HST/WFC3 Complete Phase-resolved Spectroscopy of White-dwarf-brown-dwarf Binaries WD 0137 and EPIC 2122

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Abstract

Brown dwarfs in close-in orbits around white dwarfs offer an excellent opportunity to investigate properties of fast-rotating, tidally locked, and highly irradiated atmospheres. We present Hubble Space Telescope Wide Field Camera 3 G141 phase-resolved observations of two brown-dwarf-white-dwarf binaries: WD 0137-349 and EPIC 212235321. Their 1.1–1.7 μm phase curves demonstrate rotational modulations with semi-amplitudes of 5.27% ± 0.02% and 29.1% ± 0.1%; both can be fit well by multi-order Fourier series models. The high-order Fourier component amplitudes vary with phase in a manner similar to the first-order component and are likely caused by hot spots located at the substellar points, suggesting inefficient day/night heat transfer. Both brown dwarfs’ phase-resolved spectra can be accurately represented by linear combinations of their respective day- and nightside spectra. Fitting the irradiated brown dwarf model grids to the dayside spectra require a filling factor of ~50%, further supporting a hot spot dominating the dayside emission. The nightside spectrum of WD 0137-349B is fit reasonably well by non-irradiated substellar models, and the one of EPIC 21223521B can be approximated by a Planck function. We find strong spectral variations in the brown dwarfs’ day/night flux and brightness temperature contrasts, highlighting the limitations of band-integrated measurements in probing heat transfer in irradiated objects. On the color–magnitude diagram, WD 0137-349B evolves along a cloudless model track connecting the early-L and mid-T spectral types, suggesting that clouds and disequilibrium chemistry have a negligible effect on this object. A full interpretation of these high-quality phase-resolved spectra calls for new models that couple atmospheric circulation and radiative transfer under high-irradiation conditions.

Unified Astronomy Thesaurus concepts: Exoplanet atmospheres (487); Stellar atmospheres (1584); Brown dwarfs (185); White dwarf stars (1799); Atmospheric circulation (112); Spectroscopy (1558); Time series analysis (1916)

Supporting material: animation

1. Introduction

In planetary atmospheres, the thermal, compositional, and cloud distributions vary in three dimensions, and these structures are further shaped by atmospheric circulation (e.g., Showman & Guillot 2002; Showman et al. 2008; Parmentier et al. 2013; also see a recent review by Showman et al. 2020). One of the ultimate objectives for characterizing planetary atmospheres is to precisely map the three-dimensional structures and decipher the relationship between the formation of heterogeneous atmospheric structures and external factors such as irradiation strength and spectra, as well as intrinsic factors such as the planet size, effective temperature, surface gravity, and rotation rate. Hot Jupiters have been a focus of this investigation of planetary atmospheres (e.g., Knutson et al. 2012; Stevenson et al. 2014; Zellem et al. 2014; Parmentier & Crossfield 2018; Arcangeli et al. 2019). They occupy a unique parameter space with respect to irradiation, effective temperatures, and day/night contrasts. Because hot Jupiters are typically tidally locked, a permanent and steep longitudinal temperature gradient is established in their atmosphere, which forces heat to transport globally. The self-luminous brown dwarfs and planetary-mass companions also offer critical insights into planetary atmospheric dynamics (e.g., Showman & Kaspi 2013; Apai et al. 2017; Showman et al. 2020; Tan & Showman 2021). With thermal structures determined by internal heat flux and rotation rates that are similar to solar system gas giants, these objects may display a circulation pattern that are more representative of exoplanets than the extreme cases presented by hot Jupiters. From an observational perspective, compared to other types of close-in or transiting planets, both hot Jupiters and directly imaged brown dwarfs are more favorable for high-precision observations. Their time-resolved spectroscopic observations directly probe the heterogeneous structures (e.g., Stevenson et al. 2014; Apai et al. 2013; Kreidberg et al. 2018; Arcangeli et al. 2019), delivering the most comprehensive information about the atmospheric dynamics of exoplanets.
A rare group of brown dwarfs that closely orbit their white dwarf hosts offer remarkable opportunities to test substellar atmospheric circulation models beyond the parameter space that has been explored in hot Jupiters and self-luminous brown dwarfs (e.g., Maxted et al. 2006; Casewell et al. 2018). These systems have experienced common envelope evolution, the period when the progenitor of the white dwarf expands and engulfs the brown dwarf. At the same time, the brown dwarf also truncates the red giant’s evolution by accelerating the expulsion of the stellar envelope. These interactions exert a drag force onto the brown dwarf, exhaust its kinetic energy, bring it down to a lower orbit. Eventually, as the host evolves into a white dwarf, the binary ends up with a tight orbit (on the order of $10^{-2}$ au; e.g., Maxted et al. 2006). The strong tidal force quickly locks the brown dwarf into synchronous rotation with periods as short as $\sim1.1$ hr (Casewell et al. 2018). Despite the fact that these brown dwarfs are more massive and formed differently than giant planets, their atmospheres resemble planetary ones in their compositions, equation of state, and effective temperatures. Therefore, they are interesting targets for detailed investigations of highly irradiated substellar atmospheres.

As a result of their evolution, these post-common-envelope brown dwarfs have three properties that help uniquely constrain substellar atmospheric models: First, due to their close orbits, these brown dwarfs receive approximately the same intensity of irradiation as hot and even ultra-hot Jupiters. Second, white dwarf hosts have much bluer spectra than main-sequence stars that host hot Jupiters. As a result, the peak of the irradiating spectrum is in the blue optical or even ultraviolet (UV) wavelengths. Atoms in the upper atmospheres can more easily absorb the short-wavelength irradiation, which results in temperature inversions as well as ionized hydrogen atoms. Third, the rotation rates of the brown dwarfs are more than one order of magnitude faster than those of typical tidally locked hot Jupiters. The rapid rotation introduces strong Coriolis force, which can shape the equatorial jets and reduce day/night heat transfer efficiency (Lee et al. 2020; Tan & Showman 2020). From an observational point of view, because of the moderate companion-to-host flux contrasts ($\sim10$ in the infrared, compared to $>10^2$ that is typical to hot Jupiters), the phase curves of these brown dwarfs have signal-to-noise ratios ($S/N$s) superior to those of hot Jupiters, enabling more strict tests of atmospheric theories.

The atmospheric properties of these highly irradiated brown dwarfs have been investigated through state-of-the-art models. Tan & Showman (2020) investigated the impact of fast rotation rates of these brown dwarfs by comparing GCM simulations of multiple rotation periods. Lee et al. (2020) combined GCM and radiative transfer models for the brown dwarf WD 0137-349B and compared its predicted and observed thermal phase curves. Both studies found that the fast rotation rates significantly decrease the meridional width of the equatorial jets and suppress the day-to-night heat transfer. The dayside hot spot is located near the substellar point, unlike the typically eastward-shifted hot spots in hot Jupiter atmospheres. These works predicted that these brown dwarfs that are irradiated by white dwarfs have greater day/night temperature contrasts than hot Jupiters.

Lothringer & Casewell (2020) calculated the spectra from the irradiated hemispheres of two brown dwarfs, WD 0137-349B and EPIC 212235321B. They created models based on the PHOENIX code and carefully incorporated the effect of strong UV irradiation in deriving the emission spectra of the brown dwarfs. They found that the irradiation efficiently heats the middle and upper atmospheres of the brown dwarf, which in turn breaks molecules such as H$_2$O and H$_2$ through thermal dissociation. Despite the fact that the cooler brown dwarf (WD 0137-349B) of the two has an equilibrium temperature more similar to typical hot Jupiters, its dayside spectrum resembles ultra-hot Jupiters. Both brown dwarfs are predicted to have weak or no molecular absorptions on their daysides. These model predictions can be tested by phase-resolved spectra.

We present Hubble Space Telescope (HST) Wide Field Camera 3 (WFC3) observations of two WD-BD binary systems WD 0137-349 (hereafter WD 0137$^{12}$) and EPIC 212235321 (hereafter EPIC 2122). Both systems are detached binaries with no ongoing mass exchange or accretion, and hence their phase curves only trace the atmospheres of individual components. The irradiated brown dwarfs in these two binaries are in an unexplored parameter space with respect to their irradiation, temperature, surface gravity, and rotation rates (Figure 1). Brown dwarf WD 0137B is a $M = 55M_{\text{Jup}}$ companion to its $M = 0.39 M_{\odot}$, $T_{\text{eff}} = 16,500$ K white dwarf host at a separation of $0.65 R_{\odot}$ (0.003 au) (Maxted et al. 2006). Because of the tiny orbital semimajor axis, the brown dwarf is tidally locked in a short orbital/rotational period of 116 minutes and has a radiative equilibrium temperature of 1990 K. Constant intense irradiation received by the brown dwarf’s dayside hemisphere establishes a radical temperature difference between its day- and nightside. This day/night contrast is best presented by the large amplitude rotational modulations in its optical (V/R/I bands), near-infrared ($J/H/K$ bands), and mid-infrared (Spitzer/IRAC Channels 1–4) light curves, from which Casewell et al. (2015) found that WD 0137B’s dayside brightness temperatures decreased from 2400 to 1100 K from $J$ band to Spitzer Channel 4 (8 $\mu$m) and nightside brightness temperatures decrease from 2100 to 400 K within the same wavelength ranges. The day/night brightness temperature differences range from 400 to 800 K.

