Revealing the Vertical Cloud Structure of a Young Low-mass Brown Dwarf, an Analog to the β-Pictoris b Directly Imaged Exoplanet, through Keck I/MOSFIRE Spectrophotometric Variability

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Abstract

Young brown dwarfs are analogs to giant exoplanets, as they share effective temperatures, near-infrared colors, and surface gravities. Thus, the detailed characterization of young brown dwarfs might shed light on the study of giant exoplanets that we are currently unable to observe with a sufficient signal-to-noise to allow a precise characterization of their atmospheres. 2MASS J22081363 +2921215 is a young L3 brown dwarf, and a member of the β-Pictoris young moving group (23 ± 3 Myr), which shares its effective temperature and mass with the β Pictoris b giant exoplanet. We performed a ∼2.5 hr spectrophotometric J-band monitoring of 2MASS J22081363 +2921215 with the MOSFIRE multi-object spectrograph, installed at the Keck I telescope. We measured a minimum variability amplitude of 3.22 ± 0.42% for its J-band light curve. The ratio between the maximum and the minimum flux spectra of 2MASS J22081363 +2921215 shows a weak wavelength dependence, and a potentially enhanced variability amplitude in its alkali lines. Further analysis suggests that the variability amplitudes of the alkali lines are higher than its overall variability amplitude (4.5%–11%, depending on the lines). The variability amplitudes of these lines are lower if we degrade the resolution of the original MOSFIRE spectra to HST WFC3 light curves. Using radiative-transfer models, we obtained the different cloud layers that might be introducing the spectrophotometric variability we observe for 2MASS J22081363 +2921215, which further supports the measured enhanced variability amplitudes of the alkali lines. We provide an artistic recreation of the vertical cloud structure of this β-Pictoris b analog.

Unified Astronomy Thesaurus concepts: L dwarfs (894)

1. Introduction

Brown dwarfs are substellar objects that are unable to sustain hydrogen fusion, contracting as they cool down over their lifetimes. Thus, younger brown dwarfs have larger radii and lower surface gravities than their older counterparts. Young brown dwarfs and giant exoplanet atmospheres share similar colors, temperatures, and surface gravities (Chauvin et al. 2004; Marois et al. 2008; Faherty et al. 2013). Nevertheless, young brown dwarfs, unlike giant exoplanets, are found in isolation, being technically easier to observe with current instrumentation. Thus, the characterization of young free-floating brown dwarfs might improve our understanding of the atmospheres of imaged young giant exoplanets. Some examples of these class of objects are 2MASS J00452143 +1634446 (L2, ~50 Myr; Kendall et al. 2004), PSO 318.5-22 (L7, 23 ± 3 Myr; Liu et al. 2013), 2MASS J00470038 +6803543 (L7, 130 ± 20 Myr; Gizis et al. 2012), 2MASS J035523.37 +1113343.7 (L5, ~120 Myr; Reid & Walkowicz 2006), and 2MASS J22081363 +2921215 (L3, 23 ± 3 Myr; Cruz et al. 2009), among others.

Photometric or spectrophotometric variability surveys with ground and space-based data have shown that the majority of brown dwarfs have signs of low-level variability across different spectral types, most likely due to the existence of different layers of heterogeneous clouds in their atmospheres that evolve as they rotate (Buenzli et al. 2014; Radigan 2014; Metchev et al. 2015). For example, Metchev et al. (2015) monitored 23 L dwarfs, and 16 T-dwarfs using the Spitzer telescope, and concluded that ~61% of the L dwarfs of their sample showed photometric variability signs with amplitudes >0.2%, and also, at least 31% of the T-dwarfs showed signs of low-level variability. In addition, Metchev et al. (2015) suggested that variability amplitudes for low-gravity brown dwarfs might be enhanced in comparison with the brown-dwarf field population.

Using the New Technology Telescope (NTT) and the United Kingdom Infrared Telescope (UKIRT), Vos et al. (2019) photometrically monitored a sample of 36 young brown dwarfs with spectral types between L0 and L8.5, finding that 30±10% of the young brown dwarfs were variable. In contrast, Radigan (2014) found that only 11±13% of field brown dwarfs with the same spectral types are variable using also ground-based data. These results suggest that variability may be enhanced for low-gravity/low-mass exoplanet analogs. In fact, for free-floating young planetary mass objects like WISEP J004701+680352, VHS 1256-1267Ab, and PSO J318.5-22, very high variability amplitudes have been measured (Lew et al. 2016; Biller et al. 2018; Zhou et al. 2020; Bowler et al. 2020).

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Finally, photometric and spectrophotometric variability have been also predicted for giant exoplanets (Komacek & Showman 2020; Tan & Showman 2019, respectively). The source of the photometric variability is expected to be atmospheric dynamics, as for brown dwarfs. Some attempts to measure photometric variability in giant exoplanets have been performed using extreme adaptive optics instrumentation. For example, Apai et al. (2016) and Biller et al. (2021) attempted to use the Very Large Telescope (VLT)/SPHERE to measure the photometric variability of the HR 8799 system; however, due to the lack of a long data baseline, only upper limits of its variability amplitude could be provided. In conclusion, detecting photometric and spectrophotometric variability in giant exoplanets is challenging due to instrumental limitations. Thus, as young brown dwarfs and giant exoplanets share several physical characteristics, and given the easier observability of young brown dwarfs, and the higher chances of detecting detectable variability, spectrophotometric monitoring of these objects can provide insights into the heterogeneous cloud coverage of exoplanet atmospheres, and the vertical pressure levels at which they are found.

This paper is structured as follows: In Section 2, we introduce the key properties of 2MASS J22081363+2921215. In Section 3, we describe the details of the Keck I/MOSFIRE spectrophotometric monitoring we performed for 2MASS J22081363+2921215. In Section 4, we describe the data reduction. In Section 5 we explain how the light-curve production and corrections were performed using the calibration stars. In Section 6 we account for the potential influence of systematics in the target’s light curve. In Section 7 we present the results of the photometric and spectrophotometric variability of 2MASS J22081363+2921215. Finally, in Section 8, we describe the interpretation of the spectrophotometric variability found for 2MASS J22081363+2921215 using radiative-transfer models, and we provide a general picture what the cloud structure of the object might be given the spectrophotometric variability measured.

