Chemical abundance analysis of symbiotic giants – II. AE Ara, BX Mon, KX TrA, and CL Sco

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ABSTRACT
Knowledge of the elemental abundances of symbiotic giants is essential to address the role of chemical composition in the evolution of symbiotic binaries, to map their parent population, and to trace their mass transfer history. However, there are few symbiotic giants for which the photospheric abundances are fairly well determined. This is the second in a series of papers on chemical composition of symbiotic giants determined from high-resolution (R \( \sim \) 50000) near-IR spectra. Results are presented for the late-type giant star in the AE Ara, BX Mon, KX TrA, and CL Sco systems. Spectrum synthesis employing standard local thermal equilibrium (LTE) analysis and stellar atmosphere models were used to obtain photospheric abundances of CNO and elements around the iron peak (Sc, Ti, Fe, and Ni). Our analysis resulted in sub-solar metallicities in BX Mon, KX TrA, and CL Sco by [Fe/H] \( \sim \) −0.3 or −0.5 depending on the value of microturbulence. AE Ara shows metallicity closer to solar by \( \sim \) 0.2 dex. The enrichment in \(^{14}\)N isotope found in all these objects indicates that the giants have experienced the first dredge-up. In the case of BX Mon first dredge-up is also confirmed by the low \(^{12}\)C/\(^{13}\)C isotopic ratio of \( \sim 8 \).

Key words: stars: abundances – stars: atmospheres – binaries: symbiotic – stars: individual: AE Ara, BX Mon, KX TrA, CL Sco – stars: late-type

1 INTRODUCTION
Symbiotic stars are long-period binary systems composed of two evolved and strongly interacting stars: a red giant donor and a hot luminous white dwarf companion (occasionally replaced by a neutron star) surrounded by an ionized nebula. Mass exchange between the binary system members is critical in defining their evolution. Mass-loss from the giant undergoes accretion to the compact object via wind and/or Roche lobe overflow (Podsiadlowski & Mohamed 2007; Mikołajewska 2012) resulting in the formation of an accretion disc and jet (Solf & Ulrich 1985; Tomov 2003; Angeloni et al. 2011). The hot companion had previously passed through a red giant stage. In the previous red giant stage mass was transferred from this star to the star that is currently a red giant. Abundance signatures tracing this mass transfer process have been measured in some red giant–white dwarf binary systems (Smith & Lambert 1988). In some cases the mass transfer process can result in symbiotic progenitors for supernovae Type Ia (SNe Ia). Symbiotic systems are believed responsible for between a few per cent to 30 per cent of SNe Ia events (Dilday et al. 2012; Mikołajewska 2012). The complex structure with many types of interactions make symbiotic stars excellent laboratories for studying various aspects of red giant branch (RGB)/ asymptotic giant branch (AGB) binary evolution. Knowledge of the chemical composition in symbiotic giant’s atmospheres can be used to track the mass exchange history as well as the population origin of the stellar material. However, reliable determinations of photospheric compositions exist for only a small number of objects, mostly G- or K-type giants, whereas the vast majority of symbiotic stars contain M-type giants. Prior to the current series of papers only four M giants in S-type symbiotic systems had been analysed in the literature: V2116 Oph (Hinkle et al. 2006), T CrB, RS Oph (Wallerstein et al. 2008), and CH Cyg (Schmidt et al. 2006). All of them had solar or nearly solar metallicities. The rarer symbiotic stars containing K-type giants are metal-poor with s-process elements overabundant (Smith et al. 1994, 1997; Pereira et al. 1998; Pereira & Roud 2009) whereas those with G-type giants have solar metallicity and s-process enhancement (Smith et al. 2001a; Pereira et al. 2003).

This is the second in a series of papers on the chemical abundance analysis of the symbiotic giants (Mikołajewska et al. 2014, hereafter Paper I) discuss additional motivations for this work as well as the abundance analysis for the M star in two classical S-type symbiotic systems, RW Hya and SY Mus. In this paper, we obtain photospheric abundances for the M giant in four more symbiotic systems: AE Ara, BX Mon, KX TrA, and CL Sco. We also make a concise comparative analysis of our present and previous results.
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Table 1. Journal of spectroscopic observations. Velocity parameters \(^a\) of the cool components obtained via cross-correlation technique and orbital phases calculated according to the literature ephemerides are also shown.

| Sp. Region | Date | HJD(mid) | \((V_{rot} \sin^2 \theta + \xi^2)_{b}/3\) | V\(_{rad}\) | Orbital phase\(^b\) |
|------------|------|----------|----------------------------------|--------|------------------|
| AE Ara     | H(\~1.56) | 17.02.03 | 2452687.8830 | 7.76 | -6.34 ± 0.56 | 0.05 |
| K(\~2.23)  | 20.04.03 | 2452749.8669 | 9.16 | -4.47 ± 0.54 | 0.13 |
| K(\~2.23)  | 03.04.04 | 2453098.8487 | 10.35 | -15.30 ± 0.67 | 0.56 |
| BX Mon     | H(\~1.56) | 16.02.03 | 2452686.7409 | 6.08 | 25.36 ± 0.48 | 0.30 |
| K(\~2.23)  | 20.04.03 | 2452749.5231 | 7.58 | 24.12 ± 0.40 | 0.35 |
| K(\~2.36)  | 03.04.06 | 2453828.5095 | 8.44 | 27.33 ± 0.56 | 0.20 |
| KX TrA     | H(\~1.56) | 17.02.03 | 2452687.8230 | 6.05 | -125.09 ± 1.92 | 0.73 |
| K(\~2.23)  | 20.04.03 | 2452749.7670 | 6.29 | -126.13 ± 0.87 | 0.78 |
| K(\~2.23)  | 03.04.04 | 2453098.7314 | 5.74 | -122.20 ± 1.29 | 0.03 |
| CL Sco     | H(\~1.56) | 17.02.03 | 2452687.8341 | 7.02 | -31.90 ± 0.68 | 0.07 |
| K(\~2.23)  | 20.04.03 | 2452749.7780 | 6.99 | -32.99 ± 0.36 | 0.17 |
| K(\~2.23)  | 15.08.03 | 2452866.5367 | 8.52 | -32.94 ± 0.50 | 0.56 |
| K(\~2.23)  | 03.04.04 | 2453098.7794 | 8.83 | -46.51 ± 0.80 | 0.73 |

