A Search for Variability in Exoplanet Analogues and Low-Gravity Brown Dwarfs

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ABSTRACT

We report the results of a J-band survey for photometric variability in a sample of young, low-gravity objects using the New Technology Telescope (NTT) and the United Kingdom InfraRed Telescope (UKIRT). Surface gravity is a key parameter in the atmospheric properties of brown dwarfs and this is the first large survey that aims to test the gravity dependence of variability properties. We do a full analysis of the spectral signatures of youth and assess the group membership probability of each target using membership tools from the literature. This results in a 30 object sample of young low-gravity brown dwarfs. Since we are lacking in objects with spectral types later than L9, we focus our statistical analysis on the L0-L8.5 objects. We find that the variability occurrence rate of L0-L8.5 low-gravity brown dwarfs in this survey is 30\textsuperscript{+16}_{-8}\%.

We reanalyse the results of Radigan (2014) and find that the field dwarfs with spectral types L0-L8.5 have a variability occurrence rate of 11\textsuperscript{+13}_{-4}\%.

We determine a probability of 98\% that the samples are drawn from different distributions. This is the first quantitative indication that the low-gravity objects are more likely to be variable than the field dwarf population. Furthermore, we present follow-up J\textsubscript{S} and K\textsubscript{S} observations of the young, planetary-mass variable object PSO 318.5–22 over three consecutive nights. We find no evidence of phase shifts between the J\textsubscript{S} and K\textsubscript{S} bands and find higher J\textsubscript{S} amplitudes. We use the J\textsubscript{S} lightcurves to measure a rotational period of 8.45 \pm 0.05 hr for PSO 318.5–22.

Key words: brown dwarfs – stars: variables: general
1 INTRODUCTION

Time-resolved photometric variability monitoring is a key probe of atmospheric inhomogeneities in brown dwarf atmospheres, as it is sensitive to the spatial distribution of condensates as a brown dwarf rotates. Photometric variability has been well-studied in the more massive field L and T spectral type dwarfs, but the variability properties of the population of younger, low-gravity objects are less understood.

Radigan et al. (2014) reported the results of a large, ground-based search for J-band variability in L and T dwarfs, finding that 9 out of 57 (16%) objects showed significant variability above photometric noise. Furthermore, the authors report enhanced variability frequency and amplitudes at the L/T transition, supporting the hypothesis that cloud holes contribute to the abrupt decline in condensate opacity and J-band brightening observed at the L/T transition (however subsequent variability studies have shown that varying cloud layers, as opposed to holes, are responsible for observed variability; Apai et al. 2013; Buenzli et al. 2015). Wilson et al. (2014) presented a similar ground-based variability survey, the Brown Dwarf Atmospheric Monitor program (BAM) survey, which monitored 69 brown dwarfs spanning L0 to T8. Significant variability was reported in 14 of 69 objects (20%), with no evidence for an enhancement in frequency or amplitude across the L/T transition. However, Radigan (2014) carried out a reanalysis of the 13 highly variable objects reported by Wilson et al. (2014) and found significant variability in only 4 from 13. Combining the revised BAM survey with the Radigan et al. (2014) survey, Radigan (2014) found that 24\% of objects in the L9-T3.5 range exhibit J-band variability, in contrast to 2.9\% of L0-L8.5 brown dwarfs and 3.2\% of T4-T9.5 brown dwarfs.

Buenzli et al. (2014) presented a 22 target HST grism spectroscopy survey at wavelengths of 1.1–1.7 μm, attaining point-to-point precision of 0.1–0.2% during ~40 min observations. Low-level (~1%) variability trends were detected in 6 brown dwarfs (27%), with no evidence for enhanced frequency across the L/T transition, suggesting that low-level heterogeneities are a frequent characteristic of brown dwarf atmospheres across the entire L-T spectral range. Metchev et al. (2015) reported results from a Spitzer program to search for photometric variability in a larger sample of 44 L3-T8 dwarfs at 3.6 μm and 4.5 μm, reaching 0.2–0.4% precision. Metchev et al. (2015) reach a similar conclusion, finding that photometric variability is common among L and T dwarfs. The survey included eight low or intermediate gravity brown dwarfs to probe the effects of low surface gravity on the variability properties of brown dwarfs. A tentative correlation was found between low-gravity and high amplitude variability, however a larger sample is necessary to confirm this potential relation (Metchev et al. 2015).

For the majority of directly-imaged exoplanets, the contrast between host star and planet make it difficult to obtain sufficiently high S/N photometry to allow detailed studies of their variability, thus only a handful are amenable to variability studies. In fact, Apai et al. (2016) explored the rotational variability of the HR8799 planets, reaching a photometric precision of ~10%, thus insufficient to detect variability on levels of a few percent. However, young brown dwarfs provide an excellent analogue to directly-imaged exoplanets. Recently, a handful of young brown dwarfs with colours and magnitudes similar to directly-imaged planets have been discovered (see compilation of young objects made by Faherty et al. 2016; Liu et al. 2016). The atmospheres of these young brown dwarfs can provide insight into the atmospheres of directly-imaged planets. Like their higher-mass brown dwarf counterparts (Zapatero Osorio et al. 2006), young companion exoplanets and free-floating objects appear to be fast rotators with measured rotational periods of ~7–11 hours (Snellen et al. 2014; Biller et al. 2015; Allers et al. 2016; Zhou et al. 2016). This makes them excellent targets for photometric variability monitoring.

Variability has now been detected in a small sample of low-gravity objects. As part of this survey, variability was detected in the planetary-mass object PSO J318.5338–22.8603 (PSO 318.5-22; Biller et al. 2015). With a variability amplitude of 7–10%, PSO 318.5-22 displays a very high variability amplitude compared to most objects in the field population. This was swiftly followed by a variability detection in the 3 Myr companion 2MASSW J1207334–393254 (2M1207b), which displayed ~1.36% variability in the F125W filter during a 9 hr observation with HST (Zhou et al. 2016). The 19 Myr object WISEP J004701.06+680352.1 (W0047) was found to exhibit ~8% variability during a 9 hr HST observation (Lew et al. 2016). Vos et al. (2018), reported results from a Spitzer program to monitor variability on the intermediate gravity late-L dwarfs W0047 and 2MASS J2243143+204343 (2M2244) and the planetary-mass T5.5 object SDSS 111010+011613 (SDSS1110). W0047 and 2M2244 were both found to be variable in the mid-IR, with fairly high amplitudes compared to the sample of higher-mass field dwarfs that have been studied. There is also tentative evidence that the low-gravity T dwarfs exhibit higher variability amplitudes compared to field objects. Gagné et al. (2017) find that the highly variable object SIMP0136 is a likely member of the ~200 Myr Carina-Near moving group. Gagné et al. (2018a) confirm the variable object 2M1324 as a member of the AB Doradus moving group and estimate a mass of 11.2 M_Jup. Naud et al. (2017) obtained three 5–6 hr epochs of variability monitoring observations of the young T-type companion GJ Psc b in AB Doradus. The authors detect marginal variability in one epoch but do not detect significant variability in the other two epochs. The high amplitudes observed in this small sample of low-gravity variable objects adds to the growing evidence that there is a link between low-gravity and enhanced variability.

Here we present the results of the first photometric monitoring survey of young, low-gravity L and T dwarfs, with the goal of investigating the gravity dependence of variability properties. Observations were carried out at the 3.5 m New Technology Telescope (NTT) and the 3.8 m UK Infrared Telescope (UKIRT).

2 SAMPLE SELECTION

From Autumn 2014 to Spring 2017 we observed a sample of 36 brown dwarfs that are candidate members of young moving groups in the literature and/or show signatures of youth in their spectra. Our survey targets are primarily sourced
from the BANYAN catalogues (Gagné et al. 2014a, 2015a) and Best et al. (2015). We additionally include the wide companions HN Peg B and GU Psc b (Luhman et al. 2007; Naud et al. 2014). The full survey sample is shown in Table 3. We consider the following young moving groups in this paper: TW Hydra (TWA, 10 ± 3 Myr; Bell et al. 2015), β Pictoris (β Pic, 22 ± 6 Myr; Shkolnik et al. 2017), Columba (Col, 42 ± 4 Myr; Bell et al. 2015), Tucana-Horologium (THA, 45 ± 4 Myr; Bell et al. 2015), Carina (Car, 45±11 Myr; Bell et al. 2015), Argus (Arg, 30–50 Myr; Torres et al. 2008), AB Doradus (AB Dor, 110–150 Myr; Barenfeld et al. 2013; Luhman et al. 2007) and Carina-Near (CarN, 200±50 Myr; Zuckerman et al. 2006). Our targets show signs of low-gravity in their spectra and/or are candidate members of nearby young moving groups. We reassess the spectral and kinematic evidence of low-gravity/youth for each object in Section 8.

To obtain high signal-to-noise (S/N) measurements that could be robustly compared to previous surveys (Radigan et al. 2014; Wilson et al. 2014), targets were limited to objects with magnitudes brighter than $H_{AB} ≤ 12.0$ mag, except where noted. Our targets show signs of low-gravity in their spectra and/or are candidate members of nearby young moving groups. We reassess the spectral and kinematic evidence of low-gravity/youth for each object in Section 8.

The sample consists of spectral types L0 and later, as these are less likely to exhibit magnetic spot activity due to the increasingly neutral atmospheres present in objects with $T_{\text{eff}}$ below ~2100 K. Geline et al. (2002) and Miles-Páez et al. (2017) find no correlation between magnetic activity (in the form of Hα emission) and photometric variability in a sample of L and T dwarfs. We attempt to cover the entire L-T spectral range uniformly, however few young T dwarfs sufficiently bright for ground-based IR photometric monitoring are known, preventing us from fully covering the T spectral type. Thus our sample is predominantly comprised of L-type objects.

