Elemental abundances of the supergiant stars $\sigma$ Cygnus and $\eta$ Leonis

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Abstract

This study aims to analyse the elemental abundances for the late B type supergiant star $\sigma$ Cyg and the early A-type supergiant $\eta$ Leo using ATLAS9 (Kurucz, 1995; Sbordone et al., 2004), assuming local thermodynamic equilibrium (LTE). The spectra used in this study are obtained from Dominion Astrophysical Observatory and have high resolution and signal-to-noise ratios. The effective temperature and the surface gravity of $\sigma$ Cyg are determined from the ionisation equilibria of Al I/II, Mg I/II, Fe I/II, Fe II/III, and by fitting to the wings of H$_\gamma$ and H$_\beta$ profiles as $T_{\text{eff}} = 10388$ K and log $g = 1.80$. The elemental abundances of $\eta$ Leo are determined using $T_{\text{eff}} = 9600$ K and log $g = 2.00$, as reported by Przybilla et al. (2006).

The ionisation equilibria of C I/II, N I/II, Mg I/II, Ca I/II, Cr I/II and Fe I/II/III are also satisfied in the atmosphere of $\eta$ Leo. The radial velocities of $\sigma$ Cyg and $\eta$ Leo are $-7.25\pm7.57$ km s$^{-1}$ and $10.40\pm13.37$ km s$^{-1}$, respectively. The derived projected rotational velocities $v_{\text{sin}}i$ from synthetic spectra are 27 and 2 km s$^{-1}$ for both stars, respectively. The macroturbulent velocities ($\zeta$) are $24\pm2$ km s$^{-1}$ and $14.5\pm1.5$ km s$^{-1}$. Also, the microturbulent velocities ($\xi$)

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have been determined for both of stars as 3.5 km s\(^{-1}\). The CNO abundance results of \(\sigma\) Cyg and \(\eta\) Leo show C deficiency, N overabundance and O in excess.

**Keywords:** stars: supergiants - stars: individuals: \((\sigma\) Cyg, \(\eta\) Leo) - stars: abundances - technique: spectroscopic

### 1. Introduction

Late B and early A-type supergiants (hereafter-SGs) are visually luminous stars in our galaxy and other galaxies. Therefore, they are suitable candidates for further study. BA-SGs have been previously studied by many authors.

The comprehensive study of Groth (1961) was the first study reporting the temperature and chemical abundances of \(\alpha\) Cyg. Aydin (1972) presented the microturbulent velocities of some elements and gave atmospheric parameters of \(\alpha\) Cyg. Further studies of SGs located in the Milky Way and the Magellanic Clouds were conducted by Przybylski (1968, 1971, 1972) and Wolf (1972, 1973). Wolf (1971), Lambert & Hinkle (1988) and Lobel et al. (1992) studied the optical region of \(\eta\) Leo using LTE methods and calculated the elemental abundances.

More recently, the chemical abundances of over twenty Galactic A-type SGs were calculated using progressed model atmospheres by Venn (1995a,b) and Aufdenberg et al. (2002). Subsequently, Przybilla et al. (2000) used very detailed nLTE line formation calculations to determine atmospheric parameters and elemental abundances (see also Przybilla et al. 2000, 2001a,b; Przybilla & Butler 2001). The chemical abundances of A-type SGs in many Local Group galaxies such as the, SMC (Venn 1999), M33 (McCarthy et al. 1995), M31 (Venn et al. 2000), NGC 6822 (Venn et al. 2001), WLM (Venn et al. 2003) and Sextans A (Kaufer et al. 2004) also provide important clues about the chemical compositions of other galaxies. The quantitative spectroscopy of
A-type SGs, beyond the Local Group Galaxies such as those located in NGC 3621 and NGC 300 were also presented (Bresolin et al., 2001, 2002). Further, the possibility of the quantitative analysis of supergiants in Virgo cluster using the present generation of telescopes and new model atmospheres were firstly reported by Kudritzki et al. (1995) and Kudritzki (1998).

Spectral analysis of a prototype, A-type SG, α Cyg was performed by Albayrak (2000) in LTE. Aufdenberg et al. (2002) obtained the fundamental parameters and the mass loss rate of α Cyg using PHOENIX, which computes line blanketed, nLTE atmospheric structures and synthetic spectra with winds. Tanriverdi et al. (2004) determined preliminary abundance results of η Leo in LTE using ATLAS9. Yüce (2005) gave the elemental abundances of a late B and early A-type SGs (4 Lac and ν Cep). Schiller & Przybilla (2008) presented nLTE elemental abundances of α Cyg in detail in a recent study. Markova & Puls (2008) also investigated early and late B-type SGs. Recently, Przybilla et al. (2010) reported CNO abundances of more than ten BA-type SGs in our Galaxy. Additionally, the spectral atlas of O9-A1.5-type SGs (Chentsov & Sarkisyan, 2007) and Deneb (Albayrak et al., 2003) has been published recently.

The chemical analysis of late B and early A-type SGs are important in many respects, which are discussed below:

Their spectra are clear and exhibit a wide variety of chemical species including light elements (H, B, CNO), alpha elements (Mg, Si, S, Ca), iron-group elements (Sc, Ti, Cr, Mn, Fe, Ni) and s-process elements (Sr, Zr, Ba) (Przybilla, 2002, Przybilla et al., 2006, Venn et al., 1998). Because the absorption lines of both α process and iron group elements are present in their spectra, A-type SGs are important for the determination of reliable [α/Fe] ratios (see Venn et al., 2003).
Another reason is that they are the visually brightest stars in our galaxy and other galaxies. This characteristic makes them potential candidates for use in determining distances using their wind momentum - luminosity relation (hereafter WLR) \cite{Puls1996, Kudritzki1999} and flux-weighted gravity-luminosity relation (hereafter FGLR) \cite{Kudritzki2003, Kudritzki2003a}.

Notably, \cite{Weiss2008} declared that "The results of nucleosynthesis in stars depend both on the conditions inside the star (temperature, density and chemical composition) and on the nuclear reaction rates. The accurate determination of elemental abundances therefore helps us to determine the interior stellar conditions, and properties of nuclei that are otherwise inaccessible." The elemental abundances of He, C, N, and O (C/N and N/O ratios) constitute an opportunity to test models of non-rotating \cite{Schaller1992}, as well as rotating and non-rotating models with mass loss \cite{Ekstrom2012}.

The main goal of this study is to present the elemental abundances of σ Cyg and η Leo in LTE approximation. The suitability of ATLAS9 model atmospheres for low luminosity SGs was shown by \cite{Przybilla2002} and mentioned by \cite{Kaufer2004}.

1.1. σ Cyg and η Leo

σ Cyg (HD202850, HIP 105102, SAO 71155) is a member of the Cyg OB4 association \cite{Humphreys1978}. The galactic latitude and longitude of σ Cyg are \(l = 84.1943\) and \(b = -06.8723\) respectively. It is classified as B9 Iab \cite{Morgan1953}.

η Leo (HD 87737, HIP 49583, SAO 98955) is an MK Standard and classified as A0 Ib \cite{Morgan1950}. It is one of the brightest stars in the southern sky in the visual region of the spectrum. η Leo is also a field star \cite{Blaha1989} with the galactic coordinates \(l = 219.5301\) \(b = -


The photometric variability of η Leo was determined to be 0.′′06 by Adelman & Albayrak (2001). The magnetic field of η Leo was given by Bychkov et al. (2003) as 102.5 ± 59 Gauss. The UV spectrum of η Leo was analysed by Kondo et al. (1976), Lamers et al. (1978) and Praderie et al. (1980). The mass loss rate was calculated by Kondo et al. (1976) from the resonance lines of Mg II lines and by Barlow & Cohen (1977) from the infrared excess as $3 \times 10^{-10} \, M_\odot \, yr^{-1}$ and $4.7 \times 10^{-8} \, M_\odot \, yr^{-1}$, respectively.

The effective temperature ($T_{\text{eff}}$), surface gravity (log $g$ in cgs.), microturbulence ($\xi$) and macroturbulent velocity ($\zeta$) of σ Cyg and η Leo which have been previously determined by many authors are summarised in Table 1 with the methods they used.

| Source                  | $T_{\text{eff}}$ in K | log $g$ | $\xi$ in km s$^{-1}$ | $\zeta$ in km s$^{-1}$ | Method                                                                 |
|-------------------------|-----------------------|--------|-----------------------|------------------------|------------------------------------------------------------------------|
| σ Cyg                   |                       |        |                       |                        |                                                                        |
| Przybilla et al. (2010) | 10800 ± 200           | 1.85 ± 0.10 | 6 ± 1                 | 35                     | H, He lines, ionisation equilibria, SED                                 |
| Markova & Puls (2008)   | 11000 ± 500           | 1.85    | 7                     | 33                     | Balmer lines, SiII/SiIII                                               |
| Odegard & Cassinelli (1982) | 10800             | –       | –                     | –                      |                                                                        |
| Ivanova & Lyubimkov (1988) | 11500 ± 250      | 1.80 ± 0.2 | 8.5 ± 1               | –                      | Hγ, Hδ spectrophotometry, $[c_1]$ index                              |
| η Leo                   |                       |        |                       |                        |                                                                        |
| Cenarro et al. (2007)   | 9730 ± 150            | 1.97    | 4 ± 1                 | –                      |                                                                        |
| Przybilla et al. (2006) | 9600 ± 150            | 2.00 ± 0.15 | 4 ± 1               | 16 ± 2                | Balmer lines, nLTE Mg I/II spectrophotometry                           |
| Venn (1995a)            | 9700 ± 200            | 2.00 ± 0.2 | 4                     | –                      | Hγ, nLTE Mg I/II                                                      |
| Lobel et al. (1992)     | 10200 ± 370           | 1.9 ± 0.4 | 5.4 ± 0.7             | –                      | LTE Fe I/II                                                            |
| Lambert & Hinkle (1988) | 10500                | 2.20    | 3                     | –                      | Hδ, Strömgren photometry                                              |
| Wolf (1971)             | 10400 ± 300           | 2.00 ± 0.20 | 2-10               | –                      | Hβ, Hγ, Hδ, Balmer jump, LTE Mg I/II, FeI/II                           |

2. The Spectra

The spectra of σ Cyg (17 spectrograms) and η Leo (17 spectrograms) were obtained at DAO (Dominion Astrophysical Observatory) by Dr. Saul J. Adelman. The wavelength coverages of the spectra are approximately λλ3830-5210
and, $\lambda\lambda$5580-6740 for $\sigma$ Cyg and $\lambda\lambda$3800-6680 and, 6610-6740 for $\eta$ Leo. The reciprocal line dispersions of the spectra are 2.4 Å mm$^{-1}$ for, $\lambda < 6500$ Å and 4.8 Å mm$^{-1}$ for, $\lambda > 6500$ Å, for the SITe-2 and SITe-4 detectors, respectively. Pixel-to-pixel resolution is 0.072 Å, and the corresponding resolving power at 4500 Å is $R = 62500$. The signal-to-noise ratios (S/N) of the spectra are approximately 200-300. The spectra were rectified using the interactive graphical program REDUCE (Hill & Fisher, 1986) and line measurements were made using the graphical interface program VLINE (Hill & Fisher, 1986). The scattered light was corrected with CCDSPEC (Gulliver & Hill, 2002).

The projected rotational velocities of $\sigma$ Cyg and $\eta$ Leo were determined from medium-strength lines to be 22.5 km s$^{-1}$ and 8.5 km s$^{-1}$, respectively. These values were used in VLINE as preliminary values for $\text{vsini}$ during measurements of the equivalent widths (EW) of spectral lines.

A Multiplet Table of Astrophysical Interest (Moore, 1945) was the main source of line identifications. Other sources used included Pettersson (1983) for S II, Huldt et al. (1982) for Ti II, Iglesias et al. (1988) for V II, Kiess (1953) for Cr I, Kiess (1951) for Cr II, Catalan et al. (1964) for Mn I, Iglesias & Velasco (1964) for Mn II, Nave et al. (1994) for Fe I, Dworetsky (1971) and Johansson (1978) for Fe II, Varshni (1979) for Fe III, Nilsson et al. (1991) for Y II, and Meggers, Corliss & Scribner (1975) for singly ionised rare earth species. Previous studies of these types of stars were also used in the line identification (see Albayrak et al. 2003; Gulliver et al. 2004; Yüce 2005; Chentsov & Sarkisyan 2007). Both the identified stellar lines and the calculated abundances in the spectra are given in Table 4.

After heliocentric corrections for target stars, the radial velocities (hereafter -RV) were derived by comparing the stellar and laboratory wavelengths. The mean RV of $\sigma$ Cyg was found to be -7.25±7.57 km s$^{-1}$ with amplitude of 24.28
Figure 1: The observed (black lines) H$_{\gamma}$ and H$_{\beta}$ profile with the synthetic fits (grey line) for $\sigma$ Cyg at $T_{\text{eff}} = 10388$ K and log $g = 1.80$.

However, the amplitude of the RV in the atmospheres of $\sigma$ Cyg is closer to the macroturbulent velocity ($24 \pm 2$ km s$^{-1}$) as in the case of other BA SGs (Deneb, 4 Lac and $\nu$ Cep). The radial velocity of $\eta$ Leo is $10.40 \pm 13.37$ km s$^{-1}$ with amplitude of $33.31$ km s$^{-1}$. Previous studies have shown that the radial velocities of the SGs can be attributed to radial and non-radial pulsations (Kaufer et al., 1997) or to a close or unresolved companion (see Przybilla, 2002). However, this case is not valid for $\eta$ Leo due to the obtained RV amplitude. Values given in the literature for the radial velocity of $\eta$ Leo include, $2.6 \pm 0.7$ km s$^{-1}$ (van Hoof et al., 1963), $1.6 \pm 3.1$ km s$^{-1}$ (Abt, 1970) and $1.4 \pm 0.4$ km s$^{-1}$ (Gontcharov, 2006). Therefore, the result implies that there is no evidence for the binarity of $\eta$ Leo as mentioned by Blazit et al. (1977).

3. Stellar Parameters

The wings of Balmer lines are sensitive to both the effective temperature and gravity. The predicted synthetic profiles of H$_{\gamma}$ and H$_{\beta}$ are reproduced using SYNTHE (Kurucz & Avrett, 1981) and matched with observations for several temperature-gravity pairs (Figure 1) until a consistent fit is found. In
Figure 2: A comparison of observed and computed fluxes ($T_{\text{eff}} = 10388$, log $g = 1.80$) for $\sigma$ Cyg; ATLAS9 model flux (dashed grey line), ATLAS9 reddened model flux (black line), IUE spectra (grey line), the spectrophotometric data of Kharitonov et al. (1988) (dotted line) and the photometric data (with squares).

