Chemical abundance analysis of symbiotic giants – III. V694 Mon, CD-36°8436, WRAY 16-202, Hen 3-1213, V455 Sco, and Hen 2-247

Cezary Gałan1*, Joanna Mikołajewska1, and Kenneth H. Hinkle2
1N. Copernicus Astronomical Center, Bartycka 18, PL-00-716 Warsaw, Poland
2National Optical Astronomy Observatory, PO Box 26732, Tucson, AZ 85726, USA

ABSTRACT

The elemental abundances of symbiotic giants are 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, the number of symbiotic giants with fairly well determined photospheric composition is still insufficient for statistical analyses. This is the third in a series of papers on the chemical composition of symbiotic giants determined from high resolution (R \sim 50000), near-IR spectra. We present results here for the giant star in the V694 Mon, CD-36°8436, WRAY 16-202, Hen 3-1213, V455 Sco, and Hen 2-247 systems. Spectrum synthesis employing standard local thermal equilibrium (LTE) analysis and atmosphere models were used to obtain photospheric abundances of CNO and elements around the iron peak (Sc, Ti, Fe, and Ni). Our analysis reveals metallicities from slightly super-solar for V455 Sco (\feh \sim +0.3 \dex), near solar for WRAY 16-202 and Hen 2-247, slightly sub-solar for V694 Mon and CD-36°8436 (\feh \sim −0.4 \dex), and significantly sub-solar for Hen 3-1213 (\feh \sim −0.8 \dex). The enrichment in \iso{14}N isotope, found in all these objects, indicates that the giants have experienced the first dredge-up. For three giants, V694 Mon, CD-36°8436, and WRAY 16-202, this was confirmed by the low \iso{12}C/\iso{13}C isotopic ratios, \sim 24, 8, and 11 respectively. We found that the relative abundance of [Ti/Fe] is large in all the objects studied so far. This appears to be an intrinsic characteristic of all symbiotic giants.

Key words: stars: abundances – stars: atmospheres – binaries: symbiotic – stars: evolution – stars: late-type

1 INTRODUCTION

Symbiotic stars are long-period binary systems composed of two evolved stars: typically a red giant and white dwarf surrounded by an ionized nebula. A strong interaction between components is driven by mass loss from the red giant donor that is partly accreted from the wind and/or via Roche lobe overflow (Podsiadlowski & Mohamed 2003, Mikołajewska 2012) onto the hot, luminous companion. In the past, when the now compact object underwent its red giant stage mass had to be transferred in the opposite direction from this star to the star that is currently a red giant. That mass transfer episode should have left traces in the chemical composition of the red giant observed today. Indeed such chemical pollution has been detected in some red giant–white dwarf binary systems (Smith & Lambert 1988).

Knowledge of the atmospheric chemical composition of symbiotic giants is of special significance as it can be used to track the mass exchange history as well as their population origin. However, at the moment reliable measurements of photospheric compositions exist for only ten symbiotic systems with late-type (M) giants and about a dozen ‘yellow’, i.e. G or K giant, symbiotic systems. 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 abundant (Smith et al 1996, 1997; Pereira et al 1998; Pereira & Roig 2005) whereas those with G-type giants have solar metallicity and s-process enhancement (Smith, Cunha & King 2001; Pereira et al 2005).

The number of symbiotic giants with fairly well determined photospheric composition is too small, to perform reliable statistical analysis. To improve this situation we have started a research program of detailed chemical composition measurements for over 30 southern symbiotic systems. The motivation for this work, as well as the first analysis of two classical S-type symbiotic systems (RW Hya, and SY Mus) were presented in Mikołajewska et al. (2014, hereafter Paper I) and results for the next four systems (AE Ara, BX Mon, KX Tra, and CL Sco) in Gałan, Mikołajewska & Hinkle (2014, hereafter Paper II). This is the third in a series of papers on the chemical abundance anal-
ysis of the symbiotic giants. In the present paper we measure photospheric abundances for another six objects: V694 Mon, CD-36°8436, WRAY 16-202, Hen 3-1213, V455 Sco, and Hen 2-247. We also undertake a comparative analysis of our present and previous results.

2 OBSERVATIONS AND DATA REDUCTION

High-resolution (R = λ/Δλ ~ 50000), high S/N ratio (≥ 100), near-IR spectra of symbiotic systems were observed with the Phoenix cryogenic echelle spectrometer on the 8 m Gemini South telescope. All the spectra cover narrow spectral ranges (~100 Å) located in the H and K photometric bands with mean wavelengths close to 1.56, 2.23, and 2.36 μm (hereafter H-, K-, and K_r-band spectra, respectively). For all six objects one spectrum was observed in the H-band region in 2003 February, one in the K-band in 2003 April, and in a subset of the sample additional spectra were observed in the K-band in 2003 August and 2004 April. The H-band spectra cover a region with molecular CO and OH lines and the K-band spectra CN lines. Both the H and K band regions include a number of strong atomic lines. These lines were used to determine abundances of carbon, nitrogen, and oxygen, and elements around iron peak: Sc, Ti, Fe, Ni. For V694 Mon, CD-36°8436, and WRAY 16-202 we have additional spectra observed in 2006 April in the K_r-band region. The K_r spectra are dominated by strong CO features that enable measurement of the $^{13}$C/$^{12}$C isotopic ratio. The spectra were extracted and wavelength calibrated using standard reduction techniques (Krivonosov 1992) and all 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 0.47 Å in the case of the H-, K-, and K_r-band spectra, respectively. The journal of our spectroscopic observations is given in the Table I.

