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APPLICATION FOR OBSERVING TIME

PERIOD: **101A**

Important Notice:

1. Title

Category: **C–7**

Magnetic spots on young brown dwarfs: a proof-of-concept study

2. Abstract / Total Time Requested

Total Amount of Time:

Magnetic activity is a key feature of young brown dwarfs. In particular, cool magnetic spots are expected to have a significant impact on size, chemistry and evolution of substellar objects. Here we aim to establish a new pathway for characterising the spotted surfaces of young brown dwarfs. In previous Kepler/K2 observations we have found that young brownd warfs show spot-driven photometric variability. We have also seen signs of spectral signatures of spots in young brown dwarfs, albeit at very low resolution. We propose to obtain XSHOOTER spectra for young brown dwarfs known to have spot activity, to find the spectral signature of the spots, identify the chemical fingerprint of the spotted photosphere, which is possibly affected by dust formation, and derive the spot filling factor and temperature by fitting templates. This methodology can subsequently be applied to large-sample studies of spotted brown dwarfs.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	101	XSHOOTER	11h	jun	n	1.2	THN	s	

4. Number of nights/hours

Number of nights/hours	Telescope(s)	Amount of time
a) already awarded to this project:		
b) still required to complete this project:		

5. Special remarks:

6. Principal Investigator: ASCHOLZ

6a. Co-investigators:

C.	Manara	1258
S.	Faller	1674
B.	Stelzer	1379
C.	Helling	1674

7. Description of the proposed programme

A – Scientific Rationale: Brown dwarfs are objects intermediate in mass between stars and planets, without stable fusion that can maintain their long-term energy output. Brown dwarfs start their evolution as late M dwarfs, then gradually cool down and hence change in spectral type to L, then T, then Y. In that process the atmosphere changes dramatically. In particular, with decreasing temperature of the atmosphere, the magnetic activity (spots, flares) typical for M dwarfs disappears and condensation of dust clouds sets it (Helling & Casewell 2014), developing from star-like to planet-like atmospheres. In young brown dwarfs affected by cool magnetic spots we are uniquely seeing a mixture of these two types of atmospheres.

Members of our team have made significant contributions to the progress in this field (see box 10). In particular, we showed that young brown dwarfs (and objects close to the substellar limit) commonly exhibit spot-induced variability with periods ranging from hours to days (Scholz & Eislöffel 2005). Using lightcurves from the Kepler/K2 telescope, we found variability with amplitudes of a few percent, stable over 2 months, in 16 out of ~ 50 non-accreting objects with ages of $\sim 10\,$Myr (Scholz et al. 2015, see Figure, left panel). The stability of the periodicity is remarkable and not seen in FGK stars (Giles et al. 2017) or L/T-type brown dwarfs (Metchev et al. 2015). According to Zeeman Doppler Imaging results for M dwarfs, the surface of these fast rotating young brown dwarfs is most likely dominated by a large polar spot (Morin et al. 2010), that is asymmetrically shaped and therefore modulates the flux as the object rotate. This means, if an object is spotted, the surface will always be affected by spots, but to a varying degree.

Broadband time-series observations, however, do not yet give us detailed insights into the physics of the spots. We know, however, from a variety of theoretical and observational arguments that spots are expected to have a strong influence on the fundamental properties of late M dwarfs and thus young brown dwarfs. Magnetic spots are discussed as a likely cause for the discrepancy between observed and model radii in young brown dwarfs (Stassun et al. 2012). Since spots cover a significant portion of the surface, they will have an impact on chemistry, mixing, and convection. In young brown dwarfs, the spots should be significantly cooler than 3000 K, sufficiently cool to allow for dust formation in them. For these and other reasons, it is desirable to develop tools to study the nature of magnetic spots on these objects.

