Article:

Littlefair, S.P. orcid.org/0000-0001-7221-855X, Dhillon, V.S. orcid.org/0000-0003-4236-9642, Marsh, T.R. et al. (2 more authors) (2006) Observations of ultracool dwarfs with ULTRACAM on the VLT: a search for weather. Monthly Notices of the Royal Astronomical Society , 370 (3). pp. 1208-1212. ISSN 0035-8711

https://doi.org/10.1111/j.1365-2966.2006.10523.x

Mon. Not. R. Astron. Soc. **370,** 1208–1212 (2006) doi:10.1111/j.1365-2966.2006.10523.x

Observations of ultracool dwarfs with ULTRACAM on the VLT: a search for weather*

S. P. Littlefair,[1]† V. S. Dhillon,[1] T. R. Marsh,[2] T. Shahbaz[3] and E. L. Martín[3,4]

[1]*Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH*
[2]*Department of Physics, University of Warwick, Coventry CV4 7AL*
[3]*Instituto de Astrofísica de Canarias, Tenerife, Spain*
[4]*University of Central Florida, Department of Physics, PO Box 162385, Orlando, FL 32816-2385, USA*

Accepted 2006 May 9. Received 2006 May 8; in original form 2006 March 27

ABSTRACT

We present multicolour photometry of four-field ultracool dwarfs with the triple-beam photometer ULTRACAM. Data were obtained simultaneously in the Sloan-g' band and a specially designed narrow-band Na I filter. The previously reported 1.8-h period of Kelu-1 is here recovered in the g' band, but the lack of any significant variability in the Na I light of this object precludes any conclusion as to the cause of the variability. 2MASS 2057−0252 and DENIS 1441−0945 show no convincing evidence for variability. 2MASS 1300+1912, on the other hand, shows good evidence for gradual trends in both bands at the 5 per cent level. These trends are anticorrelated at a high level of significance, a result, which is incompatible with models of star-spot induced variability. It would seem likely that dust-cloud 'weather' is responsible for the short-term variability in this object.

Key words: stars: individual: Kelu-1 – stars: individual: 2MASS 1300+1912 – stars: individual: 2MASS 2057−0252 – stars: individual: DENIS 1441−0945 – stars: low-mass, brown dwarfs.

1 INTRODUCTION

The photometric variability of brown dwarfs and very low-mass stars (collectively known as ultracool dwarfs or UCDs) has received substantial attention over the last five years. The recent review by Bailer-Jones (2004) suggests that around 40 per cent of UCDs which are surveyed show variability. The variability appears to be transient in nature – for example, observations of the L3 dwarf 2MASS 1146+2230 by Gelino et al. (2002) and Clarke, Oppenheimer & Tinney (2002a) failed to find the variability reported by Bailer-Jones & Mundt (2001). Also, extensive observations of the M9.5 dwarf BRI 0021−0214 by Martín, Zapatero Osorio & Lehto (2001) found both periodic and transient I-band variability that did not correspond to the expected rotation period. It is therefore possible that *all* UCDs show variability at some level.

The variability falls into two broad categories: periodic modulations with periods up to a few days and magnitudes of up to 100 mmag, and non-periodic variations with time-scales on the order of hours to days and amplitudes of ∼10–100 mmag in the I band, where most of the observations to date have been undertaken. The existence of non-periodic variability is interesting, as the monitoring surveys undertaken would have been sensitive to the rotation periods of UCDs. The existence of non-periodic variability led Bailer-Jones & Mundt (2001) to propose that the variability is due to surface features which evolve on time-scales shorter than the rotational period.

There are two prime candidates for the surface features responsible for variability. Cool, magnetic star-spots are an attractive explanation for the very young UCDs observed in clusters. Star-spots are known to cause variability in the more massive T Tauri stars (see e.g. Herbst et al. 1994), and furthermore, young brown dwarfs show similar X-ray properties to T Tauri stars, implying that a similar magnetic activity mechanism is at work in young UCDs and T Tauri stars (e.g. Bouy 2004; Ozawa, Grosso & Montmerle 2005). The older field UCDs may not show magnetic spots, as the cooler photospheres will be neutral and result in a weak coupling between the gas and magnetic field (Fleming, Giampapa & Schmitt 2000; Mohanty et al. 2002). For the field UCDs, dust clouds are a more plausible candidate: dust should form under the cool and dense conditions found in their photospheres, and dusty atmospheric models are more successful in reproducing the observed colours of UCDs than dust-free models (Leggett, Allard & Hauschildt 1998; Martín et al. 2000). The atmospheres of UCDs are also likely to be highly dynamic, as a result of turbulence excited by convection (Allard et al. 2001). It is quite likely that rapidly evolving dust-cloud 'weather' is responsible for the non-periodic variability seen in UCDs.

