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I_C and R_C band time-series observations of some bright ultracool dwarfs

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ABSTRACT

The results of more than 100 h of CCD photometric monitoring of 10 L dwarfs and two T dwarfs are presented. Reasonable evidence is shown for I_C band variability in DENIS 0255−4700, DENIS 1705−0516 and 2M 2104−1037. Substantial brightening of the T dwarf binary ϵ Indi Bab was observed over the course of 3.6 h; it is unlikely that this could have been caused by surface spots. No unequivocal variability could be detected in the R_C band.

Key words: stars: low mass, brown dwarfs – stars: variables: other.

1 INTRODUCTION

This paper is a continuation of the author's variability studies of ultracool (spectral classes L and T) objects. Descriptions of previous observations can be found in Koen (2003, 2004) and Koen, Matsunaga & Menzies (2004). References to earlier work in this field can be found in these three papers: a very brief update of other recently published material follows.

Occasional infrared photometry of the brown dwarf BD-Ser 1, spanning several years, was analysed by Klotz et al. (2004). The authors conclude that there is no strong evidence for variability. Brandner et al. (2004) placed limits on any possible variability in DENIS 1228.2−1547, using their *Hubble Space Telescope* (*HST*) photometry. Optical (I-band) time-series photometry of brown dwarfs in the σ Orionis cluster was obtained by Caballero et al. (2004). Their sample included two known L dwarfs (S Ori 47 and S Ori 71), neither of which showed statistically significant variability. Finally, the first R band time-series observations of ultracool dwarfs were published by Maiti et al. (2005). The authors concluded that two (2M 1300+1912, 2M 1439+1929) out of their three targets varied aperiodically. Both these objects had previously been studied in the I band by Gelino et al. (2002), who found 2M 1300+1912 to be variable. The L1 dwarf 2M 1439+192 had also been monitored by Bailer-Jones & Mundt (2001; I band) and Bailer-Jones & Lamm (2003; near-infrared) with no variability detections. Because the non-variability in Bailer-Jones & Mundt (2001) and Gelino et al. (2002) was marginal, the latter authors speculated that the object might be a low amplitude variable – but see also the assessment of the 2001–2003 data by Bailer-Jones (2004).

The present paper continues the efforts to understand the incidence and nature of variability in ultracool objects. It reports on I_C band observations of eight L dwarfs; one of these, together with two other L dwarfs, were also monitored in the R_C band. Two T dwarfs were studied in the I_C band; rapid variability in one of these claimed in a previous study is confirmed.

The observations are described in Section 2. Results are given in Sections 3 (I_C band) and 4 (R_C band). Conclusions follow in Section 5.

2 OBSERVATIONS

All observations were made with the SAAO CCD camera attached to the 1.9-m telescope at Sutherland, South Africa. The field of view of the camera is about 2.5 arcmin^2. The 1024 × 1024 chip was used in 2 × 2 prebin mode, so that the readout time was less than 20 s. Most of the observations were made through a Cousins I_C filter (Table 1), while three runs used the R_C filter (Table 2).

The data were reduced using a modified version of DoPHOT (Schechter, Mateo & Saha 1993). The final product was differential magnitudes from profile fitting.

The targets were selected from the DwarfArchives.org compilation at http://spider.ipac.caltech.edu/staff/davy/ARCHIVE/, use of which is gratefully acknowledged. The spectral classifications and J-band magnitudes in the tables are from this website.

Published measurements of I-band magnitudes could be found for some objects: DENIS 0255−4700 (Martín et al. 1999), DENIS 1705−0516 (Kendall et al. 2004), 2M 2224−0158 (Dahn et al. 2002) and ϵ Indi Bab (Scholz et al. 2003). Measurements of another ultracool object with known I magnitudes, namely 2M 0746+2000 (Dahn et al. 2002), were also interspersed with observations listed in Table 1. Measurements of these objects were used to set nightly zeropoints, and this allowed rough magnitudes to be calculated for all other objects – hence the values given in Table 1.

The R magnitudes of SSSPM 0829−1309 and DENIS 0255−4700 given in Table 2 were taken from Scholz & Meusinger (2002). As 2M 0835−0819 was observed on the same night as DENIS 0255−4700, the mean magnitude of the latter was used to calculate the nightly zeropoint, which was then applied to the data for 2M 0835−0819.

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Table 1. Observing log, and details of the objects observed. The last column gives the rms scatter in the light curve. See the text for further details.

Name	Spectrum	J	I_C	Starting time (HJD 2450000+)	Run length (h)	Exposure time (s)	N	σ (mmag)
DENIS 0255−4700	L8	13.25	17.14	3354.3446	2.0	150	39	10
				3355.2969	2.4	120	61	10
				3367.2830	4.6	90	144	14
2MASS 0439−2353	L6.5	14.40	18.0	3358.2938	3.4	180	56	12
2MASS 0523−1403	L2.5	13.08	16.6	3363.3115	1.6	120	42	8
				3366.2931	3.0	90	96	8
2MASS 1534−2952AB	T5.5/T5.5	14.90	19.3	3178.2128	1.5	150	31	25
				3180.2433	5.0	180	87	28
				3181.2221	4.5	150–180	71	23
2MASS 1555−0956	L1	12.56	16.0	3174.3055	4.3	70	168	6
				3175.2349	4.6	90	145	6
				3182.2691	2.2	120	56	4
DENIS 1705−0516	L4	13.31	16.6	3172.4680	2.1	60	87	10
				3173.3585	4.1	60	180	9
				3177.2730	5.8	100	173	9
				3178.2873	6.1	100	136	9
				3179.3044	1.5	120	40	10
				3183.2776	3.5	120	88	7
2MASS 2104−1037	L3	13.84	17.5	3174.5049	4.4	70	169	12
				3175.4357	6.2	100-150	172	12
				3181.4397	6.1	90-120	186	11
2MASS 2130−0845	L1	14.14	17.3	3178.5606	2.1	150	44	6
				3268.2641	2.7	150-180	51	9
				3269.2338	2.6	180	48	11
ϵ Indi Bab	T1/T6	11.91	16.7	3173.5455	3.6	60	159	36
2MASS 2224−0158	L4.5	14.07	18.02	3180.4822	3.1	120	78	16
				3182.5035	3.1	150	63	13
				3183.4690	5.5	180	94	17
				3185.5218	4.0	120-150	84	14

Table 2. Log of the R_C band observations, and details of the objects observed. The last column gives the rms scatter in the light curve; in the case of DENIS 0255−4700 one outlying point (Fig. 27) was excluded. See the text for further details.

