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COMMISSION 45 SPECTRAL CLASSIFICATION

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TRIENNIAL REPORT 2009-2012

1. Introduction

This report gives an update on developments since the last General Assembly in Rio de Janeiro. Classification – both photometric and spectral – continues to play a vital role in stellar astrophysics and stellar surveys. During the past three years, rapid progress has been made in the classification of brown dwarfs, with the discovery of the first Y dwarfs and the introduction of a near-IR classification system for M- and L-dwarfs. The number of known L-dwarfs now exceeds 1000, and so peculiar types are beginning to show up. For instance, there is now enough material to define a low-gravity spectral sequence for the L0 – L5 dwarfs. In addition, a number of unusally blue L-dwarfs are now known. Large-area surveys, always of interest to Commission 45, have proliferated during this period, including RAVE, SEGUE, and WISE with many more in the planning stages.

2. Developments in the Classification of Brown Dwarfs

2.1. *The Discovery of Y Dwarfs*

As of early 2011, the latest brown dwarfs (T-type) known had $T_{\rm eff} \sim 500 - 700$K; there thus existed a gap of nearly 400 K between the coolest spectroscopically confirmed brown dwarfs and Jupiter ($T_{\rm eff} \sim 124$ K), suggesting the existence of a cooler class of brown dwarfs. Targeted searches for companions to nearby stars (Luhman *et al.* 2011, ApJ, 730, L9; Liu *et al.* 2011, ApJ, 740, 108) turned up two very cool dwarfs with $T_{\rm eff} \sim 300 - 400$ K, but the faintness of those objects coupled with proximity to their primary stars frustrated spectroscopic observations. One of the science goals of the Wide-field Infrared Survey Explorer (WISE), which has recently completed a survey of the entire sky in four infrared bands (W1, W2, W3, W4) was the detection of ultra-cool brown dwarfs. The W1 (3.4μm) and W2 (4.6μm) bands were specifically designed to sample the deep CH_4 absorption band at 3.3 μm and the "opacity-free" 4.7μm region in the spectra of cool brown dwarfs. Kirkpatrick *et al.* (2011, arXiv) report on the discovery of 100 new brown dwarfs from WISE data, and Cushing *et al.* (2011, arXiv) focus on the 7 coolest dwarfs of that sample. Six of those seven are identified as the first spectroscopically verified members of a new spectral class, the Y-type dwarfs. Those Y dwarfs are distinguished from the T dwarfs spectroscopically by two features. First, a T dwarf is easily identified by the presence of prominent flux peaks in the J and H bands. When plotted in units of f_λ, the J-band peak is always higher than the H-band peak in T dwarfs. However, in these six ultracool dwarfs, the J- and H-band peaks are nearly equal in height. In addition, the Y dwarfs show evidence of NH_3 absorption in the blue wing of the H-band peak, at 1.53μm. The presence of NH_3 absorption has been suggested as a trigger for a new spectral class (cf. Kirkpatrick 2008, ASPCS, 384).

2.2. *Gravity Classification in L Dwarfs*

Brown dwarfs are sub-stellar objects with insufficient mass to sustain hydrogen burning in their cores. As a consequence, they cool with time and evolve through the MLT spectral sequence. This implies that, unlike main-sequence stars, the spectral type of a brown dwarf is not uniquely related to its mass or age, as, for instance, an early-L dwarf could be either an old low-mass star, or a young low-mass brown dwarf. This mass/age/spectral-type degeneracy has plagued the study of brown dwarfs, and it has only been recently that high-resolution spectra of L dwarfs have become available that enable the detection of gravity-sensitive features. Cruz *et al.* (2009, AJ, 137, 3345) have published the first preliminary low-gravity optical spectral sequence for L0 to L5 dwarfs, which should be considered an expansion of the spectral classification scheme for L dwarfs first published by Kirkpatrick *et al.* (1999, ApJ, 519, 802). The features that can be used to gravity type L dwarfs are the pressure-broadened wings of prominent lines of the alkali metals, and metal-oxide and metal-hydride bands (VO, TiO, CrH, and FeH).

