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NLTE ANALYSES OF SDB STARS: PROGRESS AND PROSPECTS

N. Przybilla[1], M. F. Nieva[1,2] and H. Edelmann[1]

[1] *Remeis-Sternwarte Bamberg, Sternwartstrasse 7, D-96049 Bamberg, Germany*

[2] *Observatório Nacional, R. Gal. José Cristino 77, 20921-400, São Cristóvão, Rio de Janeiro, RJ, Brasil*

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Abstract. We report on preliminary results of a hybrid non-LTE analysis of high-resolution, high-S/N spectra of the helium-rich subdwarf B star Feige 49 and the helium-poor sdB HD 205805. Non-LTE effects are found to have a notable impact on the stellar parameter and abundance determination. In particular the He I lines show significant deviations from detailed balance, with the computed equivalent widths strengthened by up to ~35 %. Non-LTE abundance corrections for the metals (C, N, O, Mg, S) are of the order ~0.05 – 0.25 dex on the mean, while corrections of up to ~0.7 dex are derived for individual transitions. The non-LTE approach reduces systematic trends and the statistical uncertainties in the abundance determination. Consequently, non-LTE analyses of a larger sample of objects have the potential to put much tighter constraints on the formation history of the different sdB populations than currently discussed.

Key words: line: formation – stars: abundances – stars: atmospheres – stars: fundamental parameters – stars: evolution – hot subdwarfs

1. INTRODUCTION

Astrophysics faces the general difficulty that almost all relevant information cannot be directly inferred from observation. One has to rely on the interpretation of the radiation from a light-emitting plasma and its interaction with matter. Accurate physical modeling is crucial, with systematic uncertainties often dominating the error budget at present. In the case of subdwarf B (sdB) stars quantitative spectroscopy is well established, relying on grids of either line-blanketed LTE or metal-free non-LTE model atmospheres (e.g., Heber & Edelmann 2004 and references therein). Here we investigate what improvements on sdB analyses can be expected from a hybrid non-LTE method, which avoids the weaknesses of both traditional approaches by combining metal line-blanketed model atmospheres with non-LTE line formation. The impact on the stellar parameter determination is of special interest, as this provides the basis for all further interpretation. Then, in the second part, non-LTE metal abundances are determined from observations in the visual spectral range for the first time. More accurate stellar parameter and abundance determinations can be expected to shed further light on the formation mechanisms of sdB stars that have been debated over the last decades.

2. MODEL CALCULATIONS AND OBSERVATIONAL DATA

The model calculations are carried out in a hybrid approach, thus solving the (so-called) restricted non-LTE problem. Hydrostatic, plane-parallel and line-blanketed – via an opacity sampling (OS) technique – LTE model atmospheres are computed with the ATLAS12 code (Kurucz 1996), which is in particular suited for the analysis of chemically peculiar stars. Then, non-LTE line formation is performed on the resulting model stratifications. The coupled radiative transfer and statistical equilibrium equations are solved, and spectrum synthesis with refined line-broadening theories is performed using DETAIL and SURFACE (Giddings 1981; Butler & Giddings 1985). Both codes have undergone major revisions and improvements over the past few years. State-of-the-art non-LTE model atoms (see Table 1) are utilized for the stellar parameter and abundance determination.

The model atoms are largely based on data from quantum-mechanical *ab-initio* computations using the R-matrix method in the close-coupling approximation, which typically have uncertainties of the order ∼10–20 %. Data sources comprise the astrophysically motivated Opacity and IRON Project, but also the vast physics literature, see the original publications for details. This allows for a realistic treatment not only of the (non-local) radiative processes, which drive the departures from detailed balance. Also the thermalizing collisions are accurately represented for the relevant transitions, in contrast to the usual approach of applying simple approximation formulae, which can be in error by orders of magnitude. Finally, state-of-the-art line-broadening theories are accounted for, like the data of Stehlé & Hutcheon (1999) for the Stark broadening of the hydrogen lines.

Spectra of HD 205805 and Feige 49 were taken with FEROS (Kaufer et al. 1999) on the ESO 1.52 m and 2.2 m telescopes, respectively. The Echelle spectra were reduced using standard procedures, giving complete wavelength coverage of the entire visual spectral region at high S/N (>100) and high resolution ($R \simeq 48\,000$).

