The Lithium Lines Formation in Brown Dwarf Atmospheres: Molecules, Chromospheres, NLTE

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Abstract. Results of the study of lithium lines formation in the spectra of brown dwarf candidates and the coolest PMS stars are discussed. LBL and JOLA models of molecular absorption were used to compute theoretical spectra containing Li I resonance 6708 Å and subordinate 8126 Å lines. These two approaches give similar (at least qualitatively) results in a wide range of $T_{\text{eff}}$.

From the comparison of observed and computed spectra for a grid of “non-dusty” Allard & Hauschildt (1995) model atmospheres of the Pleiades brown dwarfs Teide 1 and Calar 3 ($M_8$, $T_{\text{eff}} \approx 2700$ K) we found:

- The strength of molecular bands that form the background for Li I lines mainly depends on $T_{\text{eff}}$ and metallicity. For Teide 1 and Calar 3 the value found is $2700 < T_{\text{eff}} < 3000$ K.
- The fit of moderate resolution spectra of Teide 1 and Calar 3 showed that lithium abundances in their atmospheres are rather high: log N(Li)>2.5.

The possible impact of chromospheric-like features (CLF) on spectra of the latest M-dwarfs has been investigated. NLTE computations do not give any emission in the Li line cores for the CLF with weak and moderate gradients of temperature $G_r$.

The formation of lithium lines in “dusty” and “non-dusty” model atmospheres has been studied. The overall shape of the spectra of late M-dwarfs is sensitive to temperature structure changes due to the dust heating. “Dusty” models produce more pronounced lithium lines in comparison with “non-dusty”. That means the implementation of the dust improves perspectives of the lithium test, which can be applied for a rather large range of $T_{\text{eff}}$!

1. Introduction

This investigation has been carried out in the frame of the project aimed at the realization of the “lithium test” proposed by Rebolo et al.(1992) to select the real brown dwarfs in samples of late M-dwarfs.

Three strong lithium lines laying in the visible region of M-dwarfs and brown dwarfs spectra are severely blended by molecular bands. Still only resonance
6708 Å and subordinate 8126 Å lines are available for a rather reliable numerical analysis (see Pavlenko 1997).

2. Procedure

Our computations were carried out for Allard and Hauschildt (1995: AH95) "non-dusty" and Tsuji (1996) "dusty" model atmospheres. Few details of used procedure are given below:

- synthetical spectra were computed by WITA (Pavlenko et al. 1995);
- the molecular opacity was computed in the frame of LBL (line by line) and JOLA (just overlapping line) approaches. We used Kurucz (1993) and VALD line lists. JOLA input data have been described in Pavlenko et al. (1995);
- For TiO we adopt $D_0 = 6.92$ eV.

3. High resolution spectra: late-type PMS subgiants

To verify the quality of our input data and results we performed the investigation of spectra of two PMS stars: UX Tau C (M6 IV) and HHJ 430 (M5 IV).

Magazzù et al. (1993) and Pavlenko et al. (1992) got log N(Li) = 2.0 for UX Tau C. These results seem strange enough: due to theoretical predictions (D’Antona & Mazzitelli 1995) the lithium abundance should be undepleted ($\approx 3.0$ dex) in the atmosphere of UX Tau C.

Indeed, new investigations of Pavlenko and Martín (1997) for AH95 grid of model atmospheres show that log N(Li) = 3.2. We found that UX Tau C rotates with vsini$^1 = 35$ km/s.

For HHJ 430 we obtained log N(Li) = 3.2 and vsini = 65 km/s (see Figure 1) for both lithium lines. So we have confirmed the results of Oppenheimer et al. (1997).

4. High resolution spectra: BD candidates

To estimate relative strength of Li I lines in respect to the molecular band background we computed for several AH95 model atmospheres pseudoequivalent widths of lithium lines:

$$W_{\chi}^J = \int \left(1 - \frac{H_{\nu}^{JOLA+Li}}{H_{\nu}^{JOLA}}\right) d\nu$$

Pseudoequivalent widths are changed slow enough with decreasing effective temperatures for late M-dwarfs (Figure 2). Besides, analysis of synthetical spectra showed also that the strength of lithium lines correlates with the strength of molecular bands.

Let me note:

$^1$We had got the same result using JOLA models for the molecular absorptions.
Figure 1. The fitting of observed spectra of HHJ 430 by synthetical spectra normalized to the Li I 6708 Å line center. Lithium abundances are displayed within the plots.

- Our pseudoequivalent widths are much lower in comparison with the real equivalent widths given in Pavlenko et al. (1995), because $W'_{\lambda}$ are created by cores of lithium resonance doublet lines broken through a background formed by TiO bands. The extended wings of the Li I resonance doublet are covered by huge molecular absorption;

- from the comparison of Teide 1 and VB10 spectra Rebolo et al. (1996) we obtained pseudoequivalent widths $W'_{\lambda} = 1000 \pm 200$ mÅ and $100 \pm 25$ mÅ for 6708 and 8126 Å Li I lines. Using our COG's (see Figure 2) one may obtain log N(Li) > 3.0 and log N(Li) ≈ 2.9 for 6708 and 8126 Å, respectively.

