Lithium abundances in the atmospheres of SLR C–giants WZ Cas and WX Cyg from resonance and subordinate Li I lines

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Abstract.
Lithium abundances in the atmospheres of the super Li-rich C-giants WZ Cas and WX Cyg are derived by the spectral synthesis technique using the Li I resonance line at $\lambda$ 670.8 nm and three subordinate lines at $\lambda\lambda$ 812.6, 610.4 and 497.2 nm. The differences between the Li abundances derived from the $\lambda$ 670.8 nm line and the $\lambda\lambda$ 497.2, 812.6 nm lines do not exceed $\pm$ 0.5 dex. The lithium line at $\lambda$ 610.4 nm provides typically lower abundances than the resonance line (by $\approx$ 1 dex). The mean LTE and NLTE Li abundances from three Li I lines (excluding $\lambda$ 610.4 nm) are 4.7, 4.9 for WZ Cas, and 4.6, 4.8 for WX Cyg, respectively.

Keywords: Li I resonance and subordinate lines – Stars: individual: WZ Cas, WX Cyg – Stars: AGB, carbon, J – Stars: model atmospheres, Li abundances

1. Introduction

The knowledge of lithium abundances in stellar atmospheres is important because it provides information about physical processes in stars and stellar evolution. Some asymptotic giant branch (AGB) carbon stars (C/O > 1, by number) are observed to be lithium rich with respect to the solar value of log N(Li) = 1.2 (in scale log N(H)=12). WZ Cas and WX Cyg are well known super Li rich (SLR, log N(Li) $\geq$ 4) giant carbon stars. AGB SLR stars, with their strong mass loss, could be the main suppliers of lithium in the Galaxy (cf. Abia et al. 1993, Wallerstein & Knapp 1998). Furthermore, the determination of Li abundances in the atmospheres of these stars has also cosmological interest.

Currently, the overwhelming majority of determinations of the lithium abundances in carbon stars are based on the analysis of the resonance Li I line $\lambda$ 670.8 nm only. However, spectra of Li rich stars contain...
several Li lines that are possible probes of the Li abundance. In Yakovina & Pavlenko (2001), six subordinate Li I lines in the region λλ 400-820 nm were analysed. The present paper examines which of them can be used as Li abundance indicators in carbon stars, and the ranges of Li abundances over which they work. This paper is an extension of that by Abia et al. (1999), in which the formation of the Li I lines in atmospheres of SLR AGB stars was analysed.

We use echelle-spectra of WZ Cas (C9.2J) and WX Cyg (C8.2eJ) obtained in 1997–1999 with the 4.2 m WHT (Roque de los Muchachos observatory) and 2.2 m telescope (Calar Alto observatory; see Abia et al. (1999) for more details). The spectral resolution was \( \lambda/\Delta \lambda \approx 50000 \) and 35000, respectively.

2. Lithium abundance indicators.

The strong subordinate Li I lines \( \lambda \lambda 812.6, 610.4, 497.2, 460.3, 427.3 \) and 413.3 nm are formed by transitions from the level 2p. However, only the first three turn out to be useful for measuring Li abundances: the \( \lambda 460.3 \) nm line is severely blended with a Fe I line at \( \lambda 460.3 \) nm, and the \( \lambda 427.3 \) nm line with a Cr I line at \( \lambda 427.5 \) nm. In addition, the Li lines at \( \lambda 427.3 \) nm and \( \lambda 413.3 \) nm usually cannot be observed because of the strong violet depression in the spectra of carbon stars at these wavelengths.

Our analysis below shows that the \( \lambda 497.2 \) nm line is a good indicator of the lithium abundance in the range \( 3 < \log N(\text{Li}) < 5 \), lying in a spectral region only moderately obscured by CN and \( \text{C}_2 \) absorptions. The lithium lines at \( \lambda 812.6 \) nm and \( \lambda 610.4 \) nm are saturated for \( \log N(\text{Li}) > 3 \) but they are of high sensitivity on Li abundance in the range \( 2 < \log N(\text{Li}) < 3 \) (Abia et al. 1999). The only line strong enough to measure lower Li abundances is the \( \lambda 670.8 \) nm resonance line.

