Studying brown dwarf dust cloud distribution through polarisation

Ezequiel González[1], Bertrand Goldman[1,2], María Rosa Zapatero Osorio[3], Víctor Javier Sánchez Bejar[4], Thomas Henning[5], Jan Pitann[6]

[1] International Space University (ISU), 1 rue Jean-Dominique Cassini, 67400 Illkirch-Graffenstaden, France
[2] Astronomical Observatory of Strasbourg, 11 rue de l'Université, 67000 Strasbourg, France
[3] Centro de Astrobiología (CSIC-INTA), Crta. Ajalvir km 4, 28850 Torrejón de Ardoz, Madrid, Spain
[4] Instituto de Astrofísica de Canarias (IAC), Calle Vía Láctea s/n, 38200 La Laguna, Tenerife, Spain
[5] Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany
[6] Space Operations and Astronaut Training (DLR), 82234 Wessling, Germany

Introduction

Brown dwarfs (BDs) are compact objects with masses between those of stars and planets. They are not massive enough to sustainably burn hydrogen, and eventually cool down due to the lack of an energy source. Cool BDs host low-temperature atmospheres, favouring molecules over single atoms, and dust grains. Those dust grains may form clouds in their atmosphere, leading to polarised light through scattering and flux variations if the cloud deck is heterogeneous.

Variations in the cloud cover of BDs have been measured through photometry monitoring and polarisation observations. This project aims at detecting time dependence of the polarisation for 2MASS J00361617+1821104 (L3.5), LHS 102BC (L4.5), and 2MASS J15074769-1627386 (L5), which could be then explained by rotation and large-scale cloud coverage variations. Our sample, located close enough (within 12 pc) that there is no polarisation from interstellar dust, was previously observed in polarisation and showed convincing signs of polarisation variability.

Our goal is to extract new polarimetric information from our images and answer to these questions: (1) Do we see any variations of the signal with time and can we relate this to the rotation of the BD?, (2) Can we set constraints on the typical size of cloud holes?, and (3) How do the measurements compare with atmospheric models of BDs that predict polarimetric signals?

Observations

Our data consists of unique observations obtained during October 2010 and March 2011, using the FOcal Reducer and low dispersion Spectrograph (FORS2) [1][2], which is mounted on the Cassegrain focus of the 8.2-m ANTU telescope at the ESO VLT in Chile.

When used in the IPOL mode (Imaging POLarimetry), FORS2 works as dual-beam polarimeter (Fig. 1). This means that the incident light beam (I) is split by a Wollaston prism (WP) into two perpendicular beams: the ordinary (fo,i) and extraordinary beams (fe,i). In this setup, a rotating half-wave retarder plate (HWP) placed before the WP, allows to measure the intensity of both beams at different angles (θi). For linear polarization, a fixed set of 16 angles can be used, at most. FORS2 has a FoV of 6.8' x 6.8' imaged into two identical CCD detectors, with a pixel size of 0.25 arcsec with the standard binning of 2x2. The targets were all placed at the same location within one pixel, at the bottom of Chip1, which has excellent cosmetics [3].

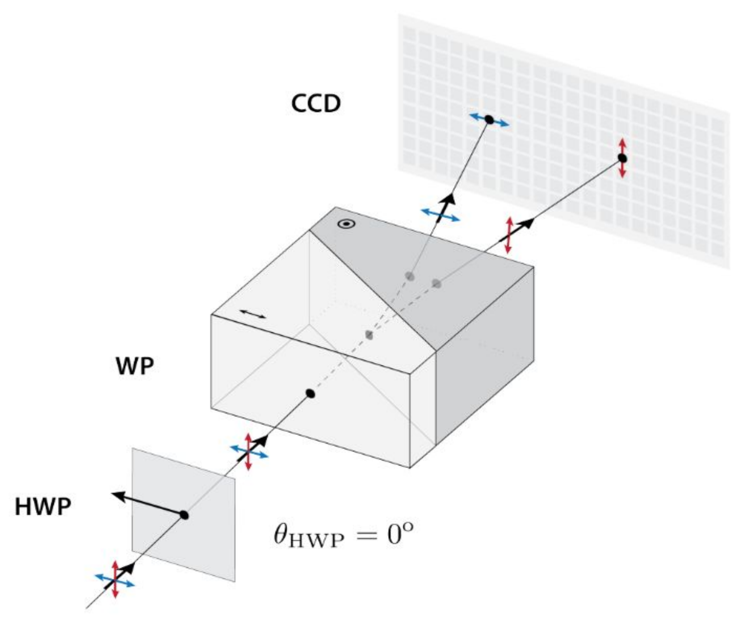

Figure 1 - FORS2 IPOL mode representation [3]

