SCIENCE IN THE SPANISH VIRTUAL OBSERVATORY

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ABSTRACT

Since the beginning of the Spanish Virtual Observatory (SVO[1]) in 2004 science is playing a key role. In order to boost the use of the VO capabilities among the Spanish astronomical community our group is fostering an initiative based on the collaboration with research teams having science cases that could benefit from using the VO. Our role in the collaboration is to evaluate the science case from the VO point of view, to provide information and support about the existing VO tools to tackle the scientific problem and, if necessary, to develop new analysis tools.

Effective liaisons have been established between the SVO and a number of funded projects and, as a result of this, several refereed VO papers have been published.

In this presentation an overview of these collaborations and the results obtained so far are presented.

Key words: Virtual Observatory: tools, science cases.

1. INTRODUCTION

Although still evolving, the Virtual Observatory is now mature enough to be used by the astronomical community. Taking advantage of its capability of efficiently correlating large, multi-dimension data sets, the Virtual Observatory is opening the possibility for discovering new features in known phenomena as well as totally unexpected astrophysics. The first major discovery made with the VO is described in (16): the VO science team involved in the project discovered 31 previously undetected supermassive black holes in the GOODS fields following a VO methodology. The classification of ROSAT sources using multiwavelength information and data mining techniques (15), the discovery of massive, dust-enshrouded, carbon stars in nearby galaxies (19) or the discovery of an extremely-rare object (8) are also excellent examples of the science that can be done with the Virtual Observatory.

However, there is a number of limiting factor (lack of knowledge of the VO initiative, absence of links between the VO groups and the research community,...) that may have a strong impact on the growth of VO. In an attempt to avoid this situation the Spanish VO is collaborating with several research groups who have identified scientific drivers to motivate the adoption of a Virtual Observatory methodology in their science cases. In what follows I will briefly describe some of these science cases.

2. IDENTIFICATION OF ACCRETING BROWN DWARFS USING VO TOOLS

Brown dwarfs (BDs), substellar mass objects that do not stabilize on the Hydrogen-burning main sequence, cool and fade continuously with time as they shrink to increasingly degenerate configurations. They start as relatively warm objects, spectral class M, and evolve to cooler temperatures, characterized spectroscopically as spectral classes L and T.

The formation process of brown dwarfs is still a matter of debate. Although the star-like formation scenario is widely accepted, there are other approaches that have to be taken into account. One of these alternative scenarios is the ejection theory (17) which suggests that brown dwarfs could be leftovers of a prematurely interrupted accretion process. One of the major drawbacks of this theory are the associated high spatial velocities, incompatible with the formation of circumstellar disks (an observational evidence in brown dwarfs). Moreover, these expected high velocities have not been seen in star-forming regions like Taurus or Chamaeleon. A possible solution to this problem can be found in (18) who proposed that brown dwarf would form by the fragmentation of the outer parts of the stellar disks. Once formed, the objects would be gently released into the field by interactions among themselves. *Gently* in this context means low velocity dispersion giving the ability of retaining the disks that produce the IR excesses and accretion phenomena seen in many young brown dwarfs.

[1]http://svo.laeff.inta.es

In order to shed light to this problem, we have started a project to study the spatial distribution of brown dwarfs (20). Using VO tools we have cross-matched IPHAS and 2MASS to search young BD candidates by their Hα emission and infrared colors. IPHAS (INT Photometric Hα survey of the Northern Galactic Plane, (10), (11)), is a major survey covering 1800 square degrees of the northern Milky Way that provides Sloan r', i' and narrowband Hα photometry down to a magnitude limit of r' = 20. So far the overwhelming majority of the surveys for the search of young very low-mass objects were concentrated in the known star-forming regions, such as, for example, the Taurus-Auriga region which is the prototypical low-density diffuse cloud. In this sense our search is a pioneering work as the wide spatial coverage provided by IPHAS offers, for the first time, the possibility of searching accreting objects that, according to the ejection theory, may have travelled far from their birth sites and, thus, would not have been revealed by previous surveys.