In this study, ATLAS9 (Kurucz 1995; Sbordone et al. 2004) is used assuming hydrostatic equilibrium, plane parallel geometry and LTE (local thermodynamic equilibrium) with solar metallicity [Fe/H = 0.0] and 4 km s$^{-1}$ microturbulent velocity. ATLAS9 models also include a very detailed line blanketing and important opacity sources (Kurucz 1993).

Another locus of temperature-gravity parameter pairs can be determined using ionisation equilibria in which equal abundances are derived from any consecutive ionic state. In this study, the ionisation equilibria are calculated for neutral and singly ionised species such as; Mg I/II, Al I/II and Fe I/II. In the case of $\sigma$ Cyg, the abundance differences between the consecutive ionisation of Mg I/II, Al I/II, Fe I/II and Fe II/III are found to be of 0.11, 0.02, 0.12 and 0.01 dex, respectively.

Theoretical fits to the wings of Balmer lines and LTE ionisation equilibrium loci give the effective temperature $T_{\text{eff}} = 10388 \pm 197$ K and surface gravity
log $g = 1.80 \pm 0.14$ dex for $\sigma$ Cyg using the Kiel diagram (see Figure 3). $T_{\text{eff}} = 9600 \pm 150$ K and log $g = 2.00 \pm 0.15$ are used for $\eta$ Leo (Przybilla et al., 2006). Moreover, the C I/II, N I/II, Mg I/II, Ca I/II, Cr I/II and Fe I/II/III ionisation equilibria are satisfied for $\eta$ Leo, see Table 2.

The angular diameter of $\sigma$ Cyg was given as 0.80, 0.26 and 0.53 mas (milli-arcsec) by Hertzsprung (1922), Morgan et al. (1953) and Wesselink (1969), respectively. The adopted value of the angular diameter is 0.44 mas to generate the spectral energy distribution (SED). The observed SED of $\sigma$ Cyg is derived by using low resolution IUE spectra (LWR 11614, SWP 15099), as well as the spectrophotometric data of Kharitonov et al. (1988), and the photometric data of Johnson (Reed, 2003; Johnson et al., 1966), Strömgren (Hauck & Mermilliod, 1998) and 2MASS (Cutri et al., 2003) photometric data.

The computed fluxes and the spectrophotometric data are reddened using the empirical approach of Cardelli et al. (1989) assuming a ratio of extinction to colour excess $R_V = A_V / E(B-V) = 3.1$ and $E(B-V) = 0.19$ (Firnstein & Przybilla, 2012). The zero-points reported by Heber et al. (2001) are used to transform the various magnitudes into fluxes. It is assumed that $y = V$ to transform $b-y$, $c_1$ and $m_1$ indexes to $u$, $v$, $y$ and $b$ magnitudes. The computed fluxes for $T_{\text{eff}} = 10388$ and log $g = 1.80$ are consistent with the SED (see Figure 2).

4. Abundance Analysis

4.1. The results of the present study

Helium abundances were calculated using SYNSPEC (Hubeny et al., 1994) and the metal abundances were derived using WIDTH9 (Kurucz, 1993). The metal line damping constants were taken from Kurucz & Bell (1995). However, the blended lines were neglected during the abundances analysis. The micro-turbulent velocity of $\sigma$ Cyg was determined from only the Fe II lines and the
microturbulent velocity of η Leo was ascertained using the Fe II lines and Cr II lines.

The microturbulent velocity was determined by finding the value at which the correlation between the derived abundances and the equivalent widths (ξ₁) was minimised and the minimum scatter about the mean abundance (ξ₂) was obtained [Blackwell et al., 1982]. The microturbulent velocity of σ Cyg was found to be approximately 3.5 km s⁻¹ and that of η Leo was calculated from Fe II and Cr II lines as 3.45 and 3.55 km s⁻¹, respectively. Therefore, it can be seen that the mean value of microturbulent velocity was approximately 3.5 km s⁻¹ for both stars (see Table 2). These derived microturbulent velocities were then used to calculate the elemental abundances.

The rotational velocities (v\text{sin}i) and macroturbulent (ζ) velocities of σ Cyg were determined from intermediate lines between λλ 4500-4540 by finding the best fit between the theoretical and observed spectra using SYNTHE [Kurucz & Avrett, 1981], and are 27 ± 5 and 24 ± 2 km s⁻¹, respectively. Those of η Leo are 2 ± 2 and 14.5 ± 1.5 km s⁻¹, respectively.
Table 2: Microturbulence determinations

| Star | Element | number of lines | ξ₁ km s⁻¹ | log (N/N_T) | ξ₂ km s⁻¹ | log (N/N_T) | Reference |
|------|---------|-----------------|----------|-------------|----------|-------------|-----------|
| σ Cyg | Fe II | 100 | 3.50 | -4.47±0.17 | 3.50 | -4.47±0.17 | KX+N4 |
|       |        | adopted | 3.50 |             |          |             |           |
| η Leo | Fe II | 39 | 3.40 | -4.65±0.17 | 3.50 | -4.65±0.17 | KX+N4 |
|       | Cr II | 150 | 3.50 | -6.49±0.21 | 3.60 | -6.49±0.21 | MF+KX+NL |
|       |        | adopted | 3.50 |             |          |             |           |

References of gf-values: MF = Fuhr et al. (1988), KX = Kurucz & Bell (1995), N4 = Fuhr & Wiese (2006), NL = Nilsson et al. (2006).

Table 3: He/H ratios of σ Cyg and η Leo.

| λ (Å) | σ Cyg | η Leo |
|-------|-------|-------|
| 4009  | ...   | 0.12  |
| 4026  | 0.13  | ...   |
| 4169  | ...   | 0.17  |
| 4437  | ...   | 0.14  |
| 4471  | 0.13  | 0.15  |
| 4713  | 0.14  | ...   |
| 4922  | 0.13  | 0.11  |

Average 0.14 0.14
Std.Dev. 0.01 0.02

The helium abundance of σ Cyg and η Leo were determined by Dr. Adelman using the program SYNSPEC (Hubeny et al., 1994). Table 3 presents the He/H ratios which were determined to be (0.14 ± 0.01 for σ Cyg and 0.14 ± 0.02 for η Leo). To calculate the log N/H from log N/N(total) an offset of 0.06 was used for both σ Cyg and η Leo.

Table 4 includes the elemental abundances of the target stars, Table 5 presents the error in our abundance analysis. For σ Cyg, carbon is deficient, nitrogen is overabundant and oxygen is near solar abundance. Neon is deficient by 0.12 dex, whereas magnesium and silicon are near solar abundance. aluminium and sulphur are underabundant, conversely, calcium is very overabundant. Light elements; aluminium and sulphur are underabundant, conversely, calcium is very overabundant. Iron group elements are near solar abundance except for scandium, titaniuam and manganese. Scandium and titanium are underabundant, whereas, manganese is overabundant by 0.21 dex. Compared to solar values, the abundances of scandium, titanium, chromium, manganese, iron and nickel are
-0.45, -0.36, -0.04, 0.19, 0.03 and -0.09 dex, respectively. Heavy elements tend to be over-abundant. Only, strontium is underabundant, whereas the abundances of yttrium and zirconium are comparable to their solar abundances. Caesium and europium are highly overabundant (see Figure 4).

For η Leo, the CNO abundance show a pattern similar to that of σ Cyg. Light elements, magnesium and aluminium are underabundant. The abundances of phosphorus matches the solar value, while the abundances of silicon, sulphur and calcium are near the solar value. Iron group elements are also near solar abundance except for scandium, titanium and vanadium in η Leo’s atmosphere. Scandium and titanium and vanadium are underabundant whereas the abundances of chromium, manganese, iron, cobalt and nickel are solar. Heavy elements tend to be overabundant. Although, strontium (-0.71 dex) and barium (-0.17 dex) are underabundant (see Figure 4): alternatively, the abundances of these elements can be assumed to be solar according to Adelman & Yüce (2010)’s scale.
Table 4: Comparison of derived and solar abundances [N/H]

| Species | Sun* | σ Cyg | n | η Leo | n |
|----------|------|-------|---|-------|---|
| He I     | 10.99| 0.16 ± 0.01| 4 | 0.16 ± 0.02| 5 |
| C I      | 8.55 | ...    | ... | -0.36 ± 0.08 | 3 |
| C II     | 8.55 | -0.19 ± 0.05 | 2 | -0.45 ± 0.01 | 1 |
| N I      | 7.97 | ...    | ... | 0.77 ± 0.19 | 8 |
| N II     | 7.97 | 0.92 ± 0.26 | 8 | 0.46 ± 0.13 | 4 |
| O I      | 8.87 | 0.08 ± 0.05 | 3 | -0.09 ± 0.14 | 4 |
| Ne I     | 8.08 | -0.13   | 1 | ...   | ... |
| Mg I     | 7.58 | -0.05 ± 0.14 | 3 | -0.31 ± 0.07 | 8 |
| Mg II    | 7.58 | 0.06 ± 0.13 | 4 | -0.18 ± 0.09 | 11 |
| Al I     | 6.47 | -0.29 ± 0.11 | 2 | -0.47 ± 0.03 | 2 |
| Al II    | 6.47 | -0.31 ± 0.10 | 4 | -0.15 | 1 |
| Si I     | 7.55 | 0.02 ± 0.12 | 5 | -0.06 ± 0.18 | 5 |
| Si II    | 7.55 | ...     | ... | +0.23 ± 0.17 | 4 |
| S I      | 7.33 | 0.24 ± 0.20 | 32 | -0.11 ± 0.20 | 17 |
| Ca I     | 6.36 | 1.35    | 1 | -0.12 | 1 |
| Ca II    | 6.36 | 0.93    | 1 | -0.04 ± 0.08 | 3 |
| Sc II    | 3.17 | -0.39 ± 0.20 | 3 | -0.56 ± 0.21 | 7 |
| Ti II    | 5.02 | -0.34 ± 0.21 | 17 | -0.45 ± 0.19 | 56 |
| V II     | 4.00 | 0.06 ± 0.22 | 5 | -0.30 ± 0.14 | 17 |
| Cr I     | 5.67 | ...     | ... | 0.03 ± 0.14 | 6 |
| Cr II    | 5.67 | -0.06 ± 0.18 | 21 | -0.12 ± 0.20 | 35 |
| Mn II    | 5.39 | 0.19 ± 0.12 | 10 | -0.06 ± 0.20 | 15 |
| Fe I     | 7.50 | 0.09 ± 0.08 | 7 | 0.00 ± 0.20 | 78 |
| Fe II    | 7.50 | -0.03 ± 0.20 | 98 | -0.11 ± 0.17 | 140 |
| Fe III   | 7.50 | -0.04   | 1 | -0.01 ± 0.14 | 4 |
| Co II    | 4.92 | ...     | ... | 0.23 ± 0.12 | 3 |
| Ni II    | 6.25 | -0.11 ± 0.08 | 3 | -0.02 ± 0.19 | 5 |
| Sr II    | 2.97 | -0.17 ± 0.06 | 2 | -0.71 ± 0.05 | 2 |
| Y II     | 2.24 | 0.19    | 1 | 0.12 ± 0.15 | 4 |
| Zr II    | 2.60 | 0.21    | 1 | 0.98 ± 0.17 | 7 |
| Ba II    | 2.13 | ...     | ... | -0.17 | 1 |
| La II    | 1.17 | ...     | ... | 2.37 ± 0.06 | 2 |
| Ce II    | 1.58 | 2.94 ± 0.05 | 3 | 1.79 ± 0.16 | 3 |
| Eu II    | 0.51 | 2.73 ± 0.01 | 2 | 1.77 ± 0.07 | 2 |
| Gd II    | 1.12 | ...     | ... | 3.19 ± 0.14 | 5 |
| Dy II    | 1.14 | ...     | ... | 3.20 ± 0.14 | 3 |

* Grevesse & Sauval (1996)

4.2. Comparison with previous studies

σ Cyg: The elemental abundance results of σ Cyg are scarce in the literature. The first extensive abundance analysis of σ Cyg was the pioneering study of Ivanova & Lyubimkov (1988). Although, Ivanova & Lyubimkov (1988) used different temperature and surface gravity values, the abundance pattern determined in that study was similar to that of the present study, except that Fe is abundant and the abundance of Ti is solar. Helium is abundant in their study.
Figure 4: Comparison with solar abundances. The open circles and squares indicate the relative abundances of σ Cyg and η Leo, respectively.

It is given in Table 6 with atmospheric parameters used and the number of lines. The measured EW, the $gf$ values used and the sources can be found in Table A.8.

Takeda & Takada-Hidai (1995, 1998, 2000) also provide an analysis of the elemental abundances of σ Cyg partially in nLTE. Helium tends to be solar in their study, whereas Helium is abundant in the present study. They used the atmospheric parameters of Ivanova & Lyubimkov (1988) in their study.

Markova & Puls (2008) also calculated the helium abundance as solar. In their study, Si was to be overabundant by 0.4 dex, as calculated using the Si II and Si III lines. Therefore, they identified σ Cyg as a silicon star. Finally, Przybilla et al. (2010) reports helium is 0.38 by mass fraction and that CNO exhibits a similar to that presented in this paper.

The main advantages of the present analysis are the wide wavelength coverage, the high quality of our spectra and the signal-to-noise ratios. I also
emphasise that not only the total number of ions (28) and elements (23), but also a greater number of lines per ion are analysed in the present study. Additionally, this is the first study reporting the heavy element abundances of σ Cyg. However, nLTE effects are not considered in the present study.

**η Leo:** The pioneering chemical abundance analysis of η Leo was provided by Wolf (1971). The results of Wolf (1971) indicated systematically larger abundance in this star due to its higher $T_{\text{eff}}$. Subsequently, Venn (1995a,b) reported elemental abundances in nLTE. Recently, η Leo was studied extensively by Przybilla (2002); Przybilla et al. (2000) (see Table 7). The most striking differences between their studies and this one is that, Sc and Ti are deficient. Because the analysis in this study was limited to nLTE calculations, however, the updated gf value of Pickering et al. (2001, 2002) was used in the Ti abundance calculations. The heavy element abundances are similar to Venn (1995a)'s result. Furthermore, their elemental abundances of rare-earth and heavy elements (Sr, Zr, La, Ce, Eu, Gd and Dy) differ from the abundances given in the comprehensive studies of Przybilla (2002); Przybilla et al. (2000) for η Leo. In the present study, we use the same $T_{\text{eff}}$ and log $g$ with Przybilla (2002) and determine the abundance of ions (35) and elements (27) using a greater number of lines.

