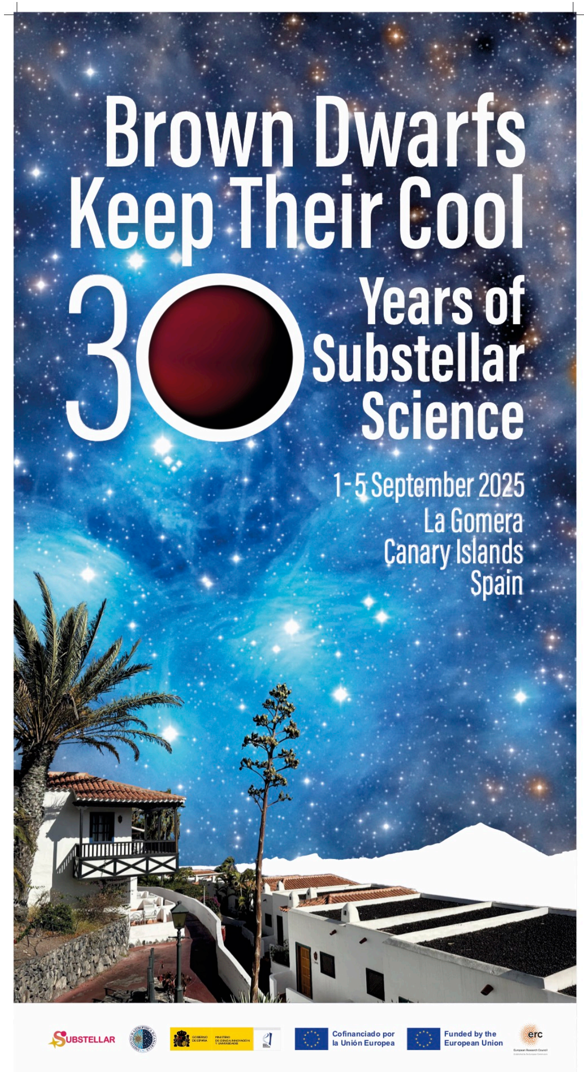
BRIDGES:
Ultracool dwarfs modeling: the bridge between planets and stars