There is only one known binary in our sample, 2MASS J03572695-4417305 (Bouy et al. 2003). The binary separation ($≈0.1″$) is less than the seeing so the photometry in this study records the combined flux from both components. The variability of one component in an unresolved binary will be diluted by flux from the non-variable component, making it more difficult to detect the variability. Alternatively, if both components of the binary are variable (as is the case for the Luhman 16AB binary system; Biller et al. 2013; Buenzli et al. 2015), their differing variability amplitudes and rotational periods will be combined in the observed lightcurve, likely resulting in a complex and/or rapidly evolving lightcurve.

3 OBSERVATIONS AND DATA REDUCTION

3.1 NTT SofI

The observations took place between October 2014 and March 2017 with the SofI (Son of Isaac) instrument, mounted on the 3.6 m New Technology Telescope (NTT) at La Silla Observatory. Observations were carried out in large field imaging mode, which has a pixel scale of 0.288″ and a 4.92" × 4.92" field of view. Targets were observed using the $J_K$ band (1.16–1.32 μm). The $J_K$ filter was chosen as it avoids contamination from the water band at 1.4 μm. Two targets were observed each night, alternating between nods in an ABBA pattern, with 3 exposures at each position. At each nod we ensured the target was accurately placed on the same original pixel in order to preserve photometric precision. 2–5 hr observations were obtained for each target. The flux of the target was kept below 10,000 ADU to prevent any non-linearity effects.

The data reduction steps are outlined in the SofI manual, and an IRAF pipeline was provided by ESO. We processed our images using both the standard IRAF routine as well as an IDL version. Here we detail our data reduction process.

3.1.1 Inter-quadrant Row Crosstalk

The SofI detector suffers from inter-quadrant row crosstalk, where a bright target imaged in one quadrant can cause a faint glow in equivalent rows of the other quadrants. The intensity of the crosstalk feature scales with the total intensity along a given row by an empirically determined value of $1.4 × 10^{-5}$ and can be removed easily.

3.1.2 Flat-fielding

The shade pattern on the array is a function of the incident flux, so the method of creating flat-fields by subtracting lamp-off from lamp-on dome flats leaves a residual shade pattern across the centre of the array. For this reason “special” dome flats are taken using standard frames along with frames in which the array is partially obscured to estimate the illumination dependent shade pattern of the array. The shade pattern can be removed as described by the ESO documentation.

3.1.3 Illumination Correction

Illumination correction removes the difference between the illumination pattern of the dome flat screen and the sky. This correction is determined from a grid of 16 observations of a standard star across the field of view. The illumination correction is created by fitting a 2D surface to the fluxes of the star after flat-fielding.

3.1.4 Sky Subtraction

The sky subtraction of images obtained with SofI serves to remove the dark current as well as the illumination-dependent shade pattern. Sky frames are created by median combining normalised frames of different nods which are closest in time. These are then re-scaled to the science frame before being subtracted from the science frame.

3.1.5 Aperture Photometry

The positions of the target star as well as a set of reference stars in the field of view were found in each frame using IDL FIND.PRO followed by GCTRND.PRO to measure the centroids. Aperture photometry was performed on the target as well as the set of reference stars. Fixed apertures of sizes similar to the median FWHM of all stars on the chip were used. The final aperture was chosen to minimise the photometric noise.

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The standard deviation provides a good estimate of noise for a non-variable lightcurve. However the standard deviation of a variable lightcurve measures both noise and intrinsic variations, and hence overestimates the noise. We estimate the typical photometric error for each lightcurve, $\sigma_{pt}$, using a method described by Radigan et al. (2014). This is the standard deviation of the lightcurve subtracted from a shifted version of itself, $f_{i+1} - f_i$, divided by $\sqrt{2}$. This quantity is sensitive to high frequency noise in the data and is insensitive to the low frequency trends we expect from variable brown dwarfs. Thus it provides a more accurate estimate of the photometric noise for variable lightcurves.

### 3.2 UKIRT WFCAM

Observations of 8 targets were taken with the infrared Wide-Field Camera (WFCAM; Casali et al. 2007). WFCAM is a wide-field imager on the 3.8 m UK Infrared Telescope on Mauna Kea, with a pixel scale of 0.4″. The observations were carried out in the $J$-band. Each target was observed using an ABBA nod pattern, as before. Frames were reduced using the WFCAM reduction pipeline (Irwin et al. 2008; Hodgkin et al. 2009) by the Cambridge Astronomy Survey Unit. The pipeline reduction steps include linearity correction, dark correction, flat-fielding, gain-correction, de-curtaining, defringing, sky subtraction and crosstalk removal (Irwin et al. 2004). We performed aperture photometry on the target and reference stars in the field of similar brightness, using a range of aperture sizes similar to the median FWHM of all stars in the field.

### 3.3 Lightcurve Analysis

The raw light curves obtained from aperture photometry display fluctuations in brightness due to changing atmospheric transparency, airmass and residual instrumental effects. To a very good approximation these changes are common to all stars in the field of view and can be removed via division of a calibration curve calculated from a set of iteratively chosen, well-behaved reference stars (Radigan et al. 2012). Firstly, reference stars with peak flux values below 10 or greater than 10,000 ADU were discarded. Different nods were normalised via division by their median flux before being combined to give a relative flux light curve. For each star a calibration curve was created by median combining all other reference stars (excluding that of the target and star in question). The standard deviation and linear slope for each light curve was calculated and stars with a standard deviation or slope divided by $\sqrt{2}$ was calculated and stars with a standard deviation or slope $\sim 1 - 3$ times greater than that of the target were discarded. This process was iterated a number of times, until a set of well-behaved reference stars was chosen. Final trended lightcurves were obtained by dividing the raw curve for each star by its calibration curve. Lightcurves shown in this paper have been binned by a factor of $1 \times 3$.

### 3.4 Independent Reduction of NTT/SofI Data

We additionally present the results of an independent data reduction process outlined in the MSc thesis of Simon Eriksson and supervisor Markus Janson (Eriksson 2016). 20 of the 21 targets observed with the NTT in 2014 were independently reduced and analysed. A further 10 observations from 2015-2017, mainly follow-ups, were investigated in late 2017 in the same way. Overall, 24 out of 30 NTT targets underwent reduction. The reduction steps previously outlined in Section 3.1.5 were performed, with the addition of a dark subtraction. The SofI pipeline provided by ESO was used for dark, flat-field and crosstalk corrections and sky subtraction. The process resulted in combined images of two different nods closest in time, and subsequent photometry
3.5 Identification of Variables

Variable targets were identified using a method similar to the periodogram analysis outlined in Vos et al. (2018). The periodograms of each target and its respective reference stars are plotted to identify periodic variability. For each observation, the 1% false-alarm probability (FAP) is calculated from 1000 simulated light curves. These light curves are produced by randomly permuting the indices of the reference star lightcurves (Radigan et al. 2014). The 1% FAP value is the periodogram power above which only 1% of the simulated lightcurves fall. This method assumes Gaussian-distributed noise in the reference stars, however to assess the significance of residual correlated noise in the reference star lightcurves we measure the $\beta$ factor of every light curve, which is the peak periodogram power of each reference star divided by the 1% FAP power (Radigan et al. 2014). Figure 2 shows the $\beta$ factor of reference stars and targets for NTT (top) and UKIRT (bottom) observations. We display these separately as each instrument has unique systematics. For reference stars exhibiting Gaussian-distributed noise, we would expect that 1% of reference star peak powers would fall above $\beta = 1$, however for both samples more than 1% of reference star peak powers fall above $\beta = 1$, and this is likely due to residual correlated noise in the lightcurves. To account for this excess noise, we find the empirical 1% FAP by finding the $\beta$ factor above which 1% of reference star peak powers fall. Blue and red dashed lines indicate the new, empirical 95% and 99% significance thresholds. This increases the 99% significance thresholds by a factor of 1.7 and 3.4 for the NTT and UKIRT samples respectively.

We additionally explore an alternative method for identifying significantly variable objects, following a method described in Heinze et al. (2015) in a survey for optical variability in T-type brown dwarfs. In this study, the authors find a weak dependence of their variability metric on the RMS of each target. We can also see this in Figure 2, where reference stars with a higher photometric error tend to have lower $\beta$ factors. We thus investigate the dependence of the periodogram power on $\sigma_p$ (defined in Section 3.1.5). We can expect some dependence because if two lightcurves vary with the same amplitude but different noise levels, the lightcurve with lower photometric error produces a periodogram with a higher power. Thus we take this into account in our significance threshold criteria. We show the peak periodogram power of targets and reference stars in Figure 3. We calculate a $\sigma$-dependent 95% threshold using a sliding box as described in Heinze et al. (2015). The box width was chosen such that $> 50$ reference star points were available to calculate the 95% threshold up to 0.02 $\sigma_p$ and 0.03 $\sigma_p$ for the NTT and UKIRT data respectively. We find that a box width of 0.02 $\sigma_p$ is suitable for both. We show the noise-dependent 95% significance threshold by the purple line in Figure 3. Both methods identify the same variable objects with the exception of PSO 071.8–12 and GU Psc b. PSO 071.8–12 is identified as variable in the $\beta$ factor method but is identified as non-variable in the noise-dependent periodogram power method. We count this object as variable since the lightcurve shows high-amplitude modulation. It is likely that the periodogram power is low because PSO 071.8–12 has a rotational period that is significantly longer than the observation duration. GU Psc b is identified as variable in the noise-dependent method shown in Figure 3. With a magnitude of $J = 18.12$, GU Psc b is at least an order of magnitude fainter than the other targets in our survey and as such, has a much higher photometric error than the other survey targets. Additionally, we have very few reference stars at $\sigma_p > 0.03$, so calculating a 95% threshold at values greater than this is not valid. For these reasons we do not count GU Psc b as a detection. Thus, we have detected variability in thirteen epochs of observations, finding seven variable objects in the survey. We show the lightcurves of each variable object and three reference stars in Figure 4.
Figure 2. $\beta$ factor plotted against the photometric error, $\sigma_{pt}$, for reference stars (grey circles) and targets (red circles) for the NTT (left) and UKIRT (right) samples. The $\beta$ factor is defined as the periodogram peak power of each reference star divided by 99% significance as calculated from our simulations. The updated, empirical 99% and 95% significance thresholds are shown by the red and blue dashed lines respectively.