### Table I. Journal of spectroscopic observations. Velocity parameters$^{a}$ of the cool components obtained via cross-correlation technique and orbital phases calculated according to the literature ephemeris are also shown.

| Sp. Region | Band(μm) | Date      | HJD(mid) | $\left(\frac{V_{rot}^2 \sin^2 i + \xi_V^2}{2}\right)^{1/2}$ | $V_{rad}$ | Orbital phase$^b$ |
|------------|---------|-----------|----------|-------------------------------------------------|----------|------------------|
| V694 Mon   | H(1.56) | 16.02.2003| 2452686.7491 | 4.19                                           | +36.65 ± 0.36 | 0.39             |
|            | K(-2.23)| 20.04.2003| 2452749.5326 | 6.34                                           | +32.16 ± 0.46 | 0.42             |
|            | K_r(-2.36)| 03.04.2004| 2453828.5187 | 7.21                                           | +34.26 ± 0.36 | 0.98             |
| CD-36°8436 | H(1.56) | 16.02.2003| 2452686.8181 | 6.94                                           | −44.45 ± 0.83 | −                |
|            | K(-2.23)| 20.04.2003| 2452749.6156 | 6.96                                           | −48.77 ± 0.46 | −                |
|            | K_r(-2.36)| 03.04.2006| 2453828.6211 | 6.45                                           | −52.76 ± 1.46 | −                |
| WRAY 16-202 | H(1.56) | 17.02.2003| 2452687.7936 | 5.97                                           | −84.60 ± 1.44 | −                |
|            | K(-2.23)| 20.04.2003| 2452749.7301 | 6.60                                           | −87.93 ± 0.70 | −                |
|            | K_r(-2.36)| 03.04.2006| 2453828.6812 | 8.39                                           | −92.13 ± 2.50 | −                |
| Hen 3-1213 | H(1.56) | 16.02.2003| 2452686.8581 | 9.89                                           | −46.34 ± 0.90 | 0.71             |
|            | K(-2.23)| 20.04.2003| 2452749.7403 | 7.24                                           | −47.02 ± 0.37 | 0.84             |
|            | K_r(-2.36)| 15.08.2003| 2452866.4846 | 8.38                                           | −37.49 ± 0.29 | 0.06             |
|            | K_r(-2.36)| 03.04.2004| 2453098.6892 | 9.43                                           | −45.95 ± 0.76 | 0.52             |
| V455 Sco   | H(1.56) | 17.02.2003| 2452687.8626 | 5.23                                           | −73.04 ± 1.62 | 0.03             |
|            | K(-2.23)| 20.04.2003| 2452749.7874 | 7.78                                           | −76.19 ± 0.93 | 0.08             |
|            | K_r(-2.36)| 03.04.2004| 2453098.7959 | 7.40                                           | −71.38 ± 0.87 | 0.33             |
| Hen 2-247  | H(1.56) | 17.02.2003| 2452687.8745 | 7.28                                           | +95.30 ± 1.06 | 0.37             |
|            | K(-2.23)| 20.04.2003| 2452749.8453 | 9.53                                           | +87.19 ± 0.85 | 0.44             |
|            | K_r(-2.23)| 15.08.2003| 2452866.5144 | 10.95                                          | +82.66 ± 1.54 | 0.57             |
|            | K_r(-2.23)| 03.04.2004| 2453098.8329 | 7.69                                           | +83.69 ± 0.56 | 0.83             |

$^a$ Units km s$^{-1}$.

$^b$ Orbital phases are calculated from the following ephemerides: V694 Mon 2448080+1931±E Gromadzki et al. (2007), Hen 3-1213 2451806+514±E Gromadzki, Mikołajewska & Soszyński (2013), V455 Sco 2452641.5+1398±E Fekel et al. (2008), Hen 2-247 2452355+898±E Fekel et al. (2008).

3 METHODS

A detailed description of the methods used to estimate the input parameters and to derive the abundance solution was presented in Paper I and applied again in Paper II. Abundance analyses were performed by fitting synthetic spectra to the observed spectra using methods very similar to those used by Schmidt et al. (2008) in determining the CH Cyg abundances. Standard LTE analysis and MARCS model atmospheres by Gustafsson et al. (2008) were used for the spectral synthesis. The code WIDMO developed by Schmidt et al. (2006), was used to calculate synthetic spectra. To perform the $\chi^2$ minimization a special overspray was developed on the WIDMO code that uses the simplex algorithm (Brandt 1998).

The atomic data were taken from the VALD database (Kupka et al. 1999) in the case of CN and OH. The complete lists of the lines from the list $^{13}$C/$^{12}$C isotopic ratio. The spectra were extracted and wavelength calibrated using standard reduction techniques (Joyce 1992) and all 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 0.47 Å in the case of the H-, K-, and K_r-band spectra, respectively. The journal of our spectroscopic observations is given in the Table I.