Yakiv’s MSC4Ukraine project



Brown Dwarfs Keep Their Cool

30 Years of Substellar Science

1-5 September 2025
La Gomera
Canary Islands
Spain

SUBSTELLAR

Cofinanciado por la Unión Europea

Funded by the European Union

erc

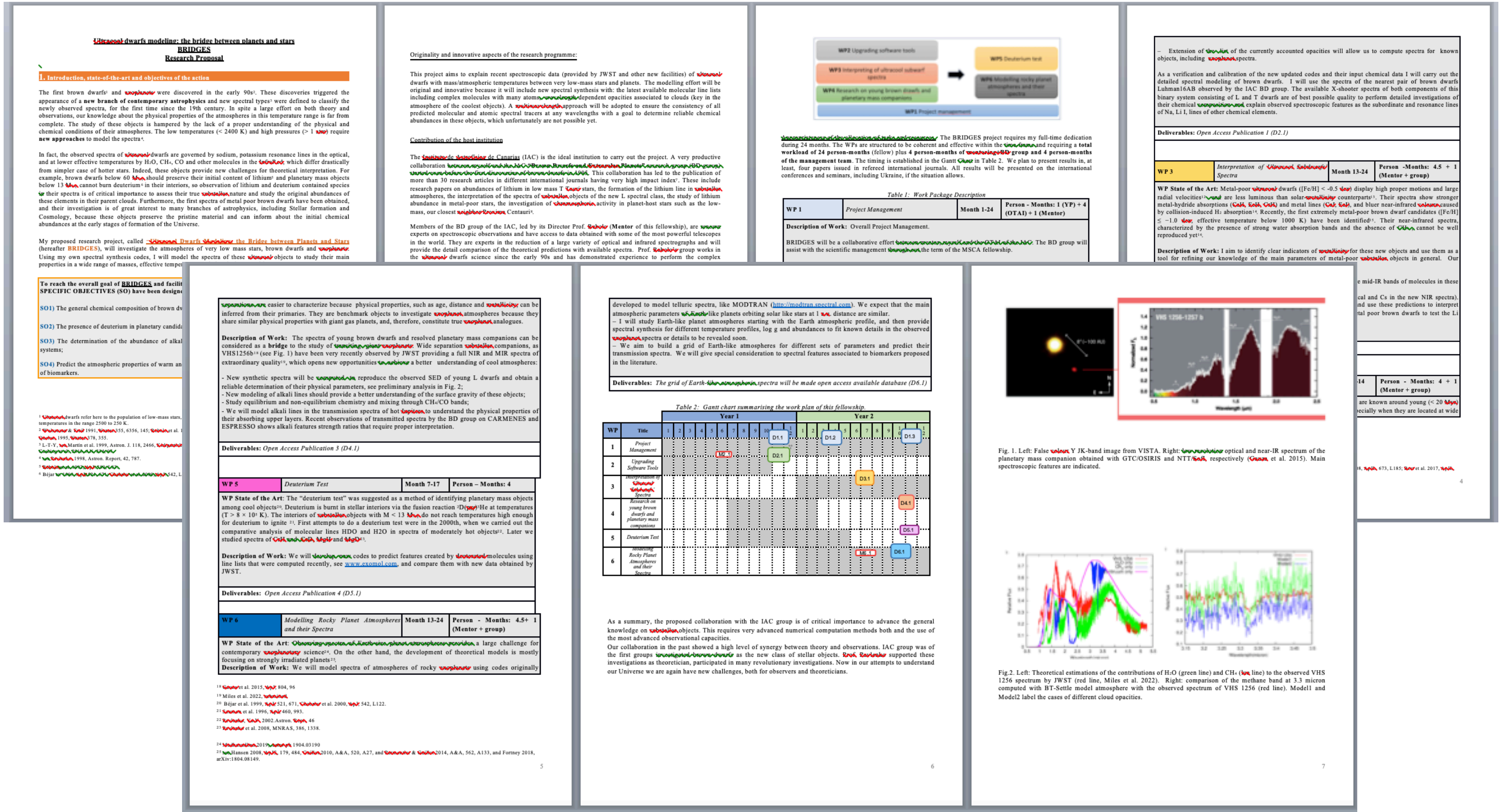
IAC visit 2022

IAC visits: 2009 (2), Nov-Dic 2011, May 2013 (Severo Ochoa), Sep-Oct 2016 (Jesus Serra) and then Sep-Nov 2022 (after covid-19, war…)

- After leaving Ukraine (February 2022), Yakiv was AGAIN a Jesus Serra visitor during September-November 2022
- During this visit we retake our old collaboration in the interpretation of the spectra of young L (VHS1256b) and metal poor (Wise1810) brown dwarfs
- We wrote **MCS4Ukraine proposal** (a UE program for Ukraine researchers to work in UE institutions).

Yakiv Pavlenko
in his visit to the IAC (2016)

MSC4Ukraine proposal



Ultracool dwarfs modeling: the bridge between planets and stars
BRIDGES
Research Proposal

1. Introduction, state-of-the-art and objectives of the action

The first brown dwarfs[1] and exoplanets were discovered in the early 90s[2]. These discoveries triggered the appearance of a **new branch of contemporary astrophysics** and new spectral types[3] were defined to classify the newly observed spectra, for the first time since the 19th century. In spite a large effort on both theory and observations, our knowledge about the physical properties of the atmospheres in this temperature range is far from complete. The study of these objects is hampered by the lack of a proper understanding of the physical and chemical conditions of their atmospheres. The low temperatures (< 2400 K) and high pressures (> 1 atm) require **new approaches** to model the spectra[4].

In fact, the observed spectra of ultracool dwarfs are governed by sodium, potassium resonance lines in the optical, and at lower effective temperatures by H_2O, CH_4, CO and other molecules in the InfraRed, which differ drastically from simpler case of hotter stars. Indeed, these objects provide new challenges for theoretical interpretation. For example, brown dwarfs below 60 M_{Jup} should preserve their initial content of lithium[5] and planetary mass objects below 13 M_{Jup} cannot burn deuterium[6] in their interiors, so observation of lithium and deuterium contained species in their spectra is of critical importance to assess their true substellar nature and study the original abundances of these elements in their parent clouds. Furthermore, the first spectra of metal poor brown dwarfs have been obtained, and their investigation is of great interest to many branches of astrophysics, including Stellar formation and Cosmology, because these objects preserve the pristine material and can inform about the initial chemical abundances at the early stages of formation of the Universe.

My proposed research project, called "Ultracool Dwarfs Modeling: the Bridge between Planets and Stars (hereafter **BRIDGES**), will investigate the atmospheres of very low mass stars, brown dwarfs and exoplanets. Using my own spectral synthesis codes, I will model the spectra of these ultracool objects to study their main properties in a wide range of masses, effective temper

To reach the overall goal of BRIDGES and facilit
SPECIFIC OBJECTIVES (SO) have been designe

SO1) The general chemical composition of brown dw

SO2) The presence of deuterium in planetary candida

SO3) The determination of the abundance of alkal
systems;

SO4) Predict the atmospheric properties of warm an
of biomarkers.

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[1] Ultracool dwarfs refer here to the population of low-mass stars,
temperatures in the range 2500 to 250 K.
[2] Wolszczan & Frail 1991, Nature 355, 6356, 145; Rebolo et al. 1
Queloz 1995, Nature 378, 355.
[3] L-T-Y, see Martín et al. 1999, Astron. J. 118, 2466, Kirkpatrick
[illegible]
[4] see Pavlenko 1998, Astron. Report, 42, 787.
[5] [illegible]
[6] Béjar [illegible] 542, L

Originality and innovative aspects of the research programme:

This project aims to explain recent spectroscopic data (provided by JWST and other new facilities) of ultracool dwarfs with mass/atmospheric temperatures between very low-mass stars and planets. The modelling effort will be original and innovative because it will include new spectral synthesis with: the latest available molecular line lists including complex molecules with many atoms, wavelength-dependent opacities associated to clouds (key in the atmosphere of the coolest objects). A multiwavelength approach will be adopted to ensure the consistency of all predicted molecular and atomic spectral tracers at any wavelengths with a goal to determine reliable chemical abundances in these objects, which unfortunately are not possible yet.

