-irradiated models, and a lower surface gravity better replicates some of the features seen in the irradiated spectra.

The best-fitting PICASO forward models for both the dayside and nightside have ages of 1.5 Gyr, which correspond to an internal heat flux of ~ 1775 K. The best-fitting models also favour low metallicity, which corroborates the spectral type of L1 peculiar and the metal-poor spectral features evidenced in Section 8.1. The PICASO models do not simultaneously fit both the short wavelength data and the water absorption feature well, however the presence of clouds improves the fit to the short wavelength data. The models predict a Na and K feature in the 1.1–1.2 μm wavelength region which is not supported by the data. Na and K are both easily ionized and the fact that we do not see evidence of their predicted features indicates that the ultraviolet heating from the white dwarf is impacting these species.

The retrievals performed on the PHOENIX model grid, which accounts for irradiation, match both the dayside and nightside spectra well. An irradiation-driven temperature inversion is seen in the dayside, a feature which is often seen in the atmospheres of irradiated brown dwarfs and exoplanets, arising due to the strong absorption of incoming ultraviolet flux by molecules such as VO and TiO (Fortney et al. 2008; Haynes et al. 2015). There is an unphysical temperature inversion seen in the nightside spectrum, but this is likely due to the increase in flux shortwards of 13 000 \AA . Such an inversion would not be expected to be retained on the nightside, as the photosphere would have more than enough time to have radiatively cooled to a non-inverted profile. For WD0137B, an irradiated brown dwarf which has a higher external irradiation flux with a similar orbital period of 114 min compared to the 132 min orbital period of WD1032+011B, the atmosphere relaxes to a non-inverted state on the nightside where the temperature is no longer externally forced by irradiation (Lothringer et al. 2024). Therefore, WD1032+011B is expected to have adequate time to radiatively cool to a non-inverted temperature profile on the nightside, which also indicates that the radiative time-scale it takes to cool is significantly shorter than the advective time-scale at which heat transport occurs between the hemispheres. The slope present in the short wavelength data could arise from the low metallicity of the brown dwarf and its L1 peculiar spectral type. However, as this slope is not adequately fit by the retrievals, the fit introduces an unphysical temperature inversion on the nightside, which increases the flux bluewards of 13 000 \AA and thus produces a better fit to the data. The slope could also arise from clouds, but the atmospheric retrievals do not recover clouds above the photosphere. Future work with more complex retrieval analyses, or a simultaneous white dwarf–brown dwarf retrieval framework may improve the retrievals and help explore why an unphysical temperature inversion is chosen to fit the spectra.

The irradiated retrievals recover surface gravities within 2σ of the calculated value for the dayside and within 1σ for the nightside. The internal temperatures retrieved corroborate the dayside–nightside temperature contrast derived from brightness temperature, with a 193 K temperature difference between the hemispheres. The performance of these irradiated model retrievals show that WD1032+011B has a dayside–nightside temperature contrast that is driven by the

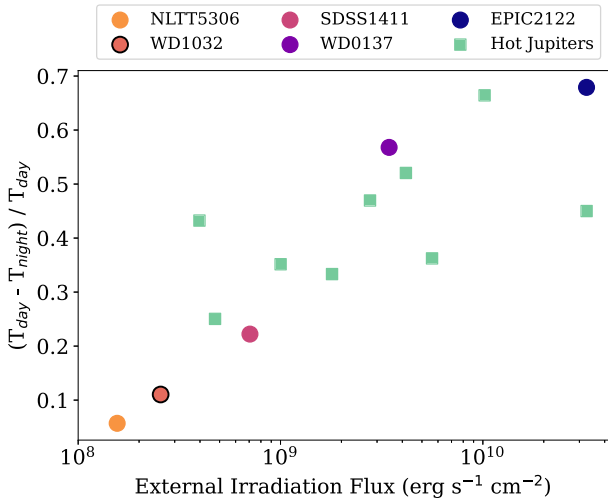


Figure 22. Comparison of dayside–nightside temperature contrast and external irradiation flux for WD1032+011B alongside the irradiated brown dwarf companions to white dwarfs NLTT5306B, SDSS1411B, WD0137B, and EPIC2122B, all shown as circles. Hot Jupiters are shown with green squares, with systems selected from Beatty et al. (2019) and Komacek & Showman (2016).

irradiation received by the white dwarf, and that this irradiation is altering the atmospheric profile of the brown dwarf.

