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Optical variability of the ultracool dwarf TVLM 513-46546: evidence for inhomogeneous dust clouds

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ABSTRACT

We present multicolour photometry of the M8.5V ultracool dwarf ‘pulsar’ TVLM 513-46546 (hereafter TVLM 513) obtained with the triple-beam photometer ULTRACAM. Data were obtained simultaneously in the Sloan-g′ and Sloan-i′ bands. The previously reported sinusoidal variability, with a period of 2 h, is recovered here. However, the Sloan-g′ and Sloan-i′ light curves are anticorrelated, a fact which is incompatible with the currently proposed starspot explanation for the optical variability. The anticorrelated nature and relative amplitudes of the optical light curves are consistent with the effects of persistent dust clouds rotating on the surface of the star. In the absence of other plausible explanations for the optical variability of TVLM 513, it seems likely that dust cloud coverage combined with the rapid rotation of TVLM 513 is responsible for the optical variability in this object. However, crude modelling of a photosphere with partial dust cloud coverage shows that the anticorrelation can only be reproduced using cooler models than the literature temperature of TVLM 513. We suggest this discrepancy can be removed if more dust is present within the photosphere of TVLM 513 than theoretical model atmospheres predict, though a definitive statement on this matter will require the development of self-consistent models of partially dusty atmospheres.

Key words: stars: individual: TVLM 513-46546 – stars: low-mass, brown dwarfs.

1 INTRODUCTION

Brown dwarfs and very low mass stars (collectively known as ultracool dwarfs, or UCDs) are strongly affected by the presence of dust in their photospheres. Dust absorbs elements from the gas phase, changing the opacity and metallicity of the atmosphere. Dust begins to form at temperatures corresponding to the transition between M and L spectral types, and becomes more prominent as the atmosphere cools; the presence of dust thus defines the L-dwarfs. Finally, when the dust clouds ‘rain-out’ at lower temperatures still, they are responsible for the L–T transition. Thus, understanding the formation, chemistry and atmospheric dynamics of dust is the central challenge facing theories of UCD atmospheres (Burrows, Sudarsky & Hubeny 2006).

The presence of dust is also thought to affect the magnetic properties of UCDs. A combination of an increasingly neutral atmosphere and frequent collisions between charged particles and dust grains in the dense atmosphere results in the atmospheres of UCDs having a high electrical resistivity (Mohanty et al. 2002). Thus, whilst strong quiescent and flaring radio emission reveals strong magnetic fields amongst the UCDs (e.g. Berger et al. 2001; Burgasser & Putman 2005; Hallinan et al. 2007), the predominantly neutral atmospheres may explain the relatively low levels of other activity indicators, such as Hα emission and X-rays (e.g. Gizis et al. 2000; West et al. 2004).

TVLM 513 (M8.5V) is an ideal object in which to study the interplay of magnetic fields with a cool, dense atmosphere. It is close by (d = 10.6 pc; Dahn et al. 2002), has known radio and Hα activity, and is rapidly rotating (Mohanty & Basri 2003). The radio emission of TVLM 513 is fascinating; observations from 1.4 to 8.5 GHz show the radio emission can switch states between highly polarized pulses with a 2-h period (Hallinan et al. 2007) to a fainter, quiescent state interrupted by stochastic flares (Berger et al. 2008). The periodic nature of the radio emission has led to this object being dubbed an UCD ‘pulsar’. Strong Hα emission, modulated on the same 2-h period, and a detection of X-ray emission (Berger et al. 2008) show that TVLM 513 is a magnetically active star, which is

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capable of supporting a chromosphere and a corona. This is despite its low effective temperature of ∼2300 K (Dahn et al. 2002), roughly the temperature at which dust is believed to start forming within the photosphere (see Burrows et al. 2006, and references within).