5. Results and Discussion

Recent studies have shown that the microturbulent velocities of A-type SGs are in the range 4 - 8 km s$^{-1}$. For example, the derived microturbulent velocities of α Cyg (A2 Ia) are 7.5 km s$^{-1}$ (Albayrak 2000) and 8 ± 1 km s$^{-1}$ (Schiller & Przybilla 2008), whereas the microturbulent velocity of ν Cep (A2 Ia) given in the literature is 5.2 km s$^{-1}$ (Yüce 2005). The microturbulent velocities of HD 111613 (A2 Iabe) and HD 92207 (A0 Iae) are 7 ± 1 and 8 ± 1 km
Figure 5: Positions of $\sigma$ Cyg and $\eta$ Leo on HR Diagram for 10 $M_\odot$ and 14 $M_\odot$ using tracks of Ekström et al. (2012), the values of C/N ratios (by mass) give some points after MS (Main-Sequence) phase.

s$^{-1}$, respectively (Przybilla et al. 2006). In this study, the determined microturbulent velocities are the same for $\sigma$ Cyg and $\eta$ Leo: 3.5 km s$^{-1}$. The obtained $T_{\text{eff}}$ and $\log g$ values for $\sigma$ Cyg are also consistent with those of Przybilla et al. (2010). The $T_{\text{eff}}$ and $\log g$ of $\eta$ Leo are taken from the values determined by Przybilla et al. (2006).

In the atmospheres of $\sigma$ Cyg, The helium is abundant. C is depleted, N is strongly enriched and O is near solar abundance. The N/C and N/O abundances ratios (by mass) are 3.95 and 0.76 respectively, whereas the theoretical values of 4.31 and 0.77 for a rotating model of 14 $M_\odot$ calculated by Ekström et al. (2012). Theoretical values are given for initial value of blue loop(if any). The spectroscopic mass of $\sigma$ Cyg is about 12 $M_\odot$. The initial value of N/C is 0.289. Light elements and iron group elements are near solar abundance. However, the abundances of heavy elements and rare-earth elements, except for Ba, are
moderately overabundant.

For η Leo, C is deficient, N is in excess and O is near solar abundance. The abundance ratio of N/C and N/O (by mass) are 3.44 and 0.49, whereas the theoretical values are 5.40 and 0.82 for 10 \( M_\odot \) by Ekström et al. (2012)’s calculations. Light elements are also solar except for Mg and Al which are underabundant. Iron group elements are also near solar abundances except for Sc, Ti and V which are underabundant due to nLTE effects. However, the heavy elements are overabundant, except for Sr, which is underabundant and Ba, which is solar.

The main contributors of s-process elements in the solar system (Sr, Y, Zr and Ba) are low to intermediate-mass asymptotic giant branch stars, whereas the r-process elements (Eu, Gd and Dy) are contributed by high mass Type II supernovae (Travaglio et al. 2004). The overabundances of some of the heavy elements are observed in the atmospheres of ”normal” late B- and early-A-type stars. This overabundance can be referred to as the general enrichment of ISM by stellar and Galactic evolution and could be the topic of further investigation (Adelman et al. 2004).

Theoretical evolutionary tracks, helium enrichment, CNO abundance patterns and light element abundances show that these stars have experienced the first dredge up phase as described by the tracks of Schaller et al. (1992) for 9\( M_\odot \). This scenario is also cited by Przybilla et al. (2006) for η Leo referring to Meynet & Maeder (2003). However, Przybilla (2002) proposed that the result was caused by the accretion of nuclear processed matter from a redward-secondary component to the present faint primary and referred to the study of Vanbeveren et al. (1998). According to the stellar tracks of Ekström et al. (2012), a second scenario suggests that these stars evolve directly from the main sequence to red giant phase. This evolution was also proposed by Venn
Figure 6: Isochrones of non-rotating (grey lines) and rotating models (black lines) of 
Ekström et al. (2012). σ Cyg and η Leo are represented by open and filled squares, respectively. Log ages are given by starting values of 7.1 and 7.2, respectively and increases with 0.1 increment for other lines.

(1995a) referring to Maeder & Meynet (1989) based on helium enrichment. This scenario also supported binary nature as in the previous case (see Figure 5).

Ekström et al. (2012) described a 10$M_\odot$ scenario with rotation, which also supported blue loops. However, the possibility of binarity can not be ignored as noted by Przybilla (2002). The blue loops becomes shorten in the tracks of the masses larger than 9$M_\odot$ as it can be seen in Figure 5, therefore, it seems that σ Cyg have evolved directly from main-sequence to red-giant phase referring to Ekström et al. (2012), this scenario was also claimed by Ivanova & Lyubimkov (1988) and its progenitor should be an early-main sequence B star. And, η Leo has already experienced the first-dredge-up and should be on a blue-loop phase due to its helium enrichment and high N/C ratio.

The luminosity and temperature values used for σ Cyg are \( \log L/L_\odot = 4.72 \) calculated using the FGLR (Kudritzki et al., 2003) and \( \log T_{\text{eff}} = 4.02 \) (this
study). Using log $L/L_\odot = 4.28$ and log $T_{\text{eff}} = 3.98$ (Przybilla et al., 2006). Figure 6 presents Log ages are near 7.2 and 7.4 for rotating models of these stars. Their ages correspond to 16 and 25 million years, respectively. The lower limit for the Cyg OB4 association age is 7 million years (Tetzlaff et al., 2010). The N/C and N/O abundance ratios of $\sigma$ Cyg and $\eta$ Leo used are compatible with the values of Log age isochrones from the studies of Ekström et al. (2012). Ivanova & Lyubimkov (1988) found log $L/L_\odot = 5.08$ and log $T_{\text{eff}} = 4.02$, and estimated its age as 10 million years.

To determine the variability of the radial velocities in such stars more spectra spanning longer times are needed. Such observations allow us to determine the variability of these stars and the binary nature of $\eta$ Leo. The elemental abundances of late B- and early A-type star indicate that it needs further refinement with new model atmospheres, updated atomic values such as new $gf$ values, and qualitative observations covering wide ranges of wavelengths with high resolution and S/N ratios. Such studies will allow us to obtain more accurate results for these types of stars and to determine the elemental abundances of heavy metals.

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Appendix A. The analyses of metal lines
Table 5: Error sources for the abundances of the chemical elements of σ Cyg.

| Ion  | log (N/N$_T$) | $\sigma_{\text{abn}}$(scatter) | $\sigma_{\text{abn}}$(T$_{\text{eff}}$) | $\sigma_{\text{abn}}$(log $g$) | $\sigma_{\text{abn}}$(v$_{\text{turb}}$) | $\sigma_{\text{abn}}$(gf-values) | $\sigma_{\text{abn}}$(EW) | $\sigma_{\text{abn}}$(syst.) |
|------|---------------|-------------------------------|---------------------------------|--------------------------------|---------------------------------|--------------------------------|--------------------------------|--------------------------|
| C II | -3.70         | 0.05                          | -0.09                           | -0.04                          | -0.06                           | -0.04                          | +0.09                          | 0.15                     |
| N II | -3.17         | 0.26                          | -0.12                           | +0.05                          | -0.04                           | -0.05                          | +0.07                          | 0.16                     |
| O I  | -3.11         | 0.26                          | -0.04                           | -0.04                          | -0.04                           | -0.05                          | +0.06                          | 0.10                     |
| Ne I | -4.11         | ...                           | -0.07                           | +0.05                          | -0.05                           | -0.03                          | +0.08                          | 0.13                     |
| Mg I | -4.53         | 0.14                          | +0.21                           | -0.13                          | -0.02                           | -0.02                          | +0.05                          | 0.25                     |
| Mg II| -4.42         | 0.04                          | +0.10                           | -0.04                          | -0.03                           | -0.04                          | +0.06                          | 0.13                     |
| Al I | -5.88         | 0.11                          | +0.12                           | -0.07                          | -0.01                           | -0.05                          | +0.04                          | 0.15                     |
| Al II| -5.90         | 0.10                          | -0.02                           | +0.01                          | -0.03                           | -0.05                          | +0.05                          | 0.07                     |
| Si II| -4.49         | 0.12                          | +0.06                           | +0.04                          | 0.00                            | -0.01                          | +0.11                          | 0.14                     |
| S II | -4.49         | 0.20                          | -0.06                           | +0.04                          | -0.05                           | -0.06                          | +0.07                          | 0.15                     |
| Ca I | -4.35         | ...                           | +0.27                           | -0.11                          | 0.00                            | -0.02                          | +0.04                          | 0.29                     |
| Ca II| -4.77         | ...                           | +0.14                           | -0.07                          | -0.06                           | -0.01                          | +0.09                          | 0.19                     |
| Sc II| -9.32         | 0.20                          | -0.09                           | -0.04                          | -0.06                           | -0.04                          | +0.04                          | 0.11                     |
| Ti II| -7.42         | 0.21                          | +0.14                           | -0.05                          | -0.01                           | -0.09                          | +0.06                          | 0.18                     |
| V II | -8.02         | 0.22                          | -0.09                           | -0.04                          | -0.01                           | -0.11                          | +0.04                          | 0.15                     |
| Cr II| -6.45         | 0.18                          | +0.07                           | -0.06                          | -0.03                           | -0.20                          | +0.16                          | 0.27                     |
| Mn II| -6.49         | 0.12                          | +0.07                           | -0.03                          | -0.00                           | -0.15                          | +0.04                          | 0.17                     |
| Fe I | -4.47         | 0.08                          | +0.23                           | -0.05                          | -0.01                           | -0.03                          | +0.05                          | 0.24                     |
| Fe II| -4.59         | 0.21                          | +0.04                           | -0.01                          | -0.06                           | -0.18                          | +0.06                          | 0.20                     |
| Fe III| -4.60        | ...                           | -0.06                           | +0.06                          | -0.05                           | -0.12                          | +0.08                          | 0.17                     |
| Ni II| -5.92         | 0.08                          | +0.03                           | +0.01                          | -0.01                           | -0.27                          | +0.05                          | 0.15                     |
| Sr II| -9.26         | 0.06                          | +0.14                           | -0.06                          | -0.01                           | -0.01                          | +0.05                          | 0.16                     |
| Y II | -9.63         | ...                           | +0.10                           | -0.11                          | -0.00                           | -0.02                          | +0.04                          | 0.16                     |
| Zr II| -9.25         | ...                           | 0.15                            | -0.05                          | 0.00                            | 0.00                           | +0.05                          | 0.17                     |
| Ce II| -7.54         | 0.05                          | +0.13                           | -0.06                          | -0.06                           | -0.01                          | +0.05                          | 0.16                     |
| Eu II| -8.84         | 0.01                          | +0.14                           | -0.06                          | 0.00                            | -0.02                          | +0.05                          | 0.16                     |

* Grevesse & Sauval (1996)
Table 6: The comparison of derived σ Cyg abundances.

| Species | This Study | Ivanova & Lyubimkov (1988) | Takeda & Takeda-Hidai (1995,1998 & 2000) | Markova & Puls (2008) |
|---------|------------|-----------------------------|------------------------------------------|-----------------------|
| He I    | 11.15 ± 0.01(4) | 11.35 ± 0.11(7) | 10.98(1) | 10.95 ± 0.02() |
| C II    | 8.36 ± 0.05(2)  | 8.25 ± 0.10(3)   | 8.13 ± 0.09(2)  | ...                  |
| N I     | ...           | ...              | 8.46 ± 0.01(7) | ...                  |
| N II    | 8.89 ± 0.26(8)  | 8.97 ± 0.08(4)   | ...          | ...                  |
| O I     | 8.95 ± 0.05(3)  | 8.99(1)          | 8.70(1)      | ...                  |
| Ne I    | 7.95(1)       | ...              | ...          | ...                  |
| Mg I    | 7.53 ± 0.14(3)  | ...             | ...          | ...                  |
| Mg II   | 7.64 ± 0.13(4)  | 7.80 ± 0.06(4)   | ...          | ...                  |
| Al I    | 6.18 ± 0.11(2)  | ...             | ...          | ...                  |
| Al II   | 6.16 ± 0.10(4)  | ...             | ...          | ...                  |
| Si II   | 7.57 ± 0.12(5)  | 7.71 ± 0.07(8)   | ...          | ...                  |
| S II    | 7.57 ± 0.20(32) | 7.50 ± 0.06(11)  | ...          | ...                  |
| Ca I    | 7.71 ±(1)      | ...             | ...          | ...                  |
| Ca II   | 7.29 ±(1)      | ...             | ...          | ...                  |
| Sc II   | 2.72 ± 0.20(3)  | ...             | ...          | ...                  |
| Ti II   | 4.73 ± 0.21(17) | 4.95 ± 0.18(9)   | ...          | ...                  |
| V II    | 4.06 ± 0.22(5)  | ...             | ...          | ...                  |
| Cr II   | 5.61 ± 0.28(21) | 5.70 ± 0.07(10)  | 5.91(2)      | ...                  |
| Mn II   | 5.58 ± 0.12(10)| ...             | ...          | ...                  |
| Fe I    | 7.59 ± 0.08(7)  | ...             | ...          | ...                  |
| Fe II   | 7.48 ± 0.20(98) | 7.73 ± 0.03(77)  | 7.51(4)      | ...                  |
| Fe III  | 7.46 ±(1)      | ...             | ...          | ...                  |
| Ni II   | 6.14 ± 0.08(3)  | 6.12 ± 0.12(4)   | ...          | ...                  |
| Sr II   | 2.80 ± 0.06(3)  | ...             | ...          | ...                  |
| Y II    | 2.43 ±(1)      | ...             | ...          | ...                  |
| Zr II   | 2.81 ±(1)      | ...             | ...          | ...                  |
| Ce II   | 4.52 ± 0.05(3)  | ...             | ...          | ...                  |
| Eu II   | 3.24 ± 0.01(2)  | ...             | ...          | ...                  |
| $T_{eff}$ (K) | 10388±197 | 11500 ± 200 | 11500 ± 200 | 11000 ± 1000 |
| log $g$ (cgs) | 1.80±0.14 | 1.80±0.20 | 1.80±0.20 | 1.85 |

1. This Study; 2. Ivanova & Lyubimkov (1988)
3. Takeda & Takeda-Hidai (1995,1998 & 2000)
4. Markova & Puls (2008).
Table 7: Comparison of derived $\eta$ Leo abundances with previous studies.