The $\sim58M_{\text{Jup}}$ brown dwarf EPIC 2122B (Casewell et al. 2018) is in an even tighter orbit (0.44 $R_{\odot}$ (0.002 au) semimajor axis) around its $M = 0.47 M_{\odot}$, $T_{\text{eff}} = 24,900$ K white dwarf host. EPIC 2122B’s has the shortest orbital/rotational period among non-interacting companions: 68.21 min. Its equilibrium temperature reaches 3435 K, making it the second-hottest irradiated substellar object after KELT-9b (Gaudi et al. 2017) and a distinctive target for atmospheric studies. Its extreme day/night contrast has been demonstrated by the enormous 17% semi-amplitude in its $i$-band light curve (Casewell et al. 2018).

The spectroscopic time series of these two WD-BD systems deliver rich information about the brown dwarfs’ fundamental atmospheric properties, including circulation patterns and day/night temperature contrasts. In this paper, we present a detailed analysis of the complete phase-resolved spectra of these two binaries. In Section 2, we describe the HST observations and time-resolved spectroscopic data reduction procedures; in Section 3, we analyze and interpret the broadband phase curves; in Section 4, we present the phase-resolved spectra of the two irradiated brown dwarfs and compare them with various models; in Section 5, we discuss the observations of WD 0137B and EPIC 2122B in the context of irradiated brown dwarfs. They found that the irradiation efficiently heats the middle and upper atmospheres of the brown dwarf, which in turn breaks molecules such as H$_2$O and H$_2$ through thermal dissociation. Despite the fact that the cooler brown dwarf (WD 0137-349B) of the two has an equilibrium temperature more similar to typical hot Jupiters, its dayside spectrum resembles ultra-hot Jupiters. Both brown dwarfs are predicted to have weak or no molecular absorptions on their daysides. These model predictions can be tested by phase-resolved spectra.

12 A note on our nomenclature: we refer the white dwarf host as WD 0137A, the brown dwarf companion as WD 0137B, and the binary system as WD 0137. The same scheme goes for EPIC 2122A, EPIC 2122B, and EPIC 2122.
planetary atmospheres and brown dwarf evolution; finally, in Section 6, we conclude and summarize our results.

2. Observations and Data Reduction

Observations of the WD-BD binary systems WD 0137 and EPIC 2122 are part of the HST program GO-1594713 (PI: Apai), carried out by the Wide Field Camera 3 infrared Channel (WFC3/IR). WD 0137 was monitored over five consecutive HST orbits from UTC 2020 June 20 18:46:25 to 2020 June 21 01:50:02. Each orbit began with one 29.6 s direct-imaging exposure in the F132N filter. We used this image to identify the target’s position on the detector and establish the wavelength solution (Pirzkal et al. 2016). Fourteen 179 s G141 spectroscopic exposures were taken immediately after. In total, 70 spectra were collected, forming a spectral time series that was 480 minutes long and covered 4.1 periods of the system.

EPIC 2122 was observed in a similar setup over four consecutive HST orbits from UTC 2020 May 06 18:09:08 to 2020 May 06 23:35:11. Because EPIC 2122 is fainter than WD 0137, the direct-imaging frames were taken in the medium-band F127M filter in order to secure sufficient photons for wavelength calibration. Thirty-two 313 s G141 exposures were obtained in total, constituting a time series that was 384 minutes long and covered 5.6 orbital periods of EPIC 2122.

We downloaded the CalWFC3 pipeline product fit files and the reduced data using a pipeline based on the WFC3/IR spectroscopic software aXe (Kümmel et al. 2008). This pipeline has been widely used in time-resolved observations of brown dwarfs (e.g., Buenzli et al. 2012; Apai et al. 2013). A window with a radius of four pixels was adopted to extract the spectra and calculate the associated uncertainties. The G141 spectral resolution was $R \sim 130$ at 1.4 $\mu$m, corresponding to a velocity resolution of $\Delta v = 2.3 \times 10^4$ km s$^{-1}$. Because this resolution is significantly coarser than the maximum radial velocities (RVs) of both systems ($210$ km s$^{-1}$ for WD 0137B in Longstaff et al. 2017, and 308 km s$^{-1}$ for EPIC 2122B in Casewell et al. 2018), the RV variations can be safely neglected in wavelength calibration. We then conducted aperture and “ramp effect” corrections. The aperture correction coefficients were derived by linearly interpolating the lookup table in Kuntschner et al. (2009). We modeled and corrected for the systematics related to detector charge-trapping, using the physically motivated RECTE model (Zhou et al. 2017), which calculated the ramp profile based on two free parameters representing numbers of two populations of trapped charges at the beginning of the observations. We simultaneously fit the RECTE model and a sine wave to the 1.12–1.65 $\mu$m broadband phase curves, and then divided the optimal ramp model from each spectrum. Figure 2 shows summaries of the data reduction results. Both targets demonstrate high-amplitude and wavelength-dependent periodic modulations.

3. Light-curve Analyses

3.1. The Broadband Light Curves

We first determine the system period and modulation amplitude by fitting Fourier series models to the normalized broadband (1.12–1.65 $\mu$m) light curves. The Fourier series is defined by Equation (1)

$$ \mathcal{F} = 1 + \sum_k a_k \sin(2\pi t/(P/k)) + b_k \cos(2\pi t/(P/k)), $$

in which $P$ is the period, and $a_k$ and $b_k$ are the $k$th-order coefficients of the sin and cos terms. They are related to the semi-amplitude (amp) and the phase offset ($\phi$) by

$$ \text{amp}_k = \sqrt{a_k^2 + b_k^2} $$

$$ \phi_k = \arctan(b_k/a_k). $$

In a hemispherically integrated light curve, amplitudes quickly diminish with an increasing $k$. Meanwhile, odd-order (except $k = 1$) signals are not present in the light curve because of symmetry (Cowan & Agol 2008). Therefore, we start the fit with the simplest model—only including the base order ($k = 1$).
Figure 2. Summary of the time-resolved WFC3/G141 spectroscopic observational results for WD 0137 (upper) and EPIC 2122 (lower). In both figures, the top subplots show three representative spectra: the brightest (blue), the faintest (orange), and the average (black). The left subplots show the normalized 1.12–1.65 μm integrated phase curves. Our observations captured 4.1 and 5.6 periods of WD 0137 and EPIC 2122, respectively. The colors of the points also represent the normalized broadband brightness. The lower right subplots show the time-resolved spectra. The color map demonstrates the flux density relative to the mean value of the same wavelength—deep red/blue colors correspond to high modulation amplitudes in that wavelength.
— and gradually increase the model complexity by adding even-order \((i = 2k, \; k \geq 1)\) terms. In each iteration, the best-fitting \(P, \; a_k,\) and \(b_i\) are determined by a least-\(\chi^2\) criterion and the Bayesian Information Criterion (BIC) value is recorded. We use \(\Delta \text{BIC}_N = \text{BIC}_N - \text{BIC}_1\), the BIC difference between fitting the \(k_{\max} = N\)-th-order and the base-order Fourier series, to select the best model: the one with the least \(\Delta \text{BIC}\).

The best-fitting values and the BICs are listed in Table 1, and the comparisons between the observed and best-fitting phase-folded light curves are presented in Figure 3. The WD 0137 light curve favors the \(N = 2\) Fourier series model, which has a best-fitting period of \(P = 1.917 \pm 0.001\) hr. This value is in the middle of published RV measurements (1.927 \pm 0.005 hr in Maxted et al. 2006, \(P = 1.9063205(7)\) hr in Casewell et al. 2015, and \(P = 1.906318536(2)\) hr in Longstaff et al. 2017). The discrepancy between ours and the most precise Longstaff et al. (2017) period is 40 s, more than 10 times the joint uncertainties. This may be attributed to the fact that the RV and phase curve observations trace different periodic motions (orbital motion of the system versus atmospheric rotation). If WD 0137B’s atmosphere contains a retrograde jet, the period measured by the phase curve can be slightly prolonged. The semi-amplitudes of the \(k = 1\) and \(k = 2\) waves are 5.28\% \pm 0.02\% and 0.45\% \pm 0.02\%, respectively. The two waves are almost in-phase, with only a small offset of 0.12 \pm 0.04 rad. Based on the most recent and precise ephemeres (Longstaff et al. 2017), the phase difference between the light-curve peak and substellar point is \(\Delta \phi = 0.01 \pm 0.03\) rad, i.e., no significant phase shift is detected.

The light curve of EPIC 2122 favors a more complex \(N = 4\) Fourier series composed of \(k = 1,\; 2,\; 4\), i.e., of three waves. The best-fitting period is 1.1368 \pm 0.0004 hr, consistent within 1\(\sigma\) with the much more precise K2 light-curve period \((P = 1.136869(1)\) hr; Casewell et al. 2018). The semi-amplitudes of the \(k = 1,\; 2,\; 4\) waves are 29.1\% \pm 0.1\%, 3.7\% \pm 0.1\%, and 0.5\% \pm 0.1\%. Similar to what is observed in WD 0137, the waves of all three orders are nearly in-phase. The phase offsets of the \(k = 2\) and \(4\) waves relative to the \(k = 1\) wave are 0.07 \pm 0.03 rad and –0.1 \pm 0.2 rad, respectively.