Figure 3. Maximum periodogram power plotted against the photometric error, $\sigma_{pt}$, for reference stars (grey circles) and targets (red circles) for the NTT (left) and UKIRT (right) samples. The $\sigma_{pt}$-dependent 95% significance is shown by the purple line.
4 PERIODOGRAM ANALYSIS AND ROTATIONAL PERIODS

Manjavacas et al. (2018) find that the Lomb-Scargle periodogram method is sensitive to gaps in their HST lightcurve of a brown dwarf companion. The authors find that the publicly available Bayesian Generalised Lomb-Scargle method (Mortier et al. 2015) is insensitive to these gaps, and produces a strong peak at the true rotational period of the brown dwarf. As some of our variable lightcurves have gaps in the data due to bad weather and/or instrumental difficulties at the telescope, we use the BGLS periodogram method to confirm that the detected trends are real, and not due to gaps in the data. The BGLS method produces periodograms with strong peaks at periods that are consistent with those of the Lomb-Scargle method for each variability detection. Thus we can conclude that the periodicity observed in the periodograms is not due to gaps in the lightcurve.

While periodogram analysis can be used to provide an estimate of the rotational periods of brown dwarfs (e.g. Croll et al. 2016; Manjavacas et al. 2018), we caution that the observation duration of our lightcurves are too short to robustly measure a period for most cases. Many of the variable lightcurves shown in Figure 4 do not exhibit a local maximum or minimum and thus we can only place lower limits on their rotational periods. For lightcurves that do appear to exhibit local maxima or minima, the rotational periods cannot be confidently measured because double-peaked and evolving lightcurves have been observed in many variable brown dwarfs to date (e.g. Apai et al. 2017; Vos et al. 2018). Longer duration follow-up observations are necessary to robustly measure the rotational periods of the variable objects detected in this survey.

5 SENSITIVITY TO VARIABILITY SIGNALS

We construct a sensitivity plot for each observation to determine our sensitivity to variability signals of given amplitudes and periods. We inject simulated sinusoidal curves into random permutations of each target lightcurve. For targets found to be variable in the survey we divide the lightcurve by a polynomial fit to the lightcurve before injecting the simulated sinusoidal signals. The 1000 simulated sine curves have peak-to-peak amplitudes of 0.5 – 10% and periods of 1.5 – 20 hr, with randomly assigned phase shifts. Each simulated lightcurve is put through our periodogram analysis, which allows us to produce a sensitivity plot, showing the percentage of recovered signals as a function of amplitude and period. Sensitivity plots for all light curves are shown in the bottom panel of Figure 5 for variable objects and Appendix 3 (available online) for non-variables in the survey.

6 SIGNIFICANT DETECTIONS OF VARIABILITY

We detect significant variability in seven objects in the survey. Variable objects and their estimated variability amplitudes are presented in Table 2. We present the light curves of these variable objects along with their reference stars in Figure 4. We show their periodograms and sensitivity plots in Figure 5. We discuss the first epoch variability detection of each object below.

2MASS J00452143+1634446 — Gagné et al. (2014a) classify the L2 object 2M0045+16 as a very low gravity brown dwarf, with Hα emission and unusually red colours. It has been identified as a bona fide member of the Argus association (30 – 50 Myr), giving it an estimated mass of 14.7 ± 0.3 M_Jup (Gagné et al. 2015a), however recent work by Bell et al. (2015) has called into question the validity of the Argus association. We observed 2M0045+16 on Nov 11 2014 using NTT SofI. We detect highly significant variability in this object at this epoch. The lightcurve of 2M0045+16 and the reference stars used for detrending are shown in Figure 4 and the periodogram and sensitivity plots are shown in Figure 5. A lack of stars in the field resulted in only 3 references stars suitable for detrending the lightcurve. We fit a sinusoid to the lightcurve using a Levenberg-Marquardt least-squares algorithm to estimate the amplitude of the modulation in the first epoch. This gives an amplitude of 1.0 ± 0.1% and a period 4.3 ± 0.3 hr. While it appears that we have covered a full rotational period, additional longer duration observations are necessary to rule out the possibility of a double-peaked lightcurve with a longer rotational period (e.g. Vos et al. 2018). We discuss followup observations of 2M0045+16 in Section 10.

PSO J071.8769−12.2713 — PSO 071.8−12 was identified as a high-probability candidate member of β Pictoris by Best et al. (2015). Assuming membership of the β Pictoris moving group, it has an estimated mass of 6.1 ± 0.7 M_Jup (Best et al. 2015), making it the lowest mass object to date to exhibit photometric variability. The lightcurve shown in Figure 4 displays high-amplitude (4.5±0.6%) variability. The periodogram shown in Figure 5 shows a highly significant (> 99%) peak. Since we did not cover a full rotational period we can only estimate a period > 3 hr. We discuss subsequent follow-up observations of this object in Section 10.

2MASS J05012010–0010452 — Gagné et al. (2015a) categorise 2M0501–00 as L3y, and an ambiguous candidate member of Columba or Carina (both moving groups are coeval at 20 – 40 Myr). If 2M0501–00 is indeed a member of Columba or Carina it has an estimated mass of 10.2^{+1.8}_{−1.0} M_Jup. We detect significant variability in 2M0501–00 on Nov 11 2014 with NTT SofI (shown in Figure 4). The periodogram shown in Figure 5 shows a highly significant peak at periods > 4 hr. A sinusoidal fit to the lightcurve gives a peak-to-peak amplitude of 2.0 ± 0.1% and a period of > 4 hr. Since we did not cover a full period of rotation in either epoch, our amplitude measurement is a lower limit and our period estimate is very uncertain. We obtained additional follow-up
Figure 4. Lightcurves of variable targets (red) compared to a sample of reference stars in the field (blue). The black line shows the least-squares best fit sinusoidal model to the lightcurve.

monitoring of 2M0501–00 and discuss these observations in Section 10. 2MASS J14252798−36502295.23 — 2M1425–36 is classified as a bona fide member of AB Doradus (Gagné et al. 2015a). Radigan et al. (2014) previously reported 2M1425–36 as a marginal variable, displaying low-level variability over a ∼ 2.5 hr observation. We detect low-amplitude variability in the L4 object 2M1425–36 on Aug 17 2015. Figure 5 shows a highly significant periodogram peak that favours a period of ∼ 3 hr. Using our least-squares algorithm we estimate a variability amplitude of 0.7 ± 0.3% for this epoch. We place a lower limit of 2.5 h on the rotational period since we did not cover a full period. We observed 2M1425–36 a second time in 2017 and discuss this observation in Section 10.

2MASS J20025073−0521524 — 2M2002–05 is classified as a L5-L7 γ object by Gagné et al. (2015a), but has not been identified as a candidate of a young moving group (Faherty
et al. 2016). Our UKIRT/WFCAM observation of this object taken on July 09 2016 shows significant variability. Fitting a sinusoid to the lightcurve we estimate an amplitude of $1.7 \pm 0.2\%$ and a period of $8 \pm 2\,$hr, however these are very uncertain as we did not cover a full rotational period in this epoch.

PSO J318.5338−22.8603 — Allers et al. (2016) confirm the L7 PSO 318.5−22 as a member of the $23 \pm 3\,$Myr (Mamajek & Bell 2014) β Pictoris moving group. This implies a mass estimate of $8.3 \pm 0.5\, M_{\text{Jup}}$, placing PSO 318.5−22 clearly in the planetary-mass regime. The lightcurves of PSO 318.5−22 from 2014 are presented in Biller et al. (2015) and are also included in this paper in Figure 4. As discussed in Biller et al. (2015), we detect significant, high-amplitude variability in PSO 318.5−22 on October 9 2014. The periodogram in Figure 5 shows a highly significant peak at periods $> 4.5\,$hr. A sinusoidal fit to the lightcurve gives a peak-to-peak amplitude of $10 \pm 1.3\%$ and a period of $10 \pm 2\,$hr. We obtained two...
Figure 5. Lightcurves, periodograms and sensitivity plots for variable objects. Top panel: Relative photometry of target. Middle panel: Periodogram of target lightcurve (black) and periodograms of reference stars (grey). Blue dashed lines show the 95% and 99% significance thresholds. Bottom panel: Sensitivity plot showing the percentage of recovered signals for injected sinusoidal signals of various variability amplitude and periods.
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additional epochs of follow-up monitoring for PSO 318.5–22 as part of the variability survey and discuss these observations in Section 10.

2MASS J2244316+204343 — 2M2244+20 is a confirmed member of AB Doradus, with an estimated mass of \( \sim 19 M_{\text{Jup}} \) (Vos et al. 2018). Morales-Calderon et al. (2006) and Vos et al. (2018) detect variability in the Spitzer 4.5 \( \mu \)m and 3.6 \( \mu \)m bands respectively. The J-band lightcurve obtained in this survey was initially presented in Vos et al. (2018), where we measured a period of \( 11 \pm 2 \) hr for this object using Spitzer data. The UKIRT/WFCAM lightcurve obtained on July 21 2016 shows significant variability. The periodogram shown in Figure 5 shows a significant peak for periods > 4 hr. We set the period to \( 11 \pm 2 \) hr (as measured in Vos et al. 2018) in our least-squares sinusoidal fit and find an amplitude of 5.5 ± 0.6% for this epoch.

7 NON-DETECTIONS

We present light curves and reference star light curves of non-variables in Appendix 1 (available online). Periodograms and sensitivity plots are shown in Appendix 3 (available online). We discuss some of the noteworthy non-detections below.