Contribution of the host institution

The Instituto de Astrofísica de Canarias (IAC) is the ideal institution to carry out the project. A very productive collaboration between myself and the IAC "Brown Dwarfs and Extrasolar Planets" research group (BD group) started even before the first discoveries of brown dwarfs in 1995. This collaboration has led to the publication of more than 30 research articles in different international journals having very high impact index[7]. These include research papers on abundances of lithium in low mass T Tauri stars, the formation of the lithium line in substellar atmospheres, the interpretation of the spectra of substellar objects of the new L spectral class, the study of lithium abundance in metal-poor stars, the investigation of chromospheric activity in planet-host stars such as the low-mass, our closest neighbor Proxima Centauri[8].

Members of the BD group of the IAC, led by its Director Prof. Rebolo (**Mentor** of this fellowship), are renown experts on spectroscopic observations and have access to data obtained with some of the most powerful telescopes in the world. They are experts in the reduction of a large variety of optical and infrared spectrographs and will provide the detail comparison of the theoretical predictions with available spectra. Prof. Rebolo's group works in the ultracool dwarfs science since the early 90s and has demonstrated experience to perform the complex

WP2 Upgrading software tools
WP3 Interpreting of ultracool subwarf spectra
WP4 Research on young brown dwarfs and planetary mass companions
WP5 Deuterium test
WP6 Modelling rocky planet atmospheres and their spectra
WP1 Project management

Appropriateness of the allocation of tasks and resources. The BRIDGES project requires my full-time dedication during 24 months. The WPs are structured to be coherent and effective within the time frame and requiring a **total workload of 24 person-months** (fellow) plus **4 person-months of mentoring+BD group and 4 person-months of the management team**. The timing is established in the Gantt Chart in Table 2. We plan to present results in, at least, four papers issued in refereed international journals. All results will be presented on the international conferences and seminars, including Ukraine, if the situation allows.

Table 1: Work Package Description

WP 1	*Project Management*	**Month 1-24**	**Person - Months: 1 (YP) + 4 (OTAI) + 1 (Mentor)**

Description of Work: Overall Project Management.

BRIDGES will be a collaborative effort between mentor, myself and the OTAI of the IAC. The BD group will assist with the scientific management throughout the term of the MSCA fellowship.

– Extension of the list of the currently accounted opacities will allow us to compute spectra for known objects, including exoplanet spectra.

As a verification and calibration of the new updated codes and their input chemical data I will carry out the detailed spectral modeling of brown dwarfs. I will use the spectra of the nearest pair of brown dwarfs Luhman16AB observed by the IAC BD group. The available X-shooter spectra of both components of this binary system consisting of L and T dwarfs are of best possible quality to perform detailed investigations of their chemical composition and explain observed spectroscopic features as the subordinate and resonance lines of Na, Li I, lines of other chemical elements.

Deliverables: *Open Access Publication 1 (D2.1)*

WP 3	*Interpretation of Ultracool Subdwarfs' Spectra*	**Month 13-24**	**Person -Months: 4.5 + 1 (Mentor + group)**

WP State of the Art: Metal-poor ultracool dwarfs ([Fe/H] < -0.5 dex) display high proper motions and large radial velocities[12] and are less luminous than solar-metallicity counterparts[13]. Their spectra show stronger metal-hydride absorptions (CaH, FeH, CrH) and metal lines (CaI, FeI), and bluer near-infrared colours caused by collision-induced H_2 absorption[14]. Recently, the first extremely metal-poor brown dwarf candidates ([Fe/H] ≤ −1.0 dex, effective temperature below 1000 K) have been identified[15]. Their near-infrared spectra, characterized by the presence of strong water absorption bands and the absence of CH_4, cannot be well reproduced yet[16].

Description of Work: I aim to identify clear indicators of metallicity for these new objects and use them as a tool for refining our knowledge of the main parameters of metal-poor substellar objects in general. Our

e mid-IR bands of molecules in these

cal and Cs in the new NIR spectra).
nd use these predictions to interpret
tal poor brown dwarfs to test the Li

14 | **Person - Months: 4 + 1 (Mentor + group)**

are known around young (< 20 Myr)
pecially when they are located at wide

08, ApJL, 673, L185; [illegible] et al. 2017, ApJL

separations are easier to characterize because physical properties, such as age, distance and metallicity can be inferred from their primaries. They are benchmark objects to investigate exoplanet atmospheres because they share similar physical properties with giant gas planets, and, therefore, constitute true exoplanet analogues.