### Table 1: Broadband Light-curve Fitting Results

| \(N\) | \(P\) (hr) | \(\text{amp}_1\) (%) | \(\text{amp}_2\) (%) | \(\text{amp}_4\) (%) | \(\Delta \phi_1^a\) (rad) | \(\Delta \phi_4^a\) (rad) | \(\Delta \text{BIC}\) | Favored |
|---|---|---|---|---|---|---|---|
| WD 0137 |
| 1 | 1.928 \pm 0.003 | 5.30 \pm 0.06 | ... | ... | ... | ... | 0 | N |
| 2 | 1.917 \pm 0.001 | 5.28 \pm 0.02 | 0.45 \pm 0.02 | ... | 0.12 \pm 0.04 | ... | –140.1 | Y |
| 4 | 1.917 \pm 0.001 | 5.27 \pm 0.02 | 0.45 \pm 0.02 | 0.04 \pm 0.02 | 0.14 \pm 0.04 | 0.7 \pm 0.5 | –135.8 | N |
| EPIC 2122 |
| 1 | 1.135 \pm 0.003 | 29.2 \pm 0.7 | ... | ... | ... | ... | 0 | N |
| 2 | 1.1368 \pm 0.0005 | 29.0 \pm 0.1 | 3.7 \pm 0.1 | ... | 0.06 \pm 0.04 | ... | –100.4 | N |
| 4 | 1.1368 \pm 0.0004 | 29.1 \pm 0.1 | 3.7 \pm 0.1 | 0.5 \pm 0.1 | 0.07 \pm 0.03 | –0.1 \pm 0.2 | –111.6 | Y |

**Note.**

\(^a\) \(\Delta \phi_2\) and \(\Delta \phi_4\) are the phase offsets of the \(k = 2\) and \(k = 4\) waves relative to the \(k = 1\) wave.

3.2. **A Comment on the Impact of Tidal Deformation**

It is predicted that tidal forces stretch both binary components into ellipsoids with major axes along the radial direction and introduce ellipsoidal oscillation—brightness variation due to changes in the projected area (e.g., Morris 1985; Pfahl et al. 2008). The projected area reaches its minimum at the \(\phi = 0, \pi\) phases and maximum at the \(\phi = \pi/2, \; 3\pi/2\) phases. The brightness variation amplitude will be proportional to the brown dwarf radius change due to tidal deformation (Pfahl et al. 2008):

\[
A \propto f_{\text{BD}} \frac{\Delta R}{R} \sin^2 i, \tag{4}
\]

in which \(i\) is the inclination and \(f_{\text{BD}}\) is the brown dwarf’s flux relative to the white dwarf. In the phase curve, the ellipsoidal oscillation manifests as a \(k = 2\) wave that is in the opposite phase to those of our observed \(k = 2\) Fourier components. In a few transiting exoplanet and brown dwarf systems, the tidal deformations of the host stars have been identified in the phase curves (e.g., Beatty et al. 2019; Wong et al. 2020). In the same studies, the planetary deformation signals are diluted by the star/planet flux ratio and fall below the detection limits. In our cases, the host white dwarfs are too compact to exhibit noticeable deformation. The brown dwarf companions—although they are more resistant to deformation than hot Jupiters, due to their higher surface gravities—suffer less from the flux diluting effect, because of the white dwarfs’ flux intensities being lower relative to typical planets’ host stars, and hence they may present detectable ellipsoidal deformation signals.

Using the ROCHE code, which is a part of the LCURVE software (Copperwheat et al. 2010), we find the amounts of deformation of the WD 0137B and EPIC 2122B to be \(\Delta R/R = 6.6\%\) and 4.5\%, respectively. Here, \(\Delta R/R\) is defined by the standard deviation of radii across all directions divided by the average radius. Inserting these numbers, as well as the inclinations and flux ratios \((i = 35^\circ, f_{\text{p}} = 7.02\%\) for WD 0137B; \(i = 56^\circ, f_{\text{p}} = 4.5\%\) for EPIC 2122B) into Equation (4), we derive the ellipsoidal oscillation amplitudes to be 0.15\% and 0.68\% for WD 0137B and EPIC 2122B, respectively. Compared to the Fourier series fitting results, these amplitudes are 33\% and 18\% of the \(k = 2\) wave amplitudes.

Two caveats regarding this estimate are worth noting. First, the observed \(k = 2\) signals and the ellipsoidal oscillations are in the opposite phases. Therefore, the tidal effect does not explain the high-order Fourier signals, but may slightly reduce the strength of the signal introduced by other effects (discussed later in Section 3.4). Second, using Equation (4) to estimate the oscillation amplitude assumes that the ellipsoid has a homogeneous brightness distribution, which is certainly not the case.
for the highly irradiated brown dwarfs. A complete model requires integrating across the heterogeneous ellipsoid, which requires precise knowledge of the surface brightness distribution and is beyond the scope of this paper. Because the exact ellipsoidal oscillation signals are likely insignificant, we will neglect this effect in our analysis.

Figure 3. Fitting Fourier series models of various maximum orders (upper: $N = 1$, middle: $N = 2$, lower: $N = 4$) to the light curves of WD0137 (left) and EPIC 2122 (right). The light curves are phase-folded to their best-fitting periods (1.917 hr for WD 0137 and 1.13368 hr for EPIC 2122) and shifted so that the peak of the $k = 1$ wave peak is at zero phase. Squared dots in different colors show broadband photometry in different HST orbits. The black solid lines show the best-fit Fourier series models, and the colored dashed lines show the model components. The $N = 1$ model is insufficient for either target and results in similar residual patterns that peak at $\pm \pi$ and 0 phases. The $N = 2$ and $N = 4$ models have much better fits in both cases. Based on BIC, the $N = 2$ model is the most favored for WD 0137 and $N = 4$ is the best one for EPIC 2122.

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3.3. Spectroscopically Resolved Light Curves

To investigate the wavelength dependence of the modulations, we fit the Fourier series to spectroscopically resolved light curves. These light curves are integrated in wavelength bins, the sizes of which are determined based on the S/N of the observations. For the higher-S/N WD 0137 data, the 1.12–1.65 μm bandpass is split into 13 0.04 μm channels, resulting an average S/N of 160 per bin; for the lower-S/N EPIC 2122 data, the bin size is 0.06 μm and the number of channels is eight, resulting an average S/N of 120 per bin. The maximum order (N) and the period (P) of the Fourier series are fixed to the best-fitting values in the broadband light-curve analyses (N = 2, P = 1.917 hr for WD 0137; N = 4, P = 1.1368 hr for EPIC 2122). Independent least-squares fits are performed for each light curve, to find their best-fitting semi-amplitudes and phase offsets.

Figure 4 shows the best-fitting semi-amplitudes and phases of the k = 1 and k = 2 waves as functions of wavelengths. In the WD 0137 case, the amplitudes of both k = 1 and k = 2 waves increase toward longer wavelengths. From 1.12 to 1.65 μm, amp1 and amp2 rise from 3.6% to 6.9% and from 0.26% to 0.72%, respectively. These trends are primarily due to the fact that the brown dwarfs cause the modulations and they contribute more to the total emission flux at longer wavelengths. Remarkably, in the wavelength intervals from 1.15 to 1.20 μm and from 1.35 to 1.50 μm, which coincide with two water absorption bands, amp1 is significantly higher than what a linear trend would predict. In contrast, amp2 agrees better with a linear trend except in the 1.50 μm channel where the amplitude is higher than the linear trend by 2σ. The phase offset of neither Fourier component shows significant wavelength dependence. The k = 2 wave is slightly ahead of the k = 1 wave by <0.2 rad (∼1σ) in most channels, similar to what has been observed in the broadband light curve.

The amplitudes and phase offsets of EPIC 2122’s spectroscopic modulations have a somewhat simpler wavelength dependence than those of WD 0137. The k = 1 wave amplitude increases with wavelength nearly linearly, from 24.9% at 1.14 μm to 31.4% at 1.62 μm, which coincide with two water absorption bands, amp1, is significantly higher than what a linear trend would predict. In contrast, amp2 agrees better with a linear trend except in the 1.50 μm channel where the amplitude is higher than the linear trend by 2σ. The phase offset of neither Fourier component shows significant wavelength dependence. The k = 2 wave is slightly ahead of the k = 1 wave by <0.2 rad (∼1σ) in most channels, similar to what has been observed in the broadband light curve.

Figure 4. The amplitudes and phase offsets of the k = 1 (blue circles) and k = 2 (yellow squares) waves as functions of wavelength for WD 0137 (left) and EPIC 2122 (right). In the amplitude plots, the left and right axes show the scales for the k = 1 and k = 2 waves, respectively. For easy visual comparisons, the k = 2 amplitudes are scaled up by 10× and 8× for WD 0137 and EPIC 2122, respectively. In the phase offset plots, the blue and yellow horizontal shades show the ±1σ ranges of the average phase offsets of the k = 1 and k = 2 waves, respectively.
observations—no significant spectroscopic variations are detected.

3.4. Interpreting the Phase Curves: Mapping WD 0137B and EPIC 2122B

To investigate the circulation patterns of the two irradiated brown dwarfs, we first retrieve top-of-the-atmospheric flux maps from the observed phase curves using the starry code (Luger et al. 2019), which constructs surface maps using spherical harmonic function as bases. Converting light curves to maps is highly degenerate. Therefore, rather than relying on spherical harmonic functions entirely, we adopt physically motivated prior setups to reduce the degrees of freedom of the model and regularize the fits. Based on the two properties of the observed light curves, namely that (1) they peak at $\phi = 0$ and (2) phase shifts between different wave modes are insignificant (Figure 4), we restrict our maps to only include the $l = 1, m = 0$ spherical harmonics basis ($Y_{1,0} = \frac{1}{2} \sqrt{3} \cos \theta$, $\theta$ is longitude) and a flat-top hot spot centered at the substellar point (lat = 0, lon = 0). The hot spot injection is implemented using starry’s built-in spot function. In this approach, there are four free parameters in map retrieval: (1) the baseline flux, (2) the scaling factor for $Y_{1,0}$, (3) the brightness contrast of the spot, and (4) the angular radius of the hot spot. The inclinations of the brown dwarfs’ spin axes are fixed based on literature values: 35° for WD 0137B (Maxted et al. 2006) and 56° for EPIC 2122B (Casewell et al. 2018). We use MCMC to find the best-fitting values.