Name	Spectrum	J	R_C	Starting time (HJD 2453350+)	Run length (h)	Exposure time (s)	N	σ (mmag)
DENIS 0255−4700	L8	13.25	20.1	6.2999	3.0	200	49	24
SSSPM 0829−1309	L2	12.8	18.8	5.4726	3.1	120	80	15
2MASS 0835−0819	L4.5	13.2	19.3	6.4481	3.7	150	79	15

3 RESULTS: I_C BAND

3.1 DENIS 0255−4700

The brown dwarf DENIS 0255−4700 is one of the best-studied ultracool dwarfs. At least two Keck spectra have been obtained, and the photometric measurements have been made over a wide wavelength range [see Creech-Eakman, Orton & Serabyn (2004) for a brief review]. Subsequently to the paper by Creech-Eakman et al. (2004) a *Spitzer Space Telescope* mid-infrared spectrum of DENIS 0255−4700 was published by Roellig et al. (2004). A rotational velocity of $v \sin i = 40$ km s^{-1} was determined by Mohanty & Basri (2003); the authors also placed an upper limit of 0.2 Å on the Hα equivalent width. Significant linear polarisation was measured

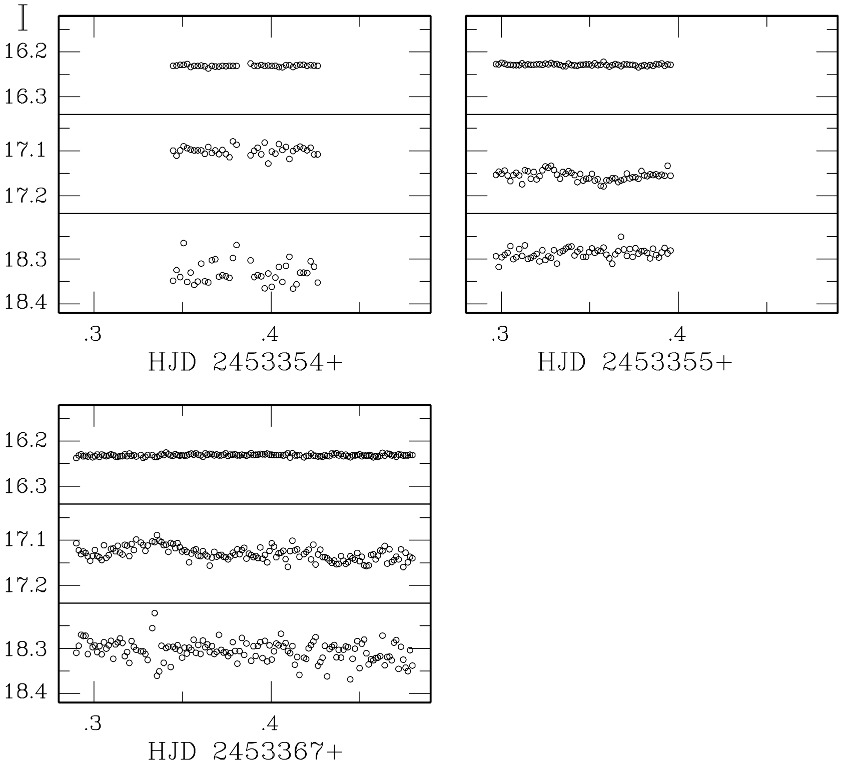

Figure 1. Observations in the I_C band of DENIS 0255−4700 (middle panel) and two other stars in the field of view. The vertical scale on each panel is 0.22 mag.

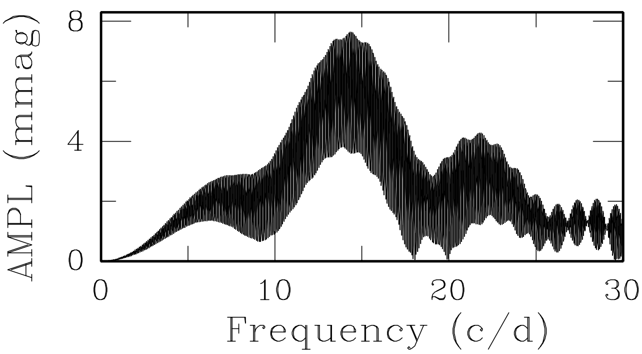

Figure 2. Amplitude spectrum of the detrended, combined I_C band observations of DENIS 0255−4700.

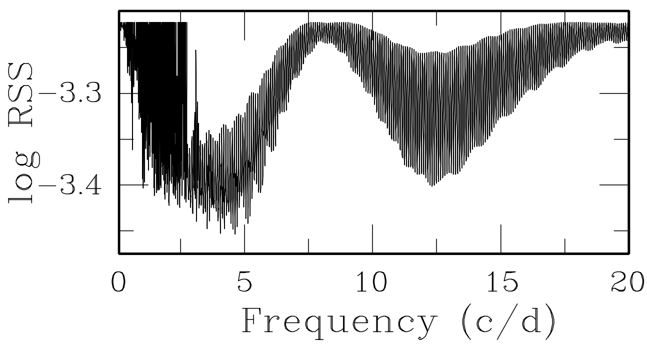

Figure 4. A residual sum-of-squares periodogram (see text) of the observations of DENIS 0255−4700.

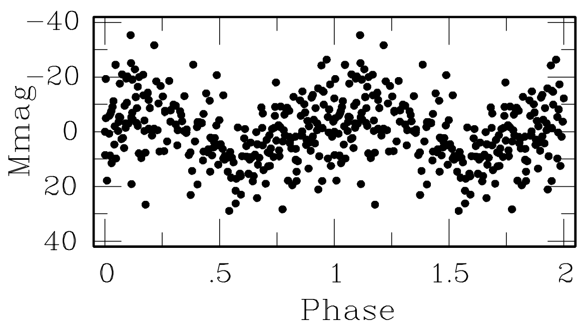

Figure 3. The observations of DENIS 0255−4700, folded with respect to the best-fitting period identified from the amplitude spectrum in Fig. 2. The data from the different nights were individually detrended.

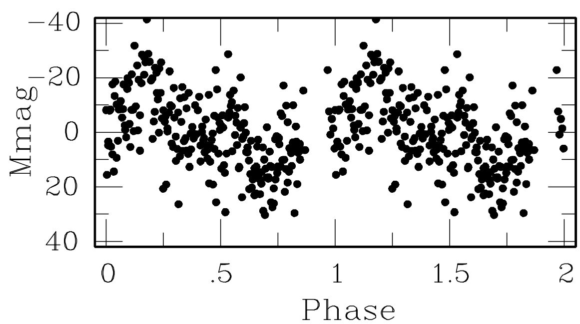

Figure 5. The observations of DENIS 0255−4700, folded with respect to the best-fitting period from the *RSS* periodogram. The data from the different nights were zeropoint-adjusted to obtain the optimal fit.