For each target, we obtained 16 observations with a different retarder orientation (moved by 22.5 degrees), in the I band. The 16-angle set allows to obtain the highest accuracy and to minimise and understand the noise sources [4]. The total duration per target/night along with the number of 16-angle observation sets and SNR per each of them, are provided in Table 1.

Table 1. Observing Log

Target	Date	Duration (h)	Nr. Obs sets (1)	SNR (2)
2MASS J0036	25/10/2010	5.13	7	414
	27/10/2010	2.24	5	479
	29/10/2010	1.13	2	587
LHS 102BC	25/10/2010	1.31	3	378
	27/10/2010	0.89	2	414
	29/10/2010	3.56	6	393
2MASS J1507	31/03/2011	2.59	7	499

(1) Each observation set consists of 16 measurements with different angles (moved by 22.5°). All were acquired with the I-Bessel filter.
(2) Average of the signal-to-noise ratio (SNR) of the ordinary and extraordinary beams.

Data Reduction

The data reduction consists of the sequence of three types of tasks: (i) data calibration, (ii) photometry measurement, (iii) polarimetry analysis. We applied the standard calibration process using the associated flat and bias frames, for each night.

The photometry phase consists of measuring the flux for both the ordinary and extraordinary beams using aperture photometry. For each target and each beam, we determine the centroid by fitting a 2D quadratic polynomial to the data, define the circular aperture through visual comparison of the target profiles using different radii, and subtract the local sky background by computing the mean flux of the corresponding circular annulus. Our analysis shows that the polarization results are not significantly dependent on the chosen aperture radius. Depending on the observation conditions we selected 4 to 6 pixels (1" to 1".5).

Lastly, we conducted the polarimetry analysis by executing the following steps and employing the formulae presented in [4]: (i) compute the normalised flux ratio, (ii) derive the Stokes parameters Q and U, (iii) compute the degree of polarisation (P). These three steps are performed for each set of 16-angle observations. Uncertainties are computed at every single step within the process and are propagated accordingly. Moreover we performed the fourier analysis suggested in [4] to assess our error results, which are often estimated with the signal included in the harmonics with k= 3, 5-8. The estimated uncertainties were consistent with the systematics obtained through the harmonics power spectrum (example in Fig. 2).

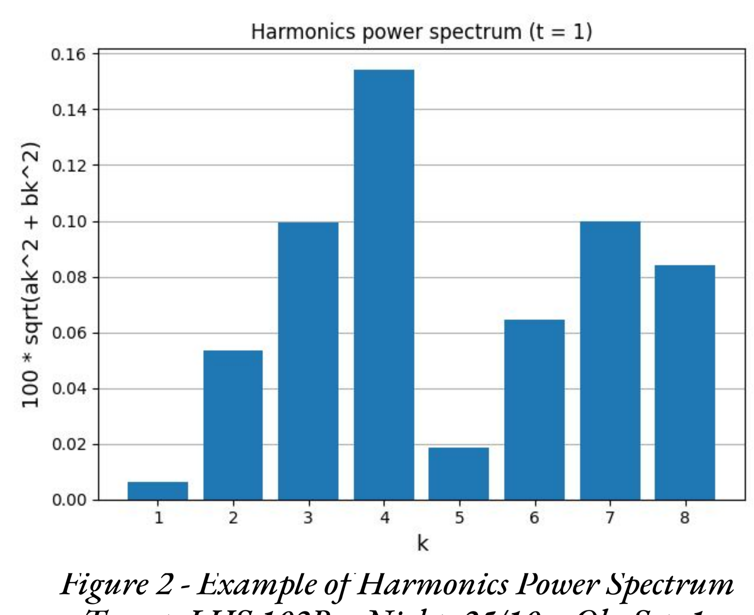

Figure 2 - Example of Harmonics Power Spectrum
Target: LHS 102B – Night: 25/10 – Obs Set: 1

The whole data reduction steps were implemented through an original pipeline developed in Python specifically for this research project, based on the *astropy*, *photutils*, and *ccdproc* packages.

