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IMPROVED HELIUM LINE FORMATION FOR EXTREME HELIUM STARS

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Abstract. Quantitative analyses of extreme helium stars to date face the difficulty that theory fails to reproduce the observed helium lines in their entirety, wings *and* line cores. Here, we demonstrate how the issues can be resolved using state-of-the-art non-LTE line formation for these chemically peculiar objects. Two unique B-type objects are discussed in detail, the pulsating variable V652 Her and the metal-poor star HD 144941. The improved non-LTE computations for helium show that analyses assuming LTE or based on older non-LTE model atoms can predict equivalent widths, for the He I 10 830 Å transition in particular, in error by up to a factor $\sim$3. Our modeling approach also succeeds in largely resolving the general mismatch for effective temperatures of EHe stars derived from ionization equilibria and from spectral energy distributions.

Key words: line: formation – stars: atmospheres – stars: fundamental parameters – stars: individual (V 652 Her, HD 144941)

1. INTRODUCTION

Extreme helium stars (EHes) are a rare class of low-mass H-deficient objects with spectral characteristics of B-giants. Most of the two dozen known EHes could be explained by post-AGB evolution, linking R CrB stars to Wolf-Rayet type central stars of planetary nebulae, see Heber (1986) and Jeffery (1996) for reviews.

LTE spectral analyses encounter two difficulties for EHe stars: (i) synthetic spectra have so far not succeeded in matching the observed helium lines in their entirety, and (ii) spectroscopic and spectrophotometric temperatures differ systematically. As inadequacies in the basic parameter determination can potentially hamper any further interpretation, the issue needs to be resolved. The necessary steps for improving the modeling will be discussed in the following for two test cases, V652 Her and HD 144941. Here, extreme helium stars turn out to be important testbeds for stellar atmosphere modeling. In particular, non-LTE model atoms for helium can be tested in more detail than in any other type of star, since all predicted transitions – including all forbidden components – can be measured. The sample stars are unique among the class members in several aspects. Both objects have gravities too large for post-AGB evolution and they show atypical surface abundances.

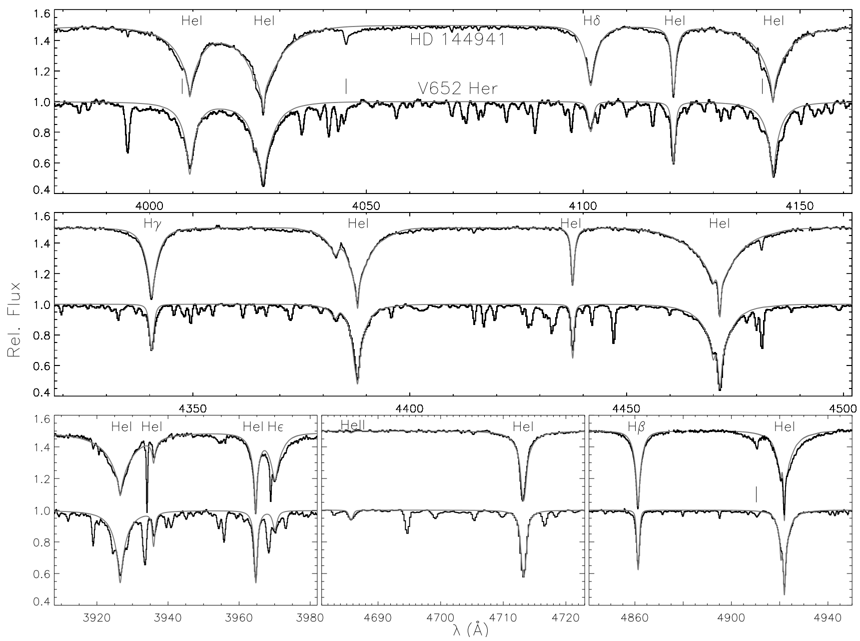

Fig. 1. Fits to He and H lines in the two sample stars.

2. MODEL CALCULATIONS AND OBSERVATIONAL DATA

The model calculations are carried out in analogy to the hybrid non-LTE approach chosen for sdB star analyses (Przybilla et al. 2006), but see also Przybilla et al. (2005) for further details. In brief, the atmospheric structure computations are carried out using the Atlas12 code (Kurucz 1996). Note that we have replaced the photoionization data for He I levels with principal quantum number $n = 2$ as used by Kurucz with data from the Opacity Project (Fernley et al. 1987). In particular the cross-sections for the $2p\,^3P^{\circ}$ level are increased by a factor $\sim$2 at the threshold, thus improving the fits of computed energy distributions with observation. Then, the restricted non-LTE problem is solved. State-of-the-art model atoms for He (Przybilla 2005) and H (Przybilla & Butler 2004) are utilised, and detailed line-broadening is accounted for in the spectrum synthesis (Barnard et al. 1969, 1974; Dimitrijević & Sahal-Bréchot 1990; Stehlé & Hutcheon 1999). For comparison, additional calculations are made using the He model atom of Husfeld et al. (1989). Details of the observations and the data reduction have been published elsewhere (Jeffery et al. 2001; Harrison & Jeffery 1997).

