INTERPRETATIONS OF STELLAR SPECTRA: NLTE EFFECTS

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ABSTRACT. The results of computations of the Li I atoms statistical equilibrium in the late-type dwarfs atmospheres are discussed. The impact of NLTE on profiles and curves of growth of resonance and subordinate lithium lines had been studied for the 20-level lithium model atom.

It was found that:
For resonance lithium lines the sign and values of the NLTE abundance correction depend on lithium abundances, metallicities and effective temperatures of stars.
In the case of the saturated 670.8 nm Li I lines NLTE effects push lithium abundances observed in PMS stars toward lower values in comparison with LTE.
Profiles of Li I lines are practically not sensitive to “weak” chromospheres with “solar-like” temperature gradients.
For Li I resonance doublet 670.8 nm the NLTE abundance corrections are small for halo dwarfs ($\Delta\log N$(Li) ≈ 0.1).
The NLTE effects in Li I lines do not increase dramatically with the decreasing of the metallicity of halo dwarfs atmospheres.
It seems NLTE effects cannot explain the slope of the lithium plateau, discovered by Spite & Spite (1982).

1. The Procedure
To solve the system of statistical balance equations and radiative transfer equations (the NLTE problem) we followed the modification of the linearization method proposed by Auer and Heasley (1976). A few details of our NLTE procedure are given below:
- we used the 20-level model of the Li I atom;
- the 70 radiative and all possible collisional transitions were included into the rate matrix. In several cases we have taken into account the rates due to inelastic collisions with the neutral hydrogen (Steenbock and Holveger 1984). I must admit the strong enough evidences exist that these collision rates have to be excluded from the consideration (see Lambert 1993, Carlsson et al. 1994);
- the opacity due to atomic lines and molecular bands has taken into account;
- we used the correction factor $E = 2$ for the Unsold approximation of van der Waals damping for lithium lines;
- to satisfy the formal boundary conditions for the procedure of the solution of the radiative transfer equation $I(-\mu, \tau = 0) = 0$ we extrapolated the model atmospheres.
Our computation procedure of the NLTE problem solution was described elsewhere (Pavlenko 1989, Magazzù et al. 1992, Pavlenko et al. 1994).

2. The NLTE in Li I resonance lines.

By definitions of Thomas (1957) the resonance Li I lines $\lambda$ 6707.76 and 6707.91 nm are photoionization dominated. Indeed, the Li I atom has a small ionization potential (5.39 eV), and Li I resonance lines (the transition $2s^2 2S - 2p^2 2P$) have a low potential of the excitation (1.8 eV). The main processes of the depopulation of the upper level 2p of the resonance transition are bound-free radiative processes (see Mihalas 1978 for details). The source function of lithium resonance lines are comparatively weak bounded with the Plank function.

These conclusions are based on formal conditions. Still an extensive Carlsson et al.'s (1994) study confirmed it directly.

3. Results

3.1. T Tauri stars

During a few years we studied the NLTE formation of the lithium lines in the atmospheres of Pre-Main Sequence stars. Spectra of these stars have prominent Li I lines. Often these lines are saturated.

Main result was obtained in the paper of Magazzù et al. (1992). We found the statistical balance of lithium transitions in the atmospheres of G – K stars depends on the strength of Li I resonance lines. An impact of the NLTE effects on profiles of strong and weak resonance lines of the lithium are different. In Fig.1a we present profiles of the Li I resonance doublet computed for the 5770/4.44/0 model atmosphere (see Pavlenko 1994 for details). In the region of the formation of the weak resonance Li I lines we have got $B_{\nu}(\tau_{lte} = 1) < S_{\nu}(\tau_{lte} = 1)$ (Fig. 1b). As a result, the NLTE profiles are weaker than the LTE ones.

In the case of weak resonance lines the overionization of the lithium dominates. So the lithium lower levels populations are decreased in comparison with the LTE: $b_i = n_i / n_i^* < 1.0$ (Fig. 1c), where $n_i$ and $n_i^*$ are NLTE and LTE populations of the Li I atoms, respectively.

I have to admit two items:

1) in the outermost part of the model atmosphere $b_i > b_j$ for $i > j < 6$.

2) lithium levels laid near the continuum are overpopulated in comparison with the LTE. They are bounded more with the continuum than with bound levels.