The input effective temperatures $T_{\text{eff}}$ were estimated (Table I).
Table 2. Stellar parameters, $T_{\text{eff}}$ and log g estimated from spectral types and $T_{\text{eff}}$–log g–colour relation.

| Sp. Type[1] | V694 Mon | CD-36°8436 | WRAY 16-202 | Hen 3-1213 | V455 Sco | Hen 2-247 |
|-------------|----------|------------|------------|------------|----------|------------|
| T$_{\text{eff}}$[K][2] | 3240 ± 75 | 3300 ± 75 | 3240 ± 75 | 3408 ± 120 | 3170 ± 80 | 3240 ± 75 |
| T$_{\text{eff}}$[K][3] | 3258 | 3312 | 3258 | 3413 | 3203 | 3258 |
| $J - K$[4,5] | 1.42 | 1.27 | 2.09 | 1.37 | 1.62 | 1.61 |
| E(B - V)[6] | 0.19–0.24 | 0.04–0.06 | 0.30–0.35 | 1.08–0.75 | 0.5 |
| $\log g$[7] | <3500 | <3500 | <3500 | <3500 | <3500 | <3500 |
| $T_{\text{eff}}$[K][8] | 3300 | 3300 | 3300 | 4100 | 3200 | 3300 |
| $\log g$[9] | 0.0 | 0.0 | 0.0 | 1.5 | 0.0 | 0.0 |

References: spectral types from [1] Mirset & Schmidt (1999), total Galactic extinction adopted according to [6] Schlafly & Finkbeiner (2011) and Schlegel, Finkbeiner & Davis (1998), infrared colours from 2MASS [4] Phillips (2007) transformed to [5] Bessell & Brett (1988) photometric system.

Calibration by: [2] Richichi et al. (1999), [3] Van Belle et al. (1999), [8] Kucinskas et al. (2005).

$\alpha$: adopted.

Table 3. Quadrature sums of the projected rotational velocities and microturbulence ($V_{\text{rot}}^2 \sin^2 i + \xi_i^2 / \Omega_i^2$) from K-band Ti I, Fe I, and Sc I lines.

| V694 Mon | CD-36°8436 | WRAY 16-202 | Hen 3-1213 | V455 Sco | Hen 2-247 |
|----------|------------|------------|------------|----------|------------|
| 2003 Apr | 8.42 ± 0.99 | 8.38 ± 1.11 | 8.54 ± 1.67 | 7.82 ± 0.59 | 8.62 ± 1.63 | 11.47 ± 1.07 |
| 2003 Aug | – | – | – | 7.60 ± 0.69 | – | 11.29 ± 0.68 |
| 2004 Apr | – | – | – | 7.68 ± 0.41 | 8.65 ± 1.30 | 9.21 ± 1.55 |
| All together $^b$ | 8.42 ± 0.99 | 8.38 ± 1.11 | 8.54 ± 1.67 | 7.70 ± 0.30 | 8.63 ± 0.98 | 10.58 ± 1.05 |

$^a$ Units km s$^{-1}$

$^b$ Used for synthetic spectra calculations

To obtain radial and rotational velocities, we used a cross-correlation technique similar to that adopted by [10] Carlberg et al. (2011) but using synthetic spectra as the templates. The obtained values are presented in Table 3. The rotational velocities were additionally estimated (Table 3) via direct measurement of the FWHM of the six relatively strong unblended atomic lines (Ti I, Fe I, Sc I) present in the K-band region. We used the radial velocities obtained by cross-correlation (Table 3) and rotational velocities obtained from atomic lines in K-band spectra (Table 3) as fixed parameters in our solutions.

The way adopted to perform the abundance solution, in a brief outline, is as 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 microturbulent velocity $\xi_i$ values sampled in the range 1.2–2.8 km/s to obtain best fits to H- and K-band spectra. For three objects (Hen 3-1213, V455 Sco, and Hen 2-247) for which we do not have the $K_r$-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 the other three systems, V694 Mon, CD-36°8436, WRAY 16-202, 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 $K_r$-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 several iterations.
Table 4. Calculated abundances and relative abundances,\(^a\) velocity parameters,\(^b\) and uncertainties\(^c\) for V694 Mon, CD-36\(^{6}\)8436, WRAY 16-202, Hen 3-1213, V455 Sco, and Hen 2-247.

