European Organisation for Astronomical Research in the Southern Hemisphere

OBSERVING PROGRAMMES OFFICE • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: opo@eso.org • Tel.: +49 89 320 06473

APPLICATION FOR OBSERVING TIME

PERIOD: **96A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title

Category: **C–7**

Outlier benchmark brown dwarfs with *Gaia* primaries

2. Abstract / Total Time Requested

Total Amount of Time:

We aim to identify and characterize a large sample of L dwarfs in wide binary systems with outlier atmospheric properties. These benchmark systems are crucial to test and improve atmospheric models, and to calibrate accurately the relation between observable properties and atmospheric parameters of sub-stellar objects. In order to do that we propose to follow-up 58 multiple system candidates, complementing the astrometric information from *Gaia* with photometry and spectroscopy. If awarded the time, we will: confirm companionship for 15 high proper motion L dwarf companions using common proper motion criteria; confirm the ultra-cool nature and constrain the companionship for 43 low proper motion L dwarf companions using common spectrophotometric distance and common radial velocity criteria; characterize the confirmed systems, achieving an unprecedented calibration of the correlations between observable properties and atmospheric parameters of sub-stellar objects.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	96	SOFI	4n	dec	n	1.0	THN	v	

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: fmarocco

6a. Co-investigators:

D.J.	Pinfield	1668
H.R.A.	Jones	1668
P.W.	Lucas	1668
B.	Burningham	1514

Following CoIs moved to the end of the document ...

7. Description of the proposed programme

A – Scientific Rationale: **Summary:** We propose to pursue the identification and characterization of a sample of 58 L dwarf candidates in binary or multiple systems with outlier atmospheric properties, complementing the *Gaia* data with spectroscopy, photometry, and astrometry. In this way our sample is fully exploiting *Gaia* to establish a benchmark population that will reveal ultra-cool atmosphere physics across the full sub-stellar parameter space. The correlations derived from our targets would then be applied to the entire population of L dwarfs, to study the properties of the solar neighbourhood population at the stellar – sub-stellar boundary.

Background: A comprehensive understanding of sub-stellar objects (brown dwarfs and extrasolar giant planets) and their population characteristics (e.g. IMF, birthrate; [1,2]) is only possible through the robust interpretation of ultra-cool objects ($T_{\rm eff}$ < 2500 K) spectroscopy. However, the physics of ultra-cool atmospheres is complicated by a variety of challenging ingredients (dust properties, non-equilibrium chemistry, molecular opacities; [3,4,5]), and theoretical model spectra must be calibrated effectively if observations are to effectively constrain physical properties ($T_{\rm eff}$, log g, [Fe/H], and in turn mass and age and composition).

A direct way to overcome these challenges is to identify ultra-cool dwarfs (UCDs) whose physical properties can be inferred indirectly – so-called "benchmark systems". UCDs as wide companions to stars of various type are a particularly crucial source of benchmarks, for which common age and compositional constraints can be determined from studies of the primaries [6]. Such systems can survive for billions of years [7], with the companions populating the full age and composition range of the Galaxy (e.g. [8,9]). While a few benchmark systems have already been found and characterized [10,11] their number remains limited, and the parameter space is therefore largely under-sampled. With this proposal we aim at characterizing a large sample of wide binaries and multiple systems, to fully populate the range of atmospheric parameter space for UCDs, focusing on the population with outlier properties, since the sensitivity of spectroscopic variations to atmospheric properties will be clearest when the range in these properties is greatest.

