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Spectroscopy of ultra-cool dwarfs

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Abstract. The discovery of a numerous population of very low mass stars and brown dwarfs in the past decades has led to the definition of the new L, T, and recently Y spectral types. In this proceeding, early discoveries and the main spectroscopic characteristics of these objects in the optical and near-infrared will be reviewed. Ultracool dwarfs (later than ∼M7) are either very low mass stars or substellar objects, depending on their age. Spectroscopic tests, such as the "Li test", have been very useful in confirming the true substellar nature of some of these objects, and in particular of brown dwarfs with masses lower than 0.055 $M_{\odot}$. The spectroscopic characterization of low-mass candidates in open clusters has also led to the identification of brown dwarfs and isolated planetary-mass objects showing features of low gravity and youth that confirm their membership. This has permitted the determination of reliable mass functions. Among the hundreds of ultracool objects currently known, several low metallicity subdwarfs and young field dwarfs have also been identified. This also includes several L and T companions of stars, which can serve as benchmark objects for substellar studies since their physical properties, such as distance, metallicity and age, are well known from their primaries. Spectroscopic studies of ultracool dwarfs are also important for learning more about extrasolar planet atmospheres, since they have similar $T_{\rm eff}$ and gravities. The comparison of the spectroscopic characteristics of free-floating ultracool dwarfs, L and T wide companions, and extrasolar planets may provide insights into the formation mechanisms of these objects.

Key words. Stars: brown dwarfs – Stars: low mass – Stars: late-type – Techniques: spectroscopic

1. Introduction

Ultracool dwarfs were first defined in a refereed paper by Kirkpatrick et al. (1997) as objects with spectral type ≥ M7. Since then, this nomenclature has been widely used but sometimes with different interpretations. In this review, we will adopt this definition. Until 1995, only 20 field dwarfs with spectral types ≥ M7 were known, and their spectra were presented and classified by Kirkpatrick et al. (1995). In this work, the latest spectral type objects, BRI 0021–0214 and GD 165 B, were classified as ≥ M9.5 and ≥ M10, respectively. Since then, thousands of ultracool dwarfs have been found. Most of them are late M, and L dwarfs, but some of them are also T, and more recently, Y dwarfs.

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2. Early discoveries and definition of L, T, and Y spectral types

2.1. L dwarfs

In the early nineties the coolest known object was found to be a companion of the GD 165 white dwarf (Becklin & Zuckerman 1988). In 1993, the first spectrum of GD 165 B was obtained by Kirkpatrick et al. (1993) and, in spite of being partially contaminated by the primary, was unlike that of any other M dwarf. Although GD 165 B is recognized as the first L dwarf, its substellar nature is still not clear. The first field L dwarfs were identified in the same year (1997) by three different groups (Kirkpatrick et al. 1997; Ruiz et al. 1997; Delfosse et al. 1997). Hence, we can consider that 1997 was a special year for the emergence of L dwarfs. The first confirmed L brown dwarf was Kelu1, which was found in isolation (Ruiz et al. 1997). After these results, several L dwarfs were also discovered in the field by the optical and near-infrared surveys *2MASS* and *DENIS* (Delfosse et al. 1997; Kirkpatrick et al. 1997, 1999, 2000).

In 1997, at the "Brown Dwarf and Extrasolar Planets" workshop in Tenerife, Kirkpatrick (1998) proposed a new spectral type for these objects and suggested to use the letters "H", "L", "T" and "Y". Martín et al. (1997) were the first to propose a new spectral class, "L", for objects cooler than M-type in a refereed paper. In 1999, two spectral classifications of L dwarfs appeared: one based on the definition of standards (Kirkpatrick et al. 1999) and other based on pseudo-continuum indexes, which were also related to a temperature scale (Martín et al. 1999). The L-type class corresponds to $T_{\rm eff}$=2200–1500 K. They are characterized in the optical by the disappearance of TiO and VO molecular bands due to the formation of dust grains, the presence of very strong alkaline lines (Li, Na, K, Rb, Cs), and hydrides (FeH, CrH), and in the near-infrared by strong water vapor absorption bands (Kirkpatrick et al. 1999; Martín et al. 1999). See optical spectra of L dwarfs in Fig. 1.