The real lithium abundances in atmospheres of late M-dwarfs and brown dwarfs may be obtained by synthetical spectra analysis. The comparison of observed Teide1 spectrum (Rebolo et al., 1996) and computed for AH95 grid of model atmospheres shows that in the atmosphere of this brown dwarf log N(Li) > 2.5 (see Figure 3)

5. Chromospheres and Li I lines

Cores of the strongest lithium lines have been formed in the outermost layers of cool M-dwarfs and brown dwarfs. We continue the study of the possible impact
Figure 2.  *(Left panel)* Comparison of observed Teide 1 and computed for several AH95 model atmospheres: a) 2500/4.5/0, b) 2700/4.5/0, c) 3000/4.5/0

Figure 3.  *(Right panel)* Pseudo equivalent widths of lithium lines $W^J_\lambda$ computed for several AH95 model model atmospheres: 2500/4.5/0 (circles), 2700/4.5/0 (squares), 3000/4.5/0 (triangles). Solid and dashed lines plot results for log $g = 4.5$ and 5.0, respectively. Long dashed lines plot COG's for models with $[\mu] = -1$
of chromospheric-like features on spectra of the latest dwarfs (see also Pavlenko et al. 1995, Houdebine & Doyle, 1995).

Here we carried out the study for 2700/4.5/0 model atmosphere. A few simplest models of chromospheric-like features were built for 2700/4.5 model "non dusty" AH95 atmosphere. To model CLF's we used two parameters: temperature minimum $T_{min} = 0.7 * T_{eff} = 1900$ K, and temperature gradient $G_{rad} = \frac{\partial T}{\partial \log m}$. The computations of LTE & NLTE lithium lines were carried out for two models of CLF with $G_{rad} = -400$ and -800 (Figure 4a). NLTE computation procedure has been described elsewhere (Pavlenko et al. 1995, Pavlenko & Magazzû 1996).

Again, NLTE computations do not give any emission in the Li line cores for the CLF with weak and moderate gradients of temperature $G_r$ (Figure 4b). Still the common shape of spectra around Li I 6708 Å line depends on $G_r$. Namely, the flux governed by the molecular absorption in 6708 Å region increases with a grow of $G_r$ (Pavlenko 1997).

Note: these results may be interpreted also as an evidence of the weak sensitivity of the strength of lithium resonance and subordinate lines on the structure of the outermost layers of atmospheres of late M-dwarfs and brown dwarfs. That conclusion seems to be very essential for the lithium lines, because our knowledge about physics of the upper layers is very restricted. As it was shown by Pavlenko et al. (1995) and Houdebine & Doyle (1995) CLF's with strong gradients and/or deep temperature minimums may severely affect lithium lines.
Figure 5. a) Comparison of the temperature structures of “non-dust” AH95 and “dusty” Tsuji (1996) model atmospheres with $T_{\text{eff}}=2000\text{K}$, log $g = 5.0$; b) observed Teide1 fluxes and theoretical JOLA fluxes normalized to the equal flux at 7049 Å (point N); c) residual LBL fluxes with Li resonance doublet (log N(Li)=3.0) and without Li lines (solid and dashed lines, respectively) computed for 2000/5.0 “dusty” and “non-dusty” model atmospheres.

On the other hand, the temperature structure of the coolest dwarf model atmospheres are governed by convection. It seems impossible to create and to keep (to reproduce?) temperature inversion (CLF) inside the adiabatic convective envelope. In that sense temperature minimums of the real CLF should lay on the smaller $\tau$ in comparison with our models. So our models present the extreme cases of CLF’s.

6. “Lithium test”: dusty and non-dusty model atmospheres

Implementation of dust into the latest M-dwarf atmospheres provides drastic changes in the physical state of uppermost layers of stellar atmospheres (Tsuji 1996 and Allard in this volume).

Dust is an efficient heat absorber, so the temperature structures of model atmospheres have been changed (Figure 5a). The accounting for dust in model atmospheres shifts the $T_{\text{eff}}$ scale of late M-stars toward lower effective temperature.

To study the impact of the changing of the model structure on theoretical flux distribution in the visible region we carried out several numerical experiments:

A) JOLA fluxes for 2000/5.0 AH95 “non-dust” and Tsuji (1996) “dusty” model atmospheres were computed (Figure 5b). Obviously, the shape of molecular TiO bands is quite sensitive to the model structure. Observed flux distribution in the visible region of the young brown dwarf Teide 1 may be well fitted by JOLA computations for 2700/5.0 “non-dust” AH95 model atmosphere (Pavlenko 1997). Note, the fit of observed Teide 1 flux by JOLA theoretical fluxes for “dusty” 2000/5.0 model (Tsuji 1996) is not perfect.

B) We synthesized resonance lithium lines in “dusty” and “non-dusty” model atmospheres. For 2000/5.0 “non-dusty” AH95 model atmosphere we got very weak lithium lines at the background of the strong, saturated TiO bands. In contrary, “dusty” 2000/5.0 Tsuji (1966) model atmosphere gave intensive...
enough lithium doublet (fig.5c). One may say that in that sense dust in coolest model atmospheres improves perspectives of the "lithium test".

Of course, our results are preliminary, because the equation of state should take into account the formation of solid and/or liquid particles.

On the second hand the dust formation should be considered as time-dependent process. The problem is that structure and physical state of atmospheres of latest M-dwarfs and brown dwarfs are controlled by the convection. _Ad hoc_, their matter should be well mixed by the granulation processes. A further investigation should be done to clarify the nature of a set of physical processes of _the dust formation/destruction inside convective envelopes_ of the stars.

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