The starry mapping results are presented in Figure 5. For both WD 0137B and EPIC 2122B, the $Y_{1,0}$ spot model reproduces the observations very well. Because the integrated phase curve of $Y_{1,0}$ is always a $k=1$ sine wave, the higher-order Fourier terms in the phase curves must come from the hot spot. As a result, the spot size can be constrained from the amplitude of the higher-order terms (Figure 6). For both WD 0137B and EPIC 2122B, the best-fitting spot angular radii are 10°–15°.

3.5. Interpreting the Phase Curves: Comparing Observations with GCMs

We then perform general circulation model (GCM) simulations for both brown dwarfs, to examine whether the top-of-atmospheric flux maps retrieved from the observations agree with the theoretical predictions. Our models are slightly modified from those used in Tan & Komacek (2019). In this model, the stellar irradiation is partitioned into two channels. This is to approximate the strong effect of the UV irradiation on
the dayside thermal structures. Under these setups, the GCMs are controlled by four free parameters: the brown dwarf Bond albedo, the partition fraction, and the two opacities of the two channels. We describe the details of our GCM simulations in the Appendix.

As shown in Figure 5, for both WD 0137B and EPIC 2122B, the GCM maps qualitatively match the starry retrieval results. In particular, the GCM maps also contain hot spots that are similar in size and position, compared to the ones in the starry maps. The close match between the GCMs and the observations is more clearly presented in the phase curve maps. The close match between the GCMs and the starry results are similar in size and position, compared to the ones in the Appendix.

4. Phase-resolved Spectra of the Brown Dwarfs

4.1. Modeling and Subtracting the White Dwarf Spectra

The observed WD+BD spectra (upper subplots in Figure 2) consist of two components: a constant white dwarf spectrum ($S_{\text{WD}}$) and a variable brown dwarf spectrum ($S_{\text{BD}}(\phi)$)

$$S_{\text{WD}+\text{BD}}(\phi) = S_{\text{WD}} + S_{\text{BD}}(\phi). \quad (5)$$

To obtain phase-resolved brown dwarf spectra for substellar atmospheric investigations, we subtract white dwarf model templates from the observations. Both WD 0137A and EPIC 2122A have pure hydrogen atmospheres, resulting in nearly featureless spectra that have been accurately modeled. In the (e.g., Koester 2010) grid that we adopted, two free parameters—$T_{\text{eff,WD}}$ and log $g_{\text{WD}}$—define the spectral template. We also include a linear scaling factor ($\alpha_{\text{WD}}$) as the third free parameter. $T_{\text{eff,WD}}$ and log $g_{\text{WD}}$ of WD 0137A and EPIC 2122A have been precisely determined in previous studies using high-resolution spectra (Maxted et al. 2006; Casewell et al. 2015; Longstaff et al. 2017; Casewell et al. 2018), and the scaling factor can be constrained using archival photometry. We collate the information from these previous studies by fitting synthetic photometry integrated from the model spectra to archival photometry with a Markov Chain Monte Carlo (MCMC) method implemented by emcee (Foreman-Mackey et al. 2013). By conducting this fit in a Bayesian manner, we incorporate the tight constraints of $T_{\text{eff,WD}}$ and log $g_{\text{WD}}$ and properly propagate the variant and covariant uncertainties to the template subtraction results.

In this fit, the best-fitting values of $\alpha_{\text{WD}}$, $T_{\text{eff,WD}}$, and log $g_{\text{WD}}$ maximize the posterior probability (expressed in the log-scale), which is defined by

$$\log P_{\text{WD}}(\theta) = \log P_{T_{\text{eff,WD}}} + \log P_{\log g_{\text{WD}}} + \log L(\theta). \quad (6)$$

![Figure 6. The amplitude ratios between the $k=1$ and $k=2$ waves in the phase curve of a hot spot map. Regardless of viewing geometry ($i=35^\circ$ and $56^\circ$) for WD 0137B and EPIC 2122B, respectively), the smaller the spot, the more significant the $k=2$ wave is. Therefore, higher-order Fourier components constrain the hot spot size.](image-url)
Figure 7. Temperature distributions at 0.05, 5, and 50 bar in the GCM simulation of WD0137B. Deep into the atmosphere, the temperature is approximately uniformly distributed. Near the top of the atmosphere, the temperature bifurcates into the two extrema of the day- and nightsides. At an intermediate pressure level, the hot spot is the most pronounced.

in which the log-likelihood function $\log L(\theta)$ is

$$\log L(\theta) \propto -\frac{\chi^2}{2},$$

and $\theta$ represents a set of $a_{\text{WD}}$, $T_{\text{eff,WD}}$, and $\log g_{\text{WD}}$. Here, $P_{T_{\text{eff,WD}}}$ and $P_{\log g_{\text{WD}}}$ are the prior probability distributions of the effective temperature and surface gravity of the white dwarf.

We assume them to be normally distributed (WD0137A: $T_{\text{eff}} \sim \mathcal{N}(16500, 500)$ K, $\log(g) \sim \mathcal{N}(7.50, 0.02)$, per Maxted et al. (2006); EPIC 2122A $T_{\text{eff}} \sim \mathcal{N}(24450, 150)$ K, $\log(g) \sim \mathcal{N}(7.63, 0.02)$, per Casewell et al. 2018). The $\chi^2$ is the chi-squared difference between model synthetic and observed photometry, for which we include the V, VST/g, and G bands for WD0137A, and the B, VST/g, and G bands for EPIC 2122A. We exclude the $U$-band observations due to the large extinction uncertainty, and the infrared data due to high brown dwarf flux contamination. Both binaries show modulations in these bands but the phases at which the photometric data were taken are unknown. Therefore, we consider the modulations as part of the photometric uncertainty: the adopted errors are the relative semi-amplitudes and the reported uncertainties combined in quadrature. Each MCMC fit contains 64 walkers and 600 iterations, with the first 300 discarded as part of the “burn-in” processes.

After the MCMC runs, we proceed by subtracting the best-fit WD models to isolate the brown dwarf components. The uncertainties in the brown dwarf spectra are a combination of the variance intrinsic to the observations (i.e., photon noise, readout noise, and dark current) and those propagated from the uncertain white dwarf properties. On average, variances in the white dwarf flux contribute to 49% and 6.7% of the total uncertainties in the spectra of WD0137B and EPIC 2122B, respectively. In Figure 8, the day- and nightside spectra of WD0137B and EPIC 2122B are presented. The day- and nightside spectra are the averages of the observations of phases of $\phi \in [-0.3, 0.3]$ rad and $\phi \in [\pi - 0.3, \pi + 0.3]$ rad, respectively. These ranges ensure that at least three observations with minimal spectral variations are included in each of the combinations and secure the precision of the derived day/night spectra. The dayside spectra of both brown dwarfs are featureless slopes. As for the nightside, a strong 1.4 $\mu$m water absorption feature is present in WD0137B, due to poor S/Ns. Between the two extrema, both brown dwarfs have flux differences of nearly an order of magnitude, and EPIC 2122B has a stronger overall flux variation than WD0137B.

In Figure 9, brown dwarf spectra at four representative phases between the day- and nightsides ($\phi = \pm \pi/3$ and $\phi = \pm 2\pi/3$) are also provided. In both brown dwarfs, the overall flux and spectral shapes evolve dramatically from day- to nightsides. In addition, a strict east–west symmetry is presented in both cases: spectra of the $+1/3\pi$ and $+2/3\pi$ agree with those of the $-1/3\pi$ and $+2/3\pi$ within 1$\sigma$.

4.2. Semi-empirically Fitting the Phase-resolved Spectra

To investigate the spectroscopic phase variations in the brown dwarf spectra, we conduct a joint analysis to fit the white dwarf and brown dwarf components together. We adopt a semi-empirical model to fit the combined white dwarf and brown dwarf spectra. This approach is motivated by the two-dimensional retrieval approach developed for hot Jupiter phase curves (Feng et al. 2020), in which the heterogeneous hot Jupiter atmospheres are approximated as linear combinations of two patches. Similarly, our model is expressed as a linear combination of the white dwarf ($S_{\text{WD}}$) and two brown dwarf spectral bases: the dayside $S_{\text{day,side}}$ and the nightside $S_{\text{night,side}}$. In the previous subsection, the white dwarf spectrum and its scaling factor have been tightly constrained, and the brown dwarf bases have also been empirically determined. We define the dayside scaling coefficient as $f(\phi)$, and thus express the nightside scaling coefficient as $1 - f(\phi)$. Therefore, the semi-empirical model can be expressed as

$$S_{\text{WD,BD}}(\phi) = a_{\text{WD}}S_{\text{WD}}(T_{\text{eff,WD}}, \log g_{\text{WD}}) + f(\phi)S_{\text{day,side}} + (1 - f(\phi))S_{\text{night,side}}.$$  

We fit each WFC3 spectra to this model, to find the best-fitting $a_{\text{WD}}$, $T_{\text{eff,WD}}$, $\log g_{\text{WD}}$, and $f(\phi)$. The same as with the white dwarf fits, the fittings here are conducted by emcee, to maximize the posterior probability:

$$\log P_{\text{WD,BD}}(\theta) = \log Pr(a_{\text{WD}}, T_{\text{eff,WD}}, \log g_{\text{WD}}) + \log L(\theta).$$

In this equation, $Pr(a_{\text{WD}}, T_{\text{eff,WD}}, \log g_{\text{WD}})$ is the joint posterior distribution derived in the previous subsection. Here, $\theta$ represents a set of $a_{\text{WD}}$, $T_{\text{eff,WD}}$, $\log g_{\text{WD}}$, and $f(\phi)$, while $\log L(\theta)$ is proportional to the $\chi^2$ difference between the observations and the WD+BD model.