2.2. T dwarfs

The first "methane" or T dwarf was found as a companion of the M star Gl 229 (Nakajima et al. 1995). In the same year, the first near-infrared spectrum of Gl 229 B was obtained, showing the typical methane absorption band characteristics of these objects (Oppenheimer et al. 1995). After this discovery, several searches, using mainly large area surveys such as *2MASS* and *SLOAN*, were successful at identifying T-type objects (Strauss et al. 1999; Cuby et al. 1999; Burgasser et al. 1999, 2000; Leggett et al. 2000). Hence, we may consider that 1999 and 2000 were special years in the emergence of T dwarfs.

In 2002, again two spectral classifications of T dwarfs appeared, one based on the definition of standards (Burgasser et al. 2002), and other based on flux ratios (Geballe et al. 2002). A unified scheme of both classifications was presented by Burgasser et al. (2006). The T-type class corresponds to $T_{\rm eff}$=1500–500 K and in their atmospheres the dust grains deposit below the photosphere. They are characterized by the disappearance of alkalines and hydrides in the optical, and by the presence of very strong water vapor and the appearance of methane absorption bands in the infrared (Burgasser et al. 2002; Geballe et al. 2002). See near-infrared spectra of T dwarfs in Fig. 2.

2.3. Y dwarfs

In 2011, two companions with estimated spectral types $\geq$T10 were found by Luhman et al. (2011) and Liu (2011) around the white dwarf WD 0806–661 and the T9.5 dwarf CFBDSIR J1458+1013, respectively. In the same year, Cushing et al. (2011) presented the discovery and characterization of the first six Y dwarfs found by the *WISE* satellite. Later on, several other Y dwarfs were located using *WISE* data (Kirkpatrick et al. 2012; Tinney et al. 2012). Tentatively, the Y-type objects corresponds to $T_{\rm eff} < 500$ K and are characterized by very red optical/near-infrared to mid-infrared colors, i.e. they emit most of their fluxes in the mid-infrared, by their narrower flux emission in the H and J-band in comparison with late

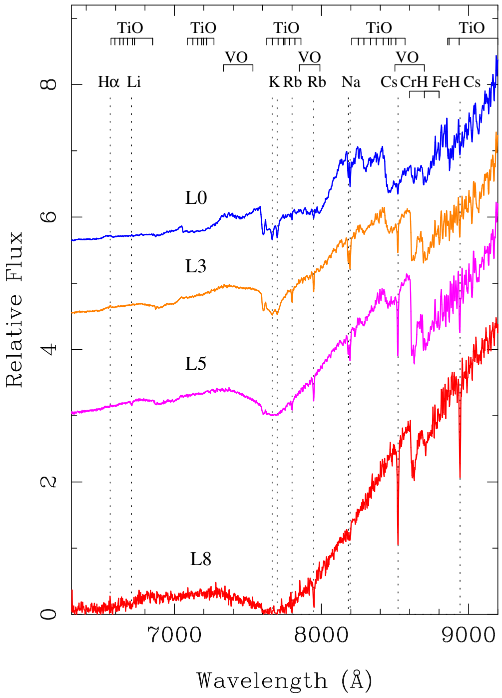

Fig. 1. Optical spectroscopy of L dwarfs obtained by Kirkpatrick et al. (1999, 2000). Main spectral features are indicated. Spectra have been normalized at 8100 Å and have been shifted for clarity.

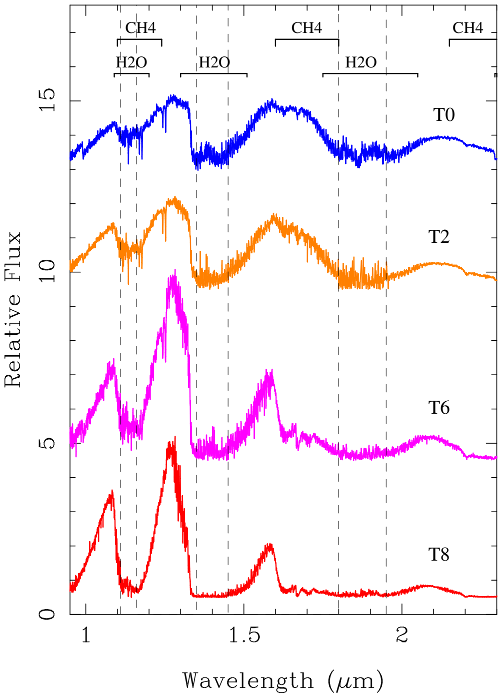

Fig. 2. Near-infrared spectroscopy of T dwarfs obtained by Burgasser et al. (1999, 2000). Main spectral features are indicated. Spectra have been normalized at 1.0 μm and have been shifted for clarity.