The different spectral signatures of variability caused by spots and dust clouds allows one, in principle, to distinguish between

*Based on observations made at the European Southern Observatory, Paranal, Chile (ESO programme 075.C-0505).
†E-mail: s.littlefair@shef.ac.uk

these two candidates based upon time-resolved spectrophotometry. Unfortunately, the results so far have been inconclusive, as no significant variability was detected in dust-sensitive wavelength regions (Bailer-Jones 2002; Clarke, Tinney & Hodgkin 2003). The reasons for this lack of success are not clear. It may be simply that variability in UCDs is transient, and the limited number of observations to date have merely been unlucky. Alternatively, it may be that the systematic errors in spectrophotometry, arising from sky subtraction, telluric correction and slit-loss correction are too large to attain the required accuracies of a per cent or better implied by the magnitude of variability in the *I* band.

A better approach may be to use time-resolved photometry, taken simultaneously in a narrow band centred on dust-centred features and a continuum filter. Photometry does not suffer from slit-loss errors, as other stars in the field can be used to correct for the light that falls outside the aperture. Also, the photons are collected in fewer pixels, allowing greater signal-to-noise ratios (S/Ns) to be achieved. Narrow-band photometry was used by Tinney & Tolley (1999), who obtained quasi-simultaneous narrow-band photometry of two UCDs, DENIS-P J1228−1547 and LP 944−20. Variability was found in both bands for LP 944−20, showing the promise of photometry for future studies. Unfortunately, the complex nature of the spectral behaviour in the narrow bands chosen by Tinney & Tolley (1999), precluded any firm conclusion as to the origin of the variability. We outline here a modification of the method proposed by Tinney & Tolley (1999). Multiband photometry has also been used succesfully to show that, in some cases at least, the variability of M-dwarfs is due to magnetic spots (Rockenfeller, Bailer-Jones & Mundt 2006). Fig. 1 shows the details of the method (which is described in more detail by Bailer-Jones & Mundt 2001). The opacity within a spot feature shows a broadly similar colour dependence to the opacity of the immaculate photosphere, but the cool spot lowers the average temperature of the visible portion of the star. Therefore, the evolution or appearance of a spot feature produces a dimming of the spectrum at all wavelengths. If we choose to observe simultaneously in two filters, one centred on the continuum, the other centred on the neutral alkali lines of Na I, a cool spot will cause magnitude changes which are *correlated* between the filters. In the case of the formation of a clearing within a dusty cloud deck, the clearing *removes* opacity in the continuum, but significantly *increases* opacity in spectral regions dominated by molecular lines (the strong resonance lines of Na I seen at 0.59 μm are good examples of such a region). A dust cloud forming on a clear photosphere has the opposite effect, increasing the continuum opacity, but decreasing the opacity at Na I wavelengths. Thus, in contrast to the case of a star-spot, a change in the cloud coverage of a UCD causes *anticorrelated* magnitude changes between the two filters. By centering our narrow-band filter on the neutral alkali lines, we can thus distinguish between spots and dust clouds.