3. STELLAR PARAMETERS

Standard methods are used for the stellar parameter determination, by simultaneous fitting the hydrogen Balmer and helium line profiles, and when possible utilizing the He I/II ionization balance. We deviate from the usual approach based on χ^2-fitting on grids of synthetic spectra, because of the largely increased computational expenses for OS model atmospheres and non-LTE line formation. For

Table 1. Non-LTE model atoms.

Ion	Source
H	Przybilla & Butler (2004)
He I/II	Przybilla (2005)
C II/III	Nieva & Przybilla (in prep.)
N II/III	Przybilla & Butler (2001), with extensions
O II	Becker & Butler (1988)
Mg II	Przybilla et al. (2001)
S II/III	Vrancken et al. (1996), with updated atomic data

Table 2. Stellar parameters.

	HD 205805	Feige 49
$T_{\rm eff}$ (K)	25 000	35 000
$\log g$ (cgs)	5.00	5.25
ξ (km/s)	0	2
y	0.01	0.15
$v \sin i$ (km/s)	0	0

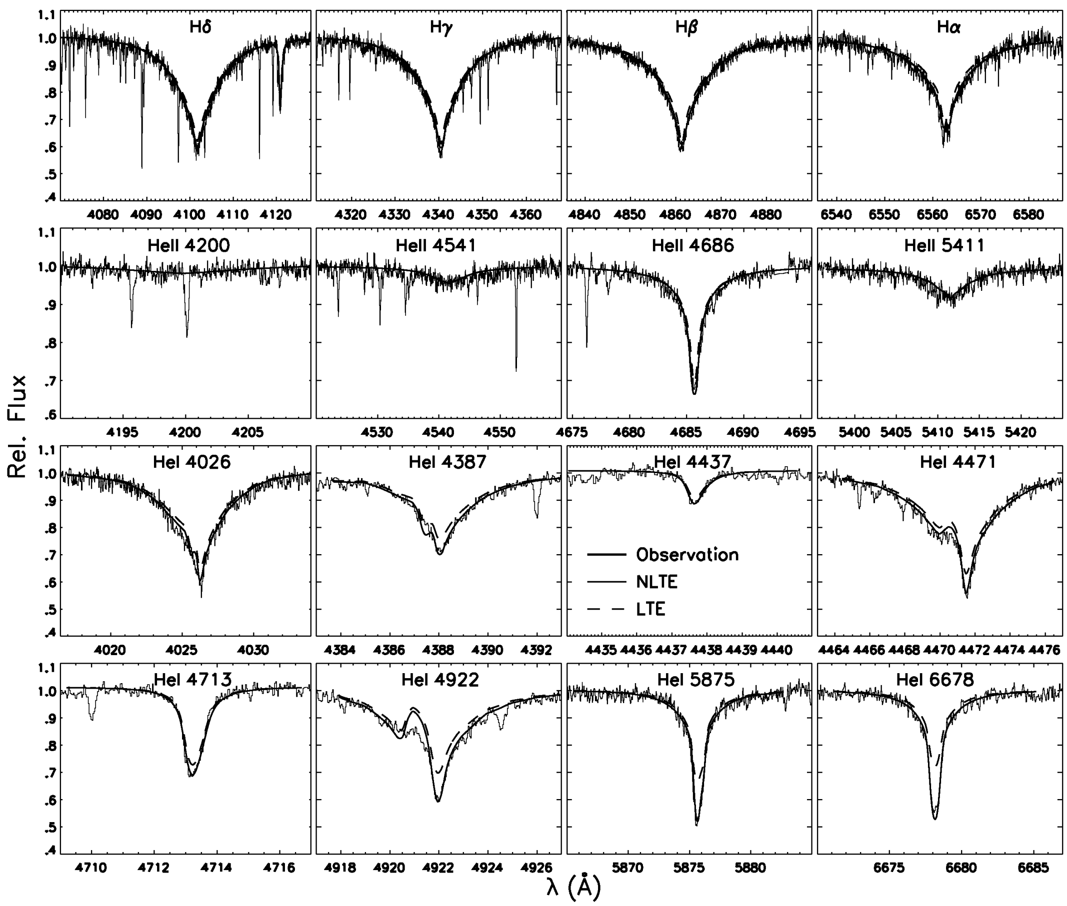

Fig. 1. Fits to H and He lines in the helium-rich sdB Feige 49.

the moment, the fits are done by eye. The resulting stellar parameters, effective temperature $T_{\rm eff}$, surface gravity $\log g$, microturbulence ξ, helium abundance y (by number) and projected rotational velocity $v \sin i$, are summarized in Table 2.

