Statistical equilibrium and the Li I 670.776 and 670.791 nm absorption lines in the spectrum of red giants. Results

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The results of a solution of the non-LTE problem for lithium in the atmospheres of K and M giants ($T_{\text{eff}} = 3600$, 3800, 4000, 4400, and 4800 K, log $g = 1.7$) are presented. Opacity at the frequencies of lithium bound–bound and bound–free transitions is determined by absorption in the continuum, molecular bands, and atomic lines. The LTE and non-LTE curves of growth for resonance lines of the Li I doublet and synthetic spectra in the vicinity of 670.8 nm are obtained. Our calculations show that non-LTE effects are significant in the atmospheres of red giants [$e_{\text{non-LTE}}(\text{Li}) - e_{\text{LTE}}(\text{Li}) \sim 0.4$ dex for lines with $W = 5$ pm].

In the present paper (P.11) we describe the results of a solution of the non-LTE problem for lithium in the atmospheres of red giants. Most of the paper is devoted to an analysis of numerical (non-LTE) calculations of the profiles and equivalent widths of resonance absorption lines of neutral lithium (670.776 and 670.791 nm), which are compared with the corresponding LTE calculations. Details of the non-LTE solution of the problem have been described in Ref. 1 (P.1). The parameters of the model stellar atmospheres have been given there in a table.

MENZEL COEFFICIENTS

The most significant manifestation of non-LTE effects in the atmospheres of late-type stars for lithium is a decrease in the concentration of neutral lithium atoms above the photosphere and the consequent weakening of Li I absorption lines in comparison with LTE. The size of the non-LTE effects is characterized by the Menzel coefficients of the levels,

$$b_i = n_i / n_{i}^{+},$$

where $n_i$ and $n_{i}^{+}$ are the populations of the $i$th level calculated in the LTE and non-LTE approximations, respectively.

The nature of the variation of the Menzel coefficients with depth in the stellar atmosphere depends on the lithium abundance. In Fig. 1 we give the Menzel coefficients of Li I levels in the atmosphere of a K giant with $T_{\text{eff}} = 4000$ K and log $g = 1.7$, obtained from the non-LTE solution for $e(\text{Li}) = 0$ dex. At such a lithium abundance, the lines of its resonance doublet in the spectrum of that K giant are weak; the Li I level populations are determined by the balance of radiative bound–free transitions. In the outer part of the atmosphere the Menzel coefficients increase monotonically with level number. The situation changes with increasing lithium abundance in the stellar atmosphere, with lines of the resonance doublet becoming stronger (Fig. 2). The radiation field at the frequencies of the resonance doublet lines is then essential in establishing a balance in transitions between lithium levels. This affects the relationship between the Menzel coefficients: $b_2 > b_1$ in the depth range $2 \times 10^{-4} < \tau_{\text{Ross}} < 2 \times 10^{-3}$ and $b_4 > b_3$ above the stellar photosphere.

**FIG. 1.** Menzel coefficients of lithium levels in the atmosphere of a 4000/1.7 giant for $e(\text{Li}) = 0.0$ dex. The level numbers are given in parentheses.

**FIG. 2.** Same as in Fig. 1, but for $e(\text{Li}) = 1.50$ dex.
SOURCE FUNCTIONS

In Fig. 3 we show the variation of the source functions with depth in the atmosphere of a 4000/1.7 K giant for different $\xi$(Li). The optical depth of the outer part of the model atmosphere at the frequencies of the lithium resonance doublet is $\tau < 1$. Here the source function is constant and does not depend on the temperature structure of the atmosphere (the chromosphere, stellar flocculi, or other manifestations of inhomogeneity). With decreasing lithium abundance, the region of production of the resonance doublet absorption lines shifts into deeper parts of the atmosphere: $S_p$ "separates" from $B_p$ at large $\tau$.

We note two important points: a) in the $10^{-2} \leq \tau_{\text{Ross}} \leq 2$ range, the Menzel coefficients of the first and second lithium levels are almost equal, but they differ from unity. Here the source function coincides with the Planck function; b) the region of the atmosphere in which $n_l = n_f$, $i = 1, 2$, lies deeper than the level at which $S_p = B_p$. Balance between the radiative bound-bound transitions that form the absorption lines of the Li I 670.78 nm doublet occurs at smaller depths in the atmosphere than for the bound-free transitions.

CURVES OF GROWTH

In Fig. 4 we give the equivalent widths of the Li I resonance doublet lines as a function of lithium abundance in the atmospheres of late-type giants, calculated in both the LTE and non-LTE approximations. As in Ref. 1, the equivalent widths of the doublet lines were calculated with respect to the theoretical continuum. The equivalent line widths in non-LTE calculations are systematically smaller than the corresponding LTE values. The absolute changes (in comparison with LTE) in the equivalent widths of absorption lines of the lithium resonance doublet are greatest for lines with $10 < W_\lambda < 25$ pm. Saturation of strong absorption lines comes into play for larger $W_\lambda$. Weak lines ($W_\lambda \leq 10$ pm) are produced at larger depths, where non-LTE effects are smaller (Figs. 1–3).

It must also be noted that the changes in the equivalent widths of lithium lines also depend on the star's effective temperature. From Fig. 4 it follows that the largest changes in $W_\lambda$ are typical of stars with $4000 \text{ K} < T_{\text{eff}} < 4400 \text{ K}$. In the atmospheres of stars with $T_{\text{eff}} > 4400 \text{ K}$, the opacity at the frequencies of bound-free transitions of neutral lithium increases due to absorption by the H$^-$ ion. At $T_{\text{eff}} < 4000$ K, molecular bands appear in stellar spectra that efficiently block the escape of radiation from the atmosphere.