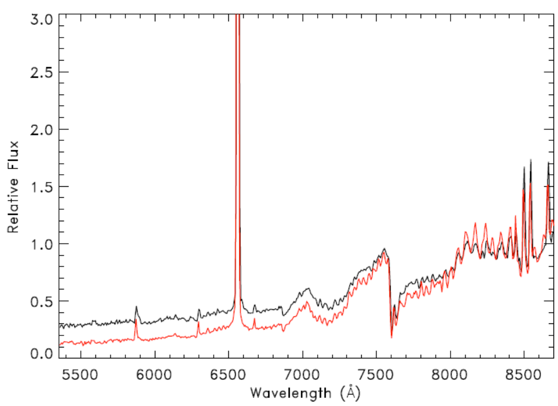

Figure 1. Spectra of IPHAS J214625.99+572829.0 observed on two different nights. A significant variability is showing in the continuum and the Hα emission.The variability might be due to co-rotating hot spots, changes in the accretion flow geometry or changes in the mass accretion rate onto the central object.

Due to mass accretion processes, many young low-mass stars and brown dwarfs show Hα emission stronger than the emission expected from chromospheric activity (Fig 1). Studying the Hα equivalent width and the spectral type using low-resolution spectra it can be determined whether or not a star is accreting (1). A spectroscopic follow-up of some of the 4000 potential candidates confirmed that thirty-three of them show strong Hα indicative of disk accretion for their spectral type (Fig 2). Ten of them, with classes in the range M5.5-M7.0, could be very young brown dwarfs. A detailed analysis of the distribution in the sky of these objects and their membership to star-forming regions will be part of a forthcoming paper (21).

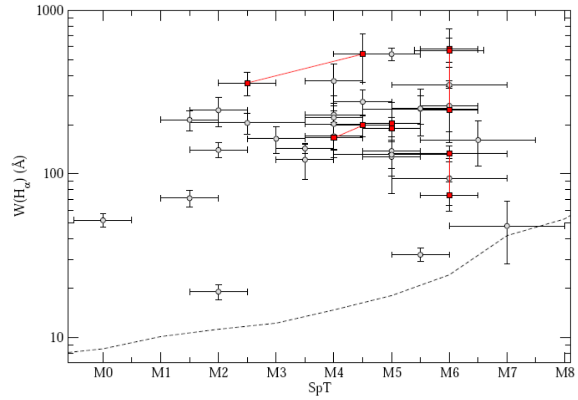

Figure 2. Hα equivalent width against adopted spectral type for our objects. The dashed line denotes the dividing line between chromospheric activity and disk accretion. Our objects are clearly above the dashed line and hence they are likely undergoing mass accretion.

3. AUTOMATED DETERMINATION OF PHYSICAL PARAMETERS USING VOSA. THE CASE OF COLLINDER 69

One of the most interesting star-forming regions is associated to the O8III star λ Orionis, located at about 400 pc from the Sun and presenting very low extinction (Av=0.36 mag.) in its inner area. This star dominates the eponymous cluster (also designated as Collinder 69), with an age of about 5 Myr (2).

Our goal is to determine physical parameters of $\sim$ 170 candidate members of this cluster. Studying the physical parameters of a large population of sources belonging to the same cluster is advantageous, as we can infer properties not only of the individual sources but also of the association as a whole, for example its age, assuming that all objects are coeval.

The physical parameters have been determined by comparing observed SEDs with theoretical data. This methodology requires, as a first step, gathering all the photometric/spectral information available for each of our sources. Once the observational SED has been built it has to be compared with different collections of models (which may translate into thousands of individual models). These tasks, if performed with classical methodologies, can easily become tedious and even unfeasible when applied to large amount of data. On the contrary, the Virtual Observatory represents the adequate framework where to tackle them.