In this paper we determine and compare the LTE and NLTE lithium abundances derived in WZ Cas and WX Cyg from theoretical fits to the resonance Li I line \( \lambda 670.8 \) nm and to the subordinate Li I lines \( \lambda \lambda 497.2, 610.4 \) and 812.6 nm. As was recently shown by Abia et al.(1999), it is essential to perform a NLTE analysis when deriving Li abundances in SLR carbon stars due to importance of non-equilibrium processes in the resonance \( \lambda 670.8 \) nm Li line.
Table I. Parameters of the model atmospheres for WZ Cas and WX Cyg

| Star   | T$_{\text{eff}}$ | log g | C/N/O$^*$ |
|--------|-----------------|-------|-----------|
| WZ Cas | 3000/0./0.      | 8.923 | 7.99/8.92 |
| WX Cyg | 3000/0./0.      | 8.93  | 7.99/8.92 |

$^*$ - in scale log N(H) =12.0

3. Synthetic spectra computations

Synthetic spectra were computed in the framework of LTE approach using the program WITA6 (Pavlenko 2000). Some specific continuum opacity sources in carbon-rich atmospheres (bound-free absorption of C I, C$^-$, O I and N I) were taken into account. In some cases we implement an additional continuum absorption to account for some not yet identified opacity sources (increasing the continuum opacity by a factor $\kappa$). We obtain NLTE Li abundances using LTE and NLTE curves of growth as computed in Abia et al. (1999).

The model atmospheres, N and O abundances are taken from the grid of Eriksson et al. (1984) (see Table 1). Carbon abundances were slightly adjusted (by less than 0.004 dex) using the fits to observed spectra. Computations were carried out using a microturbulence velocity $V_t$ =2.5 km/s and a isotopic ratio $^{12}$C/$^{13}$C =5 (cf. Abia et al. 1999) for both stars.

4. Atomic and molecular line lists

Different sources of atomic and molecular lines were used:
- VALD (Kupka et al. 1999) and Kurucz’s (1993-1994) databases;
- The line lists used by Abia et al. (1999);
- The line list kindly provided by T.Kipper which consists of an atomic line list from R.Bell (private communication) and molecular line lists from D.R.Alexander (private communication).

Atomic line data were verified by comparing synthetic spectra computed with the solar model atmosphere of Kurucz (1993-1994) to the observed spectrum of the Sun (Kurucz et al. 1984). The fits obtained to the solar spectrum in all regions studied were rather good (Yakovina & Pavlenko 2002).
Table II. Molecular systems of diatomic molecules considered in synthetic spectra calculations

| Molecule          | Transition   | Name of system | \( D_0 \) (eV) |
|-------------------|--------------|----------------|--------------|
| \(^{12}\text{C}^{12}\text{C}, ^{12}\text{C}^{13}\text{C}, ^{13}\text{C}^{13}\text{C}\) | \( a^3\Pi_u - a^3\Pi_u \) | Swan           | 6.156        |
| \(^{12}\text{C}^{12}\text{C}, ^{12}\text{C}^{13}\text{C}, ^{13}\text{C}^{13}\text{C}\) | \( A^1\Pi_u - X^1\Sigma_g^+ \) | Phillips       | 6.156        |
| \(^{12}\text{C}^{14}\text{N}, ^{13}\text{C}^{14}\text{N}\) | \( B^2\Sigma^+ - X^2\Sigma^+ \) | Violet         | 7.89         |
| \(^{12}\text{C}^{14}\text{N}, ^{13}\text{C}^{14}\text{N}\) | \( A^2\Pi - X^2\Sigma^+ \) | Red            | 7.89         |
| \(^{12}\text{CH}, ^{13}\text{CH}\) | \( A^2\Delta - X^2\Pi \) |               | 3.47         |
| \(^{12}\text{CH}, ^{13}\text{CH}\) | \( B^2\Sigma - X^2\Pi \) |               | 3.47         |

The main electronic systems of diatomic carbon-containing molecules accounted for in our synthetic spectra computations are listed in Table 2. The last column of Table 2 contains the dissociation potentials used.

We analysed molecular line lists qualitatively using spectra of molecular electronic systems computed with line lists from different sources. The best versions were chosen from comparison of computed and observed spectra of WZ Cas and WX Cyg. Our main conclusions about molecular line lists are:

– The CN line lists of Kurucz (1993-1994) and Abia et al. (1999) agree well.