8.3 Comparison to hot Jupiters

In field brown dwarfs, the effective temperature is solely dependent on the internal heat flux of the brown dwarf, which cools as it evolves through its lifetime. However, for irradiated brown dwarfs, the constant external irradiation flux received from the host star increases their effective temperature such that

$$T_{\text{eff}} = (T_{\text{internal}}^4 + T_{\text{irradiation}}^4)^{\frac{1}{4}}. \quad (5)$$

Short-period irradiated brown dwarfs companions to white dwarfs have equilibrium temperatures which are comparable to the hottest hot Jupiters, making them excellent proxies for studying hot Jupiters. In particular, the observed spectra of hot Jupiters are influenced by the presence and composition of clouds, which alter their atmospheric pressure–temperature profiles, with silicate clouds potentially disappearing for equilibrium temperatures cooler than 1600 K (Lee et al. 2016; Parmentier et al. 2016). Irradiated brown dwarfs, particularly higher contrast objects around white dwarfs, enable us to gain insight into the connections between non-irradiated brown dwarfs and hot Jupiters, and how clouds may influence their atmospheric structure and temperature profiles.

To compare WD1032+011B to irradiated brown dwarfs and hot Jupiters, we calculated the external irradiation flux received from the white dwarf, as well as its dayside–nightside temperature contrast relative to the dayside temperature. We compare WD1032+011B to the sample of four irradiated brown dwarf companions to white dwarfs alongside a selection of hot Jupiters in Fig. 22. The irradiated brown dwarfs are NLTT5306B (L5, $P = 101.88$ min; Amaro et al. 2023), SDSS1411B (T5, $P = 2.02864$ h; Lew et al. 2022), WD0137B (L6–L8, $P = 116$ min; Zhou et al. 2022a), and EPIC2122B (L3, $P = 68.21$ min; Casewell et al. 2018; Zhou et al. 2022a). The hot Jupiters included in this comparison are selected from the samples analysed by Beatty et al. (2019) and Komacek & Showman (2016). These consist of HD 149026b (Knutson et al. 2009b), HD 189733b

(Knutson et al. 2007, 2009a, 2012), HD 209458b (Crossfield et al. 2012; Zellem et al. 2014), HAT-P-7b (Wong et al. 2016), WASP-12b (Cowan et al. 2012), WASP-14b (Wong et al. 2015), WASP-19b (Wong et al. 2016), WASP-33b (Zhang et al. 2018; Chakrabarty & Sengupta 2019), WASP-43b (Stevenson et al. 2017; Kokori et al. 2023; Bell et al. 2024), and WASP-103b (Kreidberg et al. 2018).

The irradiated brown dwarfs in Fig. 22 are represented by circles, with each system labelled. The hot Jupiters are represented by green squares. We report the relative dayside–nightside temperature contrast relative to the dayside temperature, that is $(T_{\text{day}} - T_{\text{night}})/T_{\text{day}}$. Using this metric allows direct comparison between the dayside–nightside temperature contrasts of irradiated brown dwarfs and hot Jupiters, whereas the difference between the dayside and nightside temperatures alone may be sensitive to the different instruments used for observations. As can be seen, as external irradiation flux increases, often caused by a higher stellar temperature or a smaller orbital separation, the dayside–nightside temperature contrast metric also increases. Showman & Guillot (2002) predicted that hot Jupiters would follow this trend, and the irradiated brown dwarfs considered here are interspersed with the hot Jupiters and follow this trend as well. This shows that irradiated brown dwarfs can be effectively utilized as proxies for hot Jupiters, and indicates that they may undergo similar cloud and atmospheric changes due to their irradiation. WD1032+011B is well-aligned with both irradiated brown dwarfs and hot Jupiters. It receives less external irradiation flux than the majority of other known irradiated brown dwarfs, however this flux is still high enough to cause a moderate dayside–nightside temperature contrast and cause atmospheric changes on the dayside.