|       | V694 Mon | CD-36\(^{6}\)8436 | WRAY 16-202 |
|-------|----------|-------------------|-------------|
|       | \(X\)    | \([X]\)            | \(X\)       |
| \(^{12}\)C | 8.08 ± 0.13 | -0.35 ± 0.18 | 7.76 ± 0.02 | -0.67 ± 0.07 | 8.05 ± 0.01 | -0.38 ± 0.06 |
| N    | 7.90 ± 0.08 | +0.07 ± 0.13 | 7.91 ± 0.04 | +0.08 ± 0.09 | 8.27 ± 0.03 | +0.44 ± 0.08 |
| O    | 8.42 ± 0.08 | -0.27 ± 0.13 | 8.37 ± 0.02 | -0.32 ± 0.07 | 8.63 ± 0.01 | -0.06 ± 0.06 |
| Sc   | 4.04 ± 0.18 | +0.89 ± 0.23 | 3.66 ± 0.09 | +0.51 ± 0.13 | 4.22 ± 0.16 | +1.07 ± 0.20 |
| Ti   | 4.78 ± 0.25 | -0.17 ± 0.30 | 4.81 ± 0.08 | -0.14 ± 0.13 | 5.25 ± 0.04 | +0.30 ± 0.09 |
| Fe   | 7.08 ± 0.09 | -0.42 ± 0.13 | 7.12 ± 0.03 | -0.38 ± 0.07 | 7.52 ± 0.03 | +0.02 ± 0.07 |
| Ni   | 5.90 ± 0.08 | -0.32 ± 0.12 | 6.13 ± 0.07 | -0.09 ± 0.11 | 6.30 ± 0.06 | +0.08 ± 0.10 |

\(^{12}\)C/\(^{13}\)C | 24 ± 3 | 8 ± 1 | 11 ± 1 |
\(\xi\) | 2.0 ± 0.3 | 2.0 ± 0.2 | 2.1 ± 0.1 |
\(v_{rot}\sin i\) | 8.2 ± 1.0 | 8.1 ± 1.1 | 8.3 ± 1.7 |

\(^a\) 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\(\sigma\).

4 RESULTS

Table 4 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 \(e(X) = \log N(X)/N(H)\) + 12.0. Table 4 also includes values for the \(^{12}\)C/\(^{13}\)C isotopic ratio, microturbulences, \(\xi\), and projected rotational velocities, \(v_{rot}\sin i\). The abundance of scandium is based on only one strong Sc I line at \(\lambda \sim 22272.8\)Å and may be less reliable than other abundances presumably due to the broadening of the infrared scandium lines by hyperfine structure that has not been included in the analysis (see Paper I). The synthetic fits to the observed spectra of CD-36\(^{6}\)8436 are shown in Figures 1 and 2, where the molecular (OH, CO, CN) and atomic (Sc I, Ti I, Fe I, Ni I) lines used in the solution of the chemical composition are identified by ticks. The synthetic fits to the observed spectra of the other systems, V694 Mon, WRAY 16-202, Hen 3-1213, V455 Sco, and Hen 2-247, in \(H\) - and \(K\)-band regions, and in \(K\)-band region for V694 Mon, and WRAY 16-202 are shown in Figures 3 and 4 in the online Appendix A.

We also made fits with MARCS atmosphere models varying the effective temperatures by ±100 K, log \(g\) by ±0.5, and the microturbulence \(\xi\) by ±0.5 to estimate the sensitivity of abundances to uncertainties in stellar parameters. In the case of CD-36\(^{6}\)8436, V455 Sco, and Hen 2-247 additional fits were also made using...
models with [Fe/H] different by ±0.25. The changes in the abundance for each element as a function of each model parameter obtained for M-type giants are listed at the top of Table 5. For the yellow symbiotic Hen 3-1213 these dependences are significantly different and are shown separately at the bottom of Table 5. Uncertainties in the stellar parameters have a stronger impact on the uncertainty of the derived chemical composition than the uncertainties from fitting the synthetic spectrum.

5 DISCUSSION

Here, we present the first analysis of the photospheric chemical abundances (CNO and elements around the iron peak: Sc, Ti, Fe, and Ni) for six classical S-type symbiotic systems: five with M-type giant (V694 Mon, CD-36°8436, WRAY 16-202, V455 Sco, and Hen 2-247), and one yellow-type symbiotic system (Hen 3-1213). We obtained wide range of metallicities: from slightly super-solar for V455 Sco ([Fe/H]~ +0.3 dex), near solar in two cases of WRAY 16-202 and Hen 2-247, slightly sub-solar in V694 Mon and CD-36°8436 ([Fe/H]~ −0.4 dex), and significantly sub-solar in the case of Hen 3-1213 ([Fe/H]~ −0.8 dex). 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 metal abundances in Hen 3-1213 were also studied by Pereira & Roig (2009). They find log ε(Fe) = 6.59 ± 0.16, log ε(Ni) = 5.38 ± 0.15, and log ε(Ti) = 4.68. Their values are lower by ~0.2 dex than ours, but within uncertainties of these estimates. Taking into account that our adopted log g = 1.5 is higher than the log g = 1.1 adopted by Pereira & Roig (2009), and given the sensitivity of Fe, Ni, and Ti abundances to log g (Table 5), the agreement between our results is even better, in the case of iron almost perfect to the hundreds of dex. The ratios of 12C/13C ~ 8 and 11 obtained for CD-36°8436 and WRAY 16-202, respectively, are very similar to the values of 12C/13C ~ 6, 10, and 8 derived for RW Hya, SY Mus (Paper I) and BX Mon (Paper II). The CNO values and isotopic ratios indicate that the red giants in these systems have experienced the first dredge-up.

