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# The Classification of T Dwarfs

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**Abstract.** The discovery of many cool brown dwarfs similar to Gliese 229B has led to the definition of a new spectral class, the T dwarfs, whose 1–2.5 $\mu$m spectra exhibit signatures of $CH_4$ absorption. Two classification schemes have been proposed for these objects by Burgasser et al. and Geballe et al. We discuss and compare these schemes, and describe a joint classification scheme currently in development that closely follows the guidelines of the MK process. We also address future work toward establishing gravity classes, classifying at other wavelengths, and identifying those features that may signify the end of the T spectral class.

## 1. Introduction

T dwarfs are cool brown dwarfs exhibiting $CH_4$ absorption features in the near-infrared (1–2.5 $\mu$m), distinguishing them from the warmer L dwarf class of low-mass stars and brown dwarfs (Kirkpatrick et al. 1999). The prototype T dwarf is the companion brown dwarf Gliese 229B (Nakajima et al. 1995, Oppenheimer et al. 1995). Soon after the discovery of this first widely accepted *bona fide* brown dwarf, field analogues were identified in SDSS (Strauss et al. 1999), 2MASS (Burgasser et al. 1999) and the NLTT Deep Field (Cuby et al. 1999). All of these initial field discoveries have relatively strong $CH_4$ absorption, similar to Gliese 229B, although some spectral differences were noted in the first four 2MASS T dwarfs (Burgasser et al. 1999). Leggett et al. (2000) identified three objects in the SDSS survey with weak $CH_4$ and CO absorption which they termed "L/T transition objects", giving the first clear indications of a near-infrared spectral sequence (T. Geballe, these proceedings). Subsequently, Burgasser et al. (2002; hereafter B02) and Geballe et al. (2002; hereafter G02) defined T dwarf near-infrared classification schemes extending from the latest-type L dwarfs to the coolest T dwarfs so far identified. At the time of this writing, there are over 30 T dwarfs known, most identified in 2MASS and SDSS.

In this contribution, we review the classification of T dwarfs. We first describe the MK process in §2, the most rigorous and widely established method of stellar spectral classification. In §3 we review the spectra of T dwarfs at optical and near-infrared wavelengths. In §4 we discuss and contrast the classification schemes of B02 and G02, and outline work on a joint classification scheme in §5. In §6 we discuss future steps in the classification of L and T dwarfs, including extension to other wavelengths, identification of gravity diagnostics that may form the basis of a second classification dimension, and speculation on what lies beyond the T spectral class.

## 2. The MK Process

Classification is an essential step in all fields of observational science, clarifying the physical mechanisms underlying patterns observed in natural phenomena. For example, the taxonomic system for species codified by Linnaeus in 1737 has evolved directly into modern genetic-based schemes, and the development of the periodic table in the 1860s by Chancourtois, Newlands, Mendeleev, and Meyer ultimately unraveled the nuclear and electron structures of atoms. In astronomy, key classification systems include Cannon & Pickering's spectral classification of the Henry Draper (HD) catalog at the turn of the 20th century, the origin of the OBAFGKM main sequence; and Hubble's "tuning fork" sequence of galaxies in the 1920s, which may in some part trace galactic evolution.

The most successful and widely accepted stellar classification scheme is the MK system, introduced in the spectral atlas of Morgan, Keenan, & Kellman (1943) as an evolution of the HD system, and developed by W. Morgan, P. Keenan, and others over the next 50 years. The underlying philosophy of the MK system is the construction of groups, or spectral subtypes, tied to the properties of specific anchors, or spectral standards, defined over a specific spectral range and resolution. The MK process can be summarized as follows:

- Classification is based empirically on features in the observed spectra;

- Spectral types are defined by an array of individual standard stars; and

- Classification makes use of all features within a specified spectral range for a homogeneous sample by direct comparison to the spectral standards.

The advantage of the MK system is its durability. By anchoring the system to specific standard stars, classification can be done using different instruments at different sites and with different resolutions, and can be rigorously extended to other spectral regions. Furthermore, the MK system is not tied to physical interpretation, which tends to evolve over time, even as the spectra themselves generally do not.