| Species | This Study | Wolf (1971) | Venn (1995a, 1995b) | Takeda & Takeda-Hidai (1995, 1998, 2000) | Przybilla et al. (2006) |
|---------|------------|-------------|---------------------|------------------------------------------|-------------------------|
| He I    | 11.15 ± 0.01(3) | 11.09(1)    | ...                 | 10.70(1)                                 | 11.18 ± 0.04(14)        |
| C I     | 8.19 ± 0.08(3)  | 8.65(2)     | 8.34 ± 0.07(4)      | 7.82 ± 0.09(1)                           | 7.94 ± 0.10(4)          |
| C II    | 8.10 ± 0.01(1)  | ...         | ...                 | 8.13 ± 0.10(4)                           | 8.10 ± 0.09(3)          |
| N I     | 8.74 ± 0.19(8)  | ...         | 9.01 ± 0.10(3)      | 8.27(7)                                  | 8.41 ± 0.09(20)         |
| N II    | 8.43 ± 0.13(4)  | ...         | ...                 | ...                                      | 8.32(1)                 |
| O I     | 8.78 ± 0.14(4)  | 8.83 ± 0.67(7) | 8.97 ± 0.10(6) | 8.70(3)                                  | 8.78 ± 0.09(9)          |
| Mg I    | 7.27 ± 0.07(8)  | 7.51 ± 0.22(3) | 7.55 ± 0.05(4) | ...                                      | 7.52 ± 0.08(7)          |
| Mg II   | 7.40 ± 0.09(11) | 7.87 ± 0.13(8) | 7.54 ± 0.14(5) | ...                                      | 7.53 ± 0.04(12)         |
| Al I    | 6.00 ± 0.03(2)  | 6.45 ± 0.13(2) | ...                 | ...                                      | 6.11 ± 0.06(2)          |
| Al II   | 6.32(1)        | 6.44(2)     | ...                 | ...                                      | 6.39 ± 0.17(5)          |
| Si I    | 7.45 ± 0.18(5)  | 8.03 ± 0.14(9) | ...                 | ...                                      | 7.58 ± 0.19(4)          |
| Si III  | ...           | ...         | ...                 | ...                                      | ...                     |
| S II    | 7.24 ± 0.20(17) | ...         | ...                 | ...                                      | 7.15 ± 0.07(14)         |
| Ca I    | 6.24(1)        | ...         | ...                 | ...                                      | ...                     |
| Ca II   | 6.32 ± 0.08(3)  | 6.16 ± 0.11(2) | ...                 | ...                                      | 6.31(1)                 |
| Sc II   | 2.61 ± 0.21(6)  | 2.97 ± 0.24(5) | ...                 | ...                                      | 2.57 ± 0.14(3)          |
| Ti II   | 4.57 ± 0.19(56) | 4.73 ± 0.34(82) | 4.77 ± 0.21(21) | ...                                      | 4.89 ± 0.13(29)         |
| V II    | 3.70 ± 0.14(17) | 3.97 ± 0.17(13) | ...                 | ...                                      | 3.57 ± 0.06(6)          |
| Cr II   | 5.55 ± 0.20(35) | 5.57 ± 0.50(63) | 5.80 ± 0.28(2) | ...                                      | 5.62 ± 0.08(29)         |
| Mn II   | 5.33 ± 0.20(15) | 4.66 ± 0.12(6)  | 5.40(1)             | ...                                      | 5.38 ± 0.02(27)         |
| Fe I    | 7.48 ± 0.20(78) | 7.79 ± 0.36(47) | 7.22 ± 0.12(3) | ...                                      | 7.34 ± 0.12(21)         |
| Fe II   | 7.40 ± 0.17(140)| 7.76 ± 0.25(73) | 7.47 ± 0.18(19) | ...                                      | 7.52 ± 0.09(35)         |
| Fe III  | 7.49 ± 0.14(4)  | ...         | ...                 | ...                                      | ...                     |
| Co II   | 5.11 ± 0.12(3)  | 3.65(1)     | ...                 | ...                                      | ...                     |
| Ni II   | 6.22 ± 0.19(5)  | 5.18 ± 0.25  | ...                 | ...                                      | 6.30 ± 0.06(7)          |
| Sr II   | 2.26 ± 0.05(2)  | ...         | ...                 | ...                                      | 2.37 ± 0.04(2)          |
| Y II    | 3.48 ± 0.15(4)  | ...         | ...                 | ...                                      | ...                     |
| Zr II   | 3.44 ± 0.17(7)  | ...         | ...                 | ...                                      | ...                     |
| Ba II   | 1.96(1)        | 3.63(1)     | ...                 | ...                                      | 2.00(1)                 |
| La II   | 3.54 ± 0.06(2)  | ...         | ...                 | ...                                      | ...                     |
| Ce II   | 3.37 ± 0.16(2)  | ...         | ...                 | ...                                      | ...                     |
| Eu II   | 2.28 ± 0.07(2)  | ...         | ...                 | ...                                      | ...                     |
| Gd II   | 4.31 ± 0.14(5)  | ...         | ...                 | ...                                      | ...                     |
| Dy II   | 4.34 ± 0.14(3)  | ...         | ...                 | ...                                      | ...                     |

$T_{\text{eff}}$ (K) | 9600 | 10400 ± 300 | 9700 ± 200 | 10200 ± 300 | 9600 ± 150 |

$\log g$ (cgs) | 2.00 | 2.05 ± 0.2 | 2.00 ± 0.2 | 1.90 ± 0.2 | 2.00 ± 0.15 |
Table A.8: Elemental Abundances of σ Cyg and η Leo

| Species | Multiplet | λ(Å) | log gf | Ref. | $\sigma$ Cyg | $\eta$ Leo |
|---------|-----------|------|--------|------|-------------|------------|
|         |           |      |        |      | W$_\lambda$(mÅ) | log N/N$_T$ | W$_\lambda$(mÅ) | log N/N$_T$ |
| C I     |           |      |        |      |              |            |              |            |
| 6       | 4771.74   | -1.87 | FW     | ...  | ...          | 2.9        | ...          | 3.8        |
| 13      | 4932.05   | -1.66 | FW     | ...  | ...          | 3.8        | ...          | 3.99       |
| 14      | 4711.37   | -1.96 | FW     | ...  | ...          | 2.2        | ...          | 3.97       |
| C II    |           |      |        |      |              |            |              |            |
| 4       | 3918.97   | -0.53 | WF     | 25.6 | -3.76        | 12.0       | -3.97       |
| 6       | 4287.90   | +0.56 | WF     | ...  | ...          | 14.5       | -3.99       |
|         | 4287.26   | +0.74 | WF     | ...  | ...          | 19.8       | ...          |
| N I     |           |      |        |      |              |            |              |            |
| 6       | 4137.74   | -2.54 | WF     | ...  | ...          | 3.0        | ...          | 3.16       |
| 9       | 4914.94   | -2.23 | WF     | ...  | ...          | 6.0        | ...          | 3.40       |
| 10      | 4109.95   | -1.23 | WF     | ...  | ...          | 1.6        | ...          | 3.52       |
| 12      | 4113.98   | -2.17 | WF     | ...  | ...          | 11.8       | ...          | 3.65       |
| 19      | 6644.95   | -0.86 | WF     | ...  | ...          | 2.9        | ...          | 3.35       |
| 20      | 6653.41   | -1.14 | WF     | ...  | ...          | 10.5       | ...          | 3.30       |
|         | 4669.46   | -2.36 | WF     | ...  | ...          | 8.3        | ...          | 3.14       |
| N II    |           |      |        |      |              |            |              |            |
| 4       | 5010.62   | -0.36 | WF     | 8.3  | -3.67        | ...        | ...          | 3.63       |
| 5       | 4697.16   | -0.51 | WF     | 10.7 | -3.07        | ...        | ...          | 3.40       |
| 9       | 4613.87   | -0.67 | WF     | 9.1  | -3.03        | ...        | ...          | 3.52       |
| 10      | 4630.54   | +0.09 | WF     | ...  | ...          | 5.5        | ...          | 3.58       |
| 12      | 4643.09   | -0.36 | WF     | 15.0 | -2.94        | 2.4        | ...          | 3.61       |
| 6       | 3955.85   | -0.81 | WF     | ...  | ...          | ...        | ...          |            |
| 10      | 4109.95   | -0.81 | WF     | ...  | ...          | ...        | ...          |            |
| 12      | 4113.98   | -0.81 | WF     | ...  | ...          | ...        | ...          |            |
| 19      | 3994.99   | +0.21 | WF     | 35.2 | -3.06        | 8.2        | ...          | 3.86       |
| 20      | 4447.03   | +0.23 | WF     | 14.7 | -2.87        | 2.7        | ...          | 3.50       |
| 39      | 4035.08   | +0.62 | WS     | 5.7  | -3.22        | ...        | ...          |            |
|         | 4043.53   | +0.74 | WS     | 4.3  | -3.53        | ...        | ...          |            |
| O I     |           |      |        |      |              |            |              |            |
| 10      | 6155.98   | -0.66 | WF     | 33.1 | -3.08        | ...        | ...          | 3.30       |
| 13      | 5019.29   | -1.87 | WF     | ...  | ...          | 5.6        | ...          | 3.58       |
| 16      | 4772.91   | -1.71 | WF     | ...  | ...          | 6.6        | ...          | 3.61       |
|         | 4773.75   | -1.55 | WF     | ...  | ...          | 3.7        | ...          | 3.86       |
| Ne I    |           |      |        |      |              |            |              |            |
| 2       | 6382.99   | -0.26 | WX     | 26.2 | -4.11        | ...        | ...          |            |
| Mg I    |           |      |        |      |              |            |              |            |
| 2       | 5167.62   | -0.93 | AT     | ...  | ...          | 30.1       | ...          | 4.55       |
| 3       | 3829.35   | -0.19 | WS     | 22.3 | -4.34        | 55.5       | ...          | 4.86       |
| 11      | 4702.99   | -0.38 | WS     | ...  | ...          | 58.2       | ...          | 4.66       |
| 15      | 4167.27   | -0.79 | JK     | ...  | ...          | 6.0        | ...          | 4.43       |
Table A.8: continued

| Species | Multiplet | $\lambda$(Å) | log gf | Ref. | $W_\lambda$(mÅ) | log $N/N_T$ | $W_\lambda$(mÅ) | log $N/N_T$ |
|---------|-----------|--------------|--------|------|----------------|-------------|----------------|-------------|
| Mg II   |           |              |        |      |                |             |                |             |
| 5       | 3848.24   | -1.57        | FW     | ...  | 47.5           | -4.55       | 47.5           | -4.55       |
| 9       | 4428.00   | -1.21        | WS     | 22.9 | 21.2           | -4.75       | 21.2           | -4.75       |
| 18      | 4739.59   | -0.64        | KX     | ...  | 30.5           | -4.28       | 30.5           | -4.28       |
| 19      | 4436.52   | -0.64        | KX     | ...  | 13.9           | -4.74       | 13.9           | -4.74       |
| 25      | 4851.08   | -0.42        | KX     | 21.9 | 13.8           | -4.88       | 13.8           | -4.88       |
| 28      | 4193.47   | -1.07        | KX     | ...  | 4.8            | -4.81       | 4.8            | -4.81       |
| Al I    |           |              |        |      |                |             |                |             |
| 1       | 3944.01   | -0.64        | WS     | 10.5 | 21.4           | -6.03       | 21.4           | -6.03       |
| 2       | 3961.52   | -0.34        | WS     | ...  | 37.3           | -6.09       | 37.3           | -6.09       |
| Al II   |           |              |        |      |                |             |                |             |
| 2       | 4663.10   | -0.28        | FW     | 49.6 | 43.9           | -5.74       | 43.9           | -5.74       |
| 10      | 6626.18   | +0.05        | FW     | 5.8  | ...            | ...         | ...            | ...         |
|         | 6231.78   | +0.40        | FW     | 10.4 | ...            | ...         | ...            | ...         |
|         | 6243.36   | +0.67        | FW     | 20.2 | ...            | ...         | ...            | ...         |
| Si II   |           |              |        |      |                |             |                |             |
| 5       | 4075.45   | -1.40        | SG     | 36.6 | ...            | ...         | ...            | ...         |
| 7.05    | 4621.42   | -0.54        | WS     | ...  | 11.2           | -4.66       | 11.2           | -4.66       |
|         | 4621.72   | -0.38        | WS     | ...  | 14.5           | -4.68       | 14.5           | -4.68       |
| 7.15    | 4673.27   | -0.35        | KX     | 13.5 | ...            | ...         | ...            | ...         |
| 7.16    | 4376.97   | -0.84        | KX     | 8.7  | 9.7            | -4.45       | 9.7            | -4.45       |
| 7.17    | 4187.12   | -1.05        | KX     | ...  | 4.4            | -4.56       | 4.4            | -4.56       |
| 7.26    | 4190.70   | -0.35        | KG     | 15.9 | ...            | ...         | ...            | ...         |
| 7.26    | 4198.13   | -0.30        | KG     | 10.3 | ...            | ...         | ...            | ...         |
| P II    |           |              |        |      |                |             |                |             |
| 5       | 4499.23   | +0.47        | WM     | ...  | 2.7            | -6.18       | 2.7            | -6.18       |
| 4602.07 | +0.74     | WM            | ...    | ...  | 2.9            | -6.62       | 2.9            | -6.62       |
| 4475.20 | +0.45     | WM            | ...    | ...  | 2.0            | -6.44       | 2.0            | -6.44       |
| 4420.71 | -0.48     | WM            | ...    | ...  | 2.8            | -6.27       | 2.8            | -6.27       |
| S II    |           |              |        |      |                |             |                |             |
| 1       | 5027.20   | -0.71        | KX     | 26.3 | ...            | ...         | ...            | ...         |
| 7       | 4925.35   | -0.24        | KX     | 31.9 | ...            | ...         | ...            | ...         |
| 5009.56 | -0.09     | KX            | 32.1   | ...  | 9.5            | -4.87       | 9.5            | -4.87       |
| 5032.45 | +0.18     | KX            | ...    | ...  | 15.9           | -5.03       | 15.9           | -5.03       |
| 9       | 4656.78   | -0.81        | WS     | ...  | 7.8            | -4.52       | 7.8            | -4.52       |
| 4716.26 | -0.41     | WS            | 24.5   | ...  | 7.4            | -5.03       | 7.4            | -5.03       |
| 4815.55 | +0.09     | FW            | 49.8   | ...  | ...            | ...         | ...            | ...         |
| 4885.65 | -0.74     | KX            | 15.7   | ...  | ...            | ...         | ...            | ...         |
| 14      | 5647.20   | +0.04        | KX     | 41.6 | ...            | ...         | ...            | ...         |
| 5819.27 | -0.76     | WS            | 8.2    | ...  | ...            | ...         | ...            | ...         |
| 15      | 4917.21   | -0.32        | WS     | 22.7 | 5.1            | -5.07       | 5.1            | -5.07       |
Table A.8: - continued