2MASS J01033203+1935361 — 2M0103+19 has been assigned \( \beta \) and INT-G gravity classifications (Kirkpatrick et al. 2000; Faherty et al. 2012; Allers & Liu 2013), however has not been assigned membership of a young moving group. Metchev et al. (2015) obtained 21 hr of Spitzer monitoring, detecting variability in both the 3.6 \( \mu \)m and 4.5 \( \mu \)m bands. 2M0103+19 was observed to exhibit a regular periodic modulation with a period of 2.7 ± 0.1 hr. This short rotational period combined with variability amplitudes of 0.56 ± 0.03% and 0.98 ± 0.09% in the 3.6 \( \mu \)m and 4.5 \( \mu \)m bands respectively, would suggest that a J-band detection is likely for this object. Our observation taken on November 3 2014 shows no evidence of variability over a 5.3 hr observation. According to the sensitivity plot shown in Appendix 3 (available online), we would have detected variability with an amplitude > 2% for a 2.7 hr period with a 90% probability.

GU Psc b — GU Psc b is a wide separation T3.5 planetary-mass companion to the young M3 star, a likely member of the AB Doradus moving group (Naud et al. 2014). Recently, Naud et al. (2017) reported results from a J-band search for variability in this object. Photometric variability with an amplitude of 4 ± 1% was marginally detected during one ~ 6 hr observation, with no significant variations observed at two additional epochs. The authors estimate a period > 6 hr as the lightcurve does not appear to repeat during this observation. With a magnitude of \( J = 18.12 \), GU Psc b is ~ 1 mag fainter than the other targets in our survey and we do not detect significant variability in its ~ 3.5 hr lightcurve. The sensitivity plot of GU Psc b presented in Appendix 3 (available online) shows that this observation is insensitive to variability with amplitudes < 10%, and thus we cannot say whether the lightcurve has evolved from the variable epoch detected by Naud et al. (2017). While this remains a prime target for variability monitoring, long observations and high photometric precision are needed to confirm and characterise its variability.

2MASS J16154255+4953211 — 2M1615+49 is identified as a young object by Cruz et al. (2007); Kirkpatrick et al. (2008); Allers & Liu (2013), although it has not been identified as a member of a young moving group. Kirkpatrick et al. (2008) tentatively assign this object an age estimate of \( \sim 100 \) Myr based on its optical spectrum. Metchev et al. (2015) obtained 21 hr of Spitzer 3.6 \( \mu \)m and 4.5 \( \mu \)m variability monitoring, finding significant variability in the 14 hr 3.6 \( \mu \)m sequence but not in the 7 hr 4.5 \( \mu \)m sequence. The authors estimate a period of \( \sim 24 \) hr for 2M1615+49. We do not observe any significant variability in our UKIRT J-band observation of 2M1615+49 taken on Jul 10 2016. The sensitivity plot shown in Appendix 3 (available online) indicates that we are not sensitive to periods longer than \( \sim 10 \) hr, so it is unsurprising that we did not detect variability in this long-period variable.

HN Peg B — Discovered by Luhman et al. (2007), HN Peg B is a T2.5 dwarf companion to the 300 Myr old star HN Peg. Metchev et al. (2015) report significant variability in both the Spitzer 3.6 \( \mu \)m and 4.5 \( \mu \)m bands and estimate a period of \( \sim 18 \) hr. More recently, Zhou et al. (2018) obtained HST WFC3 near-IR monitoring of HN Peg B, observing significant variability at all wavelengths in the range 1.1 – 1.7 \( \mu \)m. They estimate a period of 15.4 ± 0.5 hr and measure a J-band amplitude of 1.28 ± 0.3%. We observed HN Peg B four times in total, twice with both the NTT and UKIRT telescopes, taking care to keep the primary HN Peg A off-frame. Although HN Peg A was kept off-frame for these observations, diffraction spikes still affected the quality of all of our observations. For our NTT data taken on October 8 2014 and August 7 2015, contaminated frames had to be removed from the lightcurve where the diffraction spikes coincided with the position of HN Peg B on the detector. For our UKIRT observations taken on July 11 2016 and July 13 2016 photometry from one nod position had to be removed from the data. Although the NTT lightcurves have lower \( e_{\text{pt}} \), their short duration (< 2.5 hr) means that they are insensitive to trends on timescales > 5 hr. During two ~ 5 hr observations with UKIRT, we do not detect any significant variability. Longer duration observations will be needed to characterise the variability of this young companion.
## Table 3. Signatures of Youth in Sample

| Name                  | SpT (Opt) | Ref | SpT (IR) | Ref | K05 Class | K05 Ref | AL13 Ind | AL13 Class | AL13 Ref | Signs of Youth | Ref |
|-----------------------|-----------|-----|----------|-----|-----------|---------|----------|------------|----------|----------------|-----|
| 2MASS J00011217+153535 | ...        | L1  | G11a     | β   | G11a      | 1211    | INT-G    | G11a       | ORT      | G11a           |     |
| 2MASS J00452143+163446 | L2        | C09 | L2       | AL13| G14a      | 1221    | VL-G     | AL13       | ORT      | G14a           | G14a|
| 2MASS J01033203+193536 | L6        | F12 | L6       | M03 | G14a      | 1n11    | INT-G    | AL13       | ORT      | G14a           | G14a|
| GU Psc b              | ...        |     | T3.5     | N14 | N14       | ...     | ...      | RM         | ...      | G14a           |     |
| 2MASS J01174748-140325 | L2        | C03 | L1       | AL13| G14a      | 1121    | INT-G    | AL13       | TRM      | G14a           | G14a|
| 2MASS J02340093-644206 | L0        | K10 | L0       | F16 | G14a      | 2211    | VL-G     | F16        | OR       | G14a           |     |
| 2MASS J03032042-731230 | L6        | F16 | L6       | β   | G14a      | 1212    | VL-G     | F16        | ORL      | G14a           |     |
| 2MASS J03261225-210205 | L5        | G15a| L5       | F16 | G15a      | 0n01    | FID-G    | F16        | RL       | G14a           |     |
| 2MASS J04210718-630602 | L5        | C09 | L5       | F16 | G14a      | 1122    | INT-G    | G15a       | OR       | G14a           | G14a|
| PSO J057.2893+15.2433  | ...        |     | L7       | B15 | B15       | ...     | ...      | R          | B15      | G14a           |     |
| 2MASS J05552377+113437 | L5        | C09 | L3       | AL13| G14a      | 2212    | VL-G     | G15a       | OITRL    | G14a           |     |
| 2MASS J03572695-441723 | L5        | C09 | L5       | F16 | G14a      | 0n11    | INT-G    | F16        | OIRL     | G14a           |     |
| PSO J071.5868-12.2713  | ...        |     | T2       | B15 | B15       | ...     | ...      | ...        | ...      | G14a           |     |
| 2MASS J05120636-294954 | L1        | C07 | L1       | AL13| G15a      | 2222    | VL-G     | AL13       | ORT      | G14a           |     |
| 2MASS J03101401-275645 | L5        | K08 | L5       | AL13| G15a      | 1n01    | INT-G    | G15a       | R        | G14a           |     |
| 2MASS J03231002-463123 | L0        | C09 | L0       | F16 | G14a      | 2222    | VL-G     | F16        | ORL      | G14a           |     |
| 2MASS J03261225-210205 | L5        | G15a| L5       | F16 | G15a      | 0n01    | FID-G    | F16        | RL       | G14a           |     |
| 2MASS J03421621-681732 | L4        | G15a| ...      | ... | ...       | ...     | ...      | ...        | ...      | G14a           |     |
| 2MASS J04185879-450741 | ...        |     | L3       | G15a| ...       | ...     | ...      | ...        | ...      | G14a           |     |
| 2MASS J04210718-630622 | L5        | C09 | L5       | F16 | G14a      | 1122    | INT-G    | G15a       | TR       | G14a           |     |
| PSO J071.5868-12.2713  | ...        |     | T2       | B15 | B15       | ...     | ...      | ...        | ...      | G14a           |     |
| 2MASS J111010.01+011613 | ...        |     | T5.5     | G15c| G15c      | ...     | ...      | ...        | ...      | G14a           |     |
| 2MASS J12074836-390003 | L0        | G14b| L1       | G14b| G15a      | 2222    | VL-G     | G15a       | OITR     | G14a           |     |
| 2MASS J12152978-350229 | L3        | R08 | L4       | G15a| G15a      | 1171    | INT-G    | G15a       | TR       | G14a           |     |
| 2MASS J16154255+495321 | L4        | C07 | L3       | AL13| G15a      | 2022    | VL-G     | AL13       | OITRL    | G14a           |     |
| WISE J17102.78-142255  | ...        |     | L7       | S14 | S14       | ...     | ...      | ITRM       | S14      | G14a           |     |
| PSO J127.4692-04.8036  | ...        |     | T1       | B15 | B15       | ...     | ...      | ...        | ...      | G14a           |     |
| 2MASS J13002507+052154 | L6        | C07 | L5-7     | G15a| G15a      | 2222    | VL-G     | G15a       | OT       | G14a           |     |
| 2MASS J20113196-504811 | ...        |     | L3       | G15a| G15a      | 2222    | VL-G     | G15a       | OT       | G14a           |     |
| PSO J1518.5388-22.8603 | ...        |     | L7       | L13 | G15a      | XXX2, 2X21| VL-G     | L13       | ITRM      | G14a           |     |
| 2MASS J21324036+102949 | L4        | C09 | L3       | AL13| G14a      | 0n11    | INT-G    | G15a       | TR       | G14a           |     |
| HN Peg B              | ...        |     | ...      | ... | ...       | ...     | ...      | ...        | ...      | G14a           |     |
| SIMP J215434.5-105530 | L4        | C14 | L5       | F16 | G14c      | 0n11    | INT-G    | G15a       | ITR       | G14a           |     |
| 2MASS J2224316+204343 | L6.5       | K08 | L6       | AL13| G15a      | 2n21    | VL-G     | AL13       | ITRLM    | G14a           |     |
| 2MASS J2325299+615127 | L2        | C09 | L3       | F16 | G14a      | 1221    | VL-G     | G15a       | OR       | G14a           |     |