T-dwarfs and the possible change toward bluer $Y - J$ and redder $J - K$ colors from late T to Y dwarfs (Kirkpatrick et al. 2011, 2012). Up to now, there has been no classification that properly defines the Y class and its different subclasses.

3. A test for substellarity: the Li test

According to theoretical evolutionary models, L dwarfs are either very low mass stars with ages of a few Gyr or brown dwarfs with masses close to the hydrogen burning mass limit or younger than 1 Gyr (Burrows et al. 1997; Chabrier et al. 2000). Based on the same models, T dwarfs are expected to be brown dwarfs. The Li test was developed in order to distinguish the substellar nature of ultracool dwarfs. The Li element is destroyed in the interior of stars and massive brown dwarfs at temperatures of T ~ 2.5–3 10^6 K, depending on the density. Brown dwarfs with masses lower than 0.055–0.060 $M_\odot$ do not burn this element in their interiors because their central temperature is not hot enough to produce this fusion reaction (D'Antona & Mazzitelli 1995; Ushomirsky et al. 1998; Chabrier & Baraffe 2000).

3.1. The Li test

The Li test was proposed and developed in a series of papers (Magazzù et al. 1991, 1993; Rebolo et al. 1992; Martín et al. 1994; Pavlenko et al. 1995). This test is enunciated in Rebolo (1991) as follows: "It is interesting to note that stellar structure calculations on very low mass stars predict that this temperature cannot be attained in objects with masses less than 0.060 $M_\odot$, which corresponds to the domain of substellar systems, i.e. objects that fail to reach stable hydrogen ignition (brown dwarfs). So it is possible to use Li detection in those brown dwarfs candidates as a criterion to establish their nature. The observations of UX Tau a have shown that this type of work is feasible".

Stars destroy their Li content on time scales shorter than ~ 150 Myr, hence the detection of the neutral resonance line of Li at 6708 Å in objects older than this value is a clear indication of substellarity. The Li line was first detected in PPL 15, a brown dwarf candidate in the Pleiades cluster, but weaker than expected for total preservation. For this reason, PPL15 was considered an object close to the boundary between brown dwarfs and stars (Basri et al. 1996). The first unambiguous detection of Li in brown dwarfs was made in Teide 1 and Calar 3, also in the Pleiades cluster (Rebolo et al. 1996).

An alternative formulation of the Li test, in combination with evolutionary models, was given by Basri (2000). As can be seen in his Fig. 1, objects with $T_{\rm eff} < 2800$ K, which is equivalent to spectral types M5.5–M6, and which preserves Li, are brown dwarfs because all the stars with temperatures lower than this values have already burnt all their Li content (Basri 2000). In this sense, we should note that the detection of Li in the atmosphere of the M6 dwarf UX Tau C (Magazzù et al. 1991), which in fact was the object that inspired the Li test, may be considered the first Li brown dwarf.

3.2. *The Li test in T dwarfs*

Following the chemical equilibrium calculations of Burrows & Sharp (1999) and Lodders (1999), Kirkpatrick et al. (2000) argue that Li should disappear at $T_{\rm eff} < 1500$ K, and hence that Li test may not be valid for T dwarfs. On the contrary, other authors suggest that Li line at 6708 Å should be present down to $T_{\rm eff} \sim 1000$ K (Pavlenko et al. 2000). The absence of Li in the combined spectrum of the T1+T6 binary ϵ Indi B (King et al. 2010) seem to be in favor of the claim of Kirkpatrick et al. (2000). However, a recent determination of individual masses of the binary indicates the the primary has a mass of ~74 $M_{\rm Jup}$ and should have depleted its Li content, while the secondary has a mass of ~47 $M_{\rm Jup}$ (Cardoso 2010) and should have preserved at least part of its Li. To study the disappearance of the Li line at 6708 Å at the L/T transition we should study relatively bright binaries composed of L and T components. Fortunately, we have a very good example, the late L/early T binary WISE 1049-5319 AB (also called Luhman 16 AB), recently discovered at ~ 2 pc by Luhman (2013). In the discovery paper, Luhman shows the detection of Li in the primary (EW=8±1 Å). More recently, other groups have obtained optical spectroscopy of the secondary that shows the detection of Li (see Burgasser's talk and his contribution in these proceedings, and Lodieu et al. 2013, in prep.). Hence, in conclusion, the Li test is still applicable in early T dwarfs, but good signal-to-noise spectra are necessary.

