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Letter to the Editor

# Optical linear polarimetry of ultra cool dwarfs*

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**Abstract.** We present optical linear polarimetry of 8 ultra cool field dwarfs, with spectral types ranging from M9 to L8. The linear polarisation, $P$, of each dwarf we measured is $P < 0.2\%$. Three dwarfs have polarisations compatible with zero, two are marginal detections, and three have significant polarisation. Due to their small distance, an insterstellar origin for the detected polarisation can be safely ruled out. Our detections confirm that dust is present in the atmosphere of these brown dwarfs and that the scattering geometry is not symmetric. Possibilities for asymmetry include the dwarfs rotating rapidly and being oblate, or the cloud coverage in the atmosphere being inhomogenous.

**Key words.** stars: low-mass, brown dwarfs – polarization – dust – scattering – stars: atmospheres

## 1. Introduction

Recent sky surveys have uncovered large populations of objects cooler than M dwarfs (e.g., Delfosse et al. 1997; Kirkpatrick et al. 1999). Among them, the L dwarfs were the first to be identified (Martín et al. 1997). They cover a range of effective temperature between ~2200 K and ~1400 K and are characterized by the presence of condensates (i.e., grains) in their atmospheres. Of particular interest, (spectro-)photometric monitoring revealed variability (e.g., Gelino et al. 2002; Bailer-Jones 2002) that was attributed to the presence of rapidly evolving clouds of particles covering the photospheres not uniformly. Depending on the geometry, light scattering by these clouds may yield net disk-integrated polarisation.

However, there are various ways by which the light of a star can be polarised. The presence of a magnetic field can induce polarisation by Zeeman effect. Light scattering by inhomogeneous clouds or rapid rotation leading to an elliptical photospheric disk can also, in principle, yield net disk-integrated polarisation. In this paper we explore, from an observational point of view, the linear polarisation properties of field brown dwarfs.

We present the linear polarisation measurements of eight ultra cool dwarfs (i.e., 1 very late M and 7 L dwarfs) obtained in the red, at 768 nm, in a first step to constrain the dust distribution across the photospheres of cool objects. The observations and results are presented in Sect. 2. In Sect. 3, we present arguments regarding the origin of the detected polarisation. In Sect. 4 we discuss realistic photospheric scattering geometries and propose observational tests. The behaviour of the polarisation as a function of $T_{\rm eff}$ is presented in Sect. 5.

## 2. Observations and results

All the polarimetric data were obtained with the imaging polarimetry mode of FORS1 attached to Melipal, UT3 of ESO's VLT facility located atop Cerro Paranal, Chile. FORS1 is mounted at the cassegrain focus and provides a classical set-up for accurate dual beam imaging polarimetry[1].

The observations were carried out during the periods 9–11 December 2001 and 16–19 May 2002. The Moon was set at the time of each observation. All data were collected with a broadband $I_{\rm Bessel}$ filter centered on 768 nm and 138 nm wide (*FWHM*). The efficiency and stability of the instrument was checked and confirmed on 6 occasions by measuring the highly polarised star Vela 1–95. All our measurements fell well within 1-$\sigma$ (i.e., <0.08%) of the catalog value and no night-to-night efficiency corrections were applied. We also checked for instrumental polarisation by measuring 3 nearby non-magnetic white dwarfs. With a typical 1-$\sigma$ error bar of $\sigma_{\rm P} = 0.02\%$ all three measurements are compatible with zero polarisation. In the following we will assume the imaging set-up to be free of instrumental polarisation.

The data were detrended in a standard way with NOAO/IRAF. We applied bias subtraction, cosmetic correction for deviant pixels, and division by twilight flatfields. The flatfield frames

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* Based on data collected at ESO/VLT with the FORS1 instrument during observing programs 68-C.0171 and 69-C.0679.

[1] Details of the imaging polarimetry mode of FORS1 can be found at http://www.eso.org/instruments/fors1

