ULTRACOOL DWARFS

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We present results of modelling 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 the Main Sequence. Application of the "lithium" and "deuterium" tests for assessment of ultra-cool dwarfs is discussed.

INTRODUCTION

Population of ultracool (UC) dwarfs occupies the right-right-bottom quadrant below the bottom of the conventional Main Sequence. A lot of UC dwarfs was discovered after 1995 (see [3] and [5] for reviews). Basically, we can define at least three different populations of ultracool dwarfs:

— Low mass stars (LMS). Hydrogen burns in their core.

— Brown dwarfs (BD). Hydrogen cannot burn in their core. Their existence was predicted by Kumar [17, 18]. Later investigations show that lithium burns inside the brown dwarfs of $55M_j < M < 75M_j$ (see [9] for more details). Here M_j is mass of Jupiter: $1M_j = 0.001M_\odot$. The first brown dwarfs Teide1 and Gl 229B were discovered by groups of Rebolo *et al.* [38] and Nakajima *et al.* [24], respectively. Deuterium should be depleted in atmospheres of brown dwarfs.

— Planets ($M < 13M_J$) preserve deuterium (and lithium) during their evolution [40].

First spectral classifications of UC dwarfs were provided by Kirkpatrick *et al.* [16] and Martín *et al.* [21]. Today, we can assess their spectra (see libraries of spectra in [10] or [13]):

— M-dwarfs (GJ406, VB10, VB8, *etc.*). TiO dominates in their spectra.

— L-dwarfs (GD169B, Kelu-1, 2MASS 0920+35, *etc.*). K and Na lines are the main features here [27, 28], Ti and V atoms are partially bound into dust particles.

— T-dwarfs (Gl 229B, SDSS 0151, SDSS 1110, *etc.*). Their infrared spectra contain CH_4 lines.

— planets (see a list of discovered planets at web [12], and references therein). The first confirmed discovery of the planetary system 51 Peg was carried out by Mayor & Queloz [23] (see Marcy *et al.* [20]).

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 of the radii-masses plot, see [6]) – the dependence of radii of UC dwarfs on mass is extremely weak due to the degeneracy of the gas in their cores. As result, sizes of old brown dwarfs, L-dwarfs and Jupiter are comparable.

As was noted by Zapatero Osorio (*private communication*) depending on age, T-dwarfs can be brown dwarfs (if they are old) or "planetary objects" (their masses are below the deuterium burning limit, if they are young). Hence, very young T-dwarfs do not burn deuterium. Then, giant planets around stars have been found by indirect techniques. Young objects, which are 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 a challenge to the current theories of stellar and planetary formation (see Proc. of IAUS 211 [5]).

Different UC dwarfs are of different structure as well:

— inside the LMS we have the core with a 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 [19]).

— planets are only objects without any nuclear burning processes. They preserve deuterium and lithium from times of their formation.

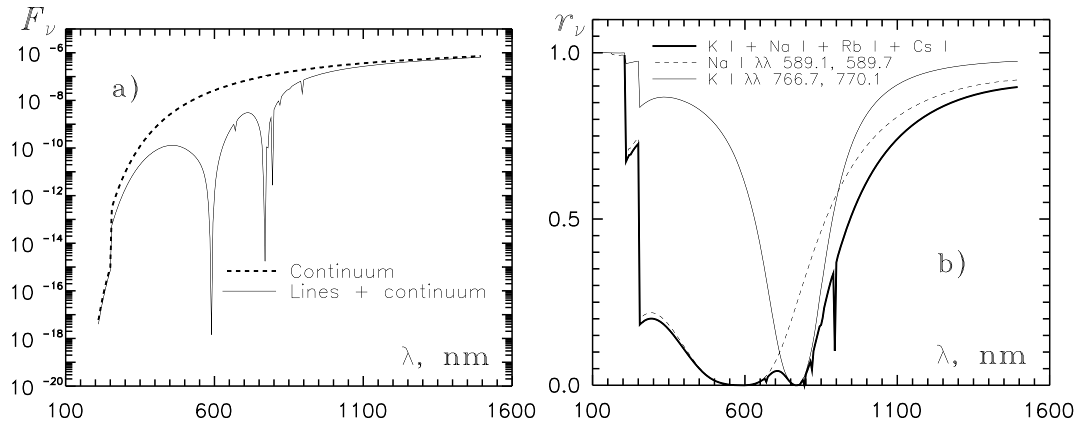

Figure 1. Profiles of resonance lines of K I ($\lambda\lambda$ 766.6, 770.1 nm) and Na I ($\lambda\lambda$ 589.1, 589.7 nm) calculated in the frame of the collisional broadening theory (the van der Waals' broadening) for the 1200/5.0 C-model atmosphere of Tsuji [41] (see [30] for more details)