The impact of *Gaia*: *Gaia* provides the means to advance benchmark studies in an unprecedented way. In combination with the latest generation of near-infrared and optical large-scale surveys it is possible to identify UCD companions to *Gaia* primaries out to ∼100 pc. These will be L dwarf companions (in which atmospheric dust first appears, strongly affecting their spectra; [12]), and with an estimated total of ≈ 2000 benchmark systems available (≈ 600000 stars out to 100 pc, 0.33% of which should have an L dwarf companion; [10]) we have the remarkable opportunity to pre-select sizeable sub-samples with extreme (outlier) physical properties, that will provide a complete test of the spectral sensitivities across a broad parameter-space. To fully access this population we must employ an optimal range of tests to statistically confirm associations, and while common proper motion can confirm nearby systems (e.g. [8,10,13,14]), more distant benchmarks will have low proper motion and we must instead rely on common radial velocity and proximity [15].

The proposed sample: We have begun a programme to identify outlier benchmark systems with *Gaia* primaries, with a first focus on metal-rich and metal-poor systems. The composition of sub-stellar objects can shed light on important aspects of brown dwarf formation (environment, and fragmentation physics; [16,17]), and is likely to form a pivotal ingredient in a developing classification system that separates brown dwarfs and giant planets (the "brown dwarf exoplanet connection"; [18]). We have constructed a sample of outlier *Gaia* primaries with [FeH] < / > 0.3 dex using (i) published catalogues from the Vizier database (CDS, e.g. [19,20]), (ii) the latest LAMOST spectroscopic database [21].

Our candidate L dwarf companions were selected using the UKIDSS (LAS and GCS) and SDSS surveys, with primary-secondary separation limits of < 3 arcminutes. We also employ distance constraints for the primaries, to apply a colour-magnitude test for the L dwarf companions (which ensures common distance consistency for candidate pairings).

Although our selection method rules out much contamination, producing a candidate list that is rich with genuine systems, observational confirmation is still an important requirement in order to reject spurious associations. In Figure 1 we compare the separation distribution for our benchmark candidates to the separation distribution of confirmed systems obtained in [14]. Our sample is clearly incomplete for projected physical separations s < 1000 AU, since we are probing out to a further distance than [14] (close systems become unresolved at large distance). Also surveys like SDSS and UKIDSS are known to have problems at cataloguing sources near bright stars (SDSS in particular). Some close companions will therefore be lost due to search algorithm issues. On the other hand the distribution at intermediate separations shows a slowly declining trend, demonstrating that the number of spurious pairs is limited. If we were dominated by contamination one would indeed expect the number of systems to increase $\propto s^2$. At separations s > 7000 AU the number of systems drops, since we lose objects due to the separation limit adopted for the initial cross-match. The systems identified here have been missed by previous efforts (e.g. using Pan-STARRS 1 data [14]) either because they lacked the depth provided by UKIDSS, or because they focused on high proper motion systems only. Our selection yields a sample of more than 500 potential systems, more than 250 of which are observable from Cerro La Silla. The 58 systems proposed here are the brightest (i.e. J < 19), and whose primaries have photometrically estimated metallicity with relative uncertainty < 30%, and with either high or low metallicity (i.e. [Fe/H] > +0.3 dex or [Fe/H] < −0.3 dex). We chose these systems because they populate regions of the parameter space that have

7. Description of the proposed programme and attachments

Description of the proposed programme (continued)

so far remained unexplored.

B – Immediate Objective: Of our 58 L dwarf candidates, 15 are potentially associated with high proper motion stars (i.e. proper motion $\geq$ 50 mas/yr, with proper motions taken from the PPMXL catalogue [22]). Here we propose to use SOFI on the NTT to obtain J band imaging follow-up for these 15 UCDs, to measure their proper motion (PM). Combining our measured PMs with the astrometric information for the primary star (provided by *Gaia*) we will be able to confirm the association of these systems. The remaining 43 UCD candidates are associated with low PM stars (i.e. PM $<$ 50 mas/yr). Common PM criteria would not be sufficient to unambiguously confirm these associations (since chance alignment contamination is high for low PM), so common spectrophotometric distance and common radial velocity would be used instead. We would use SOFI to obtain low-resolution spectra for these 43 UCDs. These spectra are needed to confirm the ultra-cool nature of the objects, measure their spectral type, radial velocity, spectral indices, and absorption lines equivalent width. The spectral types will allow a much more accurate distance estimate for the UCD (using published absolute magnitude – spectral type relationships), and combined with our measured radial velocity would constrain the companionship of our candidate benchmark systems, removing contaminating background objects. Their main-sequence primaries parameters (abundances, surface gravity, and rotational velocity) would constrain the age and atmospheric parameters of the ultra-cool companions. We would use the SOFI spectra of the UCDs to identify spectral indicators (the equivalent width of absorption lines, spectral indices, etc.) that correlate with the inferred parameters by comparing the various systems characterized.

