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ORIGINAL ARTICLE

Abundances from Disentangled Component Spectra of Close Binary Stars: An Observational Test of an Early Mixing in High-Mass Stars

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Abstract Recent theoretical calculations of stellar evolutionary tracks for rotating high-mass stars suggests that the chemical composition of the surface layers changes even whilst the star is evolving on the Main Sequence. The abundance analysis of binary components with precisely known fundamental stellar quantities allows a powerful comparison with theory. The observed spectra of close binary stars can be separated into the individual spectra of the component stars using the method of spectral disentangling on a time-series of spectra taken over the orbital cycle. Recently, Pavlovski and Hensberge (2005, A&A, 439, 309) have shown that, even with moderately high line-broadening, metal abundances can be derived from disentangled spectra with a precision of 0.1 dex. In a continuation of this project we have undertaken a detailed abundance analysis of the components of another two high-mass binaries, V453 Cyg, and V380 Cyg. Both binaries are well-studied systems with modern solutions. The components are close to the TAMS and therefore very suitable for an observational test of early mixing in high-mass stars.

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1. Introduction

New stellar evolution models which include the effects of rotationally induced mixing (Heger and Langer, 2000; Meynet and Maeder, 2000) have considerably changed our understanding of the evolution of high-mass stars, particularly during the early phases of core hydrogen burning. Rotation is now recognized as an important physical effect which substantially changes the lifetimes, chemical yields and stellar evolution. Theoretical predictions can be observationally tested, and some attempts at this have already been made (c.f. Venn et al., 2002).

Chemical analysis of the components of binary stars with precisely known fundamental stellar parameters allows a powerful comparison with theory. However, the precision of empirical abundances from double-lined binaries is hampered by increased line blending and by dilution of the spectral lines in the composite spectra. The techniques of spectral disentangling (Simon and Sturm, 1994; Hadrava, 1995) and Doppler tomography (Bagnuolo and Gies, 1991) overcome these difficulties by separating the spectra of the individual components contained in a time-series of composite spectra taken over the orbital cycle.

Pavlovski and Hensberge (2005) have performed a detailed spectral line analysis of disentangled component spectra of the eclipsing early-B binary V578 Mon in the open cluster NGC 2244, which is embedded in the Rosette Nebula. It is based on the disentangled spectra obtained by Hensberge et al. (2000) when deriving the orbit and the fundamental stellar parameters of this eclipsing, detached, double-lined system. V578 Mon consists of very young

Table 1 Fundamental parameters for the stars in V453 Cyg and V380 Cyg

Qnty/Comp	V453 Cyg A[1]	V453 Cyg B[1]	V380 Cyg A[2]	V380 Cyg B[2]
M [$M_\odot$]	14.36 ± 0.20	11.11 ± 0.13	11.1 ± 0.5	6.95 ± 0.25
log g [cgs]	3.731 ± 0.012	4.005 ± 0.015	3.148 ± 0.023	4.133 ± 0.023
$T_{\rm eff}$ [K]	$26\,600 \pm 500$	$25\,500 \pm 800$	$21\,350 \pm 400$	$20\,500 \pm 500$
$v \sin i$	107 ± 9	97 ± 20	98 ± 4	32 ± 6
$\epsilon_{\rm He}$[3]	0.13 ± 0.01	0.09 ± 0.01	0.14 ± 0.01	–

Notes. (1) Southworth et al. (2004); (2) Guinan et al. (2000); (3) This work

($2.3 \pm 0.2 \times 10^6$ yr) high-mass stars, $M_A = 14.54 \pm 0.08$ $M_\odot$ and $M_B = 10.29 \pm 0.06$ $M_\odot$. The stars rotate moderately fast ($v \sin i \sim 100$ km s^{-1}). By comparison with spectra of single stars in the same open cluster (Vrancken et al., 1997), temperature-dependent, faint spectral features are shown to reproduce well in the disentangled spectra, which validates a detailed quantitative analysis of these component spectra. An abundance analysis differential to a sharp-lined single star, as applied earlier in this cluster to single stars rotating faster than the components of V578 Mon, revealed abundances in agreement with the cluster stars studied by Vrancken et al. (1997) and the large inner-disk sample of Daflon et al. (2004). Pavlovski and Hensberge (2005) have concluded that methods applicable to observed single star spectra perform well on disentangled spectra, given that the latter are carefully normalised to their intrinsic continua.

Since the fundamental stellar and atmospheric parameters of eclipsing, double-lined spectroscopic binaries are known with much better accuracy than in the case of single stars, the comparison with evolutionary models can be more direct and precise. The present work is a continuation of an observational project to test rotationally induced mixing in high-mass stars from disentangled component spectra of close binary stars.