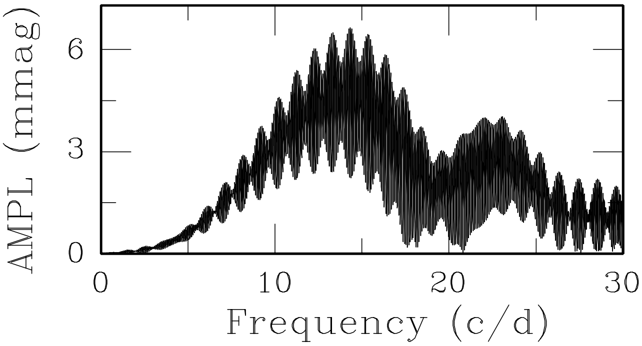

Figure 6. Amplitude spectrum of the residuals left after fitting the model (1) to the I_C band observations of DENIS 0255−4700.

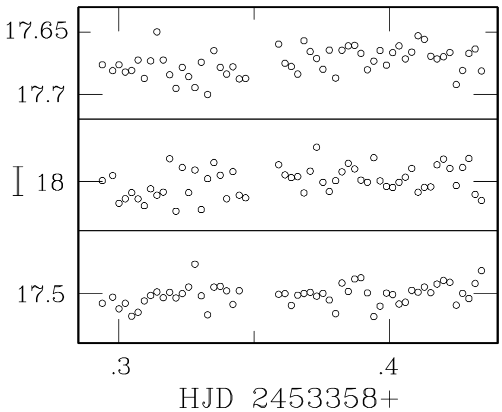

Figure 7. Observations in the I_C band of 2M 0439−2352 (middle panel) and two stars of similar brightness in the field of view. The vertical scale on each panel is 0.09 mag.

by Ménard, Delfosse & Monin (2002); theoretical interpretations in terms of dust scattering can be found in Sengupta (2003).

Careful inspection of the light curves in Fig. 1 reveals that there is variability on at least two time-scales: a modulation with a time-scale of the order of two hours or so, superimposed on a slow systematic drift over the course of a night's observing. In order to quantify the shorter time-scale the nightly data were first detrended by prewhitening by a linear line fit. The resulting residuals from the three nights were then combined and an amplitude spectrum (Fig. 2) calculated: the maximum is at 14.40 d^{-1}, with an associated amplitude just below 8 mmag. Given the large gap between the second and third runs, the extent of the aliasing in the spectrum is not surprising. Fig. 3 shows the detrended data folded with respect to the best-fitting period (1.67 h).

Alternatively, the model

$$Y_{jk} = \mu_k + A \sin \omega t_{jk} + B \cos \omega t_{jk} + e_{jk}$$
$$k = 1, 2, \cdots, K \quad j = 1, 2, \cdots, N_k \tag{1}$$

can be fit to the raw data. In (1), K is the number of nights, indexed by k; measurements Y_{jk} obtained during night k and at time t_{jk} are indexed by j; μ_k is the zeropoint associated with night k; A, B and ω are constants describing the amplitude, phase and frequency of a sinusoid; and e_{jk} is an 'error' term. A least-squares fitting procedure for (1) is described in Koen (2003); the residual sum of squares to be minimized is denoted *RSS* in what follows. In essence, the least squares problem is formulated such that *RSS* is a function of $\omega = 2\pi f$ only; an $RSS = RSS(f)$ 'periodogram' can then be used to determine the best-fitting frequency f, from which other parameters of interest can be calculated. (Of course, by contrast with the standard periodogram or amplitude spectrum, the frequency at which *RSS* reaches its *minimum* is of interest.)

The *RSS* periodogram of the Fig. 1 data is given in Fig. 4; the approximate frequencies associated with the two time-scales can be seen to be 2.5–6 d^{-1} and 11–14 d^{-1}. The overall minimum is at 4.63 d^{-1}; the associated amplitude is 10 mmag, and zeropoints are 17.108, 17.149 and 17.130. The zeropoint-corrected data are shown folded with respect to the best-fitting period (5.2 h) in Fig. 5. The scatter in the latter diagram is misleadingly large as the shorter time-scale variability has not been corrected for. After prewhitening by the low frequency component the higher frequency variation can be studied by analysing the residuals; the amplitude spectrum in Fig. 6 is similar to Fig. 2 – the peak is at 14.32 d^{-1} (amplitude ∼7 mmag). The folded lightcurve is similar in appearance to Fig. 3 and is therefore not shown.

3.2 2M 0439−2353

Cruz et al. (2003) provided the spectral classification of L6.5 and a distance estimate of 10.8 pc. The 3.4 h of photometry plotted in Fig. 7 does not show any evidence for variability.

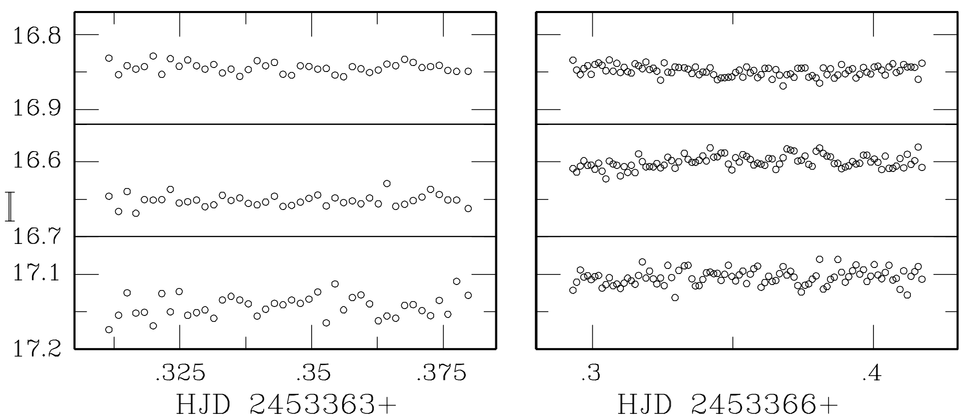

Figure 8. Observations in the I_C band of 2M 0523−1403 (middle panels) and two stars of similar brightness in the field of view. The vertical scale on each panel is 0.15 mag.