In the case of saturated Li I resonance lines the stellar atmospheres are thick in their frequencies. In that case we have the detailed balance of $2s - 2p$ radiative transitions. The populations of the first level depend on chains of transitions from the continuum. We admit the dramatic changes in the behavior of $b_1$ with depth (Fig.1d). The source function exceeds the Plank function in the region of the core formation of the 670.8 nm doublet (Fig. 1b). The NLTE core of the saturated Li I doublet is stronger in comparison with the LTE (Fig.1a).
So NLTE abundance corrections $\Delta = \log N(Li)_{\text{NLTE}} - \log N(Li)_{\text{LTE}}$ are negative for weak Li I resonance lines and positive for saturated ones. These results were confirmed by Carlsson et al. (1994).

Let me note three items:

1) the crossing point of LTE and NLTE curves of growth for resonance lithium lines shifts toward lower equivalent widths when $T_{\text{eff}}$ drops (Fig.1e).

2) LTE and NLTE profile shapes of resonance lithium lines of the same equivalent widths differ (see Pavlenko 1991a).

3) the same effects were found for red giants (Pavlenko 1992).

In papers of Magazzù et al. (1992), Martín et al. (1994), Pavlenko et al. (1994) we studied the NLTE formation of Li I lines in the atmospheres of $G - K - M$ dwarfs and subdwarfs. We found the NLTE abundances obtained due to the modelling of strong Li I lines observed in spectra PMS stars are systematically shifted toward lower values in comparison with the LTE. The majority of unevolved stars assesses the values of NLTE abundances of lithium $\log N(Li)_{\text{NLTE}} = 3.1 - 3.3$. It is less than the LTE values $\log N(Li)_{\text{LTE}} = 3.4 - 3.6$.

Grids of LTE and NLTE curves of growth of the Li I resonance lines have been published elsewhere (Martín et al. 1994; Pavlenko et al. 1994). The curves of growth for the $Li$ I subordinate line $\lambda$ 610.3 nm computed for 5270/4.44, 5770/4.44, 6270/4.44 model atmospheres are given in Fig.1f. This line is severely blended in stellar spectra. Another subordinate line $\lambda$ 812.6 nm is more weak. For these Li I subordinate lines we have got $W^{\text{NLTE}}_\lambda < W^{\text{LTE}}_\lambda$ in spectra G-K dwarfs (cf. Carlsson et al. 1994).

The same effects in subordinate Li I lines were obtained for red giants (Pavlenko 1992).

Only for coolest model atmospheres with $T_{\text{eff}} \leq 3500K$ we found $W^{\text{NLTE}}_\lambda > W^{\text{LTE}}_\lambda$ (Pavlenko et al. 1994).

3.2. Chromospheres

Most of T Tau stars have chromospheres and/or accretion disks. There are several evidences of the existence of hot outer layer in the atmospheres of these stars: emission lines in spectra, UV excesses, the emission in $H_{\alpha}$, the veiling. As a rule more young (classical T Tau) stars with undepleted lithium have stronger chromospheres (see Magazzù et al. 1992 for references). Strong Li I lines may be affected by chromospheres and/or accretion discs. So the study of the impact of chromospheric effects on LTE and NLTE Li I lines profiles are of importance.

We performed special investigations to study this problem. The coolest model atmosphere of the 3500/4.0/0 dwarf from the Kurucz (1992) grid was chosen. For convenience the model atmosphere will be labelled as “classical” (c).

To the photosphere of this dwarf were added model chromospheres:

- The “weak” (w) chromosphere with $\tau_{\min} = 10^{-4}$, $(T_{\min} = 2840K, T_{\min}/T_{\text{eff}} = 0.8)$ and the temperature gradient in the outer part of the model $G = G_{*} = \partial T/\partial \log(m) = 820$. The value $G_{*}$ was taken from the solar model chromosphere HISRA (Gingerich et al. 1971).

- The “strong” (s) chromosphere with $T_{\min} = 2840K, G = 4000$. 