We will now present preliminary results on two interesting early-B type systems, V453 Cyg and V380 Cyg. Both systems are detached, eclipsing, double-lined spectroscopic binaries and have reliable modern absolute dimensions, published by Southworth et al. (2004) for V453 Cyg and Guinan et al. (2000) for V380 Cyg (Table 1).

2. Spectroscopy and method

Several different sets of spectra were obtained for both binaries. We will briefly describe these observations.

V453 Cyg: This binary was observed in 1991 and 1992 with the 2.2-m telescope at German-Spanish Astronomical Center on Calar Alto, Spain. Four spectral windows were observed with the coudé spectrograph. A total of 28 spectra were collected. These spectra were kindly put at our disposal by Dr. Klaus Simon. Further description can be found in Simon and Sturm (1994). Another similar set, in two spectral windows, was secured by one of the authors (JS) in 2001 with the 2.5-m Isaac Newton Telescope at La Palma (Southworth et al., 2004). A total of 41 spectra were obtained. An additional set of six spectra in the red region centred on Hα were secured by DH on the 1.2-m telescope at the DAO in 2001.

V380 Cyg: Eight spectra centred on Hγ were obtained by PK and KP at the coudé spectrograph on the 2-m telescope in Ondřejov in 2004. An additional two spectra in the same region were obtained by PK on the 1.2-m telescope at the DAO, Victoria, also in 2004. An additional set of eight red spectra centred on Hα, from the same telescope, were obtained by SY in 2002 and are also used here.

To isolate the individual spectra of both components in V453 Cyg we have made use of the spectral disentangling technique (Simon and Sturm, 1994, Hadrava, 1995). The computer codes FDBINARY (Ilijić et al., 2004) and CRES (Ilijić, 2004), which rely on the Fourier transform technique (Hadrava, 1995), and the SVD technique in wavelength space (Simon and Sturm, 1994), respectively, were used. Spectral disentangling is a powerful method which has found a variety of applications in close binary research (c.f. Holmgren et al., 1998; Hensberge et al., 2000; Harries et al., 2003; Harmanec et al., 2004).

The non-LTE line-formation calculations are performed using DETAIL and SURFACE (Butler and Giddings, 1985). However, hydrostatic, plane-parallel, line-blanketed LTE model atmospheres calculated with the ATLAS9 code (Kurucz, 1983) have also been used. This hybrid approach has been compared with the state-of-the-art non-LTE model atmosphere calculations and excellent agreement has been found for the hydrogen and helium lines (Przybilla, 2005).

3. Results and conclusion

In the observed spectral ranges the helium abundance can be derived only from the lines centred at 4378, 4471, 4718 and 6678 Å. As discussed by Lyubimkov et al. (2004), calculations for He I 4378 Å are less reliable using DETAIL since only transitions up to level $n = 4$ are considered explicitly. Since level populations can be affected by the microturbulent

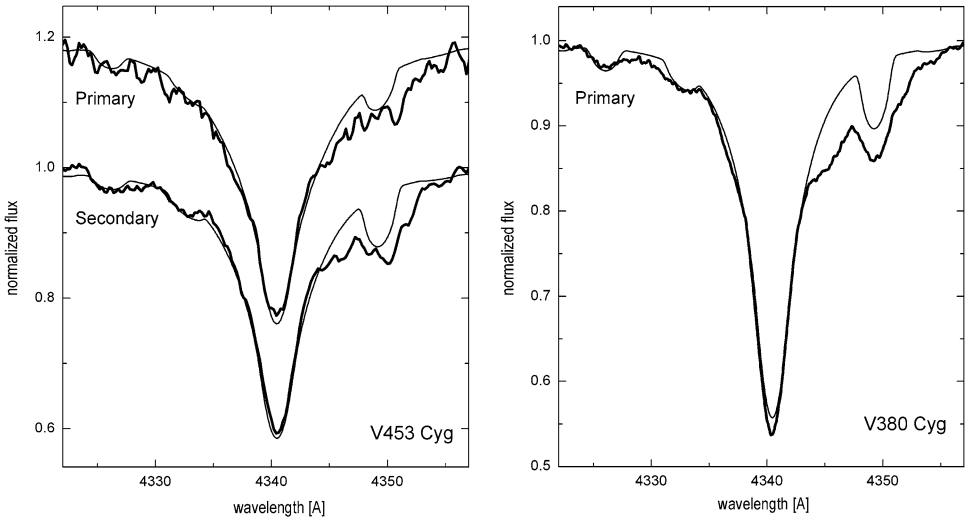

Fig. 1 The best fit of the calculated profiles (thin black line) of the Hγ line compared to the observed profiles (thick gray) for the components of V453 Cyg, left panel, and the primary component of V380 Cyg, right panel