\(^a\) Units km s\(^{-1}\).
\(^b\) Orbital phase calculated from the following ephemerides: AE Ara 2453449+803.4×E \cite{fekel2010}, BX Mon 2449796+1259×E \cite{fekel2000}, KX TrA 2453053+1350×E \cite{ferreras2003}, CL Sco 2452018+625×E \cite{fekel2007}. The zero-point corresponds to the inferior conjunction of the red giant.

Table 2. Stellar parameters, \(T_{eff}\) and log \(g\) estimated from spectral types and \(T_{eff}-\log g\)-colour relation.

| Sp. Type\(^a\) | AE Ara | BX Mon | KX TrA | CL Sco |
|----------------|--------|--------|--------|--------|
| M5.5           | 3300 ± 75 | 3355 ± 75 | 3240 ± 75 | 3355 ± 75 |
| M5             | 3312 | 3367 | 3258 | 3367 |
| \(J-K_{S}\) \(^b\) | 1.36 | 1.37 | 1.39 | 1.29 |
| \(E(B-V)\) \(^b\) | 0.19–0.25 | 0.12–0.16 | 0.13–0.23 | 0.26–0.34 |
| \(J-K_{S}\) \(^b\) | 1.29–1.29 | 1.29 | 1.39 | 1.29 |
| \(E(B-V)\) \(^b\) | 0.19–0.25 | 0.12–0.16 | 0.13–0.23 | 0.26–0.34 |

References: spectral types are from \cite{murset1999}, total Galactic extinction adopted according to \cite{schlafly2011} and \cite{schlegel1998}, infrared colours are from 2MASS \cite{phillips2003} transformed to \cite{bessell1988} photometric system. Calibration by: \cite{richichi1999} and \cite{vanbelle1999}.

Table 3. Quadrature sums of the projected rotational velocities and micro-turbulence \((V_{rot} \sin^2 \theta + \xi^2)_{b}/3\) from K-band Ti, Fe, and Sc lines. \(^a\)

| Sp. Type\(^a\) | AE Ara | BX Mon | KX TrA | CL Sco |
|----------------|--------|--------|--------|--------|
| Apr 2003       | 10.06 ± 0.32 | 8.67 ± 0.47 | 8.48 ± 0.59 | 7.84 ± 0.60 |
| Aug 2003       | 8.02 ± 0.54 | 8.42 ± 0.50 | 8.74 ± 0.44 | 8.74 ± 0.44 |
| Apr 2004       | 10.56 ± 0.48 | 8.94 ± 0.71 | 8.42 ± 0.50 | 8.09 ± 0.29 | all together \(^b\) \(10.30 ± 0.28\) | 8.67 ± 0.47 | 8.71 ± 0.44 | 8.09 ± 0.29 |

\(^a\) Units km s\(^{-1}\).
\(^b\) Used for synthetic spectra calculations.

Sc, Ti, Fe, Ni. The \(K_{S}\)-band spectra are dominated by strong CO features that enable measurement of the \(^{12}\)C/\(^{13}\)C isotope ratio. The spectra were extracted and wavelength calibrated using standard reduction techniques \cite{joyce1992}. The wavelength scales of all spectra were heliocentric corrected. In all cases, telluric lines were either not present in the interval observed or were removed by reference to a hot standard star. The Gaussian instrumental profile is in all cases about 6 km s\(^{-1}\) FWHM (full width at half-maximum) corresponding to instrumental profiles of 0.31, 0.44, and 0.47Å in the case of the \(H\)-, \(K\)-, and \(K_{S}\)-band spectra, respectively. The journal of our spectroscopic observations is given in the Table 1.

3 METHODS

Abundance analyses were performed by fitting synthetic spectra to the observed spectra using the same methods adopted in Paper I for the analyses of RW Hya and SY Mus. The technique is very similar to that used by \cite{schmidt2004} in determining the CH Cyg abundances. Standard LTE analysis and MARCS model atmospheres by \cite{gustafsson2008} were used for the spectral synthesis. The code WIDMO developed by \cite{schmidt2004}, was used to calculate synthetic spectra over the entire observed spectral region. To perform the \(\chi^2\) minimization a special overlay
...was developed on the WIDMO code with use of the simplex algorithm [Brandt 1998]. This procedure enables an improvement of the computation efficiency by a factor of ten. The atomic data were taken from the VALD database [Kupka et al. 1999] in the case of K- and $K_s$-band regions and from the list given by Melendez & Barbuy (1999) for the $H$-band region. For the molecular data we used the lists Goorvitch (1994) for CO and Kurucz (1999) for $^{12}$CN and OH.

The complete list of the lines selected for our abundance analysis with excitation potentials (EP) and $gf$-values is shown in Table B1 and B2 in the online Appendix B.