2.3. *A Near-IR Classification Sequence for M and L Dwarfs*

It is remarkable that up until now, a near-IR classification sequence along with supporting spectral standards has not been established for the M and L dwarfs, although there is such a system for the T dwarfs. Generally, we expect that optical and near-IR spectral types should be in good agreement. However, since the two spectral regions sample different layers of the atmosphere, some differences are to be expected, and those differences can give us insight into brown-dwarf physics. Kirkpatrick *et al.* (2010, ApJS, 190, 100), utilizing new spectroscopic data, constructed a standard sequence for M0 – L9, consistent with the earlier T-dwarf sequence. This project also detected a number of peculiar objects including unusually blue and red L dwarfs, and low-gravity and low-metallicity objects.

2.4. *Blue L Dwarfs – Adam J. Burgasser*

The number of identified members of the L-dwarf spectral class, first defined in 1999 (see review by Kirkpatrick 2005, ARA&A, 43, 195) has now surpassed 1000, and many rare and unusual members of this class are being uncovered. These include "unusually blue" L dwarfs, or UBLs, of which there are currently about two dozen examples (Cruz *et al.* 2003, AJ, 126, 2421; Knapp *et al.* 2004, AJ, 127, 3553; Chiu *et al.* 2006, AJ, 131, 2722; Cruz *et al.* 2007, AJ, 133, 439; Folkes *et al.* 2007, MNRAS, 378, 901; Burgasser *et al.* 2008, ApJ, 674, 451; Kirkpatrick *et al.* 2010, ApJS, 190, 100; Bowler *et al.* 2010, ApJ, 710, 45; Schmidt *et al.* 2010, AJ, 139, 1045). UBLs have near-infrared colors and/or spectral energy distributions that are significantly bluer for a given optical spectral type, with offsets of ΔJ-K $\lesssim$ 0.5–1.0 mag compared to the mean color of that subtype. The distinguishing spectral features of UBLs appear largely at near-infrared wavelengths, whereas their optical spectra are minimally affected. This segregates UBLs from L-type subdwarfs, which have distinct optical and near-infrared spectra compared to local field dwarfs, largely due to metallicity effects (e.g., Burgasser *et al.* 2007, ApJ, 657 ,494). In addition to bluer colors and spectral slopes, UBLs exhibit stronger water absorption at 1.4 μm and 1.8 μm and weaker CO absorption at 2.3 μm. Near-infrared classifications of their spectra, using the schemes of Geballe *et al.* (2002, ApJ, 564, 466) or Kirkpatrick *et al.* (2010, ApJS, 190, 100), are typically 1–3 subtypes later than optical classifications.

Kirkpatrick *et al.* (2010, ApJS, 190, 100) have described a method for identifying UBLs through direct comparison to near-infrared spectral standards. There is as yet no formal system for formally designating a source as a UBL, but various authors have adopted prefixes of "b" before the optical spectral class as a signifier (e.g., "bL5").

Considerable progress in understanding the UBL population was made in 2010 with the discovery of the nearby UBL SDSS J141624.08+134826.7 (Schmidt *et al.* 2010, AJ, 139, 1045; Bowler *et al.* 2010, ApJ, 710, 45; Burningham *et al.* 2010, MNRAS, 404, 1952; Kirkpatrick *et al.* 2010, ApJS, 190, 100) and its well-separated, unusually blue T dwarf common proper motion companion ULAS J141623.94+134836.3 (Burningham *et al.* 2010, MNRAS, 404, 1952; Scholz *et al.* 2010, A&A, 510, L8; Burgasser *et al.* 2010, AJ, 139, 2448). Spectral model fits indicate stronger H_2 absorption for both sources and reduced cloud opacity for the UBL primary (late-type T dwarfs do not typically exhibit significant cloud opacity; e.g., Tsuji *et al.* 1996, A&A, 308, L29). The common spectral and photometric peculiarities of these sources suggest older age and higher surface gravities as underlying causes, with thinner clouds in the primary being a secondary effect. Nevertheless, the distinct near-infrared spectra of UBLs as compared to other L dwarfs, and analogous spectral discrepancies among unusually red and possibly "thick cloudy" L dwarfs (e.g., Looper *et al.* 2008, ApJ, 686, 528) indicate the need for an additional classification dimension for L dwarfs that may encompass cloud and/or age characteristics.
Additional input for this report was provided by Brendon Bowler (U. Hawaii), Michael Cushing (U. Toledo), Mark Marley (NASA Ames) and Sarah Schmidt (U. Washington).

