ULTRACOOL DWARFS

Yakov V. Pavlenko

1Main Astronomical Observatory, NAS of Ukraine
27 Akademika Zabolotnoho Str., 03680 Kyiv, Ukraine
e-mail: yp@mao.kiev.ua

We present results of modeling of spectra of M-, L-, T-dwarfs. Theoretical spectra are fitted to observed spectra to study the main parameters of the low-mass objects beyond the bottom of Main Sequence. Application of “lithium” and “deuterium” tests for assessment of ultra-cool dwarfs are discussed.

INTRODUCTION

Population of ultracool (UC) dwarfs occupies the right-bottom quadrant below the bottom of the Main sequence. A lot of UC dwarfs was discovered after 1995 (see [3] and [4] for reviews). Basically, we can define at least 3 different populations of ultracool dwarfs:

— Low mass stars (LMS). Hydrogen burns in their core.
— Brown dwarfs (BD). Hydrogen cannot burns in their core. Their existence were predicted by Kumar [16], [17]. Later investigatins show that lithium burns inside the brown dwarfs of $55M_J < M < 75M_J$ (see [8] for more details). Here $M_J$ is mass of Jupiter: $1M_J = 0.001M_\odot$. First brown dwarfs Teide1 and Gl 229B were discovered by groups of Rebolo [39] and Nakajima [24], respectively. Deuterium should be depleted in atmospheres of brown dwarfs.
— Planets ($M < 13M_J$) preserve deuterium (and lithium) during their evolution [42].

Today we can asses their spectra (see libraries of spectra on [14] or [23]):

— M-dwarfs (GJ406, VB10, VB8, etc). TiO dominates in their spectra.
— L-dwarfs (GD169B, Kelu1,2MASS 0920+35, etc.). K and Na lines are the main features there ([27],[28]), Ti and V atoms are bound into dust particles.
— T-dwarfs (Gl 229B, SDSS 0151, SDSS 1110, etc) — infrared spectra show CH$_4$ lines.
— planets (see list of discovered planets on web [35], and references therein). First confirmed discovery of planetary system 51 Peg was carried out by Mayor & Queloz [22] (see Marcy et al. [19]).

M-, -L, -T dwarfs are of different effective temperatures and masses. Still, “the Main sequence” for brown dwarfs and L-, T-dwarfs forms the approximately horizontal line (Jupiter is on the left side radii-masses plot, see [10]) — the dependence of radii of UC dwarfs on mass is extremely weak due to degeneracy of the gas in their cores. As result, sizes of old brown dwarfs, L-dwarfs and Jupiter are comparatible.

As was noted by Zapatero Osorio (private communication) depending on age, T-dwarfs can be brown dwarfs (if they are old) or "planetary objects" (masses below the deuterium burning limit, if they are young). Hence, very young T-dwarfs do not burn deuterium. Then, giant planets have been found by indirect techniques around stars. Young objects a few times more massive than Jupiter have been identified using direct imaging techniques. They are characterized by ultracool atmospheres (L and T types). These objects are free-floating in star-forming regions and very young clusters. This poses challenge to current theories of stellar and planetary formation (see Proc. of IAU 211 [6]).

Different UC dwarfs are of different structure as well:

— inside the LMS we have core with hydrogen burning zone.
— Brown dwarfs burn deuterium, the most massive BDs ($55M_J < M < 75M_J$) burn lithium within short time scales (see refs in [18]).
— planets are only objects without any nuclear burning processes. They preserve deuterium and lithium from times of their formation.
Models of formation of spectra of ultracool dwarfs

To model spectra and spectral energy distributions (SEDs) of ultracool dwarfs we should account a few complicate processes which govern physical state of their atmospheres:

- **Dust formation processes.** Due to the low temperatures and high pressure regime some molecular (and atomic) species are bound in different grain particles (see [43]). Indeed, molecular bands of VO and TiO are weaker in L-dwarf spectra in comparison with M-dwarfs.

- **Damping of K and Na lines.** Resonance doublets of K and Na form the most impressive features in spectra of L-dwarfs. Formally computed equivalent widths of these lines can be of order a few kÅ (see Fig. 1 and [28, 29] for more details).

- **Dust opacities.** Importance of account of dust opacities for a procedure of numerical modelling of spectra of L- and T- dwarfs was shown by Pavlenko et al. [29]. Basically, the problem of the dust opacities in L-dwarf atmosphere is rather complicate – we should account absorption/scattering by particles of different composition, sizes, orientations. Moreover, recent researches provide some evidences of cloudy structure of dust layers of L-dwarfs atmospheres (see materials of IAUS 211 [6]).

Optical spectra: K and Na lines

Resonance lines of Na I (λλ 589.1, 589.7 nm) and K I (λλ 766.6, 770.1 nm) are very strong in spectra of UC dwarfs [26], because majority of alkali atoms exists there as neutral atoms. Na I resonance lines are stronger — in atmospheres of majority stars log N(Na) > log N(K).

Lines of alkali metals observed in UC dwarfs spectra are pressure broadened. Extremely strong broadening of K and Na resonance lines provides an serious problem for their modelling. We can use for their wings modelling the traditional approach based on collisional interactions between atoms K and Na and H, He and molecule only for qualitative analysis [30].

