Variability of the lowest mass objects in the AB Doradus moving group

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ABSTRACT

We present the detection of [3.6 μm] photometric variability in two young, L/T transition brown dwarfs, WISE J004701.06+680352.1 (W0047) and 2MASS J2244316+204343 (2M2244) using the Spitzer Space Telescope. We find a period of 16.4 ± 0.2 h and a peak-to-peak amplitude of 1.07 ± 0.04 per cent for W0047, and a period of 11 ± 2 h and amplitude of 0.8 ± 0.2 per cent for 2M2244. This period is significantly longer than that measured previously during a shorter observation. We additionally detect significant J-band variability in 2M2244 using the Wide-Field Camera on UKIRT. We determine the radial and rotational velocities of both objects using Keck NIRSPEC data. We find a radial velocity of −16.0±0.8 km s−1 for 2M2244, and confirm it as a bona fide member of the AB Doradus moving group. We find rotational velocities of u sin i = 9.8 ± 0.3 and 14.3±1.5 km s−1 for W0047 and 2M2244, respectively. With inclination angles of 85°±5° and 76°±14°, W0047 and 2M2244 are viewed roughly equator-on. Their remarkably similar colours, spectra and inclinations are consistent with the possibility that viewing angle may influence atmospheric appearance. We additionally present Spitzer [4.5 μm] monitoring of the young, T5.5 object SDSS111010+011613 (SDSS1110) where we detect no variability. For periods <18 h, we place an upper limit of 1.25 per cent on the peak-to-peak variability amplitude of SDSS1110.

Key words: brown dwarfs – stars: low-mass – stars: variables: general.

1 INTRODUCTION

The growing number of young exoplanets that have been directly imaged in the infrared (Marois et al. 2008; Lagrange et al. 2010; Macintosh et al. 2015) have revealed some unexpected results. With comparable temperatures but lower masses, the young directly imaged planets were expected to share similar atmospheric properties to the well-studied population of brown dwarfs. However most young directly imaged planets appear much redder in the near-IR than their higher mass field counterparts with similar spectral types. Fortunately, young brown dwarfs may still provide an excellent analogue to directly imaged planets, and we now have a significant population of young brown dwarfs with colours and magnitudes similar to directly imaged exoplanets, many of which have estimated masses in the planetary-mass regime (see the compilation of young, red M and L dwarfs made by Faherty et al. (2016), Liu, Dupuy & Allers (2016), and references therein). Three such objects are WISEP J004701.06+680352.1 (W0047), 2MASS J2244316+204343 (2M2244) and SDSS J111010+011613 (SDSS1110) (Gizis et al. 2012; Knapp et al. 2004; Gagné et al. 2015). W0047 and SDSS1110 are kinematically confirmed members of the 150-Myr-old AB Doradus moving group (Bell, Mamajek & Naylor 2015). 2M2244 is assigned a membership probability of 99.6 per cent for the same group based on its proper motion and distance (Gagné et al. 2014b, 2015; Gizis et al. 2015; Liu et al. 2016), but a radial velocity measurement is necessary to confirm moving group membership. We measure its radial velocity in this paper (Section 2.2) and confirm it as a member of the AB Doradus moving group. W0047 is classified as an L7 INT-G brown dwarf and 2M2244 is classified as an L6 VL-G object (Allers & Liu 2013; Gizis et al. 2015). W0047 and 2M2244 are a particularly interesting pair of young, low-gravity objects, with 0.65–2.5 μm spectra that are remarkably similar (Gizis et al. 2015). There are no other free-floating L/T transition dwarfs known to be both coeval and spectrally similar that are bright enough for detailed characterization (though see Best et al. 2015 for more candidates). SDSS1110 is a T5.5 10–12 M_Jup (Gagné et al. 2015) object, and is one of very

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few young, age-calibrated T dwarfs known to date. W0047, 2M2244 and SDSS1110 are the lowest mass confirmed members of the AB Doradus moving group (Liu et al. 2016), and can thus provide powerful insights into the atmospheres of the directly imaged planets.

A key probe of brown dwarf atmospheres is time-resolved photometric monitoring, which is sensitive to the spatial distribution of surface inhomogeneities as objects rotate. Large-scale field brown dwarf surveys have revealed ubiquitous variability across the entire L-T spectral range (Buenzli et al. 2014; Radigan et al. 2014; Wilson, Rajan & Patience 2014; Metchev et al. 2015). Due to their lower gravity, young brown dwarfs exhibit atmospheric scale heights and time-scales different from old field brown dwarfs (Fretyag et al. 2010; Marley, Saumon & Goldblatt 2010; Marley et al. 2012). Thus, studying their variability provides valuable information on atmospheric structure in brown dwarfs and exoplanet atmospheres as a function of surface gravity. Because of their more recent formation, young brown dwarfs and exoplanets have inflated radii compared to the field brown dwarfs. Hence, they are expected to rotate more slowly than their older counterparts due to conservation of angular momentum. However, the planetary mass objects β Pic b, PSO-318.5-22 and 2M1207b all have rotation periods of 6–11 h (Snellen et al. 2014; Biller et al. 2015; Zhou et al. 2016; Allers et al. 2016), similar to higher mass brown dwarfs (Zapatero Osorio et al. 2006).