Attachments (Figures)

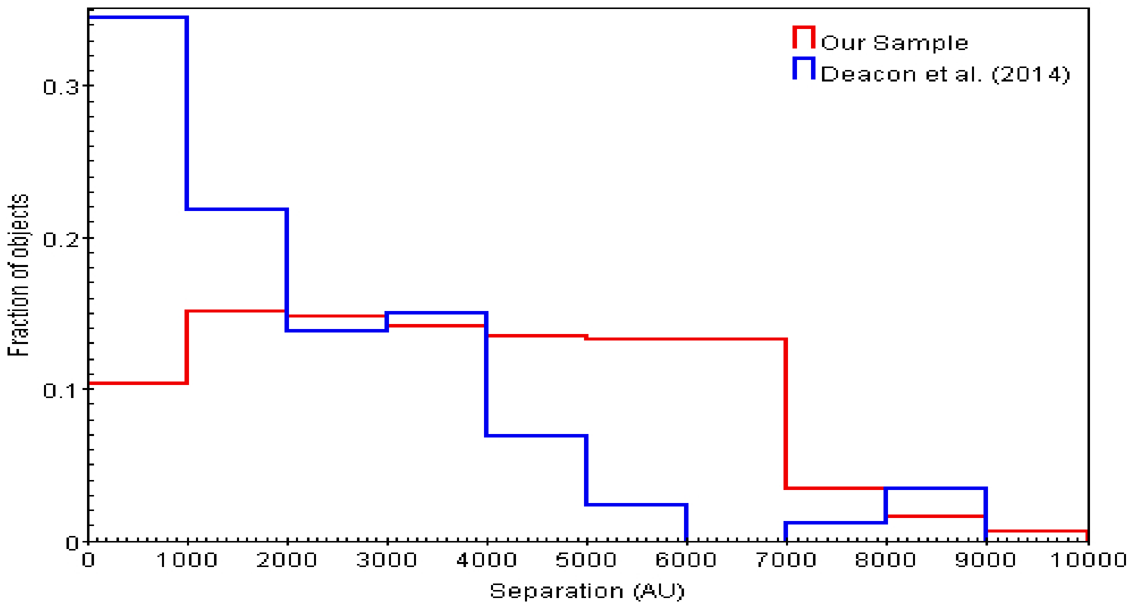

Fig. 1: The separation distribution for our candidate benchmark systems (red histogram) compared to the separation distribution of the confirmed benchmarks from [14].

References: [1] Day-Jones et al. 2013, MNRAS, 430, 1171; [2] Marocco et al. 2015, arXiv, 150305082; [3] Helling & Casewell 2014, A&ARv, 22, 80; [4] Allard et al. 2013, MSAIS, 24, 128; [5] Saumon & Marley 2008, ApJ, 689, 1327; [6] Pinfield et al. 2006, MNRAS, 368, 1281; [7] Zhang et al. 2013, MNRAS, 434, 1005; [8] Pinfield et al. 2012, MNRAS, 422, 1922; [9] Burningham et al. 2011, MNRAS, 414, 3590; [10] Gomes et al. 2013, MNRAS, 431, 2745; [11] Deacon et al. 2014, ApJ, 792, 119; [12] Marocco et al. 2014, MNRAS, 439, 372; [13] Burningham et al. 2013, MNRAS, 433, 457; [14] Deacon et al. 2014, ApJ, 792, 119; [15] Dhital et al. 2012, AJ, 143, 67; [16] Bate 2014, MNRAS, 442, 285; [17] Stamatellos & Whitworth 2011, IAUS, 270, 223; [18] Pinfield et al. 2013, MemSAIt, 84, 1154; [19] Ammons et al. 2006, ApJ, 638, 1004; [20] Kordopatis et al. 2013, MNRAS, 436, 3231; [21] Yuan et al. 2015, MNRAS, 448, 855; [22] Roeser et al. 2010, AJ, 139, 2440;