In both cases, this semi-empirical model fits the observations very well at every orbital/rotational phase. Figures 10 and 11 show the fitting results of spectra at four representative phases.
for WD 0137 and EPIC 2122, respectively. In every case, the model agrees with the observations within 1σ. The excellent fit confirms the premise that the phase-resolved spectra of the irradiated brown dwarfs can be accurately reduced into a twodimensional linear space spanned by the day- and nightside spectra. This remarkable result significantly simplifies the analysis of the spectral time series. We no longer need to examine every spectrum, but rather conduct detailed investigations of the day- and nightside spectra and the contribution factors.

In Figure 12, phase-resolved dayside contribution factors \( f(\phi) \) that best fit WD 0137B and EPIC 2122B are compared.
They both have nearly sinusoidal shapes. However, the EPIC 2122B curve has a flatter nightside valley and a more narrow peak. This difference may suggest that the temperature longitudinal gradient is steeper in the dayside of EPIC 2122B than WD 0137B.

4.3. Day- and Nightside Brightness Temperatures of the Two Brown Dwarfs

Because the day- and nightsides can serve as the linear bases that represent the entire phase curves sufficiently and accurately to the limits of the current data, we focus the analysis on these two spectra. First, we characterize the spectra by deriving the wavelength-specific brightness temperatures ($T_B$); in the next subsection, we compare the spectra to substellar models.

Expressing emission spectra as $T_B$ offers a straightforward view of the atmospheric vertical structure and is widely used in brown dwarf and exoplanet studies (e.g., Ackerman & Marley 2001; Morley et al. 2014), as well as previous works on our targets (Casewell et al. 2015, 2018). Combined with a thermal ($T$-$P$) profile, $T_B$ can be mapped to a pressure level where the emission flux emerges. This mapping enables a dissection of the vertical structures of the substellar atmospheres in which the pressure level of the photosphere varies by more than an order of magnitude as a function of wavelength due to strong molecular absorption bands. To facilitate comparisons with other irradiated atmospheres (see Section 5.1), we present the day- and nightsides spectra of WD 0137B and EPIC 2122B in brightness temperatures. It is worth noting that our wavelength range is not in the Rayleigh–Jeans tail, so the Planck function, rather than the Rayleigh–Jeans law, should be used in deriving $T_B$.

We define $T_B$ as a hemispherically averaged measure. Thus, its value satisfies the equation

$$ f(\lambda) = \frac{\pi R_{\text{BD}}^2}{d^2} B(T_B), \quad (10) $$

in which $f(\lambda)$ is the observed brown dwarf flux density at wavelength of $\lambda$, $d$ is the distance of the system, $R_{\text{BD}}$ is fixed to $1 R_{\text{Jup}}$, and $B(T_B)$ is the Planck function. At wavelength $\lambda$, we invert Equation (10) to find $T_{B,\lambda}$. The results are shown in

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10}
\caption{WD+BD spectral model fitting results for WD 0137 at four representative phases between the day- and nightsides at $\phi = \pm 1/3 \pi$ and $\phi \pm 2/3 \pi$. The best-fitting white dwarf components are subtracted from all spectra. The lines are the best-fitting brown dwarf models, which are the sum of the scaled dayside component (yellow dashed lines) and the scaled nightside component (dashed lines). In every case, this semi-empirical model fits the observations well.}
\end{figure}
In Table 2, we list the $T_B$ of the two brown dwarfs in several representative bands (G141 broadband, F127M, F139M, and F153M). In all four cases (day/night of WD 0137B and EPIC 2122B), $T_B$ demonstrates strong wavelength dependence. In the daysides of both brown dwarfs, $T_B$ decreases monotonically toward longer wavelengths, from 2010 K at 1.12 μm to 1780 K at 1.65 μm in WD 0137B and from 3290 to 2870 K in EPIC 2122B. In the nightsides, WD 0137B’s $T_B$ has non-monotonic variations, which corroborates the water absorption in its nightside spectrum. It peaks at the center of the $J$ band (1.3 μm) with a value of 1650 K, drops below 1400 K at 1.6 μm, and then rises above 1450 K at 1.6 μm. As for the nightside of EPIC 2122B, its more noisy spectra lead to a wider $T_B$ range: from 500 to 1500 K. These variations of $T_B$ demonstrate that the G141 spectra probe a wide range of the brown dwarfs’ atmospheric pressure levels where temperatures can vary by a few hundred K.

Casewell et al. (2015) derived the day- and nightside $T_B$ of WD 0137B in multiple bands, including a few that have overlapping wavelength ranges with our observations: $T_{B,\text{day}} = 2418^{+201}_{-329}$ K in $J$, $T_{B,\text{day}} = 1585 \pm 329$ K in $H$, and $T_{B,\text{night}} = 2085^{+287}_{-769}$ K in $J$. In comparison, our dayside measurements are lower in the $J$ band ($T_{B,\text{day}} = 1935 \pm 28$ K, using the F127M band result as an approximation) but higher in the $H$ band ($T_{B,\text{day}} = 1833 \pm 23$ K, using the F153M band result as an approximation). We find a somewhat less wavelength-dependent $T_B$ than Casewell et al. (2015). Because the white dwarf templates are almost identical, the inconsistent brightness temperatures are likely caused by different photometric calibrations. However, it is worth noting that the day/night brightness temperature contrasts in the $J$ band are consistent between the two observations. For the rest of the paper, we will focus on discussing the WFC3-based measurements. It is also worth noting that the values of the nightside $T_B$ of WD 0137B in the Spitzer 3.6 and 4.5 μm bands listed in Casewell et al. (2015) are in agreement with the recently identified uniform nightside temperatures of hot Jupiters (Beatty et al. 2019; Keating et al. 2019).
log 4.95, 5.20 BD
dayside to nightside grids, which are based on the model presented in Lothringer & Casewell (2020). The grids for WD 0137B and EPIC 2122B are derived separately, to accommodate for the different strengths and spectral energy distributions of the white dwarfs’ irradiation, and the irradiation’s subsequent effect on the thermal profiles and photochemistry in the brown dwarfs’ atmospheres. Each grid is defined by four parameters: metallicity (Z), surface gravity (log gBD), interior temperature (Tint), and the heat redistribution fraction (f_red) that represents the redistribution of the heat from dayside to nightside (see Equation (1) in Lothringer & Casewell 2020). The metallicity is sampled at three values Z = 0, 0.5.
The surface gravity grid sample points differ slightly between WD 0137B and EPIC 2122B models, to account for their different masses: log gBD = 4.85, 5.10, and 5.35 for WD 0137B, and log gBD = 4.95, 5.20, and 5.45 for EPIC 2122B, corresponding to MBD = 28.6, 50.8, and 90.3 M_Jup, and MBD = 36.0, 63.9, and 113.7 M_Jup, respectively (assuming R = 1 R_Jup for both brown dwarfs). The interior temperature is defined as the effective temperature of a non-irradiated brown dwarf and sampled at Tint = 1400 and 1800 K for WD 0137B and Tint = 1000, 1500, and 2000 K for EPIC 2122B. The heat redistribution fraction grids include three values: f_red = 0.125, 0.25, and 0.5.

Figure 12. Comparing the dayside spectral contribution factors as functions of rotational phase between WD 0137B (blue squares) and EPIC 2122B (yellow triangle). Both have nearly sinusoidal shapes, but the EPIC 2122B curve has a flatter valley and a more narrow peak.

4.4. Dayside Spectral Model Comparisons

We seek models that best fit the observed spectra. For the dayside spectra, we adopted the irradiated atmospheric spectral grids, which are based on the model presented in Lothringer & Casewell (2020). The grids for WD 0137B and EPIC 2122B are derived separately, to accommodate for the different strengths and spectral energy distributions of the white dwarfs’ irradiation, and the irradiation’s subsequent effect on the thermal profiles and photochemistry in the brown dwarfs’ atmospheres. Each grid is defined by four parameters: metallicity (Z), surface gravity (log gBD), interior temperature (Tint), and the heat redistribution fraction (f_red) that represents the redistribution of the heat from dayside to nightside (see Equation (1) in Lothringer & Casewell 2020). The metallicity is sampled at three values Z = 0, 0.5.

The surface gravity grid sample points differ slightly between WD 0137B and EPIC 2122B models, to account for their different masses: log gBD = 4.85, 5.10, and 5.35 for WD 0137B, and log gBD = 4.95, 5.20, and 5.45 for EPIC 2122B, corresponding to MBD = 28.6, 50.8, and 90.3 M_Jup, and MBD = 36.0, 63.9, and 113.7 M_Jup, respectively (assuming R = 1 R_Jup for both brown dwarfs). The interior temperature is defined as the effective temperature of a non-irradiated brown dwarf and sampled at Tint = 1400 and 1800 K for WD 0137B and Tint = 1000, 1500, and 2000 K for EPIC 2122B. The heat redistribution fraction grids include three values: f_red = 0.125, 0.25, and 0.5.

