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COMMISSION 45 SPECTRAL CLASSIFICATION

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TRIENNIAL REPORT 2006 - 2009

1. Introduction

This report gives an update of developments (since the last General Assembly at Prague) in the areas that are of relevance to the commission. In addition to numerous papers, a new monograph entitled *Stellar Spectral Classification* with Richard Gray and Chris Corbally as leading authors will be published by Princeton University Press as part of their *Princeton Series in Astrophysics* in April 2009. This book is an up-to-date and encyclopedic review of stellar spectral classification across the H-R diagram, including the traditional MK system in the blue-violet, recent extensions into the ultraviolet and infrared, the newly defined L-type and T-type spectral classes, as well as spectral classification of carbon stars, S-type stars, white dwarfs, novae, supernovae and Wolf-Rayet stars.

2. Working Groups

The Working Group on *Standard Stars* (chair C. Corbally) publishes a biannual newsletter edited by Richard Gray at the `<stellar.phys.appstate.edu/ssn>`. The newsletter publishes abstracts of papers relating to all aspects of standard stars, reports of ongoing work, and contributions and discussions related to standard stars.

3. Cool Brown Dwarfs (Adam J. Burgasser)

3.1. *Overview*

As of 1 May 2008 there are 131 known T-type dwarfs archived on the DwarfArchives site `<dwarfarchives.org>`. The majority of these have been found by the 2MASS and SDSS surveys, but an increasing number are now being identified in the deeper near-infrared (NIR) successor surveys UKIDSS (Kendall *et al.* 2007; Lodieu *et al.* 2007; Warren *et al.* 2007; Chiu *et al.* 2008; CHFTLS (Delorme *et al.* 2008; Delorme *et al.* 2008).

Out of the known population, eleven are companions to nearby stars, ten are resolved binaries, and one – S Ori 70 – is a candidate member of the 3 Myr σ Orionis cluster. The known population spans distances of 3.6 pc to ~ 100 pc (~ 360 pc if S Ori 70 is a member of σ Orionis), with the vast majority lying within 20 pc of the Sun.

Apparent J-magnitudes span 12.9 to > 20. Nearly all have published low- (R $\simeq 100$) and moderate-resolution (R $\simeq$ 500-2000) NIR spectroscopic data, and a fraction have published red optical and/or mid-infrared data. High-resolution (R $\simeq 20\,000$) near-infrared spectroscopic data have been reported for a few of the brightest T-type dwarfs (Zapatero Osorio *et al.* 2006; McLean *et al.* 2007; Zapatero Osorio *et al.* 2007).

3.2. *Classification*

A NIR spectral classification scheme, unifying the initial schemes has been completed and published in Burgasser *et al.* 2006. This scheme defines nine primary standards spanning subtypes T0 through T8 in integer steps, along with five alternate standards. The standards were selected to be bright and observable from both hemispheres wherever possible, and resolved binaries were excluded from the primary standard set.

Classification metrics tied to the strengths of H_2O and CH_4 absorption bands were defined in the 1-2.5 μm range for low- and moderate-resolution spectra. In addition, five classification indices were defined to enable 'quantified' classification. Cushing *et al.* 2006 have investigated spectral classification in the mid-infrared using 5.5-14.5 μm data obtained with the *Spitzer Space Telescope*. The 7.8 μm CH_4 and 10.5 μm NH_3 bands were shown to strengthen monotonically through the T sequence and could in principle be used for spectral classification. Photometric classification of T dwarfs has been demonstrated using narrow-band filters spanning the 1.6 μm CH_4 band (Tinney *et al.* 2005; Burgasser *et al.* 2006).

Several groups are now investigating the use of these filters to identify and characterize T-type dwarf candidates in deep imaging surveys.

3.3. *Secondary parameters*

As anticipated in the 2005 Commission report, a number of groups have examined secondary parameter effects in T-type dwarf spectra arising from variations in surface gravity, metallicity and vertical mixing. Key features include the 2.1 μm K-band peak modulated by pressure-sensitive, collision-induced H_2 absorption, and the 1.05 μm peak, shaped by the pressure-broadened red wing of the 0.77 μm K I doublet transition. Studies have characterized variations in these features amongst the latest-type T dwarfs, which are less affected by condensate cloud effects (see below).