In this proposal we aim to work towards a new methodology to study surface features on magnetically active brown dwarfs. Several paths that are tried and tested for more massive objects are impractical for young brown dwarfs. Space-based monitoring, as mentioned above, is only available for small samples. Ground-based monitoring is time consuming and of limited value – with rotation periods of 1-2 d the typical daytime gaps significantly disrupt the cadence, and the atmosphere-induced noise is comparable to the photometric amplitude. High-resolution spectroscopy of the temperature-sensitive TiO bands has been in the past as 'thermometer' for spots on active stars (O'Neal et al. 2004), but again requires excessive integration times for the much fainter brown dwarfs, to the extent that the integration time would be a significant portion of the rotation period and the signal of a spot would be lost. The same problem plagues Doppler Imaging for this type of targets. Here we aim to prove that spot information can be gained at medium spectral resolution.

While working on spectral confirmation of young brown dwarfs, we serendipitously found *clear signs of spectral anomalies* among a number of them (Dawson et al. 2014). Objects with very similar overall spectral shape and similar spectral type, determined from NIR water absorption features, show significant variety in the depth of absorption features between 0.8 and $1.2\,\mu m$ (see figure for example). Residual circumstellar dust cannot satisfactorily explain these anomalies, and in any case there is no evidence for dust emission in the infrared. In a subsequent analysis illustrated in the right panel below we show that the anomalous spectra are well explained as a composite of a late-M photosphere with a significantly cooler spot (approximated by a L-type spectrum). Given the propensity of magnetic activity seen in the K2 lightcurves and the ubiquity of other activity indicators in this type of object (e.g., Hα), *magnetic spots are a very plausible explanation for the spectral diversity.*

So far, there is no overlap in the samples with spectra and the samples with high-precision lightcurves. Also, spectra are only available at very low resolution ($R < 1000$), i.e. it is impossible to attribute the anomalies to spectral features and chemical species. Therefore we propose to obtain mid-resolution spectra covering a wide wavelength range for young brown dwarfs with periodic variability found in the K2 data, in addition to a control sample without measurable variability. As pointed out above, it can be expected that spots are large and always visible, thus, a single epoch of spectroscopy is sufficient. With this simple experiment, we can achieve the following three key goals: 1) Confirm that spot activity is in fact responsible for the anomalies seen at low resolution. 2) Identify the spectral features affected by spot activity on young brown dwarfs. 3) Establish a methodology for estimating spot temperatures and filling factors for this type of object. This pioneering study will pave the way for the streamlined large-sample analysis of spots on young brown dwarfs.

B – Immediate Objective:

We plan to acquire medium-resolution XSHOOTER spectra for 12 objects with masses at or below the substellar boundary (spectral types M6-L1) and ages of 10 Myr. These targets fall into three categories, **(A)** those with measured periodic variability in K2 lightcurves, with amplitudes of 1-2%, indicating spot activity, selected from Scholz et al. (2015), **(B)** those without detectable variability ($< 0.5\%$ flux modulation) in K2 lightcurves,

7. Description of the proposed programme and attachments

Description of the proposed programme (continued)

i.e. they are most likely spotless objects (again from Scholz et al. 2015), **(C)** spectral templates M6 to L1, identified with low-resolution spectra in Dawson et al. (2014). All objects have colors and proper motion that classify them as very likely members of Upper Scorpius (Dawson et al. 2013). None of these objects shows any evidence for the presence of disks and thus accretion (based on WISE colours); all have negligible line-of-sight extinction (based on optical colours). For all samples, we select the brightest brown dwarfs available, to optimise observing time. The templates will complement the available Xshooter spectral library for young stars published by Manara et al. (2017), which is sparsely populated at spectral types later than M6.

The spectra will be reduced using standard pipeline routines, including the removal of tellurics using telluric standards observed in the same night (Manara et al. 2017). Spectral activity signatures (Halpha, Ca II triplet) will be identified and measured, to confirm that sample A is more active than B and C. We will re-estimate the fundamental parameters for the sample using the methods outlined in Manara et al. (2013), supported by kinematic information from Gaia DR2 (available in April 2018). By checking for UV excess we will confirm that the targets are in fact not accreting. The spectra will be made available for public access, for further analysis by other teams. Subsequently the focus will be on investigating the spot activity, in the following three steps.

