Theoretical LTE & non-LTE curves of growth for Li I lines in G-M dwarfs and subgiants

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Abstract. Detailed simultaneous radiative transfer-statistical equilibrium calculations have been performed for lithium in atmospheres of solar metallicity G-M dwarfs and subgiants. Model atmospheres of stars with $3500 \leq T_{\text{eff}} \leq 6000$ K, $3.0 \leq \log g \leq 4.5$ have been considered. The behaviour of level populations, source functions and curves of growth for the lithium doublet at $\lambda 670.8$ nm and two subordinate lines of astrophysical interest ($\lambda 610.3$ nm and $\lambda 812.6$ nm) are discussed. For the coolest atmospheres of our grid we find that the dependence of non-LTE equivalent widths and profiles on gravity is very weak. The computed LTE and non-LTE curves of growth are given in tabular form.

Key words: Line: formation – Line: profiles – Stars: abundances – Stars: late type

1. Introduction

The importance of lithium in many fields of astrophysics has been widely recognized during the last decades. The proceedings of a recent ESO/EIPC workshop (Crane 1995) describe the status of the present knowledge on this subject. The abundance of lithium is usually determined from the resonance doublet at $\lambda 670.8$ nm. The equivalent width of this feature, quite small in general, can reach values up to hundreds of mA in spectra of young pre-main sequence objects, where the doublet can get easily saturated. We restricted our study to stars with $T_{\text{eff}} \geq 3500$ K. Most lithium in the atmosphere of these stars is in the form of Li\textsuperscript{ii} ions. Therefore, the amount of neutral lithium can be sensitive to non-LTE (non local thermodynamic equilibrium) effects, notably overionization, leading to non-LTE effects on abundance determinations, even for very weak lines. Strong lines in addition will have non-LTE affecting the source function. Studies of the non-LTE formation of Li\textsuperscript{i} lines are required in order to get accurate abundances from the observed equivalent widths.

We have presented our results on the non-LTE formation of lithium lines in the atmosphere of cool dwarfs and subgiants in several papers (Magazzù et al. 1992; Martín et al. 1994, Pavlenko 1995, Pavlenko et al. 1995), aimed mainly to determine the lithium abundance in the atmosphere of pre-main sequence objects. Recently, Carlsson et al. (1994) published results of extensive non-LTE computations for lithium for a grid of model atmospheres with $T_{\text{eff}}$ between 4500 and 7500 K. They provide numerical corrections to get non-LTE Li abundances from LTE (local thermodynamic equilibrium) curves of growth.

In this work we present new results of non-LTE studies concerning the Li I resonance line at $\lambda 670.8$ nm and also the subordinate lines at $\lambda 610.3$ nm and $\lambda 812.6$ nm, whose astrophysical interest has been recently recognized (Duncan 1991, Magazzù et al. 1995). The curves of growth presented here for the $\lambda 670.8$ nm line are a refinement of those used by Martín et al. (1994).

2. The Procedure

To solve the system of statistical balance equations and radiative transfer equations (the non-LTE problem) we followed the modification of the linearization method proposed by Auer and Heasley (1976). Our computation procedure of the non-LTE problem solution was described extensively in Pavlenko et al. (1995). Some details are given below:

– we used a 20-level model of the Li I atom;
– the 70 radiative and all possible collisional transitions were included into the rate matrix;
– the ionization-dissociation equilibrium was computed for 98 atoms and molecules including 6 lithium-containing molecules;
– the multiplet radiative transitions were replaced by single transitions, even though absorption coefficient profiles were computed taking into account the multiplet structure;
– the opacity due to atomic lines from Kurucz (1979) was taken into account. Additionally, we included the absorption due to molecular bands in JOLA approximation, which gives good results for saturated bands (Tsuji 1994).