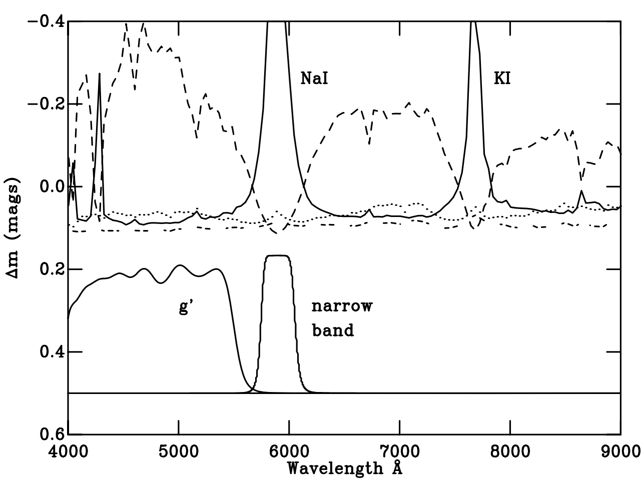

Figure 1. Calculations of the *change* in the spectrum of a UCD with $T_{\rm eff} = 1900$ K, due to the appearance of a cloud or spot which covers 10 per cent of the stellar surface. The calculations were made using the synthetic spectra of Allard et al. (2001). The four lines represent the change in the spectrum of the UCD, caused by the formation of: a clear hole in a dusty atmosphere (dashed line), a dusty cloud on a clear atmosphere (solid line), a 200 K cooler spot on a dusty atmosphere (intermittent dashed line) and a 200 K cooler spot on a clear atmosphere (dotted line). Also shown are the bandpasses of the Sloan-g' filter, and the specially designed Na I filter ($\lambda_{\rm cen} = 5900$ Å, $\delta\lambda = 220$ Å) used for the observations presented in this paper.

In this paper, we present multicolour photometry of four field UCDs with the triple-beam photometer ULTRACAM (Dhillon & Marsh 2001). Data were taken simultaneously in the Sloan-g' band and the specially designed narrow-band Na I filter shown in Fig. 1. The observations are described in Section 2, the results presented in Section 3 and discussed in Section 4, whilst in Section 5, we draw our conclusions.

2 OBSERVATIONS

The UCDs 2MASS 1300+1912, Kelu-1, DENIS 1441−0945 and 2MASS 2057−0252 were observed simultaneously in the Sloan-g' and Na I bands using ULTRACAM on the 8.2-m MELIPAL unit of the Very Large Telescope (VLT) at Paranal, Chile. Thanks to the frame-transfer CCDs employed in ULTRACAM we were able to obtain 10 s exposures with no dead-time between frames. Sloan-u' images were obtained simultaneously with the other colours, but the UCDs are too faint to produce useful light curves in this band. The observations are summarized in Table 1. Data reduction was carried out using the ULTRACAM pipeline date reduction software. Extraction of target and comparison star light curves was performed using an optimal extraction method (Naylor 1998). Due to the 2.6-arcmin field of view of ULTRACAM on the VLT and the sparse nature of the target fields, a limited number of comparison stars are available for each object.

On inspection of the images, it is clear that the images suffer from structured vignetting and scattered light components at the 10 per cent level. Further investigation of these effects suggests that they arise in the collimator optics. To prevent the scattered light in the flat-field frames from introducing an error in the flat-field process, large-scale trends were removed from the flat-field before use, by dividing the flat-field by a median-filtered version of itself. This means that vignetting is *not* corrected for by our flat-field. For the majority of our observations this is not a major problem, as the position of the stars on the chip remained stable to within 1 pixel throughout observation. Whilst the absolute flux level for these stars will be in

Table 1. Journal of observations.

UT date start	Target	UT start	UT end	Seeing (arcsec)	Airmass
2005-05-08	2MASS 1300+1912	23:22	04:13	0.6–1.0	1.4–2.3
2005-05-13	DENIS 1441−0945	03:11	07:02	0.5–0.8	1.0–1.4
2005-05-13	2MASS 2057−0252	07:05	10:14	0.5–0.8	1.1–1.5
2005-05-14	Kelu-1	02:37	06:49	0.5–1.0	1.0–2.0
2005-05-17	2MASS 2057−0252	07:52	09:50	0.8–1.1	1.0–1.1