SYNTHETIC SPECTRA

In Fig. 5a-c we show synthetic spectra in the vicinity of 670.78 nm for stars with $T_{\text{eff}} = 4800$, 4000, and 3600 K, respectively. In calculating them, non-LTE effects were taken into account only for lithium lines; the concentrations of other atoms and molecules and their level populations were calculated in the LTE approximation. In the spectra of stars with $T_{\text{eff}} < 4000$ K, fairly strong TiO, CN, and ZrO molecular absorption lines appear at the frequencies of the lithium resonance doublet lines. The absorption by molecular lines increases the opacity of the atmosphere, enhancing the thermalization of photons at the frequencies of the Li I doublet. That factor acts in the same direction as the increase in the opacity of the stellar atmosphere at the frequencies of lithium bound-free transitions, decreasing non-LTE effects.

A comparison of Fig. 5a-c enables us to refine the conclusion that non-LTE effects are significant in the atmospheres of red giants in the lithium resonance doublet lines. In the spectra of M giants, as a rule, TiO absorption lines are more intense than lithium lines. The total profile of the blend in that case (Fig. 5c) is less sensitive to non-LTE effects for neutral lithium than is the case for lines of the same intensity in the spectra of stars with $T_{\text{eff}} > 4000$ K (Fig. 5a). We have an intermediate case in the spectra of giants with $T_{\text{eff}} = 4000$ K: here the TiO lines are not so intense. In the final analysis, the presence of molecular lines in the 670.8 nm blend leads to a spurious decrease in the differences between the LTE and non-LTE results. At the same time, it follows from Fig. 3 that values of $\Delta \xi$(Li) = $\xi_{\text{non-LTE}}(\lambda) - \xi_{\text{LTE}}(\lambda)$ determined by comparing equivalent widths differ to a far smaller extent over the entire range of effective temperature of red giants.

DISCUSSION

It is of interest to compare the estimates of $\Delta \xi$(Li) obtained in this paper with the results of other authors. The results of the non-LTE solution generally depend on many parameters and approximations. The factors taken into account affect the result differently, and often in opposite directions. The estimates of $\Delta \xi$(Li) obtained here differ from other results; Steenbock and Holweger, in particular, obtained $\Delta \xi$(Li) = 0.27 dex for a 4250/0.0 supergiant. In the present paper (Fig. 3) $\Delta \xi$(Li) = 0.4 dex for a 4400/1.7 giant. The corrections to the lithium abundance due to non-LTE effects are thus larger in our case. The differences between the results are due to the combined effect of various factors.
The model atmospheres of red giants have been calculated in the classical approximations. The blanketing effect due to absorption in atomic lines has been ignored in these calculations. The temperatures in the outer layers of the atmospheres turn out to be higher, and those at $r_{Ross} > 1$ are lower, than in models from Kurucz's grid, which includes the effects of absorption by atomic lines. At the same time, absorption in molecular bands has been taken into account in the calculations of our model atmospheres. A comparison of models of K giants calculated by our method and Kurucz's models shows that the temperatures of the outer layers are 100-200 K higher and those of the inner layers are 30-50 K lower in the former. An increase in the temperature in the inner layers of the atmosphere of a red giant should, in principle, lead to an increase in the degree of lithium superionization, and hence to enhancement of the changes in Li I lines (in comparison with LTE) for two reasons: first, the degree of lithium ionization in the region of line production should increase; the efficiency of superionization generally increases with increasing degree of ionization. Second, a temperature increase in the inner parts of the atmosphere should also enhance lithium superionization, since more energetic photons will escape in weakly blended parts of the spectrum.

The chemical composition of the model atmospheres of K and M giants in our calculations differed from the solar composition. Changes in the C, N, and O abundances affect the temperature structure of the model atmosphere, and hence the equivalent widths and profiles of lithium absorption lines, in both the LTE and non-LTE calculations. We have solved the non-LTE problem for lithium in the atmosphere of a 3800/1.7 M giant with the solar chemical composition. A comparison with the results given in Fig. 3 shows that the equivalent widths of resonance lines of the Li I 670.8 nm doublet, in both LTE and non-LTE calculations, increase by 4-10% in this case. These changes in the equivalent widths of the doublet are more pronounced in the LTE case, however, since the non-LTE results depend on the temperature structure of the outer layers of the atmosphere, which are the most sensitive to changes in chemical composition. The non-LTE results are determined to a greater degree by the character of the radiation field at the frequencies of radiative transitions, for which the changes in intensity are less pronounced.

The same turbulent velocity was set in the atmospheres of all of the stars in our calculations, $V_t = 1.7$ km/sec. From fairly general considerations it follows that an increase in $V_t$ should enhance the blanketing effect, decreasing lithium superionization. In our calculations that effect was already manifested upon an increase in $V_t$ by 0.5 km/sec, but the absolute changes in equivalent width (non-LTE) are small (2-5%).

The doublet lines have been replaced by a singlet in solving the non-LTE problem, in Ref. 3, in particular. Numerical calculations carried out here showed that using that approximation leads to pronounced changes from the results.

FIG. 5. Synthetic spectra in the vicinity of the lithium resonance doublet in the spectra of stars with $T_{eff} = 4800$ K (a), 4000 K (b), and 3800 K (c).