Twenty-one molecular bands have been taken into account. For unsaturated molecular bands (in the case of stars with $T_{\text{eff}} > 4000$ K) results are not so good, but in this case the visible and violet parts of the spectrum are dominated by absorption due to atomic lines. All these opacities were treated in LTE.
we used the correction factor $E = 2$ for the Unsöld approximation of van der Waals damping for lithium lines (see Section 2.5 in Pavlenko et al. 1995);

we excluded from our computations the inelastic collisions of Li atoms with hydrogen neutral atoms, due to the strong criticism raised (see Lambert 1993, Carlsson et al. 1994) on Drawin’s (1968, 1969) formulae and their modifications by Steenbock and Holweger (1984).

The main difference between this work and computations by Pavlenko et al. (1995) is the model atmospheres. Here we use models calculated with ATLAS9 and taken from Kurucz (1993) CD-ROM 13. We consider only solar metallicity models, with microturbulence of 2 km s\(^{-1}\). Any contribution from \(^{6}\)Li to the equivalent widths of the lines in study has been neglected.

### 3. Results

We treat here the range 3500 $\leq T_{\text{eff}} \leq$ 6000 K, which includes atmospheres where the molecular absorption is relevant. In such atmospheres the thermalization processes increase due to the strong absorption by atomic and molecular lines in the frequencies of Li resonance and subordinate lines. These processes are currently studied and will be discussed in forthcoming papers. Here we give a few results, relevant for understanding the nature of non-LTE effects in Li lines in cool atmospheres. For this purpose it is useful to consider the dependence of departure coefficients and source functions of the absorption lines on the optical depth.

#### 3.1. The departure coefficients

In Fig. 1 we present the departure coefficients of lithium levels $b_i = n_i/n_i^* \, \tau_{\mu}$ versus $\tau_{\mu}$, the continuum optical depth at 1 $\mu$m, in the atmosphere of a dwarf 4000/3.0, i.e. with $T_{\text{eff}} = 4000$ K, $\log g = 3.0$. Here $n_i^*$ and $n_i$ are the LTE and non-LTE populations of the lithium levels, respectively. The model atom used was described in detail by Pavlenko (1994). We present results of computations for abundances \(\log N(\text{Li}) = 0.5\) and $\log N(\text{Li}) = 3.5$, i.e. in the case of weak and strong lithium resonance doublet, respectively.

We find that:

- the behaviour of the departure coefficients depends on the strength of Li resonance doublet, i.e. on the lithium abundance (see also Magazzù et al. 1992);
- properly speaking, we should use the definition “overionization of lithium” to describe only the relevant process of formation of the statistical equilibrium of lithium. In fact, the statistical equilibrium of lithium depends on a whole set of radiative and collisional transitions (see Carlsson et al. 1994). Still, in the formation region of weak lithium $\lambda$670.8 nm lines ($\tau \equiv \tau_{\mu} \sim 10^{-3}$) overionization dominates. As a result we have here $b_1 < b_2 < 1.0$ (see also Steenbock & Holweger 1984);
- in the case of saturated lithium resonance lines we have balance of the radiative transitions (2s-2p) in a large part of the stellar atmosphere. The population of the first lithium level is formed by chains of transitions from upper levels and continuum. In the formation region of strong resonance

$^1$Throughout this paper $\log N(\text{Li})$ is given in the scale $\log N(\text{H}) = 12$

![Fig. 1. Departure coefficients of Li levels in atmosphere of a 4000/3.0 subgiant with a lithium abundance $\log N(\text{Li}) = 0.5$ (a) and $\log N(\text{Li}) = 3.5$ (b)]
Fig. 2. The ratio $S_l/B_\nu$ for the Li I resonance doublet in atmospheres 5000/4.5 and 5000/3.0 (1), 4000/4.5 and 4000/3.0 (2), 3500/4.5 and 3500/3.0 (3). Solid lines correspond to log $g = 3.0$, dashed ones to log $g = 4.5$, with a lithium abundance log $N$(Li) = 3.5.

of the atmosphere. Note that the dependence of thermalization processes on the gravity is less pronounced.