Examples for the quality of the modeling achievements are displayed in Figures 1 and 2, where our spectrum synthesis for several diagnostic features (grey lines) is compared to observation (histogram) for the two sample stars. Obviously, non-LTE line formation (full lines) improves enormously on the LTE spectrum synthesis for identical stellar parameters (dashed lines), resulting in a practically perfect match of theory and observation (except for the forbidden component of He I at 4922 Å).

The largest discrepancies between non-LTE and LTE results occur for some He I lines. Non-LTE equivalent widths are larger by up to ∼35 % in particular for the strong features in the red. Both, line wings and cores can be affected. This is because the lower levels of the transitions (for principal quantum number $n = 2$) are overpopulated relative to states at higher excitation energy that couple closely to the He II ground state, which is in detailed balance. Among the He II lines only the He II 4686 Å line gets slightly strengthened by non-LTE effects. A similar situation as with the He I lines occurs with the hydrogen Balmer lines because of an analogous non-LTE overpopulation of the $n = 2$ level, which also can affect the line wings (most notable for Hα in Feige 49). The non-LTE effects get reduced with decreasing temperature. In HD 205805 only the line cores are affected.

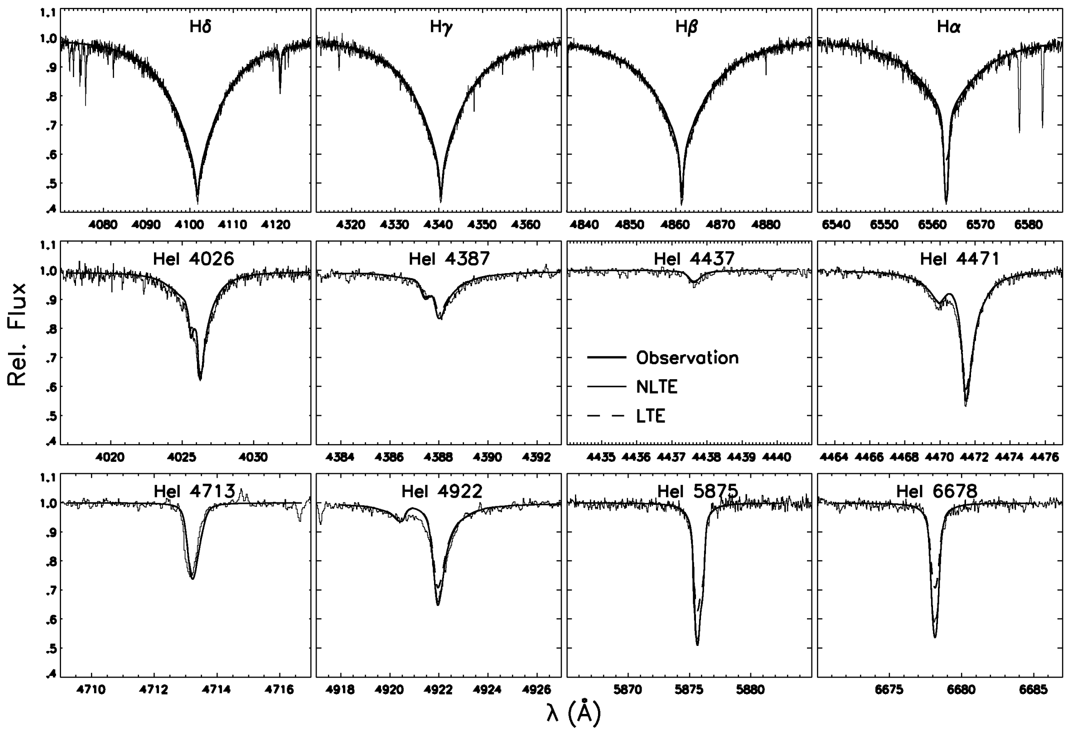

Fig. 2. Fits to H and He lines in the helium-poor sdB HD 205805.