2.5. *Ultracool Dwarf Near-Infrared Spectral Libraries – Adam J. Burgasser*

Ever-larger samples of near-infrared spectra of low-temperature dwarfs have been acquired by researchers over the past decade, and several of these researchers have created on-line spectral libraries to distribute these data to the community. As a reference, this report provides an (incomplete) list of online spectral libraries containing sizeable (>50) datasets of spectra for the coolest spectral classes, the M, L, and T dwarfs. A more comprehensive list of spectral libraries across all stellar classes is maintained by David Montes (Universidad Complutense de Madrid):
`http://www.ucm.es/info/Astrof/invest/actividad/spectra.html`

2.5.1. *The IRTF Spectral Library*

The IRTF Spectral Library is a homogenous compilation of stellar spectra observed with the NASA IRTF SpeX spectrograph (Rayner *et al.* 2003, PASP, 115, 362), based primarily on data published in Cushing *et al.* (2005, ApJ, 623, 115) and Rayner *et al.* (2009, ApJS, 185, 289). The data were acquired at a common resolving power of $\lambda/\Delta\lambda \approx 2000$ and span 0.8-2.5 μm, with a number of spectra extending to 5.2 μm. All data were reduced using the SpeXtool package (Cushing *et al.* 2003, PASP, 116, 362; Vacca *et al.* 2003, PASP, 115, 389), and have signal-to-noise ratios $S/N > 100$ for $\lambda < 4$ μm. The spectra are photometrically calibrated using 2MASS photometry. The library primarily consists of solar-metallicity, late-type stars with spectral types F through M and luminosity classes I through V; there are also AGB stars, carbon and S stars, and L and T dwarfs (Wolf-Rayet, O, B, and A star spectra are forthcoming). Data for Jupiter, Saturn, Uranus, and Neptune are also available. This library is maintained by Michael Cushing (U. Toledo) and John Rayner (U. Hawaii) and was last updated in December 2009. `http://irtfweb.ifa.hawaii.edu/ spex/IRTF_Spectral_Library`

2.5.2. *The SpeX Prism Spectral Libraries*

The SpeX Prism Spectral Libraries are a compilation of roughly 1000 low-resolution, near-infrared spectra of primarily M, L and T dwarfs, also obtained with the IRTF SpeX spectrograph. These data were acquired using SpeX's prism-dispersed mode, yielding 0.65-2.55 μm spectra with $\lambda/\Delta\lambda \approx$ 75-200, depending on the slit width used. The SpeX Prism Libraries are a heterogenous compilation, incorporating data from several dozen publications; hence, the resolution, photometric calibration and quality of the data vary (these are indicated on the webpage). Spectra are organized into separate libraries according to spectral class, luminosity class, spectral standards, and other groupings. This library is maintained by Adam Burgasser (UC San Diego) and was last updated in October 2010. `http://www.browndwarfs.org/spexprism`

2.5.3. *The NIRSPEC Brown Dwarf Spectroscopic Survey*

The NIRSPEC Brown Dwarf Spectroscopic Survey (BDSS) compiles both moderate- and high-resolution spectra for late-type M, L, and T dwarfs obtained with the Keck-II Near-Infrared Spectrometer (NIRSPEC; McLean *et al.* 1998, SPIE, 3354, 566; McLean *et al.* 2000, SPIE, 4008, 1048), with most of the data published in McLean *et al.* (2003, ApJ, 596, 561); McLean *et al.* (2007, ApJ, 658, 1217); and Rice *et al.* (2010, ApJS, 186, 63). Spectra were acquired with the same slit, dispersion and filter combinations, so this is a homogenous dataset. All sources in the moderate-resolution sample were observed with the NIRPSEC-3 filter, spanning 1.14-1.38 μm at a resolution $\lambda/\Delta\lambda \approx$ 2000. Several sources were also observed in various filters spanning 0.95–2.43 μm. The spectra are flux-calibrated and (for broader-band spectra) stitched together using 2MASS photometry. High-resolution data were also obtained with the NIRSPEC-3 filter in 8 orders spanning 1.16-1.32 μm at $\lambda/\Delta\lambda \approx$ 20,000. All data in the NIRSPEC BDSS were reduced using the REDSPEC package. This library is maintained by Gregory Mace (UC Los Angeles), Ian McLean (UC Los Angeles) and Emily Rice (CUNY College of Staten Island), and was last updated in August 2010. `http://bdssarchive.org`