In order to efficiently perform this analysis a new VO-tool was built by the Spanish Virtual Observatory. The tool was named *VOSA*[2] (Virtual Observatory SED Analyzer, (4)). In short, the tasks performed by VOSA are as follows:

[2] http://www.laeff.inta.es/svo/theory/vosa/

- Query several photometric catalogs accessible through VO services in order to increase the wavelength coverage of the data to be analysed.
- Query VO-compliant theoretical models (spectra) for a given range of physical parameters. The models are accessible in a VO-environment from the SVO theoretical data server.[3]
- Calculate the synthetic photometry of the theoretical spectra (within the required range of physical parameters) for the set of filters previously chosen by the user.
- Perform a statistical $\chi 2$ test to decide which set of synthetic photometry reproduces best the observed data. Determine physical parameters like effective temperature, surface gravity and metallicity (Fig 3).
- Use the best-fit model as the source of a bolometric correction. Determine of the luminosity.
- Generate a Hertzsprung-Russell diagram using the theoretical isochrones and evolutionary tracks available in the SVO theoretical data server to determine the age and mass of each individual target of the sample and the age of the association as a whole.

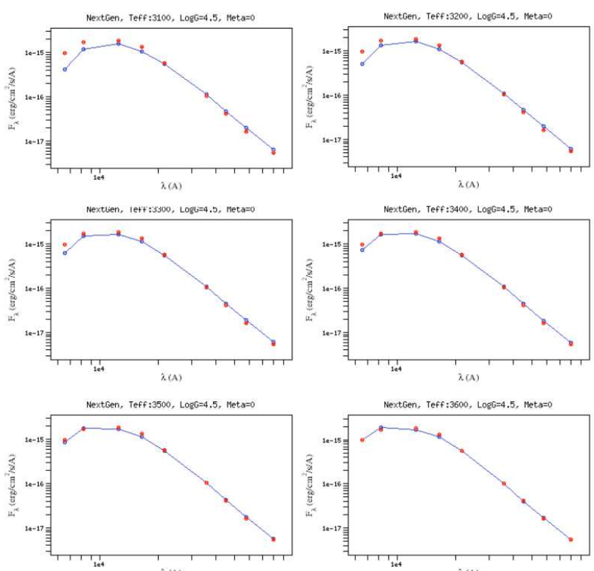

Figure 3. Fits and physical parameters estimation using VOSA for six members of Collinder 69.

Using this workflow we have provided an estimation of the age of the association through the analysis of 120 bona-fide cluster members (Fig 4). Three of these sources were fitted using the DUSTY models. In these cases we derived an upper-limit age of 5 Myr. Among the remaining 117 sources, we inferred an upper-limit age for Collinder 69 of 12.3 − 16 Myr, consistent with the estimated ages for the cluster by other authors. (e.g. (9))

[3] http://laeff.inta.es/svo/theory/db2vo/

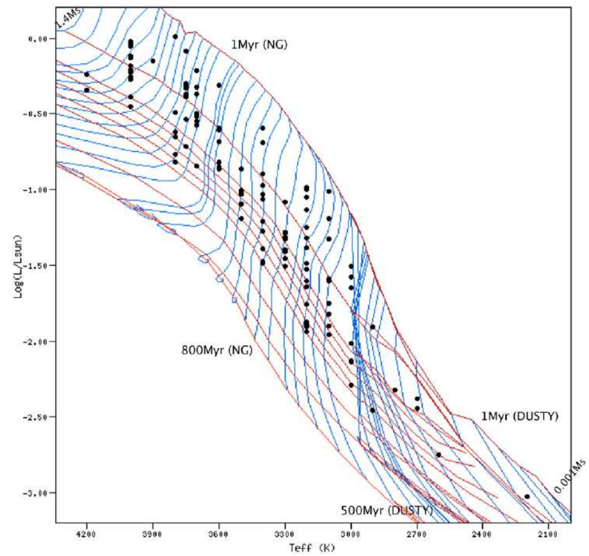

Figure 4. HR diagram of the members of Collinder 69 for which no infrared excess was detected. Isochrones corresponding to ages of 1, 5, 10, 12.5, 16, 20, 25, 50, 100 and 800 Myrs are displayed for the NextGen collection, and those corresponding to ages of 1, 5, 10, 50, 100,120 and 500 Myr for the DUSTY collection. Evolutionary tracks are also displayed for masses between 0.001M and 1.4M (Bayo et al. 2008.