Description of Work: The spectra of young brown dwarfs and resolved planetary mass companions can be considered as a **bridge** to the study of transiting giant exoplanets. Wide separation substellar companions, as VHS1256b[18] (see Fig. 1) have been very recently observed by JWST providing a full NIR and MIR spectra of extraordinary quality[19], which opens new opportunities to achieve a better understanding of cool atmospheres:

- New synthetic spectra will be computed to reproduce the observed SED of young L dwarfs and obtain a reliable determination of their physical parameters, see preliminary analysis in Fig. 2;
- New modeling of alkali lines should provide a better understanding of the surface gravity of these objects;
- Study equilibrium and non-equilibrium chemistry and mixing through CH_4/CO bands;
- We will model alkali lines in the transmission spectra of hot Jupiters to understand the physical properties of their absorbing upper layers. Recent observations of transmitted spectra by the BD group on CARMENES and ESPRESSO shows alkali features strength ratios that require proper interpretation.

Deliverables: *Open Access Publication 3 (D4.1)*

WP 5	*Deuterium Test*	**Month 7-17**	**Person – Months: 4**

WP State of the Art: The "deuterium test" was suggested as a method of identifying planetary mass objects among cool objects[20]. Deuterium is burnt in stellar interiors via the fusion reaction $^2D(p,\gamma)^3He$ at temperatures ($T > 8 \times 10^5$ K). The interiors of substellar objects with M < 13 M_{Jup} do not reach temperatures high enough for deuterium to ignite [21]. First attempts to do a deuterium test were in the 2000th, when we carried out the comparative analysis of molecular lines HDO and H2O in spectra of moderately hot objects[22]. Later we studied spectra of CaH and CaD, MgH and MgD[23].

Description of Work: We will develop own codes to predict features created by deuterated molecules using line lists that were computed recently, see www.exomol.com, and compare them with new data obtained by JWST.

Deliverables: *Open Access Publication 4 (D5.1)*

WP 6	*Modelling Rocky Planet Atmospheres and their Spectra*	**Month 13-24**	**Person - Months: 4.5+ 1 (Mentor + group)**

WP State of the Art: Observing spectra of Earth-size planet atmospheres provides a large challenge for contemporary exoplanetary science[24]. On the other hand, the development of theoretical models is mostly focusing on strongly irradiated planets[25].
Description of Work: We will model spectra of atmospheres of rocky exoplanets using codes originally developed to model telluric spectra, like MODTRAN (http://modtran.spectral.com). We expect that the main atmospheric parameters of Earth-like planets orbiting solar like stars at 1 au distance are similar.
– I will study Earth-like planet atmospheres starting with the Earth atmospheric profile, and then provide spectral synthesis for different temperature profiles, log g and abundances to fit known details in the observed exoplanet spectra or details to be revealed soon.
– We aim to build a grid of Earth-like atmospheres for different sets of parameters and predict their transmission spectra. We will give special consideration to spectral features associated to biomarkers proposed in the literature.

Deliverables: *The grid of Earth-like atmospheric spectra will be made open access available database (D6.1)*

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[18] Gauza et al. 2015, ApJ, 804, 96
[19] Miles et al. 2022, submitted
[20] Béjar et al. 1999, ApJ, 521, 671, Chabrier et al. 2000, ApJ, 542, L122.
[21] Saumon et al. 1996, ApJ, 460, 993.
[22] Pavlenko, Ya.V. 2002.Astron. Rep., 46
[23] Pavlenko et al. 2008, MNRAS, 386, 1338.
[24] Madhusudhan 2019, arXiv: 1904.03190
[25] see Hansen 2008, ApJS, 179, 484, Guillot 2010, A&A, 520, A27, and Parmentier & Guillot 2014, A&A, 562, A133, and Fortney 2018, arXiv:1804.08149.

Table 2: Gantt chart summarising the work plan of this fellowship.

