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# A Case for Clouds in L dwarfs

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**Abstract.** The effective temperatures of L dwarfs span the range where molecules can condense to form clouds. Non-uniform cloud features can provide a source of photometric variations in much the same way that non-uniform starspot coverage can cause variations in hotter objects. We present results of a small sample from a variability search of 18 L dwarfs. We find that 2MASS 0036+18 and 2MASS 0135+12 are variable, whereas 2MASS 1412+16 is not. The two variable objects exhibit significant periodicity at 2.2 hours (2MASS 0036+18) and 18.7 hours (2MASS 0135+12). Finally, we present observational and theoretical evidence that supports a non-magnetic origin for the variations.

## 1. Introduction

L Dwarfs are a class of objects whose spectra indicate effective temperatures lower than M stars (Martín et al. 1999, Basri et al. 2000, Kirkpatrick et al. 1999, 2000). Species such as iron and silicates are expected to condense in these atmospheres (Lodders 1999, Burrows & Sharp 1999) and can then settle into optically thick clouds (Ackerman & Marley 2001). Inhomogeneities can form in the cloud decks and provide a source of photometric variations.

Tinney & Tolley (1999) presented the first attempt to detect clouds in an L-dwarf atmosphere. They observed the L5 brown dwarf DENIS 1228-15 through two narrow-band filters chosen to detect changes in TiO absorption. The changes in the TiO band strength were presumed to indicate changes in the opacity, which occurs when TiO is depleted through condensation. They found that DENIS 1228-15 was not variable in these filters. However, they did discover small variations (~0.04 magnitude) in an M9 brown dwarf. These results do not exclude the possibility of clouds in their L dwarf, however, since variations of this amplitude would have been difficult to detect given that the errors for that object were larger than 0.04 magnitude.

Bailer-Jones & Mundt (1999) conducted a variability search in the broad-band *I* filter and found evidence of variability in the L1.5 dwarf 2MASS 1145+23. The object displayed ~0.04 magnitude variations that repeated with a period of 7.1 hours. In an expanded study of 21 L and M dwarfs Bailer-Jones & Mundt (2001) found that over half of their sample exhibited statistically significant variations with amplitudes 0.01 to 0.055 magnitude and time scales of 0.4 to 100 hours. They were unable to find periodic light curves for many of the

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variables. 2MASS 1145+23, however, now exhibited variability with a period of 11.2 hrs. They suggested that evolving surface features, possibly dust clouds or magnetic spots, were responsible for the change. A similar varying period was also observed in an M9.5 dwarf star by Martín et al (2001), who arrived at the same conclusion as Bailer-Jones & Mundt.

## 2. Project

We are conducting a monitoring program of bright L dwarfs ($I \lesssim 18$) that are observable from the northern hemisphere in order to determine which are photometrically variable. We use the Online Brown Dwarf Catalog to define our survey sample from the published L-dwarf lists. New Mexico State University's 1-meter telescope at Apache Point Observatory is used in its robotic mode for the observations. The telescope is equipped with a 512×512 electrically cooled Apogee CCD with a pixel scale of 0.8 arcsec/pixel. All exposures are guided and taken with the Cousins $I$ filter at a duration of 300 seconds.

A more detailed discussion of the data analysis will be given in Gelino et al. (in preparation). We summarize the important aspects here. For each L dwarf we choose several reference stars that are present in all frames. We determine which of these references are variable and construct a flux-weighted mean reference from the non-variable references. A frame is rejected if the average point spread function of the stars in the frame is greater than $3''$ or if the brightness of the mean reference deviates by more than 0.5 mag from the median brightness of all frames for the mean reference (this *only* removes faint frames). Differential magnitudes are computed for the L dwarf using the mean reference. A $\chi^2$ test is then used to determine the probability that the L dwarf is variable. Any object with a probability of being a variable >99% is flagged as a variable. Finally, a CLEAN periodogram routine (Roberts, Lehár, & Dreher 1987) is used to search for periodicity in the data.