In the case of the subordinate lines we find that in the outer part of the atmosphere $S_l/B_\nu > 1$, while in the formation region of these lines ($\tau \sim 0.01$) is $S_l/B_\nu \sim 1$. The ratio $S_l/B_\nu$ for the $\lambda 610.3$ nm line is greater than for the $\lambda 812.6$ nm line, because in the frequencies of the former line $\partial B/\partial \tau$ is greater.

3.3. The profile of the resonance doublet

Here we compare the LTE and non-LTE profiles of the resonance doublet. The absorption doublet is saturated in the case of stellar atmospheres with $T_{\text{eff}} \leq 4000$ and log $N$(Li) > 2.0. Thus, to describe the radiation transfer in the line core frequencies we extrapolated the Kurucz model atmospheres up to levels where line cores are formed, as described in Pavlenko (1984) and Magazzù et al. (1992). In Fig. 3 we show a few profiles computed for lithium abundance log $N$(Li) = 3.5. We see that non-LTE cores are deeper in comparison with LTE, as found in Magazzù et al. (1992); see also Pavlenko (1992) and Carlsson et al. (1994). The Li I resonance line computed for model atmospheres with larger log $g$ shows stronger wings, both in LTE and non-LTE, due to the pronounced damping. However, we see very small differences in the non-LTE cores computed for model atmospheres with different log $g$’s. In the case of unsaturated Li I resonance line the non-LTE profiles are shallower than the LTE ones (see Fig. 7 in Pavlenko et al. 1995).

The shape of the Li doublet becomes extremely important in some astrophysical contexts (e.g. Li isotopic ratio determinations). The difference between a LTE and a non-LTE line profile, calculated for the same equivalent width and for a model atmosphere 4000/3.0, is shown in Fig. 4. The largest differences are found in the core and core-wing transition part of the line. Note that these differences are negative in the core and positive in the wings.

3.4. The curves of growth

3.4.1. Resonance doublet

The LTE and non-LTE curves of growth of the resonance doublet, computed for model atmospheres of several dwarfs and subgiants are presented in Table 1. In Fig. 5 we plot some of these curves, corresponding to the models 3500/3.0 and 5000/4.5. We see that non-LTE abundance corrections $\Delta \log N$(Li) = $\log N^{\text{NLTE}}$(Li) − $\log N^{\text{LTE}}$(Li) are positive for unsaturated lines formed in the atmospheres of dwarfs and subgiants. As noted before, in that case the influence of overionization of lithium dominates. The formation region of the non-LTE doublet shifts (with respect to LTE) towards deeper layers, where $S_l(\tau_{\text{nlte}} = 1) > B_\nu(\tau_{\text{lte}} = 1)$, being $\tau$ the optical depth at the frequency of the resonance line. A stronger doublet is formed where $S_l(\tau_{\text{nlte}} = 1) < B_\nu(\tau_{\text{lte}} = 1)$. As a result, the sign of $\Delta \log N$(Li) changes (Magazzù et al. 1992). Again,
Table 1. Curves of growth of the \(\lambda 670.8\) nm line

