Benchmark brown dwarf companions as exoplanets analogues

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Directly imaged substellar companions around stars are key objects for better understanding the formation and evolution of brown dwarfs and massive planets, as we can infer physical properties like the age, distance or metallicity from their host stars. Moreover, we can characterize them spectroscopically, seeking for features that may provide information on the properties of gas giant exoplanets, in particular, on the composition of their complex atmospheres. Here we outline our program aiming to identify and characterize substellar companions to stars using the ongoing VISTA Hemisphere Survey (VHS). Focusing on the young L and T dwarfs and objects from the frontier of the Y-type dwarfs we enter the domain of planetary masses and below 1000 K temperatures.

1 Introduction

Brown dwarfs, unlike stars, are characterized by core temperatures too low to ignite and sustain stable hydrogen fusion. The existence of a limiting mass below which a contracting body cannot reach the H-burning main sequence stage was first predicted theoretically in the early sixties (Kumar, 1963; Hayashi & Nakano, 1963). Such objects without an internal source of energy cool down and fade during their evolution. Unlike stars, brown dwarfs do not reach the main sequence and hence their mass can not be defined solely from the effective temperature ($T_{\rm eff}$) or luminosity. A period of 30 years passed before the first two brown dwarfs were confirmed by almost simultaneous discoveries (Rebolo et al., 1995; Nakajima et al., 1995). Interestingly, the discoveries of the first extrasolar planets were announced in the same years (Wolszczan & Frail, 1992; Mayor & Queloz, 1995). Over time, brown dwarfs were recognized to play a key role for understanding of both planets and very low-mass stars, as they constitute the link between these two populations.

In the past two decades, large area imaging surveys like SDSS (Abazajian et al., 2003) or 2MASS (Skrutskie et al., 2006) have brought forth numerous discoveries of low-mass stars and brown dwarfs, allowing to extend the spectral sequence to $T_{\rm eff}$ below 2500 K (L type; Kirkpatrick et al. 1999), 1500 K (T type; Burgasser et al. 2006) and most recently, below 600 K (Y type; Cushing et al. 2011). Today, over 1000 L and T-type substellar objects have been identified, however the vast majority are isolated field objects. Only 56 M6–M9, 59 L and 21 T dwarfs are known to be companions in binary and multiple systems (Deacon et al., 2014; Scholz, 2016), most of which are old and only a few have a well constrained age. To better understand their properties, abundances, formation and evolution mechanisms a key step is to undertake systematic searches that will increase the number of known ultracool (i.e.,

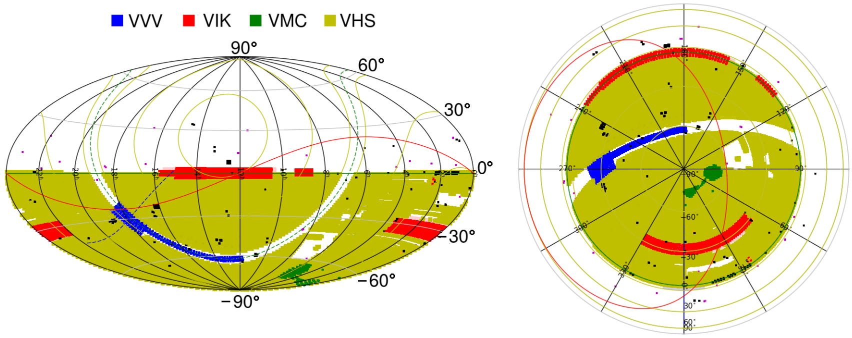

Fig. 1: Sky coverage of the VISTA surveys as of Nov. 2017. Yellow fields correspond to the VISTA Hemisphere Survey. So far about 95% of the total VHS area (~19,000 deg^2) have been observed and processed.

later than M6) companions, spanning broad range of ages, masses, temperatures and orbital separations.

Here we describe a search for substellar companions to stars carried out using the VISTA Hemisphere Survey (VHS; McMahon et al. 2013) data in combination with other large sky area surveys like 2MASS and WISE. In the following section we describe the basic facts about the VHS with its current status and we summarize our approach to select candidates. Sec. 3 and 4 concern our main objects of interest, namely the late T and Y dwarfs and the young L and T dwarfs, respectively. Final remarks are given in Sec. 5.