MODELS OF FORMATION OF SPECTRA OF ULTRACOOL DWARFS

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

- *Dust formation processes*. Due to low temperatures and a high pressure regime some molecular (and atomic) species are bound in different grain particles (see [42]). Indeed, molecular bands of VO and TiO are weaker in the L-dwarfs spectra in comparison with the M-dwarfs ones.
- *Damping of K and Na lines*. Resonance doublets of K and Na form the most impressive features in spectra of L-dwarfs. Formally, a calculated equivalent widths of these lines can be of about few kÅ (see Fig. 1 and [28, 34] for more details).
- *Dust opacities*. Importance of taking into account of dust opacities by numerical modelling the spectra of L- and T- dwarfs was shown by Pavlenko *et al.* [34]. Basically, the problem of the dust opacities in the L-dwarf atmosphere is rather complicate – we should take into account absorption/scattering by particles of various composition, sizes, orientations. Moreover, recent studies provide some evidence for a cloudy structure of dust layers in atmospheres of L-dwarfs (see materials of IAUS 211 [5]).

OPTICAL SPECTRA: K AND NA LINES

Resonance lines of Na I ($\lambda\lambda$ 589.1, 589.7 nm) and K I ($\lambda\lambda$ 766.6, 770.1 nm) are very strong in spectra of UC dwarfs [26], because the majority of alkali atoms exists there as neutral atoms. The Na I resonance lines are stronger because $\log N(\mathrm{Na}) > \log N(\mathrm{K})$ in atmospheres of most stars.

Lines of alkali metals observed in UC dwarfs spectra are pressure broadened. The extremely strong broadening of the 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 of K and Na and H, He and molecule only for qualitative analysis [29].

The more sophisticated approaches based on the quantum-chemical consideration of the impact of potential fields provided by different species on levels of K and Na were recently proposed by various groups (see [1] and [7]).

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

INFRARED SPECTRA: H_2O BANDS

Water bands cover the wide regions of infrared spectra of UC dwarfs (see [32] and the paper by Lyubchik *et al.* on this session). For a long time, the computation of the most complete lists of H_2O is the real challenge for theoretical physics (see a review in [31]). In general, the incompleteness of the water line lists used for the numerical analysis of infrared spectra of UC dwarfs can complicate the calculation of stellar spectra because:

– the outer layers of model atmospheres calculated with an incomplete line lists of H_2O are "too hot".

– results of spectral synthesis can be affected by the incompleteness of the H_2O lists.

Water bands in the IR are of interest for different topics. The 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 [14, 32]). For their theoretical modelling the use of a reliable list of H_2O lines is of crucial importance (see [15] for more details).

LITHIUM TEST

"Lithium test" was proposed by Rebolo *et al.* [37] to identify brown dwarfs from the population of LMS. Before 1995 L- and T-dwarfs were not known, and the main attention was paid for the low-gravity M-dwarfs. They suggested that at least a 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 for their substellar nature. Pavlenko *et al.* [33] 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 [36], Kelu-1 [39], *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 [43]) the smallest objects should be cooled very quickly, *i.e.*, within time scales of a few Myr. Still young, *i.e.*, low gravity dwarfs of ages 3–5 Myr preserve their lithium as well. In Fig. 2 results of determination of lithium abundances in atmospheres of the low-mass dwarfs of the open cluster σ Ori are showed. Note, these results are based on analysis of pseudoequivalent widths of lithium lines (see [27] and [43] for more details) – measurements of the pseudoequivalent widths are provided in respect to the local pseudocontinuum formed by molecular lines.