| \(\log g = 3.0\) | \(\log g = 3.5\) | \(\log g = 4.0\) |
|-----------------|-----------------|-----------------|
| \(T_{\text{eff}} = 3500K\) | \(T_{\text{eff}} = 4000K\) | \(T_{\text{eff}} = 4500K\) |
| \(\log N(\text{Ly})\) | \(W_{\lambda} (\text{mA})\) | \(\log N(\text{Ly})\) | \(W_{\lambda} (\text{mA})\) | \(\log N(\text{Ly})\) | \(W_{\lambda} (\text{mA})\) | \(\log N(\text{Ly})\) | \(W_{\lambda} (\text{mA})\) |
| \(\text{LTE}\) | \(\text{NLTE}\) | \(\text{LTE}\) | \(\text{NLTE}\) | \(\text{LTE}\) | \(\text{NLTE}\) | \(\text{LTE}\) | \(\text{NLTE}\) |
| -1.5 | 9.3 | 4.8 | 7.6 | 4.7 | 5.6 | 4.7 | 3.7 |
| -1.0 | 27.9 | 14.8 | 23.1 | 14.4 | 16.9 | 14.7 |
| -0.5 | 75.5 | 42.6 | 63.9 | 42.3 | 48.1 | 42.4 |
| 0.0 | 163.3 | 106.6 | 144.3 | 105.2 | 116.0 | 106.4 |
| 0.5 | 258.1 | 208.9 | 240.8 | 210.2 | 211.6 | 210.8 |
| 1.0 | 330.6 | 309.2 | 317.3 | 310.3 | 298.6 | 326.3 |
| 1.5 | 394.0 | 390.1 | 385.3 | 408.9 | 384.6 | 440.8 |
| 2.0 | 467.8 | 471.2 | 469.9 | 492.5 | 509.6 | 589.8 |
| 2.5 | 584.8 | 584.5 | 889.9 | 929.7 | 735.9 | 839.7 |
| 3.0 | 815.5 | 798.4 | 889.3 | 914.0 | 1166.1 | 1287.7 |
| 3.5 | 1271.5 | 1219.1 | 1427.4 | 1454.1 | 1957.1 | 2087.9 |
| 4.0 | 2121.7 | 1991.9 | 2405.6 | 2371.1 | 3335.8 | 3466.8 |
| 4.0 | 16.1 | 7.4 | 15.7 | 7.7 | 11.5 | 7.9 |
| 5.0 | 46.5 | 22.6 | 45.2 | 23.4 | 34.0 | 23.8 |
| 2.0 | 114.4 | 62.9 | 111.8 | 65.0 | 88.6 | 66.1 |
| 1.0 | 209.7 | 147.1 | 206.5 | 150.8 | 179.6 | 153.5 |
| 1.5 | 289.1 | 262.3 | 286.8 | 267.3 | 270.5 | 274.1 |
| 2.0 | 353.9 | 363.1 | 355.3 | 370.1 | 354.4 | 393.3 |
| 2.5 | 423.1 | 444.0 | 436.0 | 461.8 | 469.0 | 525.4 |
| 3.0 | 513.8 | 530.0 | 559.3 | 575.2 | 669.5 | 733.3 |
| 3.5 | 676.0 | 669.6 | 793.1 | 784.4 | 1049.8 | 1115.9 |
| 4.0 | 995.8 | 944.9 | 1246.9 | 1188.5 | 1751.1 | 1800.3 |
| -0.5 | 14.4 | 11.8 | 15.1 | 12.1 | 16.0 | 12.9 |
| 0.0 | 26.8 | 13.1 | 26.8 | 13.7 | 26.4 | 15.3 |
| 0.5 | 73.1 | 38.3 | 73.0 | 40.0 | 72.3 | 44.5 |
| 1.0 | 159.9 | 99.5 | 159.2 | 103.3 | 158.5 | 113.4 |
| 1.5 | 255.2 | 205.0 | 253.5 | 210.6 | 254.7 | 227.7 |
| 2.0 | 331.3 | 318.6 | 329.6 | 325.0 | 340.3 | 350.8 |
| 2.5 | 401.3 | 407.4 | 403.6 | 417.0 | 443.0 | 468.9 |
| 3.0 | 474.0 | 482.3 | 490.6 | 503.6 | 604.3 | 625.5 |
| 3.5 | 572.3 | 569.2 | 625.7 | 623.6 | 889.4 | 893.4 |
| 4.0 | 995.8 | 944.9 | 1246.9 | 1188.5 | 1751.1 | 1800.3 |
| 1.0 | 17.2 | 10.6 | 17.8 | 11.1 | 18.7 | 12.4 |
| 1.5 | 48.9 | 31.6 | 50.5 | 32.8 | 52.8 | 36.4 |
| 2.0 | 117.4 | 84.3 | 120.3 | 87.0 | 124.9 | 95.5 |
| 2.5 | 209.7 | 182.3 | 212.6 | 186.7 | 218.5 | 201.1 |
| 3.0 | 288.0 | 297.9 | 290.5 | 302.9 | 299.5 | 321.7 |
| 3.5 | 355.0 | 392.4 | 358.7 | 398.2 | 379.1 | 426.2 |
| 4.0 | 420.4 | 466.1 | 429.1 | 475.9 | 478.2 | 529.1 |
| 1.5 | 14.4 | 11.8 | 15.1 | 12.1 | 16.0 | 12.9 |
| 2.0 | 41.4 | 34.7 | 43.3 | 35.5 | 45.7 | 37.9 |
| 2.5 | 101.5 | 91.1 | 105.2 | 92.9 | 110.3 | 98.6 |
| 3.0 | 186.6 | 191.8 | 191.1 | 194.8 | 198.8 | 204.6 |
| 3.5 | 261.4 | 306.5 | 266.2 | 309.9 | 277.2 | 323.1 |
| 4.0 | 324.7 | 399.7 | 330.8 | 403.9 | 350.8 | 423.3 |
| 2.0 | 15.0 | 15.1 | 16.3 | 15.7 | 17.0 | 16.4 |
| 2.5 | 42.8 | 43.6 | 46.0 | 45.2 | 47.9 | 47.2 |
| 3.0 | 102.5 | 109.8 | 108.3 | 113.1 | 112.4 | 117.7 |
| 3.5 | 183.2 | 217.0 | 189.8 | 221.7 | 195.9 | 229.3 |
| 4.0 | 253.2 | 328.9 | 260.0 | 333.5 | 269.4 | 343.4 |
in the case of the subgiant 4000/3.0, when the doublet is extremely strong $\Delta \log N(\text{Li})$ changes its sign once more. The corresponding line formation region moves towards the outer boundary of the atmosphere where the overionization increases with height and wins over the source function effect. This tendency can be seen also in the top panels of Figs. 16 and 17 in Carlsson et al. (1994) and in Fig. 4 in Pavlenko et al. (1995).