Optical $i$-band photometry of TVLM 513 revealed the same 2-h periodicity as seen in the radio and Hα emission; this was assumed to be due to starspots (Lane et al. 2007). However, optical variability in UCDs can also be caused by dust clouds within the photosphere (see Bailer-Jones 2002, for a review). Simultaneous optical photometry in two or more bands can distinguish between the variability caused by starspots (Rockenfeller, Bailer-Jones & Mundt 2006) and dust clouds (Littlefair et al. 2006). We therefore obtained simultaneous, multicolour photometry using the fast photometer ULTRACAM (Dhillon et al. 2007) to determine the cause of the optical variability in TVLM 513. 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 AND DATA REDUCTION

For a duration of 2.7 h on the night of 2007 June 9, the M8.5V star TVLM 513 was observed simultaneously in the Sloan-$g′$ and Sloan-$i′$ 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 24 msec dead-time between frames. Sloan-$u′$ images were obtained simultaneously with the other colours, but the star is too faint to produce useful light curves in this band. The Sloan-$g′$ and Sloan-$i′$ magnitudes of TVLM 513 are 20.9 and 16.1, respectively. Observing conditions were excellent; the night was photometric and the seeing stable around 0.6 arcsec. Data reduction was carried out using the ULTRACAM pipeline data reduction software. The data were first bias subtracted and flat-fielded. The flat-field used was a median of ∼100 twilight frames taken on a blank piece of sky with the telescope dithering. Because the flat-fields suffer from scattered light, large-scale trends were removed from the flat-field before use, by dividing the flat-field by a median-filtered version of itself. Since the position of the stars on the CCD remains constant throughout our observations, this will not affect our photometry.

Extraction of target and reference star light curves was performed using a variable-sized aperture. The aperture size for both objects was set to 1.7 times the full-width at half maximum of the target stars spatial profile, as measured by a Gaussian fit. Differential photometry was obtained by dividing by the flux of a nearby reference star. This implicitly assumes that the same proportion of the total flux falls outside the aperture for both target and reference stars. This is only true if the target and reference stars have the same point spread function (PSF). If the instrumental PSF of the target and reference stars differ, this introduces errors into the photometry. Worse still, since the actual PSF is the convolution of the instrumental PSF and the seeing profile, it is true that the difference in PSF between the target and reference (and hence error in the photometry) is a systematic function of seeing. To minimize this source of error, one can either use many reference stars, and fit the PSF as a function of chip position and time, or you can use a single reference star as close to the target as possible. Our images do not contain enough reference stars to implement the former approach, and so here we choose to implement the latter. The reference star chosen has $g′$ and $i′$ magnitudes of 17.2 and 16.6, and is 37 arcsec from the target star.

Photometry for multiple reference stars was extracted and we have used this both as a ‘sanity check’ and as a measure of our photometric accuracy (although, for the reasons discussed above, this is likely to be an upper limit). The photometric accuracy we determine is 3 mmag for the $i′$ band and 7 mmag for the $g′$ band. This is smaller than the sinusoidal variability reported in Section 3, giving us confidence that this variability is real. Indeed, the sinusoidal variability is recovered, albeit with more noise, if other reference stars are used to produce the differential photometry.

### 3 RESULTS

The ULTRACAM photometry is shown in Fig. 1. Both the $g′$ and $i′$ light curves exhibit sinusoidal variability with a period of around 2 h. To assess the significance of this variability, 1000 copies of the data were made with the time-ordering of the data points randomized. Lomb–Scargle periodograms of these copies were computed and compared to the periodograms of the original data. None of the randomized data sets showed power in the periodograms as large as the peak power of the actual data, and so the false alarm probability for the periodic variability is less than 0.1 per cent in both bands. Errors in the periods were computed using a bootstrapping technique. We computed 1000 copies of the data using bootstrapping with replacement. Periods for these copies were determined from the peak of a Lomb–Scargle periodogram, and the scatter in these values used as an estimate of our period error. We find periods of 2.0 ± 0.5 h for the $g′$ band and 2.4 ± 0.4 h for the $i′$ band. This confirms the periodic variability seen in the $I$-band light curves of TVLM 513 (Lane et al. 2007), which is also seen in the equivalent width of Hα emission (Berger et al. 2008).