8.4 Comparison to irradiated white dwarf–brown dwarf binaries

Irradiated brown dwarfs reside between hot Jupiters and non-irradiated brown dwarfs and their atmospheres can thus be used to investigate key atmospheric processes such as condensate cloud formation and dissipation, and heat redistribution from the dayside to the nightside. WD1032+011B is the fifth irradiated brown dwarf companion to a white dwarf which has been studied by high-precision, time-resolved *HST*/WFC3 spectrophotometry, following SDSS1411B, WD0137B, EPIC2122B, and NLTT5306B (Lew et al. 2022; Zhou et al. 2022a; Amaro et al. 2023). WD1032+011B sits between NLTT5306B and the other highly irradiated white dwarf–brown dwarf binaries, as can be seen in Fig. 22. Similarly, the dayside–nightside temperature contrast metric is between those for NLTT5306B and SDSS1411B, WD0137B, and EPIC2122B. Dayside–nightside temperature contrast is influenced by the rotation rate of the brown dwarf, which is faster for shorter period brown dwarfs (Tan & Showman 2020). With the exception of NLTT5306B, these irradiated brown dwarfs all follow that trend with WD1032+011B having a period of 2.2 h, SDSS1411B has a period of 2.0 h, WD0137B with an orbit of 1.9 h and EPIC2122B having a period of only 68.21 min. EPIC2122B receives 127 times more external irradiation flux than WD1032+011B, whereas WD0137B, SDSS1411B, and NLTT5306B receive 13.7 times more, 2.8 times more, and 1.6 times less, respectively. All of these irradiated brown dwarfs follow the trend of increasing dayside–nightside temperature contrast as external irradiation flux also increases, which is also observed in hot Jupiters (e.g. Komacek & Showman 2016; Beatty et al. 2019).

We compare the dayside and nightside spectra of WD1032+011B with the non-eclipsing systems NLTT5306B and WD0137B as these have similar spectral types and differing levels of irradiation. We

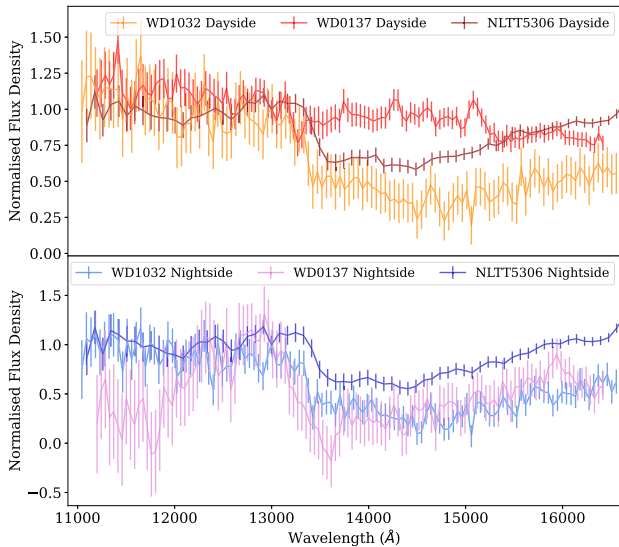


Figure 23. Comparison of dayside and nightside spectra of WD1032+011B alongside WD0137B (Zhou et al. 2022a) and NLTT5306B (Amaro et al. 2023). The upper panel shows the dayside spectra of these objects and the lower panel shows the nightside spectra. Spectra of WD1032+011B are in orange and light blue, WD0137B is shown in red and purple, and NLTT5306B is shown in dark red and dark blue. All spectra have been normalized such that the flux at 13000 Å is at a value of 1.