| Species | Multiplet | $\lambda$(Å) | log gf | Ref. | $W_{\lambda}$(mA) | log N/N$_T$ | $W_{\lambda}$(mA) | log N/N$_T$ |
|---------|-----------|---------------|--------|------|-------------------|-------------|-------------------|-------------|
| S II    | (continued) |             |        |      |                   |             |                   |             |
| 17      | 6397.36   | -1.02        | KX     | 15.8 | -4.28             | ...         | ...               | ...         |
| 29      | 3993.50   | -0.82        | KX     | 11.5 | -4.63             | ...         | ...               | ...         |
| 35      | 4391.82   | -0.56        | WS     | ...  | ...               | 2.5         | -4.65             |             |
| 40      | 4524.95   | +0.08        | WS     | 23.0 | -4.63             | 8.8         | -4.96             |             |
| 43      | 4456.39   | -0.56        | KX     | 3.7  | -4.74             | ...         | ...               |             |
|         | 4463.58   | -0.02        | KX     | 13.3 | -4.50             | 6.6         | -4.60             |             |
|         | 4483.42   | -0.43        | WS     | ...  | ...               | 3.5         | -5.15             |             |
|         | 4486.66   | -0.40        | FW     | 6.4  | -4.60             | 3.7         | -4.65             |             |
| 44      | 4142.25   | +0.24        | WS     | 14.6 | -4.84             | 10.1        | ...               |             |
|         | 4145.07   | +0.23        | KX     | 25.9 | -4.37             | 13.9        | ...               |             |
|         | 4148.37   | -0.16        | WS     | 7.3  | -4.86             | 4.3         | -4.88             |             |
| 44.64   | 4189.68   | -0.04        | WS     | 7.3  | -4.37             | ...         | ...               |             |
|         | 4162.67   | +0.78        | WS     | 14.5 | -4.86             | ...         | ...               |             |
| 45      | 3990.94   | -0.30        | WS     | 11.5 | -4.29             | 3.7         | -4.89             |             |
|         | 4028.75   | 0.00         | WS     | 18.4 | -4.31             | 7.7         | -4.74             |             |
|         | 4050.08   | +0.75        | KX     | 4.9  | -4.49             | ...         | ...               |             |
| 46      | 4900.51   | +0.31        | KX     | 4.7  | -4.45             | 5.7         | -4.58             |             |
| 49      | 4267.80   | +0.28        | WS     | 21.7 | -4.41             | ...         | ...               |             |
|         | 4269.73   | -0.12        | WS     | 8.6  | -4.68             | 3.3         | -4.92             |             |
|         | 4278.50   | -0.12        | WS     | 5.9  | -4.90             | 6.1         | -4.59             |             |
| 59      | 3979.83   | -0.26        | WS     | ...  | ...               | 5.8         | -4.55             |             |
| 66      | 4257.38   | -0.01        | KX     | 5.9  | -4.47             | ...         | ...               |             |
|         | 5103.34   | -0.28        | KX     | 18.8 | -4.76             | ...         | ...               |             |
| Ca I    |            | log Ca/N$_T$ | = -4.35 |      | log Ca/N$_T$ = -4.35 | ...         | ...               |             |
| 2       | 4226.73   | +0.24        | FW     | 7.0  | -4.35             | 6.3         | -5.82             |             |
| Ca II   |            | log Ca/N$_T$ | = -4.77 |      | log Ca/N$_T$ = -4.77 | -5.74±0.08 | ...               |             |
| 1       | 3933.64   | +0.13        | FW     | 618.0| -4.35             | 524.0       | -5.82             |             |
| 15      | 5001.49   | -0.52        | KX     | ...  | ...               | 11.9        | -5.64             |             |
| 15      | 5019.98   | -0.26        | KX     | ...  | ...               | 15.2        | -5.77             |             |
| Sc II   |            | log Sc/N$_T$ | =-9.32±0.20 |      | log Sc/N$_T$ = -9.32±0.20 | -9.45±0.21 | ...               |             |
| 7       | 4246.82   | +0.32        | MF     | 8.7  | -9.55             | 26.2        | -9.83             |             |
| 14      | 4374.16   | -0.42        | LD     | ...  | ...               | 7.9         | -9.49             |             |
|         | 4400.36   | -0.53        | LD     | ...  | ...               | 6.1         | -9.50             |             |
|         | 4415.56   | -0.68        | LD     | ...  | ...               | 6.8         | -9.31             |             |
| 15      | 4314.08   | -0.09        | LD     | ...  | ...               | 22.3        | -9.31             |             |
|         | 4320.73   | -0.26        | LD     | 2.7  | -9.34             | 10.0        | -9.55             |             |
|         | 4324.99   | -0.44        | MF     | 3.3  | -9.08             | ...         | ...               |             |
| 24      | 4670.40   | -0.37        | LD     | ...  | ...               | 7.6         | -9.12             |             |
| Ti II   |            | log Ti/N$_T$ | =-7.42±0.21 |      | log Ti/N$_T$ = -7.42±0.21 | -7.49±0.19 | ...               |             |
| 11      | 3981.99   | -2.91        | PT     | ...  | ...               | 5.7         | -7.09             |             |
|         | 3987.60   | -2.93        | PT     | ...  | ...               | 2.5         | -7.42             |             |
|         | 4025.13   | -2.14        | PT     | ...  | ...               | 16.0        | -7.37             |             |
| 17      | 4762.78   | -2.74        | PT     | ...  | ...               | 4.3         | -7.13             |             |
| 18      | 4469.14   | -2.33        | PT     | ...  | ...               | 6.4         | -7.34             |             |
| 19      | 4450.49   | -1.52        | PT     | 9.5  | -7.28             | 20.0        | -7.62             |             |
| 20      | 4284.10   | -0.93        | PT     | ...  | ...               | 56.2        | -7.63             |             |
| 29      | 4344.24   | -1.91        | PT     | ...  | ...               | 8.7         | -7.62             |             |
| 29      | 4865.61   | -2.64        | PT     | ...  | ...               | 1.3         | -7.59             |             |
| 31      | 4501.27   | -0.77        | PT     | 19.9 | -7.66             | 58.9        | -7.77             |             |
Table A.8: - continued

| Species | Multiplet | $\lambda$(Å) | log gf | Ref. | $W_\lambda$(mÅ) | log N/N$_T^W$ | $\eta$ Leo | log N/N$_T^\lambda$ |
|---------|-----------|--------------|--------|------|-----------------|----------------|------------|-------------------|
| Ti II   | (continued) |              |        |      |                 |                |            |                   |
| 34      | 3913.46   | -0.42        | PT     | 33.1 | -7.71           | 86.6           | -7.74      |
| 40      | 4417.72   | -1.19        | PT     | 8.2  | -7.63           | 35.0           | -7.61      |
|         | 4441.73   | -2.33        | PT     | ...  | ...             | 3.2            | -7.60      |
|         | 4464.45   | -1.81        | PT     | ...  | ...             | 15.7           | -7.48      |
| 41      | 4300.06   | -0.44        | PT     | 39.3 | -7.58           | ...            | ...        |
|         | 4301.93   | -1.15        | PT     | 22.8 | -7.18           | 35.9           | -7.63      |
|         | 4307.90   | -1.02        | PT     | ...  | ...             | 43.5           | -7.65      |
|         | 4312.86   | -1.10        | PT     | 17.5 | -7.35           | 46.5           | -7.52      |
|         | 4314.97   | -1.08        | PT     | 17.0 | -7.37           | ...            | ...        |
|         | 4320.96   | -1.80        | PT     | 7.0  | -7.08           | ...            | ...        |
|         | 4330.71   | -1.96        | PT     | ...  | ...             | 6.0            | -7.68      |
|         | 4529.48   | -1.64        | PT     | ...  | ...             | ...            | ...        |
| 48      | 4763.88   | -2.36        | PT     | ...  | ...             | 3.4            | -7.53      |
| 50      | 4533.97   | -0.53        | PT     | 64.6 | -7.15           | 71.0           | -7.79      |
|         | 4653.76   | -0.69        | PT     | ...  | ...             | 55.8           | -7.81      |
| 51      | 4394.06   | -1.78        | PT     | ...  | ...             | 11.2           | -7.55      |
|         | 4399.77   | -1.19        | PT     | 8.7  | -7.56           | 28.6           | -7.67      |
|         | 4432.09   | -2.10        | MF     | ...  | ...             | 3.2            | -7.79      |
| 59      | 4657.21   | -2.24        | PT     | ...  | ...             | 9.2            | -7.18      |
| 60      | 4524.69   | -2.69        | PT     | ...  | ...             | 4.5            | -7.05      |
|         | 4544.02   | -2.58        | PT     | ...  | ...             | 3.4            | -7.28      |
|         | 4580.45   | -2.79        | MF     | ...  | ...             | 2.0            | -7.32      |
| 61      | 4391.03   | -2.28        | PT     | ...  | ...             | 5.5            | -7.37      |
|         | 4411.93   | -2.52        | PT     | ...  | ...             | 2.3            | -7.52      |
|         | 4423.24   | -2.67        | KX     | ...  | ...             | 1.6            | -7.53      |
| 70      | 5154.07   | -1.75        | PT     | ...  | ...             | 9.6            | -7.47      |
|         | 5188.66   | -1.05        | PT     | 7.6  | -7.59           | 21.9           | -7.77      |
| 71      | 5013.68   | -1.94        | KX     | ...  | ...             | 4.3            | -7.63      |
| 82      | 4571.97   | -0.32        | PT     | ...  | ...             | 78.8           | -7.71      |
| 86      | 5129.15   | -1.24        | PT     | ...  | ...             | 13.2           | -7.63      |
|         | 5185.91   | -1.49        | PT     | ...  | ...             | 10.7           | -7.48      |
| 87      | 4028.34   | -0.96        | MF     | ...  | ...             | 29.3           | -7.46      |
| 92      | 4779.99   | -1.37        | MF     | ...  | ...             | 14.7           | -7.34      |
|         | 4805.09   | -1.10        | MF     | 4.5  | -7.50           | ...            | ...        |
| 93      | 4421.95   | -1.66        | PT     | ...  | ...             | 6.3            | -7.42      |
| 94      | 4316.80   | -1.58        | PT     | ...  | ...             | 7.7            | -7.41      |
|         | 4330.23   | -1.73        | PT     | ...  | ...             | 5.7            | -7.40      |
|         | 4350.84   | -1.74        | PT     | ...  | ...             | 4.6            | -7.48      |
| 104     | 4367.66   | -0.86        | PT     | ...  | ...             | 14.6           | -7.51      |
|         | 4375.33   | -1.73        | PT     | ...  | ...             | 2.0            | -7.54      |
|         | 4386.84   | -0.96        | PT     | ...  | ...             | 14.3           | -7.42      |
| 105     | 4163.64   | -0.13        | PT     | 12.6 | -7.66           | 42.4           | -7.67      |
|         | 4171.90   | -0.29        | PT     | 17.8 | -7.08           | 48.9           | -7.42      |
|         | 4174.05   | -1.26        | PT     | ...  | ...             | 9.8            | -7.28      |
| 106     | 4064.35   | -1.60        | PT     | ...  | ...             | 2.5            | -7.55      |
| 113     | 5010.20   | -1.29        | PT     | ...  | ...             | 7.9            | -7.09      |
|         | 5072.27   | -1.06        | PT     | ...  | ...             | 6.7            | -7.37      |
| 114     | 4874.01   | -0.80        | PT     | ...  | ...             | 7.6            | -7.59      |
|         | 4911.18   | -0.34        | MF     | 4.7  | -7.38           | ...            | ...        |
| 115     | 4488.34   | -0.51        | PT     | 6.4  | -7.33           | 22.6           | -7.33      |
| H       | 4129.16   | -1.77        | PT     | ...  | ...             | 8.9            | -7.24      |
|         | 4188.98   | -0.60        | PT     | ...  | ...             | 1.4            | -7.15      |
| Species | Multiplet | $\lambda$(Å) | log gc | Ref. | $W_\lambda$(mÅ) | $\log N/N_T$ | $\log N/N_T$ |
|---------|-----------|--------------|--------|------|----------------|--------------|--------------|
| V II    | 9         | 3968.11      | -1.31  | BG   | ...            | ...          | 6.6          |
|         |           |              |        |      |                |              | 3.1          |
|         |           |              |        |      |                |              | 3.1          |
|         | 10        | 3916.42      | -1.05  | BG   | 4.8            | -8.24        | 9.4          |
|         | 11        | 3866.74      | -1.55  | BG   | ...            | ...          | 3.7          |
|         | 3863.07   | -0.89        | BG     | ...  | ...            | 11.1         | -8.47        |
|         | 25        | 4209.76      | -1.94  | KX   | ...            | ...          | 1.4          |
|         | 32        | 4005.71      | -0.52  | BG   | ...            | ...          | 3.7          |
|         | 3903.39   | -0.69        | BG     | ...  | ...            | 11.1         | -8.47        |
|         | 4035.63   | -0.77        | BG     | 5.1  | -8.29          | 9.5          |
|         | 10        | 4225.23      | -1.46  | BG   | ...            | ...          | 3.5          |
|         | 56        | 4528.50      | -1.46  | BG   | ...            | ...          | 5.1          |
|         | 4564.59   | -1.46        | BG     | ...  | ...            | 3.8          |
|         | 4600.19   | -1.46        | BG     | ...  | ...            | 2.0          |
|         | 156       | 3847.32      | -0.61  | KX   | 5.0            | -7.91        | 4.2          |
| Cr I    | 1         | 4254.33      | -0.11  | MF   | ...            | ...          | 3.9          |
|         | 4274.80   | -0.23        | MF     | ...  | ...            | 4.5          |
|         | 4289.72   | -0.36        | MF     | ...  | ...            | 3.5          |
|         | 5204.50   | -0.21        | MF     | ...  | ...            | 2.4          |
|         | 5206.02   | +0.02        | MF     | ...  | ...            | 3.3          |
|         | 5208.42   | +0.16        | MF     | ...  | ...            | 6.2          |
| Cr II   | 18        | 4112.54      | -3.02  | KX   | ...            | ...          | 2.8          |
|         | 4113.24   | -2.74        | MF     | 6.3  | -6.48          | 6.9          |
|         | 4087.60   | -3.22        | MF     | ...  | ...            | 3.9          |
|         | 5153.49   | -2.70        | KX     | ...  | ...            | 11.5         |
|         | 5210.86   | -2.95        | KX     | ...  | ...            | 4.3          |
|         | 4086.14   | -2.42        | KX     | ...  | ...            | 8.9          |
|         | 4179.42   | -1.77        | KX     | 14.7 | -6.66          | 29.4         |
|         | 4307.36   | -2.48        | KX     | 4.7  | -6.47          | 6.8          |
|         | 4812.34   | -1.80        | MF     | 11.0 | -6.77          | 14.5         |
|         | 4824.13   | -1.22        | MF     | ...  | ...            | 54.5         |
|         | 4836.23   | -2.25        | MF     | 16.8 | -6.12          | 17.2         |
|         | 4856.19   | -2.26        | MF     | 6.2  | -6.58          | 14.7         |
|         | 4884.61   | -2.08        | KX     | 8.1  | -6.63          | 12.3         |
|         | 4252.63   | -2.02        | KX     | ...  | ...            | 24.5         |
|         | 4261.92   | -1.53        | KX     | 35.1 | -6.43          | ...          |
|         | 4269.28   | -2.17        | KX     | 7.0  | -6.59          | 18.2         |
|         | 4275.58   | -1.71        | KX     | 21.9 | -6.51          | ...          |
|         | 4284.21   | -1.86        | KX     | 17.0 | -6.49          | 30.8         |
|         | 4539.62   | -2.53        | MF     | 9.5  | -6.50          | 11.2         |
|         | 4657.77   | -2.11        | MF     | 11.4 | -6.33          | 25.7         |
|         | 4555.02   | -1.38        | MF     | 28.0 | -6.61          | ...          |
|         | 4558.66   | -0.66        | MF     | 115.7| -6.18          | 128.5        |
|         | 4588.32   | -0.63        | MF     | 91.1 | -6.52          | 111.4        |
|         | 4592.04   | -1.42        | NL     | ...  | ...            | 56.6         |
|         | 4616.63   | -1.29        | MF     | ...  | ...            | 45.1         |
|         | 4618.80   | -1.00        | NL     | 61.9 | -6.39          | 85.3         |
|         | 4634.07   | -1.24        | MF     | ...  | ...            | 73.2         |