2 The VISTA Hemisphere Survey and candidates selection

The VHS is a near-infrared imaging survey, which in combination with other VISTA Surveys will cover the full Southern sky. It uses the 4.1 m VISTA telescope equipped with a wide-field camera (VIRCAM) covering 1.5 deg^2 in a single contiguous tile composed of 6 individual pointings. The VHS provides data in at least two wavebands (J and K_s), reaching a depth 30 times fainter than 2MASS or DENIS, with an exposure time of 60 s per waveband to produce median 5σ point source limits of $J = 20.2$ and $K_\mathrm{s} = 18.1$ mag. In some parts of the sky, also Y and H band observations are performed. To date, the survey has covered about 19,000 deg^2 (see Fig. 1) and is expected to be completed by the second half of 2018. The discovery of the lowest-mass stars and substellar objects is one of the main scientific motivations of the VHS (McMahon et al., 2013).

To carry out the search, we cross-matched the VHS source catalog that provides astrometry and near-IR photometry, with the 2MASS and WISE catalogs. We explored an area with a radius of one-degree around each target star. For objects detected in 2MASS, we looked primarily for common proper motion candidates. Since the epochs of these two surveys are separated by 10 yr or more, we are able to find sources with proper motions as low as 0.1 arcsec yr^{-1}, taking into account the astrometric precision of VHS and 2MASS. Having the photometric information, we selected candidates showing colors consistent with those of ultracool dwarfs. As for the fainter objects, with $J > 17.5$ mag, too faint to be detected in 2MASS, we looked

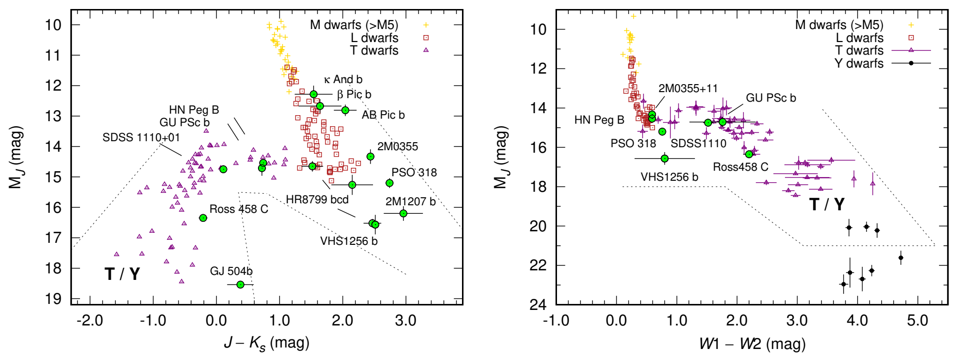

Fig. 2: $M_{\rm J}$ vs. $J - Ks$ and $M_{\rm J}$ vs. $W1 - W2$ color magnitude diagrams showing the sequence of field M (>M5), L, T and Y dwarfs (Dupuy & Liu, 2012) in comparison with young substellar objects (green points with labels). The regions we aim to explore in this project are marked with dotted lines.

for counterparts in the WISE data. With the photometry in near- and mid-IR, and given the extreme $J - K_s$, $J - W2$ and $W1 - W2$ colors, we can identify late T/early Y type companions, along with young L and T companions. On the color magnitude diagrams presented in Fig. 2 we marked with dashed lines the regions where these objects should be found, and these are the regions we aim to explore.

For efficient handling of the large data tables we employed the Virtual Observatory software TOPCAT and STILTS (Taylor, 2005) as well as custom software developed within our group. The general sample of target stars of the project can be divided into three sub-groups: 1) nearest southern stars (within 10-15 pc) – about 200 stars in total, 2) young nearby stars (<500 Myr, d<100 pc) – about 1500 stars, and 3) high proper motion stars ($\mu > 0.1$ arcsec yr^{-1}) – several thousands sources in the sample (Pérez-Garrido et al., in preparation)

3 The T/Y boundary and the Y dwarfs

The latest T-type brown dwarfs (T8-T9) have $T_{\rm eff}$ of the order of 750–600 K. There is then a gap of about 500 K between these objects and Jupiter at 124 K. The first objects with temperatures below 600 K were discovered in searching for faint and cold companions. Luhman et al. (2011) identified a wide (2500 AU) companion to a white dwarf WD 0806–661, whose $T_{\rm eff}$ was estimated at 300–345 K. Liu et al. (2011) found a tight (2.6 AU) companion to a T9.5 brown dwarf CFBDSIR 1458+10, whose $T_{\rm eff}$ was found to be 370 ± 40 K. However, it was not until the WISE satellite was launched that field objects with such low temperatures and bright enough for spectroscopic follow-up were identified (Cushing et al., 2011; Kirkpatrick et al., 2012). Beside a very narrow, peak-like emission in the J and H bands, their spectra were found to show ammonia absorption features and the presence of water clouds (Kirkpatrick et al., 2012; Leggett et al., 2015). This distinctive spectral morphology led to the birth of a new spectral type – Y. Currently, only 24 objects have been classified as Y dwarfs (Leggett et al., 2017). To better understand the trends and diversity across the late T and Y spectral sequence, more examples are badly needed.