– The line lists of \( \text{C}_2 \) Swan system of these authors provide theoretical spectra that agree well in structure but disagree in intensity.

– In some wavelength intervals, near the Li lines, the line lists by Abia et al. (1999) provide better fits to the observed spectra than the lists by Kurucz (1993-1994). On the other hand, the Kurucz line lists are more complete and uniform: that is, it supplies the better fit to observed spectra in wider spectral ranges.

We mainly used the Kurucz’s (1993-1994) molecular line lists from CD-ROM No.18 because with a more complete line list we are able to locate more confidently the pseudo-continuum level.

5. Results

Fits to the spectrum of WZ Cas in four regions containing Li I lines are shown in Fig. 1. Observed and synthetic spectra agree well enough, but there are still some discrepancies. We believe that they are mainly due to the lack of precision and completeness of the molecular line lists used.
Figure 1. Fits to observed spectra WZ Cas (solid line). The log N(Li) and $\kappa$ are specified for synthetic spectra (dashed lines). $\kappa = 1$ means absence of additional continuous absorption.
Figure 2. Sensitivity of blends containing Li I lines on the Li abundance. Observed spectra are shown by circles.

The effect of blends containing Li I lines on log N(Li) and the fits to the observed blends are shown in Fig. 2. The LTE and NLTE Li abundances obtained and the comparison with the results by Abia et al. (1999) and Abia et al. (1991) are given in Table 3. Note that for WZ Cas we specified the range of uncertainty of the Li abundance derived from the Li I λ 670.8 nm line, log N(Li)= 4.7–5.0. In this case log N(Li) was obtained by fitting the blended wings of the resonance Li I line in a region of about ∼ 2 nm. This makes our fitting rather ambiguous. We choose “the best” fit to be log N(Li) = 4.7.

Table 3 shows the results obtained for different molecular line lists taken from the Kurucz (1993-1994), Abia et al. (1999) and Kipper data. Differences in the C2 line lists change a little the carbon abundances, but the effect in log N(Li) is lower than 0.1 dex.

As it can be seen in Table 3, LTE and NLTE lithium abundances determined from subordinate Li I lines do not differ systematically from the estimations using the resonance line:

- The log N(Li) values derived from λ 497.2 nm line are equal or a bit lower than estimations from λ 670.8 nm line (Δlog N(Li) ≤ 0.4).
- Lithium abundances from λ 610.4 nm line are essentially (by ≈ 1 dex) lower than the ones from the resonance line.
Table III. LTE and NLTE lithium abundances in the atmospheres of WZ Cas and WX Cyg.

| Star    | Li I line (nm) | LTE | $\Delta_{LTE}$ | NLTE | $\Delta_{NLTE}$ | LTE APL | LTE ABIR |
|---------|---------------|-----|----------------|------|-----------------|---------|----------|
| WZ Cas  |               |     |                |      |                 |         |          |
| 497.2   | 4.7           | 0.0 | 4.8            | -0.2 | -               | -       | -        |
| 610.4   | 3.7           | -1.0| 3.8            | -1.2 | 3.1             | -       |          |
| 670.8   | 4.7           | -   | 5.0            | -    | 4.5             | 5.0     | -        |
| 812.6   | 4.7           | 0.0 | 4.8            | -0.2 | 4.6             | -       |          |
| WX Cyg  |               |     |                |      |                 |         |          |
| 497.2   | 4.3           | -0.2| 4.4            | -0.4 | -               | -       | -        |
| 610.4   | 4.0           | -0.5| 4.1            | -0.7 | 3.2             | -       |          |
| 670.8   | 4.5           | -   | 4.8            | -    | 3.7             | 4.7     | -        |
| 812.6   | 5.0           | +0.5| 5.1            | +0.3 | 4.2             | -       |          |

$\Delta_{LTE}$, $\Delta_{NLTE}$ - LTE and NLTE ($\log N$(Li)$_{\lambda}$ - $\log N$(Li)$_{670.8}$),
$\lambda$ - the wavelength of current subordinate Li line;
APL - Abia et al. 1999;
ABIR - Abia et al. 1991.

- The estimations from the line $\lambda$ 812.6 nm are approximately equal or higher than those from $\lambda$ 670.8 nm line. NLTE corrections improve the agreement between the lithium abundance estimations from the Li I $\lambda$ 812.6 nm and the resonance line.