2.5.4. *DwarfArchives M Dwarf Spectroscopic Library*

DwarfArchives, an online database of photometry and astrometry for known late M, L and T dwarfs, provides a separate catalog of red optical spectra for over 500 M dwarfs. Data are drawn from a variety of instruments and sources (including unpublished data), and are primarily low- to moderate-resolution spanning 6300–9000 Å. DwarfArchives is maintained by Chris Gelino (Caltech/Spitzer Science Center), J. Davy Kirkpatrick (Caltech/IPAC) and Adam Burgasser (UC San Diego), and was last updated in February 2011. `http://DwarfArchives.org`

2.5.5. *Ultracool Dwarf Catalog*

The Ultracool Dwarf Catalog, like DwarfArchives, compiles astrometric, photometric and spectroscopic data for over 850 M, L and T dwarfs. The heterogenous spectral data are drawn from various sources, and include red optical spectra from individual follow-up programs (mainly related to DENIS search programs) and the SDSS survey, and near-infrared spectra from the literature. The available spectral range for each source is indicated on the main table. The catalog was produced by Juan Cabrera, Elena Cenizo and Eduardo Martín (Instituto de Astrofsica de Canarias; Centro de Astrobiologa), and published in Martín *et al.* (2005, AN, 326, 1026). The site was last updated in 2007. `http://www.iac.es/galeria/ege/catalogo_espectral`

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2.5.6. *L and T Dwarf Data Archive*

Sandy Leggett (Gemini Observatory) hosts a catalog of red optical and near-infrared spectra of L and T dwarfs based primarily on data reported in Chiu *et al.* (2006, AJ, 131, 2722), Golimowski *et al.* (2004, AJ, 127, 3516) and Knapp *et al.* (2004, AJ, 127, 3553). The spectra were obtained with a variety of instrumentation (including outside sources), and include both low- and moderate-resolution data over various ranges of spectral coverage and quality. The site was last updated in January 2006.
`http://staff.gemini.edu/ sleggett/LTdata.html`

2.5.7. *Low-resolution Near-infrared Spectral Library of M-, L-, and T-dwarfs*

Testi (2009, A&A, 503, 639) published a sample of 54 low-resolution ($\lambda/\Delta\lambda \approx 100$), near-infrared (0.85–2.45 μm) spectra of M, L, and T dwarfs obtained with the TNG Near Infrared Camera and Spectrograph (NICS; Baffa *et al.* 2001, A&A, 378, 722), using that instrument's Amici prism mode. The data are homogenous in spectral coverage and resolution, but vary in S/N. Spectral data are served through Vizier at the catalog link:
`http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=J/A%2BA/503/639`

2.5.8. *Keck LRIS Spectra of Late-M, L, and T Dwarfs*

I. Neill Reid (STScI) has compiled a set of low-resolution ($\lambda/\Delta\lambda \approx 1800$), red-optical spectra (0.6-1.0 μm) of late-type M, L, and T dwarfs obtained with the Keck Low Resolution Imaging Spectrometer (LRIS; Oke *et al.* 1995, PASP, 107, 375) between 1997 and 1999. The site also contains red optical spectra of a handful of M subdwarfs. The site was last updated in December 2000. `http://www.stsci.edu/ inr/lris.html`

2.5.9. *Improving Access to Spectral Data*

These online spectral libraries span a wide range of quality, completeness and accessibility, suggesting work is needed to devise and implement more efficient and uniform methods of curating and disseminating spectral datasets (this issue was discussed specifically at the 2009 joint ESA-Constellation workshop on brown dwarf formation in Noordwijk, the Netherlands). There are several issues relevant here, including the time and funding needed for data producers to consolidate, format and curate their data; standardization of data products and formats; and optimal dissemination platforms for the data. As these issues are relevant to both stellar classification and Virtual Observatory initiatives, a joint workshop between Commissions 5 and 45 may be of benefit. *Additional input for this report was provided by Kelle Cruz (Hunter College), Michael Cushing (U. Toledo), Eduardo Martín (Centro de Astrobiolog'a), Ian McLean (UC Los Angeles), I. Neill Reid (STScI) and Emily Rice (CUNY College of Staten Island).*