References:

- AL13: Allers & Liu (2013), B15 Best et al. (2015), C03: Cruz et al. (2003), C07: Cruz et al. (2007), C09: Cruz et al. (2009), F12: Faherty et al. (2012), F16: Faherty et al. (2016), G14a: Gagné et al. (2014a), G14b: Gagné et al. (2014b), G14c: Gagné et al. (2014c), G15b Gagné et al. (2015b), G15c: Gagné et al. (2015a), K05: Kirkpatrick (2005) K08: Kirkpatrick et al. (2008), K10: Kirkpatrick et al. (2010), L13: Liu et al. (2013), M03: McLean et al. (2003), M06: Martín et al. (2006), N14: Naud et al. (2014), L07: Luhman et al. (2007), R08: Reid et al. (2008), S14 Schneider et al. (2014)

A capital letter means the object displays the associated sign of youth. O: lower-than normal equivalent width of atomic species in the optical spectrum, I: same but in the NIR spectrum, T: triangular-shaped H-band continuum, R: redder-than-normal colors for given spectral type, U: over luminous, H: \( H\alpha \) emission, L: Li absorption, M: signs of low gravity from atmospheric models fitting.
8 ASSESSING EVIDENCE OF YOUTH IN THE SAMPLE

8.1 Analysing Sample Spectra

Our targets have been identified as potentially young in the literature, through indications of low-gravity in their spectra and/or identification as probable members of young moving groups (e.g. Cruz et al. 2009; Allers & Liu 2013; Gagné et al. 2015a; Best et al. 2015). In this section, we consider gravity-sensitive features in the spectra of our targets. Kirkpatrick (2005) present a spectral classification scheme for L0-L5 brown dwarfs that includes three gravity classes based on gravity sensitive features in their optical spectra. The three gravity subtypes α, β and γ, denote objects of normal gravity, intermediate gravity and very low gravity respectively. The δ suffix is used to designate objects with an even younger age (typically less than a few Myr) and lower surface gravity than those associated with the γ suffix (Kirkpatrick et al. 2006). Gagné et al. (2015a) use optically anchored IR spectral average templates for classifying the gravity subtype for L0-L9 dwarfs. This method assigns α, β and γ subtypes for each object. Allers & Liu (2013) present an index-based infrared gravity classification method that is based on FeH, VO, K, Naδ and H-band continuum shape in the IR. A score of 0 indicates that the feature is consistent with field gravity objects, 1 indicates intermediate gravity and 2 indicates very low gravity. A score of “n” is assigned if either the spectrum does not cover the wavelength range of the index or the feature is not gravity-sensitive at the object’s spectral type. A score of “?” indicates that an index hints at low gravity, but the uncertainty in the calculated index is too large. The final gravity classification (fLD-G, nT-G, vL-G) is assigned based on the median of the individual gravity scores, ignoring “n” or “?” scores.

We present the spectral types, gravity subtypes and the specific signatures of low-gravity exhibited by each object in the sample in Table 3.

8.2 Assessing Group Membership

Following a similar method to Faherty et al. (2016), we investigate the likelihood that each object in the survey is a member of a young moving group using four methods of assessing group membership using kinematic data: the convergent point analysis of Rodriguez et al. (2013), the BANYAN I tool of Malo et al. (2013), the BANYAN Σ method in Gagné et al. (2018b) and the LACEwING analysis of Riedel et al. (2017).

Convergent point analysis estimates the probability of membership using the perpendicular motion of the candidate member and the convergent point location of a given moving group, but does not take into account radial velocity or parallax. This method considers six potential moving groups: TWA, THA, β Pic, AB Dor, CarN and Col. BANYAN I uses a Bayesian statistical analysis to identify members of kinematic groups. BANYAN I minimally requires the position, proper motion, magnitude and colour of a star but radial velocity and distance measurements can be added. In addition to the groups considered by the convergent point analysis of Rodríguez et al. (2013), BANYAN I investigates membership in the Argus association. BANYAN Σ is a new Bayesian algorithm for identifying members of young moving groups that includes 27 young associations. This algorithm improves upon BANYAN I and II (Malo et al. 2013; Gagné et al. 2014a) by using analytical solutions when marginalising over radial velocity and distance, using multivariate Gaussian models for the young moving groups and removing several approximations in the calculation of Bayesian likelihood. BANYAN Σ does not include the Argus association in its analysis, as it is likely that this association suffers from a high level of contamination (Bell et al. 2015). Proper motions, radial velocities and parallaxes used in this analysis are shown in Table 4.

The results of each membership tool should be evaluated differently: Malo et al. (2013) and Gagné et al. (2018b) use a threshold of 90% to confirm membership for the BANYAN I and Σ tools respectively. We use this threshold probability of 90% for the Convergent Point tool (Rodríguez et al. 2013). Riedel et al. (2017) find that a membership probability > 66% indicates a high membership likelihood using LACEwING.

We present the results of each method in Table 5. To assess the membership probability of each object based on the results of the kinematic analysis, we use the categories outlined in Faherty et al. (2016):

1. Non-member (NM): an object that is rejected from nearby associations due to its kinematics.
2. Ambiguous member (AM): an object requiring higher precision kinematics because it is classified as a candidate to more than one group or cannot be differentiated from field objects.
3. High-likelihood member (HLM): an object that does not have full kinematic information (proper motion, radial velocity and parallax) but is regarded as high confidence (> 90% for BANYAN I, BANYAN Σ and Convergent Point analysis, > 66% in LACEwING) in at least three out of four algorithms.
4. Bona fide member (BM): an object regarded as a high-likelihood member with full kinematic information.

Faherty et al. (2016) carried out this analysis on a larger sample of potential young objects, using Convergent Point analysis, BANYAN I, BANYAN II and LACEwING. Our results, which substitutes BANYAN Σ for BANYAN II, are mostly consistent with those found in Faherty et al. (2016) with a few exceptions. 2M0303-73 drops from an ambiguous member of Tucana-Horologium in Faherty et al. (2016) to a non-member in our analysis. 2M0045+16 had been previously identified as a bona fide member of Argus (Faherty et al. 2016), however given the uncertainty in the Argus group, Gagné et al. (2018b) excluded this group from the analysis. The convergent point method and LACEwING assign it to the Argus association while BANYAN I and Σ assign it to the Carina-Near association. The object 2M0117–34 drops from a high-likelihood member to an ambiguous member. Compared to analysis in Faherty et al. (2016), we include a parallax measurement from Liu et al. (2016) for this object. All moving group tools favour the Tucana-Horologium association, however BANYAN Σ and LACEwING probabilities are below 90% and 66% respectively. 2M0323–46, 2M0342–68 and 2M2322–61 all drop from a high-likelihood member to an ambiguous member due to lower membership probabilities calculated in BANYAN Σ.
compared to BANYAN II. 2M0326–21 is classified as an ambiguous member of AB Doradus because the Convergent Point tool and LACEwING predict membership probabilities of 66% and 55% respectively. As can be seen in Table 5, our sample is composed of six bona fide members, two high-lower membership members, twenty-four ambiguous candidates and three non-members.

We additionally look at our sample on a colour-magnitude diagram to check that they follow the general trends seen in intermediate and low-gravity objects to date (Liu et al. 2016; Faherty et al. 2016). Many objects in the sample have measured parallaxes from Dupuy & Liu (2012); Faherty et al. (2012, 2016); Liu et al. (2016). When parallaxes were not available we used their estimated distance from kinematic group membership. We plot absolute magnitude against colour in Figure 6. Overall, the survey objects appear redder and more luminous than the field brown dwarf population, as seen in a larger sample of young objects by Liu et al. (2016). However the object PSO 071.8–12, shown by red circle in Figure 6, appears to be an outlier in this sequence. PSO 071.8–12 was discovered by Best et al. (2015), who find that it is a high probability candidate of β Pic-

torius using BANYAN II. However, our group membership assigns PSO 071.8–12 a moderate probability candidacy of the AB Doradus moving group, with very low probability candidacy to Σ