1) **Verify if the targets with significant periodic variability have the spectral anomalies** discussed above and conversely, the targets without variability do not show anomalous spectra. This will confirm or refute our well-founded hypothesis that we are seeing the effects of spots in the spectra. If confirmed, XSHOOTER spectroscopy will become a prime tool for studying the surface features on magnetically active brown dwarfs.

2) **Fit the spectra of spotted objects with composites of two different templates**, representing an unspotted photosphere and a cool spot (see figure, right panel). In combination with the variability amplitude, this will yield strong constraints on filling factor and spot temperature, the only two free parameters. With empirical templates, this will be an entirely model-independent analysis.

3) **Compare the observed spectra with Drift-Phoenix model spectra** by our team (see recent papers by Helling et al.) to identify the chemical species responsible for the anomalies. For example, we will learn whether the spot signature is due to grey-absorbing dust or metal-oxides. With the spot temperature determined in step 2, a detailed chemical analysis of the spotted atmosphere in the framework of Drift-Phoenix will become feasible (see Longstaff et al. 2017) and will provide the first constraints on the spot chemistry in brown dwarfs.

Attachments (Figures)

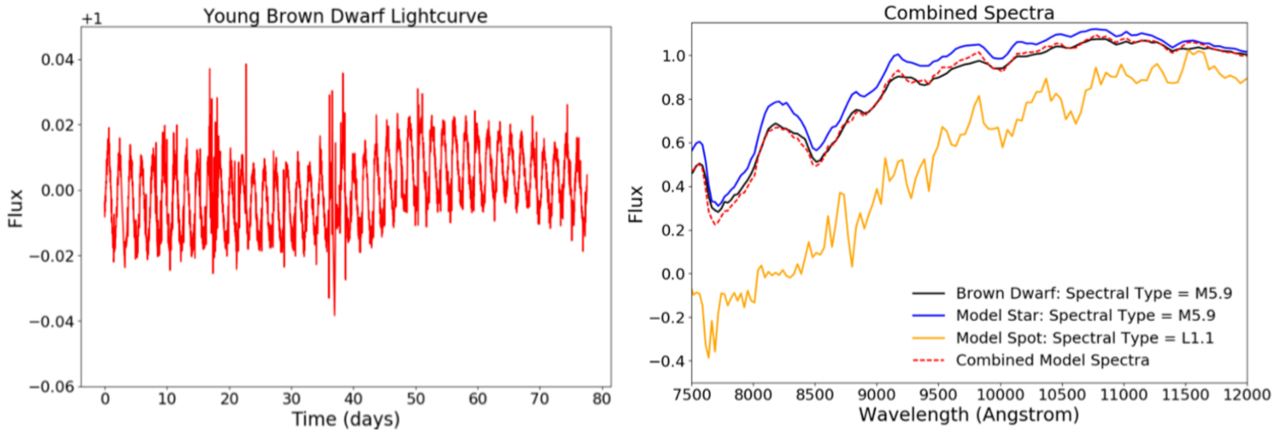

Fig. 1: **Left panel**: Long-term lightcurve of a young brown dwarf in Upper Scorpius, obtained from Kepler/K2 (Scholz et al. 2015), clearly showing the periodic modulation of the flux due to magnetic spots. The object with this lightcurve is one of our targets in this proposal. **Right panel:** Low-resolution spectra of young brown dwarfs in Upper Scorpius, observed with IRTF/SpeX (Dawson et al. 2014). The black spectrum shows anomalous absorption features compared with a template of similar spectral type (blue). The weighted combination of the blue and a L-type spectrum (yellow) reproduces the observed spectrum very well. This convincingly demonstrates that a photosphere with a cooler spot covering a fraction of the surface can explain spectral anomalies. (In both plots, fluxes are scaled to average of zero.)

8. Justification of requested observing time and observing conditions

Lunar Phase Justification: This proposal can be carried out irrespective of lunar phase. The observing time was estimated for half moon.

Time Justification: (including seeing overhead) We ask for a single spectrum for each of our 12 targets. We estimated exposure times using the ESO Exposure Time Calculator version P101 on the ESO website. Ten out of 12 of our targets have J-magnitudes between 12.5 and 13.5, while the remaining two are at 14 and 16 in J (see box 11). Note that there is good reason to think that the spots are always present on the surface (see box 7), therefore only a single epoch of spectroscopy is required.