Results

We report our measurements in Figs. 3-5. 2MASS J0036 shows a variation on the polarisation over the three nights (Fig. 3), reaching a significant degree of polarisation (DOP) of (0.26 ± 0.08)% at the end of the first night. In the case of LHS 102BC (Fig. 4), our results also show variations on the polarisation measurements but in this case the highest DOP were obtained in the first two nights (0.18 ± 0.07; 0.15 ± 0.07)%. As to 2MASS J1507, the variation in the polarisation shows a peak by the end of the night, measuring a DOP of (0.26 ± 0.05)%.

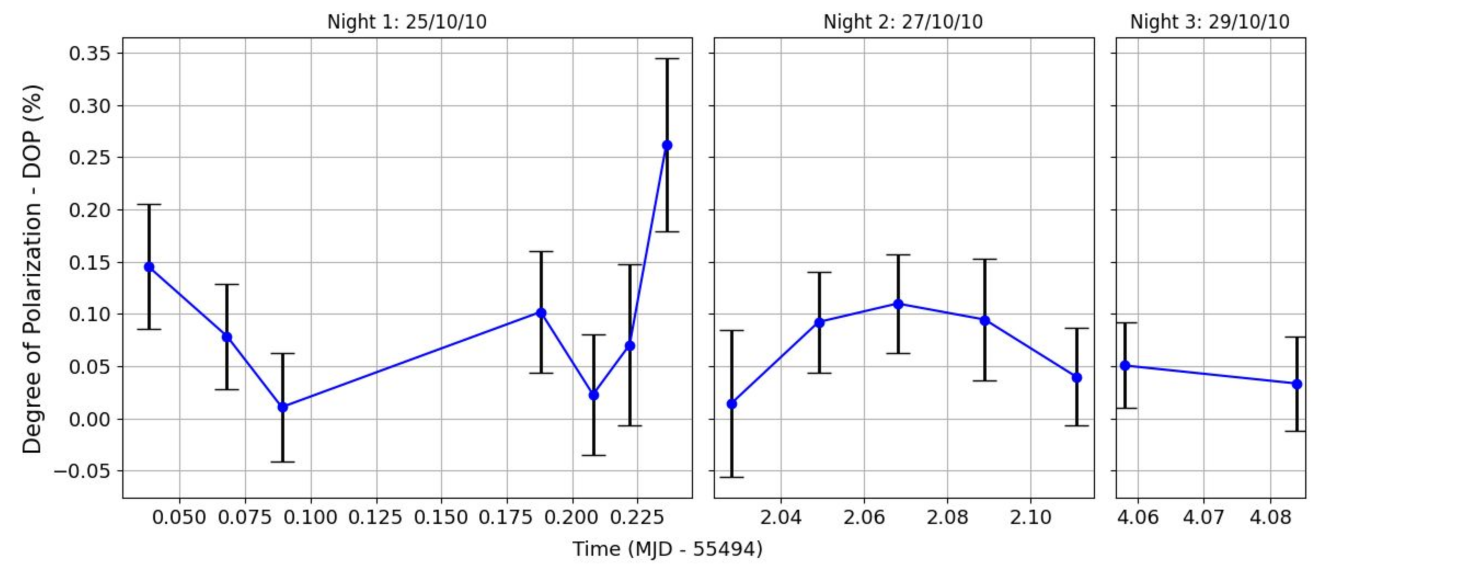

Figure 3 - Polarimetry results for 2MASS J0036

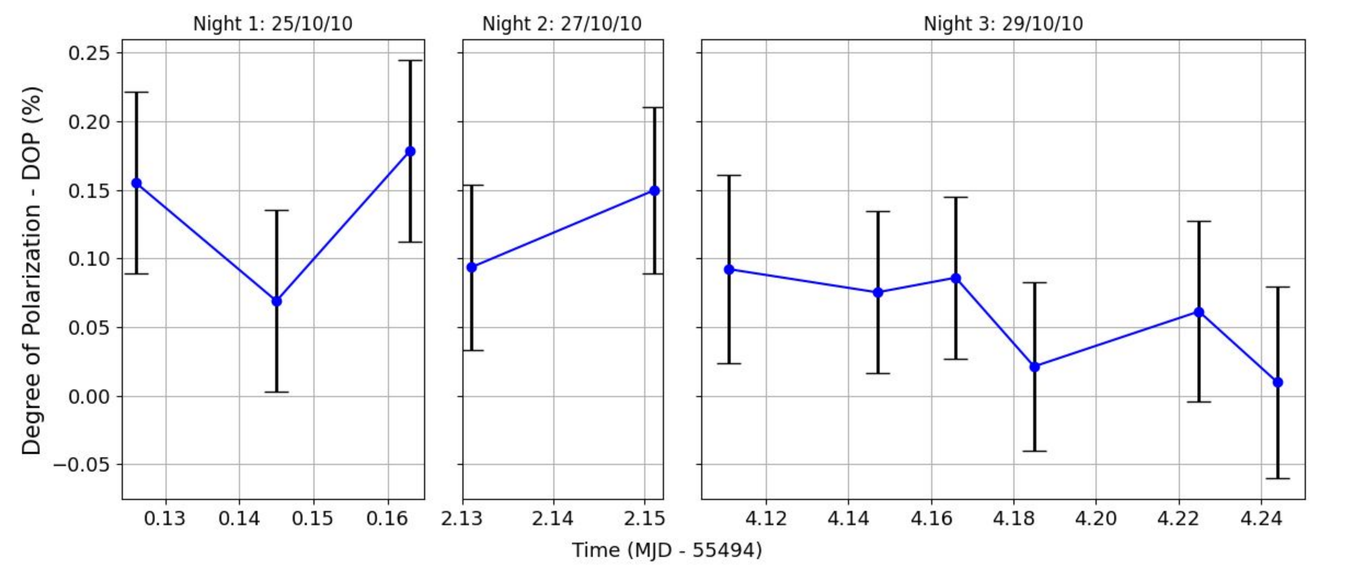

Figure 4 - Polarimetry results for LHS 102BC

Furthermore, we compared the results of 2MASS J0036 against other polarisation measurements. The amplitude of variations that we tentatively detected matches with previous observations: (0.199 ± 0.028)% in 12/2001 [5] vs. (0.077 ± 0.029)% in 08/2005 [6].
In addition, for the same target we looked for photometric variability in the literature, with the intention of understand the relation between photometry and polarisation variations. Photometric variability has been reported in I band (Fig. 6) [7] as well as radio emission [8] but the ~3h period couldn't be confirmed in our polarimetry observations, as the polarisation peak detected at MJD−55494=0.23d is not observed 3h before, partly due a lack of data.
We note that [9] determined the inclination of 2MASS J0036 and 2MASS J1507 at 51±9deg and 23±2deg resp. A lower inclination, together with a higher rotational velocity, increases the effect of the flattening on the DOP.