3.3 2M 0523−1403

The object was discovered by Cruz et al. (2003). The results of two short runs are plotted in Fig. 8. There were five stars in the field of view with brightnesses within about 1 mag of the programme object. Aside from brightenings of about 0.05 mag in 2M 0523−1403 (middle panels of Fig. 8) and 0.04 mag in one other star (bottom panels of Fig. 8), the mean magnitudes obtained in the two runs

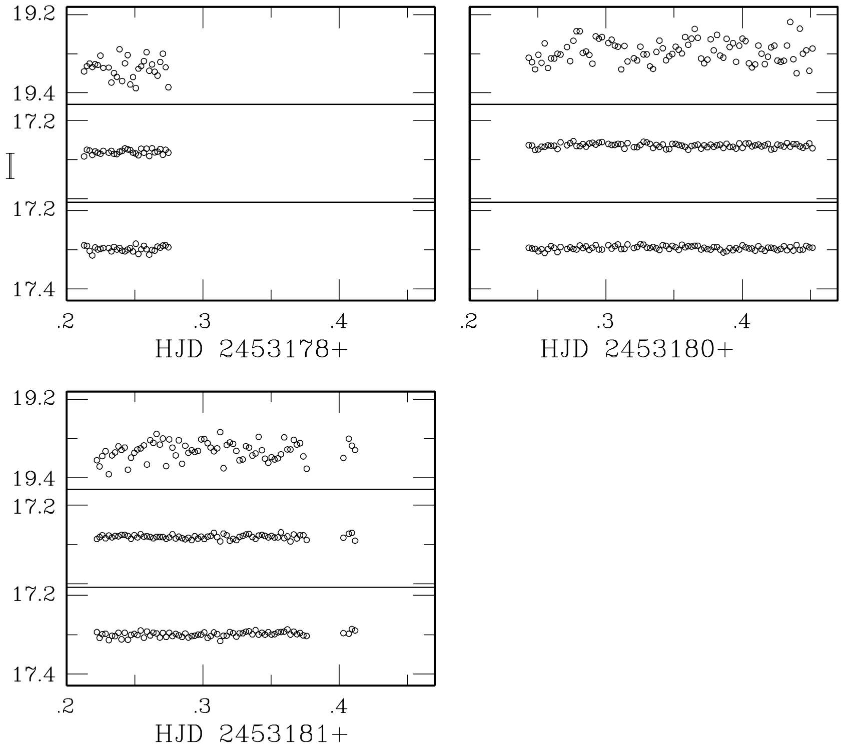

Figure 9. Observations in the I_C band of 2M 1534−2952AB (top panels) and two other stars in the field of view. The vertical scale on each panel is 0.25 mag.

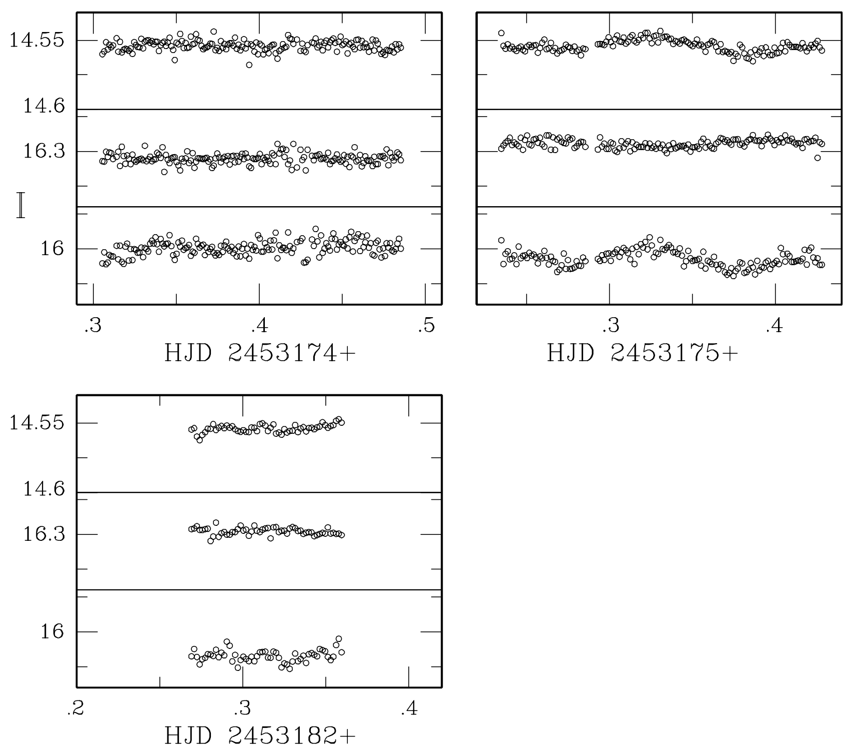

Figure 10. Observations in the I_C band of 2M 1555−0956 (bottom panels) and two other stars in the field of view. The vertical scale on each panel is 0.07 mag.

agreed to better than 0.01 mag. It would be interesting to monitor the mean brightness level of this ultracool dwarf over a long time-base.

3.4 2M 1534−2952AB

The system 2M 1534−2952A was demonstrated to be a binary by Burgasser et al. (2003), both components being of spectral type T5.5.

Koen et al. (2004) found weak evidence for low amplitude (4 mmag in H, 7 mmag in K_s) periodic variability in the near-infrared. Interestingly, a periodogram analysis of the first short run on this object (Fig. 9) found a best-fitting frequency of 25.5 d^{-} (amplitude 11 mmag), very close to the value 25.1 d^{-1} given by Koen et al. (2004). However, results from the two longer runs were substantially different, with best-fitting frequencies of 11.0 and 7.5 d^{-1} respectively. Not surprisingly, the combined data are dominated by the longest run, and have a best-fitting frequency of 11.02 d^{-1}.

It may be concluded that there is no convincing evidence for periodic variability. Furthermore the present results cast doubt on the reality of the brightness changes tentatively claimed by Koen et al. (2004) – unless there is intermittent periodic behaviour.