Moreover, 23 sources were found to have anomalous positions in the HR diagram (Fig 5). We pointed out three main reasons to explain such a behaviour.

- Sources with infrared excess caused by the presence of a disk. The dust belonging to the disk reprocesses the light emitted by the central object and, in the cases where the angle of the disk and/or the amount of flaring is high enough, the light from the star can be blocked giving rise an underestimation of the effective temperature and the bolometric luminosity.
- Degeneracy of the fitting process. When the number of points making up the SED is as low as five no conclusion can be assessed as VOSA attempts to fit four independent parameters.
- Cluster non-members: We have independently confirmed the classification of sixteen sources with an anomalous position in the HR diagram already flagged as possible non-members in (3). Based on its very low temperature, one of the non-members might be a field L dwarf.

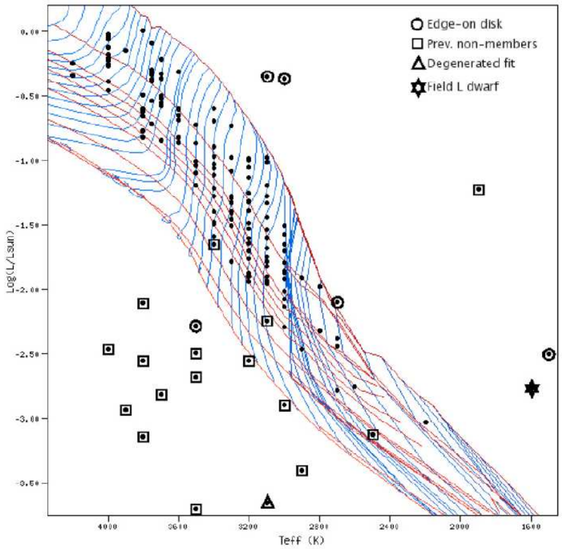

Figure 5. Location in the HR diagram of the peculiar sources.

4. YOUNG STARS AND BROWN DWARFS AROUND ALNILAM AND MINTAKA

Brown dwarfs are much brighter when younger. However, young star-forming regions typically have variable extinction that hinders the characterisation of the recently-born brown dwarfs. The σ Orionis cluster in the Ori OB1b association represents an exception to this rule due to its youth ($\sim$ 3 My), closeness (d $\sim$ 385 pc) and low extinction ($A_v \leq 0.3$ mag).

To compare substellar mass functions, spatial distributions or disc frequencies and to look for new brown dwarfs and planetary-mass objects it is necessary to search as many new locations as possible. Since the new hunting grounds for the search of substellar objects must resemble σ Orionis, it is natural to look for them not far away. (7) have investigated the stellar populations surrounding two bright supergiants in the Orion Belt: Alnilam (ϵ Ori) and Mintaka (δ Ori).

In this study the authors performed a comprehensive VO-based search and a bibliographic data compilation of more than 107,000 sources in the vicinity of these stars. The brightest sources were analyzed by cross-correlating Tycho-2 and 2MASS whereas DENIS and 2MASS were used for the less massive objects (Fig. 6).