## 3. Results

We present the results for three targets here. IR photometry, spectra, and finder charts for all three L dwarfs can be found in Kirkpatrick et al. (2000). Additional information regarding 2MASS 0036+18 is presented in Reid et al. (2000). $I$-band magnitudes for 2MASS 1412+16 and 2MASS 0135+12 are estimated from their instrumental magnitudes, $JHK_s$ magnitudes, and spectral types. Results for the remaining objects will be discussed in Gelino et al. (in preparation).

### 3.1. 2MASS 1412+16

This L0.5 object has an approximate $I$-band brightness of 17.1 mag and has H$\alpha$ present in its spectrum (Kirkpatrick et al. 2000). A total of 28 frames on 9 nights spread over 86 days were used for the analysis (Figure 1). We find that this object does not exhibit statistically significant variations, nor does a reference star at approximately the same brightness.

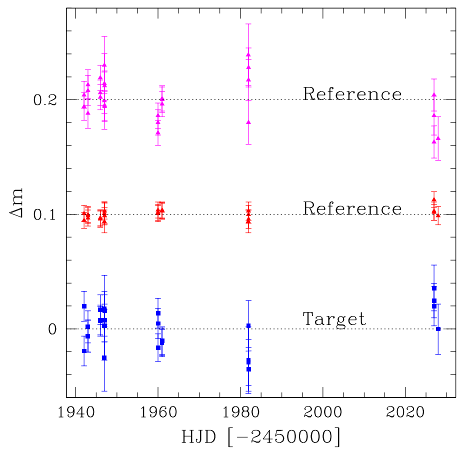


Figure 1. Differential magnitude vs. Heliocentric Julian Date for 2MASS 1412+16 (blue squares), a bright reference (red triangles) and a reference with the same brightness as the L dwarf (magenta triangles). For clarity the bright and faint references have been offset by 0.1 and 0.2 mag, respectively.

### 3.2. 2MASS 0036+18

2MASS 0036+18 is an L3.5 at a brightness of $I$=16.10 (Reid et al. 2000) and does not have H$\alpha$ in its spectrum. The final data set includes 75 frames taken on 15 nights over 54 days (Figure 2a). This object displays statistically significant variations and has a dominant peak in the CLEAN power spectrum at 2.2 hours. No reference has a strong peak in the power spectrum at 2.2 hours, indicating that the periodicity is only a property of the L dwarf, and not any of the references. Additionally, the peak power for the L dwarf is more than 6.5 times higher above the noise than the peak power is for the faint reference.

Assuming a radius equal to that of Jupiter, the extrema $v$ sin $i$ measurements of L dwarfs from Basri et al. (2000), 10 and 60 km s$^{-1}$, translate to periods of 13.2 and 2.2 hours, respectively. The period obtained for this object is consistent with these measurements. Additionally, the phased data (Figure 2b) looks quite convincing.

### 3.3. 2MASS 0135+12

2MASS 0135+12 has a spectral type of L1.5 and an approximate $I$-band brightness of 17.7 mag. Like 2MASS 1412+16, this object also shows H$\alpha$ in its spectrum. After rejection of bad points, 113 frames remain that occurred on 21 nights over 54 days. The light curve (Figure 3a) displays statistically significant variations. The largest peak in the power spectrum occurs at a period of 18.7 hours, which was not strongly present in the power spectra of the references. The peak power for this object is ~2 times higher above the noise than the peak power is for the faint reference. This period is long compared to the mea-