8. Justification of requested observing time and observing conditions

Lunar Phase Justification: Since we are observing in the near-infrared, no lunar phase restriction is required.

Time Justification: (including seeing overhead) We request a signal-to-noise ratio (SNR) of 50 for our imaging targets, to allow for precise centroiding of the objects in the field and therefore a robust astrometric calibration and a reliable proper motion measurement. Given the typical brightness of our targets, and using the SOFI ETC provided online, we estimate a total integration time requested of 1 hours. Including the recommended overheads (10 minutes preset + ∼30% of the integration time per target), the total time requested in imaging mode is therefore 3.8 hours.
We request a SNR per pixel of 20 or better for our spectroscopy targets, to allow for accurate spectral typing, spectral indices measurements, and accurate radial velocity measurements (down to a precision of ≈10 km/s). Given the typical brightness of our targets, and using the SOFI ETC provided online, we estimate a total integration time requested of 20.2 hours. Including the recommended overheads (10 minutes preset + ∼25% of the integration time per target), the total time requested is 32.4 hours. We would also need to observe telluric standards to correct our spectra for atmospheric absorption. Observing one standard every two targets (matching the airmass of the observations), and choosing bright B or A stars as standards, we estimate a total time requested (including overheads) of 4 hours to observe all of the requested standards. The total time requested in spectroscopy mode is therefore 36.4 hours.
The total time requested to complete our program is therefore 4 nights. Since our targets are homogeneously distributed in R.A. we request a night towards the middle of the semester (i.e. in December 2015 or January 2016) in order to be able to observe all of them.
The homogeneous distribution in R.A. and Dec. of our targets also allows for extra flexibility in the observational schedule, allowing real time adjustments to accommodate for pointing restrictions, therefore minimizing the impact of poor weather on our program.

8a. Telescope Justification:

We chose SOFI on the NTT because it meets all of the technical requirements for our intended observations. Our targets are bright enough for a 4m-class telescope. In imaging mode, SOFI's large field of view would provide many reference stars for accurate photometric and astrometric calibration of the images, leading to accurate proper motions (required for the confirmation of the physical association of our benchmark systems). In spectroscopy mode, the GR Blue grism combines a good resolution with a wide wavelength coverage of a crucially line-rich region. The 0.95-1.64 μm range hosts numerous alkali lines and molecular bands, fundamental to measure the radial velocity of our targets, and to test the effect of the atmospheric parameters.

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

We request visitor mode to allow for real-time adjustments of the observing strategy (exposure times, standards observed). The observing strategy proposed here has been adopted and therefore tested widely by our group in previous observing campaign (including, but not limited to, ESO programs 086.C-0450, 087.C-0639, 088.C-0048, 091.C-0450, 091.C-0452). Our group includes individuals with ample expertise in near-infrared imaging and spectroscopy.

8c. Calibration Request:

Special Calibration - One telluric standard for every two spectroscopic targets and a radial velocity standard for each night.