4. Young and low gravity ultracool dwarfs

4.1. *Ultracool dwarfs in young open clusters and associations*

In 1995, the first brown dwarf, also the first young ultracool dwarf, Teide 1 (M8.5) was discovered in the Pleiades open cluster (Rebolo et al. 1995). The first young L dwarf, Roque 25, was also found in the same cluster (Martín et al. 1998). Soon afterwards the first young L dwarf companion was discovered around the nearby G196-3 star (Rebolo et al. 1998). At the same time, first ultracool M dwarfs were also found in star-forming regions such as ρ Oph (Luhman et al. 1997). In 2000, the first L dwarfs in a star-forming region were located in Orion (Zapatero Osorio et al. 2000). According to theoretical evolutionary models, their masses are below the deuterium burning mass limit; hence, they were the first isolated planetary-mass objects (Lucas & Roche 2000; Lucas et al. 2001; Zapatero Osorio et al. 2000). In 2004, Chauvin et al. (2004, 2005) obtained the first direct image of a planetary-mass companion L dwarf, 2M1207b, around a brown dwarf in the TW Hya association. Currently, there is no definitive confirmation of young T dwarfs, although there are several candidates. S Ori 70, was the first T dwarf found in the σ Orionis cluster (Zapatero Osorio et al. 2002). Although it was considered a field T dwarf by Burgasser et al. (2004), other authors claim that S Ori 70 shows peculiar near-infrared and mid-infrared colors, which suggest that the object is young (Zapatero Osorio et al. 2008; Scholz & Jayawardhana 2008). Recently, Peña-Ramírez et al. (2011) found that the proper motion of S Ori 70 was larger than that of the σ Orionis cluster and they conclude that it can be either a field T dwarf with peculiar colors, or an isolated planet ejected from σ Orionis or another nearby star-forming region. Casewell et al. (2007) also found several T-type candidates in the Pleiades cluster, but none of them was later confirmed using narrow methane-band imaging (Casewell et al. 2011). Delorme et al. (2012, see also his talk and contribution in these proceedings) presented a T7 object CFBDSIR J214947.2–040308.9, which could be a member of the 50–120 Myr-old AB Doradus moving group and which shows a brightening in the *K*-band with respect to other field T dwarfs, which is similar to that found in S Ori 70.

4.2. Low gravity and youthful features

In general, the spectral energy distribution (SED) of young ultracool dwarfs is very similar to older field dwarfs, but there are important differences. In the optical, they show spectral features characteristic of their youth, like strong and variable Balmer lines (Hα, Hβ, etc.) in emission due to their strong chromosphere activity or the presence of an accretion disk. Because of the young age of these objects, they are still contracting and they also show low gravity features, such as weaker alkaline absorption lines (Na, K, etc.) than their older counterparts. These spectral features were first reported for ultracool dwarfs in the Pleiades cluster by Martín et al. (1996, but also see Steele & Jameson 1995). In the spectra of L-type candidates in the σ Orionis cluster shown by Zapatero Osorio et al. (2013, in preparation; see also their contribution in these proceedings), the TiO and VO absorption bands in the optical appear stronger than in field

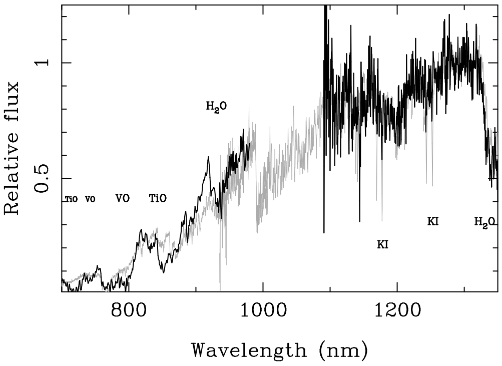

Fig. 3. Optical and near-infrared spectrum of a young L-type object in the σ Orionis cluster (dark solid line) in comparison with an older field L dwarf (grey solid line). Main spectral features are indicated. Spectra have been normalized at 1.25 μm (Zapatero Osorio et al. 2013, in prep.; see also their contribution in these proceedings).

dwarfs of similar spectral distribution in the near-infrared, the low gravity being the most likely explanation (see Fig. 3). Similar results have previously been reported in other regions such as Upper Scorpius and may lead to a different spectral classification for young objects in the optical and near-infrared (Béjar et al. 2008).