It is obvious that the overall differences in the fitting process will impact the stellar parameter determination. In the present case this transfers into a $\Delta T_{\rm eff}$ of +1000 and +1200 K and a $\Delta \log g$ of +0.10 and +0.12 dex for Feige 49 and HD 205805 relative to the LTE results of Edelmann et al. (2006). These *systematic* shifts are slightly larger than the typically attributed uncertainties of sdB analyses. Further refinements can be expected from the use of (multiple) non-LTE ionization equilibria of metals which are even more sensitive to stellar parameter changes than the hydrogen and helium lines. So far, only the S II/III ionization equilibrium has been used to verify the parameter determination for HD 205805 from H and He line profile fits (see below).

4. ELEMENTAL ABUNDANCES

Besides unbiased stellar parameters, which are a prerequisite for meaningful comparisons with stellar evolution computations, also the surface abundances of the heavier elements bear important information. They allow to put observational constraints on formation/evolution scenarios of the stars and on transport processes (in particular diffusion for sdBs) in stellar atmospheres.

For the time being, non-LTE abundances are determined only for H, He, C, N, O and the α-elements Mg and S because we lack realistic non-LTE model atoms for the other chemical species. The lighter elements are of interest because of their involvement in fusion reactions, either as catalysts or as burning products, thus giving clues on the nature of the sdB progenitors. The α-process elements on the other hand can be used as tracers for the stellar metallicity. All the present-day abundances may be of course subject to diffusion. We intend to extend the study to Al, Si and Fe in the near future. Work on this is in progress.