The Tycho-2/2MASS sources were classified in three groups according to their probability of membership in the Ori OB1b association, namely:

- Stars showing signposts of youth. By features of youth we understand early spectral types (O and B), Li i in absorption, strong X-ray or H emission (possibly associated to accretion processes), and infrared excesses by circumstellar material.We have also considered additional youth features, like the star being in the Herbig Ae/Be phase (HAeBe) or having a Vega-like disk.
- Stars with unknown association membership status. They are stars with proper motions $\mu < 12$ mas/yr that do not deviate very much from the young-star sequence in the colour−magnitude diagrams but have no known, clear, signposts of youth.
- Stars that do not belong to the association This class comprises: (i) foreground stars with proper motions $\mu < 12$ mas a^1 ; (ii) foreground G-, K-, and M-type stars with spectral type determination; (iii) Hipparcos stars with $\pi/\delta\pi > 3$ and heliocentric distances less than 250 pc; (iv) red stars without spectral type determination, and with colours $VT - Ks > 2.5$mag and spectral energy distributions of KM type stars; (v) very red objects with colours $VT - Ks > 4.5$mag and without flux excess due to discs in the mid-infrared.

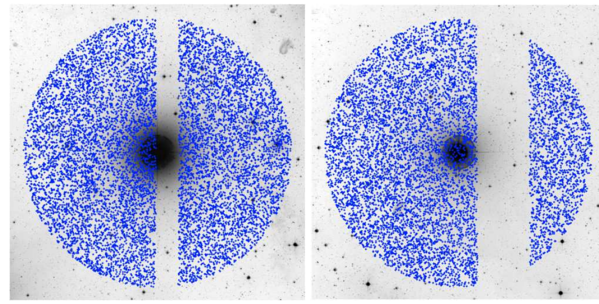

Figure 6. DENIS/2MASS sources in the Alnilam (left) and Mintaka (right) fields.

For the DENIS/2MASS sources we used data of ten, nearby comparison fields ($\sim$ 87 000 sources) to determine the region of the i vs. i−Ks colour−magnitude diagram where the probability of contamination by fore- and background sources is minimum. Known foreground dwarfs, background giants, reddened stars, and galaxies were subsequently removed from this sample.

From all this analysis we found 136 stars displaying features of extreme youth as well as two young brown dwarf and 289 star candidates. The catalogue, ranging from the two massive OB-type supergiants to intermediate M-type substellar objects, provides a characterization of the mass function from 15 to 0.07 solar masses and constitutes an excellent starting point for further, more detailed follow-up studies of the stellar and high-mass substellar populations in the Orion Belt.

In addition to this, we investigated the spatial distribution of stars surrounding Alnilam and Mintaka. We concluded that, if there is a cluster surrounding Alnilam, it must be larger than our search radius of 45 arcmin and its (sub)stellar population may, therefore, spatially overlap with neighbouring star-forming regions like the σ Orionis cluster. The evidence for a real cluster surrounding Mintaka is, however, more apparent but not conclusive from our data analysis. Less concentrated than the σ Orionis cluster, it might represent a next evolutionary stage.

4.1. Albus-1: a very bright WD candidate that turned out to be a bright He-B Subdwarf

Albus-1 was discovered on the basis of its very blue VT − Ks color in one of the comparison fields used in the study of the Alnilam and Mintaka's neighbourhood . We used the Virtual Observatory as a discovery tool to shed some light on the nature of this object. We found that only Tycho-2 and 2MASS information as well as the RI photometric data from USNO-B1 were available. No radio (NRAO VLA), mid-infrared (IRAS), ultraviolet (EUVE), or X-ray (ROSAT) source or object discussed in the literature (SIMBAD) was found at less than 5 arcmin to Albus-1. Spectroscopic information and photometry in the Johnson passbands were neither available.

We built the Spectral Energy Distribution of Albus-1 using the archive information and, on the basis of its resemblance with those of well-known white dwarfs, (8) tentatively classified Albus-1 as the brightest white dwarf discovered in the last forty years (Fig. 7).