Another result seems to be more interesting: our computations show that non-LTE curves of growth computed for dwarfs and subgiants with $T_{\text{eff}} \leq 4000$ K do not differ significantly in the case of unsaturated lines. In other words, whereas in LTE the equivalent width of the (unsaturated) Li i doublet is a function of $T_{\text{eff}}$, $\log g$, and $N(\text{Li})$, non-LTE computations give $W_\lambda$ as a function of only $T_{\text{eff}}$ and $N(\text{Li})$. This is a very useful result, because the determination of the gravity usually is more difficult than the assignment of an effective temperature.

3.4.2. Subordinate lines

In Tables 2, 3 and Figs. 6, 7 we show the case of the subordinate Li i lines at $\lambda 610.3$ and $\lambda 812.6$ nm. These lines are less intense than the resonance doublet and form in deeper parts of the atmosphere (Pavlenko et al. 1995). In spite of this, for these unsaturated lines we have also determined that the equivalent width in non-LTE practically does not depend on gravity for the model atmospheres with $T_{\text{eff}} \leq 4000$ K.

The scarce dependence of all the considered Li i lines on $\log g$ may be explained in the following way. The statistical balance of lithium in cool atmospheres is governed by the radiation field (Steenbock & Holweger 1984). The radiation field mean intensity crucially depends on the value of electron density $N_e$ in the stellar photosphere. We found that differences of $N_e$ in the region $0.1 < \tau_\mu < 1.0$ in the photosphere of stars with different $\log g$’s are much more pronounced for $T_{\text{eff}} \geq 4500$ K than for lower $T_{\text{eff}}$’s. As a result, in the last case the intensity of
Table 2. Curves of growth of the λ610.3 nm line

| log N(Li) | log g = 3.0 | log g = 3.5 | log g = 4.5 |
|-----------|-------------|-------------|-------------|
|           | LTE NLTE    | LTE NLTE    | LTE NLTE    |
| 0.5       | 2.6 1.7     | 2.2 1.7     | 1.7 1.7     |
| 1.0       | 8.0 5.4     | 6.7 5.4     | 5.3 5.3     |
| 1.5       | 23.7 16.4   | 20.2 16.2   | 15.9 16.1   |
| 2.0       | 63.2 46.1   | 54.8 45.2   | 44.2 44.8   |
| 2.5       | 133.4 108.1 | 120.1 105.9 | 101.7 105.0 |
| 3.0       | 209.4 193.7 | 197.2 190.9 | 179.8 192.7 |
| 3.5       | 274.1 275.8 | 265.6 275.8 | 258.4 288.0 |
| 4.0       | 334.8 348.3 | 331.6 354.9 | 342.7 389.0 |