3. DISCUSSION

The stellar parameters are derived in a standard manner, using the He I/II ionization balance as $T_{\rm eff}$ and the Stark-broadened He I lines as $\log g$ indicators. Data for the final models (with estimated uncertainties) are summarised in Table 1, including microturbulence ξ and also H abundance $n_{\rm H}^{\rm NLTE}$ (by number). For V652 Her the atmospheric parameters agree very well with those found by Jeffery

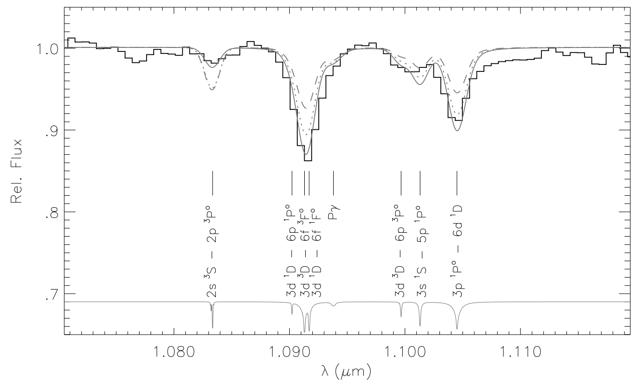

Fig. 2. Modeling of the J-band spectrum of V 652 Her.

et al. (2001), except for the hydrogen abundance, which is reduced by a factor ∼2 because of non-LTE strengthening of the Balmer lines. For HD 144941, however, the resulting parameters differ significantly from previous work of Harrison & Jeffery (1997), implying a reduction in $T_{\rm eff}$ by 1200 K and an increase in surface gravity by a factor ∼2. The reduction in the hydrogen abundance is less pronounced in this star.

Table 1. Stellar parameters.

	V652 Her ($R_{\rm max}$)	HD 144941
$T_{\rm eff}$ (K)	22 000±500	22 000±1000
$\log g$	3.20±0.10	4.15±0.10
ξ (km/s)	4±1	8±2
$n_{\rm H}^{\rm NLTE}$	0.005±0.0005	0.035±0.005

A comparison of our non-LTE spectrum synthesis for He and H (grey lines) with the observed spectra of V 652 Her and HD 144941 (histograms) is made in Figure 1. Excellent agreement for the entire line profiles – wings *and* line cores – is found. The great improvement achieved becomes obvious when comparing Figure 1 to Figure 2 of Harrison & Jeffery (1997) and Figure 5 of Jeffery et al. (2001). This resolves one of the most persistent inconsistencies in quantitative analyses of extreme helium stars. A few forbidden components of He I lines missing in our modeling are indicated by short vertical marks. The appropriate broadening data are unavailable to us.

The He I lines in the visual experience non-LTE strengthening, facilitated by the overpopulation of the $n = 2$ states relative to the levels of higher principal quantum number. This overpopulation occurs because of recombinations to levels of He I at higher excitation energies and subsequent de-excitation via downward cascades to the (pseudo-)metastable $2s$ states (the singlet resonance lines are close to detailed balance). Singlet lines are in general subject to larger non-LTE effects than the triplet lines. The level populations deviate by only a few percent from detailed equilibrium at the formation depths of the continua, indicating that the assumption of LTE for the model atmosphere computations is appropriate.

Analyses in the near-IR range are highly useful for constraining the atomic data input for the non-LTE computations because of amplified non-LTE effects in the Rayleigh-Jeans tail of the spectral energy distribution. The comparison of model calculations with the current He model (full grey line) and an old model by Husfeld et al. (1989, dotted line) with observation (histogram) for the He I 10 830 Å feature in Figure 2 demonstrates the superiority of the former. The old model predicts the line to be ∼3 times stronger than observed, showing little deviation from detailed balance (dashed line). This success is facilitated by making use of accurate photoionization cross-sections in particular for the $2s\ ^3S$ state and a proper account of line blocking. Note that the line broadening is dominated by instrumental effects.

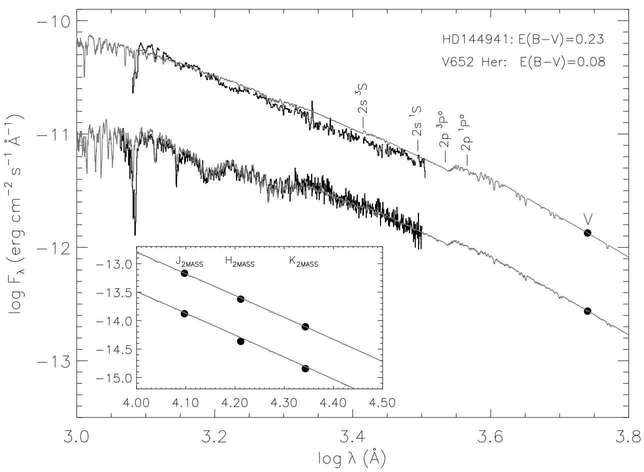

Fig. 3. SED fits for the sample stars.

High-resolution observations would be highly desirable for constraining the modeling even further.

The second major difficulty in the modeling of extreme helium stars is a general mismatch of effective temperatures derived from ionization equilibria and spectrophotometry. A comparison of the Atlas12 model fluxes (grey lines) for stellar parameters derived from the He I/II ionization equilibria (see Table 1) with IUE spectrophotometry and visual and near-IR photometry (black histograms and dots) is made in Figure 3. Excellent agreement is found for V 652 Her, and a reasonable match for HD 144941 when interstellar reddening is accounted for. We conclude that the hybrid non-LTE approach based on state-of-the-art model atoms as discussed here succeeds in solving the most persistent problems in the quantitative spectroscopy of extreme helium stars.

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