Perhaps, the determination of masses of brown dwarfs is the main problem. Fortunately, brown dwarfs often form binary systems. The study of the low-mass objects is of special interest. First observations of GJ569B provide some evidences for its substellar nature (see refs in [19]. However, later observations of Martín *et al.* [22] on the Keck Telescope show that GJ569B is a double system – GJ569Ba and GJ569Bb are orbiting with period

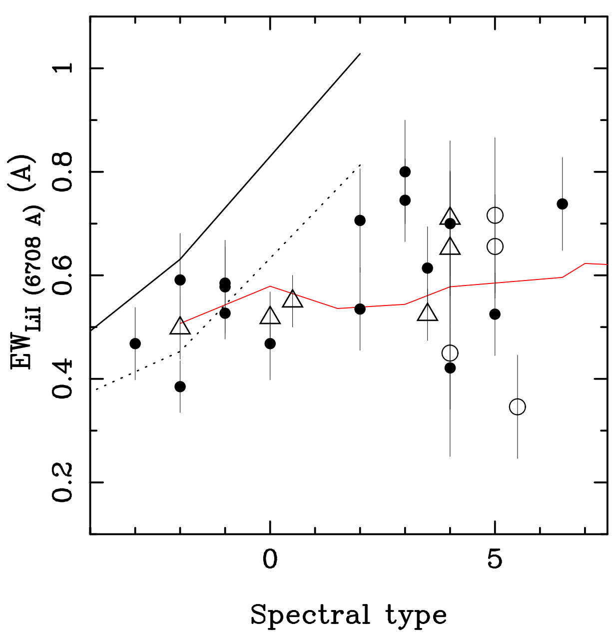

Figure 2. Comparison of pseudoequivalent widths (pEW) of the lithium resonance doublet lines 670.8 nm calculated for log N(Li) = 3.2 with the observed ones in spectra of young dwarfs of the σ Ori cluster. The TiO line list of Plez [35] and NextGen model atmospheres [11] of solar metallicity [2] were used in theoretical computations. Solid and dashed lines in the left part of the plot indicate the conventional curves of the growth of the lines computed for log N(Li) = 3.2 and 2.0, respectively. Open circles and open triangles indicate sources with H_α emission of pEW > 1 nm and objects with forbidden emission lines, respectively (see Zapatero Osorio *et al.* [43] for more details)

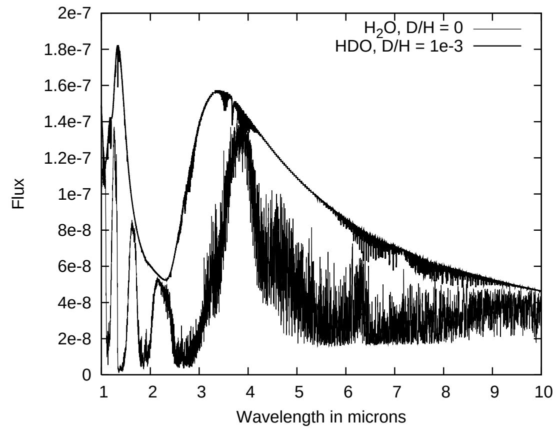

Figure 3. Calculated spectra of H_2O and HDO for various ratios D/H. Calculations were made for the model atmosphere 1200/5.0 by Tsuji (1998) and the AMES line lists [25], with step 0.5 Å (see [31] for more details)

892 ± 25 days [19]. The lithium test for this system is of crutial 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 [34]). Indeed, lithium lines were observed in spectra of some UC dwarfs.

DEUTERIUM TEST

In the cores of ultracool dwarfs, the effects of correlations between ions dominate and cause the lowering the Coloumb barrier between particles (see [9] for more details). Still, temperatures in the interiors of UC dwarfs of mass $M < 13M_J$ 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 deuterium lines contained features to determine the ages/masses ratio of the smallest UC dwarfs. The task is very difficult in both theoretical and observational aspects. The simplest case which would be proposed consists of the analysis of HDO/H_2O lines in the IR spectra of UC dwarfs. However, HDO lines are very blended by H_2O lines [31]. On the one hand, we should have the very accurate lists of both H_2O and HDO lines. Observed intensities of HDO lines cannot exceed a few per cent (see ibid and [9]). Moreover, the IR spectrum of UC dwarfs should contain lines of other polyatomic species (CH_4 and others). These factors make greater demands of the 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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