2. 2MASS J22081363+2921215

2MASS J22081363+2921215 (2M2208+2921), $M_J = 15.8$, was one of the first peculiar early L objects found (Kirkpatrick et al. 2000), because of its weak alkali lines. It was spectrally classified in the optical by Kirkpatrick et al. (2000), as an L2 object. Its peculiarity was later explained as an effect of its low surface gravity (Kirkpatrick et al. 2008). Cruz et al. (2009) classified it as L3.5 in the near-infrared. Allers & Liu (2013) classified it as a very-low surface gravity object using spectral indices. Using BT-Settl atmospheric models with solar metallicity, Manjavacas et al. (2014) estimated its effective temperature as 1800 K, and its surface gravity as log g ~ 4.0.

Zapatero Osorio et al. (2014) provided a trigonometric parallax for 2M2208+2921 of $\pi = 21.2 \pm 0.7$ mas, proper motions of $\mu_x \cos \beta = 90.7 \pm 3.0$ mas yr$^{-1}$, and $\mu_\beta = 16.2 \pm 3.7$ mas yr$^{-1}$, and a luminosity of $\log(L/L_\odot) = -3.71 \pm 0.10$. Gagné et al. (2014) found, with a modest probability of 53.8%, that 2M2208+2921 belongs to the β-Picoris young moving group (23 ± 3 Myr, Mamajek & Bell 2014). Dupuy et al. (2018) confirmed 2M2208+2921 to be a likely member of the β-Picoris using the radial velocity measurements of Vos et al. (2017). In this case, 2M2208+2921 would have an estimated mass between 9 and 11 $M_{Jup}$ being an analog of the planet/brown dwarf companion βPicoris b (Lagrange et al. 2009).

βPictoris b was one of the first directly imaged planets detected. It is a companion to the β-Picoris star at 8–14 AU, with a spectral type of L2 ± 2 (Bonnefoy et al. 2013), and with a dynamical mass of 13 $+0.2/-0.3 M_{Jup}$ (Dupuy et al. 2019). Dupuy et al. (2019) also showed that 2M2208+2921 and β-Picoris b share a similar position in the color–magnitude diagram, further confirming the similarity of the two objects.

Metchev et al. (2015) measured a rotational period of 3.5 ± 0.2 h for 2M2208+2921 using the Spitzer [3.6] and [4.5] bands, with variability amplitudes of 0.69 ± 0.07% and 0.54 ± 0.11%, respectively. Miles-Páez et al. (2017) measured low values of J-band polarization for this object. Finally, Vos et al. (2017) measured an inclination of $i = 55 \pm 10^\circ$.

3. Observations

Performing spectrophotometric monitoring observations from the ground using single-slit spectrographs is technically challenging, since at least one calibration star is needed for spectral calibration, to account for telluric contamination, changes in the airmass, humidity, and temperature variations in the atmosphere, etc., which might potentially introduce spurious variability signals. Normally, brown dwarfs are isolated, and no other object is found close enough to be observed simultaneously as a spectrophotometric calibrator together with the target, in few-arcsseconds-long single-slit spectrographs. This is only possible in the case of well-resolved binary brown dwarfs like Luhman-16AB (Kellogg et al. 2017). Since brown dwarfs are in their majority single objects (Bouy et al. 2003; Burgasser et al. 2003; Luhman et al. 2007), near-infrared multi-object spectrographs like MOSFIRE (McLean et al. 2010, 2012) are needed to perform spectrophotometric monitoring of brown dwarfs from the ground. MOSFIRE is installed at the Cassegrain focus of Keck I, and it performs simultaneous spectroscopy of up to 46 objects in a 6′1 × 6′1 field of view, using the Configurable Slt Unit (CSU), a cryogenic robotic slit mask system that is reconfigurable electronically in less than 5 minutes without any thermal cycling of the instrument. A single photometric band is covered in each instrument setting ($Y, J, H$, or $K$).

We observed 2M2208+2921 on UT 2019-10-13 with MOSFIRE at the KeckI telescope during half a night. We obtained in total 13 spectra of 2M2208+2921 in the $J$ band (1.153–1.352 μm) using an ABBA pattern during a total of ~2.5 hr of monitoring. We used wide slits of 4′5 to avoid slit losses for all 10 calibration stars and the target, obtaining a spectral resolution of $R \sim 1000$. In Table 1 we show the list of

| Num. Mask | Num. obj. | R.A. | Decl. | $M_J$ |
|-----------|-----------|-----|-------|-------|
| 20        | 1         | 22:08:13.962 | 29:23:19.62 | 16.14 |
| 21        | 2         | 22:08:05.925 | 29:22:34.83 | 16.32 |
| 15        | 3         | 22:08:05.925 | 29:22:34.83 | 15.61 |
| 7         | 4         | 22:08:18.266 | 29:21:56.62 | 15.83 |
| 2         | 5         | 22:08:15.857 | 29:21:41.9 | 15.86 |
| 2M2208    | 2M2208    | 22:08:13.631 | 29:21:21.54 | 15.80 |
| 3         | 6         | 22:08:11.258 | 29:20:55.81 | 15.88 |
| 9         | 7         | 22:08:10.257 | 29:20:19.74 | 15.16 |
| 26        | 8         | 22:08:07.198 | 29:19:37.43 | 16.43 |
| 18        | 9         | 22:08:14.818 | 29:19:27.78 | 16.49 |
| 30        | 10        | 22:08:10.930 | 29:19:05.76 | 16.04 |
objects used as calibrators, their coordinates, and their J-band magnitudes. In general, the calibration stars had similar magnitudes as the target. In Figure 1, we show the configuration of the CSU mask, with the position of the target and the calibration stars. We used exposure times of 150 s for each nod position in the first ABBA pattern, and 180 s for each nod position of the rest of the ABBA patterns. We observed over a airmass range of 1.01 to 1.35.

For data-reduction purposes, 13 dome flats of 11 s exposure were obtained. Due to challenges in producing a successful wavelength calibration using sky lines with 4"5 slits, we obtained on UT 2020-03-05 four J-band “sky” spectra using the same configuration for the multi-object mask as for the observations, but using 1"0 slits to obtain higher resolution sky lines. The 1"0 slits provided spectra with sky lines with enough resolution to allow the pipeline to produce an accurate wavelength calibration.