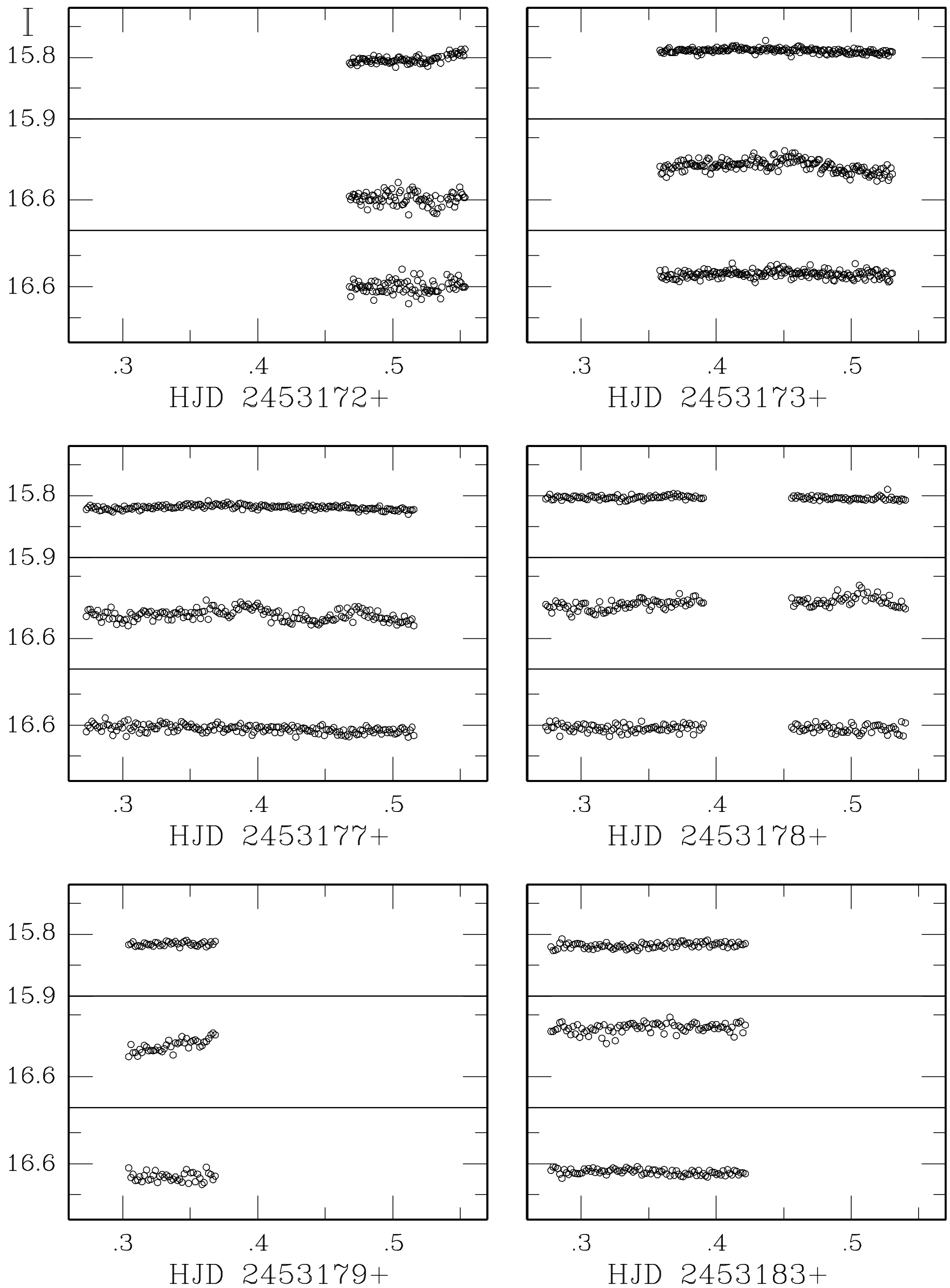

Figure 11. Observations in the I_C band of DENIS 1705−0516 (middle panels) and two stars of similar brightness in the field of view. The vertical scale on each panel is 0.18 mag.

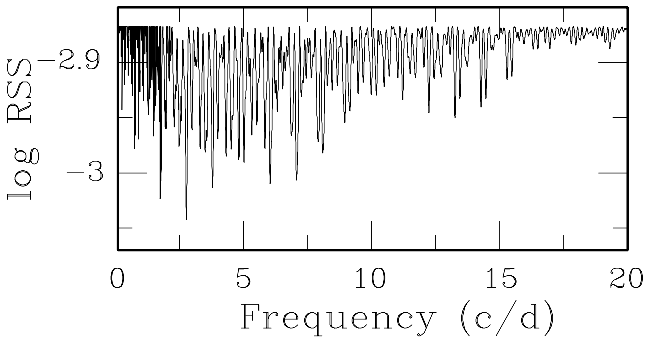

Figure 12. A residual sum-of-squares periodogram (see text) of the observations of 2M 1705−0516.

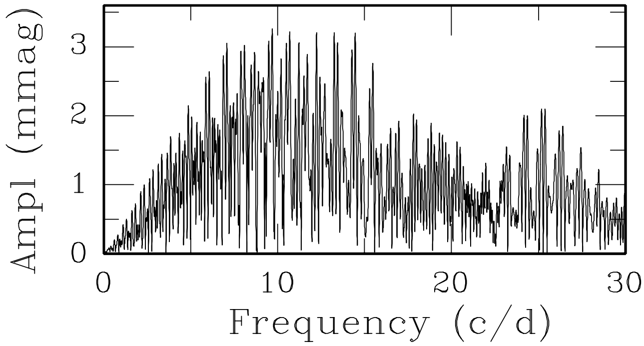

Figure 14. Amplitude spectrum of the residuals left after fitting the model (1) to the I_C band observations of 2M 1705−0516.

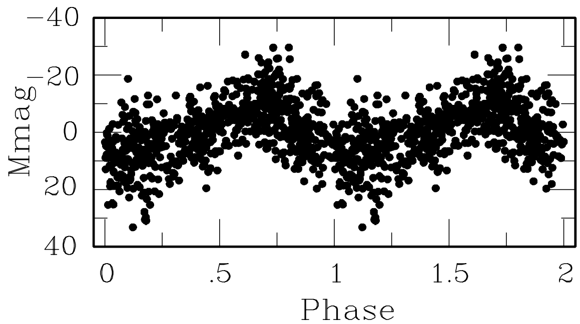

Figure 13. The observations of 2M 1705−0516, folded with respect to the best-fitting period. The data from the different nights were zeropoint-adjusted to obtain the optimal fit.

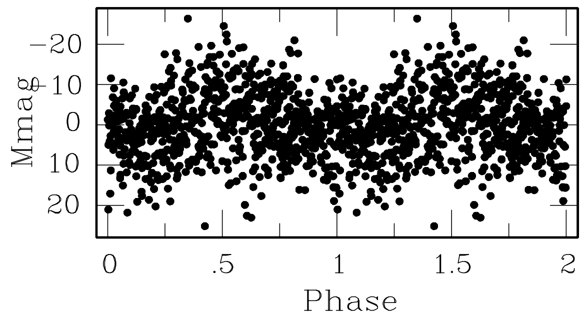

Figure 15. The residuals of the observations of 2M 1705−0516, folded with respect to the best-fitting period identified from the amplitude spectrum in Fig. 14. See the text for further details.

3.5 2M 1555−0956

Gizis (2002) discovered that 2M 1555−0956 is an ultracool dwarf.

Our data can be seen in Fig. 10. Periodogram analyses of the three nights identified 17.1, 9.5 and 14.6 d^{-1} as the best-fitting frequencies, with amplitudes of 3, 4 and 2 mmag respectively. Despite the seductive appearance of the data obtained on JD 2453175 it may therefore be concluded that there is no consistent periodicity in the data. Furthermore, a close look at the JD 2453175 light curve of the brighter of the two comparison stars shows a similar modulation to that seen in the ultracool dwarf, suggesting that it is spurious.

3.6 DENIS 1705−0516

The L4 classification of this object is based on infrared spectroscopy by Kendall et al. (2004).

From the light curves in Fig. 11 it is evident that, similarly to the case of DENIS 0255−4700, there are at least two time-scales of variation in the brightness. The *RSS* spectrum in Fig. 12 has a minimum at 2.7805 d^{-1}; the nightly zeropoints are 16.591, 16.550, 16.566, 16.544, 16.542 and 16.516 mag. Fig. 13 shows the zeropoint-adjusted observations folded with respect to the best-fitting period of 8.632 h.