To date, the observed variability has been interpreted as evidence for condensate clouds, which are required by the majority of brown dwarf and exoplanet models (Marley et al. 2010; Morley et al. 2014). Magnetic phenomena, such as starspots, have also been suggested as a driver of photometric variability. While some L-T type brown dwarfs have been found to possess strong magnetic fields (Kao et al. 2015; Pineda et al. 2016), Miles-Páez et al. (2017) report no correlation between magnetic activity and photometric variability in a sample of L0–T8 brown dwarfs. Recently, Tremblin et al. (2016) proposed cloud-free models, suggesting that the observed variability is due to differing CO abundances or temperature fluctuations. Further work is required to establish which scenario is appropriate for these objects.

W0047 and 2M2244 present the unique opportunity to explore the effects of both viewing angle and age on observed variability. For an equator-on object (with an inclination angle, \(i \approx 90\)°) we measure the full variability amplitude via photometric monitoring. In contrast, lower variability amplitudes are measured for objects that are close to pole-on (Vos, Allers & Biller 2017). Determining the variability amplitude and inclination angle of each object allows us to disentangle the effects of viewing angle on the observed variability.

Metchev et al. (2015) find evidence for higher variability amplitudes for young L3–L5.5 objects. This is unexpected because atmospheric models for young objects typically require very thick clouds (Madhusudhan, Burrows & Currie 2011) and variability studies have suggested that older objects with patchy coverage of thinner and thicker clouds tend to have the highest variability amplitudes (Apai et al. 2013; Buenzli et al. 2015). 2M2244, W0047 and SDSS1110 provide three valuable data points to further explore this trend beyond the early L-type dwarfs.

Periodic variability has previously been detected in W0047 and 2M2244. Lew et al. (2016) report variability with a peak-to-peak J-band amplitude of 8 per cent for W0047 during a 9 h observation, determining a period of 13.2 ± 0.14 h. Morales-Calderon et al. (2006) obtained Spitzer [4.5 \(\mu m\)] time-resolved photometry of 2M2244 and report variability with a period of 4.6 h and a peak-to-peak amplitude of 8 mmag during a 5.7-h observation. SDSS1110 has no previous variability detections in the literature. We have obtained Spitzer photometric monitoring for W0047, 2M2244 and SDSS1110 and J-band monitoring of 2M2244 taken with WFCAM at UKIRT, as well as high dispersion NIRSPEC spectra of W0047 and 2M2244. The spectrum of W0047 was first presented by Gizis et al. (2015), and we use the same data set in this paper. The paper is organized as follows. In Section 2, we discuss the analysis and results of our Keck NIRSPEC high-resolution spectra of 2M2244 and W0047. In Section 3, we present the light curves of our three targets 2M2244, W0047 and SDSS1110. In Section 4, we calculate the inclination angles of W0047 and 2M2244.

2 KECK NIRSPEC HIGH DISPERSION SPECTROSCOPY

We obtained high dispersion NIRSPEC spectra for W0047 from the Keck Observatory Archive (Prog ID: U055NS, PI: Burgasser) and observed 2M2244 as part of a larger programme (Prog ID: N160NS, PI: Allers). NIRSPEC is a near-infrared echelle spectrograph on the Keck II 10 m telescope on Mauna Kea, Hawaii. The NIRSPEC detector is a 1024 × 1024 pixel ALADDIN InSb array. Observations were carried out using the NIRSPEC-7 (1.839 – 2.630 \(\mu m\)) passband in echelle mode using the 3 pixel slit (0.32”) echelle angles of 62.68 – 62.97, and grating angles of 35.42 – 35.51. Observations of targets were gathered in nod pairs, allowing for the removal of sky emission lines through the subtraction of consecutive images. Arc lamps were observed for wavelength calibration. 5 – 10 flat-field and dark images were taken for each target to account for variations in sensitivity and dark current on the detector. W0047 was observed on 2013 September 17 with 2 × 1200 s exposures at an airmass of 1.5 and a mean DIMM seeing of 1.0 arcsec. 2M2244 was observed on 2013 July 6 with 4 × 240 s exposures at an airmass of 1.0 and a mean DIMM seeing of 0.5 arcsec.