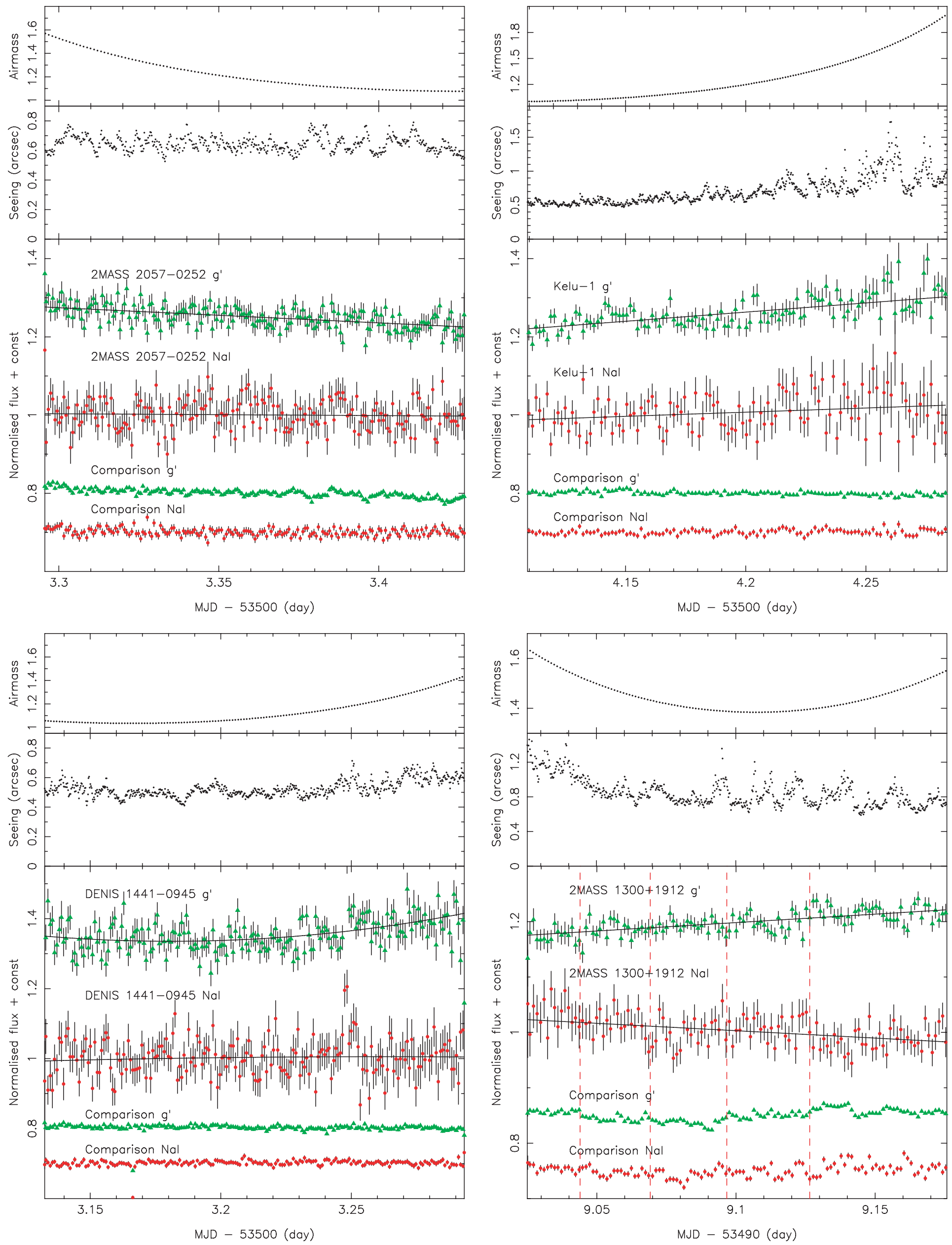

Figure 2. Clockwise from top left-hand panel: light curves of 2MASS 2057−0252, Kelu-1, 2MASS 1300+1912 and DENIS 1441−0945. The flux of the target star, divided by a nearby comparison, is plotted against Modified Julian Date (MJD). The light curves have been binned to a time resolution of approximately 1 min, normalized by division of the mean value, and a vertical offset of 0.2 has been applied to the Sloan-g' light curve. The Na I light curve is plotted with red circles, the Sloan-g' light curve is plotted with green triangles. The light curves of the comparison star, divided by a third, nearby comparison star are plotted beneath the target star's light curves, with the same symbols. These light curves have also been normalized and an offset added for clarity. Also shown are first-order polynomial fits to the UCD data (except in the case of DENIS 1441−0945, where a second-order fit is shown). The dashed vertical lines in the 2MASS 1300+1912 panel show the times at which the star's position on the chip was changed. For each object, additional panels show the seeing in arcseconds (middle panel) as measured from the full width at half-maximum of stellar images, and the airmass of the UCD (top panel).