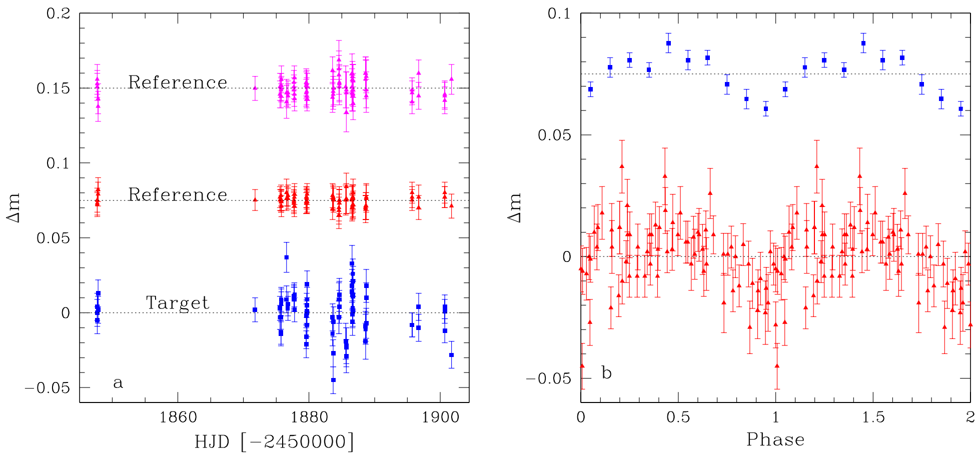


Figure 2. a) Same as Figure 1 except for 2MASS 0036+18 with references offset by 0.075 and 0.15 mag. Neither reference is flagged as a variable. b) Differential magnitude vs. phase for 2MASS 0036+18 plotted over two phases with a period of 2.2 hours. The red triangles are the entire data set seen in Figure 2a; the blue squares are the average differential magnitude in bins 0.1 phase units wide.

surements of Basri et al. (2000), but within $2\sigma$ of their slowest rotator. The phased light curve (Figure 3b) shows peak-to-trough variations of 0.08 mag in the average.

## 4. Discussion

The suspected cause of the variations seen in these and other L dwarfs is most likely either clouds or magnetic spots. Magnetic spots exist in the slightly hotter M dwarfs, so their existence in L dwarfs seems plausible. Also, many L dwarfs show H$\alpha$ in their spectra (Kirkpatrick et al. 2000), indicating some level of magnetic activity. Finding that most or all of the suspected variables have H$\alpha$ in their spectra would be strong support for spot-caused variations. In Figure 4a we plot the results of our 18 L dwarfs, as well as most of the Bailer-Jones & Mundt (2001) results (only their early M dwarfs are excluded). It is quite evident that no clear trend exists between the suspected variables and the H$\alpha$ emitters. This can be explained by the fact that H$\alpha$ emission is produced the chromosphere, a low density, high temperature region with very low optical depth. Therefore, the chromosphere does not effect the emitted spectrum outside of the excited emission lines.

Further evidence against magnetic spots comes from the magnetic Reynolds number, $R_m$. This dimensionless parameter describes how well a gas and a magnetic field interact. If $R_m \ll 1$ the gas and magnetic field do not interact. For $R_m \gg 1$ the gas and field are coupled, providing the scenario needed for the creation of magnetic spots (Parker 1955). In Figure 4b we see that $R_m$ is quite