We focus our analysis on order 33 (2.286–3.236 \(\mu m\)) since this part of the spectrum contains a good blend of sky lines and brown dwarf lines, allowing for an accurate fit. This spectral region is rich in CO features, as well as H₂O and CH₄ features. These features are discussed in detail by Blake, Charbonneau & White (2010). Order 33 is also commonly used in the literature for NIRSPEC high dispersion N-7 spectra (Blake et al. 2010; Gizis et al. 2013). We additionally look at orders 32 (2.364–2.398 \(\mu m\)) (for W0047) and 38 (1.987–2.016 \(\mu m\)) (for both W0047 and 2M2244) to check for consistency. Data were reduced using a modified version of the REDSPEC reduction package to spatially and spectrally rectify each exposure. The NIRSPEC Echelle Arc Lamp Tool was used to identify the wavelengths of lines in our arc lamp spectrum. After nod-subtracting pairs of exposures, we create a spatial profile which is the median intensity across all wavelengths at each position along the slit. We use Poisson statistics to determine the noise per pixel at each wavelength. We extract the flux within an aperture in each nod-subtracted image to produce two spectra of our source. The extracted spectra are combined using a robust weighted mean with the xcombsec procedure from the splotool package (Cushing, Vacca & Rayner 2004).

2.1 Determining radial and rotational velocities

We use the approach outlined in Allers et al. (2016) to determine the radial and rotational velocities of W0047 and 2M2244. We employ forward modelling to simultaneously fit the wavelength solution of our spectrum, the rotational and radial velocities, the scaling of telluric line depths, and the FWHM of the instrumental line spread.
Variability in lowest mass AB Doradus members

Figure 1. Left: The observed spectrum of W0047 (black) compared to our best-fitting forward model (red). Residuals are plotted in the bottom panel. Right: The observed and best-fitting forward model of 2M2244.

Figure 2. Top panel shows the normalized, pixel phase corrected light curve of W0047 with best-fitting sinusoidal function overplotted in red. The best-fitting function gives a period of 16.3 ± 0.2 h and an amplitude of 1.08 ± 0.04 percent. The middle panel shows the best fitting function injected into a simulated light curve. The bottom panel shows the periodogram of the target and the simulated curve, as well as the periodogram of several reference stars in the field. The blue dashed line shows the 1 percent false-alarm probability.

Table 1. Physical properties of W0047 and 2M2244 from the Saumon & Marley (2008) fsed = 2 evolutionary model.

|          | W0047       | 2M2244     |
|----------|-------------|------------|
| log (L/L_⊙) | −4.44 ± 0.04 | −4.48 ± 0.02 |
| Mass (M_Jup) | 19.5^{+1.6}_{−1.7} | 19.0^{+1.4}_{−1.5} |
| T_eff (K) | 1250_{−20}^{+20} | 1230_{−15}^{+16} |
| Radius (R_Jup) | 1.28 ± 0.02 | 1.28 ± 0.02 |
| log (g) (dex) | 4.49 ± 0.05 | 4.48^{+0.04}_{−0.05} |

To determine the best-fitting parameters of our forward model as well as their posterior distributions, we use a Markov Chain Monte Carlo (MCMC) approach. This involves creating forward models that allow for a continuous distribution of T_eff and log(g) by linearly interpolating between atmosphere grid models. We employ the DREAM(ZS) algorithm (Ter Braak & Vrugt 2008), which uses an adaptive stepper, updating model parameters based on chain histories. To ensure that the median absolute residual of the fit agrees with the median uncertainty of our spectrum, we include a systematic uncertainty of 1.4 percent in the spectrum of W0047.

We plot our spectra and best-fitting models along with the residuals in Fig. 1. Final values for v sin i and radial velocities (RV) are shown in Table 2. Their 1σ uncertainties are determined from their marginalized distributions obtained from our MCMC method. Although we obtain values for T_eff and log(g), these derived values should not be considered physical since we are using a narrow wavelength range in K band. Furthermore, atmospheric models are known to be unreliable for young L/T transition objects, even if J-band data are included (Liu et al. 2013; Allers et al. 2016). These parameters are more reliably determined from evolutionary models, as is done in Section 2.3. The results for both 2M2244 and W0047 are consistent across orders 32, 33 and 38 at the 2σ level. The mean and standard deviation of the LSF FWHM is 0.08 ± 0.01 and 0.081 ± 0.002 nm for 2M2244 and W0047, respectively, resulting in a resolution R = λ/Δλ ≃ 29 000 for both objects. The precision of our wavelength solution is determined to be 0.0025 and 0.0124 nm for 2M2244 and W0047.