### Table 4. Kinematic Information of Variability Sample

| Name                | $\mu_\alpha$ cos $\delta$ | $\mu_\delta$ | Ref | RV  | Ref | $\pi$ | Ref |
|---------------------|---------------------------|--------------|-----|-----|-----|------|-----|
| 2M0001+15           | 135.2 ± 10.7              | –169.6 ± 13.7| F16 | ... |     |      |     |
| 2M0045+16           | 355 ± 10                  | –40 ± 10     | F16 | 3.16 ± 0.83 | F16 | 65.9 ± 1.3 | L16 |
| 2M0353+19           | 293.0 ± 4.6               | 27 ± 4.7     | F12 | ... |     |      |     |
| GU Psc b            | 90 ± 6                    | –102 ± 6     | N14 | –1.6 ± 0.4 | N14 | ... |     |
| 2M0117–34           | 84 ± 15                   | –45 ± 8      | F16 | (3.96 ± 2.09) | F16 | 26.1 ± 1.9 | L16 |
| 2M0234–64           | 88 ± 12                   | –15 ± 12     | F16 | 11.76 ± 0.721 | F16 | (21 ± 5) | F16 |
| 2M0303–73           | 43 ± 12                   | 3 ± 12       | F16 | ... |     |      |     |
| 2M0310–27           | –119 ± 18                 | –47 ± 16     | C08 | ... |     |      |     |
| 2M0325–26           | 66 ± 8                    | 1 ± 16       | F16 | 13.001 ± 0.045 | F16 | (17 ± 3) | F16 |
| 2M0326–21           | 108 ± 14                  | –146 ± 15    | F16 | (22.91 ± 2.07) | F16 | (41 ± 1) | F16 |
| 2M0352–68           | 65.3 ± 2.8                | 18.5 ± 9.1   | F16 | (13.87 ± 2.62) | F16 | (21 ± 9) | F16 |
| PSO 057.2+15        | 68 ± 11                   | –127 ± 12    | B15 | ... |     |      |     |
| 2M0355+11           | 225 ± 13.2                | –630 ± 15    | F16 | 11.92 ± 0.22 | F16 | 109.5 ± 1.4 | F16 |
| 2M0357–44           | 64 ± 13                   | –20 ± 19     | F16 | 10.73 ± 4.6 | F16 | ... |     |
| 2M0418–45           | 53.3 ± 8.4                | –8.2 ± 12.6  | F16 | ... |     |      |     |
| 2M0421–63           | 146 ± 8                   | 191 ± 18     | F16 | 14.7 ± 0.33 | F16 | ... |     |
| PSO 071.8–12        | 20 ± 19                   | –89 ± 19     | B15 | ... |     |      |     |
| 2M0501–00           | 190.3 ± 9.5               | –142.8 ± 12.5| F16 | 21.77 ± 0.66 | F16 | 48.4 ± 1.4 | F16 |
| 2M0512–29           | –10 ± 13                  | 80 ± 15      | F16 | ... |     |      |     |
| 2M0518–27           | 28.6 ± 4.2                | –16 ± 4      | F16 | 24.35 ± 0.19 | F16 | 18.4 ± 1.1 | F16 |
| 2M0536–19           | 24.6 ± 5.3                | –30.6 ± 5    | F16 | 22.065 ± 0.695 | F16 | 21.1 ± 1.6 | F16 |
| SDSS 1110+0          | –217.1 ± 0.7              | –280.9 ± 0.6 | G15a | 7.5 ± 3.8 | G15a | 52.1 ± 1.2 | D12 |
| 2M1207–39           | –57.2 ± 7.9               | –24.8 ± 10.5 | F16 | (9.48 ± 1.91) | F16 | (15 ± 3) | F16 |
| 2M1256–27           | –67.4 ± 10.2              | –56.5 ± 12.7 | F16 | ... |     |      |     |
| 2M1257–36           | –284.89 ± 1.4             | –463.08 ± 1  | F16 | 5.37 ± 0.25 | F16 | 86.45 ± 0.83 | F16 |
| 2M1615+49           | –80 ± 12                  | –18 ± 12     | F16 | –25.59 ± 3.18 | F16 | 32 ± 1 | L16 |
| Wise 1741–46         | –20.4 ± 9.2               | –343 ± 13.7  | F16 | –5.7 ± 5.1 | F16 | ... |     |
| PSO 272.4–04         | –46 ± 4                   | –400 ± 13    | B15 | ... |     |      |     |
| 2M2002–05           | –98 ± 5                   | –110 ± 8     | F16 | ... |     |      |     |
| 2M2011–50           | 21.3 ± 8.1                | –71.3 ± 14.5 | F16 | ... |     |      |     |
| PSO 318.5–22         | 137.3 ± 1.3               | –138.7 ± 1.4 | F16 | –6.0 ± 0.95 | A16 | 45.1 ± 1.7 | L16 |
| 2M2132–10           | 107.8 ± 16.4              | 29.7 ± 18.1  | F16 | ... |     |      |     |
| HN Peg B            | ...                      | ...          | ... | ... |     |      |     |
| SIMP 2154–10         | 175 ± 12                  | 9 ± 12       | F16 | ... |     | 32.6 ± 1 | L16 |
| 2M2214–20           | 252 ± 14                  | –214 ± 11    | F16 | –16.0 ± 0.85 | V17 | 58.7 ± 1.0 | L16 |
| 2M2222–61           | 62 ± 10                   | 85 ± 9       | F16 | 6.747 ± 0.75 | F16 | (22 ± 1) | F16 |

References: C08: Casewell et al. (2008) D12: Dupuy & Liu (2012) G15a: Gagné et al. (2015c) F12: Faherty et al. (2012) F16: Faherty et al. (2016) N14: Naud et al. (2014) V17: Vos et al. (2017)
of youth. These objects are classified as ‘Uncertain’ in Table 5. We discuss the excluded objects below. The object PSO 057.2+15 is excluded from the survey. This L7 object appears redder than the field population and exhibits a triangular shaped $H$-band, however a gravity class could not be determined due to its low $S/N$ spectrum (Best et al. 2015). The moving group tools suggest possible membership in AB Doradus or β Pictoris but are not consistent with each other. Updated kinematics and/or spectral analysis are needed to confirm the possible youth of this object. We thus exclude PSO 057.2+15 from the ‘Young’ sample. PSO 272.4–04 is a low-probability AB Doradus member using 3/4 membership tools. Gravity sensitive indices only apply to objects with spectral types $\geq$L7, since low-gravity spectral signatures are not very well established for late-L and T-type objects. Thus, signatures of youth for the T1 objects PSO 272.4–04 could not be analysed (Best et al. 2015). We thus exclude it from the ‘Young’ sample. Gravity indices could not be analysed for the T2 object PSO 071.8–22 for the same reason. PSO 071.8–12 also has uncertain membership status, as discussed above, and we thus exclude it from the final statistical analysis of the survey. We additionally exclude the binary 2M0357–44 from the final survey. Although 2M0357–44 is likely young (Cruz et al. 2009; Gagné et al. 2015b), we have a reduced likelihood of detecting variability in either component of the binary, since the non-variable component would effectively dilute the variability signal. 2M2322–61 and 2M0412–63 are also left out of the survey because they were observed during poor weather conditions which prohibited us from determining meaningful constraints on their variability properties. Their lightcurves are shown in Appendix 2 (available online). In total we exclude 6 objects that we observed in our survey from the final sample of 30 young, low-gravity objects used in our analysis. We show

### Table 5. Moving Group Membership Probabilities

| Name                | Convergencea | P(%)       | BANYAN I | BANYAN Σ | LACEwING | Memb | Decisionb |
|---------------------|--------------|------------|----------|----------|----------|------|-----------|
| 2M0001+15           | AB Dor       | 43.2       | AB Dor   | 99.04    | AB Dor   | 76.0 | BM        |
| 2M0045+16           | CarN         | 74.2       | Arg      | 99.97    | CarN     | 89.0 | AM        |
| 2M0103+19           | CarN         | 15.7       | Old      | 96.0     | Field    | 76.1 | AM        |
| Gu Pac b            | AB Dor       | 99.5       | AB Dor   | 99.88    | AB Dor   | 89.0 | BM        |
| 2M0117–34           | THA          | 99.6       | THA      | 92.4     | THA      | 79.3 | AM        |
| 2M0234–64           | THA          | 79.5       | THA      | 99.99    | THA      | 96.3 | AM        |
| 2M0303–73           | THA          | 97.6       | Old      | 92.5     | FLD      | 99.9 | AM        |
| 2M0357–44           | THA          | 98.3       | THA      | 98.4     | THA      | 67.7 | AM        |
| PSO 057.2+15        | AB Dor       | 82.4       | βPic     | 65.19    | AB Dor   | 67.2 | AM        |
| 2M0355+11           | AB Dor       | 17.5       | AB Dor   | 99.99    | AB Dor   | 99.9 | AM        |
| 2M0357–44           | THA          | 62.1       | THA      | 53.07    | Field, THA | 66.6, 17.5 | AM        |
| 2M0418–45           | AB Dor       | 91.5       | AB Dor   | 64.0     | AB Dor   | 41.9 | AM        |
| 2M0421–63           | βPic, CarN   | 95.8, 95.9 | βPic     | 92.8     | CarN     | 93.8 | AM        |
| PSO 071.8–12        | AB Dor       | 77.8       | AB Dor   | 62.7     | AB Dor   | 56.5 | AM        |
| 2M0501–00           | THA          | 98.7       | Old      | 99.86    | Field    | 99.9 | AM        |
| 2M0122–29           | CarN         | 5.5        | Old      | 89.49    | Field    | 99.5 | AM        |
| 2M0518–27           | CarN         | 22.1       | Col      | 86.5     | βPic     | 62.7 | AM        |
| 2M0536–19           | βPic         | 77.5       | βPic     | 57.28    | βPic     | 81.1 | AM        |
| SDSS1110+01–01      | AB Dor       | 17.2       | THA      | 99.91    | AB Dor   | 99.3 | AM        |
| 2M1207–39           | βPic, TWA    | 100, 91.6  | TWA      | 99.14    | TWA      | 91.6 | AM        |
| 2M1256–27           | AB Dor       | 75.8       | TWA      | 99.14    | Field    | 99.8 | AM        |
| 2M1425–36           | AB Dor       | 39.3       | AB Dor   | 99.98    | AB Dor   | 99.7 | AM        |
| 2M1615–49           | AB Dor       | 59.3       | AB Dor   | 95.12    | AB Dor   | 84.0 | AM        |
| WISE 1741–166       | βPic, AB Dor | 94.1, 91.8 | βPic     | 99.88    | AB Dor, βPic | 52.7, 45.9 | AM        |
| PSO 272.4–04        | TWA          | 61.8       | AB Dor   | 86.45    | AB Dor   | 89.0 | AM        |
| 2M2002–05           | None         | 0          | Old      | 100      | Field    | 99.9 | AM        |
| 2M2011–50–2         | Col          | 96.5       | THA      | 66.53    | Field    | 72.2 | AM        |
| PSO 318.5–22        | βPic         | 98.9       | βPic     | 99.99    | βPic     | 99.6 | BM        |
| 2M2312–10           | CarN         | 92.8       | Arg      | 53.44    | Field    | 99.9 | AM        |
| HN Peg B            | ...          | ...        | ...      | ...      | ...      | ...  | Young     |
| SIMP 2154–10        | CarN         | 28.8       | Old      | 89.97    | CarN     | 71.4 | AM        |
| 2M2244–20           | AB Dor       | 68.9       | AB Dor   | 99.99    | AB Dor   | 99.8 | BM        |
| 2M2322–61           | THA          | 34.1       | THA      | 99.78    | THA      | 79.7 | AM        |