Elemental abundances are derived from line profile fits using a χ^2-minimization

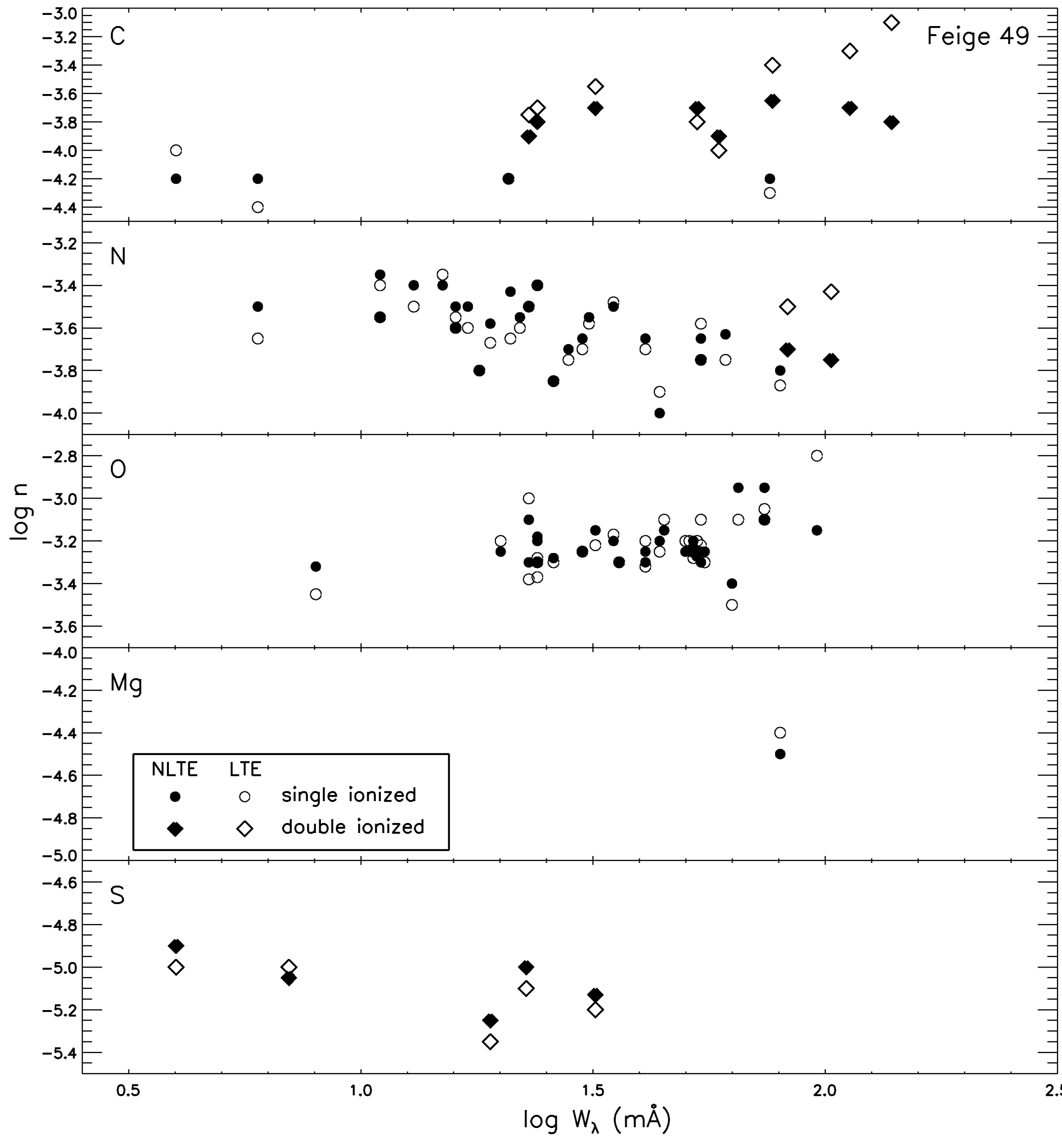

Fig. 3. Elemental abundances in Feige 49 from individual spectral lines.

technique based on small grids of synthetic spectra with varying abundances for given stellar parameters. This puts tighter constraints than the standard equivalent-width analysis. Abundances (by number) from individual spectral lines as a function of equivalent width are displayed in Figures 3 and 4. Non-LTE abundances are denoted by full and LTE results by open symbols; circles mark single-ionized and diamonds double-ionized species. The grey bands indicate the 1σ-uncertainty range of the resulting abundances for the chemical species.

The results have to be viewed as preliminary, as abundances from the different ionization stages of the elements – in particular C II/III and N II/III – indicate a need to improve on the stellar parameters. Metal ionization equilibria react much more sensitively to changes than the hydrogen and helium lines, such that the necessary fine-adjustments will barely impact the fit quality of the latter. However, already now the advantages of non-LTE computations become apparent: a tendency towards a reduced statistical scatter relative to LTE and a reduction of systematic trends, like for N II in HD 205805. The aim is to push the statistical 1σ-