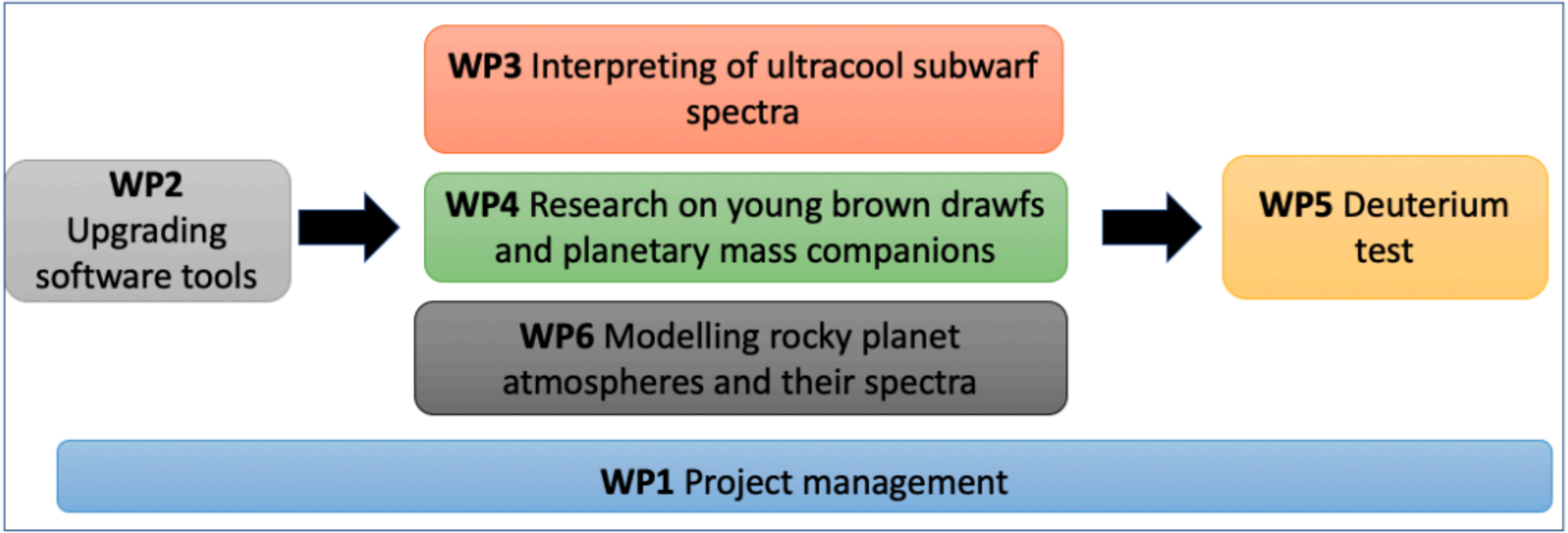
WP	**Title**	Year 1												Year 2											
		1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1	*Project Management*	▨	▨	▨	▨	▨	▨ M2.1	▨	▨	▨	▨	▨ D1.1	▨	▨	▨	▨ D1.2	▨	▨	▨	▨	▨	▨	▨	▨ D1.3	▨
2	*Upgrading Software Tools*	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	D2.1													
3	*Interpretation of Ultracool Subdwarfs' Spectra*													▨	▨	▨	▨	▨	▨	▨ D3.1	▨	▨	▨	▨	▨
4	*Research on young brown dwarfs and planetary mass companions*							▨	▨	▨	▨	▨	▨	▨	▨								D4.1		
5	*Deuterium Test*							▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨						D5.1	
6	*Modelling Rocky Planet Atmospheres and their Spectra*													▨	▨	▨	▨	▨	▨	▨ M6.1	▨	▨	▨ D6.1	▨	▨

As a summary, the proposed collaboration with the IAC group is of critical importance to advance the general knowledge on substellar objects. This requires very advanced numerical computation methods both and the use of the most advanced observational capacities.
Our collaboration in the past showed a high level of synergy between theory and observations. IAC group was of the first groups investigated brown dwarfs as the new class of stellar objects. Prof. Pavlenko supported these investigations as theoretician, participated in many revolutionary investigations. Now in our attempts to understand our Universe we are again have new challenges, both for observers and theoreticians.

Fig. 1. Left: False colour Y JK-band image from VISTA. Right: low-resolution optical and near-IR spectrum of the planetary mass companion obtained with GTC/OSIRIS and NTT/SofI, respectively (Gauza et al. 2015). Main spectroscopic features are indicated.

Fig.2. Left: Theoretical estimations of the contributions of H_2O (green line) and CH_4 (blue line) to the observed VHS 1256 spectrum by JWST (red line, Miles et al. 2022). Right: comparison of the methane band at 3.3 micron computed with BT-Settle model atmosphere with the observed spectrum of VHS 1256 (red line). Model1 and Model2 label the cases of different cloud opacities.