## 3. The Spectra of T Dwarfs

The first step toward spectral classification is the characterization of the spectra themselves. Figure 1 shows the spectra of two T dwarfs, Gliese 229B and 2MASS 0559−1404 (Burgasser et al. 2000b) from 0.63–4.7 $\mu$m, providing an excellent map of the key features in this spectral class. The red optical region is highly depressed, largely by pressure-broadened Na I (5890/5895 Å) and K I (7665/7699 Å) resonance doublets (Tsuji, Ohnaka, & Aoki 1999; Burrows, Marley & Sharp 2000). There are also a number of weaker atomic features present, including Cs I (8521/8943 Å) and Rb I (7800/7948 Å) lines. $H_2O$ (9250 Å) is quite prominent in the T dwarfs, and the 9896 Å FeH and 9969 Å CrH bands are present in the early- and mid-type T dwarfs. The 8692 Å FeH and 8611 Å CrH bands are also seen in the early-type T dwarfs, but these higher excitation bands rapidly disappear. Overall, the metal hydride bands that are prominent in L dwarf red optical spectra are weakening or absent in the T dwarfs. Oppenheimer et al. (1998) have noted the presence of weak $CH_4$ absorption at 8950 Å in the spectrum of Gliese 229B.

$H_2O$ and $CH_4$ absorption bands are the dominant features shaping the near-infrared spectra of T dwarfs. $CH_4$ absorption at 1.6 and 2.2 $\mu$m effectively removes half of the emitted flux from the H- and K-bands; 1.15 $\mu$m $CH_4$ and $H_2O$ absorption divides the J-band into two peaks at 1.08 and 1.27 $\mu$m; and the red slope of the J-band peak is shaped by $CH_4$ absorption at 1.3 $\mu$m. $H_2O$ bands at 1.4 and 1.9 $\mu$m are stronger than those seen in the L dwarfs, and early-type T dwarfs also show CO absorption at 2.3 $\mu$m. $H_2$ collision-induced absorption (CIA) is present at K-band, suppressing flux throughout the 2–2.5 $\mu$m region. Na I (1.138/1.141 $\mu$m) and K I (1.169/1.177 and 1.243/1.252 $\mu$m) doublet lines are present in most of the T dwarfs, but are weakening in the latest-type objects. At longer wavelengths, the fundamental bands of $CH_4$ (3.3 $\mu$m) and CO (4.7 $\mu$m) can be seen; the presence of the latter band has been attributed to convective mixing in the upper atmospheres of these objects (D. Saumon, these proceedings).

## 4. Proposed T Dwarf Classification Schemes

Following the discovery of field counterparts to Gliese 229B in the 2MASS and SDSS surveys, B02 and G02 derived the first classification schemes for T dwarfs based primarily on near-infrared data, the spectral region in which T dwarfs emit most of their flux. The B02 study is based on a relatively large, though

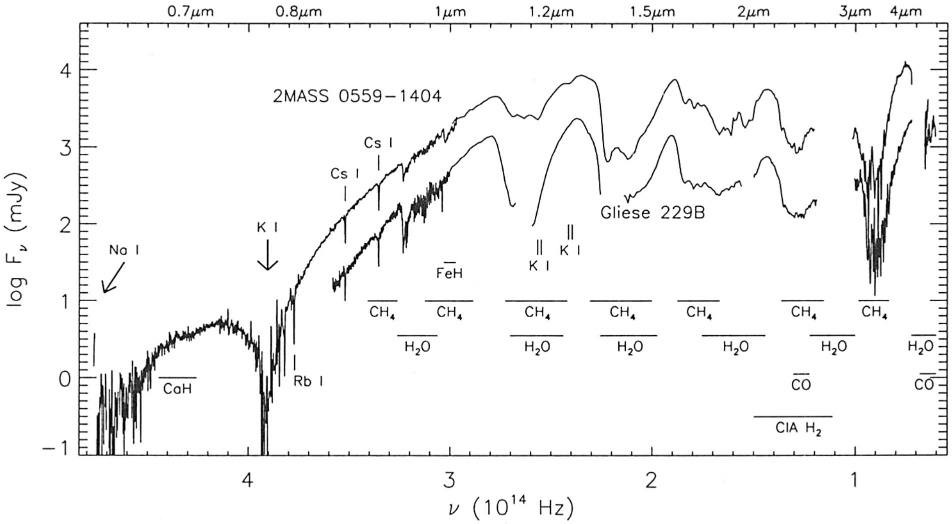

Figure 1. Spectra of two T dwarfs, 2MASS 0559−1404 (Burgasser 2001) and Gliese 229B (Oppenheimer et al. 1998), from 0.63–4.7 μm. Major absorption features are indicated.