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Fig. 1. Results of the solution of the NLTE problem for the lithium in atmospheres of solar-like dwarfs: a) - LTE (solid lines) and NLTE profiles (dashed line) profiles computed for the 5770/4.44/0 model atmosphere; b) - the ratio \( S_i/B_i \) for resonanse \( Li I \) lines in the same model atmosphere; c) - Menzel coefficients of lithium levels computed for the same model atmosphere and \( log N(Li) = 2.0 \). Level numbers are given in Fig.; d) - the same as in Fig.1c but for \( log N(Li) = 3.50 \); e) - LTE and NLTE curves of growth of the \( Li I \) resonance doublet \( \lambda 670.8 \) nm (solid and dashed lines, respectively); f) - the same as in Fig.1e, but for the subordinate line \( \lambda 610.3 \) nm.
The temperature structure of these model atmospheres are shown in Fig. 2a. The equation of state of atoms and molecules (but not the lithium!) was treated in LTE. The LTE electron densities in these models are shown in the 2b.

The "weak" chromosphere. On my opinion, the most interesting fact is that LTE results (line profiles, curves of growth) are more sensitive to the temperature structure of the outer part of the stellar atmosphere than LTE ones. Indeed, the "weak" chromosphere does not produce any additional continuum. The radiation flux emitted from (c) and (u) model atmospheres are practically the same. Only the cores of strongest lines (computed in the LTE!) are affected in this case. Note, NLTE cores of photoinization dominated Li I resonance lines computed for these two model atmospheres don't differ significantly. On the contrary, LTE cores of the Li I resonance doublet depend on the temperature structure of outermost layers of the stellar atmosphere. So we have found large differences in LTE profiles computed for (c) and (u) model atmospheres.

The "strong" chromosphere produces additional flux of the radiation field in the ultraviolet and visible regions of the spectrum. In fact we have the combined effect of the strong overionization and the veiling (Fig. 2c). So the resonance and subordinate lithium line profiles and curves of growth are severely affected by chromospheric effects in that case (Fig.2e and 2f).

We have to admit that these computations may be considered as a numerical experiment only. Indeed, the physical state of the matter and the radiation field in the chromosphere were treated in the LTE. From the common point of view we have to realize an iterative algorithm of the model chromosphere-computation. But even in the frame of our simple approach we show that the presence of the "weak" chromospheres doesn't mean the significant changes in the the NLTE (!) equivalent widths of the Li I lines.

3.3. Dwarfs of halo and disc

We performed the computations to study the NLTE formation of lithium lines in the atmospheres of metal deficient dwarfs. A grid of metal deficient model atmospheres of dwarfs with \( T_{\text{eff}} = 6270, 5770, 5270 \)K, \( \log g = 4.44 \), \( [\mu] = 0, -1, -2, -3 \) was computed by SAM71 program (see Pavlenko 1994 for details). Afterwards for these model atmospheres we solved NLTE problems for the 20-level lithium model atom.

We found that for dwarfs with \( 5200 < T_{\text{eff}} < 6200 \) K (cf. Carlsson et al. 1994 also):

- classical results of Spite & Spite (1982) related to the discovery of the lithium plateau in halo dwarfs cannot be changed by NLTE. In a wide range of abundances (\( 1.0 < \log N(\text{Li}) < 2.8 \)) the lithium abundance corrections due to NLTE effects are less than 0.1 dex for solar type Pop I and Pop II dwarfs.

- the NLTE abundance correction depends on the model atmosphere structure, transition rates due to inelastic collisions and the abundance of lithium.

  for subordinate line 610.3 nm the sign and values of NLTE abundance corrections are always positive.

  the dependence of our results on rates due to inelastic collisions with neutral hydrogen is not critical.
Fig. 2. a) - The temperature structure of 3500/4.44/0 dwarf model atmospheres: c - the classical model, w - the "weak" chromosphere, s - the "strong" chromosphere. b) - electron densities in c, w, s model atmospheres. c) and d) - LTE (solid lines) & NLTE (dashed lines) residual intensities and fluxes, respectively, in the Li I 670.8 nm line computed for c, w, s models, e) - LTE (solid lines) and NLTE (dashed lines) curves of growth of the Li I resonance doublet λ 670.8 nm, f) - LTE (solid lines) and NLTE (dashed lines) curves of growth of the Li I subordinate line λ 610.3 nm.
for solar-like dwarfs the dependence of the NLTE lithium abundance corrections on their metallicity is rather weak. The intensity of NLTE effects in metal deficient model atmospheres do not increase dramatically despite the decreasing of opacities in the frequencies of bound-bound and bound-free Li I transitions in comparison with models of the solar metallicity.