Main objectives



WP3 Interpreting of ultracool subwarf spectra

WP2 Upgrading software tools

WP4 Research on young brown drawfs and planetary mass companions

WP5 Deuterium test

WP6 Modelling rocky planet atmospheres and their spectra

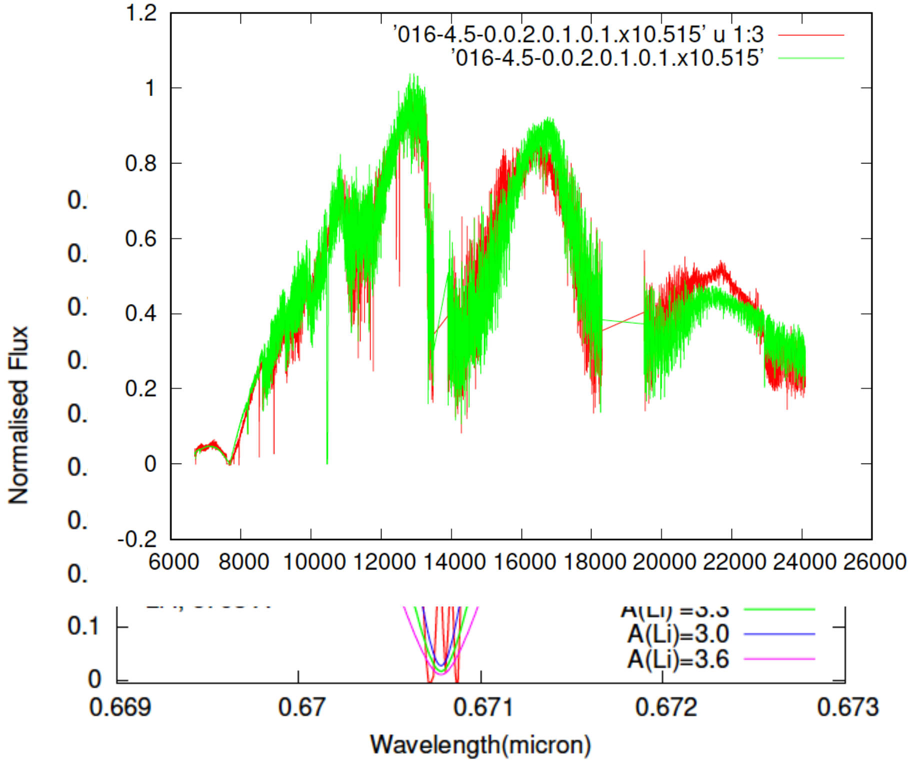
WP1 Project management

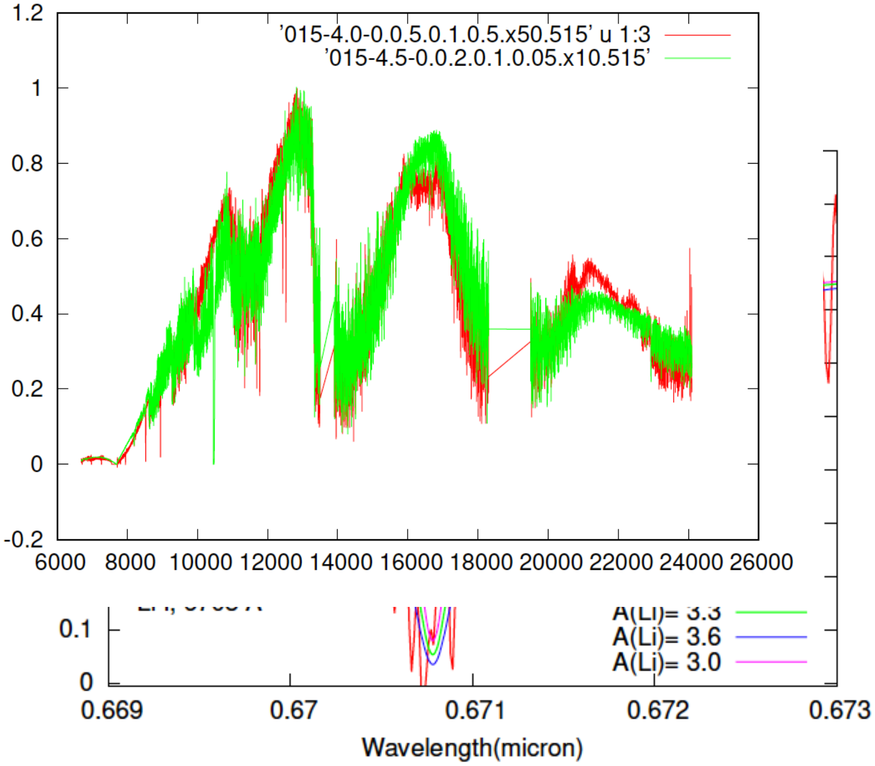
Since 2009 visit:

- Earth-like spectra
- Subestellar objects <1000K. "Y dwarfs"
- Deuterium test: deuterated hidrures.
- Young bd's and IPMOs spectra.

Results: Update WITA code

- Model the spectra of BDs Luhman 16AB: Additional oppacity above photosphere is needed. Cosmic Li abundance is found