inhomogeneous, sample of spectra drawn primarily from low-resolution NIRC (R ~ 60-120) and higher-resolution OSIRIS (R ~ 1200) and CGS4 (R ~ 300) data. Spectra were grouped according to morphology, representative standards were chosen (Figure 2, left), and the remaining objects were classified using spectral indices ($CH_4$ and $H_2O$ band strengths and peak color ratios) that were compared to those of the selected standards. Gaps at T0 and T4 were left in this classification due to the paucity of early-type T dwarfs in the B02 sample, drawn primarily from the 2MASS database. The remaining subtypes extend to T8, which includes the coolest known brown dwarf Gliese 570D (Burgasser et al. 2000a).

The G02 scheme is based on a homogenous sample of CGS4 spectra and includes more early-type T dwarfs, drawn primarily from SDSS. G02 extended their study to include L dwarfs, tying the earliest L subtypes to the Kirkpatrick et al. (1999) red optical classification, but introducing a later (L9) class which includes objects with $CH_4$ absorption at 2.2 μm but not 1.6 μm[1] (T. Geballe, these proceedings). No spectral standards were specified in this study (Figure 2, right), as the number and assignment of subtypes were set by a "smooth progression of the indices used for both L and T classification." This scheme does not completely follow the MK process (no standard stars), but is based on a more complete and homogenous spectral sample than that used in B02.

While the underlying philosophies of the B02 and G02 schemes are somewhat different, comparison between the assigned spectral types (Table 1) shows excellent agreement, with discrepancies of no more than 0.5 subclasses. This

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[1] Noll et al. (2000) have identified the fundamental 3.3 μm $CH_4$ band (a feature which is two orders of magnitude stronger than the 1–2.5 μm bands) in objects as early as L5.

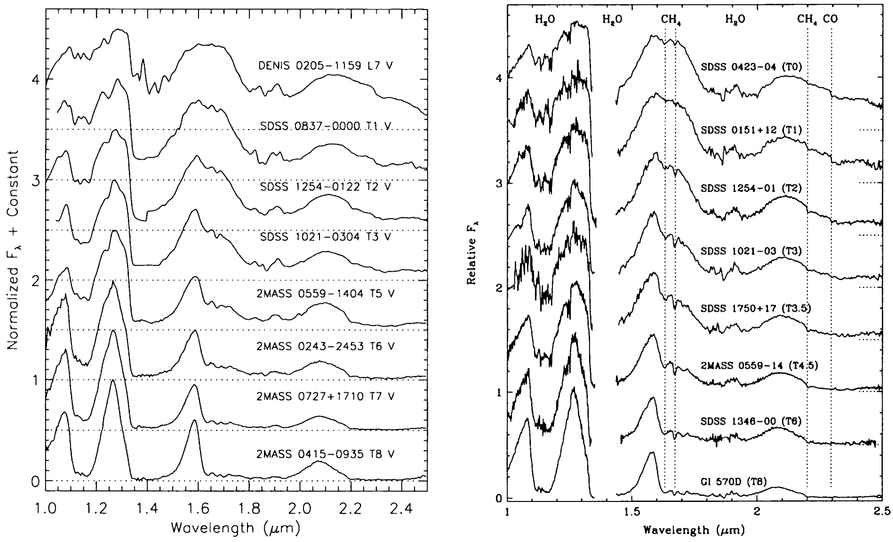

Figure 2. (Left) T dwarf near-infrared spectral standards spanning types T1, T2, T3, T5, T6, T7, and T8 from B02. (Right) T dwarf near-infrared spectra and subtypes from G02.