3. Spectroscopic and Photometric Surveys

Caroline Soubiran

Spectral and photometric surveys provide the raw materials for stellar classification, and cross-correlation is an effective technique for isolating peculiar and astrophysically interesting objects. The following is a partial list of recent surveys, most of which provide not only spectra and/or photometry, but also derived stellar parameters:

RAVE (RAdial Velocity Experiment, `http://www.rave-survey.aip.de/rave/`) is a spectroscopic survey at $R = 7500$, wavelength range 8400-8800Å, magnitude range $9 < I < 12$. The Third Data Release (Siebert *et al.* 2011, AJ, 141, 187S) provides stellar parameters for 39,833 stars.

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SEGUE (Sloan Extension for Galactic Understanding and Exploration, `http://www.sdss3.org/surveys/segue2.php`) is a spectroscopic survey at $R \sim 2000$, wavelength range 3820-9200Å, magnitude range $14 < g < 20.3$, providing atmospheric parameters for ~250,000 stars (Yanny *et al.* 2009, AJ, 137, 4377, Lee *et al.* 2011, AJ, 141, 90).

The Geneva-Copenhagen survey of the Solar neighbourhood (Nordstrom *et al.* 2004, A&A, 418, 989, Holmberg *et al.* 2009, A&A, 501, 941) provides effective temperatures and metallicities from uvbyβ photometry for 16,682 nearby F and G dwarfs with $V < 8.6$. Query at `http://cdsarc.u-strasbg.fr/viz-bin/Cat?V/130`

PASTEL is a regularly updated bibliographical compilation of atmospheric parameters (Soubiran *et al.* 2010 A&A, 515. 111). Latest version has 31724 records including 6527 stars with ($T_{\rm eff}$, $\log g$, [Fe/H]) relying on high-resolution spectroscopy. Query at `http://cdsarc.u-strasbg.fr/viz-bin/Cat?B/pastel`

4. Catalogues, Atlases, & Search Engines

B.A. Skiff (Lowell Obs) continues to build a comprehensive catalogue of published spectral classifications. That catalog can be found at the URL: `http://cdsarc.u-strasbg.fr/viz-bin/Cat?B/mk`. The latest version contains 452890 entries, but still lags the current literature by a number of years. The Skiff catalog has served as the source of spectral types for an innovative search engine/spectral class encoding system that has been developed to make archives such as the VO and NASA's MAST searchable in terms of detailed spectral types (Smith *et al.* 2011, IVOA Design note 2011 Oct 24). The system encodes spectral classes into a digital format of the form TT.tt.LL.PPPP, where TT and tt refer to spectral type and subtype, LL to luminosity class, and PPPP to possible spectral peculiarities. Archive centers can utilize this system to quantify classes of formerly arbitrary spectral classification strings found in classification catalogs. The encoding system will also allow users to request archived data based on spectral class ranges. The encoding system may also have applications to automatic classification of stellar spectra. See `http://www.ivoa.net/Documents/latest/SpectClasses.html`

The previous triennial report (2006 – 2009) listed a number of large-scale spectral classification catalogs and stellar spectral atlases, most of which are still active. The reader is referred to that document for that listing.

5. Closing remarks

Stellar classification, the mandate of IAU Commission 45, is an area of long-standing interest to the IAU. While stellar classification is a traditional discipline, it has been at the forefront of astronomical research for over a century. Most recently, classification has played a crucial role in the discovery and characterization of brown dwarfs, leading to the establishment, now, of three new stellar classes, the L, T, and Y dwarfs. We are convinced that stellar classification will be of increasing importance in the future, especially with the advent of deep Galactic surveys, such as Pan Starrs, LSST, *Gaia* and others. Because of this, we expect the relevance of our Commission to increase with the years.

It is a pleasure to thank the contributors to this report, and for the cooperation of the organizing committee over the past 3 years.

Richard Gray
President of the Commission