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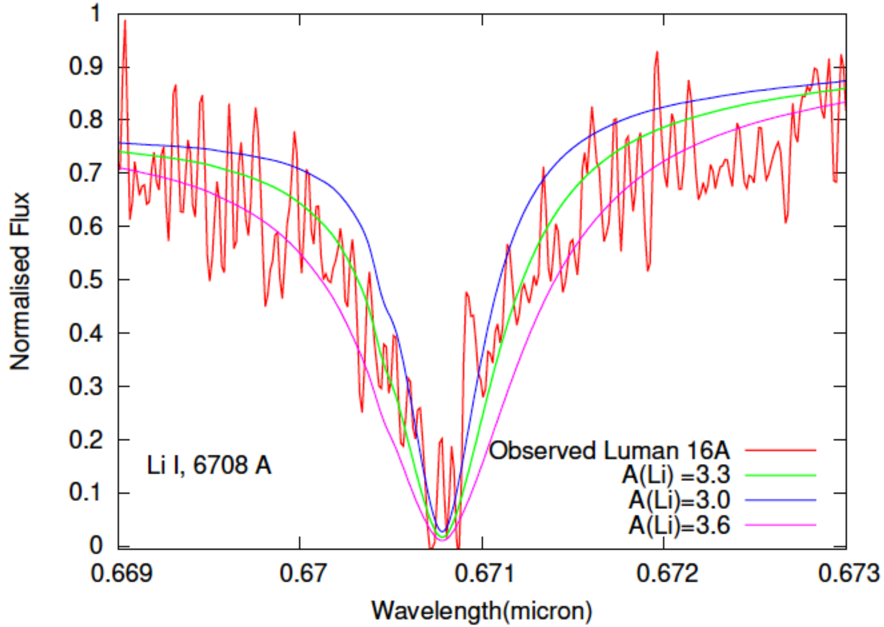
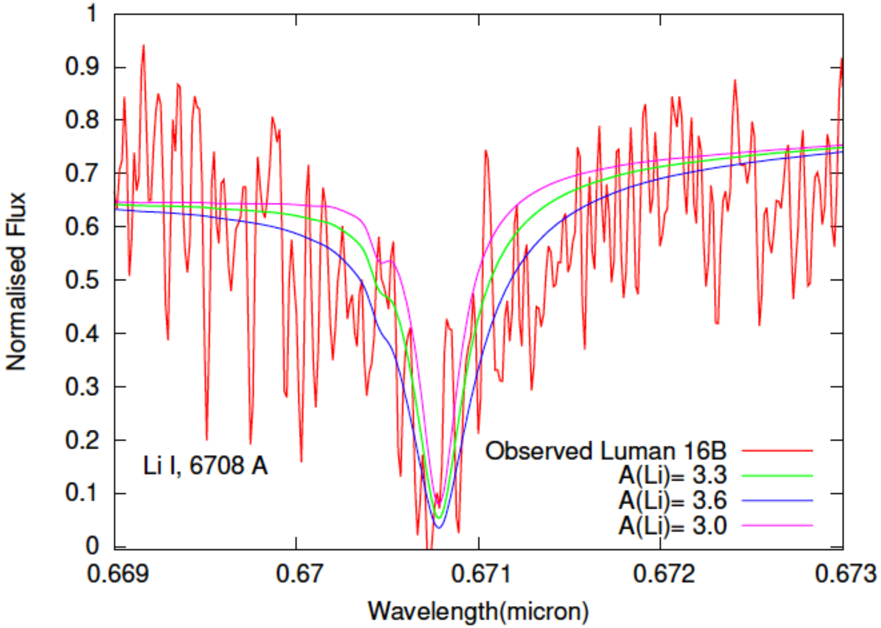
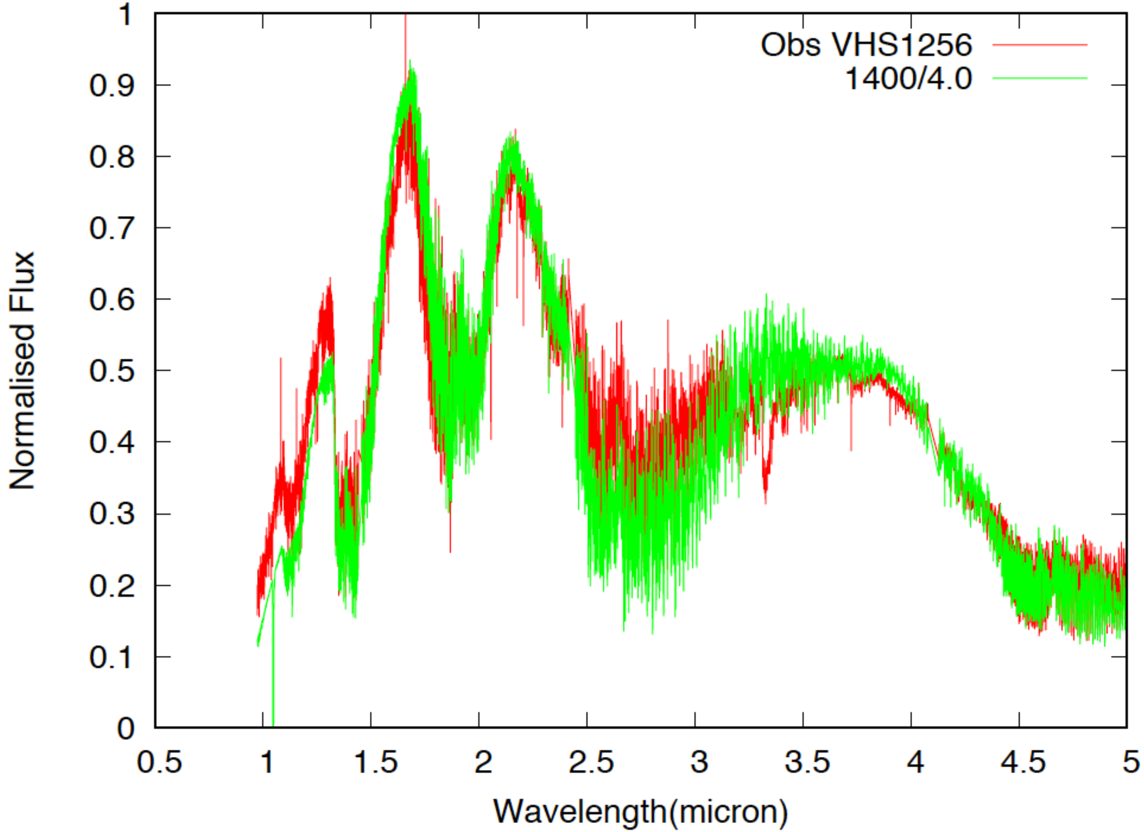
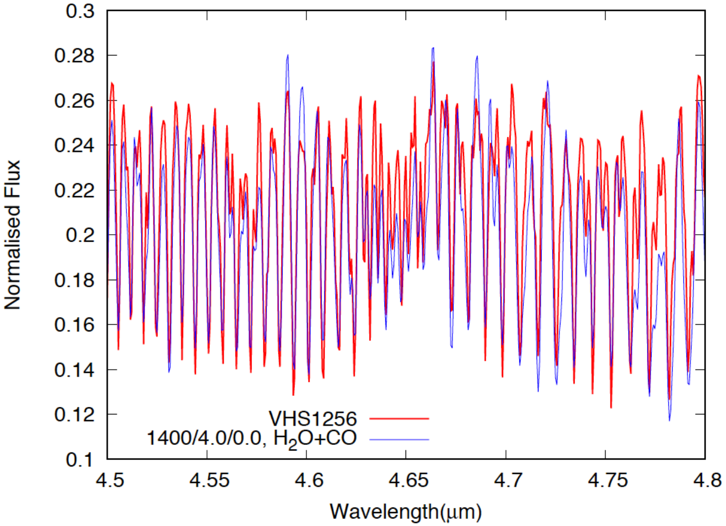