**Table 1.** (Spectro-)Photometric data for the targets.

| name | $I$ | $I-J$ | $J-K$ | sp.ty. | $\pi$ mas | $v \sin i$ | $EW(H\alpha)$ | phot. var. mag |
|---|---|---|---|---|---|---|---|---|
| LHS 102B | 17.0(3) | 3.70(3) | 1.90(3) | L5(3) | 104.7(7) | 32.5 ± 2.5(11) | <4.0(4) | |
| 2MASSW J001544.7+351603 | 17.3(8) | 3.50(8) | 1.58(2) | L2(2) | 54.2(10) | | 2(2) | 0.02?(13) |
| 2MASSW J003615.9+182110 | 16.11(6) | 3.67(6) | 1.41(2) | L3.5(5) | 114.2(6) | 15(12) | <0.5(2) | <0.01(13) |
| DENIS-P J0255.0-4700 | 17.14(4) | 3.66(4) | 1.62(4) | L8(4,2) | 159.2(10) | 40 ± 10(11) | <2(4) | |
| DENIS-P J200048.4-752306 | 15.88(1) | 3.23(1) | 1.19(1) | M9(8) | 58.5(9) | | | |
| DENIS-P J203608.6-130638 | 18.24(1) | 3.54(1) | 1.17(1) | L1-L2(8) | 31.3(9) | | | |
| DENIS-P J205754.1-025229 | 16.61(1) | 3.42(1) | 1.56(1) | L0-L1(8) | 55.7(9) | | | |
| 2MASSW J222443.8-015852 | 18.02(6) | 3.97(6) | 2.03(2) | L4.5(2) | 88.1(6) | | 1(2) | 0.08(13) |

Note: (1) From DENIS survey, Delfosse et al. (1997), in preparation; (2) Kirkpatrick et al. (2000); (3) Goldman et al. (1999); (4) Martín et al. (1999); (5) Reid et al. (2000); (6) Dahn et al. (2002); (7) Proper motion of LHS 102A, from van Altena et al. (1995); (8) Following the $(I-J)$ vs. spectral type relations of Dahn et al. (2002); (9) Following the $(I-J)$ vs. $M_I$ relation of Dahn et al. (2002); (10) Following the $M_J$ vs. spectral type relation of Dahn et al. (2002); (11) Basri et al. (2000); (12) Schweitzer et al. (2001); (13) Gelino et al. (2002).

**Table 2.** I-band linear polarisation data.

| name | obs. date d/m/y | MJD | $P$ (%) | $\sigma_P$ (%) | $\theta$ deg |
|---|---|---|---|---|---|
| LHS 102B | 10/12/01 | 52253.050 | 0.105 | 0.036 | 70.1 |
| 2M J0015 | 9/12/01 | 52252.047 | 0.065 | 0.032 | – |
| 2M J0036 | 9/12/01 | 52252.089 | 0.199 | 0.028 | 17.6 |
| D J0255 | 11/12/01 | 52254.048 | 0.167 | 0.040 | 80.6 |
| D J2000 | 17/05/02 | 52411.394 | 0.083 | 0.017 | 122.9 |
| D J2036 | 19/05/02 | 52413.391 | 0.122 | 0.042 | 170.4 |
| D J2057 | 18/05/02 | 52412.398 | 0.044 | 0.023 | – |
| 2M J2224 | 8/05/01 | 52251.046 | 0.095 | 0.046 | – |

were obtained without the polarising optics. Due to a slight but systematic variation of the bias level from night to night, i.e., an increase by 1–2 ADU every day, we obtained and used new sets of calibrations frames every night for safety.

Except for LHS 102B (Goldman et al. 1999), we selected our targets from the 2MASS and DENIS near-infrared sky surveys. They are listed in Table 1 together with photometric and spectroscopic information. Columns 2–4 list the $I$-band magnitudes and $I-J$ and $J-K$ colors respectively. Column 5 lists the spectral types. A range is given when the spectral type is estimated from near-infrared colors (except for the M9 DENIS-P J200048.4-752306), all others are confirmed by spectroscopy. When there is ambiguity, the spectral types are given in the Kirkpatrick et al. (1999) system. The last four columns list the annual parallax, $\pi$, the projected rotational velocities, $v \sin i$, the H$\alpha$ equivalent widths and the photometric variability, when available. References are listed in parenthesis next to the data and refer to the notes at the bottom of the table.

Our results are presented in Table 2. In order, the columns list the abreviated target name, the date of observation, the modified Julian date of the middle of the observation, and the polarisation data, $P$, its associated error $\sigma_P$, and the position angle of the plane of vibration of the $E$-vector in the equatorial coordinate system, when $P/\sigma_P \sim 3.0$ or more. The modified Julian date (MJD) is related to the julian date (JD) by MJD = JD − 2 400 000.5.

## 3. The origin of the polarisation

### 3.1. An interstellar origin?

The annual parallaxes listed in Table 1 place all the objects between 6 pc and 32 pc from the Sun. Leroy (1993, 1999) measured a sample of 1000 stars within ∼150 pc from the Sun. Out to a distance of 50 pc no significant interstellar polarisation is found and only 18 stars have $P \geq 0.1\%$ in the distance range between 60 pc and 90 pc of the Sun, from Hipparcos distances. Furthermore, they are found in small and well defined regions of the sky, away from our targets. An interstellar origin for the linear polarisation presented here is therefore extremely unlikely and we rule it out. *A consequence of this result is that the frequency of intrinsically polarised brown dwarfs in our sample (i.e., from M9 to L8 dwarfs) appears extremely high, ∼50%* (i.e., 3/8 (37%), or 5/8 (62%) if we include the marginal detections, see Sect. 4)[2]. For comparison, in nearby FGKM stars (dwarfs and giants), the fractions are 2.5%, 7%, 5.5%, and 11% respectively in the distance range 60–90 pc from the Sun (Leroy 1999). Those fractions go to zero for smaller distances.