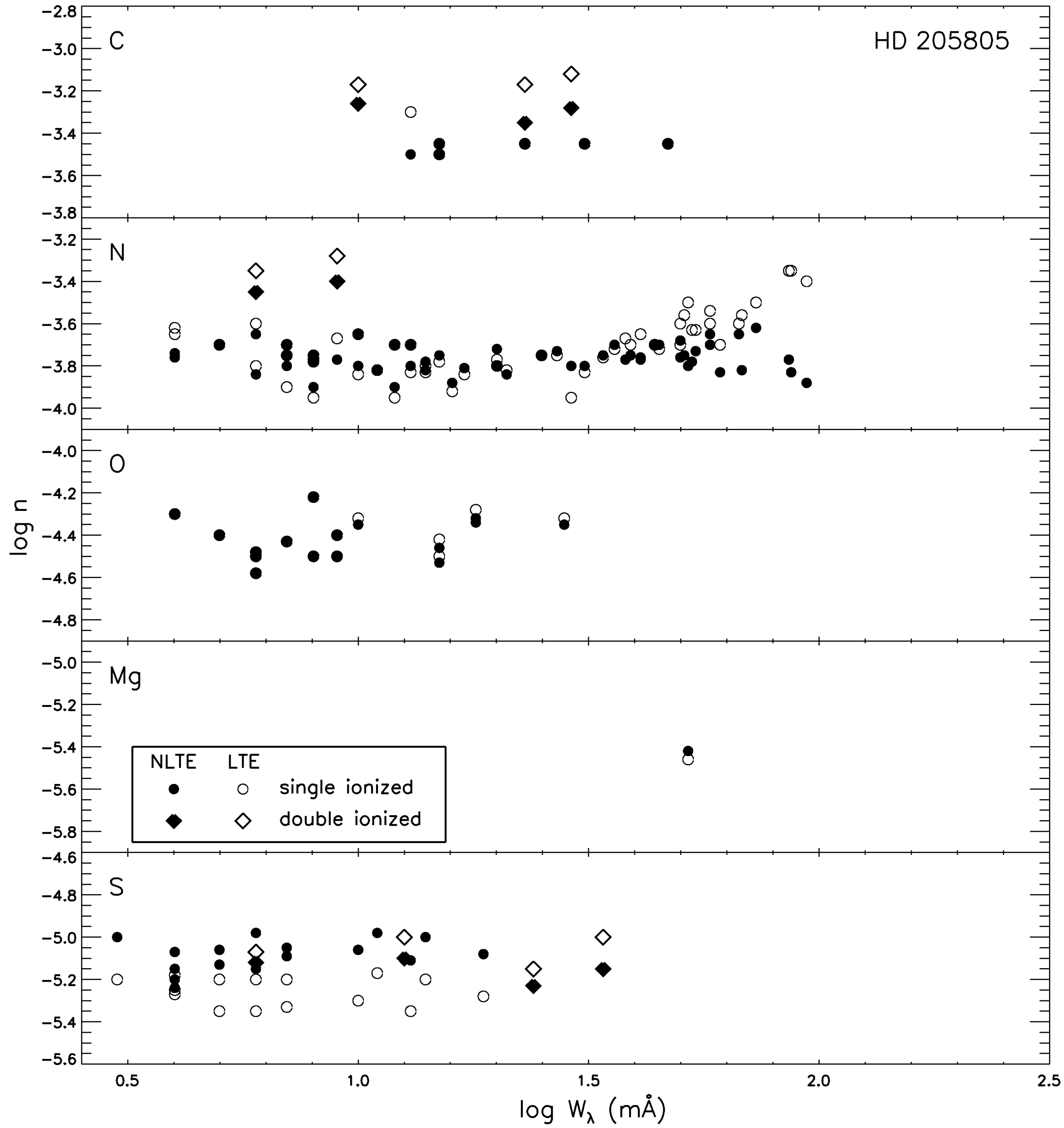

Fig. 4. Elemental abundances in HD 205805 from individual spectral lines.

Table 3. Metal abundances in the sample stars, relative to the solar standard (Grevesse & Sauval 1998): [log n] = log $n_\star$ − log $n_\odot$.

		C II	C III	N II	N III	O II	Mg II	S II	S III
Feige 49	NLTE	−0.72	−0.29	+0.48	+0.35	−0.05	−0.08	...	−0.27
		...	0.10	0.16	0.04	0.10	...	...	0.13
	LTE	−0.75	−0.10	+0.44	+0.61	−0.06	+0.02	...	−0.33
		0.17	0.30	0.15	0.05	0.14	...	...	0.15
HD 205805	NLTE	+0.01	+0.18	+0.32	+0.65	−1.25	−1.00	−0.28	−0.35
		0.03	0.05	0.06	0.04	0.10	...	0.08	0.06
	LTE	+0.05	+0.33	+0.38	+0.77	−1.24	−1.04	−0.46	−0.25
		0.07	0.03	0.14	0.05	0.10	...	0.07	0.07