The effective temperatures $T_{\text{eff}}$ were estimated (Table 2) from the known spectral types (Mørset & Schmid 1999) adopting the calibrations by Richichi et al. (1999) and Van Belle et al. (1999). The infrared intrinsic colours derived from the 2MASS (Phillips 2007) magnitudes and colour excesses (Schlafly & Finkbeiner 2011, Schlegel et al. 1998) combined with the Kucinskas et al. (2005) $T_{\text{eff}}$–log $g$–colour relation for late-type giants resulted in surface gravities and effective temperatures that are in good agreement with those from the spectral types. The adopted model atmospheres had effective temperatures $T_{\text{eff}} = 3300$ K for AE Ara and XX TrA and $3400$ K for CL Sco and BX Mon. log $g = 0$ with the exception of CL Sco where log $g$ was set to 0.5. It is difficult to estimate uncertainty in the adopted log $g$, however, it should not be larger than $\sim 0.5$ which is the resolution of the MARCS model atmosphere grid used in our calculation. In the case of BX Mon, an additional constraint on the log $g$ can be obtained using the red giant mass, $M_g = 3.7 \pm 1.9$ M$_\odot$, and radius, $R_g = 160 \pm 50$ R$_\odot$ derived by Dunham et al. (1998). The resulting log $g = 0.6^{+0.5}_{-0.6}$. Using the significantly improved orbital solution (Brandt 2009) the red giant mass is $M_g \sim 1.5$ M$_\odot$, and the resulting log $g \sim 0.2$, in good agreement with the value(s) adopted in our study. The macroturbulence velocity $\xi_t$ was set at 3 km/s, a value typical for the cool red giants (e.g. Fekel et al. 2003).

To obtain radial and rotational velocities, we used a cross-correlation technique similar to that adopted by Carlberg et al. (2011) but using synthetic spectra as the templates. The method is described in detail in Paper I and the obtained values are presented in Table 3. The rotational velocities were additionally estimated (Table 4) via direct measurement of the FHWM of the six relatively strong unblended atomic lines (Ti, Fe, Sc) present in the $K$-band region. The same lines were used by Fekel et al. (2003) to measure the rotational velocities in roughly a dozen symbiotic systems. We used the radial velocities obtained by cross-correlation (Table 3) and rotational velocities obtained from atomic lines in $K$-band spectra (Table 4) as fixed parameters in our solutions.

A detailed description of the methods used to estimate the input parameters and to derive the abundance solution was presented in Paper I. A brief outline follows. Values of the abundance parameters (C, N, O, Sc, Ti, Fe, Ni) were initially set to the solar composition (Asplund et al. 2009). Abundances of the oxygen, carbon, nitrogen, and iron peak elements were adjusted by fitting by eye, alternately from the OH, CO, CN, and atomic lines, over several iterations. Next, the initial grid of the $n + 1$, $n$ dimensional sets of free parameters, the so-called simplex needed for the simplex algorithm, was prepared. Nine different simplexes were used with different macroturbulent velocity $\xi_t$ values sampled in the range 1.2–2.6 km/s to obtain best fits to $H$- and $K$-band spectra. For three objects (AE Ara, XX TrA, and CL Sco) for which we do not have the $K_s$-band spectrum the $^{12}$C/$^{13}$C isotopic ratio was set to 8, a value close to the average for our objects with known isotopic ratios. For BX Mon after we found the sets of parameters that give the best fit to the $H$- and $K$-band spectra, we applied these abundances to the $K_s$-band spectrum as a fixed parameter and searched for $^{12}$C/$^{13}$C isotopic ratio. After obtaining the optimal fit, we made a reconciliation of $^{12}$C and $^{12}$C/$^{13}$C in three iterations.

4 RESULTS

Table 1 summarizes the final abundances and formal uncertainties derived from CNO molecules and atomic lines (Sc I, Ti I, Fe I, Ni I) on the scale of log $\epsilon(X) = \log N(X)/N(H)^{-1} + 12.0$, the isotopic ra-
Table 4. Calculated abundances and relative abundances, $^a$ velocity parameters, $^b$ and uncertainties $^c$ for AE Ara, BX Mon, KX TrA, and CL Sco.

|      | AE Ara | BX Mon | KX TrA | CL Sco |
|------|--------|--------|--------|--------|
| $X$  | log $\epsilon(X)$ | $[X]$ | log $\epsilon(X)$ | $[X]$ | log $\epsilon(X)$ | $[X]$ | log $\epsilon(X)$ | $[X]$ |
| $^{12}$C | 8.10$\pm$0.02 | -0.33$\pm$0.07 | 7.79$\pm$0.02 | -0.64$\pm$0.07 | 8.03$\pm$0.02 | -0.40$\pm$0.07 | 8.02$\pm$0.04 | -0.41$\pm$0.09 |
| C    | 8.15$\pm$0.06 | +0.32$\pm$0.11 | 7.89$\pm$0.04 | +0.06$\pm$0.09 | 8.04$\pm$0.06 | +0.21$\pm$0.11 | 8.14$\pm$0.13 | +0.31$\pm$0.18 |
| O    | 8.64$\pm$0.04 | -0.05$\pm$0.08 | 8.37$\pm$0.03 | -0.32$\pm$0.07 | 8.66$\pm$0.05 | -0.03$\pm$0.10 | 8.61$\pm$0.06 | -0.08$\pm$0.11 |
| Sc   | 4.53$\pm$0.24 | +1.38$\pm$0.28 | 3.82$\pm$0.26 | +0.67$\pm$0.30 | 4.02$\pm$0.18 | +0.87$\pm$0.22 | 3.47$\pm$0.25 | +0.32$\pm$0.29 |
| Ti   | 5.40$\pm$0.12 | +0.45$\pm$0.17 | 4.96$\pm$0.15 | +0.01$\pm$0.20 | 5.08$\pm$0.17 | +0.13$\pm$0.22 | 4.93$\pm$0.22 | -0.02$\pm$0.27 |
| Fe   | 7.41$\pm$0.06 | -0.09$\pm$0.10 | 7.16$\pm$0.06 | -0.34$\pm$0.10 | 7.17$\pm$0.03 | -0.33$\pm$0.07 | 7.21$\pm$0.09 | -0.29$\pm$0.13 |
| Ni   | 6.28$\pm$0.18 | +0.06$\pm$0.22 | 6.18$\pm$0.13 | -0.04$\pm$0.17 | 6.21$\pm$0.09 | -0.01$\pm$0.13 | 6.23$\pm$0.10 | +0.01$\pm$0.14 |