The rms variability in the $g′$ band is about 1.5 per cent. rms variability in the $i′$ band is 0.15 per cent. The $i′$-band variability is thus much smaller than that reported in the $I$ band by Lane et al. (2007), which was nearer 0.8 per cent. The most striking fact about the optical variability is that the $g′$ light curve and $i′$ light curves are in antiphase. A discrete cross-correlation function (Edelson & Krolik 1988) yields a phase shift between the two light curves of 0.50 ± 0.05. It is not easy to reconcile this observation with the claim that the broad-band optical variability of TVLM 513 is due to starspots (Lane et al. 2007); since starspots cause a dimming of the star at all wavelengths, starspot-induced variability would produce $g′$ and $i′$ light curves which are in phase. We therefore turn our attention to other possible causes of the optical variability.

#### 3.1 Starspots and faculae

Whilst starspots alone cannot reproduce the optical variability, it is possible, in principle, to explain it using a combination of starspots and faculae. Because the faculae are hotter than the surrounding photosphere, we can conceive of a situation in which the effect of cool starspots dominates in the $i′$ band, whilst the faculae have a dominant effect in the $g′$ band. In these circumstances, an excess of spots would cause a dimming in the $i′$ band. Due to the corresponding excess of faculae, this would be accompanied by a brightening in the $g′$ band.

In the absence of constraints on spot and faculae properties in UCDs, we cannot rule out this scenario entirely. However, we note the following points, which make this explanation unlikely. First, to ensure that the effect of spots dominates in the $i′$ band, whilst the effects of faculae dominate in the $g′$ band requires considerable fine tuning of the relative areas of spot and faculae coverage. We find that for plausible spot and faculae temperatures of $T_s = 1800$ K and $T_f = 2400$ K, respectively, the ratio of faculae area to spot area must lie between 1.4 and 2.2. This fine tuning of relative areas makes this scenario unlikely a priori. Furthermore, the $g′$ and $i′$ light curves are...
observed to vary in antiphase to a good level of accuracy (see Fig. 1). This requires additional fine tuning of the spatial arrangement of the spots and faculae, as the contrast of faculae is greatest at the limb, whereas spot contrast is roughly independent of limb position (Gondoin 2008). For these reasons, we consider an explanation of the optical variability in terms of spots and faculae unlikely.

3.2 Chromospheric emission

Anticorrelated variability in the Sloan-g' and Sloan-i' bands is possible with a combination of starspots and chromospheric emission. Whilst the Ca H&K lines lie outside the g' and i' bands, several of the higher order Balmer lines fall in the g' band. Thus, a more active region of the star might show lower i'-band flux (due to the dimming caused by starspots), but a higher g'-band flux (due to the contribution to the g' band from Balmer emission lines). However, the spectrum of TVLM 513 appears to rule out this conjecture (Fig. 2). From the Gemini spectra of Berger et al. (2008), we can see that the higher order Balmer lines contribute very little to the g'-band flux, even in the high state. In fact, Balmer emission only contributes an additional 0.3 per cent to the g' flux, so it is unable to account for the 3 per cent peak-to-peak variability seen in the g'-light curve. Since the Hα equivalent widths in the Berger et al. (2008) spectra span the range of observed Hα equivalent widths in the literature for TVLM 513, it is likely that the Balmer emission in these spectra adequately reflects the Balmer emission at the time of our observations, and so we judge it unlikely that chromospheric emission is responsible for the optical variability.

3.3 Magnetospheric emission

The radio emission of TVLM 513 is highly variable in nature. The radio emission seems to change between the bright pulsations with 2-h period reported by Hallinan et al. (2007) to a fainter, quiescent, state interrupted by stochastic flares (Berger et al. 2008). There is some debate as to whether the radio emission results from an electron cyclotron maser (ECM) emission mechanism (Hallinan et al. 2006), or the same gyrosynchrotron emission which powers the radio emission in warmer M-dwarfs (Berger et al. 2008). As a narrow-band emission mechanism, ECM emission will not contribute to the optical flux, and so here make the conservative assumption that the radio emission is caused by gyrosynchrotron radiation.

