SF2A 2024
M. Béthermin, K. Baillié, N. Lagarde, J. Malzac, R.-M. Ouazzani, J. Richard, O. Venot, A. Siebert (eds)

ATMOSPHERIC CHARACTERISATION OF GAIA ULTRA-COOL DWARFS

T. Ravinet[1], C. Reylé[1], N. Lagarde[2], R. L. Smart[3], A. J. Burgasser[4] and J. G. Fernandez-Trincado[5]

Abstract.
The exquisite *Gaia* data offer a new way to detect ultra-cool dwarfs (UCD) at the stellar/substellar transition. Their spectroscopic follow-up permits constraining their properties, such as their spectral types and their peculiarities. Using atmosphere models, we can retrieve their characteristics. It also allows us to verify how the atmosphere models reproduce UCD near-infrared spectra.

We analyse the properties of 60 UCD detected by *Gaia*, expected to span the M/L spectral types. Through template matching, we confirm their spectral types and reveal some properties : we detect binary systems and peculiar objects likely belonging to old stellar population.

Through comparisons with synthetic spectra issued from four atmosphere models, we attempt to retrieve their stellar parameters, from effective temperatures to radii. We show that model struggle reproducing the near-infrared spectra of objects at the M/L transition, likely because of treatments of dust in models.

Keywords: Ultra-cool dwarfs, stars, brown dwarfs, spectroscopy, Gaia

1 Introduction

Ultra-cool dwarfs (UCD) are at the boundary between stars and brown dwarfs. With spectral types later than M7 (Kirkpatrick et al. 1997) and low effective temperatures (below 2800 K, e.g., Rajpurohit et al. 2013), they are intrinsically faint and difficult to detect. UCD make the link between stars and (exo-)planets, and due to the limited understanding of their atmospheric properties and weather, they are key targets for the *James Webb Space Telescope* (Marley & Leggett 2009), as demonstrated by observations of objects like VHS 1256 b (Miles et al. 2023).

The UCD census in the vicinity of the Sun is still ongoing (Bardalez Gagliuffi et al. 2019; Best et al. 2021, 2024; Kirkpatrick et al. 2021a). The *Gaia* space mission (Gaia Collaboration, Brown et al. (2016)) provides new ways of discovering UCD candidates through astrometry and photometry. In *Gaia* Data Release 2, Reylé (2018) identified 14,200 UCD candidates, including over a thousand within 50 pc of the Sun, with additional candidates reported by Smart et al. (2019) and Scholz (2020). The more recent *Gaia* Data Release 3 has provided further UCD candidates and their parallaxes (Smart et al. 2021; Sarro et al. 2023).

UCD spectra, once acquired, are used to study the characteristics of the objects, to confirm their spectral types (Cushing et al. 2005), study their ages and surface gravity (Cruz et al. 2009; Allers & Liu 2013), their kinematics (Burgasser et al. 2015; Hsu et al. 2021), or reveal some hidden companions (e.g., Burgasser 2007; Burgasser et al. 2011; Bardalez Gagliuffi et al. 2014). UCD spectra are also important to study the complex physics occurring in their atmospheres (Marley & Robinson 2015): not only do they allow one to retrieve their characteristics (Hurt et al. 2024; Lueber et al. 2022; Manjavacas et al. 2014), but also to impose constraints on the stellar atmospheric models (Allard et al. 2013).

In this proceeding, we present a sample of 60 UCD low-resolution, near infrared spectra, that was published in Ravinet et al. (2024). We describe their spectral types and peculiarities in Sect. 2, and compare them with synthetic models in Sect. 3 to retrieve their stellar parameters.

---

[1] Université de Franche-Comté, CNRS UMR6213, Institut UTINAM, OSU THETA Franche-Comté-Bourgogne, Observatoire de Besançon, BP 1615, 25010 Besançon Cedex, France

[2] Laboratoire d'Astrophysique de Bordeaux, Université Bordeaux, CNRS, B18N, Allée Geoffroy Saint-Hilaire, 33615 Pessac, France

[3] Istituto Nazionale di Astrofisica, Osservatorio Astrofisico di Torino, Strada Osservatorio 20, I-10025 Pino Torinese, Italy

[4] Department of Astronomy & Astrophysics, University of California San Diego, La Jolla, CA 92093, USA

[5] Instituto de Astronomía, Universidad Católica del Norte, Av. Angamos 0610, Antofagasta, Chile

2 Spectral types and peculiarities

2.1 Methods

We used the Son Of ISAAC (SOFI Moorwood et al. 1998) spectrograph, at the New Technology Telescope (NTT) in La Silla Facility, to acquire spectra of 60 UCD, under ESO programmes 106.214E.001 and 108.22G4.001. These objects were revealed by *Gaia* from their locus in the colour-absolute magnitude diagram (Reylé 2018; Smart et al. 2019; Scholz 2020; Smart et al. 2021). The spectra have a moderate resolution ($R \simeq 600$) and span the near-infrared, between $0.95 - 2.5\,\mu$m.