$^{12}$C/$^{13}$C

$\xi_4$ | 1.7$\pm$0.2 | 1.8$\pm$0.2 | 1.9$\pm$0.2 | 1.9$\pm$0.3 |
$V_{rot}$ | 10.2$\pm$0.3 | 8.5$\pm$0.5 | 8.5$\pm$0.5 | 7.9$\pm$0.3 |

$^a$ Relative to the Sun $[X]$ abundances estimated in relation to the solar composition of Asplund et al. (2009).
$^b$ Units km s$^{-1}$
$^c$ 3$\sigma$

Table 5. Sensitivity of abundances to uncertainties in the stellar parameters

| $\Delta X$ | $\Delta T_{\text{eff}} = +100$ K | $\Delta \log g = +0.5$ | $\Delta \xi_4 = +0.5$ | $\Delta [\text{Fe}/\text{H}] = +0.25$ |
|------------|-------------------------------|---------------------|---------------------|---------------------|
| C          | +0.02                         | +0.22               | -0.08               | +0.05               |
| N          | +0.04                         | +0.02               | -0.11               | +0.07               |
| O          | +0.13                         | +0.08               | -0.12               | +0.12               |
| Sc         | +0.12                         | +0.20               | -0.09               | -0.01               |
| Ti         | +0.07                         | +0.16               | -0.52               | -0.02               |
| Fe         | -0.05                         | +0.16               | -0.17               | -0.02               |
| Ni         | -0.07                         | +0.20               | -0.22               | -0.02               |

5 DISCUSSION

Here, we present the first ever analysis of the photospheric chemical abundances (CNO and elements around the iron peak: Sc, Ti, Fe, and Ni) for four classical S-type symbiotic systems: AE Ara, BX Mon, KX TrA, and CL Sco. Our analysis reveals an approximately solar metallicity for AE Ara and slightly sub-solar metallicities ([Fe/H] $\sim -0.3$) for BX Mon, KX TrA, and CL Sco. The CNO abundances are similar to typical values derived for single Galactic M giants. In particular, they all show carbon depletion and nitrogen enhancement (Smith & Lambert 1990). The ratio of $^{12}$C/$^{13}$C $\sim 8$ obtained for BX Mon is very similar to the values of $^{12}$C/$^{13}$C $\sim 6$ and 10 derived for RW Hya and SY Mus (Paper I). The CNO values and isotopic ratios indicate that the red giants in these systems have experienced the first dredge-up.

Relative abundances of C/N/O for these systems were previously derived based on nebular emission lines in ultraviolet spectra by Nussbaumer et al. (1988) and Pereira (1993). Pereira (1995) also estimated Fe/O from optical emission lines. A comparison of these estimates with our present results and those from Paper I is shown in Table 8. The abundances from emission lines should be most reliable when based on spectra taken during superior conjunction of the cool giant ($\phi \sim 0.5$) when the hot component and the nebula are visible in front of the giant. This was the case for KX TrA, AE Ara, and BX Mon and perhaps SY Mus. The C/O ratios obtained using emission line technique are in fairly good agreement with our photospheric values especially for KX TrA and AE Ara. For the other objects the differences are bigger. In the case of BX Mon, the difference is likely due to poor quality of the $\text{IUE}$ spectrum used by Nussbaumer et al. (1988). The $\text{IUE}$ spectra of CL Sco and RW Hya were taken relatively close to the inferior conjunction of the red giant when the emission lines are affected by eclipse and Rayleigh scattering effects. Nussbaumer et al. (1988) also noted that their method may systematically underestimate the...
C and O abundances relative to the N abundance and this effect in the worst cases may reach 30 per cent.

The elemental abundances of the symbiotic giants summarized in Table 5 can be used to address evolutionary status and to associate symbiotic systems with stellar populations of the Milky Way. In particular the C and N abundances are very good monitors of dredge-up on the RGB provided that only the CN cycle has operated significantly in the dredged material. In such a case, the total number of C+N nuclei should be conserved since the α-element originate mostly from massive stars and their clear separation in the [O/Fe] versus [Fe/H] plane (e.g. Cunha & Smith 2006, Bensby & Feltzing 2006).

Figure 5 shows [O/Fe] versus [Fe/H] of the symbiotic giants along with the values for various stellar populations taken from a number of studies (Edvardsson et al. 1993, Prochaska et al. 2000, Meléndez et al. 2001, Smith et al. 2001, Meléndez 2002, Fulbright & Johnson 2003, Reddy et al. 2003, Rich & Origlia 2005, Bensby et al. 2005, Cunha & Smith 2006, Alves-Brito et al. 2010, Ryde et al. 2010, Rich et al. 2012, Smith et al. 2013) and scaled to the solar composition of Asplund et al. (2009). We have distinguished four populations: thin and thick discs, halo, and bulge. Part of the bulge population containing objects from Baade’s Windows and from two other nearby inner bulge fields F175 and F265 (Rich & Origlia 2005, Rich et al. 2012) is highlighted with red. These objects are more chemically homogeneous than the rest of the bulge sample as indicated by their grouping in a small area of the diagram. The rest of the sample contains objects spread in the bulge (Cunha & Smith 2006, Alves-Brito et al. 2010, Ryde et al. 2010) and is more representative for the whole bulge population.