It is beyond the scope of this Letter to determine whether gyrosynchrotron radiation can provide sufficient flux at optical
wavelengths to cause the variability seen here. However, since
gyro-synchrotron radiation produces a broad continuum, it is not
likely that it is directly responsible for the anticorrelation between
the \( g' \) - and \( i' \)-band variability. It is possible to construct a vi-
ble physical model whereby the \( i' \)-band variability is caused by
starspots, and the \( g' \)-band variability is caused by variations in the
gyro-synchrotron radiation. Such a model can plausibly produce an-
ticorrelated variability between the two bands, if areas of the star
with an excess of starspots are associated with brighter gyrosyn-
chrotron radiation. The sinusoidal nature of the \( g' \)-band light curve
argues against such a model, however, as the emission in the radio is
not observed to vary sinusoidally. We therefore believe it is unlikely
that magnetospheric emission, or a combination of magnetospheric
emission and starspots, is responsible for the optical variability.

3.4 Dust clouds

The presence of dust clouds can, in principle, explain the optical
variability seen in TVLM 513. Consider the formation of a dust
cloud in a largely dust-clear photosphere. The cloud increases the
continuum opacity, whilst at the same time the condensation in dust
clouds of gas-phase alkali-metals reduces the opacity in spectral
regions dominated by alkali absorption. Since the Sloan-\( g' \) band
is dominated by continuum opacity, whilst the Sloan-\( i' \) band is dom-
inated by molecular absorption, the formation of a dust cloud will
reduce \( g' \)-band flux, and simultaneously increase the \( i' \)-band flux.

Following Bailer-Jones (2002), we create a toy model of this pro-
cess by combining the \textsc{cond} and \textsc{dusty}\footnote{Both \textsc{cond} and \textsc{dusty} models include dust for the purposes of calculating the chemistry, but \textsc{cond} models assume the dust settles below the photosphere, whilst \textsc{dusty} models assume the dust remains in the visible part of the atmosphere.} models of Allard et al. (2001) in the ratio 1:9, and comparing the resulting spectrum with a 100 per cent \textsc{cond} model of the same effective temperature. We
would like to stress that this model is only meant as an illustration,
and is far too crude to attempt a detailed analysis such as light
curve modelling, or derivation of cloud coverage. Such an analysis
would require more sophisticated modelling which properly and
self-consistently treated the dust content of cloudy and 'cloud-free'
regions of the photosphere. Examples of the spectral changes result-
ing from our toy model are shown in Fig. 3 for effective temperatures
of 1900 and 2300 K, as compared to the effective temperature for
TVLM 513 of \~2300 K (Dahn et al. 2002).

The models in Fig. 3 show that both the \( g' \) and \( i' \) bands show
spectral changes due to resonance lines and changes in the contin-
uum brightness. Whether the star gets brighter or fainter in a given
band depends on whether line or continuum changes dominate. We
determine this by folding the spectral changes in Fig. 3 through the
\( g' \) and \( i' \) bandpasses. For the 2300 K model, we find the continuum
change dominates in both bands; the warmer model thus predicts
correlated variability in the \( g' \) and \( i' \) bands. By contrast, in the
1900 K model, the resonance lines dominate the \( i' \) band whilst the
continuum dominates the \( g' \) band. The cooler model thus predicts
the observed anticorrelated \( g' \) and \( i' \) variability. Therefore, only
by using significantly cooler synthetic spectra than appropriate for
TVLM 513 can we obtain the observed anticorrelation between \( g' \)
and \( i' \). Fig. 3 shows why this should be the case. Whilst the models
at 2300 and 1900 K produce spectral changes of similar shape, it is
clear that, in the 2300 K model, the change in the alkali metal lines
is much smaller. This is presumably a natural consequence of the