Table 1. Comparison of T Subtypes

| Object | B02 | G02 | Object | B02 | G02 |
|---|---|---|---|---|---|
| SDSS 0837−0000 | T1 | T0.5 | Gliese 229B | T6.5 | T6±1 |
| SDSS 1254−0122 | T2 | T2 | SDSS 1346−0031 | T6 | T6 |
| SDSS 1021−0304 | T3 | T3 | 2MASS 1047+2124 | T6.5 | T6.5 |
| 2MASS 0559−1404 | T5 | T4.5 | 2MASS 1237+6526 | T6.5 | T6.5 |
| SDSS 1624+0029 | T6 | T6 | 2MASS 1217−0311 | T7.5 | T7.5 |
| 2MASS 1225−2739 | T6 | T6 | Gliese 570D | T8 | T8 |

agreement is largely due to the small sample of objects studied (most of which were common to both investigations), the use of the same spectral region, and the averaging of several similar indices to derive final subtypes.

## 5. A Joint Classification Scheme

The similarity in the classification and indices in the B02 and G02 studies, and the complementary 2MASS and SDSS T dwarf search efforts, has led the authors to establish a joint working group to define a single classification scheme for T dwarfs. This work has the following goals:

- Define T dwarf spectral standards for each subclass from T0 to T8, preferably single, bright, and accessible from both hemispheres;

- Obtain uniform spectral data for these standards and other T dwarfs for accurate comparison; and
- Define optimal spectral indices, useful over a broad range of spectral resolutions, that avoid contaminating telluric absorption features.

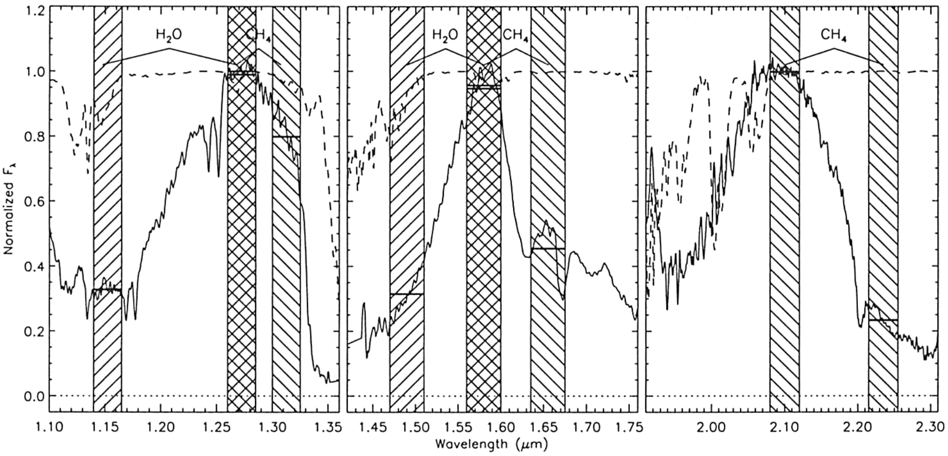

Figure 3. Spectral indices defined in our joint classification scheme. Hatched areas indicate spectral regions sampled for $H_2O$ and $CH_4$ band indices. Normalized CGS4 spectra of 2MASS 0559−1404 (G02; solid lines) and telluric absorption at Mauna Kea (dashed lines) are plotted for comparison.

Preliminary standards have been selected: SDSS 0423−0414 (T0), SDSS 0837−0000 (T1), SDSS 1254−0122 (T2), SDSS 1021−0304 (T3), 2MASS 2254+3123 (T4), 2MASS 2339+1352 (T5), SDSS 1624+0029 (T6), 2MASS 0727+1710 (T7), and 2MASS 0415−0935 (T8). A final list will be defined as additional early- and mid-type T dwarfs are identified in ongoing searches using 2MASS and SDSS. CGS4 observations of all of the standards are currently underway. Finally, we have selected three $H_2O$ and two $CH_4$ classification indices. As shown in Figure 3, these indices are broad (250–400 Å) and provide excellent contrast for the band features while avoiding telluric and atomic lines. Preliminary tests indicate that these indices have internal consistencies better than 0.5 subclasses, meaning that each are robust measures of spectral type. Our procedures are aimed at following the MK Process described in §2, so that this joint classification remains robust as more T dwarfs are identified.