We note that the derivation of the lithium abundance in the atmospheres of SLR carbon giants from saturated lines Li I $\lambda\lambda$ 812.6 and 610.4 nm are less reliable in comparison with the log N(Li) values from the unsaturated line Li I $\lambda$ 497.2 nm. Considering the LTE results in this work, Abia et al. (1999) for 3 stars and Plez et al. (1993) for 6 stars, we find that log N(Li)$_{610.4}$–log N(Li)$_{670.8}$ and log N(Li)$_{812.6}$–log N(Li)$_{670.8}$ are in the ranges $-0.5$ to $-1.4$ and $0.0$ to $+0.7$, respectively.

Finally, for the lithium lines $\lambda\lambda$ 497.2, 670.8 and 812.6 nm we obtain the mean log N$_{LTE}$(Li) = 4.7 and 4.6 for WZ Cas and WX Cyg, respectively. The mean NLTE lithium abundances for the same lithium lines are 4.9 for WZ Cas and 4.8 for WX Cyg.

6. Discussion

Our results show that the differences in the lithium abundances estimated from subordinate lines Li I $\lambda\lambda$ 497.2 and 812.6 nm and from the resonance line Li I $\lambda$ 670.8 nm are of the same order: $\pm$ 0.5 dex. This
is similar to the possible errors in log N(Li) due to uncertainties in the atmosphere parameters, model atmospheres and continuum level (see Denn et al. 1991, Abia et al. 1991, Plez et al. 1993, Abia et al. 1999).

The underestimations of the Li abundance from the \( \lambda 610.4 \) nm line might be explained by the bad fits to the observed spectra in this region. On the other hand, as it was already mentioned, the saturated Li I line \( \lambda 610.4 \) nm shows a rather weak dependence on log N(Li).

Finally, we conclude that the resonance \( \lambda 670.8 \) nm and subordinate \( \lambda 497.2 \) nm Li I lines are the best lithium abundance indicators in atmospheres of SLR carbon stars.

Our lithium abundances for WZ Cas and WX Cyg (Table 3) agree well with results of Abia et al. (1991) based on the resonance Li I line. Their Li estimations are higher by 0.2–0.3 dex, probably due to the incompleteness of the line lists used. Lithium abundances by Abia et al. (1999) agree well with our results for WZ Cas. For WX Cyg our estimations are higher by 0.7–0.8 dex. We believe that this difference is due to the different location of continuum level.

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References

Abia C., Boffin H.M.J, Isern J., Rebolo R.: 1991, *Astron. Astrophys.* **245**, L1.
Abia C., Isern J., Canal R.: 1993, *Astron. Astrophys.* **275**, 96.
Abia C., Pavlenko Y., de Laverny P.: 1999, *Astron. Astrophys.* **351**, 273.
Denn G.R., Luck R.E., Lambert D.L.: 1991, *Astrophys.J.* **377**, 657.
Eriksson K., Gustafsson B. et al.: 1984, *Astron. Astrophys.* **351**, 273.
Kipper T.A.: 2000, private communication.
Kurucz R.L.: 1993-1994, *Data Bank.* - CD-ROM NN 1-22, Cambridge, Harvard Univ.
Kurucz R.L., Furenlid I., Braulet J., Testerman L.: 1984, *Solar flux atlas from 296 to 1300 nm*, National Solar Observatory Atlas No.1, Cambridge, Harvard Univ.
Pavlenko Ya.V.: 2000, *Astron. Reports.* **44**, 219.
Kupka F., Piskunov N., Ryabchikova T.A., Stempels H.C., Weiss W.W.: 1999, *Astron. Astrophys. Suppl.* **138**, 119.
Plez B., Smith V.V., Lambert D.: 1993, *Astrophys.J.* **418**, 812.
Yakovina L.A., Pavlenko Ya.V.: 2001, *Kinemat. and Physics of Celest. Bodies* **17**, 446.
Yakovina L.A., Pavlenko Ya.V.: 2002, *Kinemat. and Physics of Celest. Bodies*, submitted.
Wallerstein G., Knapp G.R.: 1998, *Annu. Rev. Astron. Astrophys.* **36**, 360.