Table A.8: - continued
Table A.8:  - continued

| Species | Multiplet | $\lambda$(Å) | log gf | Ref. | $W_{\lambda}$(mA) | log N/N$_T$ | Cr II |
|---------|------------|--------------|--------|------|-------------------|--------------|-------|
| Cr II   | (continued) |              |        |      |                   |              |       |
| 129     | 3911.32    | -2.06        | KX     | ...  | ...               | 7.3 -6.36    |       |
| 130     | 3866.00    | -2.35        | KX     | ...  | ...               | 4.7 -6.28    |       |
| 162     | 4145.77    | -1.16        | KX     | ...  | ...               | 9.4 -6.24    |       |
| 167     | 3865.60    | -0.78        | KX     | ...  | 10.8 -6.02        | 27.2 -6.42   |       |
| 177     | 3905.64    | -0.90        | KX     | ...  | 24.9 -6.43        | ...          |       |
| 190     | 4145.77    | -1.16        | KX     | ...  | ...               | 9.4 -6.24    |       |
| 193     | 4256.17    | -1.39        | KX     | ...  | ...               | 3.9 -6.20    |       |
|         | 4070.84    | -0.75        | KX     | ...  | ...               | 13.7 -6.52   |       |
| Mn II   |              |              |        |      |                   |              |       |
| 2       | 4205.38    | -3.44        | KG     | ...  | ...               | 6.8 -6.94    |       |
| 5       | 4730.40    | -2.15        | KX     | ...  | 3.6 -6.22         | ...          |       |
| 6       | 4764.73    | -1.35        | KX     | ...  | 10.6 -6.52        | 12.9 -6.67   |       |
| 6       | 4326.64    | -1.36        | KS     | ...  | 8.6 -6.60         | ...          |       |
| 7       | 4343.98    | -1.10        | KX     | ...  | ...               | 9.8 -7.06    |       |
| 7       | 4296.37    | -1.55        | KS     | ...  | 6.1 -6.54         | 4.1 -7.00    |       |
| 1       | 4104.98    | -1.35        | KX     | ...  | ...               | 10.8 -6.53   |       |
| 20      | 3840.44    | -0.51        | N4     | ...  | 7.8 -4.54         | ...          |       |
| 22      | 3950.82    | -1.73        | N4     | ...  | ...               | 4.4 -4.45    |       |
| 41      | 4383.54    | +0.20        | N4     | 18.9 | -4.48             | ...          |       |
| 4        | 3859.91    | -0.71        | N4     | 18.9 | -4.48             | ...          |       |
| 4        | 3878.57    | -1.38        | N4     | ...  | 12.2 -4.87        | ...          |       |
| 4        | 3899.71    | -1.53        | N4     | ...  | 8.8 -4.88         | ...          |       |
| 4        | 3920.25    | -1.75        | N4     | ...  | 7.2 -4.73         | ...          |       |
| 4        | 3922.91    | -1.65        | N4     | ...  | 7.6 -4.85         | ...          |       |
| 4        | 3927.92    | -1.52        | N4     | ...  | 9.5 -4.84         | ...          |       |
| 4        | 3840.44    | -0.51        | N4     | 7.8  | -4.54             | ...          |       |
| 4        | 3950.82    | -1.73        | N4     | 7.8  | -4.54             | ...          |       |
| 41       | 4383.54    | +0.20        | N4     | 18.9 | -4.48             | ...          |       |
| 42       | 4404.75    | -0.14        | N4     | 14.9 | -4.33             | ...          |       |
| 43       | 4045.82    | +0.28        | N4     | 26.4 | -4.48             | ...          |       |

$\log$ Mn/N$_T$ = -6.48±0.12

$\log$ Fe/N$_T$ = -4.47±0.08

Fe I

| Species | Multiplet | $\lambda$(Å) | log gf | Ref. | $W_{\lambda}$(mA) | log N/N$_T$ | Mn II |
|---------|------------|--------------|--------|------|-------------------|--------------|-------|
| 4       | 3859.91    | -0.71        | N4     | 18.9 | -4.48             | ...          |       |
| 4       | 3878.57    | -1.38        | N4     | ...  | 12.2 -4.87        | ...          |       |
| 4       | 3899.71    | -1.53        | N4     | ...  | 8.8 -4.88         | ...          |       |
| 4       | 3920.25    | -1.75        | N4     | ...  | 7.2 -4.73         | ...          |       |
| 4       | 3922.91    | -1.65        | N4     | ...  | 7.6 -4.85         | ...          |       |
| 4       | 3927.92    | -1.52        | N4     | ...  | 9.5 -4.84         | ...          |       |
| 4       | 3840.44    | -0.51        | N4     | 7.8  | -4.54             | ...          |       |
| 4       | 3950.82    | -1.73        | N4     | 7.8  | -4.54             | ...          |       |
| 41      | 4383.54    | +0.20        | N4     | 18.9 | -4.48             | ...          |       |
| 42      | 4404.75    | -0.14        | N4     | 14.9 | -4.33             | ...          |       |

$\log$ Fe/N$_T$ = -4.56±0.20

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Table A.8: - continued

| Species | Multiplet | λ(Å) | log gf | Ref. | $W_\lambda$(mA) | log $N/N_T$ | $W_\lambda$(mA) | log $N/N_T$ |
|---------|-----------|------|--------|------|----------------|-------------|----------------|-------------|
| Fe I    | (continued) |      |        |      |                |             |                |             |
| 43      |           | 4071.74 | -0.02  | N4   | 14.8           | -4.40       | ...            | ...         |
| 68      |           | 4132.06 | -0.67  | N4   | ...            | ...         | 11.6           | -4.72       |
|         |           | 4442.34 | -1.26  | N4   | ...            | ...         | 1.9            | -4.60       |
|         |           | 4447.77 | -1.34  | N4   | ...            | ...         | 3.1            | -4.29       |
|         |           | 4459.12 | -1.28  | N4   | ...            | ...         | 3.5            | -4.33       |
|         |           | 4494.57 | -1.14  | N4   | ...            | ...         | 3.1            | -4.51       |
|         |           | 4598.61 | -0.82  | N4   | ...            | ...         | 6.8            | -4.49       |
| 71      |           | 4282.41 | -0.78  | N4   | ...            | ...         | 8.0            | -4.45       |
| 72      |           | 4352.74 | -1.29  | N4   | ...            | ...         | 1.9            | -4.56       |
| 152     |           | 4387.04 | -0.55  | N4   | ...            | ...         | 10.9           | -4.37       |
|         |           | 4187.80 | -0.55  | N4   | ...            | ...         | 28.9           | -3.90       |
|         |           | 4191.43 | -0.67  | N4   | ...            | ...         | 4.1            | -4.68       |
|         |           | 4210.35 | -0.93  | N4   | ...            | ...         | 2.8            | -4.58       |
|         |           | 4222.22 | -0.97  | N4   | ...            | ...         | 4.2            | -4.38       |
|         |           | 4233.60 | -0.60  | N4   | ...            | ...         | 12.0           | -4.26       |
|         |           | 4235.94 | -0.34  | N4   | ...            | ...         | 10.2           | -4.62       |
| 117     |           | 3589.21 | -0.75  | N4   | ...            | ...         | 4.0            | -4.63       |
|         |           | 3873.76 | -0.88  | N4   | ...            | ...         | 2.7            | -4.66       |
| 217     |           | 4095.97 | -1.48  | N4   | ...            | ...         | 1.6            | -4.21       |
| 221     |           | 3883.31 | -1.03  | N4   | ...            | ...         | 2.5            | -4.46       |
| 278     |           | 3956.67 | -0.43  | N4   | ...            | ...         | 5.9            | -4.61       |
|         |           | 3997.39 | -0.48  | N4   | ...            | ...         | 4.6            | -4.65       |
|         |           | 4021.87 | -0.73  | N4   | ...            | ...         | 4.1            | -4.44       |
| 280     |           | 3897.90 | -0.74  | N4   | ...            | ...         | 4.9            | -4.38       |
|         |           | 3907.94 | -1.12  | N4   | ...            | ...         | 2.0            | -4.36       |
| 282     |           | 4871.32 | -0.36  | N4   | ...            | ...         | 4.0            | -4.79       |
| 318     |           | 4872.14 | -0.57  | N4   | ...            | ...         | 2.3            | -4.82       |
|         |           | 4891.49 | -0.11  | N4   | ...            | ...         | 6.2            | -4.86       |
|         |           | 4918.99 | -0.34  | N4   | ...            | ...         | 1.0            | -4.80       |
|         |           | 4920.50 | +0.07  | N4   | ...            | ...         | 10.1           | -4.82       |
| 350     |           | 5006.12 | -0.62  | N4   | ...            | ...         | 3.7            | -4.59       |
|         |           | 4443.19 | -1.04  | N4   | ...            | ...         | 3.2            | -4.20       |
|         |           | 4466.55 | -0.60  | N4   | ...            | ...         | 5.4            | -4.43       |
|         |           | 4476.55 | -0.82  | N4   | ...            | ...         | 3.7            | -4.37       |
| 354     |           | 4107.49 | -0.88  | N4   | ...            | ...         | 1.6            | -4.67       |
|         |           | 4156.80 | -0.81  | N4   | ...            | ...         | 3.3            | -4.42       |
|         |           | 4175.64 | -0.83  | N4   | ...            | ...         | 3.4            | -4.38       |
|         |           | 4181.75 | -0.37  | N4   | ...            | ...         | 6.1            | -4.59       |
| 355     |           | 4154.50 | -0.69  | N4   | ...            | ...         | 3.2            | -4.55       |
|         |           | 4134.68 | -0.65  | N4   | ...            | ...         | 4.5            | -4.44       |
|         |           | 4062.44 | -0.86  | N4   | ...            | ...         | 2.0            | -4.58       |
| 383     |           | 5191.45 | -0.55  | N4   | ...            | ...         | 7.0            | -4.25       |
|         |           | 5192.34 | -0.42  | N4   | ...            | ...         | 5.7            | -4.50       |
| 430     |           | 3918.64 | -0.73  | N4   | ...            | ...         | 4.4            | -4.25       |
|         |           | 3897.22 | -0.45  | N4   | ...            | ...         | 3.2            | -4.67       |
| 522     |           | 4199.10 | +0.16  | N4   | ...            | ...         | 11.8           | -4.69       |
| 523     |           | 3843.26 | -0.24  | N4   | ...            | ...         | 4.4            | -4.71       |
| 529     |           | 3839.26 | -0.33  | N4   | ...            | ...         | 3.5            | -4.73       |
| 554     |           | 4736.77 | -0.75  | N4   | ...            | ...         | 3.8            | -4.22       |
| 558     |           | 4070.77 | -0.85  | N4   | ...            | ...         | 2.8            | -4.21       |
|         |           | 4098.18 | -0.88  | N4   | ...            | ...         | 2.2            | -4.29       |
| Species | Multiplet | \( \lambda (\text{Å}) \) | \( \log gf \) | Ref. | \( W_{\lambda} (\text{mÅ}) \) | \( \log N/N_T \) | \( \log N/N_T \) |
|---------|-----------|----------------|---------|-------|----------------|-------------|-------------|
| Fe I    | (continued) |                |         |       |                |             |             |
| 559     | 4067.98   | -0.47          | N4      | ...   | 2.7            | -4.62       |             |
| 561     | 4005.24   | -0.61          | N4      | ...   | 10.4           | -4.62       |             |
| 562     | 3948.10   | -0.56          | N4      | ...   | 3.6            | -4.38       |             |
| 661     | 3951.16   | -0.30          | N4      | ...   | 1.8            | -4.92       |             |
| 664     | 3846.80   | -0.02          | N4      | ...   | 6.5            | -4.64       |             |
| 693     | 4225.45   | -0.51          | N4      | ...   | 2.7            | -4.47       |             |
| 695     | 4227.43   | 0.27           | N4      | ...   | 9.4            | -4.74       |             |
| 696     | 4126.18   | -0.92          | N4      | ...   | 2.0            | -4.24       |             |
| 800     | 4219.36   | +0.00          | N4      | ...   | 4.9            | -4.62       |             |
| 801     | 4118.55   | +0.22          | MF      | ...   | 6.9            | -4.68       |             |
| 965     | 5014.95   | -0.30          | N4      | ...   | 1.7            | -4.60       |             |
| 984     | 5005.71   | -0.18          | KX      | ...   | 2.7            | -4.55       |             |
| 1098    | 5162.29   | +0.02          | N4      | ...   | 2.2            | -4.67       |             |
| Fe II   | log Fe/N_T = -4.59 ± 0.21 |        |         |       | -4.67 ± 0.17  |             |             |
| 3       | 3914.50   | -4.37          | N4      | ...   | 46.1           | -4.50       |             |
| 3       | 3938.29   | -4.07          | N4      | 36.8  | -4.73          | 53.8        | -4.70       |
| 3       | 3945.25   | -4.44          | N4      | 17.3  | -4.74          | ...         |             |
| 3       | 3981.61   | -5.05          | N4      | 7.6   | -4.50          | ...         |             |
| 21      | 4177.69   | -3.75          | KX      | ...   | 66.1           | -4.38       |             |
| 22      | 4183.20   | -4.87          | KX      | ...   | 5.1            | -4.56       |             |
| 25      | 4634.61   | -5.35          | KX      | ...   | 2.5            | -4.44       |             |
| 26      | 4648.94   | -4.39          | KX      | ...   | 8.8            | -4.83       |             |
| 26      | 4670.18   | -4.07          | N4      | 18.4  | -4.62          | 16.1        | -4.87       |
| 27      | 4386.57   | -4.95          | KX      | ...   | 5.4            | -4.49       |             |
| 27      | 4461.43   | -4.11          | KX      | ...   | 18.8           | -4.75       |             |
| 28      | 4580.06   | -3.73          | KX      | ...   | ...            | ...         |             |
| 28      | 4128.74   | -3.58          | N4      | 33.7  | -4.78          | 46.4        | -4.77       |
| 28      | 4173.46   | -2.16          | N4      | ...   | 145.7          | -4.92       |             |
| 28      | 4233.17   | -1.81          | N4      | ...   | 198.4          | -4.52       |             |
| 28      | 4385.38   | -2.57          | MF      | 117.4 | -4.59          | ...         |             |
| 28      | 4416.83   | -2.60          | N4      | 120.5 | -4.52          | 107.7       | -4.90       |
| 28      | 4665.80   | -4.92          | KX      | ...   | 4.3            | -4.56       |             |
| 29      | 4087.27   | -4.52          | N4      | 6.1   | -4.67          | 8.1         | -4.73       |
| 29      | 4122.66   | -3.30          | N4      | 38.6  | -4.98          | 70.1        | -4.76       |
| 29      | 4178.86   | -2.44          | N4      | 165.3 | -4.98          | 138.9       | -4.74       |
| 29      | 4225.16   | -3.48          | N4      | 34.5  | -4.80          | 34.5        | -4.99       |
| 29      | 4369.40   | -3.58          | N4      | 26.7  | -4.81          | ...         |             |
| 30      | 3872.76   | -3.31          | KX      | 26.1  | -5.10          | ...         |             |
| 30      | 3908.54   | -4.80          | KX      | ...   | 2.8            | -4.85       |             |
| 30      | 3964.57   | -3.93          | KX      | ...   | 19.7           | -4.78       |             |
| 30      | 3974.16   | -4.05          | N4      | 19.7  | -4.52          | 37.1        | -4.36       |
| 30      | 4002.08   | -3.47          | KX      | ...   | 29.5           | -5.03       |             |
| 32      | 4314.31   | -3.48          | KX      | 33.9  | -4.83          | 33.9        | -5.01       |
| 32      | 4384.33   | -3.68          | N4      | 35.0  | -4.62          | 57.4        | -4.49       |
| 32      | 4413.60   | -4.19          | N4      | 10.6  | -4.71          | 19.0        | -4.61       |
Table A.8: - continued