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

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 data requested in this proposal are NOT 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

Marocco F. et al., 2015, arXiv, 150305082: A large spectroscopic sample of L and T dwarfs from UKIDSS LAS: peculiar objects, binaries, and space density

Marocco F. et al., 2014, MNRAS, 439, 372: The extremely red L dwarf ULAS J222711-004547 - dominated by dust

Marocco F. et al., 2013, AJ, 146, 161: Parallaxes of Southern Extremely Cool Objects (PARSEC). II. Spectroscopic Follow-up and Parallaxes of 52 Targets

Pinfield D.J. et al., 2014MNRAS, 444, 1931: Discovery of a new Y dwarf: WISE J030449.03-270508.3

Gelino C. et al., 2014, AJ, 148, 6: WISEP J061135.13-041024.0 AB: A J-band Flux Reversal Binary at the L/T Transition

Wang Y. et al., 2014, PASP, 126, 15: Parallaxes of Five L Dwarfs with a Robotic Telescope

Frith J. et al., 2013, MNRAS, 435, 2161: A catalogue of bright ($K < 9$) M dwarfs

Zhang Z.H. et al., 2013, MNRAS, 434, 1005: A spectroscopic and proper motion search of Sloan Digital Sky Survey: red subdwarfs in binary systems

Smart R.L. et al., 2013, MNRAS, 433, 2054S: NPARSEC: NTT Parallaxes of Southern Extremely Cool objects. Goals, targets, procedures and first results

Burningham B. et al., 2013, MNRAS, 433, 457: 76 T dwarfs from the UKIDSS LAS: benchmarks, kinematics and an updated space density

Gomes J.I. et al., 2013, MNRAS, 431, 2745: Two new ultracool benchmark systems from WISE+2MASS

Day-Jones A.C. et al., 2013, MNRAS, 430, 1171: The sub-stellar birth rate from UKIDSS

11. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	HPM1	00 05 33	+07 40 34	0.20	17.87	1	Imaging	
A	HPM2	00 39 19	+06 34 50	0.20	18.19	1	Imaging	
A	HPM3	05 31 58	-04 00 38	0.18	15.87	1	Imaging	
A	HPM4	20 51 35	-01 08 40	0.18	15.84	1	Imaging	
A	HPM5	21 25 24	+01 21 06	0.18	16.45	1	Imaging	
A	HPM6	21 53 06	+01 07 39	0.18	15.24	1	Imaging	
A	HPM7	22 01 59	+04 45 31	0.18	16.76	1	Imaging	
A	HPM8	23 53 45	+00 38 34	0.18	16.96	1	Imaging	
A	HPM9	09 10 36	+07 22 02	0.39	18.68	1	Imaging	
A	HPM10	10 22 31	+02 24 35	0.39	19.14	1	Imaging	
A	HPM11	10 57 06	+06 23 49	0.39	18.82	1	Imaging	
A	HPM12	13 13 59	-02 27 37	0.39	18.88	1	Imaging	
A	HPM13	14 13 40	-00 50 59	0.18	15.25	1	Imaging	
A	HPM14	15 23 29	+05 21 00	0.39	18.90	1	Imaging	
A	HPM15	18 05 29	-00 06 17	0.18	16.03	1	Imaging	
A	LPM1	02 24 38	-07 21 58	0.50	15.15	1	Spectroscopy	
A	LPM2	03 27 31	+05 08 44	0.83	15.33	1	Spectroscopy	
A	LPM3	05 30 35	-06 39 22	0.83	15.54	1	Spectroscopy	
A	LPM4	05 33 31	-06 30 33	0.50	15.09	1	Spectroscopy	
A	LPM5	05 34 26	-05 19 10	0.33	13.93	1	Spectroscopy	
A	LPM6	05 52 07	+02 50 24	1.00	15.89	1	Spectroscopy	
A	LPM7	06 05 20	+06 23 59	1.00	15.92	1	Spectroscopy	
A	LPM8	06 06 46	-06 25 12	0.33	14.21	1	Spectroscopy	
A	LPM9	06 10 42	-00 21 01	0.33	14.61	1	Spectroscopy	
A	LPM10	06 42 54	-00 26 48	0.83	15.51	1	Spectroscopy	
A	LPM11	07 30 05	-14 08 10	0.83	15.38	1	Spectroscopy	
A	LPM12	07 32 51	+01 22 25	1.00	15.90	1	Spectroscopy	
A	LPM13	07 43 40	-10 02 41	0.83	15.30	1	Spectroscopy	
A	LPM14	20 14 17	-00 09 53	0.50	15.16	1	Spectroscopy	
A	LPM15	20 12 55	+09 17 30	0.50	15.21	1	Spectroscopy	
A	LPM16	20 16 53	-00 03 07	0.83	15.52	1	Spectroscopy	
A	LPM17	20 59 08	-02 14 40	0.83	15.65	1	Spectroscopy	
A	LPM18	21 04 31	-09 39 21	1.00	15.85	1	Spectroscopy	
A	LPM19	21 15 05	-07 39 34	0.83	15.54	1	Spectroscopy	
A	LPM20	21 21 46	+09 49 07	1.00	15.96	1	Spectroscopy	