Table 6. Calculated abundances and relative abundances, a velocity parameters, b and uncertainties c for AE Ara, BX Mon, KX TrA, and CL Sco. The case for fixed microturbulences.

| X           | AE Ara     | BX Mon     | BX Mon a | KX TrA     | CL Sco     |
|-------------|------------|------------|----------|------------|------------|
|            | log ε(X)   | [X]        | log ε(X) | [X]        | log ε(X)   | [X]        | log ε(X) | [X]        | log ε(X) | [X]        | log ε(X) | [X]        |
| 12C        | 7.93±0.03  | -0.50±0.08 | 7.66±0.03| -0.77±0.08 | 7.87±0.03  | -0.56±0.08 | 7.89±0.03| -0.54±0.07 | 7.92±0.04| -0.51±0.09 |
| N          | 7.89±0.09  | +0.06±0.14 | 7.65±0.06| -0.13±0.11 | 7.67±0.05  | -0.16±0.10 | 7.82±0.09| -0.01±0.14 | 7.96±0.10| +0.13±0.15 |
| O          | 8.35±0.03  | -0.34±0.07 | 8.14±0.01| +0.10±0.04 | 8.23±0.02  | -0.46±0.06 | 8.39±0.05| -0.30±0.10 | 8.39±0.03| -0.30±0.08 |
| Sc         | 3.45±0.22  | +0.30±0.25 | 3.15±0.22| +0.00±0.26 | 3.29±0.18  | +0.14±0.22 | 3.33±0.12| +0.18±0.16 | 3.16±0.23| +0.01±0.27 |
| Ti         | 4.55±0.08  | -0.40±0.13 | 4.33±0.06| -0.62±0.11 | 4.48±0.07  | -0.47±0.12 | 4.46±0.12| -0.49±0.17 | 4.53±0.12| -0.42±0.17 |
| Fe         | 7.16±0.06  | -0.34±0.10 | 6.95±0.04| -0.55±0.08 | 7.10±0.04  | -0.40±0.08 | 6.96±0.06| -0.40±0.10 | 7.07±0.08| -0.43±0.12 |
| Ni         | 5.95±0.09  | -0.27±0.13 | 5.93±0.10| -0.29±0.14 | 6.09±0.08  | -0.13±0.12 | 5.96±0.08| -0.26±0.12 | 6.11±0.10| -0.14±0.14 |

| 12C/13C    | –          | 12±2       | –         | 11±1       | –          | –         | –         | –         | –         | –         |

| δi         | 2.5        | 2.5        | 2.5       | 2.5        | 2.3        | 2.3        | 2.3        | 2.3        | 2.3        | 2.3        |
| Vrot sin i | 10.0±0.3   | 8.3±0.5    | 8.3±0.5   | 8.3±0.5    | 7.8±0.3    | 7.8±0.3    | 7.8±0.3    | 7.8±0.3    | 7.8±0.3    | 7.8±0.3    |

Table 7. Sensitivity of abundances to uncertainties in the stellar parameters. The case for fixed microturbulences.

| ΔX        | ΔTeff = +100 K | Δlog g = +0.5 | Δδi = +0.5 |
|-----------|----------------|---------------|------------|
| C         | +0.02          | +0.22         | -0.04      |
| N         | +0.02          | +0.03         | -0.12      |
| O         | +0.10          | +0.10         | -0.09      |
| Sc        | +0.10          | +0.16         | -0.38      |
| Ti        | +0.06          | +0.17         | -0.39      |
| Fe        | -0.05          | +0.17         | -0.19      |
| Ni        | -0.05          | +0.18         | -0.17      |
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Table 8. Comparison of our photospheric abundances with those derived using emission line technique.

| Object | C/N | O/N | C/O | Fe/O | Phase$^a$ | Ref. |
|--------|-----|-----|-----|------|-----------|------|
| KX TrA | 1.59 | 4.42 | 0.36 | 0.046 | 0.52 [3] |      |
|        | 2.28 | 6.91 | 0.33 | –     | 0.27 [3] |      |
|        | 0.98 | 4.17 | 0.23 | 0.032 | –         | [1]  |
| AE Ara | 1.2  | 3.7  | 0.32 | –     | 0.43 [4] |      |
|        | 0.89 | 3.09 | 0.29 | 0.059 | –         | [1]  |
| BX Mon | 0.29 | 2.0  | 0.15 | –     | 0.49 [4] |      |
|        | 0.79 | 3.02 | 0.26 | 0.062 | –         | [1]  |
| CL Sco | 0.77 | 5.7  | 0.14 | –     | 0.87 [4] |      |
|        | 0.76 | 2.96 | 0.26 | 0.040 | –         | [1]  |
| SY Mus | 0.97 | 1.9  | 0.51 | –     | 0.36 [4] |      |
|        | 1.15 | 3.55 | 0.32 | 0.058 | –         | [2]  |
| RW Hya | 0.42 | 1.7  | 0.25 | –     | 0.15 [4] |      |
|        | 1.17 | 5.13 | 0.23 | 0.037 | –         | [2]  |

References: [1] this work, [2] Paper I, [3] Pereira (1995).$^a$ Orbital phase the same as in Table 1 and table 2 in Paper I.

Table 9. Absolute and relative abundances adopted for the comparison with the Galactic stellar populations. Two cases for the microturbulence being free and fixed parameter are shown at the top and at the middle, respectively. Abundances of RW Hya and SY Mus from Paper I and CH Cyg and V2116 Oph from the literature are shown for comparison at the bottom.

| Object  | $A^{12}$C | $A^{14}$N | [O/Fe] | [Fe/H] | $\xi$ |
|---------|----------|----------|--------|--------|------|
| AE Ara  | 8.10     | 8.15     | +0.04  | -0.09  | 1.7  |
|         | 7.93     | 7.89     | +0.00  | -0.34  | 2.5  |
| BX Mon  | 7.79     | 7.89     | +0.02  | -0.34  | 1.8  |
|         | 7.66     | 7.65     | +0.00  | -0.55  | 2.5  |
|         | 7.87     | 7.67     | -0.06  | -0.40  | 2.5a |
| KX TrA  | 8.03     | 8.04     | +0.30  | -0.33  | 1.9  |
|         | 7.89     | 7.82     | +0.24  | -0.34  | 2.5  |
| CL Sco  | 8.02     | 8.14     | +0.21  | -0.29  | 1.9  |
|         | 7.92     | 7.96     | +0.13  | -0.43  | 2.3  |
| RW Hya  | 7.53     | 7.46     | +0.24  | -0.76  | 1.8  |
| SY Mus  | 8.17     | 8.11     | +0.05  | -0.08  | 2.0  |
| CH Cyg  | 8.37     | 8.08     | +0.07  | +0.00  | 2.2  |
| V2116 Oph | 8.03  | 8.97     | -0.22  | -0.05  | 2.4  |

References: [1] Paper I, [2] Schmidt et al. (2006), [3] Hinkle et al. (2006).$^a$ $\log g = 0.5$.