4. Data Reduction

We used the version 1.0 of PypeIt\(^9\) to reduce the multi-object spectroscopic data acquired with MOSFIRE in the J band. PypeIt is a Python-based data-reduction pipeline for spectroscopic data, applicable for a variety of spectrographs in different facilities (Prochaska et al. 2019, 2020). The pipeline corrected all the raw images for dark current, and a bad-pixel mask is generated. The edges of the slits were traced using the dome flats. A master flat was also created. PypeIt produced a wavelength calibration for our data using the sky arc frames taken using the same multi-object mask we employed for our observations, but with narrower slits of 1"0 to obtain well-resolved sky lines that would allow PypeIt to find a wavelength solution automatically. The wavelength calibration accounted for the spectral tilt across the slit. The calibrations were applied to our science frames, and the sky was subtracted using the A-B or B-A frames following Kelson (2003). 1D science spectra were extracted from the 2D sky-corrected frames. Finally we coadded the extracted A-B and B-A 1D science spectra to obtain a signal-to-noise ratio of ~65 at 13000 Å for our science target. The signal-to-noise ratio achieved for each object in the field is summarized in Table 2. No telluric calibration was performed for these spectra, since the spectral types of the calibration stars, necessary to perform this correction, could not be determined. Instead, for the upcoming analysis, we have used the wavelength range between 12,200 and 13,200 Å, avoiding the most prominent telluric contamination.

5. Production and Correction of the Light Curves

We produce a J-band light curve for each object in the field, restricting the wavelength range of the spectra between 12,200 and 13,200 Å to avoid the most prominent telluric contamination that might introduce spurious variability for the objects in the field.

As these data were obtained from the ground, there might be other additional sources of non-astrophysical contamination affecting the shape of the light curve extracted for each object, such as varying atmospheric transparency, changes in the water vapor content of the atmosphere, the seeing, variations in the ambient temperature during the ~2.5 hr of observation, wind speed and direction variations, airmass variations, etc. Thus, the science target light curve needs to be corrected for those potential sources of contamination.

To perform the light-curve correction, we followed a similar approach to Radigan (2014), but with more conservative criteria to select the best calibration stars. We corrected each light curve by dividing it by a calibration light curve produced by median combining the relative-flux light curves of all the other objects in the field, beside the science target. First, we normalized the light curves of all objects to the median flux for each of them. For each reference star, a calibration light curve

\(^9\) https://github.com/pypeit/PypeIt

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Table 2

| Object Number | SNR at 13,000 Å | \(\sigma\) uncorrected light curve | \(\sigma\) corrected light curve | Variability after correction |
|---------------|-----------------|-----------------------------------|-------------------------------|-----------------------------|
| 2M 2208-2921  | 64.3            | \(1.12 \times 10^{-2}\)           | \(9.70 \times 10^{-3}\)       | 3.22%                       |
| Object 1      | 48.5            | \(5.30 \times 10^{-3}\)           | \(4.17 \times 10^{-3}\)       | 1.32%                       |
| Object 2      | 36.2            | \(1.07 \times 10^{-2}\)           | \(5.15 \times 10^{-3}\)       | 2.00%                       |
| Object 3      | 36.8            | \(7.03 \times 10^{-3}\)           | \(5.76 \times 10^{-3}\)       | 2.10%                       |
| Object 4      | 98.6            | \(5.93 \times 10^{-3}\)           | \(3.73 \times 10^{-3}\)       | 1.22%                       |
| Object 5      | 55.3            | \(6.31 \times 10^{-3}\)           | \(3.55 \times 10^{-3}\)       | 1.18%                       |
| Object 6      | 53.0            | \(5.59 \times 10^{-3}\)           | \(3.40 \times 10^{-3}\)       | 1.39%                       |
| Object 7      | 76.4            | \(8.31 \times 10^{-3}\)           | \(3.72 \times 10^{-3}\)       | 1.26%                       |
| Object 8      | 40.1            | \(1.03 \times 10^{-2}\)           | \(5.79 \times 10^{-3}\)       | 2.24%                       |
| Object 9      | 43.4            | \(1.02 \times 10^{-2}\)           | \(6.93 \times 10^{-3}\)       | 2.21%                       |

Note. We highlight in boldface the best reference stars, selected as those with \(\sigma_{\text{calibration stars}} < \sigma_{\text{2M2208}}/2\).
variability introduced by changes in the Earth’s atmosphere during the observation. Thus, we use a similar approach as Radigan (2014) to estimate the uncertainties for each point of the light curve. We used the mean of the $\sigma_i$ calculated for the target and the selected calibration stars as the uncertainty for each point in the light curve of the target. This method accounts for any residual uncorrected atmospheric contamination variability in the target’s light curve. The uncorrected light curve of 2M2208+2921 is shown in Figure 2, left, and the corrected light curve in Figure 2, right.

5.1. BIC Test for Significant Variability

To test the significance of the observed fluctuations in the light curve of 2M2208+2921, we use the Bayesian Information Criterion (BIC). The BIC is defined as

$$\text{BIC} = -2 \ln L_{\text{max}} + k \ln N,$$

where $L_{\text{max}}$ is the maximum likelihood achievable by the model, $k$ is the number of parameters in the model, and $N$ is the number of data points used in the fit (Schwarz 1978). In our case, we calculate $\Delta \text{BIC} = \text{BIC}_{\text{flat}} - \text{BIC}_{\text{sin}}$ to assess whether a variable sinusoidal or non-variable flat model is favored by the data. This method has previously been used for identifying brown dwarf variability by Naud et al. (2017) and Vos et al. (2020). The BIC penalizes the sinusoidal model for having additional parameters compared with the flat model. The sinusoidal and flat models are shown in Figure 3. A $\Delta \text{BIC}$ value of 37 implies that the variable model (sinusoidal) is very strongly preferred over the flat model.

6. Systematics Corrections

6.1. Comparison of Variability Between the Blue and Red Halves of the Spectra

Telluric contamination in the $J$-band spectra asymmetrically affects the blue and the red edges, and also some intermediate wavelengths (Rudolf et al. 2016) that could potentially influence the variability amplitude we measure for 2M2208+2921. To test the potential influence of telluric contamination in the light curve of 2M2208+2921, we produced two different light curves using only the first and the second half of the wavelength range of the spectra. The first-half-spectra light curve was produced using the spectra between 12,200 and 12,700 Å, and the second-half-spectra light curve was produced using the range between 12,700 and 13,200 Å (see both light curves in the Appendix, Figure 15). Both light curves looked visually similar, but to quantitatively test that both light curves are similar, and thus, the telluric contamination is not significantly affecting the spectra in the blue and red ends, we run a Mann–Whitney U test, which is a nonparametric test that checks the similarity of the distributions of two samples (Neuhäuser 2011). The Mann–Whitney U test does not assume a normal distribution for the data. The null hypothesis asserts that the medians of the two samples are identical. We calculate the value, $U$, and compared it to tabulated $U_{\text{critical}}$ values given by the number of points in the sample. If $U > U_{\text{critical}}$, the null
hypothesis $H_0$ (i.e., the samples are similar), is accepted. For the case of our target, the calculated $U = 94.5 > U_{\text{critical}} = 45$, for a sample of 13 points, as in the case of 2M2208+2921 light curve. We calculate the Kendall $\tau$ nonparametric correlation test (Puka 2011) between the target’s light curve done with the first-half and the second-half wavelength ranges. We chose the Kendall $\tau$ correlation test since it is a nonparametric test used to measure correlations in data, and is more robust that other parametric correlation tests like the Spearman $\rho$ test (Langfelder & Horvath 2012). We obtained a Kendall $\tau$ coefficient of 0.85, (significance $= 5.2 \times 10^{-6}$), indicating a strong correlation between both light curves, supporting the U-test result.