Our v sin i measurement of 9.8 ± 0.3 km s^{-1} for W0047 is higher than both previous measurements by Gizis et al. (2015)
Figure 3. Posterior distributions of parameters of the Spitzer light curve of W0047 (shown in Fig. 2). The middle dashed line is the median, the two outer vertical dashed lines represent the 68 per cent confidence interval. The contours show the $1 \sigma$, $1.5 \sigma$ and $2 \sigma$ levels.

(4.3 $\pm$ 2.2 km s$^{-1}$) and Lew et al. (2016) (6.7$^{+0.7}_{-1.4}$ km s$^{-1}$), despite all three measurements using the same data set. The model atmosphere for W0047 used by Gizis et al. (2015) has $T_{\text{eff}} = 2300$ and $\log (g) = 5.5$ while evolutionary models predict $T_{\text{eff}} = 1270$ and $\log (g) = 4.5$ (Gizis et al. 2015). Our model (with $T_{\text{eff}} = 1670$ and $\log (g) = 5.2$) is in better agreement with the evolutionary model. Higher effective temperature and surface gravity results in more pressure broadening, producing a lower value of $v \sin i$. Lew et al. (2016) do not provide details on the atmospheric model used. Again, the consistency between orders 32, 33 and 38 further supports our results.

2.2 2M2244+20 Membership in AB Doradus

A radial velocity measurement is required to confirm moving group membership. Using Bayesian analysis to assess the membership of $>$M5 brown dwarfs, Gagné et al. (2014a) find a 99.6 per cent probability that 2M2244 is a member of the AB Doradus moving group, predicting a radial velocity of $-15.5 \pm 1.7$ km s$^{-1}$. Our measured radial velocity of $-16.0 \pm 0.9$ km s$^{-1}$ is consistent with the predicted radial velocity. Including the measured radial velocity, along with parallax and proper motion measurements from Liu et al. (2016), and using the BANYAN-II web tool (Gagné et al. 2014a; Malo et al. 2013), the probability of AB Doradus membership increases to 99.96 per cent. Thus, our radial velocity measurement confirms 2M2244 as a member of the AB Doradus moving group.

2.3 The physical properties of W0047 and 2M2244

Filippazzo et al. (2015) provide radius, $\log (g)$, $T_{\text{eff}}$ and mass estimates from evolutionary models for W0047 and 2M2244; however, the estimated age range used in this analysis of 50–110 Myr for AB Doradus is systematically younger than current estimates. Barenfeld et al. (2013) place a strong lower limit of 110 Myr and Luhman, Stauffer & Mamajek (2005) provides an upper limit of 150 Myr on the age of AB Doradus. Furthermore, Filippazzo et al. (2015) use a kinematic distance to determine the luminosity of 2M2244 while Liu et al. (2016) has since measured its parallax. We use these measured parallaxes to update the luminosities of 2M2244 and W0047. The errors on the updated luminosities are slightly overestimated, since the bolometric magnitudes and errors are not given in Filippazzo et al. (2015). For a uniformly distributed age of 110–150 Myr and normally distributed luminosities, we determine the physical properties of 2M2244...
inclination angles for W0047 and 2M2244. µ radial velocities, periods, Table 2. The Fourier function gives a period of 10.15 h and the large peak at ∼ 4 h and the large peak at ∼ 10 h.

Table 2. Calculated effective temperatures, log(g), rotational velocities, radial velocities, periods, [3.6 µm] peak-to-peak variability amplitudes and inclination angles for W0047 and 2M2244.

| Parameter | W0047     | 2M2244    |
|-----------|------------|-----------|
| v sin i (km s⁻¹) | 9.8 ± 0.3  | 14.3 ± 1.3 |
| RV (km s⁻¹)     | −19.8 ± 0.2 | −16.0 ± 0.8 |
| P (h)            | 16.4 ± 0.2  | 11.0 ± 2.0 |
| [3.6 µm] Amp (per cent) | 1.07 ± 0.04 | 0.8 ± 0.2 |
| R (R_Jup)       | 1.3 ± 0.04  | 1.29 ± 0.03 |
| i               | 85° ± 5°    | 76° ± 14°  |

and W0047 using model isochrones (final parameters shown in Table 1). W0047 and 2M2244 both exhibit extremely red J − K colours, indicating a dusty atmosphere. Thus, we use the Saumon & Marley (2008) solar metallicity f_K = 2 models. The older age of the AB Doradus moving group that is used in this analysis pushes both masses above the deuterium burning limit, and above the masses presented in Filippazzo et al. (2015). The revised radii are consistent with those reported by Filippazzo et al. (2015).