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure3.png}
\caption{Top panel: calculations of the change in spectrum of an ultracool
dwarf, due to the appearance of a dust cloud that covers 10 per cent of the
stellar surface. The calculations use the synthetic spectra of Allard et al.
(2001) – see the text for details. The thick solid line shows a model with
\( T_{\text{eff}} = 1900 \) K, whilst the thick dashed line shows a model with \( T_{\text{eff}} = 2300 \) K.
The thin solid line shows a hybrid model in which dust forms within
a 1900 K starspot on a 2300 K photosphere. Bottom panel: also shown are
the bandpasses of the Sloan-\( g' \) filter and the Sloan-\( i' \) filter.}
\end{figure}

fact that the amount of the dust formed in the warmer model is itself
much smaller than in the cooler one. Therefore, if the models under-
estimate the amount of dust that forms in a 2300 K photosphere,
it would be possible to reproduce the observed anticorrelation vari-
ability in \( g' \) and \( i' \) using models of the appropriate effective tem-
perature. One might suspect this problem can be overcome using a
‘hybrid model’ in which dust clouds form in the cooler regions of
the photosphere created by starspots. Fig. 3 shows that this is not
the case. In the figure we show such a model, with a dusty, 1900 K
starspot covering 10 per cent of the surface of a dust-free 2300 K
photosphere. The starspot introduces such strong variability that it
overwhelms the effects of the dust clouds, and this model produces
correlated variability in the \( g' \) and \( i' \) bands.

4 DISCUSSION

Based upon a lack of plausible alternative explanations for the opti-
cal variability in TVLM 513, we suggest that the most likely cause
of the variability we observe is the rotation of a dust cloud covering
a significant fraction of the stellar photosphere. This explanation is
not without its problems. Crude modelling of a photosphere with
partial dust cloud coverage shows that the observed optical variabil-
ity can only be reproduced using models which are too cool by some
400 K. This may be an indication that the models of Allard et al.
(2001) underestimate the amount of dust that has formed in the
photosphere of TVLM 513. Alternatively, this discrepancy could
be a consequence of our simplistic modelling process; a definitive
statement on this matter awaits the arrival of self-consistent models
of the emission from partially dusty atmospheres.

Based upon the strong magnetic field inferred from radio observa-
tions of TVLM 513, and the strong Hz emission seen in this object,
it is perhaps surprising that the optical variability is not dominated
by starspots, as was previously assumed. Indeed, optical multiband
photometric monitoring by Rockenfeller et al. (2006) shows that
starspots can cause periodic variability in objects as late as M9V.
In this context, it is worth mentioning that the \( i' \)-band variability re-
ported by Lane et al. (2007) is four times larger than the variability
reported here in \( i' \). Such large amplitudes are difficult to explain
using a dust cloud model, and may indeed be due to starspots. Thus, there is some evidence that the nature of the optical variability in TVLM 513 might not be stable, being at times dominated by dust clouds, at other times by starspots. Further multiwavelength observations will be needed to see if the nature of the optical variability is linked to changes in the radio behaviour (Hallinan et al. 2007; Berger et al. 2008) of this remarkable object.

5 CONCLUSIONS

We present simultaneous monitoring of the M8.5V star TVLM 513 in the Sloan-g′ and Sloan-i′ bands. Both bands show sinusoidal variability on the $\sim$2-h rotation period. The g′- and i′- band light curves are in antiphase, a fact which is incompatible with the optical variability being due to starspots. Without a plausible alternative explanation for this behaviour, we conclude that the optical variability in TVLM 513 is caused by the presence of a dust cloud in a predominantly dust-free photosphere. The optical variability is consistent with a dust cloud covering a significant fraction of the photosphere, but only if cooler stellar models than appropriate are used. This could be a consequence of the crudity of our modelling, or it may imply there is more dust in the atmosphere of TVLM 513 than the stellar atmosphere models of Allard et al. (2001) predict. The i′-band variability reported here is a factor of 4 smaller than previously reported by Lane et al. (2007). Since such a high amplitude of variability is difficult to reconcile with dust cloud models, we suggest that the optical variability of TVLM 513-46546 can change in nature. It is unclear if this is related to the observed changes in radio emission from this object.

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