Some of the symbiotic giant abundances can be used to address evolutionary status and to associate the symbiotic binaries with their parent populations in the Milky Way. The absolute and relative abundances adopted for comparison with Galactic stellar populations are shown for comparison at the bottom of Table 4. This is also confirmed by the low 12C/13C isotopic ratios for those stars with measured values. The system V694 Mon is less elevated compared to other Galactic symbiotic stars.

Table 4 - The $K_c$ band spectrum of CD-36°8436 observed 2006 April (blue line) and a synthetic spectrum (red line) calculated using the final abundances and $^{12}$C/$^{13}$C isotopic ratio (Table 3).

Figure 3 - The $K_c$ band spectrum of CD-36°8436 observed 2006 April (blue line) and a synthetic spectrum (red line) calculated using the final abundances and $^{12}$C/$^{13}$C isotopic ratio (Table 3).
in the log $N$–log $C$ plane like CH Cyg and both these systems have larger $^{12}$C/$^{13}$C ratios, ~24 and 18 respectively. We would expect a somewhat increased $^{12}$C/$^{13}$C ratio with regard to the symbiotic sample for Hen 3-1213 given its position in Fig. 4. Unfortunately the $^{12}$C/$^{13}$C ratio has never been measured for this system.

We can thus assume, as did Cunha & Smith (2006) for their sample of the bulge giants, that the O and Fe and other elemental abundances roughly represent the values with which the symbiotic stars were born. These abundances can then be used to identify the parent Galactic population. The ratio of $\alpha$-elements (e.g. O and Ti in our study) to Fe is of particular importance because the $\alpha$-elements originate mostly from massive stars and SNe II. $\alpha$-elements are produced over relatively short time-scales whereas Fe is most effectively produced in SNe Ia over much longer time-scales. Thus, differences in contamination by SNe II and SNe Ia lead to significantly different trends for particular populations. Clear separation results in the [O/Fe] and/or [Ti/Fe] versus [Fe/H] plane (e.g. Cunha & Smith 2006, Bensby & Feltzing 2006).

Figures 5 and 6 show [O/Fe] and [Ti/Fe], respectively, versus [Fe/H] for the symbiotic giants along with the values for various stellar populations taken from a number of studies (Gratton & Sneden 1988, Edvardsson et al. 1992, McWilliam et al. 1995, Fulbright 2000, Prochaska, Nair & Carney 2000, Melendez, Barbuy & Snite 2001, Smith, Pereira & Cunha 2001, Boyarchuk et al. 2001, Melendez & Barbu 2002, Johnson 2003, Fulbright & Johnson 2003, Reddy et al. 2003, Rich & Origlia 2005, Bensby et al. 2005, Cunha & Smith 2006, Alves-Brito et al. 2010, Bensby et al. 2011, Ryde et al. 2010, Rich, Origlia & Valenti 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. The 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, Origlia & Valenti 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 through the bulge Cunha & Smith 2006, Alves-Brito et al. 2010, Ryde et al. 2010 and is more representative for the whole bulge population.

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 of the objects studied here in the planes [O/Fe]–[Fe/H] and [Ti/Fe]–[Fe/H] can be related to membership in Galactic populations. Most appear to belong to the Galactic disc or bulge while the position of RW Hya and Hen 3-1213 supports their membership in the extended thick-disc/halo population. Pereira & Roig (2009) based on their analysis of four yellow symbiotic systems, including Hen 3-1213, concluded that the general abundance pattern follows the halo standard abundances. In the [Ti/Fe]–[Fe/H] plane (Figure 5) our M-type giants are elevated towards higher [Ti/Fe] into the region occupied mainly by thick-disc and bulge stars. The only yellow symbiotic in our sample, Hen 3-1213, shows even higher [Ti/Fe]. Similar enhancement of [Ti/Fe] was found by Pereira & Roig (2009) for all yellow symbiotic giants studied by them and other authors. They also noticed that the other $\alpha$-elements to Fe are typical of halo giant stars of the same metallicity. We used
the published [Ti/Fe] values for AG Dra (Smith et al. 1996), BD-21°3873 (Smith et al. 1997), Hen 2-467 (Pereira et al. 1999a, CD+43°14304, Hen 3-863, StHz 176, and Hen 3-1213 (Pereira & Rondi 2009) to plot their positions in Figure 6. This plot demonstrates that this Ti-anomaly shows increasing trend with decreasing metallicity. The reason of such high Ti abundance in symbiotic giants is not known. However, our present results indicate that this anomaly is present in both red, i.e. M-type giants, and yellow symbiotic systems, which strongly suggest that this is a genuine characteristic of the giants in S-type symbiotic systems.

Paper II addressed the important issue related to the microturbulence. This parameter is difficult to determine but its value has a strong influence on the derived abundances. In Paper II, two solutions were considered: (i) microturbulent velocity as a free parameter and (ii) microturbulence as a fixed parameter where with its value estimated from the relationship between the microturbulence and the red giant bolometric magnitude (Smith et al. 2002). In the case (i), we obtained the microturbulence values of ~2.0 with a dispersion ~0.3, while in the case (ii) the microturbulences were larger by several tenths of dex and the resulted abundances were shifted towards lower metallicities by ~0.2 dex. To decide which approach produces the most reliable results we compared the results obtained using both methods for all the systems that we have analysed so far (see Appendix B for details). In our opinion, this comparative study shows that using the microturbulence as a free parameter is a superior analysis technique.