$T_{\text{eff}} = 3500K$

|           | log g = 3.0 | log g = 3.5 | log g = 4.5 |
|-----------|-------------|-------------|-------------|
|           | LTE NLTE    | LTE NLTE    | LTE NLTE    |
| 1.0       | 3.0 1.8     | 3.0 1.9     | 2.3 1.9     |
| 1.5       | 9.3 5.6     | 9.2 5.8     | 7.1 5.8     |
| 2.0       | 27.6 16.9   | 27.3 17.5   | 21.4 17.6   |
| 2.5       | 72.2 47.2   | 71.7 48.7   | 58.1 49.1   |

$T_{\text{eff}} = 4000K$

|           | log g = 3.0 | log g = 3.5 | log g = 4.5 |
|-----------|-------------|-------------|-------------|
|           | LTE NLTE    | LTE NLTE    | LTE NLTE    |
| 2.0       | 9.7 6.1     | 9.8 6.3     | 9.9 7.0     |
| 2.5       | 28.6 18.2   | 28.9 19.0   | 29.3 21.0   |
| 3.0       | 74.4 50.5   | 75.0 52.3   | 76.2 57.6   |
| 3.5       | 149.6 116.0 | 150.5 119.0 | 153.7 130.5 |
| 4.0       | 223.8 203.2 | 224.9 208.0 | 233.1 226.0 |

$T_{\text{eff}} = 4500K$

|           | log g = 3.0 | log g = 3.5 | log g = 4.5 |
|-----------|-------------|-------------|-------------|
|           | LTE NLTE    | LTE NLTE    | LTE NLTE    |
| 2.0       | 3.6 2.6     | 3.7 2.7     | 3.9 2.9     |
| 2.5       | 11.0 8.0    | 11.4 8.3    | 12.0 9.1    |
| 3.0       | 32.0 23.6   | 33.1 24.4   | 34.6 26.8   |
| 3.5       | 80.5 62.7   | 82.7 64.7   | 86.3 70.7   |
| 4.0       | 154.2 134.2 | 157.1 137.6 | 162.5 148.3 |

$T_{\text{eff}} = 5000K$

|           | log g = 3.0 | log g = 3.5 | log g = 4.5 |
|-----------|-------------|-------------|-------------|
|           | LTE NLTE    | LTE NLTE    | LTE NLTE    |
| 2.0       | 1.5 1.3     | 1.6 1.3     | 1.7 1.4     |
| 2.5       | 4.8 4.1     | 5.0 4.2     | 5.3 4.5     |
| 3.0       | 14.6 12.5   | 15.2 12.8   | 16.1 13.7   |
| 3.5       | 41.0 35.7   | 42.6 36.4   | 44.8 39.0   |
| 4.0       | 95.6 87.3   | 98.7 89.0   | 103.3 94.7  |

$T_{\text{eff}} = 5500K$

|           | log g = 3.0 | log g = 3.5 | log g = 4.5 |
|-----------|-------------|-------------|-------------|
|           | LTE NLTE    | LTE NLTE    | LTE NLTE    |
| 2.5       | 2.3 2.3     | 2.5 2.4     | 2.6 2.5     |
| 3.0       | 7.3 7.1     | 7.9 7.4     | 8.2 7.7     |
| 3.5       | 21.5 20.9   | 23.2 22.0   | 24.1 22.8   |
| 4.0       | 56.8 56.0   | 60.5 58.4   | 62.9 60.7   |

the outgoing radiation field in the frequencies of lithium transitions is less sensitive to log $g$. Moreover, the role of inelastic collisions in the formation of statistical equilibrium decreases with lowering $T_{\text{eff}}$ due to the decrease of $N_e$. Note that the independence from log $g$ is seen only for unsaturated lines, which do not have extended, sensitive to log $g$, wings.