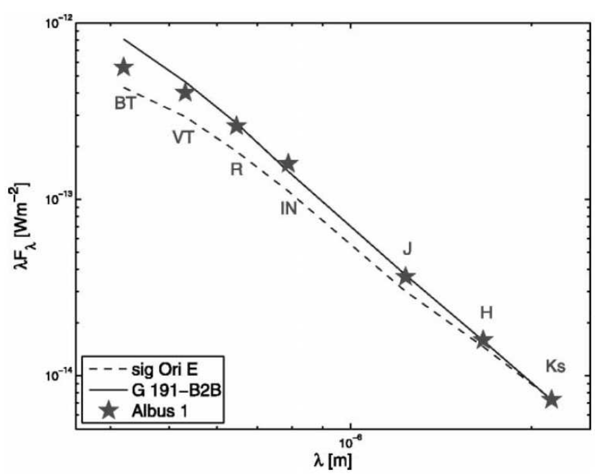

Figure 7. Spectral energy distributions of Albus 1, the DA1 white dwarf G191-B2B, and the B2 Vp star σ Ori E (shifted to a heliocentric distance of 0.5 kpc). The seven passbands (BVRIJHK) are indicated.

Albus-1 was later spectroscopically followed-up by (22) who demonstrated that it was indeed an extremely rare object: a bright helium-rich B subdwarf (Fig. 8). Hot subdwarf B (sdB) stars are core helium burning stars that lie at the hot end of the horizontal branch (the extreme horizontal branch stars). These stars cover a narrow mass range around 0.5 $M_\odot$ and have very thin hydrogen , ($< 0.02\ M_\odot$) envelopes. They possibly evolved via two main branches. The first is through single-star

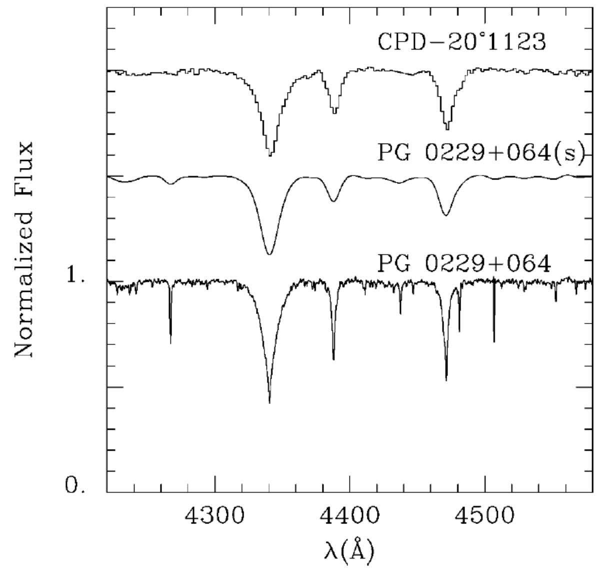

Figure 8. Comparing CPD -20 1123 (Albus-1) (shifted up by 1.0 unit) and PG 0229-064. The spectrum of PG 0229-064 is presented at the nominal resolution of 0.8 Å as well as degraded to a resolution of 8 Å (labeled s and shifted up by 0.5 units).

evolution where the star fails to ascend the asymptotic giant branch and loses most of its mass via extensive mass loss. The second is through binary-star evolution, with one proposed scenario involving the merger of two helium white dwarfs. This is, in particular, the most likely approach to explain the origin of He-sdB stars.

5. IDENTIFICATION AND CHARACTERIZATION OF ULTRACOOL SUBDWARFS

Ultracool subdwarfs are metal-deficient, very low mass stars and brown dwarfs with late spectral types (6). They are the metal-poor analogs of ultracool dwarfs, spectral types M7 and later, and represent the low-temperature ($T_{\rm eff} \leq 3000$ K) extensions of the M subdwarf (sdM; [M/H] $\sim$ -1.2) and extreme subdwarf classes (esdM; [M/H] $\sim$ -2.0). Subdwarfs are easily distinguished from dwarfs with solar abundances because they exhibit stronger metal-hydride absorption bands (FeH, CrH) and metal lines (CaI, FeI) as well as blue infrared colours caused by collision-induced H_2 absorption (Fig. 9).