We assumed a seeing of 1.2 arcsec and a conservative airmass of 1.5, half moon, and gave as input a 2800 K blackbody normalized to target magnitudes. With slits matching the seeing of 1.3, 1.2, and 1.2 arcsec in the three arms, and aiming for a signal-to-noise ratio > 100 for $\lambda > 700$ nm (the spectral range most relevant for these red targets), we obtain on-source times of 24 min for all our 10 bright targets. For the two faint objects, on-source times of 36 min and 60 min are planned. This will yield lower s/n (> 30 in the relevant wavelength domain), but since these targets are only used as templates this is still sufficient. Note that this setup will also give us decent s/n (> 20) in the UVB arm, sufficient to check for UV excess emission, based on our previous experience with this instrument.

The objects will be observed with a nodding pattern and shorter sub-exposures in the NIR arm to be able to correct for cosmics and background. With typical overheads for acquisition and instrument setup of 12 min per target, this requires a total telescope time ranging of 36 min to 72 min, per target. For 11/12 targets, this fits into one OB, for the only exception we will ask for permission to use a slightly extended OB. The time on target for each individual object is listed in box 11 of this proposal. Therefore, the science targets need 8 h of telescope time.

In addition we need to observe telluric standards for each of our targets. These stars are bright and need only 15 min of observing time each (including all overheads). They need to be observed close in time to each of our targets, therefore we add an additional 12×0.25 h for calibration purposes. In total, the required telescope time is 11 h.

8a. Telescope Justification:

XSHOOTER is the ideal instrument for this project. As outlined in the Science Case, the spectral anomalies we want to analyse are seen in low-resolution spectra, but cannot be clearly attributed to specific features – this is why medium resolution (R of a few thousand) is required. XSHOOTER is also the only ESO spectrograph that covers the wavelength domain 0.8 to 1.2 μm with sufficient resolution – this is the domain where young brown dwarfs show an abundance of atomic and molecular features and where their spectral energy distribution peaks. The additional coverage of UV, optical and IR provides a wealth of information about the photospheric properties and activity of these objects that is a useful complement for our analysis. In principle, we can do the same project with spectrographs at the NTT, namely EFOSC2 and SOFI, in 2×2 observing nights, but only with significantly lower resolution and less spectral coverage.

8b. Observing Mode Justification (visitor or service):

This proposal can in principle be carried out in service or visitor mode. It does not require run-time decisions, therefore Service Mode is the preferred option. We point out that up to 2.5 h of observing time could be shaved off the total, if the program is carried out in 1 night of visitor time. In that case, telluric standards only need to be observed a couple of times during the observing night (since our targets are all in the same area of the sky).

8c. Calibration Request:

Special Calibration - Telluric corrections are a necessary requirement for a detailed analysis of the optical and near-infrared spectrum. Since the telluric standards are not anymore part of the baseline calibration, we plan to observe one telluric standard (a nearby early type A-star) for each of our targets. This standard star needs to be observed either before or after the corresponding science target.

9. Report on the use of ESO facilities during the last 2 years

The PI has not used ESO facilities in periods 97-100 as Principal Investigator. He was Co-I on proposals 097.C-0458 (led by Muzic, analysis in progress), 097.C-0572 (led by Muzic, analysis in progress), 097.C-0378 (led by Manara, observations incomplete), and 099.D-0107 (led by Stelzer, data acquired in June 2017).

Co-I Manara has led several projects in recent ESO periods. The data from 097.C-0349 was published in Alcala et al. (A&A, 2017, 600, 20) and Frasca et al. (A&A, 2017, 602, 33). Data for 299.C-5048 was acquired in September 2017, the analysis is underway.

9a. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If so, explain the need for new data.

The targets for this proposal have not been observed spectroscopically before, hence, there are no spectra of them in the ESO archive.