3 SPITZER AND WFCAM PHOTOMETRY

For our Spitzer observations of W0047, 2M2244 and SDSS1110 we followed standard observing practices for obtaining precise, stable, and nearly photon limited performance. We employed ‘staring mode’ AORs in which the object did not move on the chip through-
of well-behaved reference stars is chosen. Reference stars are also examined by eye to check for any residual trends. Final detrended light curves are obtained by dividing the raw curve for each star by its calibration curve.

3.1 Identification of variables

We plot the periodogram of the target as well as a number of reference stars in the field to identify periodic variability in our targets. For each periodogram, the 1 per cent false-alarm probability (FAP) is calculated from 1000 simulated light curves. These light curves are produced by randomly permuting the indices of reference star light curves (Radigan et al. 2014). This produces light curves with Gaussian-distributed noise. The 1 per cent FAP is plotted in blue in each periodogram. The rotational periods and peak-to-peak variability amplitudes of targets showing periodic variability are determined by fitting an appropriate function to the data using mpfit.pro. This is an implementation of the Levenberg–Marquardt least-squares minimization algorithm which provides the best-fitting periods and variability amplitudes with their 1σ uncertainties. Finding that the least-squares method can be sensitive to initial parameter guesses, we also use the MCMC algorithm EMCEE (Foreman-Mackey et al. 2013) to fully explore the posterior probability distributions of our model parameters.
Aperiodic or stochastic variations are not easily detectable from Lomb–Scargle periodograms so we additionally check for stochastic variability by comparing the photometric standard deviation of our target with the mean standard deviation of comparison stars of similar brightness. If the standard deviation of the target is considerably larger than the mean standard deviation of the comparison stars this suggests stochastic variability in the target.

### 3.2 W0047

The light curve of W0047 (Fig. 2) appears sinusoidal over an entire period. The periodogram displays a strong peak at ~16 h that is well above the 1 per cent FAP value. The least-squares best-fitting sinusoidal function gives a period of 16.3 ± 0.3 h and an amplitude of 1.08 ± 0.04 per cent. We also use the emcee package (Foreman-Mackey et al. 2013) to obtain the full posterior probability distribution for each parameter of the sinusoidal model. We use 1000 walkers with 7500 steps (after discarding the initial burn-in sample) in the four-dimensional parameter space to model the light curve. Fig. 3 shows the posterior probability distributions of the amplitude, period, phase and constant parameters of the fit. Each parameter is well constrained, and the MCMC method gives a period of 16.4 ± 0.2 h and a peak-to-peak amplitude of 1.07 ± 0.04 per cent.

Assuming rigid rotation, we use our measured \( v \sin i \) and a radius estimate of 1.28 ± 0.02 \( R_{\text{up}} \), which allow us to place an upper limit of 16.3 ± 0.8 h on the rotational period of W0047. We can therefore discount the possibility of a double-peaked light curve with a longer rotational period. The measured period is significantly longer than the previously measured 13.2 ± 0.14 h (Lew et al. 2016), however this initial period was determined from an ~9-h observation that did not cover a full rotation. The photometric noise of our target is similar to that measured for comparison stars in the field of similar brightness; thus we find no evidence for aperiodic variability.

With a peak-to-peak amplitude of 1.07 ± 0.04 per cent, this is among the highest Spitzer [3.6 \( \mu \)m] variability amplitudes detected. Metchev et al. (2015) notes a tentative correlation between low-gravity and high-amplitude variability among a sample of eight L3-L5.5 dwarfs. The variability detection measured here adds to a growing number of young, L objects that display high-amplitude variability, suggesting that this correlation may extend into the late-L spectral types (Biller et al. 2015; Metchev et al. 2015; Lew et al. 2016).

### 3.3 2M2244

#### 3.3.1 Spitzer [3.6 \( \mu \)m] monitoring

In contrast to W0047, the Spitzer [3.6 \( \mu \)m] light curve of 2M2244 does not appear sinusoidal (Fig. 4). The photometric noise of 2M2244 is similar to the noise measured in comparison stars of similar brightness in the field. Thus we do not detect any stochastic or aperiodic variability for 2M2244. Morales-Calderon et al. (2006) report a sinusoidal light curve period of 4.6 h for this object; however, the latest observations look very different. The periodogram shows a small peak at ~4 h that is approximately at the 1 per cent FAP level which roughly coincides with the 4.6 h period determined by Morales-Calderon et al. (2006). We also identify a broad peak at ~9.6 h that is highly significant. The light curve does not exhibit a sinusoidal shape, so we consider a two-term truncated Fourier series, which is an appropriate model for more complex light curves (Heinze, Metchev & Kellogg 2014; Yang et al. 2016). This model describes a scenario in which two atmospheric features are located on either hemisphere of the brown dwarf, each causing changes in brightness as they rotate in and out of view. The two-term Fourier series is given by:

\[
F(t) = a_0 + \sum_{a=1}^{2} A_a \sin \left( \frac{2\pi t}{P/i} \right) + B_i \cos \left( \frac{2\pi t}{P/i} \right)
\]

The least-squares fit requires a ‘first guess’ for the parameters, which we set to the peak of the periodogram for the period and one for all other parameters. The least-squares best-fitting Fourier series model gives a period of 10.0 ± 2.4 h. We inject this function into simulated light curves and reference stars to compute their periodograms. As seen in the bottom panel of Fig. 4, the two-term Fourier signal produces a periodogram shape very similar to that of 2M2244, with a strong peak at ~10 h and a smaller peak at ~4 h.