To obtain their spectral type, we used a template-matching method, using the *SpeX Prism Library Analysis Toolkit* (SPLAT, Burgasser & Splat Development Team 2017). The templates - spectra of objects that are already classified - were obtained from the SpeX Prism Library. Our observed candidates spectral types are obtained by minimizing :

$$\chi^2_R \equiv \sum_{\{\lambda\}} w[\lambda] \left[\frac{C[\lambda] - \alpha T[\lambda]}{\sqrt{\sigma_C[\lambda]^2 + \sigma_T[\lambda]^2}} \right]^2 ,$$

following the method proposed by Cushing et al. (2008). We adopt a vector of weights $w[\lambda]$ where each pixel is weighted by its spectral size ($w_i \propto \Delta\lambda_i$) to avoid a bias towards the blue region of the spectra, where the spectral sampling is greater than in the red regions (Cushing et al. 2008). Also, α is a scaling factor minimising the χ^2 between a template $T[\lambda]$ and an observed spectrum $C[\lambda]$, while $\sigma_C[\lambda]$ and $\sigma_T[\lambda]$ are the noise spectra of SOFI observations and of templates, respectively.

Spectra are also analysed from the perspective of spectral binarity, using the framework proposed by Burgasser (2007); Burgasser et al. (2011); Bardalez Gagliuffi et al. (2014).

2.2 Results

We find that all the 60 spectra are compatible with those of UCD, with 57 having a spectral type between M7 and L4.5, and the three remaining having a spectral type of M6.5. Seven objects share common proper motions and parallaxes with other sources, and thus are in binary systems. Seven more have a 90% chance of being spectral binaries. One object is both sharing common proper motions and shows features of spectral binarity, which, if confirmed from a more detailed analysis, would reveal a trinary composed only of UCD.

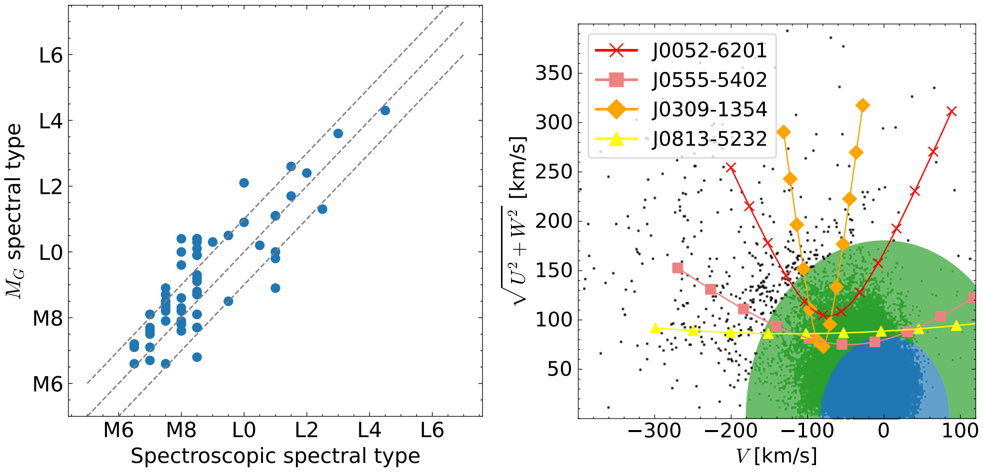

Fig. 1. Left: Spectroscopic spectral types vs spectral types obtained through the Reylé (2018) M_G - spectral type relation. **Right:** Toomre diagram of four objects suspected to be subdwarfs from kinematics criteria, following Nissen (2004) criteria to distinguish thin disk (blue), thick disk (green) and halo (black) stars. Stars are issued from the *Gaia* Catalogue of Nearby Stars (Smart et al. 2021).

On the left panel of Fig. 1, we show how our *spectroscopic* spectral types compare to M_G spectral types, derived using the Reylé (2018) relation. We show that they agree within 1-subtype for most of the objects.

In our sample, eight objects are best-matched by "peculiar" templates, which are spectra of objects exhibiting signs of subsolar metallicity, youthfulness, blue or red excess. The four shown on the right panel of Fig. 1 are compatible with being subdwarfs. Following the Kirkpatrick et al. (2021b) method, and given their *Gaia* proper motions, we assume different radial velocities for them and display where they would stand on a Toomre diagram. The four objects might have kinematics compatible with those of old galactic populations, such as the thick disk or the halo, assuming Nissen (2004) criteria to disentangle them. To confirm their membership to old populations, additional measures of their radial velocities and chemical analysis of their atmospheres would be of interest.