We aim to find new Y dwarf companions to the nearest stars, within a distance

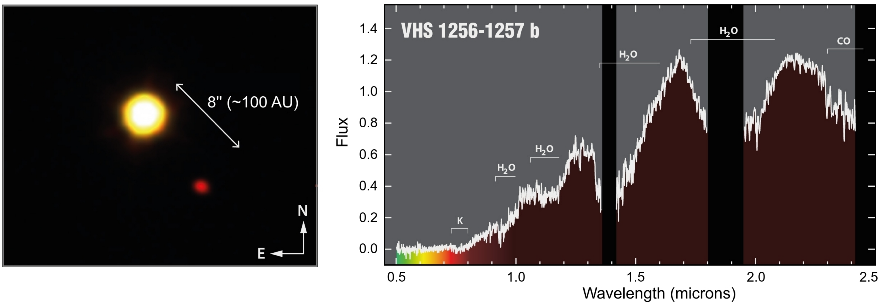

Fig. 3: Left: False color YJK_s-bands image of the young M dwarf VHS 1256AB and its L7-type planetary mass companion (Gauza et al., 2015), found using the VHS data. Right: low-resolution 0.5–2.4 μm spectrum of VHS 1256 b, with main spectral features indicated.

of 10 pc. This is made possible thanks to the sensitivity of VHS and its large sky coverage. It is now known that objects from the T/Y-type frontier have absolute magnitudes of $M_J = 19$–20 mag, so that with the VHS sensitivity of $J = 20.2$ mag, we will be able to detect such companions within 10 pc distance. Sky coverage of VHS allows to study a wide range of separations around each star, which are currently unexplored to this sensitivity. With a sample of $\sim$200 stars, we plan to measure the Y-type companions frequency at wide orbits. Each newly found and characterized Y dwarf will support the understanding of this barely known population.

4 Young L and T dwarfs

Direct imaging surveys have found a number of young (< 500 Myr) L dwarfs, which exhibit distinctive spectral and photometric features, like weak alkali lines, peaked shape of the H-band or excessively red $J - K_s$ color (> 2 mag), making them appear significantly different than their older (> 1 Gyr) counterparts in the field. Studies have revealed a strong resemblance between these young L dwarfs and directly imaged massive planets (e.g., 2MASS 1207-39 b, Chauvin et al. 2005, HR 8799 bcde, Marois et al. 2010). They have similar colors and absolute magnitudes, overlapping $T_{\rm eff}$ of $\sim$1000–1500 K, and masses of a few to a few tens of Jupiter mass (Bowler et al., 2013; Faherty et al., 2014). However, still only a handful of young L dwarfs are known, and many of their properties, like extremely red $J - K_s$ colors, remain unexplained. Each new discovery is therefore crucial for improving our understanding of this class of objects. An example of a young L-type companion, VHS 1256 b, identified using VHS data is presented in Fig. 3. From a thorough characterization of this system we found the mass of the companion to be close to deuterium burning mass limit (Gauza et al., 2015). Spectroscopic characterization of such objects provide valuable information on the properties of gas giant exoplanets, in particular, on the composition of their complex atmospheres.

Even less is known about T dwarfs at ages below 1 Gyr. Until now, only two Ts were confirmed to be young: a wide 9–13 $M_{\rm Jup}$ planetary mass companion to the young star GU Psc (T3.5 $\pm$ 1 at 70–130 Myr, Naud et al. 2014) and SDSS 1110+0116, a T5.5 member of the AB Dor moving group (110–130 Myr, Gagné et al. 2015). Other three are suspected to have young or intermediate ages, below

1 Gyr: GJ 504b, a $4\,M_{Jup}$ planet with a spectral type estimated to be late T - early Y (Kuzuhara et al., 2013), Ross 458 C (T8-9, Goldman et al. 2010), and HN Peg B (T2.5 $\pm$ 0.5, Luhman et al. 2007). Interestingly, no spectral characteristics of these young Ts appear to be strongly different from the field counterparts, unlike the case of young Ls. However, with such a small number of objects, no firm conclusions can be drawn yet. We aim to search for young L and T-type companions around known young nearby stars. With ∼1500 stars covered by the VHS, we plan to study the occurrence rate of such companions up to 20,000 AU separations. Based on previous work sensitive to L dwarfs and estimates of frequency of at least 1%, a few of these objects are expected to be found.