Cool and ultracool subdwarfs typically exhibit halo kinematics including large proper motions and large heliocentric velocities and were presumably formed early in the history of the Galaxy. With their extremely long nuclear burning lifetimes, these low-mass objects are important tracers of Galactic structure and chemical enrichment history and are representatives of the first generations of star formation.

Over the past few years, the number of known ultracool subdwarfs has increased, due largely to new proper-motion surveys based on photographic R- and I-band imaging like SUPERBLINK (13) or the SuperCOSMOS Sky Survey (12). These surveys exploit the high space velocities of halo subdwarfs and their relative brightness at red wavelengths. More recently, (14) identified a large sample of ultracool subdwarfs in the spectroscopic database of the Sloan Digital Sky Survey (SDSS). In addition, several late-type subdwarfs, including the two latest type L subdwarfs now known, have been serendipitously identified with 2MASS based on their unusual photometric colors and offset optical counterparts (due to proper motion).

In an effort to find new ultracool subdwarfs, we have conducted using Virtual Observatory tools two photometric and proper motion searches over 1200 square degrees using SDSS (bright sources) and UKIDSS/LAS (faint sources). We have imposed various constraints based on the expected color of these objects. Candidates were later filtered based on their position in a reduced proper motion diagram. The final list contain 21 (bright) and 15 (faint) candidates. If confirmed spectroscopically, we would double the number of known ultracool subdwarfs and open new prospects in the study of low-metallicity ultracool dwarfs using large-scale surveys.At the time of writing this paper, we have obtained spectra for three of our candidates which have confirmed their ultracool subdwarf nature (Fig. 10).

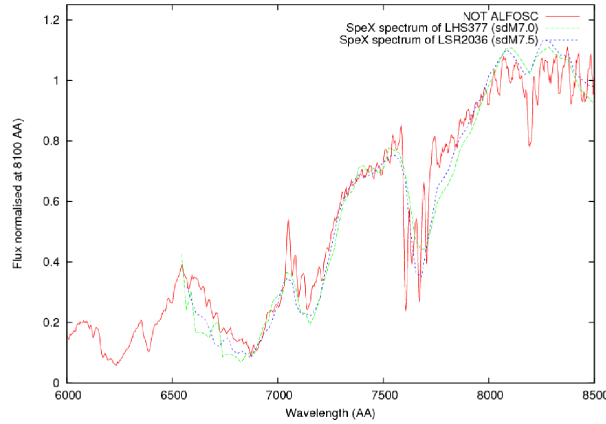

Figure 10. Determination of the spectral type for one of our spectroscopically confirmed ultracool subdwarfs.

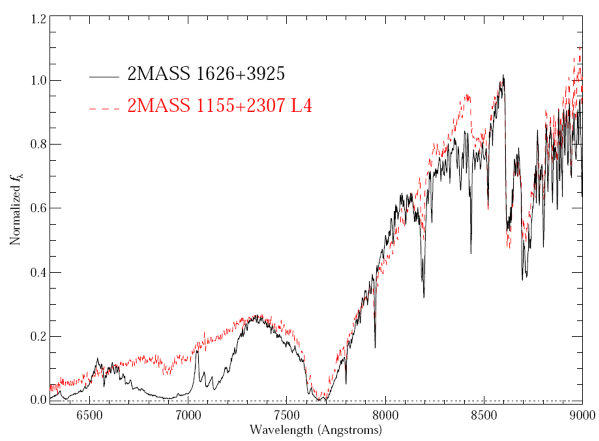

Figure 9. Comparison of the 6300−9000Å optical spectra of 2MASS1626+3925 (black solid line) and the L4 field dwarf 2MASS1155+2307 (red dashed line). Note the fairly good agreement between the spectra over 7500 to 9000Å, and the difference at shorter wavelength. Figure taken from (5).

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