## 6. Future Work

### 6.1. Gravity Diagnostics: Two-Dimensional Classification

The T classifications discussed above are one-dimensional, while the MK system is (at minimum) a two-dimensional scheme based nominally on temperature and luminosity diagnostics. While the equivalent of giant or supergiant stars will not exist in the low-mass stellar and brown dwarf regimes due to the lack of exhaustive Hydrogen burning, brown dwarfs can have surface gravities that vary by 2-3 orders of magnitude depending on age and mass (Burrows et al. 2001). This can have important consequences on the atmospheric chemistry (Burrows & Sharp 1999) and strength of certain molecular features. Furthermore, a low-gravity brown dwarf is younger and less massive than a high-gravity brown dwarf of the same $T_{eff}$. Hence, it is important to distinguish objects of different gravities in order to ultimately determine physical properties.

Gravity diagnostics in young cluster M and L dwarfs are discussed in the literature (e.g., Martín, Rebolo, & Zapatero Osorio 1996; Luhman et al. 1998; Lucas et al. 2001). To date, no young cluster T dwarfs have been confirmed, although a candidate has been identified by Zapatero Osorio et al. (2002; these proceedings). Leggett et al. (2002) have proposed that Gliese 229B may be a young (~30 Myr), low-mass (~7 $M_{Jup}$) brown dwarf based on the possible youth of its M1 primary. A potential high-gravity T dwarf has been identified, 2MASS 0937+2931 (B02), based on its highly depressed K-band peak due to strong CIA $H_2$ absorption. This molecular feature is sensitive to photospheric pressure and hence surface gravity. However, 2MASS 0937+2931 may instead be metal-poor. These differing interpretations must be examined by improved theoretical models. S. Leggett et al. (these proceedings) have similarly proposed that J-K color may be an excellent gravity diagnostic for T dwarfs.

## 6.2. Classification in Other Spectral Regions

While the 1–2.5 $\mu$m region encompasses most of the flux emitted by T dwarfs, there are a variety of interesting features found at other wavelengths that can be used for classification and the investigation of physical properties. At red optical wavelengths, T dwarfs are exceedingly faint, making accurate classification difficult. Burgasser (2001) has made a preliminary attempt to address classification in this wavelength regime by examining the behavior of spectral indices with near-infrared subtypes. He finds that spectral slope, $H_2O$ band strength, and possibly the 8521 and 8943 Å Cs I lines can be used to derive approximate spectral types for T dwarfs, consistent to within ±2 subclasses of the near-infrared types. At longer wavelengths, the 3.3 $\mu$m $CH_4$ band appears to be generally tuned to $T_{eff}$, while the 4.7 $\mu$m CO band may be more sensitive to secondary parameters such as gravity or rotation due to its non-equilibrium origin. Further work beyond 5 $\mu$m, which can be accomplished with SIRTF and NGST, could potentially enable the direct detection of dust species in early-type T dwarfs (e.g., silicate bands between 6-9 $\mu$m), as well as bands of $NH_3$, $H_2S$, and alkali chlorides, the latter being the repository for atomic alkali species below ~800 K (Lodders 1999). These mid-infrared features may provide important classification diagnostics in even lower temperature objects than those currently known.

## 6.3. What Comes After T?

The new T spectral class spans $T_{eff} \approx 1300$ to below 800 K, masses from 0.075 $M_\odot$ to well below the substellar limit, and gravities of $10^3$ to $10^{5.5}$ cm $s^{-2}$. This is a substantial range of parameters for classification, but what about cooler and lower-mass objects? What constitutes the end of the T spectral class and the beginning of the next (perhaps Y?) class? And how do we find these objects? Following the MK philosophy, we seek a significant shift in spectral morphology for the next class. This may arise in the weakening of steam bands as $H_2O$ condenses, or the formation of strong $NH_3$ absorption bands. This shift may occur in the near-infrared where T dwarfs are currently classified, or at longer wavelengths where spectral energy distributions peak for cooler objects. Furthermore, as the luminosities of brown dwarfs plummet with cooler $T_{eff}$, future infrared missions (SIRTF, NGSS) may be necessary to detect them (J. D. Kirkpatrick, these proceedings). Nonetheless, based on the mass function estimates of Reid et al. (1999) and Chabrier (2002; these proceedings), a large population of very cold ($T_{eff}$ < 500 K) brown dwarfs should exist as members of a yet-unnamed spectral class.

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