6.2. Correlation Between the Stars and Target Light Curves

To evaluate the effects of potential contamination on the target’s light curve due to atmospheric effects, and potentially thin clouds, we investigate the correlation between the uncorrected light curve of the target and those of the comparison stars. The Kendall’s $\tau$ coefficients suggests a weak to a moderate correlation between the light curves, depending on the “good” comparison stars. The Kendall $\tau$ correlation coefficients vary between 0.18 (significance $= 0.43$) and 0.46 (significance $= 0.03$). In Figure 16 in the Appendix, we show the correlation plots between the target and each of the stars that we use for calibration.

After correcting the 2M2208+2921 light curve using the method explained in Section 5, we run the Kendall $\tau$ nonparametric correlation test again, finding correlation coefficients that range between 0.05 (significance $= 0.85$) and $-0.33$ (significance $= 0.12$), suggesting anything from a noncorrelation to a weak anticorrelation for some of the “good” comparison stars (see Figure 17 in the Appendix).

6.3. Correlation with the FWHM of the Spectra

We obtained spectra following an ABBA pattern; thus, the slit losses might vary slightly at the A and B positions of the pattern, potentially influencing the measured variability of the target. Thus, we investigated a potential relationship between the variability found for 2M2208+2921, and the FWHM of the target spectra taken during the 2.5 hr of monitoring with MOSFIRE. We measured the FWHM at three different positions of each coadded ABBA spectrum. We obtained a median FWHM of $0.84 \pm 0.15$ during the 2.5 hr of monitoring (see Figure 18, left, in the Appendix). We calculated the Kendall $\tau$ correlation of the mean FWHM for each spectrum and the evolving fluxes of the spectra with time, obtaining a very weak negative correlation between both quantities ($\tau = -0.077$, significance $= 0.76$; Figure 18, right).

6.4. Correlation with Atmospheric Parameters

The evolution of the atmospheric conditions during the observation might influence the amount of flux collected by MOSFIRE, affecting simultaneously the target and the calibration stars. Namely, the most relevant factors that might potentially affect our observations are the humidity content, the external temperature, and the airmass (Figure 19 in the Appendix). The evolution of these parameters are registered in the header, and/or in the Mauna Kea Weather Center webpage (http://mkwc.ifa.hawaii.edu). We calculated the Kendall $\tau$ correlation coefficient between the uncorrected light curve for 2M2208+2921, and each of the atmospheric parameters mentioned above. We found no correlation between the target’s light curve and the humidity content ($\tau = -0.08$, significance $= 0.72$), a weak correlation with the external temperature (0.35, significance $= 0.09$), and a weak anticorrelation with the airmass ($\tau = -0.20$, significance $= 0.37$).

Since these correlations are very small or not statistically significant, we conclude that there is no correlation between the external conditions and the target’s light curve.

7. Results

7.1. Photometric Variability

As we did not cover the entire known rotational period of the target (3.5 ± 0.2 hr; Metchev et al. 2015) with our MOSFIRE spectrophotometric observations, we are just able to provide a minimum variability amplitude for its light curve in the J band, which we found to be $3.22 \pm 0.42\%$. As expected, this minimum variability amplitude is higher than the variability amplitude measured by Spitzer in the 3.6 and 4.5 channels (Metchev et al. 2015), which were $0.69 \pm 0.07\%$ and $0.54 \pm 0.11\%$, respectively. The J band is tracing deeper layers of the atmosphere of 2M2208+2921 than the 3.6 and 4.5 bands, and thus, a higher variability amplitude is expected, assuming that the variability amplitudes measured with Spitzer have not changed significantly between epochs (Yang et al. 2016).

Although we do not have enough temporal coverage to observe a full rotational period of the target (3.5 ± 0.2 hr; Metchev et al. 2015), we still searched for other periods on the J-band light curve using a Lomb–Scargle periodogram (Lomb 1976; Scargle 1982; Horne & Baliunas 1986), and a Bayesian generalized Lomb–Scargle (BGLS) periodogram (Mortier et al. 2015) which did not find any periodicity in the J-band light curve.

7.2. Spectral Variability

We explored the amplitude of the variability as a function of the wavelength by comparing the maximum and the minimum flux spectra among the 13 spectra obtained. In Figure 4, left, we
show the brightest and faintest spectra, indicating the molecular and atomic absorption features for 2M2208+2921.

In Figure 4, right, we show the ratio between the maximum and the minimum flux spectra, i.e., the relative amplitude across the spectral wavelength range, with its uncertainties, and indicating as well the molecular and atomic absorption features for our target. We fit a line to the ratio of the maximum and minimum flux spectra using the `numpy.polyfit` Python library, obtaining a negative slope to the ratio \( \text{ratio} = 1.2589 \pm 0.0666 - [1.8714 \pm 0.5225] \times 10^{-5} \lambda \); see Figure 4, right), suggesting that the variability amplitude decreases monotonically from 12,200 to 13,200 Å, as has been found for other L dwarfs like WISE0047+6803 \( \text{ratio} = 1.19 \pm 0.01 - [0.7 \pm 0.1] \times 10^{-5} \lambda \) and LP261-75B \( \text{ratio} = 1.05 \pm 0.01 - [0.27 \pm 0.05] \times 10^{-5} \lambda \). As proposed for WISE0047+6803 by Lew et al. (2016), the variability amplitude, and wavelength dependence for 2M2208+2921 could be explained by the existence of haze and dust particles in the atmosphere of the object. Hiranaka et al. (2016) proposed the existence of submicron-sized particles in the atmospheres of L0–L6 brown dwarfs. For L3 dwarfs Hiranaka et al. 2016 finds an effective radius of \( \sim 0.27 \mu \text{m} \) and slightly smaller particles than for WISE0047+6803’s atmosphere (0.3–0.4 \( \mu \text{m} \); Lew et al. 2016). For the same number of particles, smaller particles imply smaller variability amplitudes, and a stronger wavelength dependence of the variability (Hiranaka et al. 2016), which is what we find for 2M2208+2921 compared to WISE0047+6803. WISE0047+6803 has a variability amplitude of \( \sim 8\% \), higher than the 3.22 \( \pm 0.42\% \) for 2M2208+2921, and a less-strong wavelength dependence than 2M2208+2921.