3 Atmospheric characterisation

We compare our low-resolution spectra to synthetic spectra produced by different families of atmosphere models. We use the BT-Settl (e.g., Hauschildt et al. 1997; Allard et al. 2003, 2011, 2013; Baraffe et al. 2015) in two different flavours (BT-Settl AGSS09 based on Asplund et al. (2009) Sun's chemical composition and CIFIST based on Caffau et al. (2011) ones), ATMO (Tremblin et al. 2015; Petrus et al. 2023) and PHOENIX-Drift (Helling et al. 2008; Witte et al. 2011) synthetic grids of spectra to infer the T_{eff}, $\log g$ and [M/H] of our objects from our SOFI spectra. The fitting procedure will be fully described in Ravinet et al. (in prep.), and is based on Markov-Chain Monte Carlo (MCMC) techniques to sample the posterior distributions in parameter space. Adding photometry data and *Gaia* parallax, we can also retrieve objects radii estimations.

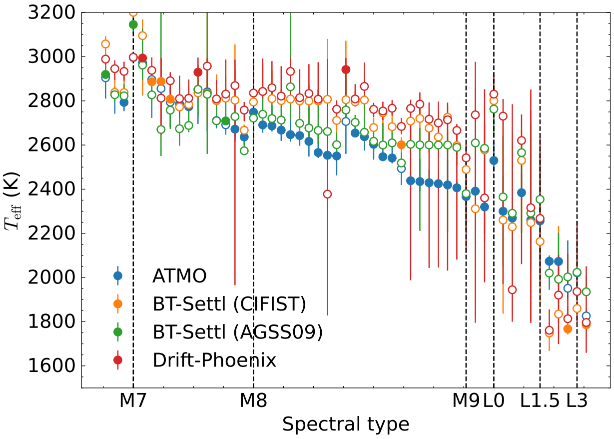

Fig. 2. T_{eff} of the objects obtained through the various atmospheric models. We plot with filled circles the model with the lowest χ^2_R. Each column present one of the objects.

Fig. 2 presents the effective temperatures (and errors) inferred from the various model's grids. The reduced χ^2_R statistic is generally the best for ATMO models, while we find that other models seem to fail to reproduce the near-infrared pseudo-continuum of our SOFI spectra. We find considerable discrepancies in estimated stellar parameters for the same object, with different models, especially at the M/L transition. As this transition is characterised by the appearance of dust in stellar atmospheres, and that this component is hardly modelled, synthetic spectra struggle to reproduce observations in the near-infrared. Apart from effective temperature, the metallicity is also hardly constrained from low resolution spectra: the analysis of the four suspected subdwarfs leads to a single sdM7 having a metallicity consistently below −0.5 dex. Finally, radii and $\log g$ are not fitted consistently : $\log g$ are very uncertain and retrieved radii appear smaller to what is predicted from evolutionary models for field UCD.

4 Conclusions

Using a sample of near-infrared spectra of UCD, we provide their spectral characterisation and show it follows closely the spectral types estimated from their absolute magnitudes. Spectra reveal the presence of hidden companions and of peculiarities. Their stellar parameters are, however, hardly constrained from atmosphere models, especially at the transition between M and L dwarfs, where a dust component might be missing or poorly modelled.

This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www. cosmos.esa.int/web/gaia/dpac/consortium). This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. Based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere under ESO programmes 106.214E.001 and 108.22G4.001. This research has been supported by the Centre National d'Etudes Spatiales (CNES) PhD grant 2021-262, and a PhD grant from the Région Bourgogne-Franche-Comté. Processing steps have been executed on computers from the Utinam Institute of the Université de Franche-Comté, supported by the Région de Franche-Comté and Institut des Sciences de l'Univers (INSU). T.R., C.R., and N.L. acknowledge financial support from the "Programme National de Physique Stellaire" (PNPS) and "Programme National de Cosmologie et Galaxies" (PNCG) of CNRS/INSU, France. J.G.F-T gratefully acknowledges the grant support provided by Proyecto Fondecyt Iniciación No. 11220340, and also from the Joint Committee ESO-Government of Chile 2021 (ORP 023/2021).