3.4.3. Comparison with other works

The LTE and non-LTE curves of growth presented here agree well with those used in the works of Martín et al. (1994) and García López et al. (1994), the differences in equivalent width being less than 5 percent. There is a good agreement also with Magazzu et al.’s (1992) results, except for cooler stars. Reasons and consequences of this disagreement at lower temperatures are discussed in Pavlenko et al. (1995). Note that in this paper we use a refined value of the damping constant for the Li resonance doublet. We use also an extended opacity list, that makes the curves of growth presented here more reliable, especially for lower effective temperatures. For these points see also Pavlenko et al. (1995).

Carlsson et al. (1994) did not give the computed equivalent widths of lithium lines, but only non-LTE abundance corrections to apply to LTE curves of growth for the lithium resonance doublet. In order to compare our results with theirs, we use the data of Table 1 to compute our non-NLTE corrections. In Fig. 8 we present $\Delta\delta$, i.e. the difference between our corrections ($\Delta\delta_u$) and those ($\Delta\delta_C$) by Carlsson et al. (1994) for several models in common.

We find that the agreement of these results is fairly good (see also Pavlenko 1995), the differences being less than 0.1 dex. The greater differences are seen in strong Li I lines and are caused by the cumulative effect of different model at-
Table 3. Curves of growth of the $\lambda$812.6 nm line

| $\log N$(Li) | $\log g = 3.0$ | $\log g = 3.5$ | $\log g = 4.5$ |
|--------------|----------------|----------------|----------------|
|              | LTE | NLTE | LTE | NLTE | LTE | NLTE |
| $T_{\text{eff}} = 3500K$ |       |       |     |       |     |       |
| 0.5          | 0.6 | 0.4  | 0.5 | 0.4  | 0.4 | 0.4  |
| 1.0          | 1.8 | 1.3  | 1.5 | 1.3  | 1.2 | 1.3  |
| 1.5          | 5.5 | 4.1  | 4.7 | 4.1  | 3.7 | 4.2  |
| 2.0          | 16.8| 13.0 | 14.5| 12.9 | 11.5| 12.9 |
| 2.5          | 48.1| 38.7 | 41.8| 38.3 | 33.8| 38.2 |
| 3.0          | 117.3| 101.8| 104.7| 100.3| 87.2| 100.0|
| 3.5          | 218.3| 210.8| 203.0| 208.3| 179.2| 207.4|
| 4.0          | 314.3| 333.0| 302.4| 330.9| 284.5| 331.5|
| $T_{\text{eff}} = 4000K$ |       |       |     |       |     |       |
| 0.5          | 1.0 | 0.6  | 0.6 | 0.4  | 0.5 | 0.4  |
| 1.5          | 2.1 | 1.3  | 2.0 | 1.4  | 1.6 | 1.4  |
| 2.0          | 6.4 | 4.2  | 6.3 | 4.3  | 4.9 | 4.4  |
| $T_{\text{eff}} = 4500K$ |       |       |     |       |     |       |
| 0.5          | 2.5 | 1.9  | 2.6 | 2.0  | 2.7 | 2.1  |
| $T_{\text{eff}} = 5000K$ |       |       |     |       |     |       |
| 2.0          | 0.8 | 0.6  | 0.8 | 0.6  | 0.8 | 0.7  |
| 2.5          | 2.5 | 1.9  | 2.6 | 2.0  | 2.7 | 2.1  |
| $T_{\text{eff}} = 5500K$ |       |       |     |       |     |       |
| 2.5          | 1.0 | 0.9  | 1.1 | 1.0  | 1.2 | 1.0  |
| 3.0          | 3.2 | 3.0  | 3.4 | 3.1  | 3.6 | 3.3  |
| $T_{\text{eff}} = 6000K$ |       |       |     |       |     |       |
| 3.5          | 5.5 | 5.4  | 5.5 | 5.6  | 5.6 | 5.6  |
| 4.0          | 14.8| 15.7 | 16.5| 16.8 | 17.0| 17.3 |

mospheres, opacity sources, cross sections, model atoms. Note that the slope of curves of growth for strong lithium lines decreases. We point out that the differences in the computed non-LTE abundance corrections are smaller than the corrections themselves. We also note that the data for weak lines formed deep in the atmosphere agree quite well. It is evident that these lines are formed in regions in the deep photosphere, where the temperature structures of models by different authors are practically the same.