In the process of fitting the synthetic spectra we measured radial and rotational velocities for the programme stars (Tables I and E). Radial velocities obtained using cross-correlation techniques for V455 Sco and Hen 2-247 are consistent with recent spectroscopic orbits published for these stars by Fekel et al. (2008). In the case of V455 Sco, the individual radial velocities derived from the same spectra by Fekel et al. (2008) and here differ by ~2.1 +1.1 km s⁻¹. These discrepancies are likely due to differences in methods of measurement. Different templates were used and different spectral ranges were cross-correlated. Residuals from the synthetic orbit calculated by Fekel et al. (2008) have values between ~2.1 and +3.3 km s⁻¹. Similarly the radial velocities obtained for Hen 2-247 agree with synthetic radial velocities predicted from the orbit of Fekel et al. (2008) with an accuracy generally better than ~2.0 +1.5 km s⁻¹ and O–C residuals from the synthetic orbit are in the range ~2.2 +0.9 km s⁻¹. For the other four systems studied in this paper, there are no published spectroscopic orbits in the literature.

Giants in symbiotic stars are characterized with large rotational velocities. In the systems analysed so far by us $V_{rot} \sin i$ makes the largest contribution to the physical line broadening. The rotational velocities obtained with the cross-correlation method generally have smaller values than those obtained with FWHM method (Table I and E). 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 the resulting final values of the rotational velocities and abundances (Paper I). Therefore, our analysis used velocities obtained with FWHM method. This gives results consistent with those obtained from the same spectra by cross-correlation.

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 components of the S-type symbiotic binaries: V694 Mon, CD-36°8436, WRAY 16-202, Hen 3-1213, V455 Sco, and Hen 2-247. Our analysis revealed metallicities distributed in a wide range from slightly super-solar for V455 Sco ([Fe/H]~+0.3 dex), near solar for WRAY 16-202 and Hen 2-247, slightly sub-solar for V694 Mon and CD-36°8436 ([Fe/H]~−0.4 dex), and significantly sub-solar for Hen 3-1213 ([Fe/H]~−0.8 dex). The enrichment in $^{14}$N isotope obtained for all these objects indicates that the giants have experienced the first dredge-up. This is also confirmed by the low $^{12}$C/$^{13}$C isotopic ratios of ~24, 8, and 11 for V694 Mon, CD-36°8436, and WRAY 16-202, respectively. We also found large [Ti/Fe] in both red and yellow symbiotic giants suggesting that this is a characteristic of the giants in S-type symbiotic systems.

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REFERENCES

Alves-Brito A., Meléndez J., Asplund M., Ramírez I., Yong D., 2010, A&A, 513, 35
Asplund M., Grevesse N., Sauval A., Scott P., 2009, ARA&A 47, 481
Bensby T., Feltzing S., Lundström I., Ilyin I., 2005, A&A, 433, 185
Bensby T., Feltzing S., 2006, MNRAS, 367, 1181
Bensby T., Alves-Brito A., Oey M. S., Yong, D., Meléndez, J., 2011, ApJ, 735, 46
Bessell M. S., Brett J. M., 1988, PASP, 100, 1134
Boyarchuk A. A., Antipova L. I., Boyarchuk M. E., Savanov I. S., 2001, Astr. Rep., 45, 301
Brandt S., 1998, Data Analysis, Statistical and Computational Methods, Polish edition. Polish Scientific Publishers PWN, Warsaw
Carlberg J. K., Majewski S. R., Patterson R. J., Bizyaev D., Smith V. V., Cunha K., 2011, ApJ, 732, 39
Cunha K., Smith V. V., 2006, ApJ, 651, 491
Dumm T., Schild H., 1998, New Astronomy, 3,137
Edvardsson B., Andersen J., Gustafsson B., Lambert D. L., Nissen P. E., Tomkin J., 1993, A&A, 275, 101
Fekel, F.C., Hinkle, H. K., Joyce, R. R., 2003, in Corradi R. L. M., Mikolajewska R., Mahoney T. J., eds, ASP Conf. Ser. Vol. 303, Symbiotic Stars Probing Stellar Evolution. Astron. Soc. Pac., San Francisco, p. 113
APPENDIX A: OBSERVED AND SYNTHETIC SPECTRA OF V694 MON, WRAY 16-202, HEN 3-1213, V455 SCO, AND HEN 2-247
Figure A1. The \( H \) band spectrum of V694 Mon observed 2003 February (blue line) and a synthetic spectrum (red line) calculated using the final abundances and \(^{12}\text{C}/^{13}\text{C} \) isotopic ratio (Table 4).

Figure A2. The \( K \) band spectrum of V694 Mon observed 2003 April (blue line) and a synthetic spectrum (red line) calculated using the final abundances and \(^{12}\text{C}/^{13}\text{C} \) isotopic ratio (Table 4).