5 Final remarks

We carry out a search for ultracool companions to stars in the VHS, focusing on sources with the lowest known temperatures – late T and Y type objects, and the young L and T-type planetary mass objects. At the age of the Sun, late T and Y dwarfs, and at ages below 500 Myr, L dwarfs, are at the borderline between brown dwarfs and massive planets, therefore our research will focus on objects with planetary masses. The characterization of these benchmark companions will be the key to improve our understanding of the physical properties of exoplanets discovered by other techniques, since they have similar temperatures, masses and gravities.

Since the first discoveries, the populations of brown dwarfs and extrasolar planets have largely been examined independent of one another. However, over the last years comparative brown dwarf/exoplanet studies have rapidly advanced. The Y dwarfs and young L and T dwarfs, both isolated and identified as companions, represent valuable points of reference which may reveal strong connections in the features of the two populations. In the near future these faint objects will shed new light on our current paradigm of how planets and the least massive brown dwarfs may form.

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References

Abazajian, K., et al., *AJ* **126**, 2081 (2003)

Bowler, B. P., Liu, M. C., Shkolnik, E. L., Dupuy, T. J., *ApJ* **774**, 55 (2013)

Burgasser, A. J., et al., *ApJ* **637**, 1067 (2006)

Chauvin, G., et al., *A&A* **438**, L25 (2005)

Cushing, M. C., et al., *ApJ* **743**, 50 (2011)

Deacon, N. R., et al., *ApJ* **792**, 119 (2014)

Dupuy, T. J., Liu, M. C., *ApJS* **201**, 19 (2012)

Faherty, J. K., Cruz, K. L., Rice, E. L., Riedel, A., in M. Booth, B. C. Matthews, J. R. Graham (eds.) IAU Symposium, *IAU Symposium*, volume 299, 36–37 (2014)

Gagné, J., et al., *ApJL* **808**, L20 (2015)

Gauza, B., et al., *ApJ* **804**, 96 (2015)

Goldman, B., et al., *MNRAS* **405**, 1140 (2010)

Hayashi, C., Nakano, T., *Progress of Theoretical Physics* **30**, 460 (1963)

Kirkpatrick, J. D., et al., *ApJ* **519**, 802 (1999)

Kirkpatrick, J. D., et al., *ApJ* **753**, 156 (2012)

Kumar, S. S., *ApJ* **137**, 1121 (1963)

Kuzuhara, M., et al., *ApJ* **774**, 11 (2013)

Leggett, S. K., Morley, C. V., Marley, M. S., Saumon, D., *ApJ* **799**, 37 (2015)

Leggett, S. K., et al., *ApJ* **842**, 118 (2017)

Liu, M. C., et al., *ApJ* **740**, 108 (2011)

Luhman, K. L., Burgasser, A. J., Bochanski, J. J., *ApJL* **730**, L9 (2011)

Luhman, K. L., et al., *ApJ* **654**, 570 (2007)

Marois, C., et al., *Nature* **468**, 1080 (2010)

Mayor, M., Queloz, D., *Nature* **378**, 355 (1995)

McMahon, R. G., et al., *The Messenger* **154**, 35 (2013)

Nakajima, T., et al., *Nature* **378**, 463 (1995)

Naud, M.-E., et al., *ApJ* **787**, 5 (2014)

Rebolo, R., Zapatero Osorio, M. R., Martín, E. L., *Nature* **377**, 129 (1995)

Scholz, R.-D., *A&A* **587**, A51 (2016)

Skrutskie, M. F., et al., *AJ* **131**, 1163 (2006)

Taylor, M. B., in P. Shopbell, M. Britton, R. Ebert (eds.) Astronomical Data Analysis Software and Systems XIV, *Astronomical Society of the Pacific Conference Series*, volume 347, 29 (2005)

Wolszczan, A., Frail, D. A., *Nature* **355**, 145 (1992)