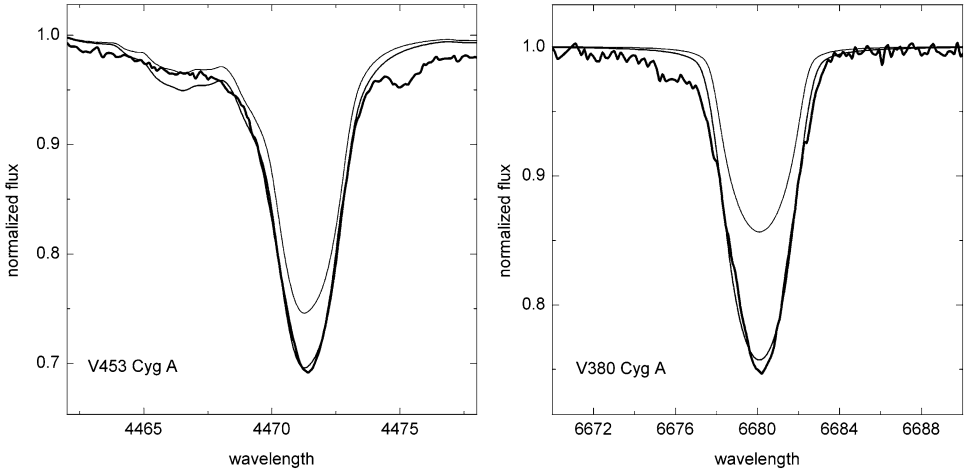

Fig. 2 The best fitting calculated profiles (thin black) of the He I 4471 Å and 6678 Å lines compared to the observed profiles (gray) in the primary component of V453 Cyg (left panel), and the primary component of V380 Cyg (right panel). Light gray lines represent profiles for the solar helium abundance

parameter $V_{\rm turb}$ it should be also included in calculations and adjusted to the observed line profiles.

First, a check and slight adjustment of the effective temperature to the individual component spectra for V453 Cyg, and the primary of V380 Cyg, has been made. As an example, fitting of the calculated to the observed line profiles of the Hγ line is shown in Fig. 1. A simultaneous fit of the helium abundance $\epsilon_{\rm He}$, and microturbulent velocity $V_{\rm turb}$ has then been performed from the grid of the calculated spectra, while $T_{\rm eff}$ and $\log g$ have been kept fixed (Fig. 2).

The helium enrichment has been found for the primary component in the system V380 Cyg by Lyubimkov et al. (1996). The helium abundance they derived, $\epsilon_{\rm He} = 0.19 \pm 0.05$, is considerably larger than the value derived in the present work. The complete analysis and discussion of possible sources of the discrepancy will be published elsewhere.

Recently, Lyubimkov et al. (2004) have derived the helium abundances in a large sample of early-B type stars. Their results are plotted in Fig. 3 as open symbols. This confirmed their finding that helium is becoming enriched in high-mass stars already on the main sequence. However, due to large

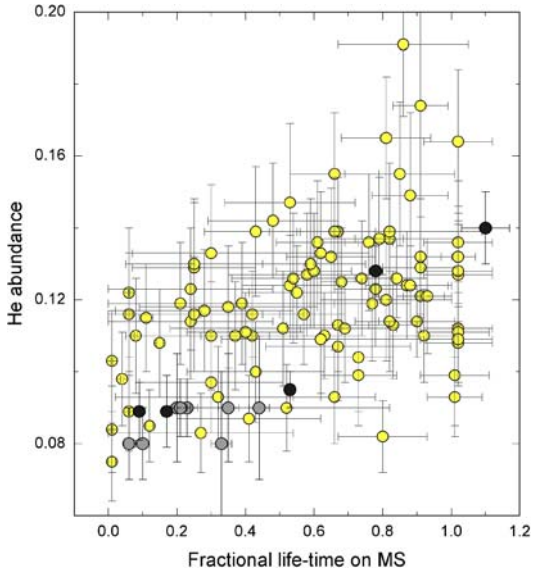

Fig. 3 Abundances of helium in the components of the close binaries (filled symbols; dark symbols show the results of this work) overplotted on the results for large sample of single early-B type stars (open symbols) of Lyubimkov et al. (2004)

errors in deriving the fundamental parameters for the single stars, there is considerable scatter in their diagram. Overplotted by filled symbols are results for the components of eclipsing, double-lined spectroscopic binaries, in light-gray (c.f. Pavlovski, 2004). In dark-gray are presented the results of this work. The general finding that in the later phases on the main sequence helium is enriched is confirmed, but there is disagreement for early phases for which results from the close binaries are very consistent and are giving a helium abundance close to the solar value. However, the sample is still rather limited and more work is needed to have complete picture on the helium enrichment on the MS for high-mass stars.

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