Research Note

C, N, O in λ Boo stars and in composite spectra

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Abstract. The selective abundance of C, N, O (almost solar) with respect to that of other elements (underabundant) in λ Boo stars has been interpreted as a characteristic peculiarity of these objects, when considered as single stars. We show here that a similar selective abundance is predicted from the composite spectra resulting from two unresolved stars in the same temperature range as the λ Boo stars.

Key words. stars: atmospheres – stars: chemically peculiar – stars: binaries: spectroscopic

1. Introduction

Weak metal lines were discovered by Morgan et al. (1943) in the λ Boo spectrum; this star became the prototype of a new class of Ap stars when similar characteristics were detected in other A-type stars with small space velocity.

The almost solar abundance of oxygen in the λ Boo stars has been known for more than 40 years (Baschek & Searle 1969); however the solar C, N, O, and S abundances did not enter in the definition of this class until quite recently. The approximately solar abundances of C, N, O, and S are discussed by Venn & Lambert (1990) for 3 λ Boo stars. The interpretation, proposed by these authors of the dichotomy between the solar abundances of C, N, O, and S and those of the other elements (selective accretion of gas, but not dust from circumstellar or interstellar medium) is still the most widely accepted for these stars when considered as single peculiar objects.

On the basis of this paper by Venn & Lambert, Paunzen et al. (1997) introduced the definition of λ Boo class as “Pop I hydrogen burning A-type stars, which are, except of (sic) C, N, O and S, metal poor”. However several stars classified λ Boo in this paper do not belong to the A spectral type; for example, the following stars have $T_{\text{eff}}$ lower than 7000 K: HD 81290, HD 83041, HD 84948, HD 106223, HD 142994. One cause of concern in this definition is that the optical lines used to derive the abundances of C, N, O are of high excitation and show a non-monotonic behaviour with $T_{\text{eff}}$.

In 1999 Faraggiana & Bonifacio suggested that the λ Boo phenomenon could be produced by the combination of an unresolved binary composed of two stars with not very different L and $T_{\text{eff}}$. In the subsequent series of papers we demonstrated that this is indeed the case for a significant percentage of stars classified as λ Boo. In this paper we investigate theoretically the properties of composite spectra for the optical lines of C, N, O.

2. CNO line intensity variation with $T_{\text{eff}}$

We restrict the analysis to C, N, O since the abundance of S is very uncertain in λ Boo stars; Venn & Lambert (1990) did not measure any SI line in λ Boo, and the scatter of the S abundance is 0.5 dex between the 4 measured lines in 29 Cyg and 0.7 dex between the 2 lines measured in π 1 Ori.

Synthetic spectra were computed for solar abundances of all elements by using Kurucz (1993) model atmospheres and SYNTHE code; the atomic line data are taken from the modified Kurucz line lists available at the CDS and http://wwwuser.oat.ts.astro.it/castelli/stars.html (see also Castelli & Kurucz 2004). All the spectra have been computed by adopting $v \sin i = 50 \, \text{km s}^{-1}$, which is a lower limit for the λ Boo stars (see Table 4 in Gerbaldi et al. 2003). The selected spectral regions are those that include the C, N, O lines selected by Venn & Lambert (1990), and the computations were performed over a wavelength range broad enough to also include nearby lines of other “underabundant” elements. We added the OI 777.4 nm triplet region because this feature is often used for oxygen abundance determination.

The variations of EWs with spectral type or $T_{\text{eff}}$ were studied by Faraggiana et al. (1988) for oxygen and by Takeda & Takada-Hidai (1995) for nitrogen. In the first study the behaviour of the OI 777.4 nm triplet was studied and the result of the measured EWs vs. spectral type plotted in Figs. 2 and 3.
of that paper. The maximum intensity of this pattern is reached for late A-type stars of the main sequence. The high sensitivity to the log $g$ parameter does not alter the bell-shaped behaviour, which is enhanced at lower gravities even when the NLTE effect is included (Baschek et al. 1977). In the second paper the NI 870.3 and 862.9 nm are analyzed in A–F supergiants. The theoretical $\text{EW}$ vs. $T_{\text{eff}}$ are plotted in their Fig. 3; the bell-shaped variation, similar to that of OI triplet is evident. For both elements the line intensity reaches the maximum at $T_{\text{eff}}$ of about 8000 K and decreases for higher and lower temperatures. A similar study was not made for CI broad blends, as the carbon abundance was always derived by synthetic spectra analysis.