Comparisons of model predictions to the spectra of empirical benchmarks (sources with astrometric distance and bolometric luminosity measurements, companions to nearby stars, resolved binary systems) have shown that these features are linked to both surface gravity and metallicity variations (Burgasser *et al.* 2006, Liu *et al.* 2006; Burgasser *et al.* 20007; Cushing *et al.* 2008; Looper *et al.* 2008). High-angular resolution imaging and spectral template analyses have verified these effects as intrinsic to the evolution of brown dwarfs across the L/T transition and not the result of age or metallicity variations (Burgasser *et al.* 2006; Liu et.al 2006; Looper *et al.*2008). Condensate cloud effects are likely responsible, although fully-consistent models are still progressing (Burrows *et al.* 2006;Helling *et al.* 2008). The L/T transition problem is of course relevant to the classification of early-type T-type dwarfs; of particular concern is the possibility that currently-defined subtypes may be biased by or entirely populated with hybrid spectra. High-resolution imaging and spectroscopic studies of early-type T-type dwarf standards to weed out unresolved pairs is ongoing.

3.4. *Beyond class T: the Y-type dwarfs*

Two discoveries made this term by UKIDSS (Warren *et al.* 2007) and CFHTLS (Delorme *et al.* 2008) appear to be cooler and later-type than the current T8 standard 2MASS J0415–0935. Their NIR spectra also exhibit a subtle feature attributable to NH_3 absorption at 1.55 μm. The detection of this feature at NIR wavelengths (NH_3 has already been detected in mid-infrared T-type dwarf spectra) has raised the issue as to what will define the end of the T-type dwarf class and the start of the next cooler class, already dubbed the 'Y-type dwarfs' (see Kirkpatrick 2005). Delorme *et al.* (2008) advocate that the appearance of NH_3 in the NIR – a new molecular species at these wavelengths – while Leggett *et al.* (2007) contend that only with the condensation of H_2O will spectral energy distributions change sufficiently to warrant a new class.

The current absence of a substantially cooler benchmark, comparable to the L-type dwarf (GD 165B) and T-type dwarf (Gliese 229B) prototypes, is likely to make this a contentious issue in the upcoming term. Continued survey work by UKIDSS and CFHTLS, and the upcoming *WISE* satellite mission (an infrared successor to both 2MASS and IRAS, with an expected launch in late 2009), will aid this endeavor by (hopefully) identifying many more such cool brown dwarfs.

4. **White dwarf spectral classification** (James W. Liebert)

The spectral classification system currently in use is described in Sion *et al.* 1983 (Jim Liebert being one of the coauthors, theorists and observers included.) Until recently, white dwarf atmospheres came in two flavors – hydrogen-rich and helium-dominated, sometimes with traces of hydrogen. The former are classified DA, until about 5 000 K below which the hydrogen is not excited so there are no Balmer lines in absorption. Likely the helium sequence begins with the stars above 40 000 K which show He II and are classified DO, then from 12 000 to about 39 000 K they show only neutral helium (He I) and are classified DB. Below 12 000 K they can be featureless (DC), show carbon bands and/or atomic lines (DQ) or accreted heavy metals (DZ). There are hybrid classes which show traces of metals, such as DBZ. An interesting discovery of the few years is a class of cool, hydrogen atmosphere white dwarfs that show evidence of a debris disk (DAZ). Refractory heavy elements continually rain down on the atmosphere so that heavy metal lines (Ca, Mg, Fe mainly) are seen in the spectrum, and the mid-IR energy distribution shows an excess due to heating of the external debris disk by the white dwarf. The *Spitzer* satellite has contributed to the study of these.

A new class of white dwarf atmosphere has been found in the last few years, rare objects appearing among the over 9 000 white dwarfs found in the Sloan Digital Sky Survey. These are hotter DQ stars showing lines of singly-ionized carbon (C II). Now the long-established cool DQ stars, most of which show bands of diatomic carbon (C_2 Swan bands), have helium-dominated atmospheres with traces of carbon no more than one carbon for every 100 helium atoms. These have carbon dredged up from the core of the star into the helium envelope. We have recently discovered that some of the hot DQ stars with $T_{\rm eff}$ near 20 000 K actually have atmospheres dominated by carbon. Helium is usually not detected (see Dufour *et al.* 2007). Oxygen is also detected as a trace element in a few of these stars.

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5. Carbon star classification (Thomas H. Llyod Evans)

There has been great activity in this area over the last three years. First, there have been several searches for carbon stars by classical objective prism work in galactic fields, as well as confirmation by slit spectroscopy of those discovered earlier and slit spectroscopy of candidates selected by their colours in the *IRAS* or 2MASS catalogues. Some of the important contributions are listed below. In addition, rejection of suspected members by MacConnell (2006) and detection of new RCB stars by Tisserand *et al.* (2008) has been carried out.

There have also been numerous discoveries of carbon stars in galaxies of the Local Group. A reliable survey technique, which avoids the problems with crowding and a poor limiting magnitude in objective prism surveys, uses photometry in R, I and in narrow bands centred on TiO and CN (cf. Battinelli & Demers 2006; Demers, Battinellii & Artigai 2006). Many recent surveys use infra red photometry, as many carbon stars occupy a distinctive position in colour-magnitude and two-colour diagrams.