The periodogram of the residuals can be seen in Fig. 14; the severe aliasing means that the best-fitting frequency of 9.685 d^{-1} (P = 2.478 h) is very uncertain. The peak amplitude is only 3.3 mmag. The folded data are plotted in Fig. 15.

3.7 2M 2104−1037

Aside from the discovery paper (Cruz et al. 2003), the only mention of this object in the literature appears to be by Koen et al. (2004), who tentatively identified a period of 1.6 h (f = 14.8 d^{-1}) in their near-infrared observations. There are noticeable changes on somewhat longer time-scales visible in the optical lightcurves (Fig. 16). Application of the least squares method of Koen (2003, 2004) leads to a best-fitting frequency of 3.9992 d^{-1}, with strong 1 d^{-1} aliases: this, of course, suggests differential extinction as the origin of the variations.

Plots of brightness against air mass for the three nights show a strong linear relation during the first night only. The analysis was therefore repeated excluding those data. The *RSS* periodogram of the remaining data is plotted in Fig. 17; the overall minimum is at a frequency of 4.671 d^{-1}, but the 99 per cent confidence interval includes numerous aliases in the range [3.83, 5.347] d^{-1}. The amplitude of the best-fitting sinusoid is 8 mmag, and the two nightly zeropoints 17.498 and 17.501 (i.e. effectively equal). The light curve folded with respect to the best-fitting period (5.138 h) can be seen in Fig. 18.

3.8 2M 2130−0845

The spectral typing of 2M 2130−0845 is from McLean et al. (2003).

The *RSS* spectrum of the three rather short runs on this object (Fig. 19) is plotted in Fig. 20. The severe aliasing is a consequence of the long interval between the first data set and the other two. The best-fitting frequency is 16.32 d^{-1}, with an amplitude of 5 mmag. The three solutions for the nightly zeropoints are 17.339, 17.345

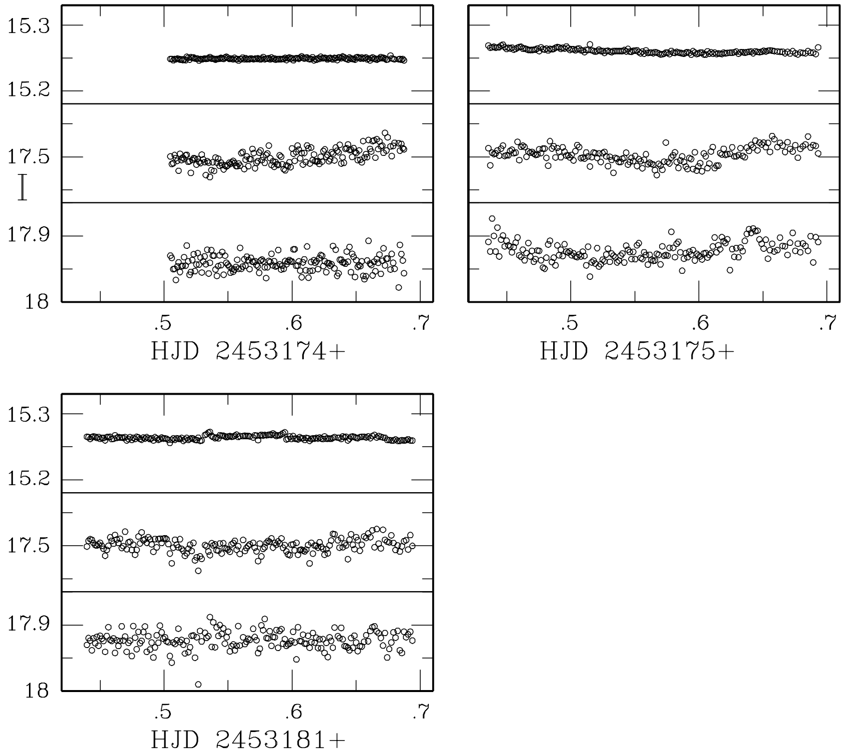

Figure 16. Observations in the I_C band of 2M 2104−1037 (middle panels) and two other stars in the field of view. The vertical scale on each panel is 0.15 mag.

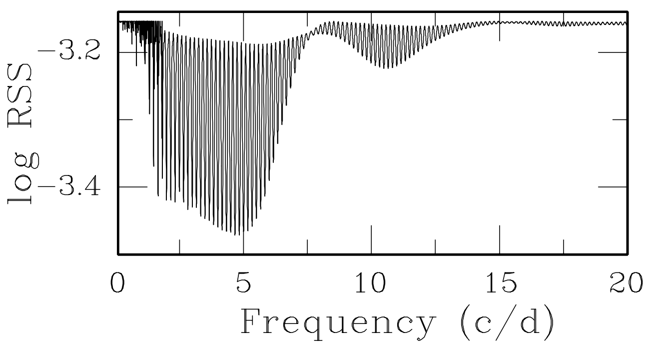

Figure 17. A residual sum-of-squares periodogram (see text) of the observations of 2M 2104−1037.

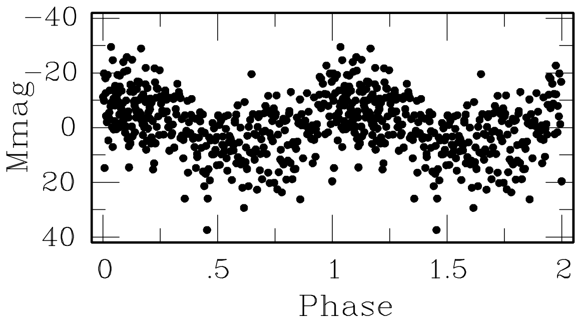

Figure 18. The observations of 2M 2104−1037, folded with respect to the best-fitting period. The data from the different nights were zeropoint-adjusted to obtain the optimal fit.

and 17.381. Fig. 21 shows the zeropoint-adjusted data folded with respect to the best-fitting period (1.5 h).

3.9 ϵ Indi Bab

McCaughrean et al. (2004) showed that this object is a T1/T6 binary.

The light curve in Fig. 22 confirms the I_C band variability of this brown dwarf claimed in Koen (2003). A straight line fits the data very well and gives a rate of brightening of 0.75 mag d^{-1}. The residuals from the linear fit are plotted in Fig. 23; comparison with the other two light curves in the diagram shows that the scatter around the straight line cannot be ascribed purely to atmospheric and instrumental effects. Put differently, the increase in brightness is not completely smooth – it has a random element.

Although not extensive (3.6 h), the present data clearly show that the possible 3.1-h period seen in the near-infrared (Koen et al. 2004) was either spurious or transient. Furthermore, Smith et al. (2003) determined a maximum rotation period of about 3 h for ϵ Indi Ba: unless this figure is substantially in error, the systematic brightening seen in Fig. 22 cannot be ascribed to modulation due to rotation.