7.3. Potentially Enhanced Variability in the Alkali Lines

In Figure 4 we found potentially prominent peaks at the wavelengths where the K I and NaI alkali lines are located, suggesting a potentially enhanced variability amplitude around those wavelengths. In the following, we investigate in depth the potentially enhanced variability amplitude at those wavelengths. For this purpose, in the following sections we measure the amplitude of variability inside the K I doublet and the NaI alkali lines, and the variability amplitude of the blue and the red continua of those lines. Finally we compare those variability amplitudes between them and with the overall J-band variability, and conclude if they are significantly different.

7.3.1. Variability of Flux Inside the K I and Na I Lines

We investigated the variability of the fluxes of the K I doublet and the NaI line themselves, creating light curves. We used the range between 12,400–12,463 Å for the K I line at 12,430 Å, the range between 12,495–12,540 Å for the K I line at 12,525 Å, and the range between 12,675–12,683 Å for the NaI line at 12,682 Å. To correct the light curves for the K I doublet and NaI lines from potential non-astrophysical contamination, we follow the same approach to correct the light curve as used for the J-band light curve (see Section 5), but using only the wavelength ranges of the calibration stars’ spectra corresponding to the K I doublet and NaI wavelengths specified above (see the corrected light curves in the Appendix, Figures 22, 23, 24, 25, and 26). This correction accounts for potential telluric contamination at those specific wavelengths. This correction is particularly important for the NaI continuum and line, since there is telluric O2 absorption between 12,600 Å and 12,750 Å (Vernet et al. 2008; Sameshima et al. 2018). In spite of our efforts to correct for telluric contamination at those wavelengths, we acknowledge that some contamination might remain uncorrected.

In Figure 5, right panel, we show the corrected light curves corresponding to the alkali lines. We find that the variability of the flux for the K I lines at 12,430 Å and 12,525 Å is \( 2–3\sigma \) higher than the variability found for the J-band light curve of 2M2208+2921 (4.60 \( \pm 0.54\% \) and 4.48 \( \pm 0.54\% \), respectively). Finally, the variability of the NaI line is about \( 2\sigma \) higher than for the overall J-band light curve, and also larger than the variability of the continuum, 10.93 \( \pm 3.17\% \).

7.3.2. Variability of the Alkali Lines’ Continuum Fluxes

We measured the variability of the continua at the blue and red ends of each line, expanding each by 40 Å at both ends. The wavelength range used as the continuum for K I at 12,430 Å is 12,360–12,400 Å at the blue end and...
12,463–12,503 Å for the red end. For the K I line at 12,525 Å, we have used for the blue-side continuum the wavelength range between 12,455–12,495 Å, and for the red-side continuum 12,540–12,580 Å. Finally, for the Na I line at 12,682 Å, we have used a blue-end continuum wavelength range between 12,635–12,675 Å, and a red-end continuum in the range between 12,720–12,760 Å. We corrected the K I doublet and Na I continuum light curves as explained in Section 5 (see the corrected light curves in the Appendix, Figures 22, 23, 24, 25, and 26).

In Figure 5, left and middle panels, we show the normalized continuum flux variabilities. As we observe in Figure 5, the variability amplitude of the continuum of the alkali lines, and the variability of the alkali lines themselves are similar within the uncertainties for the K I lines. For the Na I line the variability of the line is 1–2σ higher than the variability of the continuum. In any case, the variability amplitudes found for the continuum of the K I doublet and Na I alkali lines are slightly higher (1–2σ) than the overall variability found in the J band for 2M2208+2921 (3.22 ± 0.42%).

7.3.3. Comparison to Low-resolution Spectrophotometric Data

Although some spectrophotometric data for other brown dwarfs of similar spectral types to 2M2208+2921 have already been collected using the Hubble Space Telescope (HST), and its WFC3 with the G141 grism (R ~ 100) (e.g., 2MASS J17502484-0016151, a L4.5 brown dwarf by Buenzli et al. 2014; 2MASS J18212815+1414010, a L5.0 by Yang et al. 2015), no enhanced variability amplitudes have been found for the alkali lines in the J band for those objects. Thus, we investigated if the enhanced variability of those lines is washed out when the spectral resolution of the MOSFIRE/Keck I spectra is degraded to the resolution of the HST/WFC3 + G141 grism spectra. For this purpose, we degraded the MOSFIRE/Keck I spectra resolution (R ~ 1000) to the resolution of HST/WFC3 + G141 (R ~ 100) using a Gaussian convolution. We reproduced Figures 4, and 5 using the R ~ 100 resolution spectra, after correcting the light curves following the same procedure than in Section 5 (see the correcting light curves in the Appendix, Figures 27, 28, 29, 30, and 31), and we compared the variability amplitudes found for the continuum and for the K I doublet and Na I alkali lines.

In Figure 6, similar as Figure 4, we show a comparison and the ratio between the maximum and the minimum flux spectra in the 2M2208+2921 light curve. As in Figure 4, we mark the atomic and molecular features in the J-band spectrum. We show the minimum spectrum in orange (corresponding to the second point in the J-band light curve in Figure 2), and the maximum spectrum in blue (corresponding to the 8th point in the J-band light curve in Figure 2). In Figure 6, right, we observe that within the uncertainties, the maximum and minimum spectra overlap, and in Figure 6, left, we observe that there is a wavelength-dependent slope, as in Figure 4, but we observe no remarkable peaks, indicating potentially enhanced variability amplitudes at some wavelengths. Nevertheless, the overall maxima and/or minima in the spectral lines do not necessarily coincide with the maxima and/or minima of the J-band light curve. The values of the linear fit to the ratio between the maximum and the minimum spectra are consistent with those in Figure 4 (right).
In Figure 7, similar to Figure 5, we show the variability of the KI doublet lines and the NaI alkali line measured as for the original-resolution MOSFIRE/Keck I spectra, but for the MOSFIRE/Keck I spectra degraded to a resolution similar to the HST/WFC3 + G141 spectra. For the case of the KI doublet lines, the variability amplitudes of the lines for the original-resolution spectra and the degraded spectra are similar within the uncertainties. For the KI line at 12,430 Å the variability amplitude of the line at the original resolution is 3.95 ± 0.54%, and for $R \sim 100$ it is 3.90 ± 0.53. For the KI line at 12,525 Å the variability amplitude is 4.80 ± 0.54% for the original-resolution spectra, and 4.27 ± 0.53 for the $R \sim 100$ spectra.