In the near-infrared, several spectral features have also been suggested as characteristic of youth, such as weaker Na and K absorption lines (Martín et al. 2001; McGovern et al. 2004), or the triangular shape in the *H*-band of young L-type objects due to water vapor absorption (Lucas et al. 2001). However, we should treat this latter feature with caution because not all the young L-type objects show it. For example, some of the L-class members of the young open Pleiades cluster show it and some others do not (Bihain et al. 2010). At the same time, some of the L field dwarfs may also show this triangular shape (see Allers' talk and her contribution in these proceedings).

4.3. Low gravity field dwarfs

Among the numerous field L dwarfs discovered by 2MASS, Kirkpatrick et al. (2006) found a peculiar L-type object, 2MASS J01415823–4633574, that exhibits very strong VO absorption bands but weak Na and K lines in its optical spectrum. These spectral features are indicative of low gravity. Other similar objects were presented in Cruz et al. (2009), where the spectral classification of L0–L5 was expanded to include three gravity classes. Some of these objects show redder $J - K$ colors and mid-infrared excesses, which can be associated with the presence of dusty envelopes or disks (Zapatero Osorio et al. 2010). These features have also been associated with their youth, but we also have to exercise caution with them, because many ultracool dwarfs in very young star-forming regions such as Orion, Taurus and Scorpius show similar colors to their older field counterparts. Although some authors have reported that these objects are underluminous in M_{JH} compared to field counterparts of the same spectral types (Faherty et al. 2012), more recent works indicate that these objects have absolute magnitudes intermediate between older field dwarfs and ultracool objects in star-forming regions, suggesting they are brown dwarfs with age in the range $\sim$50–500 Myr (Zapatero Osorio et al. 2013).

5. Low metallicity ultracool dwarfs

The first classification of low metallicity ultracool objects, the so called ultracool subdwarfs, was carried out by Gizis (1997). In this work, two metallicity classes for late M-type objects were defined: sub-dwarfs (sdM) and extremely sub-dwarfs (esdM), corresponding to metallicities of [Fe/H]$\sim$-1 and -2, respectively. A new classification based on three classes (sdM, esdM, and usdM) was proposed for these objects by Lepine et al. (2007), where the new usdM class correspond to the lowest metallicities. Although about a thousand L field dwarfs have already been identified only a few L subdwarfs are known (Lodieu et al. 2010). The first low metallicity L-type objects were discovered in 2003 (Burgasser et al. 2003; Lepine et al. 2003).

6. Ultracool dwarf–planet connection

Spectroscopic studies of ultracool dwarfs found in isolation and as companions around stars can provide insights into the formation mechanisms of these objects. The SED of very young late M and L substellar companions are indistinguishable from free-floating objects of similar spectral types in star-forming regions (see Fig. 4). This seems to indicate that the formation of these objects is similar, or that different formation mechanisms led to the existence of similar objects. Some directly imaged planetary-mass companions, such as 2MASS1207 b and HR8799 bcde (Chauvin et al. 2005; Marois et al. 2008), seem to be redder and subluminous with respect to their isolated counterparts, but, as we have seen before in young field L dwarfs, low gravity and/or dusty-atmospheres/disks can explain some of their peculiarities.