In order to show the behaviour of C, N, O, we computed synthetic spectra in the range of $T_{\text{eff}}$ between 7000 and 9000 K with 500 K steps and the results are plotted in Figs. 1 to 4. The small variations of C, N, O lines compared to those of other elements are evident in Figs. 1 to 3.

This result is the consequence of the fact that the excitation potentials of the lower level of the neutral C, N, O lines are rather high (about three times higher than those of other lines). Therefore, in going from $T_{\text{eff}} = 8000$ K to 7500 K, the number densities of the neutral species increases because of the shift in the ionization balance, at the same time the population of the highly excited levels decreases; the two effects partially cancel out so that the line strength is roughly the same.

3. CNO in composite spectra

CNO line intensities are almost constant in the $T_{\text{eff}}$ range 7000–9000 K, where most of the $\lambda$ Boo stars lie, and are equal for two $T_{\text{eff}}$ that are symmetric with respect to the maximum. If the composite spectrum is interpreted as due to a single object, the derived parameters are a weighted average of those of the components, and most of the metal lines appear too weak except for C, N, O lines, as observed in $\lambda$ Boo stars. In order to better illustrate this fact the following simulation was made.

4. Colours of a binary star

Given two stars of known $T_{\text{eff}}$ and log $g$, let us suppose we know the Strömgren colours of the two stars denoted as $A$ and $B$: $(b - y)_A, m_{1A}, c_{1A}$ and $(b - y)_B, m_{1B}, c_{1B}$. Furthermore suppose we know the flux ratios of the two stars in the four Strömgren bands: $p = F_{\lambda A}/F_{\lambda B}$, $q = F_{\nu A}/F_{\nu B}$, $r = F_{b A}/F_{b B}$, $s = F_{y A}/F_{y B}$. Let us then compute the Strömgren
colours of a binary system made up of stars A and B. The quantities referring to the binary system will have no sub-
scripts, while the ones referring to the single stars will have sub-
scripts A and B, respectively.

By definition \( b - y = -2.5 \log [(Fb/Fy)/(Fb/Fy)_s] \), where sub-
script s refers to the zero colour standard star (typically
Vega). Now \( Fb/Fy = (Fb_b/Fy_b) \times (r + 1)/(s + 1) \), hence,
\[
b - y = (b - y)_s - 2.5 \log [(r + 1)/(s + 1)].
\]
The definition of m1 is a bit more complex:
\[
m1 = (v - b) - (b - y) = -2.5 \log \left[ \frac{(Fv/Fy/Fb)^2}{(Fv/Fy/Fb)^2_s} \right].
\]

It can be shown that
\[
m1 = m1_b - 2.5 \log \left[ \frac{(q + 1)(s + 1)/(r + 1)^2} \right].
\]

Finally, since \( c1 = (a - v) - (v - b) \), it can be shown that
\[
c1 = c1_b - 2.5 \log \left[ \frac{(p + 1)(r + 1)/(q + 1)^2} \right].
\]

We shall now work out an example which applies the above
formulae. From the isochrone of Girardi et al. (2002) with \( Z = 0.01900 \), age = 10 Myr, we may read that a star of mass 1.5 \( M_\odot \)
has \( T_{\text{eff}} = 7185 \) K, \( \log g = 4.29 \), and a star of mass 1.95 \( M_\odot \) has
\( T_{\text{eff}} = 8997 \) K, \( \log g = 4.31 \). To compute the colours of a binary
system made by the above two stars, we refer to the 1.5 \( M_\odot \)
star as A and to the 1.95 \( M_\odot \) star as B. At our request L. Girardi
computed the Strömgren magnitudes for this isochrone, which
allowed us to compute the ratios (\( p = 0.363, q = 0.316, r = 0.258, s = 0.307 \))