The purity of such samples has been checked by the more specific narrow band photometry, and confusion between bluer carbon stars and M-type stars, as well as between M-type stars and hotter stars, demonstrated by Battinelli, Demers & Mannucci (2007). Much work has been done on near- and mid-infrared spectra of carbon stars in the Galaxy and nearby galaxies. Some of this work has relevance for stellar classification, and is of particular importance because it extends spectral classification to stars which are in many cases practically optically invisible, as well as extending classification to a new spectral region, which may contain new information.

6. Photometric classification (Thomas H. Llyod Evans)

The photometric classification based on Medium Band photometric systems such as Stromvil and Vilnius Systems has been carried out by Bartasiute, Straizys, Laugalys and few others and the Strömgren system had been employed. To classify stars in clusters of various metallicity by Anthony-Twarog and collaborators. Numerous broadband (Washington) as well as *UBVRI* photometry to classify stars in clusters at different Galactic locations reaching fainter limits continue to provide useful data for the study of Galactic structure. The references listed below are arranged following the classification system mentioned above.

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Strömgren photometry 2005 - 2008
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Washington photometry 2005 - 2008
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Broadband UBVRI photometry 2005 - 2008
Busso, G., Moehler, S., Zoccali, M., Heber, U., & Yi, S. K. 2006, *BaltA*, 15, 25
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Piatti, A. E., Clariá, J. J., & Ahumada, A. V. 2006, *MNRAS*, 367, 599
Piatti, A. E., Clariá, J. J., Mermilliod, J.-C., *et al.* 2007, *MNRAS*, 377, 1737
Rubin, K. H. R., Williams, K. A., Bolte, M., & Koester, D. 2008, *AJ*, 135, 2163

7. Catalogues and atlases (Richard O. Gray)

7.1. *General Catalog of Stellar Spectral Classifications* (Brian A. Skiff)

Brian A. Skiff (Lowell Obs) continues to build a comprehensive catalogue of published spectral classifications. It now contains some 300 000 entries and as of mid-2008 is asymtotically complete up to about 1985 in the literature; some more recent data is included. Several important objective-prism surveys from the 1950s and 1960s are omitted at present, however. The file is updated a few times each year at the Strasbourg VizieR service as item 'B/mk'. See: `<cdsarc.u-strasbg.fr/viz-bin/Cat?B/mk>`.

In late 2007 Skiff also acquired most of the remaining Burrell Schmidt and some Curtis Schmidt objective-prism plates taken for the northern extension of Nancy Houk's HD reclassification project. The 1 700 plates have complete coverage north of about $+37^o$ Dec, but include substantial coverage between $+05^o$ and $+37^o$ Declination. The plate limit is about B mag 10.5. It is his intention to finish classifying the northern HD stars to the extent possible. Considerable experience in examining the plates will be necessary before being able to match the quality and consistency of Houk's work.

The classifications in this compilation include only those types determined from spectra, omitting those determined from photometry. Classifications include MK types as well as types not strictly on the MK system, such as white dwarfs, Wolf-Rayet stars, etc. This catalogue includes for the first time results from many large-scale objective-prism spectral surveys done at Case, Stockholm, Crimea, Abastumani, and elsewhere. The stars in these surveys were usually identified only on charts or by other indirect means, and have been overlooked heretofore because of the difficulty in recovering the stars. Many of these stars are not included in SIMBAD.

7.2. *Other large-scale spectral classification catalogues*

Other spectral classification catalogues, published in the past three years, include:
A Unified Near-Infrared Spectral Classification Scheme for T Dwarfs, Burgasser, A. J., Geballe, T. R., Leggett, S. K., Kirkpatrick, J. D., & Golimowski, D. A., 2006, *ApJ*, 637, 1067. This paper details a new unified near-infrared spectral classification scheme for T dwarfs, and presents spectral types for many of the known T dwarfs.

On-line spectral catalogs of T dwarfs are currently maintained by:
- A. Burgasser, (low resolution NIR: `<www.browndwarfs.org/spexprism>`;
red optical: `<web.mit.edu/~ajb/www/tdwarf/#spectra>`);
- S. Leggett (moderate resolution NIR: `<www.jach.hawaii.edu/~skl/LTdata.html>`),
- I. McLean (moderate resolution NIR: `www.astro.ucla.edu/~mclean/BDSSarchive/>`),

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- J. Rayner (moderate resolution NIR: irtfweb.ifa.hawaii.edu/∼spex/WebLibrary/index.html#T>).