error because of the lack of vignetting correction, the shape of the light curves will not be affected. One exception to this is the observation of 2MASS 1300+1912. At various times in the observation of this object, the target was moved around the chip. In principle, this might introduce spurious features into the light curve, as the relative vignetting between target and comparison star changes. In practice, the distance between comparison star and target was small (∼140 pixel), and we believe this effect is negligible, a conclusion which is reinforced by the relative flatness of the comparison star light curve in Fig. 2, and the lack of sudden jumps in the light curves at times when the star was moved.

3 RESULTS

3.1 Rapid variability

We performed a search for rapid variability in all our objects, by calculating the reduced χ-squared with respect to the polynomial fits shown in Fig. 2. In each case, the reduced χ-squared with rspect to the fits was less than or equal to a value of 1.5. We conclude that no objects show evidence for 'rapid' variability, that is, variability on time-scales of a few minutes. In the rest of this paper, the term variability refers to medium term trends within the data, that is, variability on the time-scale of hours.

3.2 2MASS 2057−0252

2MASS 2057−0252 is an L1.5 dwarf with an I-band magnitude of 16.5 (Koen 2003). The object showed tentative evidence for I-band variability on one night, which was absent on the second night it was observed (Koen 2003). Our observations of 2MASS 2057−0252 are presented in Fig. 2. No evidence of variability is present in the Na I light curve, as determined by a one-sided F-test. Whilst the g'-band light curve shows a steady decline in flux with time, the flux is strongly correlated with airmass, which strongly suggests that this is due to a colour effect, arising because the target is redder than the comparison star. This also naturally explains the lack of variability in the Na I filter, as this filter is much narrower, and redder, than the Sloan-g' filter. We therefore conclude that this object shows no strong evidence for variability on a 3 h time-scale.

3.3 Kelu-1

Kelu-1 is an L2 dwarf (Ruiz, Leggett & Allard 1997), and a known binary star (Liu & Leggett 2005; Gelino, Kulkarni & Stephens 2006). Observations centred on the complex of molecular bandheads at ∼8600 Å show strong periodic variability, with a period of 1.8 h (Clarke, Tinney & Covey 2002b). Time-resolved spectroscopy of the object showed no evidence for variability in the dust-sensitive TiO bandheads, however (Clarke et al. 2003). Our observations are presented in Fig. 2. The Na I light curve shows no evidence of variability: we used a one-sided F-test to show that a first-order polynomial was a better match to the data than a constant fit at a significance of just 50 per cent.

The g'-band flux, however, shows a rising trend with time. This rising trend is strongly correlated with airmass and is most likely a colour effect. Additional variability *is* visible, however, at the start of the observations, where the airmass was low, and S/N is better. A Lomb–Scargle periodogram of the g'-band data taken before MJD 53504.22 (airmass 1.3) has a peak at the known 1.8-h period of Kelu-1. Following the analysis of Schwarzenberg-Czerny (1998), the significance of this peak is better than 99.9 per cent. The formal significance should be treated with caution; non-white noise, deviations of the light curve from a pure sinusoid and irregular sampling can all affect the periodogram, and the length of our run is only just longer than the expected period. However, the significance is high enough for us to conclude that the 1.8-h periodic variability at 8600 Å reported by Clarke et al. (2002b) is also present in the g'-band light of Kelu-1. The phased light curve is plotted in Fig. 3.

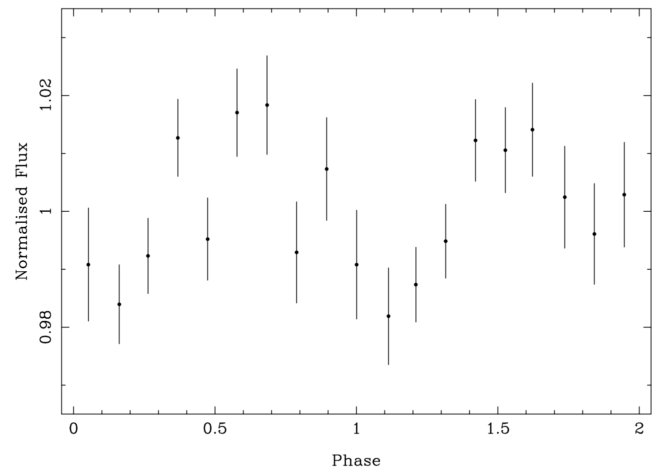

Figure 3. The g'-band light curve of Kelu-1, phased on the known 1.8-h period, and binned into 19 phase bins. Data taken at high airmass and with a poor S/N (after MJD 53504.22) was masked out prior to phasing.