In fitting the grid models, we include a filling factor (f_fill) as a free parameter. It represents the proportion of the projected area where the dayside emission comes from, and to account for the possibility that the observed dayside emission is dominated by a hot spot that only occupies part of the dayside hemisphere. The inclusion of the filling factor is further supported by the study of Taylor et al. (2020), who found that a single thermal profile with a filling factor performs as well as the more complex multi-profile approach in the retrieval of a heterogeneous atmosphere composed of high-contrast hot and cool components. For each grid point, we optimize f_fill such that it minimizes the residuals and we record the χ^2 values. Then, χ^2 values at all grid points are compared and the model that has the overall least χ^2 is the best-fitting one. The best-fitting model for WD 0137B’s dayside spectrum has Z = −0.5, log(g) = 4.85, T_{int} = 1400 K, f_red = 0.5, and f_fill = 0.43, although increasing Z to 0 or log(g) to 5.10 also results in reasonably good fits. All models with f_red = 0.5 and Z ≥ 0 fit EPIC 2122B’s dayside well, and the best one has Z = 0, log(g) = 4.95, T_{int} = 1000 K, f_red = 0.5, and f_fill = 0.54.

Despite the fact that these two brown dwarfs receive different irradiation, the dayside spectral fitting results of WD 0137B and EPIC2122B share multiple commonalities. In both cases, f_red is the most critical parameter determining the fit qualities, and f_red = 0.5, the upper bound in the grid, is required to reproduce the steep slopes in the observations. This value corresponds to the dayside-only redistribution scenario. This result is in agreement with what we find from the band-integrated phase curves: circulation is inefficient in transporting heat from dayside to nightside in these fast-rotating objects. For both brown dwarfs, the best-fitting f_fill values are around 50%.

This result, again, is in agreement with what the phase curves suggest: there is a hot spot that partially covers the dayside hemisphere. Additionally, because the distance between the binary components is on the same order as the brown dwarf radius, the incident angle at the limb regions of the brown dwarf is greater than those in the parallel beam incidence scenario. This leads to an even smaller amount of energy received by the limb, further reducing its contribution to the dayside spectra. Based on the best-fitting results, the dayside effective temperatures (T_{eff, day} = (T_{int}^4 + T_{int, irr}^4)^{1/4}, where T_{int} is the irradiation temperature defined in Lothringer & Casewell 2020) are 2430 and 4050 K for WD 0137B and EPIC2122B, respectively.

The reason that the irradiated atmospheric models perform better than non-irradiated models or blackbodies is illustrated by Figure 15, in which we break down the opacity contributions from atomic, molecular, and continuum sources, as well as present the flux contribution functions and thermal profiles of the best-fitting models. Due to their difference in irradiation and temperatures, the opacity sources differ significantly between the two brown dwarfs. In the cooler WD 0137B, molecular opacities dominate most of the 1.1 to 1.7 μm wavelength range, except at a few alkane lines where atomic opacities peak and the λ > 1.6 μm region where the continuum opacities (from H2-H2/He collision-induced absorption, henceforth abbreviated CIA) become significant. In the hotter EPIC 2122B, the continuum opacities contribute the most at shorter wavelengths (λ < 1.4 μm) but their importance drops below molecular opacities at longer wavelengths (λ > 1.4 μm). These differences result in a divergence in their flux contribution functions; in WD 0137B, longer wavelengths probe lower pressure levels (higher altitude); in EPIC 2122B, longer wavelengths probe higher pressure levels (lower altitude). There is another crucial difference between the daysides of the two brown dwarfs: while thermal inversions are predicted in both daysides, WD 0137B’s dayside flux in the G141 bandpass is mostly from below the inversion but EPIC 2122B’s dayside flux is mostly from above the inversion. Combining the effects of the contribution functions and the thermal profiles, we find that the shorter-wavelength emission is from a hotter region (and vice versa) in both brown dwarfs. Therefore, the dayside brightness temperature should decrease with wavelength, and this is exactly what we observed in WD 0137B and EPIC 2122B (Figure 13). However, the blackbody and non-irradiated models predict either a flat T_{B}
trend or a decrease of $T_B$ in molecular bands, contrary to the observed trend. We attribute this considerable disagreement to incorrect opacities and thermal profiles of those models in describing the brown dwarfs’ daysides.

The reason that the dayside brightness temperatures and effective temperatures differ are twofold. First, our brightness temperatures are hemispherically averaged quantities. However, the effective temperatures, which are derived from the spectral model fitting, characterize the hot spots, which dominate the emission, even though they occupy only fractions of the dayside surface area. Therefore, it is not surprising that the effective temperatures are higher than the band-averaged brightness temperatures, because the former represents only the hotter part of the hemisphere. Similarly, $f_{\text{fil}}$ is also applied to the Planck spectra in Figure 14; hence, on the shorter-wavelength side ($\lambda < 1.25 \, \mu m$), the blackbody models have
lower flux than the observed spectra despite their higher temperatures. Second, brightness temperatures characterize the pressure levels where the emission at a specific wavelength comes from, while effective temperatures describe the source function. In the irradiated atmospheres that contain significant molecular and continuum absorption sources, a joint use of the two quantities provides a more complete view of the atmospheric thermal structure (Figure 15).

4.5. Nightside Spectral Model Comparisons

For the nightside spectrum of WD 0137B, we experimented with two non-irradiated and clear atmosphere grids: the BTSettl (Allard et al. 2012) and Sonora (Marley et al. 2018) models. In this fit, we fix the scaling of the model to $R_{BD}^2/d^2$, in which $R_{BD} = R_{BDP}$ and $d$ is derived from the Gaia DR2 parallaxes (Gaia Collaboration et al. 2018), leaving the effective temperature ($T_{eff}$) and surface gravity ($\log(g)$) as the only free parameters. We optimize these parameters using a least-$\chi^2$ criterion, and find that the observed spectra favor a 1000–1100 K $T_{eff}$ and a high log($g$) of 5.5 for both grids. In the left panel of Figure 16, the best-fitting BTSettl and Sonora models are compared with the WD 0137B’s nightside spectrum. The models fit well in the $J$ band but overestimate the water absorption depth at 1.4 $\mu$m. This mismatch suggests that the temperatures at high altitude are too low in the models, compared to the brown dwarf, resulting in water bands deeper than those in reality.

Due to the low-S/N of EPIC 2122B’s nightside spectrum, we only fit a blackbody model and find a best-fitting $T_{eff}$ of $\sim$1300 K. This result is within the range of its nightside brightness temperatures.

5. Discussion

5.1. Comparing Day/Night Contrasts of Irradiated Substellar Objects

In Figure 17, we compare the day/night contrasts between WD 0137B and EPIC 2122B and hot Jupiters.
Two sets of measurements are adopted in this comparison: the relative flux contrast, defined as $A_F = (F_{\text{Day}} - F_{\text{Night}})/(F_{\text{Day}})$, and the relative brightness temperature contrast, defined as $\Delta T_B = (T_B,\text{Day} - T_B,\text{Night})/(T_B,\text{Day})$. In describing day/night contrasts, $A_F$ is directly derived from observations and $\Delta T_B$ is a close approximation (which may require minor correction; see, e.g., Taylor et al. 2020) of the true temperature contrasts, and hence both variables are popular in exoplanet and brown dwarf literature (e.g., Perez-Becker & Showman 2013; Komacek et al. 2017; Parmentier & Crossfield 2018; Beatty et al. 2019; Keating et al. 2019; Parmentier et al. 2020). For hot Jupiters, the $A_F$ data are from the collections in Parmentier & Crossfield (2018) with updates from Parmentier et al. (2020); the $\Delta T_B$ data are from Beatty et al. (2019). Most of the hot Jupiter measurements are taken with Spitzer/IRAC in its 3.6 and 4.5 μm channels, with the exception of three WFC3 flux contrast measurements of WASP-43b (Stevenson et al. 2014), WASP-18b (Arcangeli et al., 2018), and WASP-103b (Kreidberg et al. 2018). For WD 0137B and EPIC 2122B, their $A_F$ and $\Delta T_B$ are both wavelength-dependent within the G141 bandpass. Therefore, we present their spreads in Figure 17; the rectangles demonstrate the ±1σ ranges. In addition, a few representative band-averaged values (G141 broadband, HST F127M, F139M, and F153M) are also overplotted.

Based on atmospheric circulation models, the day/night contrast is positively correlated with the effective temperature, because the radiative cooling timescale is the primary factor that determines the day/night temperature difference (Komacek & Showman 2016). Objects with high equilibrium temperatures have shorter radiative cooling timescales and therefore have greater day/night temperature contrasts—and vice versa. Nevertheless, additional factors such as frictional drags, rotation rates (Komacek & Showman 2016; Komacek et al. 2017), and nightside clouds (Parmentier et al. 2020) can also affect the temperature contrast. Trends found in brightness temperatures of hot Jupiters measured in the Spitzer bandpasses support this prediction (Beatty et al. 2019; Keating et al. 2019), notwithstanding the large scatters and uncertainties in those measurements (see the gray triangles in Figure 17).