Figure A3. The \( K_r \) band spectrum of V694 Mon observed 2006 April (blue line) and a synthetic spectrum (red line) calculated using the final abundances and \(^{12}\text{C}/^{13}\text{C} \) isotopic ratio (Table 4).

Figure A4. The \( H \) band spectrum of WRAY 16-202 observed 2003 February (blue line) and a synthetic spectrum (red line) calculated using the final abundances and \(^{12}\text{C}/^{13}\text{C} \) isotopic ratio (Table 4).

Figure A5. The \( K \) band spectrum of WRAY 16-202 observed 2003 April (blue line) and a synthetic spectrum (red line) calculated using the final abundances and \(^{12}\text{C}/^{13}\text{C} \) isotopic ratio (Table 4).

Figure A6. The \( K_r \) band spectrum of WRAY 16-202 observed 2006 April (blue line) and a synthetic spectrum (red line) calculated using the final abundances and \(^{12}\text{C}/^{13}\text{C} \) isotopic ratio (Table 4).
**Figure A7.** The \( H \) band spectrum of Hen 3-1213 observed 2003 February (blue line) and a synthetic spectrum (red line) calculated using the final abundances (Table 4).

**Figure A8.** \( K \) band spectra of Hen 3-1213 observed 2003 April (blue line), 2003 August (green line), and 2004 April (dark-orange line) and a synthetic spectrum (red line) calculated using the final abundances (Table 4).

**Figure A9.** The \( H \) band spectrum of V455 Sco observed 2003 February (blue line) and a synthetic spectrum (red line) calculated using the final abundances (Table 4).

**Figure A10.** \( K \) band spectra of V455 Sco observed 2003 April (blue line) and 2004 April (green line) and a synthetic spectrum (red line) calculated using the final abundances (Table 4).

**Figure A11.** The \( H \) band spectrum of Hen 2-247 observed 2003 February (blue line) and a synthetic spectrum (red line) calculated using the final abundances (Table 4).

**Figure A12.** \( K \) band spectra of Hen 2-247 observed 2003 April (blue line), 2003 August (green line), and 2004 April (dark-orange line) and a synthetic spectrum (red line) calculated using the final abundances (Table 4).
APPENDIX B: ESTIMATION OF THE MICROTURBULENCE: A COMPARISON OF THE ADOPTED METHODS

To decide which microturbulence analysis gives the most reliable results we compare results obtained by using both methods for those objects discussed in this series of papers that have spectra in $H$-, $K$-, and $K_r$-bands. The symbiotic systems observed in all three bands are V694 Mon, CD-36°8436, and WRAY 16-202 (this work), BX Mon (Paper II), RW Hya, and SY Mus (Paper I). The results obtained in the case of fixed microturbulence (ii) are summarized at the top of Table B1. The quality of fit resulting from the two methods, with (i) fixed and (ii) free microturbulent velocity, are compared at the bottom. We define the quality of the fit, $Y_{band}$, as the function of $\chi^2$

$$Y_{band} = \sqrt{\frac{\sum \chi^2}{N_i}} = \sqrt{\frac{\sum (x_0 - x_i)^2}{N_i}}$$

(B1)

where $(x_0 - x_i)$ are O–C residuals for each point of the observed spectrum, and $N_i$ is the total number of the points used. Smaller $Y_{H,K}$, corresponding to a better fit, resulted in all cases when microturbulent velocity was treated as free parameter and using the combined $H$- and $K$-band spectra. This, however, probably reflects the larger number of free parameters. Nevertheless, even in the case of $K_r$-band spectrum for which the elemental abundances and the microturbulence were adopted from the solution based on the $H$- and $K$-band spectra the $Y_{K_r}$ values are lower when the method with free microturbulence was used. Microturbulent velocities are commonly determined by requiring that abundances resulting from individual lines of the same species but with differing line strengths be independent of the equivalent widths (e.g. Smith et al. 2002; Schmidt et al. 2006). We do not have enough unblended lines of the same species with different intensities to use this method. Instead we use all the species together making use of the fact that the spectra cover a wide spectral range which makes our approach sensitive to the microturbulence. The values $\xi_t \sim 2.0$ obtained with this method are typical for cool Galactic red giants (Smith & Lambert 1985, 1986, 1990). Summarizing, we find our results obtained with the microturbulent velocity as a free parameter to be more reliable.

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Table B1. Calculated abundances and relative abundances, $^{12}$C/$^{13}$C isotopic ratios, velocity parameters, and uncertainties for V694 Mon, CD-36°8436, WRAY 16-202, BX Mon, RW Hya, and SY Mus, in the case of fixed microturbulences estimated based on bolometric magnitudes. The quality of fit $Y_{HK}$ and $Y_{K}$ obtained with (i) fixed and (ii) free microturbulent velocity parameters are compared at the bottom.