3.4 2MASS 1300+1912

2MASS 1300+1912 is an L1 dwarf with an I-band magnitude of 15.9 (Gelino et al. 2002). Convincing evidence for non-periodic I-band variability with an amplitude of ∼0.2 mag was reported by Gelino et al. (2002). Our observations are presented in Fig. 2. The observations taken above airmass of 1.7 are not shown as the S/N is too low to be useful. It is clear from Fig. 2 that the object shows variability at a level of about 5 per cent in both bands. This variability is significant, and clearly anticorrelated (the correlation coefficient between the two light curves is -0.09 ± 0.01). To determine the significance of the anticorrelation we computed second-order polynomial fits to the light curves of the target and comparison star. The difference between the g' band and Na I slopes is -0.6 ± 0.1 and 0.00 ± 0.02 for the target star and comparison star, respectively. Futhermore, the individual slopes of the comparison star's light curves are both consistent with zero. We conclude that the anticorrelation is significant, and not introduced by variability in the comparison star. Although the g'-band light curves of the other objects are affected by colour-term effects, this is not the case here. Whilst the airmass first falls and then rises, the g'-band light curve of 2MASS 1200+1912 shows a steady rising trend. We conclude that colour-term effects *do not* affect the g'-band light curve of 2MASS 1300+1912. Furthermore, the variability is not correlated with the seeing, sky brightness or transparency, and we conclude that systematic errors resulting from the removal and/or correction of these factors do not cause the observed variability.

Such variability, if real, would be strong evidence that the variability in this system is caused by dust clouds. Unfortunately, the position of the target on the CCD was not constant throughout the run. As discussed in Section 2, this could lead to spurious variability in the light curve. A reasonable check of the presence of such effects would be the structure in the differential light curve of our chosen comparison and another star on the CCD. Only one such star is present, approximately 530 pixels away from our comparison star. The differential light curve of our comparison star divided by this second star is plotted in Fig. 2. Variability is indeed present, but only at a level of approximately 1 per cent. Futhermore, there are no sudden jumps in the light curves at the times when the star's position was changed. We conclude that vignetting has not introduced features into the light curve, although the variability in the light curve at the 1 per cent level suggests that one of the comparison stars is itself variable, albeit at a low level.

We therefore conclude that the anticorrelated variability seen in 2MASS 1300+1912 is real. This conclusion is strengthened by the fact that most systematic errors would produce spurious variability that is *correlated* between the two wavebands. In particular, this applies to both colour effects, and any errors introduced by the uncorrected vignetting (the vignetting patterns are very similar in both CCDs).

3.5 DENIS 1441−0945

DENIS 1441−0945 is an L1 dwarf with an I-band magnitude of 16.9 (Koen 2003), and a known binary (Bouy et al. 2003). It was observed in the I band by Koen (2003) – no convincing evidence for variability was reported. Although a rising trend was present in the light curve, this may have been a colour-term effect. Our observations of DENIS 1441−0945 are presented in Fig. 2. No evidence of variability is present in the Na I light curve, as determined by a one-sided F-test. Whilst the g'-band light curve shows a gradual change in flux with time, the flux is strongly correlated with airmass, which suggests that this is due to a colour-term effect. We therefore conclude that this object shows no evidence for variability.

4 DISCUSSION

The detection of anticorrelated variability between the g' band and the Na I band in 2MASS 1300+1912 is incompatible with models of star-spot induced variability. Given that anticorrelated variability is expected from models of dust-cloud variability, and that rapid evolution of dust clouds is to be expected in UCDs, it is likely that dust clouds are responsible for the variability in this system. The relative amplitude of variability between the two bands can constrain the nature of the cloud evolution responsible for variability. The models used in Fig. 1 show that a dust cloud forming on a predominantly clear amosphere would produce a much stronger signal in the Na I band than the Sloan-g' band. In contrast, a small clearing in a predominantly dusty atmosphere produces variability of about the same magnitude in each band. The amplitude of variability can also constrain the size of the cloud or clearing; our observations are consistent with the development of a clear patch covering approximately 4 per cent of a predominantly dusty atmosphere.