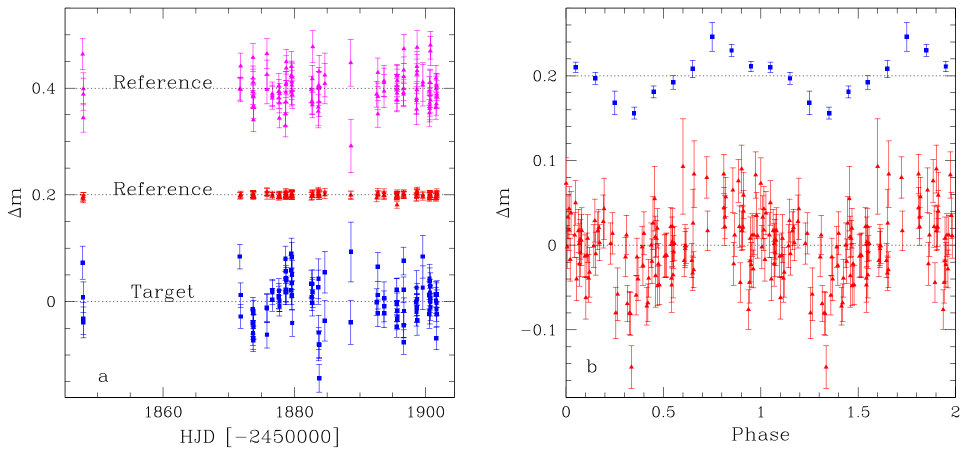


Figure 3. a) Same as Figure 1 except for 2MASS 0135+12 with references offset by 0.2 and 0.4 mag. The bright reference is not flagged as a variable. Although the faint reference is flagged as a variable, its significance is much less than that of the L dwarf (i.e. the faint reference is less variable than 2MASS 0135). b) Same as Figure 2b except for 2MASS 0135+12 and for a period of 18.7 hours.

small throughout most of the atmosphere and starts approaching 1 well below the photosphere. As a result, there should be essentially no interaction between the gas and magnetic field in the visible atmosphere. Any coupling at depth will not be observable above the photosphere. Consequently, the photometric variations observed here and by Bailer-Jones & Mundt (1999, 2001) are not caused by magnetic spots and are more likely caused by non-uniform clouds (see also Mohanty et al. 2001).

Objects that do not show statistically significant variations still have clouds in their atmospheres. The lack of variation simply indicates that there are no large inhomogeneities in the cloud features over the course of the observations. The objects that exhibit variations must have some inhomogeneity in their clouds, be it one or more large spots or evolutionary changes in the clouds throughout the observations.

## 5. Conclusions

We have presented a first look at the results of our L-dwarf monitoring program. Both of the variable objects mentioned here show strong periodicity at periods consistent with those estimated from rotational velocity measurements of other L dwarfs. The lack of a correlation between H$\alpha$ and suspected variables and the low magnetic Reynolds number in L-dwarf atmospheres points to a non-magnetic origin for the variations.

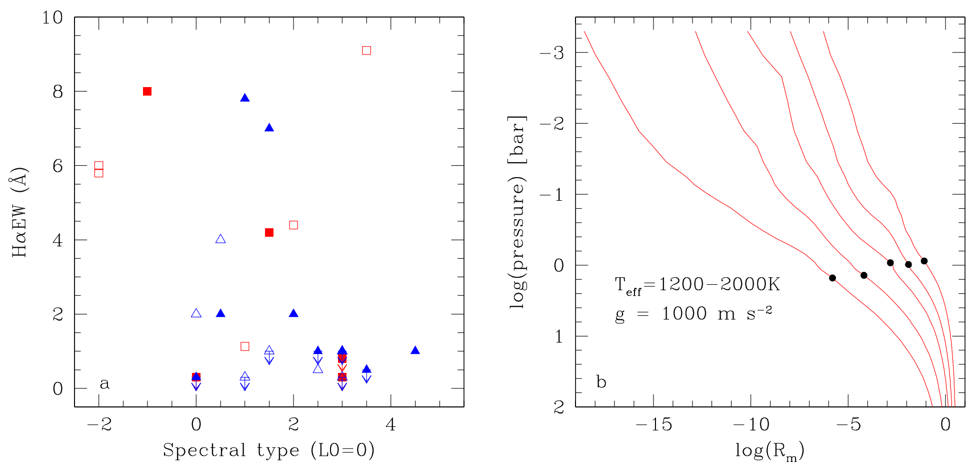


Figure 4. a) H$\alpha$ equivalent width as a function of spectral type for suspected variables (solid symbols) and non-variables (open symbols) from this project (blue triangles) and Bailer-Jones & Mundt (2001) (red squares). H$\alpha$ upper limits are shown with arrows. No trends are seen between variability and magnetic activity, suggesting that magnetic spots are not a likely source for the variations. b) Pressure vs. magnetic Reynolds number ($R_m$) for $T_{\rm eff}$=1200, 1400, 1600, 1800, and 2000 K (left to right) model atmospheres. Also plotted is the approximate pressure at which the photosphere occurs in these objects. At pressures above and around the photosphere $R_m \ll 1$, indicating that there is little or no interaction between the magnetic field and the gas and that magnetic spots cannot form.

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