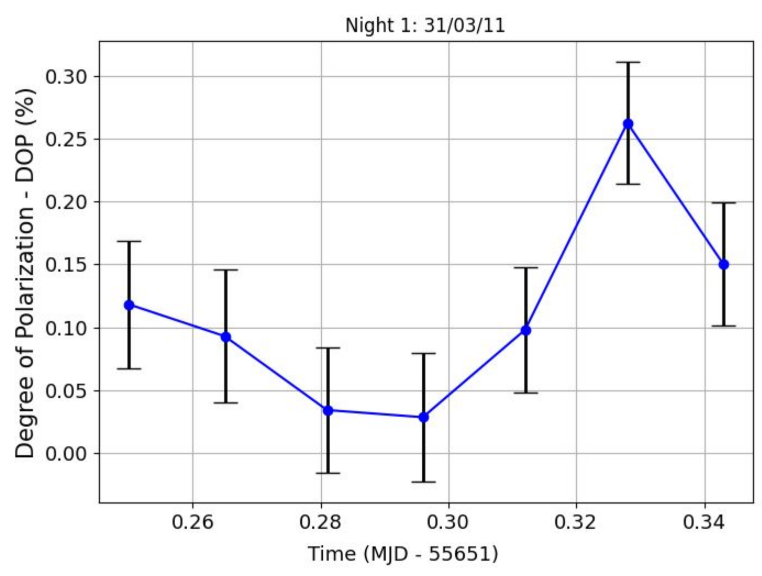

Figure 5 - Polarimetry results for 2MASS J1507

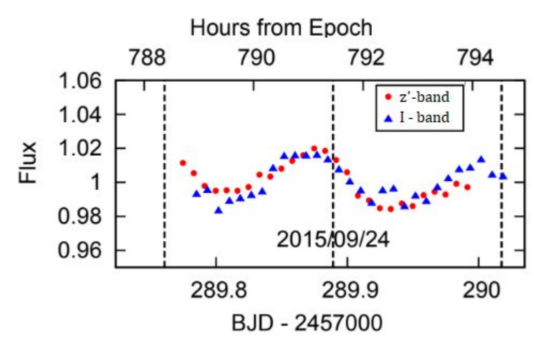

Figure 6 - Photometry of 2MASS 0036 [7]

Conclusions

We tentatively observed a variation of the polarisation degree in all three targets. Yet, we detected significant polarization measurements in only ≈ 15% of the data points obtained and even then the polarisation significance is low.

Over the past decade, there has been a dramatic improvement in the sensitivity of photometric monitoring of BDs and in the understanding of their cloud structure thanks to photometric variability studies [10]. Polarimetric measurements of high quality like ours and others [11] provide us with an additional set of constraints related specifically to the dust distribution.

Simultaneously, the degeneracies that affect the polarization signal can be partly lifted thanks to those independent measurements [9], which paves the way for a more accurate interpretation of polarimetric observations of brown dwarfs.

Acknowledgements

This research is based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO programme 086.C-0812(A/C/D/F), and has made use of the SIMBAD database and VizieR catalogue access tool, both operated and maintained at the CDS, Strasbourg, France.

Tools employed

Vizier, Simbad
SAOImage DS9
Astropy
python
photutils
ccdproc

Ezequiel González

Master student at the International Space University (ISU). Completing Master thesis titled "Cosmic weather on Brown Dwarfs". Supervisor: Dr. Bertrand Goldman. ESA Sponsorship.

References

[1] Appenzeller, I. et al., 1998. *The Messenger 94*, 1; **[2]** ESO, 2022. FORS2 FOcal Reducer/low dispersion Spectrograph 2 [https://www.eso.org/sci/facilities/paranal/instruments/fors/overview.html]; **[3]** González-Gaitán, S., et al., 2020. Tips and tricks in linear imaging polarimetry of extended sources with FORS2 at the VLT. *A&A, 634*, p.A70. **[4]** Patat, F. and Romaniello, M., 2006. Error Analysis for Dual-Beam Optical Linear Polarimetry. *PASP, 118*(839), p.146.; **[5]** Ménard, F., et al., 2002. Optical linear polarimetry of ultra cool dwarfs. *A&A, 396*(3), pp.L35-L38; **[6]** Goldman, B., et al., 2009. Polarisation of very-low-mass stars and brown dwarfs I.VLT/FORS1 optical observations of field ultra-cool dwarfs. *A&A, 502*(3), pp.929-936; **[7]** Croll, B., et al., 2021. Long-term, Multiwavelength Light Curves of Ultra-cool Dwarfs: I. An Interplay of Starspots & Clouds Likely Drive the Variability of the L3. 5 dwarf 2MASS 0036+ 18. *arXiv preprint arXiv:1609.03586*; **[8]** Berger, E., et al., 2005. The Magnetic Properties of an L Dwarf Derived from Simultaneous Radio, X-Ray, and Hα Observations, *ApJ*, 627, p. 960; **[9]** Vos, J.M., et al., 2017. The Viewing Geometry of Brown Dwarfs Influences Their Observed Colors and Variability Amplitudes, *ApJ* 842, p. 78; **[10]** Luna, J.L. and Morley, C.V., 2021. Empirically determining substellar cloud compositions in the era of the James Webb Space Telescope. *ApJ, 920*(2), p.146; **[11]** Millar-Blanchaer, M.A., et al., 2020. Detection of Polarization due to Cloud Bands in the Nearby Luhman 16 Brown Dwarf Binary, *ApJ* 894, 42.