The result presented here demonstrates that simultaneous, multicolour photometry is effective in distinguishing between different variability scenarios for UCDs, and opens up the possibility of understanding the variability of UCDs in more detail. Clearly, the method should be applied to a large sample of UCDs to determine if the variability in *all* UCDs is due to dust clouds, and at what effective temperatures dust-cloud variability becomes important.

5 CONCLUSIONS

We present simultaneous, multicolour photometry of four ultracool dwarfs with the triple-beam photometer ULTRACAM. Data were obtained simultaneously in the Sloan-g' band and a specially designed narrow-band Na I filter. Of the four objects, only 2MASS 1300+1912 shows good evidence for variability in both bands. For this object, the variability is anticorrelated at a high level of significance, providing the first direct evidence that dust-cloud weather is responsible for the variability in UCDs.

ACKNOWLEDGMENTS

TRM acknowledges the support of a PPARC Senior Research Fellowship. ULTRACAM and SPL are supported by PPARC grants PP/D002370/1 and PPA/G/S/2003/00058, respectively. TS acknowledges support from the Spanish Ministry of Science and Technology under the programme Ramón Y Cajal. The authors would like to thank Tim Naylor for useful discussions.

REFERENCES

Allard F., Hauschildt P. H., Alexander D. R., Tamanai A., Schweitzer A., 2001, ApJ, 556, 357
Bailer-Jones C. A. L., 2002, A&A, 389, 963
Bailer-Jones C. A. L., 2004, preprint (astro-ph/0409463)
Bailer-Jones C. A. L., Mundt R., 2001, A&A, 367, 218
Bouy H., 2004, A&A, 424, 619
Bouy H., Brandner W., Martín E. L., Delfosse X., Allard F., Basri G., 2003, AJ, 126, 1526
Clarke F. J., Oppenheimer B. R., Tinney C. G., 2002a, MNRAS, 335, 1158
Clarke F. J., Tinney C. G., Covey K. R., 2002b, MNRAS, 332, 361
Clarke F. J., Tinney C. G., Hodgkin S. T., 2003, MNRAS, 341, 239
Dhillon V., Marsh T., 2001, New Astron. Rev., 45, 91
Fleming T. A., Giampapa M. S., Schmitt J. H. M. M., 2000, ApJ, 533, 372
Gelino C. R., Marley M. S., Holtzman J. A., Ackerman A. S., Lodders K., 2002, ApJ, 577, 433
Gelino C. R., Kulkarni S. R., Stephens D. C., 2006, PASP, 118, 611
Herbst W., Herbst D. K., Grossman E. J., Weinstein D., 1994, AJ, 108, 1906
Koen C., 2003, MNRAS, 346, 473
Leggett S. K., Allard F., Hauschildt P. H., 1998, ApJ, 509, 836
Liu M. C., Leggett S. K., 2005, ApJ, 634, 616
Martín E. L., Brandner W., Bouvier J., Luhman K. L., Stauffer J., Basri G., Zapatero Osorio M. R., Barrado y Navascués D., 2000, ApJ, 543, 299
Martín E. L., Zapatero Osorio M. R., Lehto H. J., 2001, ApJ, 557, 822
Mohanty S., Basri G., Shu F., Allard F., Chabrier G., 2002, ApJ, 571, 469
Naylor T., 1998, MNRAS, 296, 339
Ozawa H., Grosso N., Montmerle T., 2005, A&A, 429, 963
Rockenfeller B., Bailer-Jones C. A. L., Mundt R., 2006, A&A, 448, 1111
Ruiz M. T., Leggett S. K., Allard F., 1997, ApJ, 491, L107
Schwarzenberg-Czerny A., 1998, MNRAS, 301, 831
Tinney C. G., Tolley A. J., 1999, MNRAS, 304, 119

This paper has been typeset from a TEX/LATEX file prepared by the author.