The $A_F$ and $\Delta T_B$ of WD 0137B and EPIC 2122B illustrate a more complicated picture. Rather than support or refute the hot Jupiter trends, the measurements of the irradiated brown dwarfs highlight a different characteristic of day/night contrasts: they are highly wavelength-dependent. Across the G141 bandpass, both $A_F$ and $\Delta T_B$ have a wide spread and their exact value depends on the specific wavelength. Given the fact that different wavelengths trace different pressure levels of the atmospheres and the day- and nightside thermal profiles vary, this wavelength dependence is not surprising, but rather is a consequence of the three-dimensional nature of the irradiated atmospheres. Spectral variations in $A_F$ and $\Delta T_B$ should be common among hot Jupiters and irradiated brown dwarfs (as predicted in Parmentier et al. 2020), and the primary reason that they are exhibited so strongly in WD 0137B and EPIC 2122B is the high S/N of our observations. The broad ranges of $A_F$ and $\Delta T_B$ increase the complexity of comparing day/night contrasts among irradiated objects and testing model predictions against observations. Based on the results of WD 0137B and EPIC 2122B, we strongly advocate for specifying the wavelengths and bandpasses of $A_F$ and $\Delta T_B$ when discussing the day/night contrasts of irradiated objects.

In the atmosphere of EPIC 2122B, hydrogen dissociation/recombination can accelerate day-to-night heat transport and decrease the day/night temperature contrasts (Bell & Cowan 2018; Komacek & Tan 2018). In the right panel of Figure 17, we overlay the theoretical $\Delta T_B - T\text{eq}$ relationships derived from the formalism in Komacek & Tan (2018) and assuming the rotation period of EPIC 2122B ($P = 1.14$ hr). Even for such a rapid rotator, the theory still predicts an enhanced day–night heat transport rate when hydrogen dissociation and recombination are considered. This results in a decreasing trend in $\delta T_B - T\text{eq}$ when $T\text{eq} > 2500 K$. Unfortunately, we are not able to incorporate this effect into our GCMs because the simulations become numerically unstable when it is included in the extremely fast-rotating models. While the lack of a GCM simulation prevents a detailed and spectroscopically resolved comparison between the model and observations, the general agreement of the observed $\Delta T_B$ of EPIC 2122B and the predicted trend (Figure 17) motivates implementing hydrogen dissociation/recombination as part of GCMs.
5.2. Tracking the Irradiated Brown Dwarfs on the Substellar Color–Magnitude Diagram

We derive the synthetic photometry of WD 0137B and EPIC 2122B from the G141 spectra and compare it with the substellar \( M_r\)–\( H \) color–magnitude diagram (CMD). Because the G141 grism does not cover the entire \( H \) band, we use the HST F127M and F153M filters instead of the \( J \) and \( H \) filters. The slight differences caused by different filter throughputs do not affect the subsequent discussion. The absolute photometry is obtained by applying the distance modulus derived from its GAIA DR2 parallax (9.7786 mas for WD 0137B and 2.5851 mas for EPIC 2122B; see Gaia Collaboration et al. 2018). Figure 18 shows the color–magnitude tracks of WD 0137B and EPIC 2122B overlaid onto the substellar CMD (isolated brown dwarf data are from Best et al. 2020).

The effective temperatures of WD 0137B in its day- and nightside match those of isolated brown dwarfs of early-L and mid-T types, respectively. The L/T transition (Kirkpatrick 2005) occurs between these two spectral types. This transition is not only a change of course in the color–magnitude diagram (Figure 18), but also conveys essential information about substellar atmospheres. The change from the cloudy L-type atmospheres to clear T-type atmospheres due to condensation fronts submerging below the \( \tau = 1 \) layer in cooler effective temperatures or cloud break-up is the most favored explanation for this transition (e.g., Burgasser et al. 2002; Saumon & Marley 2008). Nevertheless, a change from unstable to stable chemical reactions involving CO and CH\(_4\) has also been proposed to contribute to this sharp color variation (Tremblin et al. 2016). Between the day- and nightsides of WD 0137B, there are regions in its atmosphere where the effective temperatures are favorable for formation and dissipation of clouds (e.g., Ackerman & Marley 2001), as well as disequilibrium chemistry. If these processes also happen in WD 0137B, we expect its day/night color–magnitude evolution to match the CMD of isolated brown dwarfs.

On the CMD, WD 0137B’s track starts from the blue edge of the early-L region and directly connects to the mid-T region without showing any color variations akin to the L/T transition. It deviates from the trend empirically established by isolated brown dwarfs, but follows the theoretical cloudless model tracks (Marley et al. 2018) shown as black lines in Figure 18. This implies that the atmosphere of WD 0137B does not contain longitudinally variable clouds. The cloud opacity and disequilibrium chemistry that operate in isolated brown dwarf atmospheres, if present at all, are not the key drivers of the color changes in WD 0137B. This stark difference between WD 0137B and non-irradiated brown dwarfs in color–magnitude space demonstrates that strong irradiation fundamentally affects clouds, chemistry, and thermal structures in substellar atmospheres, which has also been shown for hot Jupiters (e.g., Fortney et al. 2008; Parmentier et al. 2016; Beatty et al. 2019).

As for EPIC 2122B, its CMD track is parallel to the M dwarf to mid-L dwarf evolution, but has a bluer NIR color. This color difference is due to the irradiation that causes EPIC 2122B’s dayside spectrum to have a steep slope and contain strong flux at short wavelengths (the right panel of Figure 14). As the dayside spectrum’s filling factor decreases, EPIC 2122B’s CMD track naturally evolves toward the red and faint direction. Based on the spectral model fitting results (Section 4), we construct an ad hoc semi-empirical model by linearly combining EPIC 2122B’s best-fitting day- and nightside model spectra with a tunable dayside filling factor. The color–magnitude trend of the model was derived and shown as a gray solid line in Figure 18. As expected, as EPIC 2122 B rotates from its day- to nightside, its brightness diminishes and its color reddens.
5.3. The Formation and Evolution of WD 0137B and EPIC 2122B

The nightside temperatures of WD 0137B and EPIC 2122B can probe their interior heat flux. We define a non-irradiated temperature \( T_{\text{non-irr}} \) to represent the effective temperature of a hypothesized isolated WD 0137B or EPIC 2122B. The nightside temperatures are upper limits of \( T_{\text{non-irr}} \). We can then compare their nightside temperatures to substellar evolutionary models (e.g., Saumon & Marley 2008) to probe their cooling stages. In Figure 19, we compare the best-fit nightside temperatures to a \( M = 55 \, M_{\text{Jup}} \) theoretical cooling track in the Saumon & Marley (2008) model, and find the cooling ages of WD 0137B and EPIC 2122B to be \( 4.0^{+1.6}_{-1.8} \) Gyr and \( 2.1^{+0.7}_{-0.5} \) Gyr, respectively. Considering that these temperatures are upper limits for \( T_{\text{non-irr}} \) and irradiation may slow down the cooling processes, these results are the lower limits of the ages of the brown dwarfs.

These results are significantly longer than the white dwarf cooling ages of \( 0.25 \pm 0.8 \) Gyr and \( 0.014–0.018 \) Gyr for WD 0137 and EPIC 2122, respectively (Maxted et al. 2006; Burleigh et al. 2006; Casewell et al. 2018). Therefore, our results support a formation and evolution scenario that has been advocated for in previous studies (Burleigh et al. 2006; Maxted et al. 2006; Casewell et al. 2018); in these systems, the brown dwarfs used to be the companions of the white dwarf progenitors and experienced the common envelope evolution.

Figure 18. The evolution of WD 0137B and EPIC 2122B on the substellar color–magnitude diagram. We use the synthetic F127M and F153M photometry of WD 0137B and EPIC 2122B to estimate the J and H magnitude and overplot their tracks (green and magenta squares) onto the substellar CMD established using data from Best et al. (2020). Several measurements of EPIC 2122B near its nightside are discarded because of low S/Ns. For the WD 0137B and EPIC 2122B tracks, we also overlay the best-fitting second-degree polynomials with solid lines to highlight the overall trends. The substellar CMD is color-coded by spectral types: M in brown, L in red, and T in blue. For comparison, we overplot the Sonora cloudless CMD tracks in three surface gravities (dashed–dotted line: \( \log g = 4.5 \); dashed line: \( \log g = 5.0 \); solid line \( \log g = 5.5 \)). The WD 0137B track connects the early-L and mid-T regions in approximately a straight line that is parallel to the Sonora tracks in the same color range. The EPIC 2122B track is parallel to the M to mid-L evolution, but has a bluer color. The gray solid line shows a semi-empirical model for EPIC 2122B. It is constructed by conducting synthetic photometry on a series of spectral mixtures composed of its best-fitting day- and nightside models.
phase. Such an evolutionary path is further supported by the low masses of the white dwarfs in these systems.

5.4. Comparing WD 0137B and EPIC 2122B

WD 0137B and EPIC 2122B demonstrate many similarities. The phase curves of both objects require multi-order Fourier series to fit and are consistent with the shapes of theoretical phase curves predicted by the GCM simulations. This favors a surface map including a hot spot that is located at the substellar point. The phase-resolved spectra of both objects can be reduced to a two-dimensional linear space spanned by their respective day- and nightside spectra. The dayside spectra of both objects are explained very well by the irradiated brown dwarf models (Lothringer & Casewell 2020) scaled by a filling factor of \( \sim 50\% \). The \( T_{\text{ren-irr}} \) of WD 0137B and EPIC 2122B favor cooling ages much older than those of their host white dwarfs, supporting the formation scenario where the brown dwarfs have formed before the post-main-sequence evolution and have undergone the entire common envelope phases.