After experimentation with different starting parameters for the least-squares fit, we find that the results are not consistent across different initial guesses for the model parameters. Using the Morales-Calderon et al. (2006) measurement of 4.6 h as an initial guess on the period of 2M2244, the best-fitting solution gives a period of ~4 h. In contrast, using the peak of our periodogram (~10 h) as an initial guess on the period, we obtain a best-fitting period of 10 h for the Fourier model. In fact, any initial guess >5 h yields a best-fitting period of 10 h. It is clear that the least-squares fitting procedure cannot locate global minima, and is over-dependent on initial guesses. Hence, we use the emcee algorithm to explore the posterior distribution of the model parameters using the two-term Fourier series model.
Figure 7. Posterior distributions of parameters of the sinusoidal fit to the Morales-Calderon et al. (2006) Spitzer light curve of 2M2244 (shown in Fig. 6). The middle dashed line is the median, the two outer vertical dashed lines represent the 68 per cent confidence interval. We have placed an upper limit on the period of 13 h using our radius estimate from Table 1 and $v \sin i$ measurement from Table 2. The contours show the 1σ, 1.5σ and 2σ levels.

Fourier model. We use 1000 walkers with 7500 steps (after discarding the initial burn-in sample) to model the light curve. Our measured $v \sin i$ value of $14.3^{+1.1}_{-1.3}$ km s$^{-1}$ and estimated radius of $1.28 \pm 0.02 R_{\text{Jup}}$ allow us to place an upper limit of $11.5^{+1.9}_{-1.2}$ h on the period of 2M2244, hence we use an upper limit of 13 h as a prior in our MCMC analysis. The posterior distributions of the parameters for the Fourier model are shown in Fig. 5. This model favours a period of $11.1^{+0.4}_{-0.6}$ h and this value is insensitive to the initial parameter guesses.

3.3.2 Spitzer [4.5 μm] monitoring

Our measured period is inconsistent with that of Morales-Calderon et al. (2006) who find a period of 4.6 h during a ∼6 h observation in the Spitzer [4.5 μm] band. We downloaded these data from the Spitzer Heritage Archive. The reduced light curve and periodogram are shown in Fig. 6. The periodogram peaks at 4.6 h, as reported by Morales-Calderon et al. (2006). The curve appears sinusoidal over the observation period but we investigate the possibility of a double-peaked light curve. Fitting a pure sinusoid to the data gives a period of $4.6 \pm 0.2$ h while fitting a two-term truncated Fourier series gives a period of $10 \pm 3$ h; however, the functions are indistinguishable from each other over this observation. Injecting the 4.6 h sinusoidal fit and the 10 h truncated Fourier fit into simulated light curves and reference stars produces the same periodogram shape as the target, seen in the bottom panel of Fig. 6. We use the MCMC method to explore the parameter posterior distributions for both the sinusoid model and the Fourier model. Again we use an upper limit of 13 h as a prior on the period. The posteriors are shown in Figs 7 and 8. Again, both models fit the light curve well, with the sinusoidal model giving a period of $4.8^{+0.3}_{-0.2}$ h and the Fourier series model giving a period of $12.01^{+0.2}_{-0.1}$ h. Thus, we conclude that the original observation is too short to rule out a double-peaked light curve with the ∼11 h period of the Spitzer [3.6 μm] data set, and from this data set either scenario is possible.

3.3.3 UKIRT WFCAM monitoring

The WFCAM photometry of 2M2244 is shown in Fig. 9. In this 4 h J-band observation we see evidence of significant (∼4 per cent) variability. The periodogram shows a highly significant peak that favours periodicities >5.5 h. This observation is too short to accurately measure the period, but it is consistent with an ∼11 h period. Since we have not covered a full period we cannot measure the full J-band variability amplitude, but can set a lower limit of ∼4 per cent.
3.3.4 The period of 2M2244