3.10 2M 2224−0158

The spectral classification of L4.5 is from Kirkpatrick et al. (2000).

There have been two published attempts to detect variability in this object: Gelino et al. (2002) obtained 15 usable *I* exposures over five nights, and concluded with a high degree of confidence that the object was variable. On the other hand, the *JHK* observations of Koen et al. (2004) did not give any evidence of brightness changes.

Inspection of Fig. 24 does not show any obvious variability aside from the possibility of small changes in the mean light level from

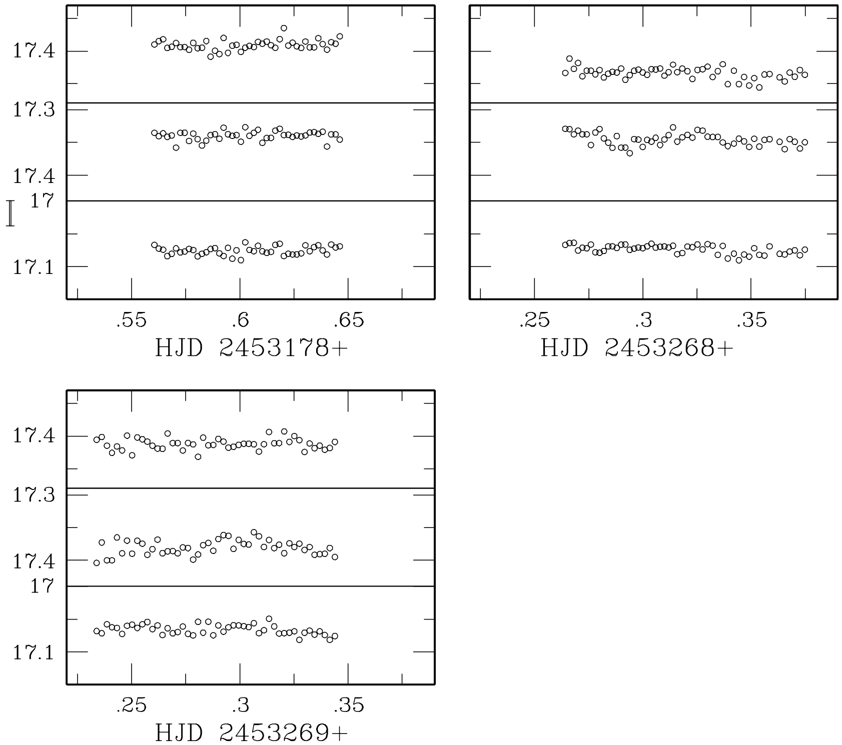

Figure 19. Observations in the I_C band of 2M 2130−0845 (middle panels) and two stars of similar brightness in the field of view. The vertical scale on each panel is 0.15 mag.

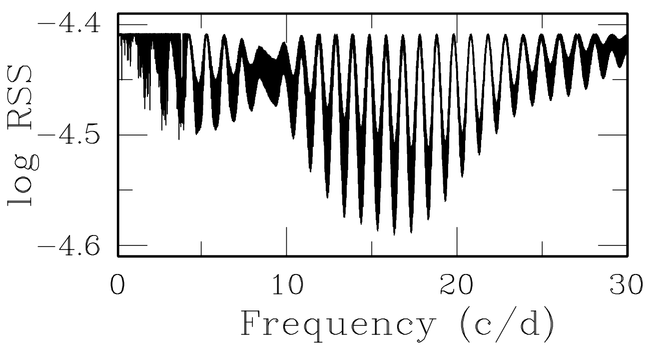

Figure 20. A residual sum-of-squares periodogram (see text) of the observations of 2M 2130−0845.

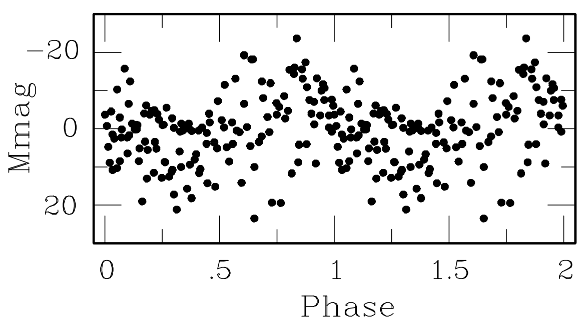

Figure 21. The observations of 2M 2130−0845, folded with respect to the best-fitting period. The data from the different nights were zeropoint-adjusted to obtain the optimal fit.

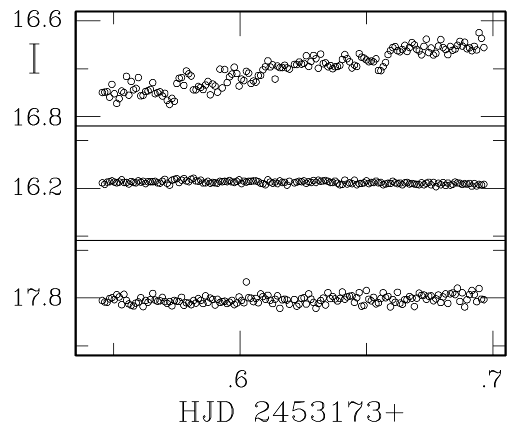

Figure 22. Observations in the I_C band of ϵ Indi Bab (top panel) and two stars of comparable brightnesses in the field of view. The vertical scale on each panel is 0.24 mag.

night to night. Application of the period-finding algorithm described in Koen (2003, 2004) confirms the visual impression given by the light curves, i.e. that there is no periodic brightness change on a time-scale of hours. It is noteworthy that, based on the projected rotational velocity, Bailer-Jones (2004) placed upper limits of less than 6 h on the rotation period.

4 RESULTS: R_C BAND

Koen (2004) identified tentative periods of 2.9 and 3.1 h in his I_C band observations of SSSPM 0829−1309 and 2M 0835−0819, with respective amplitudes of 12 and 10 mmag. Inspection of Figs 25 and 26 shows no sign of such variability in the R_C band. This may be

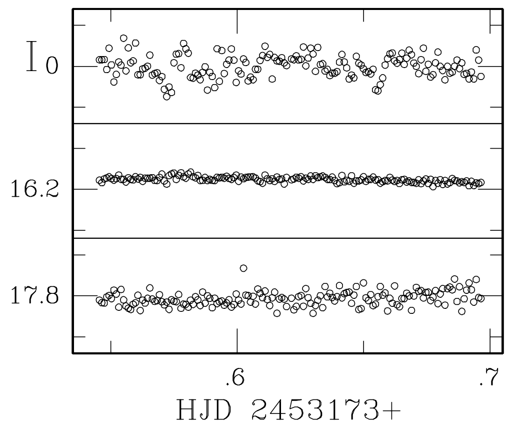

Figure 23. As in Fig. 20, but the top panel shows residuals after linear detrending of the ϵ Indi Bab observations. The vertical scale on each panel is 0.14 mag.