9b. GTO/Public Survey Duplications:

10. Applicant's publications related to the subject of this application during the last 2 years

Dawson, P.; Scholz, A.; Ray, T. P.; Peterson, D. E.; Rodgers-Lee, D.; Geers, V., 2014, MNRAS, 442, 1586: *Near-infrared spectroscopy of young brown dwarfs in upper Scorpius*

Stelzer, B.; Damasso, M.; Scholz, A.; Matt, S. P., 2016, MNRAS, 463, 1844: *A path towards understanding the rotation-activity relation of M dwarfs with K2 mission, X-ray and UV data*

Scholz, Alexander; Kostov, Veselin; Jayawardhana, Ray; Muzic, Koraljka, 2015, ApJ, 809, 29: *Rotation Periods of Young Brown Dwarfs: K2 Survey in Upper Scorpius*

Bozhinova, I.; Scholz, A.; Eislöffel, J., 2016, MNRAS, 458, 3118: *Variability in young very low mass stars: two surprises from spectrophotometric monitoring*

Street, R. A.; Fulton, B. J.; Scholz, A.; Horne, Keith; Helling, C.; Juncher, D.; Lee, G.; Valenti, S., 2015, ApJ, 812, 161: *Extended Baseline Photometry of Rapidly Changing Weather Patterns on the Brown Dwarf Binary Luhman-16*

Manara, C. F.; Frasca, A.; Alcala, J. M.; Natta, A.; Stelzer, B.; Testi, L., 2017, A&A, 605, 86: *An extensive VLT/X-shooter library of photospheric templates of pre-main sequence stars*

Manara, C. F.; Testi, L.; Natta, A.; Alcala, J. M., 2015, A&A, 579, 66: *X-Shooter study of accretion in Rho-Ophiucus: very low-mass stars and brown dwarfs*

Manara, C. F.; Testi, L.; Rigliaco, E.; Alcala, J. M.; Natta, A.; Stelzer, B.; Biazzo, K.; Covino, E.; Covino, S.; Cupani, G.; D'Elia, V.; Randich, S.: 2013, A&A, 551, 107: *X-shooter spectroscopy of young stellar objects. II. Impact of chromospheric emission on accretion rate estimates*

Frasca, A.; Biazzo, K.; Alcal, J. M.; Manara, C. F.; Stelzer, B.; Covino, E.; Antoniucci, S., 2017, A&A, 602, 33: *X-shooter spectroscopy of young stellar objects in Lupus. Atmospheric parameters, membership, and activity diagnostics*

Helling, Christiane; Casewell, Sarah, 2014, A&ARv, 22, 80: *Atmospheres of brown dwarfs*

11. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	A1	16 03 37.99	-26 11 54.4	0.53	12.974		spotted	
A	A2	16 11 38.37	-23 07 07.2	0.53	13.807		spotted	
A	A3	16 09 52.17	-21 36 27.7	0.53	12.569		spotted	
A	A4	16 08 22.29	-22 17 02.9	0.53	13.016		spotted	
A	A5	16 11 26.30	-23 40 05.9	0.53	13.450		spotted	
A	A6	16 13 26.65	-22 30 34.8	0.53	13.578		spotted	
A	B1	16 09 01.69	-27 40 52.1	0.53	12.939		clear	
A	B2	16 13 21.79	-27 31 22.3	0.53	13.301		clear	
A	B3	16 15 28.19	-23 15 43.9	0.53	13.228		clear	
A	C1	15 52 48.57	-26 21 45.3	0.53	13.297		template M7	
A	C2	16 10 13.16	-28 56 30.8	0.7	14.097		template M8	
A	C3	16 19 58.27	-28 32 27.6	1.2	16.160		template L1	

Target Notes: Targets labelled 'A' ('spotted') are from the list of objects with K2-detected spot modulation (Scholz et al. 2015). Targets labelled 'B' have also been observed by K2, but do not show evidence for spots ('clear'). Targets labelled 'C' are spectral templates from Dawson et al. (2014). All magnitudes are 2MASS J-band.

12. Scheduling requirements

13. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
101	XSHOOTER	A	SLT	1.3,1.2,1.2