Notes:

| Decisionb | Moving groups: AB Dor: AB Doradus, Arg: Argus, β Pic: β Pictoris, CarN: Carina, Col: Col, THA: Tucana-Horologium, TWA: TW Hydrae. |
|-----------|--------------------------------------------------|
| BM: bona fide member, HLM: high-likelihood member, AM: ambiguous member, NM: non-member. |
| Final decision based on spectral signatures of youth, membership probabilities and colour-magnitude diagrams. Young: Object is a high likelihood member of a young-moving group and/or has clear indications of youth in its IR and/or optical spectrum. Uncertain: This object does not have sufficient evidence of youth and is thus excluded from the final statistical sample. |
Figure 6. Colour-magnitude diagrams showing the field brown dwarf population (grey points) and our full sample of objects showing signs of low-gravity. Absolute magnitudes were calculated either using measured parallaxes or kinematic distances. From this analysis it is clear that the T2 object PSO 071.8-12 (shown in red circle) is an outlier in the sample. Assuming AB Doradus membership for PSO 071.8-12 results in magnitudes that are $\sim 1$ mag brighter than other T dwarfs in the field and young populations.

Figure 7. Histogram showing the distribution of spectral types in our final sample of 30 low-gravity brown dwarfs. Few young, low-gravity T dwarfs bright enough for variability observations are known, so our sample is predominantly composed of objects with spectral types $< L8.5$.

9 VARIABILITY STATISTICS

Figure 8 shows the spectral type of our sample plotted against $(J-K)_{2MASS}$ colour. Blue symbols correspond to variability detections, where the symbol size is proportional to the variability amplitude. Although many of our measured variability amplitudes are only a lower limit estimate, we see evidence for increasing $J$-band amplitude along the L sequence, something that is noted in Metchev et al. (2015) for mid-IR variability.

To explore the effect of low surface gravity on variability properties, we compare our results to the results of variability surveys of the field brown dwarf population reported by Radigan et al. (2014); Radigan (2014). Our methods for determining variability significance are very similar to the methods presented by Radigan et al. (2014). In both papers the significance of a variability detection is based on the Lomb-Scargle periodogram power. In Radigan et al. (2014), the 1% FAP periodogram power is empirically increased in the same way as our analysis (Section 3.5). Furthermore, the same method is used to create the sensitivity plots in both surveys – by injecting simulated sinusoidal signals into reference star lightcurves and measuring the recovery rates. Thus, the two surveys can be robustly compared.

We find that 6/30 (20%) of objects in the full statistical sample exhibit significant variability, similar to the 9/57 (16%) reported by Radigan et al. (2014) for a similar high-gravity sample of field dwarfs. However, with only three young objects with spectral types $> L9$ included in our sample, we are lacking in L/T transition and T spectral type objects compared to the Radigan et al. (2014) and Radigan (2014) samples and thus we cannot obtain a robust comparison between the low-gravity and high-gravity populations as a function of spectral type. We thus consider objects with
spectral types of L0-L8.5 in both samples. We find that 6/27 of L0-L8.5 low-gravity objects appear variable while Radi- 

gan (2014) report 2/34 variables in the field brown dwarf sample of L0-L8.5 objects.

9.1 Statistical Formalism

Our formalism for the statistical analysis of this survey is based on the method described in Lafreniere et al. (2007) and Vigan et al. (2012). We consider the observation of N targets enumerated by \( j = 1...N \). We note \( f \), the fraction of objects that exhibit variability with amplitude and rotational period in the interval \([a_{\text{min}}, a_{\text{max}}] \cap [r_{\text{min}}, r_{\text{max}}] \), and \( p_j \), the probability that such variability would be detected from our observations. With this notation, the probability of detecting variability in target \( j \) is \( (f p_j) \) and the probability of not detecting variability is \( (1 - f p_j) \). Denoting \( d_j \) the detections made by the observations, such that \( d_j = 1 \) for a variability detection in target \( j \) and 0 otherwise, the likelihood of the data given \( f \) is

\[
L(d_j|f) = \prod_{j=1}^{N} (1 - f p_j)^{1-d_j} (f p_j)^{d_j}
\]

(1)

According to Baye’s theorem, from the a priori probability density \( p(f) \), or prior distribution, and the likelihood function \( L \), we can calculate the posterior distribution \( p(f|d_j) \), the probability density updated in light of the data:

\[
p(f|d_j) = \frac{L(d_j|f)p(f)}{\int_{f_0}^{f_1} L(d_j|f)p(f)df}
\]

(2)

This is the frequency of variable objects, or variability occurrence rate of objects in the survey.

9.2 Estimating the Frequency of Variable Objects

We use a modified version of the Quick Multi-purpose Exoplanet Simulation System (QMESS; Bonavita et al. 2013, 2016) to calculate the posterior distribution of the frequency of variable objects in their survey. QMESS is a grid-based, non-Monte Carlo simulation code that uses direct-imaging sensitivity plots to estimate the frequency of giant planets. We use QMESS to estimate the fraction of objects that display variability using the statistical framework discussed above. We use the sensitivity plots obtained for each observation (described in Section 5) as \( p_j \) in Equation 1 to calculate the likelihood, \( L \) for values of \( f \) between 0 and 1. For the Radigan (2014) sample, we use the average sensitivity plot from the Radigan et al. (2014) survey. This is reasonable since the reported photometric precision and observation lengths are comparable for both surveys (Radigan 2014). Since we have no prior knowledge of the variability frequency of low-gravity brown dwarfs, we use a uniform prior distribution of \( p(f) = 1 \) in Equation 2 to calculate the posterior probability density, \( p(f|d_j) \). This is the probability density function (PDF) of the frequency of variable objects. The PDFs of the frequency of variable objects for the ‘Young’ sample and field brown dwarf sample (Radigan 2014) are plotted in Figures 9 and 10. For the low- 

Figure 8. Spectral type of variable objects plotted against \((J-K)_{\text{2MASS}}\) colour. Blue symbols represent young objects displaying significant photometric variability, where the radius is proportional to the variability amplitude. Dark blue symbols denote the objects that are highly likely to be young while light blue circles denote objects whose youth is more uncertain.

Figure 9. Probability distribution of the frequency of variable objects in the ‘Young’ sample. The dark grey area shows the 1σ regions while the light grey area shows the 3σ region.

The rate of variables objects is \( 30^{+16}_{-8}\% \), which is higher than the rate of \( 11^{+15}_{-9}\% \) that we find for the Radigan (2014) survey.

We additionally employ a second method to analyse how statistically significant the correlation between low-gravity and frequent variability is. To do this we use a Bayesian framework to analyse the 2 \( \times \) 2 contingency table shown in Table 6, following the method described by Biller et al. (2011) to determine the probability that the samples are drawn from different distributions. We denote \( \gamma_1 \) as the num-
number of field objects with detected variability. We model the number of high-amplitude variability detections in young T objects in the field brown dwarf sample (Radigan 2014). The dark grey area shows the $1\sigma$ regions while the light grey area shows the $3\sigma$ region.

Table 6. Contingency table showing the number of variability detections and non-detections in the Radigan (2014) survey (field objects) and this survey (low-gravity).

|                | Variable | Non-Variable |
|----------------|----------|--------------|
| Field objects  | 2        | 62           |
| Low-gravity    | 6        | 21           |

dwarfs that suggest that this trend between low-gravity and high amplitude variability may extend into the T dwarfs. Metchev et al. (2015) report Spitzer 3.6 µm and 4.5 µm in the intermediate-gravity T2.5 companion HN Peg B, the only low-gravity T dwarf in the survey. The T2.5 known variable object SIMP 0136 was recently found to be a likely planetary-mass member of the Carina-Near moving group (Gagné et al. 2017). With its 1–6% J-band variability, SIMP 0136 exhibits one of the highest variability amplitudes of the known variable T dwarfs. Gagné et al. (2018a) recently reported that the T2 object 2M1324+63 is a planetary-mass member of the AB Doradus moving group. This object is known to exhibit high-amplitude variability in the optical and the mid-IR (Heinze et al. 2015; Apai et al. 2017) and also provides a good spectrophotometric match to the directly-imaged planet HR8799b (Bonnell et al. 2016). Finally, we report high-amplitude variability in PSO 071.8–22 in this survey. Although it does not have sufficient evidence of youth to be classified as ‘Young’ in our sample, additional kinematic information may confirm PSO 071.8–12 as a young object. As we identify more low-gravity T dwarfs it will become clearer whether the link between low-gravity and enhanced variability holds for cooler T-type objects.

10 FOLLOw-up Observations of Variable Objects

When possible, we obtained follow-up observations of objects found to be variable in their first epoch. These observations were carried out so that we could confirm variability and also look for evidence of lightcurve evolution for our variable objects (Apai et al. 2017; Vos et al. 2018). We obtained follow-up observations of 2M0045+16, PSO 071.8–12, 2M0501–00, 2M1425–36 and PSO 318.5–22. We discuss each object below.