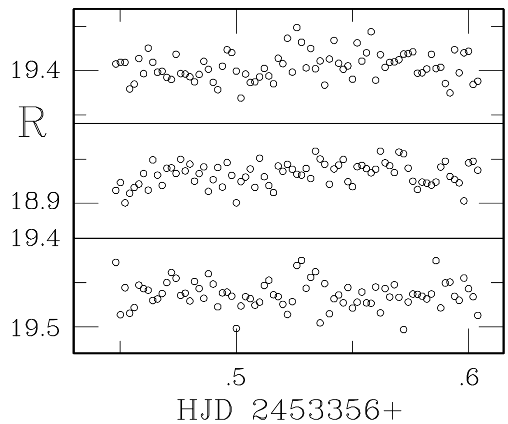

Figure 25. Observations in the R_C band of SSSPM 0829−1309 (bottom panel) and two stars of similar brightness in the field of view. The vertical scale on each panel is 0.13 mag.

due either to rather lower variability levels in R_C, or to the transient nature of any brightness changes.

In the case of DENIS 0255−4700 the most striking feature is the high point at HJD 2453356.39, due to an apparent brightening of the object by about 0.15 mag (Fig. 27). Given that the scatter around the mean value is 24 mmag (excluding the discrepant point), it appears unlikely that the bright point is due to noise. On the other hand, the fact that only one such event was seen certainly raises questions regarding its origin. Given the late spectral type (L8) of the object it will be of considerable interest to establish whether it does indeed flare in the optical.

5 CONCLUSIONS

Three of the results above are worthy of emphasis.

(1) Both DENIS 0255−4700 and DENIS 1705−0516 appear to be variable on more than one time-scale. This has very definite implications for the mechanism(s) responsible for brightness changes. In particular, if it can be conclusively established that objects are multiperiodic, then pulsation (Marconi & Palla 2003; Palla & Baraffe 2005) is indicated as a prime candidate for the brightness changes.

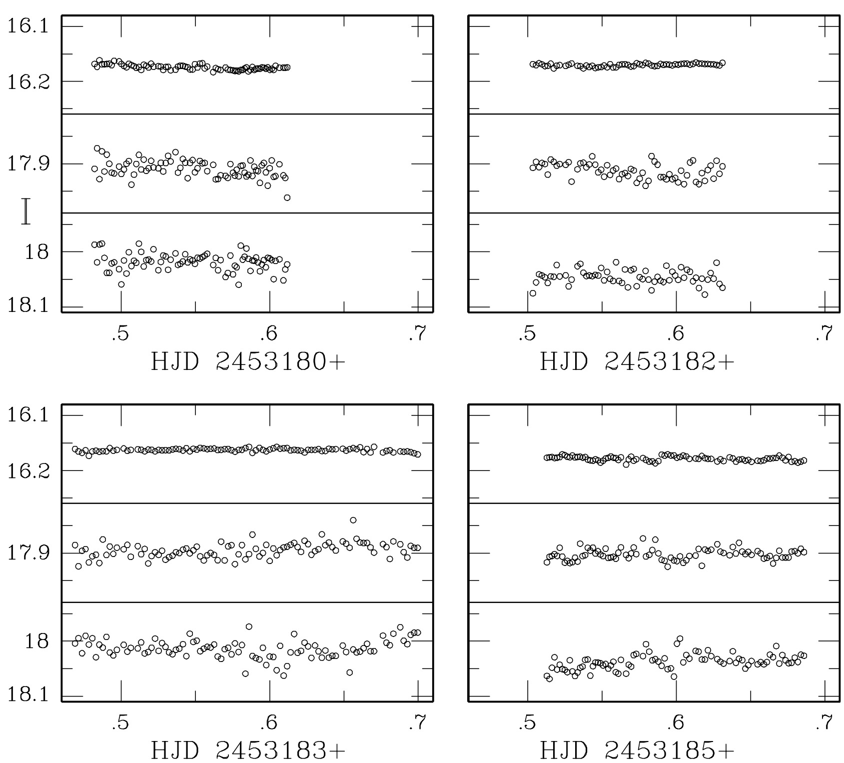

Figure 24. Observations in the I_C band of 2M 2224−0158 (bottom panels) and two stars of comparable brightness in the field of view. The vertical scale on each panel is 0.18 mag.

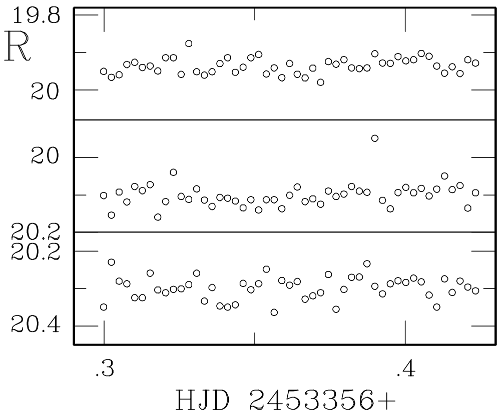

Figure 26. Observations in the R_C band of 2M 0835−0819 (top panel) and two stars of similar brightness in the field of view. The vertical scale on each panel is 0.12 mag.

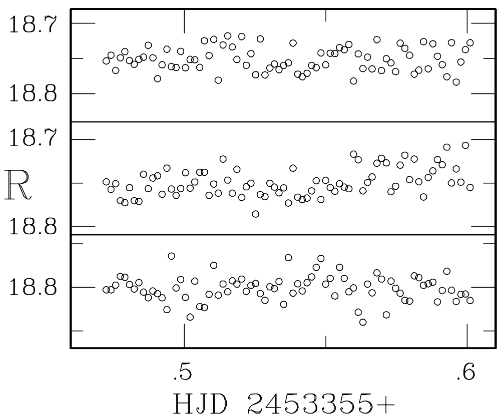

Figure 27. Observations in the R_C band of DENIS 0255−4700 (middle panel) and two stars of similar brightness in the field of view. The vertical scale on each panel is 0.3 mag.

(2) Aside from the possible flare in DENIS 0255−4700, there was no sign of brightness changes in the R_C band in any of the three targets. Given that reasonable evidence for I_C band variability has been found in all three targets, it seems likely that amplitudes are smaller in the R_C band.

(3) The substantial brightening of ϵ Indi Bab over a period of more than 3 h is probably unrelated to rotation. This implies that the origin is most likely *not* dark or bright spots on the surface of either of the two T dwarfs. The rate, and amplitude, of the change suggests either an accretion event, or a magnetic 'flare' as the cause.

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