The thin and thick disc samples contain only those objects with membership confirmed by their kinematic characteristics. Finally, the 'field star' group represents the objects for which there is no kinematic information about their population membership. It may contain stars from all Galactic populations but it seems to be dominated by the thin disc members.

The position in the [O/Fe]–[Fe/H] plane of the objects studied here can be related to membership in Galactic populations. Most appear to belong to the Galactic disc or bulge while the position of RW Hya supports its membership in the extended thick disc/halo population. Additional independent methods, e.g. simultaneous kinematic studies on the Toomre diagram (Feltzing et al. 2003; Galan et al. 2014), are necessary to sort out this question. Such studies will be performed in the near future on a more statistically significant sample.

In the process of fitting the synthetic spectra we measured radial and rotational velocities for the programme stars (Tables 1 and 3). Radial velocities obtained for three objects, AE Ara, BX Mon, and CL Sco, using cross-correlation techniques are consistent with recent spectroscopic orbits published for these stars. Radial velocities obtained for AE Ara are in agreement with results obtained with the same spectra by Fekel et al. (2010) with discrepancies no larger than 2 km s$^{-1}$. Residuals calculated by Fekel et al. (2010) from the synthetic orbit are within the range $-1.5$–$2$ km s$^{-1}$. Similarly the radial velocities obtained for CL Sco agree with values obtained by the Fekel et al. (2007) with the same spectra with differences in the range $-0.2$–$2.3$ km s$^{-1}$. Residuals from the synthetic orbit calculated by Fekel et al. (2007) have values between $-1$ and $3$ km s$^{-1}$. Radial velocities obtained for BX Mon are in accord with synthetic radial velocities predicted from the orbit of Fekel et al. (2000) with an accuracy generally better than $\sim$2 km s$^{-1}$. In the case of KX TrA, however, we could not achieve agreement with published orbits. The range of the velocities measured by us, $-122$ to $126$ km s$^{-1}$, is covered by the $y$ velocity of $-123.7$ km s$^{-1}$ and $K$ of $6.8$ km s$^{-1}$ found by Ferrer et al. (2003) but computed versus observed velocities are not consistent with an orbital period of 1350 d. The orbit of Harries & Howard (2008) from spectropolarimetric observation is similar to that of Ferrer et al. (2003). The Marchiano et al. (2008) orbit is similar but the 1916 d period is significantly longer. Further study and possibly recalculating with another period is needed.

Giants in symbiotic stars are characterized with large rotational velocities and in all the systems studied by us so far $V_{rot}\sin i$ makes the largest contribution to the physical line broadening. The rotational velocities obtained with the cross-correlation method generally have smaller values than obtained with FWHM method (Table 1 and 3). The rotational velocities obtained from strongly blended spectra with strong molecular lines (like H-band spectra) appear to be significantly underestimated, and the use of rotational velocities as a free parameters does not lead to significant differences in obtained values of the rotational velocities and abundances (Paper I). Therefore, our analysis used velocities obtained with FWHM method that gives more self-consistent results in accord with those obtained from the same spectra with cross-correlation method.
6 CONCLUSIONS
We have performed a detailed analysis of the photospheric abundances of CNO and elements around the iron peak (Sc, Ti, Fe, and Ni) for the red giant objects of the S-type symbiotic binaries: AE Ara, BX Mon, KX TrA, and CL Sco. Our analysis revealed a near-solar metallicity for AE Ara, and slightly sub-solar metallicities ([Fe/H] ≈ −0.3) for BX Mon, KX TrA, and CL Sco. However, the metallicities are lower by ~0.2 dex when the microturbulence values were estimated from bolometric magnitudes instead of keeping the microturbulence as a free parameter. The enrichment in $^{14}$N isotopic ratio obtained for all these objects indicates that the giants have experienced the first dredge-up which is also confirmed by the very low $^{12}$C/$^{13}$C isotopic ratio $\sim 8$ obtained for BX Mon.

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APPENDIX A: OBSERVED AND SYNTHETIC SPECTRA OF AE ARA, KX TRA, AND CL SCO
Figure A1. The spectrum of AE Ara observed in 2003 February (blue line) in the $H$ band and a synthetic spectrum (red line) calculated using the final abundances (Table 4).

Figure A2. Spectra of AE Ara observed in 2003 April (blue line) and April 2004 (green line) in the $K$ band and a synthetic spectrum (red line) calculated using the final abundances (Table 4).

Figure A3. The spectrum of KX TrA observed in 2003 February (blue line) in the $H$ band and a synthetic spectrum (red line) calculated using the final abundances (Table 4).

Figure A4. Spectra of KX TrA observed in 2003 April (blue line) and April 2004 (green line) in the $K$ band and a synthetic spectrum (red line) calculated using the final abundances (Table 4).

Figure A5. The spectrum of CL Sco observed in 2003 February (blue line) in the $H$ band and a synthetic spectrum (red line) calculated using the final abundances (Table 4).

Figure A6. Spectra of CL Sco observed in 2003 April (blue line), 2003 August (green line), and April 2004 (dark-orange line) in the $K$ band and a synthetic spectrum (red line) calculated using the final abundances (Table 4).