| Species | Multiplet | $\lambda$(Å) | log gf | Ref. | $\sigma$ Cyg | $W_\lambda$(mÅ) | log N/N$^T$ | $\eta$ Leo | $W_\lambda$(mÅ) | log N/N$^T$ |
|---------|-----------|--------------|--------|------|------------|-----------------|------------|-----------|-----------------|------------|
| Fe II   | (continued) |              |        |      |            |                 |            |           |                 |            |
| 32      | 4439.13   | -5.27        | KX     | ...  | ...        | 2.1             | -4.53      |           |                 |            |
| 33      | 4372.22   | -4.38        | KX     | 3.1  | -5.07      | ...             | ...        |           |                 |            |
| 35      | 5161.18   | -4.48        | KX     | ...  | ...        | 9.4             | -4.55      |           |                 |            |
| 36      | 4993.35   | -3.68        | N4     | ...  | ...        | 39.9            | -4.65      |           |                 |            |
| 37      | 4472.92   | -3.53        | N4     | ...  | ...        | 41.5            | -4.75      |           |                 |            |
|         | 4489.18   | -2.97        | N4     | ...  | ...        | 93.8            | -4.67      |           |                 |            |
|         | 4491.40   | -2.64        | N4     | 95.9 | -4.77      | 101.5           | -4.89      |           |                 |            |
|         | 4515.34   | -2.36        | N4     | 126.9| -4.63      | ...             | ...        |           |                 |            |
|         | 4520.23   | -2.62        | N4     | 117.5| -4.51      | 114.1           | -4.79      |           |                 |            |
|         | 4582.84   | -3.06        | N4     | 53.2 | -4.89      | ...             | ...        |           |                 |            |
|         | 4629.34   | -2.26        | N4     | ...  | ...        | 131.4           | -4.93      |           |                 |            |
|         | 4666.76   | -3.33        | N4     | 41.8 | -4.78      | 47.3            | -4.88      |           |                 |            |
| 38      | 4508.28   | -2.35        | N4     | ...  | ...        | 157.3           | -4.45      |           |                 |            |
|         | 4522.63   | -1.99        | N4     | ...  | ...        | 183.1           | -4.46      |           |                 |            |
|         | 4541.52   | -2.97        | N4     | 79.2 | -4.65      | 90.3            | -4.70      |           |                 |            |
|         | 4576.33   | -2.92        | N4     | 74.3 | -4.77      | 77.8            | -4.91      |           |                 |            |
|         | 4583.83   | -1.74        | N4     | ...  | ...        | 9.0             | -4.79      |           |                 |            |
|         | 4595.68   | -4.26        | KX     | ...  | ...        | 43.5            | -4.90      |           |                 |            |
|         | 4620.51   | -3.19        | N4     | 45.3 | -4.90      | ...             | ...        |           |                 |            |
| 39      | 4088.76   | -4.81        | KX     | ...  | ...        | 5.2             | -4.49      |           |                 |            |
|         | 4138.40   | -4.47        | KX     | ...  | ...        | 12.1            | -4.46      |           |                 |            |
| 42      | 5019.45   | -2.70        | KX     | 16.6 | -4.43      | ...             | ...        |           |                 |            |
| 43      | 4566.97   | -3.57        | N4     | ...  | ...        | 30.7            | -4.86      |           |                 |            |
|         | 4731.44   | -3.13        | N4     | 45.4 | -4.90      | ...             | ...        |           |                 |            |
| 54      | 4720.15   | -4.82        | N4     | ...  | ...        | 3.5             | -4.47      |           |                 |            |
| 74      | 6416.96   | -2.88        | N4     | 42.2 | -4.63      | ...             | ...        |           |                 |            |
| 126     | 4032.94   | -2.70        | KX     | ...  | ...        | 35.9            | -4.73      |           |                 |            |
| 127     | 4046.81   | -4.10        | KX     | ...  | ...        | 2.6             | -4.60      |           |                 |            |
| 141     | 4147.27   | -3.51        | KX     | ...  | ...        | 6.3             | -4.72      |           |                 |            |
| 148     | 4180.97   | -3.64        | N4     | ...  | ...        | 3.8             | -4.76      |           |                 |            |
| 149     | 4182.69   | -3.66        | KX     | ...  | ...        | 2.3             | -4.96      |           |                 |            |
| 150     | 4138.23   | -3.18        | N4     | ...  | ...        | 8.8             | -4.84      |           |                 |            |
| 152     | 3863.38   | -2.87        | KX     | ...  | ...        | 10.8            | -5.05      |           |                 |            |
| 153     | 3827.08   | -2.36        | N4     | ...  | ...        | 51.2            | -4.71      |           |                 |            |
| 167     | 5127.86   | -2.54        | KX     | ...  | ...        | 26.3            | -4.44      |           |                 |            |
| 167     | 5160.83   | -2.64        | KX     | ...  | ...        | 22.9            | -4.42      |           |                 |            |
| 169     | 4760.15   | -3.55        | KX     | ...  | ...        | 3.4             | -4.43      |           |                 |            |
| 170     | 4810.74   | -3.23        | KX     | ...  | ...        | 2.0             | -4.98      |           |                 |            |
| 171     | 4610.59   | -3.55        | KX     | 4.3  | -4.20      | ...             | ...        |           |                 |            |
| 172     | 4474.19   | -3.14        | KX     | ...  | ...        | 6.5             | -4.56      |           |                 |            |
| 173     | 4041.64   | -3.13        | KX     | ...  | ...        | 4.7             | -4.72      |           |                 |            |
| 174     | 4044.01   | -2.41        | KX     | ...  | ...        | 17.3            | -4.83      |           |                 |            |
| 175     | 4048.83   | -2.15        | KX     | ...  | ...        | 32.1            | -4.76      |           |                 |            |
| 176     | 4051.21   | -3.11        | KX     | ...  | ...        | 4.4             | -4.89      |           |                 |            |
| 177     | 3906.04   | -1.70        | N4     | 72.1 | -4.50      | 63.2            | -4.75      |           |                 |            |
| 186     | 4549.19   | -1.77        | N4     | ...  | ...        | 37.8            | -4.84      |           |                 |            |
| 187     | 4625.91   | -2.22        | KX     | ...  | ...        | 15.7            | -4.86      |           |                 |            |
| 188     | 4635.33   | -1.58        | N4     | 78.3 | -4.34      | 60.7            | -4.67      |           |                 |            |
| 189     | 4446.25   | -2.44        | KX     | 6.8  | -4.90      | 9.0             | -4.90      |           |                 |            |
| 190     | 4069.88   | -2.75        | KX     | ...  | ...        | 7.9             | -4.68      |           |                 |            |
|         | 4111.90   | -2.16        | KX     | 9.3  | -5.04      | ...             | ...        |           |                 |            |
|         | 3938.97   | -1.93        | N4     | ...  | ...        | 40.9            | -4.65      |           |                 |            |
### Table A.8 - continued