More sophisticated approaches based on quantum-chemical consideration of the impact of potential fields provided by different species on levels K and Na were proposed recently by different groups (see [5] and [1]).

On the other hand, in atmospheres of L-dwarfs the dust absorbs/scatters photons in wide spectral regions. Dust opacity affects the overall spectral distributions (see [24] for more details). Perhaps, for core and near wings of resonance lines K I and Na I we can still use the collisional approach [34].

Infrared spectra: H₂O bands

Water bands cover the wide spectral regions in the infrared spectra of UC dwarfs (see [33] and the poster by Lyubchik et al. on this session). For a long time the computation of the most complete lists of H₂O is the real challenge for theoretical physics (see a review in [32]). In general, incompleteness of water line lists used for the
numerical analysis of infrared spectra of UC dwarfs can increase our problems of stellar spectra computations in different ways:

- outer layers of model atmospheres computed with incomplete line lists of H$_2$O are “too hot”.
- results of spectral synthesis can be affected by incompleteness of H$_2$O lists.

Water bands in the IR are of interest for different topics. Infrared CO band at 2.3 and 4.5 micron can be used for determination of basic parameters of UC dwarfs: abundances, effective temperatures, rotational velocities (see [11, 33]). For their theoretical modelling the use of reliable list of H$_2$O lines is of crucial importance (see [12] for more details).

**Lithium test**

“Lithium test” was proposed Rebolo et al. [38] to identify brown dwarfs from the population of LMS. Before 1995 L- and T-dwarfs were not known, and main attention was paid for the low-gravity M-dwarfs. They suggested that at least part of low-mass dwarfs in young open clusters should preserve their lithium. Observation of lithium lines in spectra of late M-dwarfs provides the direct evidence of their substellar nature. Pavlenko et al. [25] showed that lithium lines can be detected in spectra of brown dwarfs despite of severe blending of the atomic lines by molecular bands. Later lithium lines were really found in spectra of some brown dwarfs (Teide1 [10], Kelu1 [11], etc. see [3]).

On the other hand, observation of lithium lines in spectra of late-type low gravity dwarfs of open clusters provide the information about their age. Due to theoretical predictions (see refs. in [15]) the smallest objects should be cooled very quickly, i.e within time scales of a few Myrs. Still young, i.e low gravity dwarfs of ages 3-5 Myrs preserve their lithium as well. In Fig. 2 results of determination of lithium abundances in atmospheres of the low-mass dwarfs of open cluster σ Ori are showed. Note, these results are based on analysis of pseudoequivalent widths of lithium lines (see [27] and [35] for more details) – measurements of the pseudoequivalent widths are provided in respect to the local pseudocontinuum formed by molecular lines.

Perhaps, determination of masses of brown dwarfs is the main problem. Fortunately, often brown dwarfs form binary systems. The study of the low-mass objects is of special interest. First observations of GJ569B provide some evidences about its substellar nature (see refs in [15]). Still, later observations of Martín et al. [24] on Keck Telescope show that GJ569B is double system – GJ569Ba and GJ569Bb are orbiting with period 892 ± 25 days [19]. Lithium test for this system is of crucial importance. However, in this case we should manage a combine spectrum formed in atmospheres of both components of different masses.

Later the application of the “lithium test” was discussed for L-dwarfs and even T-dwarfs (see [29]). Indeed, lithium lines were observed in spectra of some UC dwarfs.

**Deuterium test**

In the cores of the ultracool dwarfs the correlations effects between ions dominate lowering Coloumb barrier between particles (see [8] for more details). Still temperatures in the interiors of UC dwarfs of masses M < 13M$_J$ cannot be high enough (T < 0.5 MK) to initiate there a nuclear burning of deuterium.

Béjar et al. [4] propose to use observations of lines of deuterium contained species to determine the ages/masses of the smallest UC dwarfs. The task is very difficult in both theoretical and observational aspects. The simplest case would be proposed consists of the analysis of HDO/H$_2$O spectra in the IR spectra of UC dwarfs. Still, HDO lines are very blended by H$_2$O lines [32]. From one side, we should have very accurate line lists both H$_2$O and HDO. Observed intensities of HDO lines cannot exceed a few percent (see ibid and [8]). Moreover, IR spectrum of UC dwarfs should contain lines of other polyatomic species (CH$_4$ and others). These factors increase the demands for a capacity of observational facilities and the quality of theoretical data to identify and to carry the analysis of HDO lines in spectra of UC dwarfs.

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Figure 2. Comparison of pseudoequivalent widths (pEW) of the lithium resonance doublet lines 670.8 nm computed for log N(Li) = 3.2 and observed in spectra in young dwarfs of σ Ori cluster. TiO line list by Plez [37] and NextGen model atmospheres [9] of solar metallicity [2] were used in theoretical computations. Solid and dashed lines in the left part of the plot indicate the conventional curves of growth for the line computed for log N(Li) = 3.2 and 2.0, respectively. Open circles and open triangles indicate sources with Hα emission of pEW > 1 nm and objects with forbidden emission lines, respectively – see Zapatero Osorio et al. [45] for more details.

Figure 3. Computed spectra of H$_2$O and HDO for different ratios D/H. Computations were carried for model atmosphere 1200/5.0 by Tsuji (1998), AMES line lists [36], with step 0.5 Å, see [32] for more details.
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