|       | V694 Mon |       | CD-36°8436 |       | WRAY 16-202 |
|-------|----------|-------|------------|-------|------------|
|       | log $\epsilon(X)$ | [X] | log $\epsilon(X)$ | [X] | log $\epsilon(X)$ | [X] |
| $^{12}$C | 7.90±0.02 | -0.53±0.07 | 7.69±0.01 | -0.74±0.06 | 8.01±0.01 | -0.42±0.06 |
| N     | 7.67±0.06 | -0.16±0.11 | 7.76±0.04 | -0.07±0.09 | 8.19±0.03 | -0.36±0.08 |
| O     | 8.18±0.01 | -0.51±0.06 | 8.21±0.02 | -0.48±0.07 | 8.57±0.02 | -0.12±0.07 |
| Sc    | 3.23±0.14 | 0.08±0.18 | 3.25±0.08 | +0.10±0.12 | 3.86±0.11 | +0.71±0.15 |
| Ti    | 4.11±0.11 | -0.84±0.16 | 4.45±0.10 | -0.50±0.15 | 4.93±0.04 | -0.02±0.09 |
| Fe    | 6.83±0.07 | -0.67±0.11 | 6.98±0.05 | -0.52±0.09 | 7.44±0.04 | -0.06±0.08 |
| Ni    | 5.67±0.10 | -0.55±0.14 | 5.98±0.14 | -0.24±0.18 | 6.18±0.08 | -0.04±0.12 |
|       |          |       |            |       |            |       |
| $^{12}$C/$^{13}$C | 34±3 | 10±1 | 13±1 |
| Sp. Type $^{[1]}$ | M6 | M5.5 | M6 |
| $M_{bol}$ | -4.9$^d$ | -3.5$^c$ | -3.5$^c$ |
| $\xi$ | 2.8 | -2.4 | ~2.4 |
| $V_{rot} \sin i$ | 7.9±1.1 | 8.0±1.2 | 8.2±1.8 |

fixed microturbulence

|       | Y_{HK} |       | Y_{K} |       |       |
|-------|--------|-------|-------|-------|-------|
|       | 0.04196 | 0.02705 | 0.03204 |
|       | 0.08700 | 0.05191 | 0.06012 |

free microturbulence

|       | Y_{HK} |       | Y_{K} |       |       |
|-------|--------|-------|-------|-------|-------|
|       | 0.04060 | 0.02682 | 0.03160 |
|       | 0.06850 | 0.04759 | 0.06190 |

|       |       |       |       |       |       |       |
|-------|-------|-------|-------|-------|-------|-------|
|       | BX Mon | RW Hya | SY Mus |
|       | log $\epsilon(X)$ | [X] | log $\epsilon(X)$ | [X] | log $\epsilon(X)$ | [X] |
| $^{12}$C | 7.66±0.02 | -0.77±0.07 | 7.44±0.03 | -0.99±0.08 | 8.02±0.04 | -0.41±0.09 |
| N     | 7.65±0.05 | -0.18±0.10 | 7.22±0.07 | -0.61±0.12 | 7.97±0.14 | +0.14±0.19 |
| O     | 8.14±0.01 | -0.55±0.06 | 7.94±0.03 | -0.75±0.08 | 8.45±0.04 | -0.24±0.09 |
| Sc    | 3.15±0.20 | 0.00±0.24 | 2.51±0.08 | -0.64±0.12 | 3.57±0.09 | +0.42±0.13 |
| Ti    | 4.33±0.06 | -0.62±0.11 | 4.04±0.03 | -0.91±0.08 | 4.71±0.02 | -0.24±0.07 |
| Fe    | 6.95±0.03 | -0.55±0.07 | 6.52±0.04 | -0.98±0.08 | 7.27±0.05 | -0.23±0.09 |
| Ni    | 5.93±0.08 | -0.29±0.12 | 5.49±0.09 | -0.73±0.13 | 6.21±0.09 | -0.01±0.13 |
|       |          |       |            |       |            |       |
| $^{12}$C/$^{13}$C | 12±2 | 7±1 | 10.5±1 |
| Sp. Type $^{[1]}$ | M5 | M2 | M5 |
| $M_{bol}$ | -3.6$^d$ | -4.1$^d$ | -3.5$^c$ |
| $\xi$ | 2.5 | -2.6 | ~2.4 |
| $V_{rot} \sin i$ | 8.3±1.5 | 6.0±1.1 | 6.5±0.7 |

fixed microturbulence

|       | Y_{HK} |       | Y_{K} |       |       |
|-------|--------|-------|-------|-------|-------|
|       | 0.02475 | 0.01761 | 0.02475 |
|       | 0.06300 | 0.04629 | 0.04949 |

free microturbulence

|       | Y_{HK} |       | Y_{K} |       |       |
|-------|--------|-------|-------|-------|-------|
|       | 0.02351$^f$ | 0.01639$^f$ | 0.02444$^f$ |
|       | 0.06099$^f$ | 0.03526$^e$ | 0.04889$^e$ |

References: spectral types are from $^{[1]}$Müser & Schmidt (1999).

$^a$ Relative to the Sun [X] abundances estimated in relation to the solar composition of Asplund et al. (2009).

$^b$ Units km s$^{-1}$

$^c$ 3σ

$^d$ based on known radii and/or pulsation properties.

$^e$ upper estimation based on spectral type.

$^f$ Paper II

$^g$ Paper I