Finally, for the NaI at 12,682 Å line, the variability amplitude differs if it is measured in the original-resolution spectra, or in the degraded-resolution spectra. For the original-resolution
spectra, the variability of the NaI line is 10.93 ± 3.17%, and measured from the $R \sim 100$ resolution spectra it is 4.63 ± 2.38%, which is consistent with the variability amplitude measured for the overall J-band light curve. Therefore, this result suggests that the enhanced variability of the NaI line is partially washed out when the resolution of the spectra is low, and the individual alkali lines cannot be resolved, as happens in the case of the HST/WFC3 + G141 grism spectra. Thus, this would explain why any enhanced variability of the NaI line has not been found in the HST/WFC3 + G141 grism spectra of brown dwarfs of a similar spectral type.

In Figure 7, similar to Figure 5, we show the variability of the continuum measured 40 Å around the alkali lines as done previously, but for the MOSFIRE/Keck I spectra smoothed to $R \sim 100$. In Figure 7, we observe that for both the blue and red sides of the continuum for the KI doublet and the NaI line the variability amplitudes are consistent with the variability amplitudes found for the continuum at the original resolution of the MOSFIRE/Keck I spectra within the uncertainties. Thus, degrading the resolution of the spectra does not significantly influence the measured variability amplitude for the continuum around the KI doublet, and the NaI line.
obtaining the MOSFIRE J-bandpass, and also for the KI and the NaI alkali lines, that nearly 3% variability amplitude, similar to our MOSFIRE The Astronomical Journal, fsed variability amplitude consisted of 1800 K and 1650 K with clouds with different pressure levels. As in Yang et al. (2016), we modeled the J-band, NaI, and KI light curves produced from cloud maps at these three different pressure layers. To produce the light curves we used pixelated maps (similar to Karalidi et al. 2015) and compared their disk-integrated light-curve shapes and variability amplitudes. Figure 9 shows the light curves produced at the top of the atmosphere by blending three random, independent maps for three clouds layers of our model atmosphere. We randomly assigned two to four spots in each cloud layer and placed them in different, random locations on the map. To calculate the contrast ratio of the cloud features to the background atmospheric layer, we used information from the temperature—pressure profile of our model atmosphere (Teff = 1800 K and log g = 4.0). We then calculated the average light curve we would observe at the top of the atmosphere by blending the individual light curves using the contribution function information as a weight for each one. The relative shapes of all light curves appear the same, in agreement

8. Interpretation

8.1. Description of the Radiative-transfer Models

The emergent flux at different wavelengths of the J-band MOSFIRE spectrum traces different pressure levels of the atmosphere of 2M2208+2921, providing information about the cloud coverage at different levels of the atmosphere of the object. Spectrophotometric variability at those wavelengths can be used to trace the various cloud layers in the atmosphere of the target. We used state-of-the-art radiative transfer to calculate the flux contribution of the different modeled pressure levels. We used the effective temperature and surface gravity estimated for 2M2208+2921 by Manjavacas et al. (2014, with a VLT/ISAAC spectrum that covers the J, H, and K bands. Manjavacas et al. (2014) used BT-Settl models (Allard et al. 2001, 2003, 2012) from two different released versions (2010 and 2013) to estimate the effective temperature and surface gravity of 2M2208+2921. The adopted atmospheric parameters were Teff = 1800 ± 100 K, and log g = 4.0 ± 0.5, respectively. Further details on how the spectral fitting was performed can be found in Manjavacas et al. (2014).

To obtain the contribution functions for 2M2208+2921, we followed a similar approach to Yang et al. (2016), using standard radiative-convective, equilibrium, thermal-structure atmosphere models following the approach of Saumon & Marley (2008). Then, a temperature perturbation was applied at different pressure levels of the atmosphere of the object consecutively, and each time, a new temperature profile was generated, as well as a new emergent spectrum. The ratio between each emission spectrum generated for each perturbation at each pressure level, and the spectrum relative to the baseline case, provides the sensitivity of each wavelength range to temperature perturbations at different pressure levels.

As in Yang et al. (2016), this procedure was repeated at different pressure levels between 1.8 × 10−4 bar to ~23 bars, obtaining the flux contributions for the wavelengths covered by the MOSFIRE J band, after applying the MOSFIRE J-band bandpass, and also for the KI and the NaI alkali lines, that trace slightly different, and narrower pressure levels. As in Yang et al. (2016), the results strictly apply only to variations in the atmospheric temperature, but they reflect the atmospheric region to which the spectra at a given wavelength are most sensitive.

8.2. Cloud Layers Probed by the Alkali Lines and the J-band Fluxes

In Figure 8, we show the result of the radiative-transfer model for the different atmospheric pressure levels traced by the MOSFIRE J-band spectrum, and the KI and the NaI alkali lines. We also include an uncertainty for the pressures probed by assigning an error bar equal to the average pressure difference probed between the core and edge of the wings the KI and the NaI alkali lines. For the J band we use half the average pressure range probed in the band. We overplot the predicted condensate mixing ratio (mole fraction) for three different types of silicate clouds: Mg2SiO4, MgSiO3, and Al2O3. The pressure levels where the condensate mixing ratio reaches a maximum indicate the bottom of the that type of silicate cloud. Above that pressure level, the condensate mixing ratio decreases as the pressure level decreases. The bottom of the Mg2SiO4 cloud is around 1.0 bar, the MgSiO3 cloud is around 0.58 bar, and Al2O3 is around 1.7 bar.

As observed in Figure 8, the radiative-transfer model predicts that the K I lines trace around the 0.55 bar pressure level and above, the Na I line traces the pressure level around 0.9 bar and above, and the J band traces the pressure levels around 1.5 bar and above. Thus, with the integrated J-band light curve, we are observing the blended cloud maps of three silicate cloud layers (Mg2SiO4, MgSiO3, and Al2O3). With the integrated flux over the Na I line, we are sensitive to the top two layers of clouds (Mg2SiO4 and MgSiO3). Finally, with the integrated flux over the K I doublet, we are tracing the uppermost layer (MgSiO3) of the atmosphere of 2M2208+2921.