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12. Scheduling requirements

13. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
96	SOFI	A	Imaging-LargeField	J
96	SOFI	A	Spectroscopy-long-slit	Blue Grism, 0.6” slit

6b. Co-investigators:

...continued from Box 6a.

J.A.	Caballero	8545
N.J.	Cook	1668
N.R.	Deacon	1668
M.C.	Gálvez-Ortiz	8545
M.	Gromadzki	1842
J.	Jenkins	1823
R.	Kurtev	1842
D.	Montes Gutiérrez	1803
M.T.	Ruiz	1823
R.L.	Smart	1346
Z.H.	Zhang	1393

11a. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
	...continued from box 11.							
A	LPM21	21 38 15	+01 11 51	0.50	14.98	1	Spectroscopy	
A	LPM22	21 53 06	+01 07 39	0.50	15.24	1	Spectroscopy	
A	LPM23	08 31 51	+07 11 56	0.83	15.27	1	Spectroscopy	
A	LPM24	08 31 52	+00 55 14	1.00	15.99	1	Spectroscopy	
A	LPM25	08 36 13	+02 21 06	0.50	14.76	1	Spectroscopy	
A	LPM26	09 14 52	-02 45 55	1.00	15.80	1	Spectroscopy	
A	LPM27	09 38 36	+08 15 10	0.33	14.37	1	Spectroscopy	
A	LPM28	09 38 58	+04 43 43	0.83	15.26	1	Spectroscopy	
A	LPM29	09 44 38	+03 21 31	0.50	14.82	1	Spectroscopy	
A	LPM30	10 19 39	-01 48 10	0.83	15.52	1	Spectroscopy	
A	LPM31	11 48 05	+02 03 48	0.83	15.52	1	Spectroscopy	
A	LPM32	12 12 38	+00 07 21	0.83	15.68	1	Spectroscopy	
A	LPM33	12 19 32	+01 54 32	0.50	15.00	1	Spectroscopy	
A	LPM34	13 46 07	+08 42 33	0.83	15.49	1	Spectroscopy	
A	LPM35	14 22 40	+05 28 52	0.83	15.49	1	Spectroscopy	
A	LPM36	15 44 41	-26 19 05	0.50	15.21	1	Spectroscopy	
A	LPM37	15 46 53	-02 46 05	1.00	15.86	1	Spectroscopy	
A	LPM38	16 30 56	+06 53 27	1.00	15.85	1	Spectroscopy	
A	LPM39	16 32 02	-27 24 01	0.83	15.36	1	Spectroscopy	
A	LPM40	16 32 22	-24 40 15	1.00	15.93	1	Spectroscopy	
A	LPM41	16 35 12	-26 28 49	0.83	15.45	1	Spectroscopy	
A	LPM42	17 53 22	+07 07 01	0.83	15.63	1	Spectroscopy	
A	LPM43	19 23 23	-07 10 34	1.00	15.90	1	Spectroscopy	