The Strömgren colours of star B may be taken from the
grid by Castelli & Kurucz (2004) with solar metallicity and
microturbulent velocity of 2 km s\(^{-1}\). Just reading off this ta-
ble for the model with \( T_{\text{eff}} = 9000 \) K, \( \log g = 4.5 \), one finds
\( b - y \approx 0.035, m1_b = 0.211 \), and \( c1_b = 0.929 \). For the binary
system made of stars A and B we obtain \( b - y = 0.076, m1 = 0.120, c1 = 0.925 \). The well-known code TEFFLOGG of Moon &
Dworetsky (1985) also requires knowledge of the \( \beta \) magnitude
to determine the atmospheric parameters of the star; however
since for many stars the measure of \( \beta \) is not available, the com-
mon practice is to estimate \( \beta \) using the code UVBYBETA of Moon
(1985), which also estimates the reddening. Using the above
values we obtain a very small reddening \( E(b - y) = 0.002 \) and
\( \beta = 2.871 \); and by feeding this estimate and dereddened colours
to the code TEFFLOGG, we obtain \( T_{\text{eff}} = 8330 \) K, \( \log g = 4.21 \).

In the V band the luminosity ratio is \( L_{\text{A}}/L_{\text{B}} = 0.307 \), which
implies \( L_{\text{A}}/L_{\text{tot}} = 0.235 \) and \( L_{\text{B}}/L_{\text{tot}} = 0.765 \).

5. Simulated composite spectrum

In order to clarify the behaviour of the lines of these elements
in single and composite spectra in the \( T_{\text{eff}} \) domain covered by
\( \lambda \) Boo candidates we made some computed spectra simulations.
We compare the line intensity of C, N, O lines to those of other
elements in a single spectrum and also in a composite spectrum,
that, according to our binary hypothesis, may roughly represent

![Fig. 5. CI 710.893, 711.147, 711.318, 711.517, 711.699, and 711.966 nm in a composite spectrum simulating a \( \lambda \) Boo star (black line) and in the single one (grey line) based on the average parameters of this binary. Note that the very weak (so no-measurable in \( \lambda \) Boo stars) CaI 713.843 nm arising from a high EP level shows the same behaviour as CI lines.](http://www.edpsciences.org/aa)

![Fig. 6. The NI 744.230 and 746.831 nm in the same couple of computed spectra as those in Fig. 5.](http://dx.doi.org/10.1051/0004-6361:20042109)
In contrast, the CNO lines have practically the same intensity in both spectra.

6. Conclusion

We can conclude that an unresolved binary, if erroneously interpreted as a single object, produces average colours intermediate between those of the binary components, while the corresponding computed spectrum shows the same kind of abundance peculiarities as a $\lambda$ Boo spectrum. In particular, the apparently solar abundances of C, N, O in $\lambda$ Boo stars cannot be considered a selective criterion to distinguish single peculiar stars belonging to the $\lambda$ Boo class. We have thus shown that the effect of a combined spectrum is not necessarily to uniformly weaken the lines of all elements by the same amount. This implies that the deduced abundance pattern of a star with a composite spectrum, when interpreted as a single object, will be altered when compared to the real one.

The interpretation of the C, N, O abundances higher than that of Fe-peak elements remains ambiguous: it can be explained either as the effect of the "$\lambda$ Boo phenomenon" in a single star or as due to a binary system that shows a composite spectrum but has been analysed as single object.

Therefore the argument that a C, N, O pattern different from that of other elements is sufficient to classify a star as $\lambda$ Boo and to exclude that it is a binary with a composite spectrum appears unjustified. This argument cannot be used to reject our interpretation (see Acke & Waelkens 2004) that many $\lambda$ Boo stars are unresolved binaries with composite spectra.

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