References

Allard, F., Guillot, T., Ludwig, H.-G., et al. 2003, 211, 325

Allard, F., Homeier, D., & Freytag, B. 2011, 448, 91

Allard, F., Homeier, D., Freytag, B., Schaffenberger, W., & Rajpurohit, A. S. 2013, Memorie della Societa Astronomica Italiana Supplementi, 24, 128

Allers, K. N. & Liu, M. C. 2013, The Astrophysical Journal, 772, 79

Asplund, M., Grevesse, N., Sauval, A. J., & Scott, P. 2009, Annual Review of Astronomy and Astrophysics, 47, 481

Baraffe, I., Homeier, D., Allard, F., & Chabrier, G. 2015, Astronomy and Astrophysics, 577, A42

Bardalez Gagliuffi, D. C., Burgasser, A. J., Gelino, C. R., et al. 2014, The Astrophysical Journal, 794, 143

Bardalez Gagliuffi, D. C., Burgasser, A. J., Schmidt, S. J., et al. 2019, The Astrophysical Journal, 883, 205

Best, W. M. J., Liu, M. C., Magnier, E. A., & Dupuy, T. J. 2021, The Astronomical Journal, 161, 42

Best, W. M. J., Sanghi, A., Liu, M. C., Magnier, E. A., & Dupuy, T. J. 2024, The Astrophysical Journal, 967, 115

Burgasser, A. J. 2007, The Astrophysical Journal, 659, 655

Burgasser, A. J., Bardalez-Gagliuffi, D. C., & Gizis, J. E. 2011, The Astronomical Journal, 141, 70

Burgasser, A. J., Logsdon, S. E., Gagné, J., et al. 2015, The Astrophysical Journal Supplement Series, 220, 18

Burgasser, A. J. & Splat Development Team. 2017, 14, 7

Caffau, E., Ludwig, H. G., Steffen, M., Freytag, B., & Bonifacio, P. 2011, Solar Physics, 268, 255

Cruz, K. L., Kirkpatrick, J. D., & Burgasser, A. J. 2009, The Astronomical Journal, 137, 3345

Cushing, M. C., Marley, M. S., Saumon, D., et al. 2008, The Astrophysical Journal, 678, 1372

Cushing, M. C., Rayner, J. T., & Vacca, W. D. 2005, The Astrophysical Journal, 623, 1115

Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. ????, 595, A2

Hauschildt, P. H., Baron, E., & Allard, F. 1997, The Astrophysical Journal, 483, 390

Helling, Ch., Ackerman, A., Allard, F., et al. 2008, Monthly Notices of the Royal Astronomical Society, 391, 1854

Hsu, C.-C., Burgasser, A. J., Theissen, C. A., et al. 2021, The Astrophysical Journal Supplement Series, 257, 45

Hurt, S. A., Liu, M. C., Zhang, Z., et al. 2024, The Astrophysical Journal, 961, 121

Kirkpatrick, J. D., Gelino, C. R., Faherty, J. K., et al. 2021a, The Astrophysical Journal Supplement Series, 253, 7

Kirkpatrick, J. D., Henry, T. J., & Irwin, M. J. 1997, The Astronomical Journal, 113, 1421

Kirkpatrick, J. D., Marocco, F., Caselden, D., et al. 2021b, The Astrophysical Journal, 915, L6

Lueber, A., Kitzmann, D., Bowler, B. P., Burgasser, A. J., & Heng, K. 2022, The Astrophysical Journal, 930, 136

Manjavacas, E., Bonnefoy, M., Schlieder, J. E., et al. 2014, Memorie della Societa Astronomica Italiana, 85, 684

Marley, M. S. & Leggett, S. K. 2009, 10, 101

Marley, M. S. & Robinson, T. D. 2015, Annual Review of Astronomy and Astrophysics, 53, 279

Miles, B. E., Biller, B. A., Patapis, P., et al. 2023, The Astrophysical Journal, 946, L6

Moorwood, A., Cuby, J. G., & Lidman, C. 1998, The Messenger, 91, 9

Nissen, P. E. 2004, 154

Petrus, S., Chauvin, G., Bonnefoy, M., et al. 2023, Astronomy & Astrophysics, 670, L9

Rajpurohit, A. S., Reylé, C., Allard, F., et al. 2013, Astronomy & Astrophysics, 556, A15

Ravinet, T., Reylé, C., Lagarde, N., et al. 2024, Astronomy & Astrophysics, 685, A6

Reylé, C. 2018, Astronomy & Astrophysics, 619, L8

Sarro, L. M., Berihuete, A., Smart, R. L., et al. 2023, Astronomy and Astrophysics, 669, A139

Scholz, R.-D. 2020, Astronomy & Astrophysics, 637, A45

Smart, R. L., Marocco, F., Sarro, L. M., et al. 2019, Monthly Notices of the Royal Astronomical Society, 485, 4423

Smart, R. L., Sarro, L. M., Rybizki, J., et al. 2021, Astronomy & Astrophysics, 649, A6

Tremblin, P., Amundsen, D. S., Mourier, P., et al. 2015, The Astrophysical Journal, 804, L17

Witte, S., Helling, Ch., Barman, T., Heidrich, N., & Hauschildt, P. H. 2011, Astronomy and Astrophysics, 529, A44