### 3.2. Possible mechanisms for intrinsic polarisation

A possibility to produce intrinsic linear polarisation is via the presence of magnetic field, either from Zeeman splitting of atomic or molecular lines or synchrotron emission. The evidence for magnetic field in L dwarfs is not clear yet. Observations show that the $H_\alpha$ activity rapidly declines from mid-M to L dwarfs (Gizis et al. 2000). This may result from the high electrical resistivities of their cool, hence mostly neutral, atmospheres (Mohanty et al. 2002). On the other hand, Berger (2002) detected high persistent levels of radio emission in 3 late M and L dwarfs, including 2MASSW J003615.9+182110, the most highly polarised source in our sample. Magnetic fields in the range 10–1000 G are deduced assuming that the radio emission is

[2] We choose to quote 50% by taking the average of the two, hence 4/8.

coronal and that it peaks sharply at 8.5 GHz. Therefore, the (gyro-)synchrotron processes invoked will not lead to significant polarisation in the optical, especially linear polarisation.

Zeeman splitting of atomic lines is also unlikely the source of the linear polarisation. For comparison, a sample of Ap stars with a ~1 kG dipolar field at the surface show a maximum net linear polarisation of order of a few times 0.01% only (Leroy 1995). This polarisation, produced by Zeeman splitting in saturated atomic lines, is maximum where a large number of atomic lines are present in the spectrum, i.e., in the blue for these stars. For ultra cool dwarfs, atomic absorption does not dominate in the red where we made our measurements. Wider molecular bands do, but these are complex, made of numerous molecular lines side by side (e.g. Valenti et al. 1998) and their global Zeeman polarisation, especially linear, is almost always much lower than that of atomic lines.

Pending definitive measurements of the magnetic fields, we will assume that they are not powerful enough at the surface of late-M and L type brown dwarfs to induce a detectable linear polarisation in the $I$-band. Scattering by photospheric dust grains therefore remains the most likely mechanism for the polarisation.

## 4. The scattering geometry: Oblate photospheres or inhomogeneous dust clouds?

### 4.1. The polarised sources

In a recent paper, Sengupta & Krishan (2001, hereafter SK01) argued that the photosphere of a brown dwarf will in general be oblate due to fast rotation. The fast rotation is suggested by the large $v \sin i$ values measured in late-M and L dwarfs (Basri et al. 2000). This oblateness will result in an asymmetric scattering geometry where cancellation of the contribution of each point on the photosphere is not perfect (as it would on a sphere) and a net disk-integrated linear polarisation results. They calculated the linear polarisation expected from single and multiple scattering by uniformly distributed dust in an oblate photosphere seen edge-on (see their Figs. 1 and 2 respectively).

In our sample, 3 targets have a significant polarisation: 2MASSW J003615.9+182110, DENIS-P J0255.0-4700, and DENIS-P J200048.4-752306. The maximum polarisation we detect is ~0.2% at 768 nm.

From these data, the single scattering case of SK01 for highly eccentric ($e > 0.3$) photospheres and most grain sizes except the very smallest ($\alpha \ll 1.0$) can be excluded, because they would produce too much polarisation, unless all targets in our sample are seen pole-on and their projected photospheric disk is circular. This is unlikely, and not compatible with the $v \sin i$ values presented in Table 1 for 2MASSW J003615.9 and DENIS-P J0255.

Multiple scattering usually lowers the polarisation because the planes of the scattering events are randomly oriented and average each other's contribution out from the final polarisation. At 768 nm, the predictions made by SK01 reflect that fact but the curves for small (0.1 $\mu$m) and large (1.0 $\mu$m) grains are too close to the polarisations we measured to choose between the two cases. Measurements at longer wavelengths are needed to decide.

On the other hand, the models of SK01 do not consider the possibility that the dust is distributed non uniformly in the photosphere. This configuration may also be relevant to produce net linear polarisation and in principle does not require projected photospheric oblateness. Schubert & Zhang (2000) argue that the dust in L dwarfs should be organized in one of two states: in bands as in the giant planets of our Solar System or in chaotic clouds.