Interestingly, the temperature and gravity of young late M, L and T-type objects are very similar to that of the extrasolar giant planets found at very close separations from their parents stars by the radial velocity and transit methods, i.e. the so called "hot Jupiters". The observations of optical and near-infrared transmission spectra of these exoplanets have led to the identification of molecular species in their atmospheres such as H_2O, CH_4 (Tinetti et al. 2007; Swain et al. 2008), similar to those found in the atmospheres of free-floating brown dwarfs of L and T spectral types. In Fig. 5 we show the near-infrared spectrum of HD 189733 b (Swain et al. 2008) in comparison with that of S Ori 70 (Zapatero Osorio et al. 2002). Both objects show similar H_2O and CH_4 absorption bands, which suggests they have a similar $T_{\rm eff}$ and composition, and possibly a similar gravity. Both spectra have been normalized at the peak of the H-band, at about 1.6 μm, and to do the proper comparison, we have assumed that the atmosphere of HD 189733 b is opaque in the CH_4 bands, i.e. its transmitted spectrum is nearly null at these wavelengths.

Giant extrasolar planets located at larger separations from their primaries, such as those of our Solar System, will have $T_{\rm eff} < 500$ K.

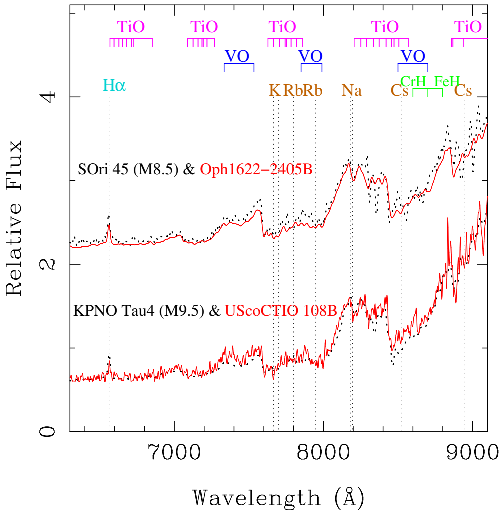

Fig. 4. Optical spectra of free-floating late M-type objects (solid lines) in comparison with companions of similar spectral type (dotted lines).

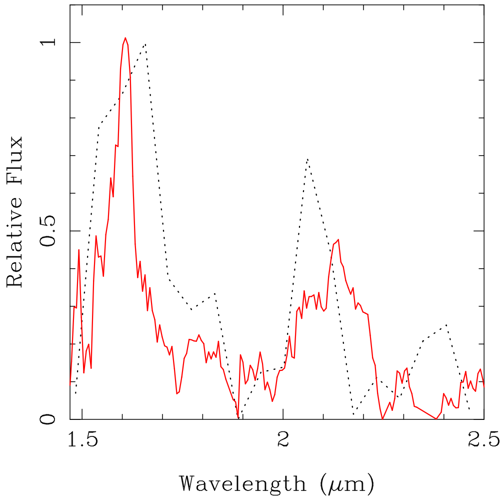

Fig. 5. Near-infrared spectrum of T-type object S Ori 70 (solid line) in comparison with the transmission spectrum of HD 189733 b (dashed line). See details in the text.

This range of temperatures corresponds to the new Y spectral class. According to the theoretical models, their masses are estimated at a few times the mass of Jupiter; hence, their gravity will also be similar to that of these cold exoplanets. Hence, the study of the atmospheres of free-floating Y dwarfs will be critical to understanding the composition and properties of the cold extrasolar planets that will be discovered in future searches. Since Y dwarfs emit most of their light in the mid-infrared, future classification of these objects is expected to be done at these wavelengths. In this sense, objects such as Jupiter ($T_{\rm eff} \sim 175$ K) that are dominated by reflected light in the optical and near-infrared, but that irradiate most of their directly emitted light in the mid-infrared can be included as a standard reference for the classification of this Y spectral type.

7. Summary and final remarks

- In the last 25 years, more than a thousand ultracool dwarfs have been identified. These investigations have led to the development of the new spectral classes L, T and Y.
- Not all ultracool dwarfs are brown dwarfs, but, depending on their temperature and age, they may be also very low mass stars or planetary mass objects. Spectroscopic tests of substellarity, such as the Li test, have been and are still a very powerful tool for distinguishing between stars and bona fide substellar objects.
- Among the numerous ultracool dwarfs, some young low gravity objects and metal poor subdwarfs have also been identified. In this sense, we have also learnt that gravity (age) and metallicity play an important role in the spectral energy distribution of these objects.
- The study of the atmospheres of ultracool dwarfs is also critical for understanding the properties of extrasolar planets, since these have similar $T_{\rm eff}$ and gravities. Hence, exoplanets and substellar communities should work more closely together because they need to address similar problems.

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