do not compare to EPIC2122B due to the difference in external irradiation flux being too vast to show the key effects of irradiation. Similarly, we do not compare to the eclipsing system SDSS1411B due to its significantly later spectral type, which causes morphological differences in its spectra. Fig. 23 shows the dayside and nightside spectra of these three irradiated brown dwarfs, with all spectra normalized such that the flux at 13000 Å is at a value of 1.

As can be seen, the dayside and nightside spectra for WD1032+011B and NLTT5306B are particularly similar, following the same overall trend with only minor differences in the depth of the water feature. WD0137B exhibits a much flatter dayside spectrum and a nightside spectrum that differs shortwards of 13000 Å. As WD0137B receives an external irradiation flux an order of magnitude higher than that received by WD1032+011B and NLTT5306B, this apparent flattening of the water absorption feature present in the spectrum of the dayside is likely due to an increased level of irradiation. WD0137B also exhibits an irradiation-driven temperature inversion on the dayside (Lee et al. 2020). Additionally, the nightside spectrum of WD0137B does not exhibit the rise in flux seen in at shorter wavelengths in the spectra of both WD1032+011B and NLTT5306B, which deviates from what would be expected from atmospheric models. Part of this difference in the J band of WD1032+011B can be explained by the best-fitting spectral type being an L1 peculiar type, which tend to exhibit this slope bluewards of 13000 Å. However, this characteristic is also seen for NLTT5306B, which has been classified as an L5 spectral type. We note that both of these objects are inflated, whereas WD0137B does not exhibit signs of inflation (Lew et al. 2022). Thus, it seems that the inflation of the brown dwarf, which is likely due to the irradiation from the white dwarf slowing down the contraction of the brown dwarf, is causing this increase at the short wavelength end of the dayside and nightside spectra of both WD1032+011B and NLTT5306B.

8.5 Inflation of WD1032+011B

As they age, brown dwarfs cool, contract, and evolve through spectral types M, L, T, and Y. Less massive brown dwarfs tend to have a faster cooling rate compared to more massive brown dwarfs (Marley et al. 2021). Older brown dwarfs therefore have smaller radii than younger, less-evolved brown dwarfs. Casewell et al. (2020a) performed a kinematic analysis on WD1032+011 which determined it as a likely member of the thick disc within our Galaxy. As such, they derived an age estimate of 5–10 Gyr. Using the Sonora brown dwarf evolutionary models, a $70 M_{\text{Jup}}$ brown dwarf at an age of 5 Gyr and an effective temperature of 1748 K should have a radius of $\sim 0.086 R_{\odot}$. The radius of WD1032+011B measured from its eclipse is $0.1052 R_{\odot}$, indicating that it is inflated. An inflated radius is also suggested for the non-eclipsing brown dwarf NLTT5306B, which Amaro et al. (2023) propose can be explained by revising the age estimate to be significantly younger. If we consider a younger age, in order to have a radius of $0.1052 R_{\text{Jup}}$, WD1032+011 would have to be only 500 Myr old. Since the cooling age of the white dwarf is 455 Myr, this would require a main-sequence lifetime of only 45 Myr. This is unphysically short as a main-sequence star would need to be at least $8.7 M_{\odot}$ for its lifetime to be 45 Myr, and such a star would not evolve into a $0.4502 M_{\odot}$ white dwarf. Therefore, we suggest that the radius of $0.1052 R_{\text{Jup}}$ is larger than models would predict due to the constant irradiation slowing down the contraction of the brown dwarf.