| Species | Multiplet (continued) | λ(Å) | log gf | Ref. | $\sigma$ Cyg | $\eta$ Leo |
|---------|------------------------|------|--------|------|-------------|-------------|
|         |                        |      |        |      | $W_\lambda$(mÅ) | log N/N$_T$ | $W_\lambda$(mÅ) | log N/N$_T$ |
| Fe II   |                        |      |        |      |             |             |             |             |
| 190     | 3996.35                | -2.93| KX     | 4.8  | -4.57       | 3.2         | -4.89       |             |
| 212     | 3960.90                | -1.42| KX     | 21.3 | -4.70       | 23.5        | -4.76       |             |
| 213     | 4354.34                | -1.74| KX     | 22.1 | -4.16       | 19.1        | -4.34       |             |
| 219     | 4507.10                | -1.92| KX     | 11.4 | -4.25       | 9.4         | -4.43       |             |
|         | 4598.53                | -1.50| KX     | 10.9 | -4.67       | ...         | ...         |             |
|         | 4625.55                | -2.07| KX     | ...  | ...         | 4.3         | -4.58       |             |
|         | 4631.87                | -1.87| KX     | ...  | ...         | 6.9         | -4.57       |             |
| 220     | 4313.03                | -1.71| KX     | ...  | ...         | 4.8         | -4.95       |             |
|         | 4318.19                | -1.98| KX     | ...  | ...         | 7.6         | -4.43       |             |
|         | 4319.68                | -1.69| KX     | ...  | ...         | 11.8        | -4.53       |             |
|         | 4321.31                | -1.83| KX     | ...  | ...         | 10.5        | -4.43       |             |
| 221     | 5081.90                | -0.59| KX     | ...  | ...         | 4.7         | -4.69       |             |
| 222     | 4431.64                | -1.77| KX     | ...  | ...         | 9.7         | -4.49       |             |
|         | 4449.66                | -1.59| KX     | 11.3 | -4.50       | 9.9         | -4.66       |             |
| D       | 3844.79                | -0.96| KX     | ...  | ...         | 12.3        | -4.65       |             |
|         | 3894.63                | -1.83| KX     | ...  | ...         | 6.7         | -4.82       |             |
|         | 3898.62                | -1.64| KX     | 6.2  | -4.92       | 14.1        | -4.66       |             |
|         | 3922.04                | -1.07| KX     | ...  | ...         | 5.7         | -4.86       |             |
|         | 4202.52                | -2.33| KX     | ...  | ...         | 11.2        | -4.46       |             |
|         | 4319.42                | -2.12| KX     | ...  | ...         | 6.5         | -4.48       |             |
|         | 4354.30                | -1.40| KX     | 22.1 | -4.50       | ...         | ...         |             |
|         | 4384.08                | -2.28| KX     | ...  | ...         | 12.9        | -4.75       |             |
|         | 4418.98                | -1.97| KX     | ...  | ...         | 8.2         | -4.49       |             |
|         | 4467.97                | -2.33| KX     | ...  | ...         | 4.8         | -4.38       |             |
|         | 4487.50                | -2.14| KX     | 8.9  | -4.18       | 9.0         | -4.28       |             |
|         | 4569.02                | -1.84| KX     | 42.6 | -4.42       | ...         | ...         |             |
|         | 4638.05                | -1.52| KX     | 13.2 | -4.61       | ...         | ...         |             |
| G       | 4213.52                | -2.21| KX     | 6.1  | -4.25       | ...         | ...         |             |
| J       | 4097.51                | -1.91| KX     | ...  | ...         | 5.5         | -4.78       |             |
|         | 4263.87                | -1.71| KX     | ...  | ...         | 16.0        | -4.44       |             |
|         | 4357.58                | -2.11| KX     | 38.4 | -4.29       | 31.9        | -4.52       |             |
|         | 4361.25                | -2.11| KX     | 19.7 | -4.63       | ...         | ...         |             |
|         | 4451.55                | -1.84| KX     | 36.3 | -4.57       | 36.3        | -4.68       |             |
|         | 4455.27                | -2.14| KX     | 25.5 | -4.42       | 29.5        | -4.45       |             |
|         | 4480.68                | -2.39| KX     | ...  | ...         | 10.0        | -4.75       |             |
|         | 4499.71                | -1.76| KX     | 11.0 | -4.46       | 10.5        | -4.58       |             |
|         | 4579.53                | -2.51| KX     | ...  | ...         | 17.5        | -4.36       |             |
|         | 4640.84                | -1.88| KX     | 7.6  | -4.51       | 9.2         | -4.51       |             |
|         | 4810.74                | -3.23| KX     | 7.0  | -4.31       | ...         | ...         |             |
|         | 4820.85                | -0.69| KX     | 3.3  | -4.76       | 4.3         | -4.70       |             |
|         | 4824.84                | -1.89| KX     | ...  | ...         | 2.6         | -4.83       |             |
|         | 4826.68                | -0.44| KX     | ...  | ...         | 5.7         | -4.83       |             |
|         | 4836.95                | -1.95| KX     | ...  | ...         | 2.0         | -4.87       |             |
|         | 4843.21                | -2.16| KX     | 10.5 | -4.14       | 3.9         | -4.68       |             |
|         | 4845.36                | -2.09| KX     | 4.6  | -4.27       | ...         | ...         |             |
|         | 4883.28                | -0.64| KX     | ...  | ...         | 6.0         | -4.61       |             |
|         | 4893.82                | -4.27| N4     | 7.6  | -4.71       | ...         | ...         |             |
|         | 4908.15                | -0.30| KX     | ...  | ...         | 8.7         | -4.74       |             |
|         | 4913.29                | +0.01| KX     | 20.9 | -4.58       | 16.0        | -4.76       |             |
|         | 4948.10                | -0.32| KX     | 12.8 | -4.49       | ...         | ...         |             |
|         | 4948.79                | -0.01| KX     | 13.1 | -4.77       | ...         | ...         |             |
|         | 4951.58                | 0.18 | KX     | 31.1 | -4.51       | ...         | ...         |             |
|         | 4953.98                | -2.76| KX     | 12.3 | -4.51       | ...         | ...         |             |
| Species | Multiplet  | \(\lambda\) (\(\text{Å}\)) | \(\log gf\) | Ref. | \(W_\lambda\) (m\(\text{Å}\)) | \(\log N/N_T\) | \(\sigma\) Cyg | \(W_\lambda\) (m\(\text{Å}\)) | \(\log N/N_T\) | \(\eta\) Leo |
|---------|------------|----------------|-----------|-----|----------------|----------------|------------|----------------|----------------|-----------|
| Fe II   | (continued)|               |           |     |                |                |            |                |                |           |
| 4974.22 | -0.84      | KX             | 6.8       | -4.26 | ...            | ...            | ...        | ...            | ...            | ...       |
| 4977.03 | 0.04       | KX             | 21.7      | -4.55 | ...            | ...            | ...        | ...            | ...            | ...       |
| 4977.92 | -0.67      | KX             | 8.4       | -4.33 | ...            | ...            | ...        | ...            | ...            | ...       |
| 4984.49 | +0.01      | KX             | 25.9      | -4.44 | 20.9          | -4.58          | ...        | ...            | ...            | ...       |
| 4990.50 | +0.18      | KX             | 28.5      | -4.55 | 28.8          | -4.56          | ...        | ...            | ...            | ...       |
| 4999.18 | -0.48      | KX             | ...       | ...    | 10.0          | -4.51          | ...        | ...            | ...            | ...       |
| 5000.74 | -4.74      | MF             | ...       | ...    | 7.8           | -4.42          | ...        | ...            | ...            | ...       |
| 5021.59 | -0.30      | KX             | 15.2      | -4.43 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5022.42 | -0.06      | KX             | ...       | ...    | 17.1          | -4.61          | ...        | ...            | ...            | ...       |
| 5022.79 | -0.02      | KX             | ...       | ...    | 21.2          | -4.56          | ...        | ...            | ...            | ...       |
| 5026.80 | -0.22      | KX             | ...       | ...    | 13.8          | -4.58          | ...        | ...            | ...            | ...       |
| 5070.90 | +0.24      | KX             | 31.6      | -4.56 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5082.23 | -0.10      | KX             | ...       | ...    | 11.4          | -4.74          | ...        | ...            | ...            | ...       |
| 5089.21 | -0.04      | KX             | 15.0      | -4.68 | 14.3          | -4.73          | ...        | ...            | ...            | ...       |
| 5106.11 | -0.28      | KX             | 11.7      | -4.56 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5107.11 | -0.73      | KX             | 4.2       | -4.58 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5112.99 | -0.50      | KX             | 6.8       | -4.56 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5115.06 | -0.45      | KX             | 7.1       | -4.57 | 6.5           | -4.65          | ...        | ...            | ...            | ...       |
| 5117.01 | -0.13      | KX             | 12.7      | -4.62 | 12.9          | -4.63          | ...        | ...            | ...            | ...       |
| 5119.34 | -0.56      | KX             | ...       | ...    | 5.4           | -4.64          | ...        | ...            | ...            | ...       |
| 5120.35 | -4.21      | KX             | 7.0       | -4.81 | 12.4          | -4.71          | ...        | ...            | ...            | ...       |
| 5132.66 | -4.09      | N4             | 10.6      | -4.75 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5143.88 | +0.10      | KX             | ...       | ...    | 14.4          | -4.79          | ...        | ...            | ...            | ...       |
| 5144.36 | +0.31      | N4             | 24.2      | -4.70 | 19.5          | -4.83          | ...        | ...            | ...            | ...       |
| 5149.46 | +0.55      | N4             | 43.4      | -4.57 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5150.49 | -0.12      | KX             | 13.0      | -4.60 | 13.2          | -4.62          | ...        | ...            | ...            | ...       |
| 5154.43 | -4.14      | KX             | 12.8      | -4.59 | 13.7          | -4.72          | ...        | ...            | ...            | ...       |
| 5157.28 | -0.31      | KX             | 17.1      | -4.27 | 12.0          | -4.47          | ...        | ...            | ...            | ...       |
| 5166.56 | -0.03      | KX             | ...       | ...    | 18.2          | -4.53          | ...        | ...            | ...            | ...       |
| 5179.78 | -0.36      | KX             | ...       | ...    | 9.8           | -4.52          | ...        | ...            | ...            | ...       |
| 5180.31 | +0.04      | KX             | 12.5      | -4.81 | 18.2          | -4.63          | ...        | ...            | ...            | ...       |
| 5186.87 | -0.30      | KX             | ...       | ...    | 9.0           | -4.99          | ...        | ...            | ...            | ...       |
| 5194.89 | -0.15      | KX             | 10.4      | -4.67 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5197.57 | -2.05      | N4             | 137.1     | -4.67 | 134.9         | -4.85          | ...        | ...            | ...            | ...       |
| 5199.12 | +0.10      | KX             | 23.3      | -4.55 | 20.3          | -4.64          | ...        | ...            | ...            | ...       |
| 5203.64 | -0.05      | KX             | 14.7      | -4.64 | 15.2          | -4.64          | ...        | ...            | ...            | ...       |
| 5643.88 | -1.46      | KX             | 10.3      | -4.68 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5645.39 | +0.09      | KX             | 19.1      | -4.53 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5648.90 | -0.24      | KX             | 9.0       | -4.57 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5783.63 | +0.21      | KX             | 16.1      | -4.81 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5811.63 | -0.49      | KX             | 9.5       | -4.26 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5813.82 | -2.75      | N4             | 14.3      | -4.44 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5823.15 | -2.99      | N4             | 7.3       | -4.51 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5835.49 | -2.37      | KX             | 12.2      | -4.71 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5842.30 | -0.21      | KX             | 7.3       | -4.60 | ...            | ...            | ...        | ...            | ...            | ...       |
| 5871.77 | +0.02      | KX             | ...       | ...    | ...            | ...            | ...        | ...            | ...            | ...       |
| 5785.14 | -2.05      | KX             | 34.8      | -4.26 | ...            | ...            | ...        | ...            | ...            | ...       |
| 6151.98 | +0.04      | KX             | ...       | ...    | 4.1           | -4.84          | ...        | ...            | ...            | ...       |
| 6622.76 | -0.28      | N4             | ...       | ...    | 3.0           | -4.63          | ...        | ...            | ...            | ...       |
| KX      | 6179.38    | -2.80 | N4 | 12.4 | -4.45 | 9.2 | -4.65 | | | | |
Table A.8: - continued

| Species | Multiplet | $\lambda$(Å) | log gf | Ref. | $\sigma$ Cyg | log N/N$_T$ | W$_\lambda$(mÅ) | log N/N$_T$ |
|---------|----------|-------------|--------|------|-------------|-------------|----------------|-------------|
| Fe III  |          |             |        |      | -4.60       | -4.57±0.14  |                |             |
|         | 4        | 4382.51     | -3.02  | KX   | ...         | 4.0         | -4.44          |             |
|         | 4        | 4395.76     | -2.60  | KX   | ...         | 8.5         | -4.44          |             |
|         | 4        | 4419.66     | -2.22  | KX   | 21.5        | 9.3         | -4.76          |             |
|         | 4        | 4431.02     | -2.57  | KX   | ...         | 6.3         | -4.63          |             |
| Co II   |          |             |        |      | log Co/N$_T$ = -6.91±0.12 | | | |
|         | KX       | 3983.02     | -2.35  | RP   | ...         | 4.6         | -6.88          |             |
|         | 4068.41  | -2.71       | RP     | ...  | ...         | 2.5         | -6.76          |             |
|         | 4569.25  | -2.40       | RP     | ...  | ...         | 2.8         | -7.06          |             |
| Ni II   |          |             |        |      | log Ni/N$_T$ = -5.92±0.08 | | | |
|         | 9        | 4244.80     | -3.11  | KX   | 8.4         | 10.6        | -5.89          |             |
|         | 12       | 4015.50     | -2.42  | KX   | 30.6        | 17.6        | -6.03          |             |
|         | 13       | 3881.91     | -1.96  | KX   | ...         | 2.3         | -5.64          |             |
|         | K        | 5003.41     | +0.70  | KX   | ...         | 5.9         | -5.61          |             |
| Sr II   |          |             |        |      | log Sr/N$_T$ = -9.26±0.06 | | | |
|         | 1        | 4077.71     | +0.14  | B    | 18.4        | 24.7        | -9.84          |             |
|         | 2        | 4215.52     | -0.18  | B    | 7.5         | 16.4        | -9.74          |             |
| Y II    |          |             |        |      | log Y/N$_T$ = -9.63 | | | |
|         | 13       | 4374.93     | +0.16  | HL   | 2.3         | 7.5         | -9.60          |             |
|         | 14       | 4177.52     | -0.16  | HL   | ...         | 7.5         | -9.60          |             |
|         | 22       | 4854.86     | -0.38  | HL   | ...         | 1.8         | -9.69          |             |
|         | 23       | 4883.68     | +0.07  | HL   | ...         | 6.0         | -9.55          |             |
|         | 24       | 4960.10     | +0.19  | HL   | ...         | 1.9         | -9.94          |             |
| Zr II   |          |             |        |      | log Zr/N$_T$ = -9.25 | | | |
|         | 15       | 4258.05     | -1.20  | LN   | ...         | 12.1        | -8.31          |             |
|         | 30       | 4045.64     | -0.86  | LN   | ...         | 6.9         | -8.80          |             |
|         | 41       | 4149.22     | -0.04  | LN   | 2.5         | ...         | ...            |             |
|         | 42       | 4034.10     | -1.51  | LN   | ...         | 2.5         | -8.54          |             |
|         | 54       | 4024.42     | -0.97  | LN   | ...         | 8.5         | -8.41          |             |
|         | 55       | 3941.92     | -1.50  | LN   | ...         | 3.5         | -8.27          |             |
|         | 79       | 4414.54     | -1.17  | LN   | ...         | 2.6         | -8.63          |             |
|         | 99       | 4231.64     | -1.02  | LN   | ...         | 2.9         | -8.40          |             |
| Ba II   |          |             |        |      | log Ba/N$_T$ = -9.25 | | | |
|         | 15       | 4554.03     | +0.14  | FW   | ...         | 4.1         | -10.10         |             |
|         | 42       | 4269.50     | +0.03  | KW   | ...         | 3.0         | -8.58          |             |
|         | 4619.87  | -0.14       | KW     | ...  | ...         | 2.9         | -8.46          |             |
| La II   |          |             |        |      | log La/N$_T$ = ... | | | |
|         | -        | 4269.50     | +0.03  | KW   | ...         | 3.0         | -8.58          |             |
|         | 4619.87  | -0.14       | KW     | ...  | ...         | 2.9         | -8.46          |             |
| Ce II   |          |             |        |      | log Ce/N$_T$ = -7.54±0.05 | | | |
|         | 6        | 4593.92     | +0.07  | ZS   | 6.5         | ...         | ...            |             |
|         | 15       | 5187.46     | -0.10  | ZS   | 2.9         | -7.47       | ...            |             |
|         | 22       | 4115.37     | +0.12  | PQ   | ...         | 3.2         | -8.50          |             |
|         | 37       | 3942.15     | -0.22  | PQ   | ...         | 3.5         | -8.69          |             |
|         | 59       | 4349.78     | -0.11  | ZS   | 3.9         | -7.59       | ...            |             |
|         | 159      | 4153.67     | +0.83  | PQ   | ...         | 2.8         | -8.59          |             |
| Eu II   |          |             |        |      | log Eu/N$_T$ = -8.84±0.01 | | | |
|         | 1        | 4129.70     | +0.22  | LW   | 8.8         | 5.6         | -9.85          |             |
|         | 5        | 3907.10     | +0.17  | LW   | 6.2         | 6.3         | -9.71          |             |
|         | 5        | 3907.49     | +0.27  | LW   | ...         | ...         | ...            |             |
Table A.8: - continued

| Species | Multiplet | $\lambda$(Å) | log gf | Ref. | $W_\lambda$(mÅ) | log $N/N_T$ | $W_\lambda$(mÅ) | log $N/N_T$ |
|---------|-----------|--------------|--------|------|-----------------|-------------|-----------------|-------------|
| Gd II   | 115       | 4463.24      | -0.97  | CB   | ...             | ...         | 8.3             | -7.75±0.14   |
|         | 4755.24   | -0.24        | CB     | ...  | ...             | ...         | 3.3             | -7.93       |
|         | 5130.27   | -0.95        | CB     | ...  | ...             | ...         | 3.3             | -7.66       |
|         | 5191.80   | -0.94        | KX     | ...  | ...             | ...         | 3.0             | -7.81       |
|         | 5210.48   | -0.93        | KX     | ...  | ...             | ...         | 5.2             | -7.58       |
| Dy II   | -         | 3872.10      | +0.01  | WL   | ...             | ...         | 8.3             | -9.07±0.14   |
|         | 4077.96   | -0.06        | WL     | ...  | ...             | ...         | 3.5             | -9.27       |
|         | 4103.30   | -0.38        | WL     | ...  | ...             | ...         | 3.5             | -8.95       |

Note: gf value references follow:
AT = Aldenius et al. (2007); B = Brage et al. (1998);
BG = Biemont et al. (1981) for Zr II, Biemont et al. (1989) for VII;
CB = Corlis & Bernard (1962); FW = Fuhr & Wiese (2002) and Fuhr et al. (1996);
HL = Hannaford et al. (1982); KG = Kling & Griesmann (2000); KS = Kling et al. (2001);
KX = Kurucz & Bell (1995); LA = Lanz & Artru (1989); LD = Lawler & Dakin (1989);
LN = Ljung et al. (2006); LW = Lawler et al. (2001); NL = Nilsson et al. (2006);
N4 = Fuhr & Wiese (2006); MF = Fuhr et al. (1988) and Martin et al. (1988);
RP = Raassen et al. (1999); PT = Pickering et al. (2001) and Pickering et al. (2002);
SG = Schulz-Guldet (1960); WF = Wiese et al. (1996); WL = Wihlbäck et al. (2001);
WM = Wiese & Martin (1980); WS = Wiese et al. (1969); ZS = Zhang et al. (2001);