Contributions to the Nearby Stars (NStars) Project: spectroscopy of stars earlier than M0 within 40 pc – The southern sample, Gray, R. O., Corbally, C. J., Garrison, R. F., McFadden, M. T., Bubar, E. J., McGahee, C. E., O'Donoghue, A. A., & Knox, E. R., 2006, *AJ* 132, 161. This paper is the second in a series of three classifying the nearby solar-type stars (stars earlier than M0 within 40 pc of the sun). Results are reported for 1676 stars south of the equator.

Visual Multiples. IX. MK Spectral Types, Abt, H. A. 2008, *ApJS* 176, 216. Classifications for 546 stars in multiple systems are given.

The Galactic O Star Catalog V.2.0, Sota, A., Maíz Apellániz, J., Walborn, N. R., & Shida, R. Y., *RMxAC* 33, 56. The Galactic O-Star Catalog continues to be updated with spectral types and other information on the known O-type stars with $V < 8$ in the Galaxy. A total of 378 stars with precise spectral classifications are featured. See <www-int.stsci.edu/ jmaiz/research/GOS/GOSV2main.html>.

7.3. *Stellar spectral atlases*

A number of stellar spectral atlases were published during this period, featuring stellar spectra across the electromagnetic spectrum:

X-Atlas: An On-line Archive of Chandra's Stellar High-Energy Transmission Grating Observations, Westbrook, O. W., Evans, N. R., Wolk, S. J., Kashyap, V. L., Nichols, J. S., *ApJS*, 176, 218; and *Visual Multiples. IX. MK Spectral Types*, Abt, H. A. 2008, *ApJS*, 176, 216. Classifications for 546 stars in multiple systems are given. This web-based atlas (<cxc.harvard.edu/XATLAS/>) features spectra of high-mass (O, B and Wolf-Rayet) and low-mass (F, G, K, M) stars as well as spectra of white dwarfs, X-ray binaries and cataclysmic binaries observed with the *Chandra* X-ray telescope.

A high resolution spectral atlas of brown dwarfs, Reiners, A., Homeier, D., Hauschildt, P. H., & Allard, F., 2007, *A&A* 473, 245.

Spectral atlas of O9.5-A1-Type supergiants, Chentsov, E.L., & Sarkisya, A.N. 2007, *Astrophysical Bulletin* 62, 257.

SpectroWeb: An Interactive Graphical Database of Digital Stellar Spectral Atlases, Lobel, A. This interactive database contains high resolution spectra of a number of standard stars. See: <spectra.freeshell.org/spectroweb.html>.

Spectral atlas of massive stars around He I *10830 Å*, Groh, J. H., Damineli, A., & Jablonski, F. 2007, *A&A* 465, 993.

A Medium Resolution Near-Infrared Spectral Atlas of O and Early-B Stars, Hanson, M. M., Kudritzki, R.-P., Kenworthy, M. A., Puls, J., & Tokunaga, A. T. 2005, *ApJS* 161, 154. Contains spectra and spectral types of O and early-B stars in the infrared *K*-band.

7.4. *A new spectral class encoding system* (Myron A. Smith, Richard O. Gray, Christopher J. Corbally, Randall Thompson, and Inga Kamp)

A new spectral class encoding system has been developed to make archives such as in the VO and NASA's MAST more responsive to specific query needs. Although MAST has archived UV and optical wavelength spectra for well over 10 000 stars observed by NASA satellites, there has been up to now only little design work on a system that organizes these objects by spectral type in order for researchers to obtain information about targeted groups of stars.

For someone interested in identifying all stars of a chosen spectral type and luminosity class and downloading the spectra the authors have designed a 'spectral class' nomenclature system for spectra of stars across the HR Diagram into a finite number of bins. The nomenclature scheme has the form `TT.tt.LL.PPPP`, where `TT` and `tt` are numerical digits (0-9) representing spectral types and subtypes, `LL` luminosity classes, and `PPPP` represent spectral peculiarities. An entry '00' is returned for an unknown attribute. To take the example of the (incomplete) spectral classification just 'A0', the `LL` codes will be '00' because the luminosity class is unspecified. The four spectral peculiarities are arranged into two subgroups of two each. Then, `P1P2` are reserved for peculiarities that can be expected across the HR Diagram (e.g. 'e', 'p' or 'n'), and `P3P4` are codes for peculiarities common only to a smaller range of spectral types, e.g., types AF. In this way, one can represent as many as four spectral peculiarities, including the possible composite nature of the spectrum. The details of this have been published in an IVOA (International Virtual Observatory Alliance) Design Note, see: `<www.ivoa.net/Documents/latest/SpectClasses.html>`

8. Closing remarks

It is a pleasure to thank the contributors whose names appear at the head of their sections in this report. I am particularly thankful to Tom Lloyd Evans and Chris Corbally for their help and guidance over my term as vice president and later as president. I am also thankful to Richard Gray for hosting the commission page and all OC members for their support and co-operation.

Sunetra Giridhar
president of the Commission

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