Although numerical simulations are needed to assess the polarising power of these configurations, predictions can be made on geometrical arguments. An oblate and uniformly dusty photosphere will always produce stable polarisation, with both the position angle and the polarisation level fixed, as the scattering geometry is constant. Dust bands in the atmospheres will also produce a stable polarisation. On the other hand, a photosphere covered with randomly distributed clouds is likely to see its polarisation change because the scattering geometry will change with time as the object rotates and the clouds form, move and disappear. Therefore, the detection of variable linear polarisation, especially variations of the polarisation position angle, would clearly point toward cloud covered photospheres rather than homogeneous or banded dust distributions in ultra cool dwarfs.

### 4.2. The unpolarised sources

In our sample, there are also three objects whose polarisation is not detected, and two more which are just marginally detected, i.e., with $P/\sigma_P$ at 2.9, just below 3. Many possibilities exist to explain their non detection. Obviously they could be devoid of dust, but this is unlikely in view of the models and observations. For example, 2MASSW J222443.8-015852 is the only target in our list with a confirmed photometric variability, presumably caused by inhomogeneous dust clouds, but its polarisation is not detected.

Also, the objects that do not have $v \sin i$ measurements could be slow rotators, or could be seen close to pole-on, hence showing a low ellipticity to the observer and/or symmetric dust band structure. Although statistically improbable, this possibility cannot be ruled out yet.

To yield a low net polarisation in the optical, the scattering grains may also be much larger than 1 $\mu$m, which would agree with recent theoretical predictions for dust size in L dwarf atmospheres. Also, it is possible that the photospheres are covered by a very large number of small randomly distributed dust clouds. Such a configuration should not produce a large detectable polarisation. A few large clouds probably being more favorable.

## 5. Linear polarisation vs. spectral type

Models predict that the amount and vertical location of dust is a function of $T_{\rm eff}$ (e.g., Allard et al. 2001). In order to match the rapid blueing of mid-L dwarfs, Ackerman & Marley (2001) suggest that the horizontal distribution of the dust is also a function of $T_{\rm eff}$.

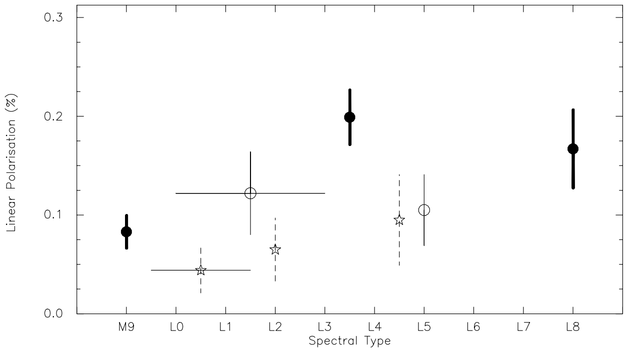


**Fig. 1.** Plot of the measured linear polarisation as a function of spectral type. The thick circles are detections. The marginal detections (i.e., $P/\sigma(P) = 2.9$) are the open circles. The open stars with dashed error bars are the non-detections (i.e., $P/\sigma(P) < 2.1$). Stars with uncertain spectral types have error bars plotted along the spectral type direction. 1-$\sigma$ polarisation error bars are plotted.

Figure 1 is a plot of the measured linear polarisation as a function of spectral type. Different symbols are used for detections and non-detections (see the figure caption for details). A slight trend for larger polarisation in cooler objects may be present, but more data are clearly needed before we dare claim of anything real. It would be interesting to extend the sample to include cooler objects as their dust is expected to settle below the photosphere and no polarisation from scattering should result.

## 6. Conclusions

We have measured the linear polarisation of one very late-M and seven L dwarfs at a wavelength of 768 nm. We have 3 detections, 2 marginal cases, and 3 unpolarised targets. In all cases the polarisations remain low, below $P = 0.2\%$. The linear polarisation is intrinsic to the objects and not of interstellar origin. The fraction of polarised nearby brown dwarfs in our sample is high, ~50%. It appears much higher than for nearby FGKM stars.

Our small sample does not allow to identify the mechanism responsible for the linear polarisation. However, fast spinning dwarfs with oblate photospheres and uniform, or banded, dust clouds are expected to produce a polarisation constant in time. On the other hand, large randomly distributed dust clouds may produce more erratic polarisations. Searching for polarimetric variability is needed to solve this issue.

For now, we find no definite correlation of polarisation with spectral type although we note a potential trend upward for cooler objects, up to spectral type mid-L. More data are clearly needed, as well as the extension of the sample to cooler T dwarfs. These objects are not expected to have significant amounts of dust in their photospheres and should therefore not show detectable linear polarisation.

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