We note that of the irradiated brown dwarf companions to white dwarfs presented in Fig. 22, only the two least irradiated systems, NLTT5306B and WD1032+011B, show evidence of inflation. As the white dwarf hosts of these brown dwarfs have lower effective temperatures, they have had more time to cool and pump heat into the interior of the brown dwarfs, which could slow the contraction and cause inflated radii (Casewell et al. 2020b). The longer wavelength irradiation from these white dwarfs is more easily absorbed by deeper layers of the atmosphere. Additionally, ultraviolet and shorter wavelength incident flux are more susceptible to scattering in the brown dwarf atmosphere, making it more difficult to reach the interior (Christiansen et al. 2019), and the brown dwarfs with higher levels of irradiation may have had more of their upper atmosphere dissociated by the ultraviolet heating.

It is possible that WD1032+011B migrated inwards towards the end of the main-sequence lifetime of the white dwarf, and energy dissipation from the brown dwarf re-inflated it and set the evolution time to zero (Rozner et al. 2022). However, this is unlikely due to cooling age of the white dwarf. Another potential scenario for the inflation of WD1032+011B is that it is a post-bounce cataclysmic variable, where the orbital period has decreased and then increased again during evolution and mass transfer (e.g. Pala et al. 2018). The loss of angular momentum occurs on a comparable time-scale to the thermal time-scale of the donor star. This perturbs the donor star from its thermal equilibrium, causing it to have a slightly inflated radius compared to an isolated star (Knigge, Baraffe & Patterson 2011). However, it is most likely that the constant irradiation from the white dwarf is slowing the contraction of the brown dwarf as it evolves, causing it to appear inflated. WD1032+011B is the only eclipsing white dwarf–brown dwarf binary which shows evidence that the brown dwarf is inflated.

8.6 Potential cataclysmic variable evolution

We consider a potential evolution scenario for WD1032+011 if it is a detached cataclysmic variable. We calculate the Roche Lobe

filling factor of WD1032+011B as 0.474, leading to the stellar surface of the brown dwarf having a maximum deformation from a perfect sphere of 3.5 per cent. The ellipsoidal variation is equal to ~ 7 per cent of the total flux from the secondary, which corresponds to a 0.5 per cent ellipsoidal variability in the total flux of the system, which is negligible compared to the ~ 8 per cent variation in flux which is introduced by irradiation and reflection.

Schreiber, Belloni & van Roestel (2023) proposed a mechanism where short period cataclysmic variables can detach due to the emergence of a magnetic field on the white dwarf, which transfers angular momentum from the spin of the white dwarf into the orbit and increases the orbital radius. Simulations of this evolutionary scenario were performed using the MESA code (Paxton et al. 2011, 2013, 2015, 2018, 2019; Jermyn et al. 2023, r24.03.1). The initial conditions are a detached post-common-envelope binary with a secondary mass of $0.65 M_{\odot}$ and an initial period of 0.5 d. Evolution until the end of the cataclysmic variable phase assumed angular momentum loss using the same prescription as (Knigge, Baraffe & Patterson 2011) which is tuned to reproduce the observed masses and radii of cataclysmic variable donor stars. Once the donor star reaches a mass of $69 M_{\text{Jup}}$, we detach the binary by increasing the orbital period to 2.2 h and follow the evolution of the secondary star alone.

It takes approximately 2 Gyr from the common envelope phase for the system to come into contact and reach a donor mass of $69 M_{\text{Jup}}$, at which point the newly detached secondary has a temperature of 2300 K and a radius of $0.11 R_{\odot}$. It takes a further 0.2 Gyr for the secondary to shrink to the observed radius of WD1032+11B, at which point it has cooled to an effective temperature of 2100 K. During the cataclysmic variable phase the white dwarf would be heated by compressional heating to 10 000–15 000 K (Pala et al. 2022). The observed temperature of 9950 K is consistent with 0.2 Gyr of cooling from an initial temperature of 12 500 K. The total age of the system would depend upon the initial orbital period of the binary, since a wider orbit would take longer to come into contact. We conclude that an evolutionary scenario whereby WD1032+011 is a detached cataclysmic variable is consistent with both the kinematic age and the observed radii and temperatures of the white dwarf and secondary star. The main objection to this explanation is that the spectrum of the white dwarf shows no sign of magnetism. Therefore if a strong field on the white dwarf is responsible for detaching the cataclysmic variable, the field must be short-lived.