8.3. Modeling the Amplitudes and Wavelength Dependence of the Spectral Variability

The smaller amplitude variability measured in our MOSFIRE spectra for the J band in comparison to the alkali lines can be due to a more homogeneous cloud deck in the lower Al2O3 cloud, which would reduce the observed variability. The larger number of cloud layers probed, which when added produce a more “homogeneous” cloud coverage, can also affect the observed amplitude in the J band. To test the assumption that the different number of cloud layers probed could affect the observed variability in the J band vs. the alkali lines, we modeled the J-band, NaI, and K I light curves produced from cloud maps at these three different pressure layers. To produce the light curves we used pixelated maps (similar to Karalidi et al. 2015) and compared their disk-integrated light-curve shapes and variability amplitudes. Figure 9 shows the light curves produced at the top of the atmosphere by blending three random, independent maps for three clouds layers of our model atmosphere. We randomly assigned two to four spots in each cloud layer and placed them in different, random locations on the map. To calculate the contrast ratio of the cloud features to the background atmospheric layer, we used information from the temperature—pressure profile of our model atmosphere (Teff = 1800 K and log g = 4.0). We then calculated the average light curve we would observe at the top of the atmosphere by blending the individual light curves using the contribution function information as a weight for each one. The relative shapes of all light curves appear the same, in agreement.
Figure 13. Variability of the $\text{K} \text{I}$ and $\text{Na} \text{I}$ lines and their blue and red continuums as measured by the model spectra for $f_{\text{sed}} = 3$.

Figure 14. Variability of the $\text{K} \text{I}$ lines and their blue and red continuums as measured by the model spectra for $f_{\text{sed}} = 1$, 2, and 3.
with our MOSFIRE K I, Na I, and J-band light curves. The light curve that would correspond to the J-band observations has the smallest peak-to-trough amplitude as the chances of a peak of one layer’s light curve coinciding with the trough of another (i.e., a cloud clearing of one layer coinciding with a cloud-decked area of another layer) are larger. This prediction actually agrees with the spectrophotometric variability amplitudes detected in the MOSFIRE data, as described previously in Section 7.

In Figure 10 we show an illustrative representation of the vertical structure of the atmosphere of 2M2208+2921, using the outcome of the radiative-transfer models, which indicates at which pressure levels the different silicate clouds condense. In addition, we include the pressure levels that our light curves for the K I doublet, the Na I line, and the entire J-band trace.

We modeled the wavelength dependence of the ratio between the maximum and the minimum spectra of 2M2208+2921 at low resolution (similar to Figure 6, right). We modeled the low-resolution ratio, since the slope is not affected by the resolution of the spectra, and the radiative-transfer models converge faster to a best fit. We used a grid of cloudy and truncated cloud models similar to Morley et al. (2014) and Lew et al. (2020). We found that the best-fitting model to the ratio of the maximum and the minimum 2M2208+2921 spectra is a combination of $T_{\text{eff}} = 1800$ K and $T_{\text{eff}} = 1650$ K models with a coverage fraction, $\delta A$, of 0.22. This means that 22% of the atmosphere has $T_{\text{eff}} = 1650$ K and 78% of the atmosphere has $T_{\text{eff}} = 1800$ K. In Figure 11 we show the best-fitting model to the ratio of the maximum spectrum divided by the minimum spectrum (same as in Figure 4, blue line), and the best fit to the slope (similar as in Figure 4, orange line) plotted between 1.10 and 1.32 $\mu$m for plot clarity. The linear fit of the best-fitting model is $1.2483 - 1.366 \times 10^{-5} \lambda$, which agrees within the error bars of the slope of the MOSFIRE observations in Figure 4, right panel.

To test our approach to retrieving the spectrophotometric variability of 2M2208+2921, we then modeled a heterogeneous atmosphere that produces a light curve with a comparable amplitude to that of 2M2208+2921. We note that our aim was to test the validity of our method and not to map the atmosphere of 2M2208+2921, so we did not aim to find the best-fitting phase-resolved combination of models that reproduces the observed MOSFIRE J-band light curve, but just a light curve with a comparable amplitude. Our best-fitting model combination consisted of $T_{\text{eff}} = 1800$ K and $T_{\text{eff}} = 1600$ K with clouds with $f_{\text{sed}} = 1$ and 3, respectively, with $\delta A = 0.13$. Note that this model combination is slightly different from our best-fitting model combination for the spectral slope mentioned before (1800 K and 1650 K). The linear fit of this model is $1.0292 - 1.5879 \times 10^{-5} \lambda$, which is a better fit than our best-fitting model combination for the spectral slope in Figures 4 and 6, right panels. We blended the models in 13 time steps to create time-resolved simulated “observations” that create a sinusoidal-like light curve with a variability amplitude of $\sim 3\%$, i.e., comparable to that of our MOSFIRE observations (see Figure 12). Each of the 13 model spectra was assigned a random Poissonian noise to mimic their corresponding uncertainties. We then used the same method we did for our MOSFIRE observations to obtain the modeled “observed” variability in the K I doublet, and the Na I alkali lines.

Figure 13 shows the variability of the K I doublet and the Na I alkali lines, and their respective blue and red continuums, measured in the model spectra following the same methodology as for our observed MOSFIRE spectra in Sections 7.3.1 and 7.3.2. In Figure 13 we observe that the variability amplitudes of the alkali lines, and their blue and red continuums is between 3.6% and 5.1%, generally inconsistent with the variability amplitude of $\sim 3\%$ in the simulated J-band light curve. The enhanced variability amplitude predicted by the model spectra for the K I doublet is consistent, in amplitude value, with the enhanced variability amplitude measured in Sections 7.3.1 and 7.3.2 for the observed MOSFIRE spectra at their original resolutions. For the Na I line, we measured a variability amplitude of $10.93 \pm 3.17\%$ in the observed MOSFIRE spectra. Since such an enhanced variability amplitude is not predicted by the models, we suspect that there might be uncorrected telluric contamination remaining in the Na I light curve, even after the corrections performed using the other calibration stars in the field. Nevertheless, qualitatively, the radiative-transfer models still predict that the variability amplitude of the Na I line is enhanced.

Finally, as an illustration, we tested the effect of the cloud properties on the retrieved variability for the K I line. Figure 14 shows the retrieved amplitude of the K I line as a function of $f_{\text{sed}}$ for a combination of 1800 K and 1650 K clouds as in our best-fitting slope model. Changes in $f_{\text{sed}}$ correspond to a change in the cloud properties, and thus should correspond to changes in the retrieved variability. Indeed, Figure 14 shows that the
average retrieved variability of the model K1 line changes slightly with a reduction of the optical thickness across our model atmospheres, even though the variability amplitudes for the three $f_{\text{sed}}$ values are similar within the error bars. 