The two brown dwarfs also have distinctive differences. While EPIC 2122B’s spectra are featureless at all phases, WD 0137B has a significant water absorption at every phase except the dayside. This is likely due to the higher level of UV irradiation that EPIC 2122B receives, which efficiently heats the upper atmospheres, creates temperature inversion, and causes water molecules to dissociate (Lothringer et al. 2018). EPIC 2122B has greater day/night temperature contrasts than WD 0137B, perhaps due to its shorter radiative cooling timescale and faster rotation rate slowing down the day/night heat transfer. The high-order Fourier components are also more significant in EPIC 2122B’s phase curves, suggesting a more confined hot spot and less efficient heat transfer. However, the differences in the shapes of the phase curves can also be attributed to differences in viewing geometry or surface structures.

6. Conclusions

The key results of our study are as follows:

1. We present HST/WFC3/G141 phase-resolved spectra of white-dwarf-brown-dwarf binaries WD 0137 and EPIC 2122. Both binaries demonstrate strong photometric and spectroscopic modulations over their respective orbital periods. These modulations probe the day–night cycles of the tidally locked brown dwarfs.

2. We find that multi-order Fourier series models fit well to the observed phase curves. The best-fitting model to the 1.12 to 1.65 \( \mu \text{m} \) broadband phase curve of WD 0137 contains \( k = 1 \) and 2 waves with semi-amplitudes of 5.28% ± 0.02% and 0.45% ± 0.02%, respectively. For EPIC 2122, the best-fitting model consists of \( k = 1, 2, \) and 4 waves with semi-amplitudes of 29.1% ± 0.1%, 3.7% ± 0.1%, and 0.5% ± 0.1%, respectively. The high-order components and the base order do not have significant phase offsets.

3. The shapes of the observed phase curves agree well with the theoretical predictions from GCM simulations, as well as models assuming RCE. The good fit of the RCE models implies inefficient day/night heat transfer, which results from the strong Coriolis force counter-balancing the day/night pressure gradients. In these models, hot spots form at the substellar points and can introduce high-order harmonics in the hemispherically integrated phase curves.

4. The modulations show significant wavelength dependence. In both binaries, because the flux contributions of the brown dwarfs increase toward longer wavelength, the modulation amplitudes rise from 1.1 to 1.7 \( \mu \text{m} \). For WD 0137, the modulation amplitude is further enhanced in the 1.4 \( \mu \text{m} \) water absorption band, revealing strong phase-dependent variations of water vapor absorption.

5. By removing the white dwarf components with model spectra, we obtained phase-resolved brown dwarf spectra. The day/night spectral variations are primarily driven by temperature differences. The spectra of WD 0137B show a significant water absorption feature in the nightside and gradually become nearly featureless from night to day. In comparison, the spectra of EPIC 2122B are featureless at all phases.

6. For both brown dwarfs, the phase-resolved spectra can be accurately represented as a two-dimensional linear space spanned by the day- and nightside spectra. For WD 0137B, its nightside spectrum agrees well with a \( \sim 1050 \pm 100 \text{ K} \) non-irradiated, cloudless brown dwarf model and the dayside is best-fit by an irradiated model with dayside-only heat redistribution and a \( T_{\text{eff}} \) of 2430 K. For EPIC 2122B, the nightside emission is only marginally detected and is best-fit by a 1300 K blackbody. Its dayside is also best-fit by an irradiated brown dwarf model with dayside-only heat redistribution and a \( T_{\text{eff}} \) of \( \sim 4050 \text{ K} \). Both daysides’ spectra require a filling factor of \( \sim 50\% \) for the model, supporting the notion that the irradiated hemispheres of the brown dwarfs contain a hot spot that dominates the dayside emission.

7. The day- and nightside spectra of WD 0137B and EPIC 2122B demonstrate their flux and brightness temperature contrasts are strongly wavelength-dependent. The spectral variations of the day/night contrasts are

![Figure 19](image-url)
likely a joint consequence of two properties of these brown dwarfs: (1) different wavelengths trace different pressure levels of the atmosphere; and (2) the irradiated and non-irradiated hemispheres differ in their thermal profiles. This wavelength-dependent contrast highlights the complexity in establishing the relationship between temperature contrasts and fundamental properties of irradiated atmospheres. Based on this result, we also advocate for specifying the wavelengths when cross-comparing day/night contrasts of multiple irradiated objects.

8. The day- and nightside of WD 0137B have color and brightness similar to those of early-L and mid-T types brown dwarfs, respectively. On the substellar CMD, its day-to-night evolution directly connects these two regions by approximately a straight line rather than following the L/T transition turn. This suggests that cloud formation/dissipation, as well as disequilibrium chemistry, which are essential mechanisms that drive the color–magnitude evolution of non-irradiated brown dwarfs, do not play a critical role in the highly irradiated and tidally locked atmosphere of WD 0137B.

9. Using the nightside temperatures as proxies for internal thermal temperatures, we constrain the cooling timescale for WD 0137B and EPIC 2122B to be 4.0 and 2.0 Gyr. They are significantly longer than the cooling ages of the respective white dwarfs. This supports the formation scenario where the brown dwarfs form before the white dwarfs and have experienced the common envelope evolution.

Finally, our study exemplifies the remarkable opportunities that the white-dwarf-brown-dwarf binaries provide for investigating irradiated substellar atmospheres. The phase curve amplitudes are more than two orders of magnitude greater than those of hot Jupiters, resulting in extremely high S/Ns. The telescope time request is only a fraction of that required for a complete hot Jupiter phase curve. The irradiated brown dwarfs’ properties are in an interesting parameter space, exhibiting fast rotation rates, high UV irradiation, and extreme day/night contrasts. These properties cannot be probed with hot Jupiters or free-floating brown dwarfs. Continuing phase-resolved spectroscopic observations with a larger sample and a broader wavelength coverage will result in excellent data that help deepen the understanding of irradiated atmospheres and strengthen the connection between studies of brown dwarfs and transiting exoplanets.

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Facilities: Hubble Space Telescope, Exoplanet Archive.
Software: Numpy (Harris et al. 2020), Scipy (Virtanen et al. 2020), matplotlib (Hunter 2007), Astropy (Robitaille et al. 2013), Pysynphot (STScI Development Team 2013), starry (Luger et al. 2019).

Appendix

The General Circulation Model for Brown Dwarfs around White Dwarfs

We briefly describe the GCM used in this study for WD 0137B and EPIC 2122B. The general model structure is similar to that used in Komacek et al. (2017) and the ones without hydrogen dissociation and recombination in Tan & Komacek (2019). The GCM solves the global, three-dimensional hydrostatic primitive equations that govern the large-scale flow in atmospheres using the dynamical core of the MITgcm (Adcroft et al. 2004). An idealized semi-gray, two-stream radiative transfer scheme that includes a broad thermal band and two sub-bands in the visible is used to represent the permanent dayside irradiation and nightside cooling. The opacity in the thermal band is a function of pressure alone and is the same as that used in Tan & Komacek (2019). In the visible band, rather than using only one broadband as previous studies, the stellar irradiation is partitioned into two channels with different opacities:

\[ F_{11} = (1 - A)(1 - \beta)C_{\text{irr}} T_{\text{irr}}^4 \mu_r \exp \left(- \frac{\tau_{11}}{\mu_r} \right) , \]

\[ F_{12} = (1 - A)\beta C_{\text{irr}} T_{\text{irr}}^4 \mu_r \exp \left(- \frac{\tau_{12}}{\mu_r} \right) , \]

where \( A \) is the Bond albedo, \( \mu_r \) is the local zenith angle of the irradiation, \( \tau_{11} = \kappa_{11} P/g \) and \( \tau_{12} = \kappa_{12} P/g \) are the respective optical depths of each channel, \( p \) is pressure, \( g \) is surface gravity, \( \kappa_{11} \) and \( \kappa_{12} \) are opacities that are assumed to be constants, \( T_{\text{irr}} \) is the irradiated temperature at the substellar point, \( \sigma \) is the Stefan–Boltzmann constant, and \( \beta \) is the partition constant. Here, \( A, \beta, \kappa_{11}, \kappa_{12} \) are free parameters. The total radiative flux at a location on the dayside is \( F_r = F_{11} + F_{12} \). This treatment crudely mimics the effects of strong UV absorption on generating strong thermal inversion in the dayside atmosphere (Lothringer & Casewell 2020). We consider absorption only and omit scattering. The effects of scattering in energy balance are implicitly included in a nonzero bond albedo. We apply a fixed, globally uniform temperature at the bottom pressure to represent the assumption that the thermal structure merges to the same adiabatic profile in the deep interior. This bottom temperature is a free parameter. We apply two types of frictional drag as in
Komacek et al. (2017): a weak frictional drag, with a spatially independent drag timescale of $\tau_{\text{drag}} = 10^4$ s; and a basal drag that is applied only to pressure larger than 200 bars, with a bottom drag timescale of $10^4$ s.

For EPIC 2122B, we apply $A = 0.2$, $\beta = 0.25$, $\kappa_1 = 0.01$ m$^2$kg$^{-1}$, and $\kappa_2 = 0.05$ m$^2$kg$^{-1}$. These parameters result in a global-mean PT profile that is reasonable, compared to that found using comprehensive models in Lothringer & Casewell (2020), and has been used regularly in hot Jupiter studies (e.g., Line et al. 2013; Parmentier & Guillot 2014). The pressure domain of this model is between 0.01 and 500 bars, and temperature at the bottom pressure is assumed to be 4500 K.

In all models, we assumed a radius of $7 \times 10^7$ m, similar to that of Jupiter. The models have a horizontal resolution equivalent to $512 \times 256$ in longitude and latitude, and have 36 vertical layers evenly discretized in log-pressure space. A fourth-order Shapior filter is applied to maintain numerical stability.

References

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