Considering all three epochs of data for 2M2244, we favour a longer period of $11 \pm 2 \text{ h}$. We conclude that the initial *Spitzer* [4.5 μm] monitoring observation by Morales-Calderon et al. (2006) is too short to completely rule out a longer period. The light curve is most likely double-peaked in this epoch, due to two different atmospheric structures in either hemisphere. We see a very different shape in the 2016 September *Spitzer* [3.6 μm] light curve. This is plausibly due to evolution of the cloud structure in $\sim 10$ years between epochs. This could also be due to the fact that we are probing different pressure levels in each *Spitzer* band; however, recent studies have found [3.6 μm] and [4.5 μm] light curves to have similar shape and phase (Metchev et al. 2015; Cushing et al. 2016). A recent paper by Apai et al. (2017) suggests another possible explanation for evolving light curves such as that observed for 2M2244. In this paper, the variability of three brown dwarfs is modelled by longitudinal bands with sinusoidal surface brightness modulations and an elliptical spot. When two bands have slightly different periods due to differing velocities or directions, they interfere to produce beat patterns. These beat patterns produce high amplitude variability when the waves are in phase and produce double-peaked variability when the phase shift between the waves is close to 90°. This model can explain light curves that are sometimes single peaked and other

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**Figure 8.** Posterior distributions of parameters of the Fourier model fit to the Morales-Calderon et al. (2006) *Spitzer* light curve of 2M2244 (shown in Fig. 6). The middle dashed line is the median, the two outer vertical dashed lines represent the 68 per cent confidence interval. We have placed an upper limit on the period of 13 h using our radius estimate from Table 1 and $v \sin i$ measurement from Table 2. The contours show the $1\sigma$, $1.5\sigma$ and $2\sigma$ levels.
times double peaked as well as providing an explanation for the shape of the periodogram in the bottom panel of Fig. 4, where the higher frequency peak at $\sim 5\, \text{h}$ may be explained by a beat pattern with wavenumber $k = 2$.

Both our periodogram and MCMC analysis of the new [3.6 $\mu$m] data set point to a period of $\sim 11.0\, \text{h}$. This period is also consistent with our UKIRT WFCAM $J$-band observation. As we still have not covered a full period for 2M2244, we combine the periods obtained from our MCMC Fourier models (shown in Fig. 5 and 8) to make a conservative estimate of $11 \pm 2\, \text{h}$ for 2M2244.

The observed peak-to-peak amplitude of $0.8 \pm 0.2\, \text{percent}$ for the more recent Spitzer [3.6 $\mu$m] is comparable to the $1.0 \pm 0.1\, \text{percent}$ modulation observed in the original Spitzer [4.5 $\mu$m] epoch of Morales-Calderon et al. (2006). The amplitude ratio, $A(4.5)/A(3.6)$ of $1.25 \pm 0.2\, \text{percent}$ is similar to the amplitude ratios found by Metchev et al. (2015).

### 3.4 SDSS1110

The light curve of SDSS1110 (top panel of Fig. 10) does not display any obvious trends, and our periodogram analysis (middle panel) confirms this. To determine the sensitivity of our observation, we inject simulated sinusoidal curves into random permutations of our SDSS1110 light curve. The simulated sine curves have peak-to-peak amplitudes ranging from $0.4 \sim 1.6\, \text{percent}$ per cent and periods of $2 \sim 18\, \text{h}$, with randomly assigned phase shifts. Each simulated light curve is put through our periodogram analysis, which allows us to produce a sensitivity plot, shown in the bottom panel of Fig. 10. The blue region corresponds to periods and amplitudes detected with a FAP $< 1\, \text{percent}$, the white region corresponds to those detected with $1\, \text{percent} < \text{FAP} < 5\, \text{percent}$, and the orange region corresponds to those with FAP $> 5\, \text{percent}$. For periods $< 18\, \text{h}$, an upper limit of $1.25\, \text{percent}$ is placed on the variability amplitude of SDSS1110. Considering only periods $< 10\, \text{h}$, as done by Metchev et al. (2015), we place an upper limit of $0.9\, \text{percent}$ on the variability amplitude. However, since we expect that young brown dwarfs will rotate more slowly due to conservation of angular momentum, the limit based on periods $< 18\, \text{h}$ is more robust.

The photometric noise measured for SDSS1110 is comparable to the noise measured for comparison stars of similar brightness, and thus we do not find evidence for stochastic or aperiodic variability. We additionally check the periodogram of the unbinned light curve to search for evidence of very short period ($< 1\, \text{h}$) deuterium pulsations proposed by Palla & Baraffe (2005). The periodogram does not display significant peaks at these short periods. A photometric variability survey of late-M brown dwarfs with $T_{\text{eff}} > 2400\, \text{K}$ and ages of $1 \sim 10\, \text{Myr}$ concluded that pulsations cannot grow to observable amplitudes in these objects (Cody & Hillenbrand 2014).