Note that Zhou et al. (2020) found a subdued variability of the alkali lines of VHS 1256b, but their target was a cooler, L7 atmosphere with a different cloud structure than our target. Changes in the temperature of the atmosphere affect the cloud structure and expected variability, both in the J band and Spitzer channels (Vos et al. 2017, 2020) as well as for the alkali lines (see also Morley et al. 2014, for T and Y atmospheres). Our result thus does not contradict that of Zhou et al. (2020), but complements it with another spectral type. Future James Webb Space Telescope (JWST) observations that constrain the changes of alkali variability vs. continuum variability as a function of atmospheric temperature would be important to map the changes in cloud structures as these atmospheres cool down.

Our observations highlight the importance of high-resolution spectroscopy to understand the atmospheric variability and 3D structures of brown dwarfs and giant exoplanets obtained with ground-based, multi-object spectrographs like Keck I/MOSFIRE, or EMIR at the Gran Telescopio de Canarias (GTC) telescope, but also from space-based telescopes like HST/WFC3. In the near future, JWST will be launched, and it is expected to produce ground-breaking discoveries in the field of brown dwarfs and exoplanets. The Near Infrared Spectrograph (NIRSpec) and Near Infrared Imager and Slitless Spectrograph (NIRISS) on board JWST will provide high signal-to-noise ratios and resolution, and broad-wavelength coverage.

Figure 16. Correlation between the target’s uncorrected light curve, and the uncorrected calibration-star light curves.
spectroscopic observations, which will enable the detection of variability in multiple pressure layers, allowing us to probe the vertical structure of brown dwarf and imaged exoplanet atmospheres with unprecedented accuracy.

9. Conclusions

1. We have used MOSFIRE at the Keck I telescope to monitor over \(\sim 2.5\) hr 2M2208+2921, an L3 young brown dwarf, which is a member of the \(\beta\)-Pictoris young moving group, and an analog to the \(\beta\)Pictoris b directly imaged giant exoplanet.

2. We found a significant spectrophotometric variability amplitude in the \(J\) band using MOSFIRE spectroscopy with a minimum variability amplitude of 3.22 \(\pm\) 0.42%.

3. The ratio between the maximum and the minimum spectra of 2M2208+2921 shows a slight wavelength dependence, with the variability amplitude descending toward redder wavelengths. It also shows potentially enhanced variability amplitudes in the K I doublet and Na I alkali lines.

4. A more detailed analysis of the variability amplitude of the continuum and the flux of the K I and Na I lines further suggests the enhanced variability amplitudes of those lines. The enhanced variability partially disappears if we degrade the resolution of the spectra to \(R\sim 100\), especially for the Na I line, coinciding with the spectral resolution of the HST/WFC3 + G141 grism, explaining why an enhanced variability amplitude has not been

Figure 17. Correlation between the target’s corrected light curve, and the corrected calibration-star light curves.
found in previous works using low-resolution data for brown dwarfs of similar spectral type.

5. We use radiative-transfer models to predict the different heterogeneous layers of clouds that might be introducing the detected spectrophotometric variability and their composition.

6. Using radiative-transfer models, we produced simulated $J$-band spectra for an object with the same $T_{\text{eff}}$ and $\log g$ as 2M2208+2921, and with the same $J$-band variability amplitude and rotational period. We measured the variability amplitude of the K1 doublet and Na1 alkali lines and their respective continua, finding enhanced variability for the alkali lines, in agreement with our observations.

7. Using the Aeolus code to produce brown dwarf maps, we are able to reproduce that the $J$-band light curve has a smaller variability amplitude than the K1 or the Na1 light curves, in agreement with our observations.
Figure 20. Normalized uncorrected light curves of the calibration stars in the field of 2M2208+2921.
Figure 21. Normalized corrected light curves of the calibration stars in the field of 2M2208+2921.
Figure 22. Variability inside the wavelength ranges of the blue and red continuums, and inside the alkali-lines wavelength range for calibration star 1 used for spectra with the original $J$-band MOSFIRE resolution.

Figure 23. Variability inside the wavelength range of the blue and red continuums, and inside the alkali-lines wavelength range for calibration star 4 used for spectra with the original $J$-band MOSFIRE resolution.
Figure 24. Variability inside the wavelength range of the blue and red continuums, and inside the alkali-lines wavelength range for calibration star 5 used for spectra with the original J-band MOSFIRE resolution.

Figure 25. Variability inside the wavelength range of the blue and red continuums, and inside the alkali-lines wavelength range for calibration star 6 used for spectra with the original J-band MOSFIRE resolution.
Figure 26. Variability inside the wavelength range of the blue and red continua, and inside the alkali-lines wavelength range for calibration star 8 used for spectra with the original $J$-band MOSFIRE resolution.

Figure 27. Variability inside the wavelength range of the blue and red continua, and inside the alkali-lines wavelength range for calibration star 1 used for spectra with $R \sim 100$. 
Figure 28. Variability inside the wavelength range of the blue and red continuum, and inside the alkali lines wavelength range for the calibration star 4 for spectra with $R \sim 100$.

Figure 29. Variability inside the wavelength range of the blue and red continuum, and inside the alkali lines wavelength range for the calibration star 5 for spectra with $R \sim 100$. 
Figure 30. Variability inside the wavelength range of the blue and red continua, and inside the alkali-lines wavelength range for calibration star 6 used for spectra with $R \sim 100$.

Figure 31. Variability inside the wavelength range of the blue and red continua, and inside the alkali-lines wavelength range for calibration star 8 used for spectra with $R \sim 100$. 
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Facility: MOSFIRE (W. M. Keck Observatory).
Software: astropy (Astropy Collaboration et al. 2013), Pypeit (Prochaska et al. 2019, 2020).

Appendix A
Correlation Between Parameters

We show the correlations between the light curves created using the blue and red half of the spectra of the correcting stars and the target, the correlation between the light curve and the FWHM measured for the target’s spectra, and the correlation with atmospheric parameters.

Appendix B
J-band Light Curves of the Calibration Stars Before and After Correction

We show the J-band light curves for each calibration star before and after correcting them using the rest of the calibration stars in the field (excluding the target).

Appendix C
Light Curves of the Calibration Stars at the Wavelengths of the K1 Doublet and the NaI Alkali Lines

We show the light curves of the calibration stars at the wavelengths where we find K1 and NaI alkali lines in the target’s spectrum. These light curves have been previously corrected using the method explained in Section 5.
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