9 CONCLUSIONS

We present *HST* Wide Field Camera 3 time-resolved spectrophotometry of the eclipsing white dwarf–brown dwarf binary WD1032+011B. We derive a broad-band light curve which shows the primary eclipse, where the brown dwarf fully occults the white dwarf. Sub-band light curves do not show any wavelength-dependent changes in intensity, indicating that the irradiation equally penetrates the entire pressure range probed by our WFC3 spectra. We isolate the brown dwarf spectrum for different orbital phases including noon and midnight, and find that our dayside spectrum is on average 81 per cent brighter than our nightside spectrum. We calculate the brightness temperature across the entire spectral range, and find a 210 K difference between the dayside and nightside. Via comparison to field brown dwarfs, we identify the most likely spectral type of WD1032+011B as L1 pec. We use atmospheric retrievals to derive a dayside temperature of 1748^{+66}_{-67} K and a nightside temperature of 1555^{+76}_{-62} K. We do not recover clouds above the photosphere, and the dayside spectrum favours a cloud-free scenario, however the PICASO forward models fit the short wavelength data better when

including clouds. We find that WD1032+011B is well-aligned in the mass–radius and temperature contrast–external irradiation flux parameter spaces of hot Jupiters and irradiated brown dwarfs. The brown dwarf radius is inflated compared to evolutionary models, and this inflation is likely driven by the irradiation from the white dwarf, which slows the brown dwarf’s contraction. WD1032+011B is the only known inflated brown dwarf in an eclipsing white dwarf–brown dwarf binary, and upcoming *JWST* observations will further characterize the differences between its dayside and nightside atmospheres.

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DATA AVAILABILITY

The Hubble WFC3 data are available via the Mikulski Archive for Space Telescopes portal at <https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>.

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APPENDIX A: CORNER PLOT OF BROAD-BAND LIGHT CURVE MCMC

This paper has been typeset from a $\text{\TeX}/\text{\LaTeX}$ file prepared by the author.

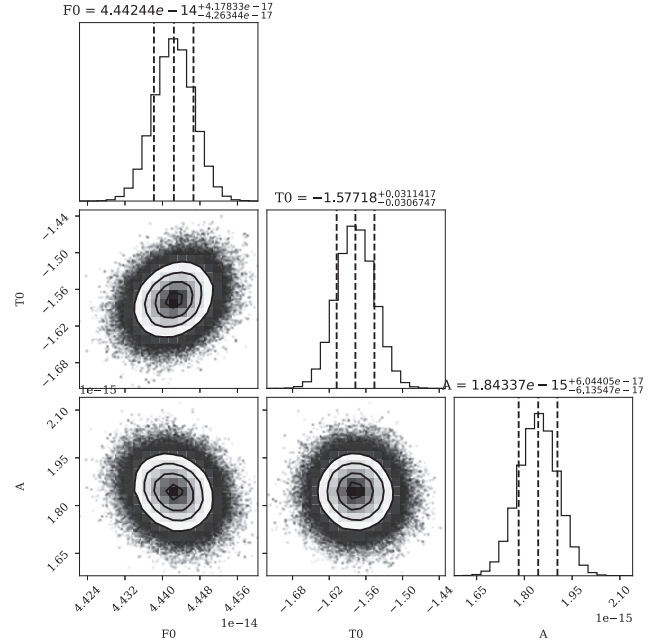


Figure A1. Corner plot showing the posterior distribution of the light-curve model parameters for our MCMC fitting.