APPENDIX B: LIST OF ATOMIC AND MOLECULAR LINES

This paper has been typeset from a TeX/LaTeX file prepared by the author.
Table B1. List of atomic lines selected for calculations together with gf-values and excitation potentials.

| Wavelength (air) (Å) | EP (eV) | log gf | Ref. |
|----------------------|---------|--------|------|
| 15598.890            | 4.690   | -0.030 | M´ elendez & Barbuy (1999) |
| 15602.840            | 2.270   | -1.810 | M´ elendez & Barbuy (1999) |
| 22210.636            | 4.213   | -1.444 | Kupka et al. (1999) |
| 22211.228            | 1.734   | -1.770 | Kupka et al. (1999) |
| 22224.530            | 4.933   | -0.263 | Kupka et al. (1999) |
| 22232.838            | 1.739   | -1.658 | Kupka et al. (1999) |
| 22274.012            | 1.749   | -1.756 | Kupka et al. (1999) |
| 22282.973            | 4.690   | -0.586 | Kupka et al. (1999) |
| 22310.617            | 1.734   | -2.124 | Kupka et al. (1999) |

| Wavelength (air) (Å) | EP (eV) | log gf | Ref. |
|----------------------|---------|--------|------|
| 22273.969            | 1.628   | -1.818 | Kurucz (1999) |
| 22248.297            | 1.457   | -1.862 | Kurucz (1999) |
| 22243.514            | 1.245   | -1.732 | Kurucz (1999) |
| 22239.814            | 1.600   | -1.816 | Kurucz (1999) |
| 22236.898            | 1.107   | -2.249 | Kurucz (1999) |
| 22228.994            | 1.303   | -1.633 | Kurucz (1999) |
| 22220.176            | 1.103   | -2.055 | Kurucz (1999) |
| 22198.955            | 1.600   | -1.825 | Kurucz (1999) |
| 22194.477            | 1.230   | -1.747 | Kurucz (1999) |
| 22189.324            | 1.723   | -2.022 | Kurucz (1999) |
| 22189.324            | 1.723   | -2.022 | Kurucz (1999) |
| 2203.804             | 0.345   | -1.345 | Kurucz (1999) |
| 2200.571             | 0.345   | -1.345 | Kurucz (1999) |
| 2200.176             | 1.045   | -2.206 | Kurucz (1999) |
| 2189.293             | 1.075   | -2.868 | Kurucz (1999) |
| 2189.324             | 1.723   | -2.022 | Kurucz (1999) |
| 22190.012            | 1.097   | -2.737 | Kurucz (1999) |
| 2192.684             | 1.117   | -2.235 | Kurucz (1999) |
| 2194.477             | 1.230   | -1.747 | Kurucz (1999) |
| 2196.680             | 1.457   | -1.875 | Kurucz (1999) |
| 2198.914             | 1.437   | -1.872 | Kurucz (1999) |
| 2198.955             | 1.600   | -1.825 | Kurucz (1999) |
| 2216.477             | 1.216   | -1.747 | Kurucz (1999) |
| 2220.176             | 1.103   | -2.055 | Kurucz (1999) |
| 22228.924             | 1.079   | -2.204 | Kurucz (1999) |
| 22228.924             | 1.079   | -2.204 | Kurucz (1999) |
| 22236.898             | 1.107   | -2.249 | Kurucz (1999) |
| 22239.814             | 1.600   | -1.816 | Kurucz (1999) |
| 22243.514             | 1.245   | -1.732 | Kurucz (1999) |
| 22245.525             | 1.362   | -1.803 | Kurucz (1999) |
| 22245.752             | 1.128   | -2.213 | Kurucz (1999) |
| 22248.297             | 1.457   | -1.862 | Kurucz (1999) |
| 22248.438             | 1.477   | -1.866 | Kurucz (1999) |
| 22262.354             | 1.230   | -1.732 | Kurucz (1999) |
| 22273.969             | 1.628   | -1.818 | Kurucz (1999) |

* Not used for the chemical composition determination.
### Table B2 – continued

| Wavelength (air) (Å) | EP (eV) | log g f | Ref. |
|---------------------|--------|--------|------|
| 22276.160          | 1.3036 | -1.624 | Goorvitch (1994) |
| 22277.008          | 1.1080 | -2.197 | Goorvitch (1994) |
| 22280.246          | 1.1036 | -2.047 | Goorvitch (1994) |
| 22285.527          | 1.1177 | -2.225 | Goorvitch (1994) |
| 22294.160          | 1.2609 | -1.718 | Goorvitch (1994) |
| 22295.695          | 1.1216 | -2.042 | Goorvitch (1994) |
| 22296.930          | 1.3900 | -1.803 | Goorvitch (1994) |
| 22299.426          | 1.4778 | -1.853 | Goorvitch (1994) |
| 22300.430          | 1.1397 | -2.192 | Goorvitch (1994) |
| 22301.910          | 1.4986 | -1.856 | Goorvitch (1994) |
| 22302.410          | 1.3260 | -1.624 | Goorvitch (1994) |
| 22309.961          | 1.2457 | -1.718 | Goorvitch (1994) |
| 22311.473          | 1.2942 | -2.377 | Goorvitch (1994) |
| 22314.611          | 1.6282 | -1.809 | Goorvitch (1994) |
| 22317.520          | 1.7561 | -2.009 | Goorvitch (1994) |
| 22321.525          | 1.1314 | -2.195 | Goorvitch (1994) |