Results: vhs1256b

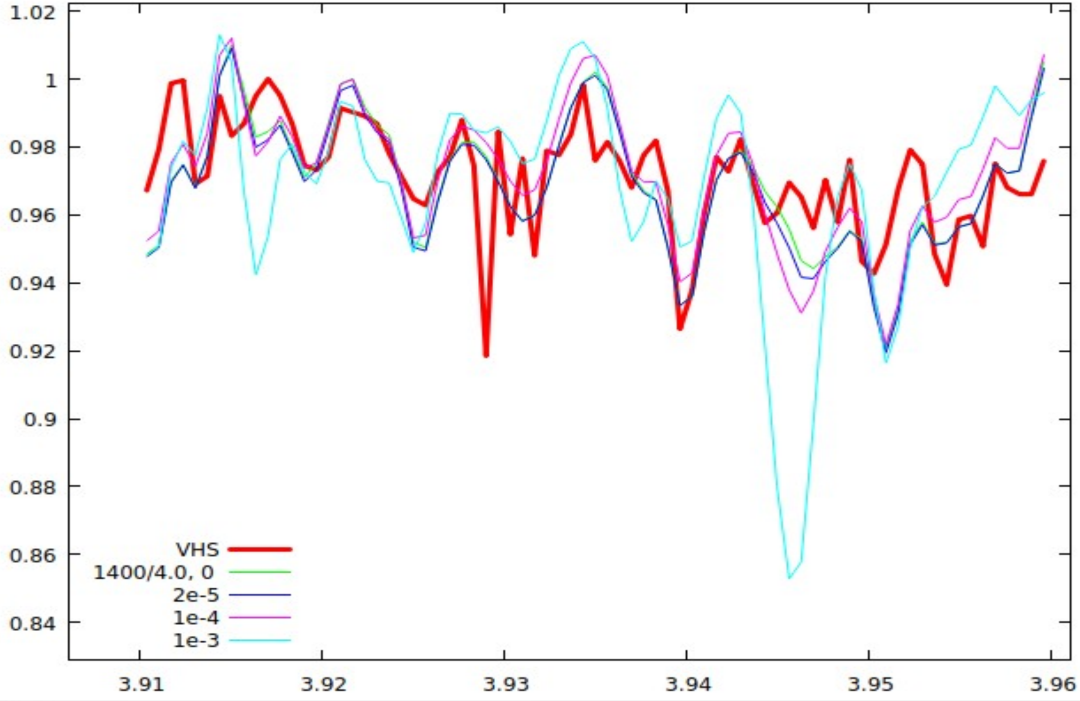




CO bands

Results: Deuterium test

NEW HDO/H2O ; (1400/4.0)



Yakiv’s last visit at the Teide Observatory