2M0045+16 — We observed 2M0045+16 on November 11 2014 and August 17 2015 with the NTT and November 13 2016 with UKIRT. 2M0045+16 was found to be variable in two out of three epochs - the NTT November 11 2014 and UKIRT November 13 2016 observation. As can be seen from the sensitivity plots in Figure 5, both lightcurves exhibit a similar shape, with periodograms indicating a period of $\sim 3–6$ hr. We measure amplitudes of $1.0\pm0.1%$ and $0.9\pm0.1%$ for the 2014 and 2016 lightcurves respectively, thus we do not see any indication of lightcurve evolution in this case. The NTT August 17 2015 lightcurve shows a similar trend, however the periodogram peak power does not fall above our significance threshold. According to the sensitivity plot of the August 17 2015 observation (shown in Appendix 3 which is available online), we can place an upper limit on the variability amplitude of this epoch of $\sim 2%$ for a rotational period of $\sim 3–6$ hr. Thus, we did not reach the photometric
Figure 11. Left panel shows probability distributions for the variability occurrence rate of the field brown dwarf sample (blue) from Radigan et al. (2014) and the low-gravity sample (red) from this survey, assuming binomial statistics and a uniform prior. The right panel shows the difference between these distributions. We find a 98% probability that the planetary-mass sample has a higher variability occurrence rate than the field brown dwarf sample.

precision necessary to robustly detect a 1% modulation in
the lightcurve in this observation.

**PSO 071.8–12** — We reobserved the variable object PSO 071.8–12 with UKIRT on December 8 2017. During this 4 hr observation we do not detect significant variability. The sensitivity plot shown in Appendix 3 (available online) rules out significant variability $>5\%$ for short periods, however we believe that PSO 071.8–12 has a somewhat longer period. For a rotational period of $5 \sim 8$ hr we place an upper limit of $6 \sim 8\%$ on the variability amplitude of PSO 071.8–12 in this epoch.

**2M0501–00** — We observed 2M0501–00 a total of four times with the NTT. We detect significant variability on November 11 2014 and October 19 2016 and do not detect variability on August 16 2015 and March 12 2017. In the two variable epochs (Figures 4 and 5), which are separated by almost two years we observe a similar lightcurve shape - a slowly decreasing relative flux over the entire observation. Both periodograms favour a period $>5$ hr and the Levenberg-Marquardt least-squares fits give amplitudes of $1 \sim 2\%$, although both the rotational period and variability amplitude are very uncertain since we did not observe a maximum or minimum in either lightcurve. We do not detect variability during two $\sim 2$ hr observations on August 16 2015 and March 12 2017 (shown in Appendix 3; available online). As these observations are shorter than the variable epochs, they are less sensitive to long period variability. The sensitivity plot from August 16 2015 shows that this observation is sensitive to amplitudes $>6\%$ for a rotational period of 5 hr. The March 12 2017 lightcurve is noisier than the other epochs due to poor weather conditions, and the sensitivity plot indicates that the observation is not sensitive to periods of $\geq 5$ hr in this epoch. Thus, our observations do not show evidence for an evolving lightcurve in this case.

**2M1425–36** — We obtained two epochs of variability monitoring of 2M1425–36 with NTT/SofI. The initial observation on August 17 2015 shows a low-amplitude ($\sim 0.7\%$) trend with a period $>2.5$ hr. Our second epoch observation, obtained using the NTT on March 14 2017 (shown in Appendix 4; available online) suffered from poor weather conditions, with the seeing ranging from 0.9 $\sim 1.7''$. While the sensitivity plot suggests sensitivity to very low variability amplitudes, the periodograms of the reference stars display significant trends due to changing weather conditions.

**PSO 318.5–22** — As part of the initial survey observations, we obtained three epochs of NTT variability monitoring for the L7 object PSO 318.5–22. On October 9 2014 we observed significant $J$ variability, with an amplitude of $10 \pm 1.3\%$, and a period $>5$ hr (Figure 5). The $J$ lightcurve obtained on November 9 2014 again shows similar variability, this time varying with an amplitude of $4.8 \pm 0.7\%$ over a $\sim 3$ hr observation. Finally, we observed PSO 318.5–22 in the $K_S$ band on November 10 2014. Since PSO 318.5–22 is much brighter in $K_S$, we attain higher photometric precision in this band. The lightcurve shows a smooth upward trend with an amplitude of $2.2 \pm 0.6\%$ (Figure 5). All three lightcurves were originally presented in Biller et al. (2015).

11 FOLLOW-UP OBSERVATIONS OF PSO 318.5–22

Additional observations of PSO 318.5–22 were taken in August 2016, to more accurately constrain the rotational period and to investigate the wavelength dependence of the variability. On August 9 2016 we observed using the $J_S$ filter, followed by the $K_S$ filter on August 10 2016. Finally, on August 11 2016, we observed with both filters, swapping over every 20 minutes. The data were reduced and analysed as de-
Figure 12. Follow-up observations of PSO 318.5-22 taken over three consecutive nights. Orange points show observations taken with the $J_S$ filter and the teal points show the $K_S$ filter observation. These three nights allow us to constrain the rotational period of PSO 318.5-22 to $\sim 8.5$ hr, in agreement with the $8.6$ hr period reported by Biller et al. (2018).

The simultaneous $J_S$ and $K_S$ monitoring obtained on August 11 2016 allows us to directly compare the variability in both bands during a single rotational phase. We observe significant variability in both filters and we measure a $A_K/A_J$ ratio of $0.36 \pm 0.25$. This is similar to the ratios previously observed for the population of field brown dwarfs (Artigau et al. 2009; Radigan et al. 2012; Apai et al. 2017). The $K_S$ lightcurve obtained on August 10 2016 also shows significant variability. We fit a sinusoid to the lightcurve to obtain a variability amplitude of $0.48 \pm 0.08\%$.

The simultaneous $J_S$ and $K_S$ variability monitoring obtained on August 11 2016 allows us to directly compare the variability in both bands during a single rotational phase. We observe significant variability in both filters and we measure a $A_K/A_J$ ratio of $0.36 \pm 0.25$. This is similar to the ratios previously observed for the population of field brown dwarfs (Artigau et al. 2009; Radigan et al. 2012; Apai et al. 2017), suggesting that the variability mechanism for the exoplanet analogues is similar to that of the field brown dwarfs. Biller et al. (2018) obtained simultaneous $HST$ WFC3 and $Spitzer$ IRAC variability monitoring of PSO 318.5-22, detecting variability amplitudes of $\sim 3\%$ in the $Spitzer$ 3.6 $\mu$m band and $\sim 4 - 6\%$ in the near-IR bands ($1.07 - 1.67 \mu$m). The variability amplitude was found to decrease with increasing wavelength and we observe this same trend with the high $J_S$ amplitude and lower $K_S$ amplitude.

Additionally, we find that the $J_S$ and $K_S$ variability is in phase. Biller et al. (2018) report large phase shifts between the near-IR and mid-IR lightcurves of PSO 318.5-22, and tentative phase shifts between the near-IR spectral bands. Phase changes have been attributed to different wavelengths probing different heights in the atmosphere Buenzli et al. (2012); Biller et al. (2013), so this suggests that the $J_S$ and $K_S$ bands probe similar heights in the photosphere, while the mid-IR band is sensitive to surface homogeneities that are located at higher atmospheric levels.

The long baseline of this observation allows us to constrain the rotational period of PSO J318.5-22 using Monte Carlo analysis. We use the emcee package (Foreman-Mackey et al. 2013) to obtain the full posterior probability distributions for each parameter of the sinusoidal model. We use 500 walkers with 20000 steps and discard an initial burn-in sample of 1000 steps to explore the four-dimensional parameter space to model the light curve. Figure 13 shows the posterior distributions of the amplitude, period, phase and constant parameters of the fit. Each parameter is well-constrained, and the MCMC method gives a rotational period of $8.45 \pm 0.05$ hr for PSO J318.5-22. The derived error of 0.05 hr on the period is very small, which shows the advantage of having long temporal coverage. However it is important to keep in mind that the above fit assumes a sinusoidal model that did not change between nights, and in reality the full light curve may resemble a more complex or evolving function. In any case, our estimated rotational period is consistent with the $8.6 \pm 0.1$ hr period reported by Biller et al. (2018) using 16 hr of $Spitzer$ monitoring. This further supports our choice of a sinusoidal model and the derived posterior parameters.

12 CONCLUSIONS

We report the first large survey for photometric variability in young low-gravity brown dwarfs with NTT/Sofi and UKIRT/WFCAM. We monitored a total of 36 objects continuously for $\sim 2 - 6$ hr, detecting significant ($p > 99\%$) variability in seven objects. We assess the spectral indicators of youth and moving group membership of each object in the sample, finding that three objects have rather uncertain ages and are thus left out of the survey analysis. We also leave one unresolved binary out of the survey and lose two objects due to poor weather conditions. We detect variability in six
Figure 13. PSO 318.5–22 posterior distributions for amplitude, period, phase and the mean obtained from MCMC analysis.

In the ‘Young’ sample, we detect variability in 6/30 (20%) objects, which is consistent with the 16% variability fraction reported by Radigan et al. (2014) for the higher mass, field dwarfs. However, since we are lacking in objects with spectral types >L9 compared to earlier surveys of field L and T dwarf population, we focus our analysis on the L0-L8.5 objects in our sample. We find that the frequency of variable L0-L8.5 objects in this survey is $30^{+16}_{-8}\%$, which is higher than the frequency of variable objects of $11^{+4}_{-4}\%$ that we find for the field brown dwarf population (Radigan 2014). We find that the PDFs of the variability occurrence rates of our two samples are drawn from different underlying distributions with a probability of 98%. Thus, we have found the first quantitative indication that the L-type low-gravity objects are more likely to be variable than the higher mass field dwarf counterparts.

We additionally present 3 consecutive nights of photometric monitoring of the highly-variable L7 spectral type object PSO 318.5–22 with NTT/SofI. We find no evidence of phase shifts between the $J_S$ and $K_S$ bands and find a $A_K/A_J$ ratio of $0.36 \pm 0.25$, consistent with previous amplitude ratios of field brown dwarfs (Artigau et al. 2009; Radigan et al. 2012). This suggests that the underlying variability mechanism is the same for both populations. We perform MCMC analysis on the $J_S$ light curves to measure a rotational period of $8.45 \pm 0.05$ h for PSO 318.5–22.
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