Rebolo et al. (1988) suggested an existence of the “lithium plateau” ($log N(Li) \simeq 2.1$) in halo dwarfs discovered by Spite & Spite (1982). Recently Thorburn (1994) give the gradient of this slope $S_p = \Delta log N(Li)/\Delta T_{eff} = 0.017(100K)^{-1}$.

Two attempts were made to explain this slope by NLTE effects. Carlsson et al. (1994) obtained $S_p \approx 0.01(100K)^{-1}$. At the same time we have obtained $S_p \approx 0.004 - 0.006(100K)^{-1}$ (see Table 1). The NLTE abundance correction increases from + 0.038 up to + 0.07 dex when $T_{eff}$ drops from 6250 to 5250 K. In these computations the rates due to inelastic collisions with hydrogen were excluded from the consideration.

In another set of the NLTE computations these rates were included into the rate matrix. As it was noted before, we followed an approach developed by Steenbock and Holweger (1984). The NLTE abundance corrections became negative, but the slope of the lithium plateau was not changed!

| Table 1 |
|------------------|------------------|------------------|------------------|
| Model atm.       | $\mu$            | $log N(Li)_{lte}$| $W_{\lambda}(670.8)$| $log N(Li)_{nlte}$| $\Delta_{nlte-lte}$|
| 5270/4.44        | 0                | 2.1              | 9.94             | 2.138            | 0.038              |
|                  | -1               | 2.1              | 9.52             | 2.163            | 0.063              |
|                  | -2               | 2.1              | 8.88             | 2.189            | 0.089              |
|                  | -3               | 2.1              | 7.76             | 2.17             | 0.070              |
| 6270/4.44        | 0                | 2.1              | 2.04             | 2.11             | 0.01               |
|                  | -3               | 2.1              | 1.976            | 2.13             | 0.03               |

So at the time we cannot explain this slope by the impact of the NLTE only.

In our analysis we ignored the dependence of equivalent widths on poor defined parameters of stellar atmospheres: e.g. gravity, microturbulence velocities, etc. Possibly the slope of the lithium plateau and the dispersion of observed equivalents widths of Li I lines in dwarfs spectra may be explained also by their dependence on these factors.

4. Conclusions

A few results of the computations of NLTE problems for the lithium obtained during last years are discussed in this paper. It is shown the NLTE has to be considered to resolve “lithium mysteries” of modern astrophysics. For the moment we can give qualitative and “zero approach quantitative” estimation of the impact of the NLTE on well known results.

Considering the results obtained for T Tau stars we may admit:

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• In the case of the saturated 670.8 nm Li I lines NLTE effects push lithium abundances toward lower values in comparison with the LTE.

• The NLTE abundances corrections depend on \( \log N(\text{Li}) \), and \( T_{\text{eff}}, [\mu], \log g \) of dwarf atmospheres.

• The impact of the NLTE on saturated Li I lines are increased toward lower luminosity stars.

• Previously derived high lithium (LTE) abundances (see Magazzù and Rebolo 1989, Strom et al. 1989, Basri et al. 1991, King 1993) may be systematically affected by the NLTE.

The impact of stellar chromospheres on Li I lines was studied. It has been found that Li I lines are practically not sensitive to the chromospheres with temperature gradients like the solar one. Still in the case of "strong" chromospheres with temperature gradients several times solar the Li I lines may be severely affected.

Another important conclusions of this paper addresses to the interpretations of the Li I lines in halo stars spectra:

• The values of abundance correction due to NLTE effects in the resonance doublet 670.8 nm are small for halo dwarfs \( \Delta \log N(\text{Li}) \approx 0.1 \).

• The NLTE effects in Li I lines do not increase dramatically with the decreasing of the metallicity of halo dwarfs atmospheres. The reason is that with the decreasing of the metallicity of stars the gradient of temperature in its atmosphere decreases also.

• It seems NLTE effects cannot explain the slope of the lithium plateau, discovered by Spite & Spite (1982).

On my opinion, more refined results could be obtained for the better defined model atmospheres, model atoms and the homogeneity of observed data. Further theoretical work is required to provide more reliable interpretations of lithium lines in stellar spectra.

Acknowledgements

I am grateful to Prof. F. Spite for comments helped to clarify and improve my talk, and Drs. R. Rebolo, E.L. Martin, R.J.Garcia Lopez, A. Magazzù all contributed generously problems, thoughts, ideas which prompted my investigations.

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