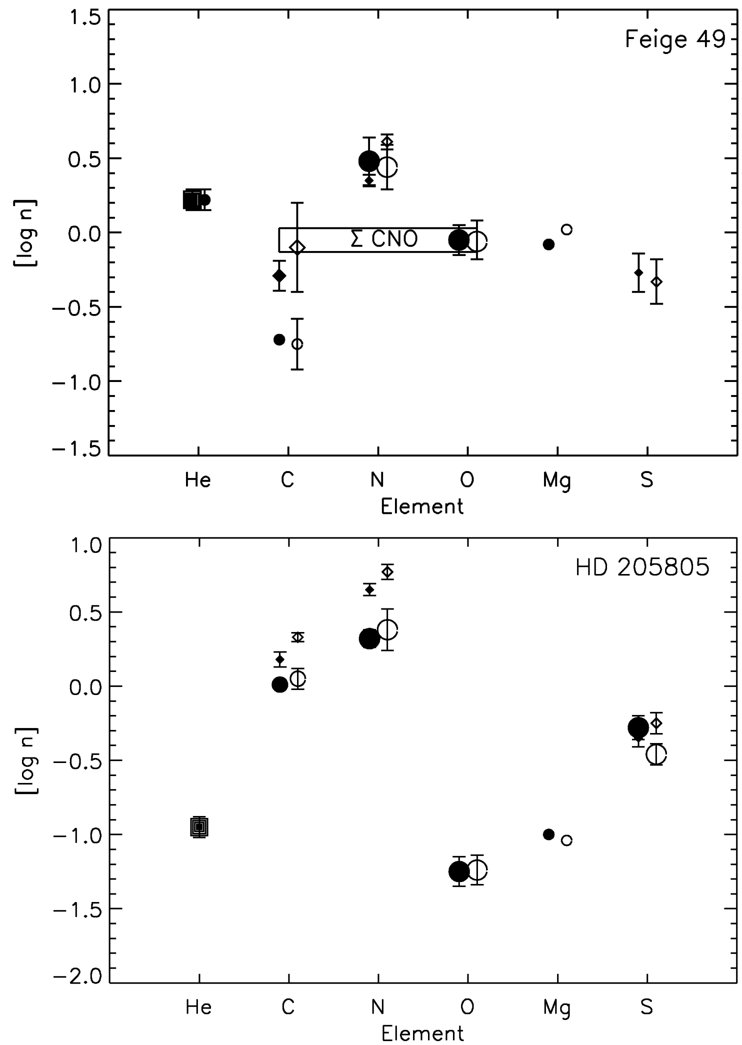

Fig. 5. Elemental abundances in the two sample sdBs (symbols as in Fig. 4).

uncertainties below 0.1 dex, like in similar computations for BA-type supergiants (Przybilla 2002) and B-type main-sequence stars (Nieva & Przybilla, in prep.). The systematic uncertainties need to be determined, but they can be expected to be of the order ~0.1 dex on the mean, as in the other cases.

The metal abundances of the sample stars relative to the solar standard are summarized in Table 3. For each ionic species non-LTE and LTE results with uncertainties derived from the line-to-line scatter are given. The data is also displayed in Figure 5, using the same symbols as in the figures before, with the symbol size encoding the number of lines used for the abundance determination.

The abundance pattern for Feige 49 indicates mixing of the surface layers with CNO-processed material: He and N are enriched and C is depleted. Oxygen appears to be unchanged relative to the other α-elements, which indicate approximately solar metallicity for this star. Note that the sum of the CNO abundances also gives a value close to solar, emphasizing the catalyst role of these species. The pattern is unusual for a sdB star. On the other hand, HD 205805 shows an abundance pattern more typical for sdB stars, indicating that diffusion processes have been active.

5. CONCLUSIONS AND PROSPECTS

Hybrid non-LTE analyses of two sdB stars demonstrate that non-LTE effects have to be accounted for in the stellar parameter and abundance determination, resulting in excellent fits of *all* the diagnostic spectral features. Systematic shifts in the basic parameters $T_{\rm eff}$ and $\log g$ are implied and non-LTE abundance corrections on the order of $\sim$0.05–0.25 dex on the mean. The latter are similar to corrections of metal abundances in (less-luminous) BA-type *supergiants* (Przybilla 2002).

The next steps in the refinements of the method will include the necessary fine-adjustments in the stellar parameter determination in order to meet the constraints imposed by various metal ionization equilibria. The uncertainties in the metal abundances can then be expected to drop below 0.1 dex, as experience tells us from analyses of objects in other parts of the Hertzsprung-Russell diagram. Additional non-LTE model atoms are required for a few other important diagnostic chemical species, like aluminum (an element with odd neutron number), silicon (another α-element, highly valuable for stellar parameter estimations) and iron (to cover iron group abundances).

Similar analyses of a larger sample of sdB stars, and an extension towards the sdO regime, will allow for unbiased positioning in the $T_{\rm eff}$ vs. $\log g$ plane. This will help to delineate the different populations of subluminous stars with unprecedented accuracy and may provide the crucial clues for uncovering their formation history (single vs. binary star evolution channels). A stellar sample with highly accurate parameter and abundance determinations will hereby also put tight observational constraints on the stellar evolution computations. These can be used for an empirical calibration of the parametrization of complex (hydrodynamical) phenomena involved in the stellar evolution calculations, thus leading to an improved modeling.

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