Our referee, Dr. Carlsson, kindly informed us about the results of a comparison between our equivalent widths and those computed by Carlsson et al. (1994) for the 5000/4.5 model atmosphere (solar metallicity). For LTE he found an agreement better than 10% with a difference of 5% for most abundances. The non-LTE equivalent widths agree within 15%, but typically within 10%.

4. Conclusions

In this paper we give, in tabular form, the LTE & non-LTE curves of growth of lithium resonance ($\lambda$670.8 nm) and subordinate lines ($\lambda$610.3 and 812.6 nm) computed using the newest Kurucz (1993) models. These data may be used for lithium abundance determinations as well as for the redetermination of abundances obtained so far in the frame of the LTE approach. In particular, we point out the importance of the $\lambda$812.6 nm data. This line lies in the red part of the spectrum and its blending is not as strong as for the other two lithium lines. The use of this line may give more accurate results.

Our theoretical curves of growth cover a different effective temperature range than in Carlsson et al. (1994). In fact, our main interest is shifted towards lower temperatures which were not considered by these authors. We note a good agreement between our results and those obtained in other works, despite the differences in non-LTE procedure details.
Let us note that lithium in the stellar atmospheres considered in this paper exists mainly in ionized form. So the relatively small deviations from LTE obtained in our work for the coolest models of our grid have not to be considered as an obvious result. Indeed, with decreasing effective temperature we have a dramatic drop of the electron pressure. On the other hand, opacities in the frequencies of lithium transitions increase due to the strong molecular absorption. In the case of high lithium abundances the resonance doublet becomes very strong with saturated core and extended wings are formed deep in the atmosphere, very close to LTE conditions. In the case of $T_{\text{eff}} < 3500$ K lithium exists in stellar atmospheres mainly in the form of neutral atoms, so non-LTE effects should not be large a priori. This was confirmed by direct computations by Pavlenko et al. (1995).

For the coolest stars of our grid ($3500 \leq T_{\text{eff}} \leq 4000$ K) we find that equivalent widths and profiles of unsaturated Li I lines computed in non-LTE show only a very weak dependence on the log $g$ parameter. Instead, we note that the corresponding LTE curves of growth show a quite strong dependence on gravity. The use of non-LTE curves of growth gives a chance to minimize the possible effects of errors in log $g$ in lithium abundance determinations using non-saturated absorption lines. Moreover we note that, using LTE calculations to perform Li abundance determinations, the knowledge of gravity seems not crucial for $T_{\text{eff}} \geq 4500$ K, but it appears important for cooler stars. However, when using non-LTE calculations, the reverse holds.

In this paper we have discussed results for classical model atmospheres. The cool star spectra often show emission lines created in chromospheric-like features (CLF). However, as shown in Pavlenko (1995) and Pavlenko et al. (1995), CLF affect mainly the LTE results (both profiles and curves of growth). On the contrary, non-LTE results show weak dependence on CLF. Still in the case of the strongest CLF producing veiling the lithium lines may be severely affected. Let us note that

- only the youngest and the most active stars may have such CLF producing additional continuum in the visible part of the spectrum;
- these results may be interpreted as a weak dependence of the (non-LTE) lithium lines on the structure of the outermost layers of model atmospheres. At the present time we cannot be sure that we describe these layers properly in the frame of the classical one-dimensional approach.

These two reasons give additional support to the use of non-LTE results for numerical analysis of lithium lines in stellar spectra.

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