### Table B2 – continued

| Wavelength (air) (Å) | EP (eV) | log g f | Ref. |
|---------------------|--------|--------|------|
| 15590.144          | 0.4690 | -7.3583 | Goorvitch (1994) |
| 15591.363          | 0.1427 | -7.7310 | Goorvitch (1994) |
| 15592.908          | 0.4901 | -7.3428 | Goorvitch (1994) |
| 15594.223          | 0.1313 | -7.7545 | Goorvitch (1994) |
| 15595.946          | 0.5118 | -7.3273 | Goorvitch (1994) |
| 15597.348          | 0.1204 | -7.7786 | Goorvitch (1994) |
| 15599.257          | 0.5339 | -7.3121 | Goorvitch (1994) |
| 15600.737          | 0.1100 | -7.8035 | Goorvitch (1994) |
| 15602.842          | 0.5564 | -7.2971 | Goorvitch (1994) |
| 15604.392          | 0.1000 | -7.8294 | Goorvitch (1994) |
| 15606.702          | 0.5794 | -7.2822 | Goorvitch (1994) |
| 15608.312          | 0.0905 | -7.8564 | Goorvitch (1994) |
| 15612.497          | 0.0814 | -7.8841 | Goorvitch (1994) |
| 15615.250          | 0.6268 | -7.2530 | Goorvitch (1994) |
| 15616.948          | 0.0729 | -7.9133 | Goorvitch (1994) |
| 15619.940          | 0.6512 | -7.2385 | Goorvitch (1994) |
| 15621.663          | 0.0648 | -7.9439 | Goorvitch (1994) |
| 15624.908          | 0.6760 | -7.2242 | Goorvitch (1994) |
| 15626.644          | 0.0572 | -7.9755 | Goorvitch (1994) |
| 15630.155          | 0.7012 | -7.2101 | Goorvitch (1994) |
| 15631.891          | 0.0500 | -8.0092 | Goorvitch (1994) |
| 15635.682          | 0.7269 | -7.1961 | Goorvitch (1994) |
| 15637.404          | 0.0434 | -8.0446 | Goorvitch (1994) |
| 15641.490          | 0.7531 | -7.1822 | Goorvitch (1994) |
| 15643.182          | 0.0372 | -8.0824 | Goorvitch (1994) |
| 15647.580          | 0.7797 | -7.1685 | Goorvitch (1994) |
| 15649.227          | 0.0314 | -8.1226 | Goorvitch (1994) |
| 15653.953          | 0.8068 | -7.1548 | Goorvitch (1994) |
| 15655.537          | 0.0262 | -8.1659 | Goorvitch (1994) |
| 15660.610          | 0.8343 | -7.1412 | Goorvitch (1994) |
| 15662.115          | 0.0214 | -8.2128 | Goorvitch (1994) |
| 15667.552          | 0.8622 | -7.1277 | Goorvitch (1994) |
| 15668.960          | 0.0172 | -8.2640 | Goorvitch (1994) |
| 15550.686          | 1.2764 | -9.9838 | Goorvitch (1994) |
| 15550.681          | 1.4307 | -4.2927 | Goorvitch (1994) |
| 15552.653          | 0.8557 | -5.8380 | Goorvitch (1994) |
| 15553.865          | 0.2917 | -5.4983 | Goorvitch (1994) |
| 15544.786          | 0.0048 | -6.4587 | Goorvitch (1994) |
| 15556.234          | 1.4594 | -4.2830 | Goorvitch (1994) |
| 15558.269          | 0.8385 | -4.5974 | Goorvitch (1994) |
| 15562.231          | 1.4886 | -4.2734 | Goorvitch (1994) |
| 15564.307          | 0.8218 | -4.6121 | Goorvitch (1994) |
| 15564.951          | 2.1495 | -4.3503 | Goorvitch (1994) |
| 15568.674          | 1.5182 | -4.2638 | Goorvitch (1994) |
| 15569.215          | 2.5958 | -4.7140 | Goorvitch (1994) |
| 15570.273          | 0.2870 | -5.5423 | Goorvitch (1994) |
### Table B2 – continued

| Wavelength (air) (Å) | $EP$ (eV) | $\log gf$ | Ref.          |
|----------------------|-----------|-----------|--------------|
| 23603.818            | 1.4476    | -4.9412   | Goorvitch (1994) |
| 23605.733            | 0.1256    | -5.6360   | Goorvitch (1994) |
| 23615.711            | 1.4831    | -4.9329   | Goorvitch (1994) |
| 23617.268            | 0.1151    | -5.6574   | Goorvitch (1994) |
| 23628.043            | 1.5189    | -4.9248   | Goorvitch (1994) |
| 23629.197            | 0.1051    | -5.6794   | Goorvitch (1994) |
| 23640.814            | 1.5552    | -4.9165   | Goorvitch (1994) |
| 23641.522            | 0.0956    | -5.7025   | Goorvitch (1994) |
| OH                   |           |           |              |
| 15593.179            | 0.8740    | -5.358    | Kurucz (1999) |
| 15593.563            | 0.8740    | -5.358    | Kurucz (1999) |
| 15608.357            | 0.4942    | -7.209    | Kurucz (1999) |
| 15609.683            | 0.4942    | -7.209    | Kurucz (1999) |
| 15621.766            | 0.8374    | -6.734    | Kurucz (1999) |
| 15624.434            | 0.8415    | -7.006    | Kurucz (1999) |
| 15624.660            | 0.1336    | -8.233    | Kurucz (1999) |
| 15626.704            | 0.5413    | -5.198    | Kurucz (1999) |
| 15627.290            | 0.8871    | -5.435    | Kurucz (1999) |
| 15627.293            | 0.8871    | -5.435    | Kurucz (1999) |
| 15627.413            | 0.5413    | -5.198    | Kurucz (1999) |
| 15627.902            | 0.1337    | -8.233    | Kurucz (1999) |
| 15636.235            | 0.8876    | -7.202    | Kurucz (1999) |
| 15636.596            | 0.8876    | -7.202    | Kurucz (1999) |
| 15643.302            | 0.8420    | -7.007    | Kurucz (1999) |
| 15650.557            | 0.8643    | -5.587    | Kurucz (1999) |
| 15650.797            | 0.8643    | -5.587    | Kurucz (1999) |
| 15651.896            | 0.5341    | -5.132    | Kurucz (1999) |
| 15653.480            | 0.5343    | -5.132    | Kurucz (1999) |
| 15654.116            | 0.8383    | -6.734    | Kurucz (1999) |
| 15655.053            | 0.3041    | -7.713    | Kurucz (1999) |
| 15658.127            | 0.3038    | -7.713    | Kurucz (1999) |