The absence of short period pulsations detected in the light curve of SDSS1110 suggests that this conclusion may extend to even cooler ($T_{\text{eff}} \sim 900 \sim 1300\, \text{K}$) brown dwarfs, however a larger sample will be needed to robustly explore this possibility. Deuterium pulsations are not expected to occur in objects with masses over the deuterium burning limit at the age of AB Doradus so would not be expected to occur in W0047 and 2M2244.

### 4 THE INCLINATION ANGLES OF W0047 AND 2M2244

With measured values for $\nu \sin i$ and the rotation period, $P$, in hand, an assumption of radius allows us to determine the angle of inclination, $i$. We assume that the brown dwarf rotates as a rigid sphere.
intermediate and low-gravity objects. Since W0047 and 2M2244 dwarfs, and these were used to calculate the median colours for the spectral type and absolute magnitude for VL-G and INT-G brown et al. (2010). Liu et al. (2016) provide linear relations between their spectral types and gravity flags. Median colours for L0-

Thus, positive and negative values of colour anomaly refer to ob-

clination angle of 2M2244 is found to be 76

+5

−9 for W0047, so this object

have nearly identical spectra (Gizis et al. 2015), we treat them both as L7 INT-G objects, and apply the same colour anomaly correction to both. The error bars for these objects are simply the J and Ks magnitude uncertainties combined. Our estimate of the median colour of low-gravity objects is limited by the low number of such objects known. As more of these objects are discovered this median colour will become more accurate. Vos et al. (2017) find that the correlation between near-infrared colour anomaly and inclination angle of field brown dwarfs is statistically significant at the 99 per cent level. Variable brown dwarfs viewed equator-on appear redder than the median while objects closer to pole-on are bluer than the median. This figure is updated in Fig. 11. W0047, 2M2244 and the low-gravity objects 2M0103+19, 2M1615+49, PSO-318 and 2M2208+29 may follow this trend, although more inclination data for young dwarfs are needed to fully explore this possibility. This may be explained if clouds are inhomogeneously distributed in latitude or if grain size and cloud thickness vary in latitude. If thicker or large-grained clouds are situated predominantly at the equator, while thinner or small-grained clouds are situated at the poles then we would expect to observe objects with i ∼ 90° to be redder than the median and objects with lower inclination angles to be bluer than the median. The addition of more inclination data for brown dwarfs is likely to reveal the physical origin of the correlation seen in Fig. 11. Vos et al. (2017) also find a relation between the colour anomaly of an object and its variability amplitude, where objects that are redder than the median for their spectral type and gravity class tend to have higher variability amplitudes. Fig. 12 shows an updated version of this plot, showing that W0047 and 2M2244 are also consistent with this trend.

5 CONCLUSIONS

We have obtained Spitzer [3.6 μm] photometric monitoring for two young free-floating objects, W0047, 2M2244, and Spitzer [4.5 μm] monitoring of SDSSJ1101 as well as J-band monitoring of 2M2244. Additionally, we obtain NIRSPEC N-7 spectra of W0047 and 2M2244. We detect variability in the two late-L, low-mass dwarfs, W0047 and 2M2244. MCMC analysis of the Spitzer [3.6 μm] light curve of 2M2244 gives a period of 11 ± 2 h and a peak to trough amplitude of 0.8 ± 0.2 per cent. We detect significant (∼3 per cent)
J-band variability in 2M2244. We find a period of 16.4 ± 0.2 h for W0047 and an amplitude of 1.07 ± 0.04 per cent. Variability is not observed in the T5.5 object SDSS1110 during an 8.5-h observation. For periods < 18 h, we place an upper limit of 1.25 per cent on the variability amplitude of SDSS1110.

With a peak to trough amplitude of 1.07 ± 0.04 per cent for W0047, this is among the highest Spitzer [3.6 μm] variability amplitudes detected. This variability detection adds to a growing number of young, L-type objects that display high amplitude variability, suggesting that this correlation may extend into the late-L spectral types (Metchev et al. 2015; Biller et al. 2015; Lew et al. 2016).

The $v \sin i$ of both targets is determined using NIRSPEC-7 high dispersion spectra, finding $v \sin i = 14.3^{+1.5}_{-1.2}$ km s$^{-1}$ for 2M2244 and $v \sin i = 9.8 \pm 0.3$ km s$^{-1}$ for W0047. Assuming rigid sphere rotation and using expected radii from evolutionary models, we find that both objects are close to equator-on, with inclination angles of 85$^\circ$ and 76$^\circ$ for W0047 and 2M2244, respectively. Their remarkably similar colours, spectral appearance and inclination angles are consistent with the possibility that viewing angle shapes the observed spectrum of a brown dwarf or giant exoplanet.

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