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Observational approach to the chemical evolution of high-mass binaries

K. Pavlovski[1,2], J. Southworth[2], E. Tamajo[1], and V. Kolbas[1]

[1] Department of Physics, University of Zagreb, Croatia
[2] Astrophysics Group, Keele University, Staffordshire, UK

Abstract: The complexity of composite spectra of close binaries makes the study of the individual stellar spectra extremely difficult. For this reason there exists very little information on the chemical composition of high-mass stars in close binaries, despite its importance for understanding the evolution of massive stars and close binary systems. A way around this problem exists: spectral disentangling allows a time-series of composite spectra to be decomposed into their individual components whilst preserving the total signal-to-noise ratio in the input spectra. Here we present the results of our ongoing project to obtain the atmospheric parameters of high-mass components in binary and multiple systems using spectral disentangling. So far, we have performed detailed abundance studies for 14 stars in eight eclipsing binary systems. Of these, V380 Cyg, V 621 Per and V453 Cyg are the most informative as their primary components are evolved either close to or beyond the TAMS. Contrary to theoretical predictions of rotating single-star evolutionary models, both of these stars show no abundance changes relative to unevolved main sequence stars of the same mass. It is obvious that other effects are important in the chemical evolution of components in binary stars. Analyses are ongoing for further systems, including AH Cep, CW Cep and V478 Cyg.

1 Introduction

In the last decade theoretical stellar evolutionary models, particularly for higher masses, were improved considerably with the inclusion of additional physical effects beyond the standard ingredients. It was found that rotationally induced mixing and magnetic fields could cause substantial changes in the resulting predictions (Meynet & Maeder 2000, Heger & Langer 2000). Some of these concern evolutionary changes in the chemical composition of stellar atmospheres. Due to the CNO cycle in the core of high-mass stars some elements are enhanced (such as helium and nitrogen), some are depleted (e.g. carbon), whilst some (e.g. oxygen) are not affected at all. The rotational mixing predicted by stellar models is so efficient that changes in the atmospheric composition should be identifiable whilst the star is still on the main sequence.

On the observational side, substantial progress has also been made. The VLT/FLAMES survey (Evans et al. 2005) produced CNO abundances for a large sample of B stars in the Milky Way, and the Magellanic Clouds. This survey has opened new questions since a large population of slow rotators have shown an enhancement of nitrogen (Hunter et al. 2009). Also, important empirical constraints on models arose from the observational study performed by Morel, Hubrig & Briquet (2008) who found that magnetic fields have an important effect on the atmospheric composition of these stars.

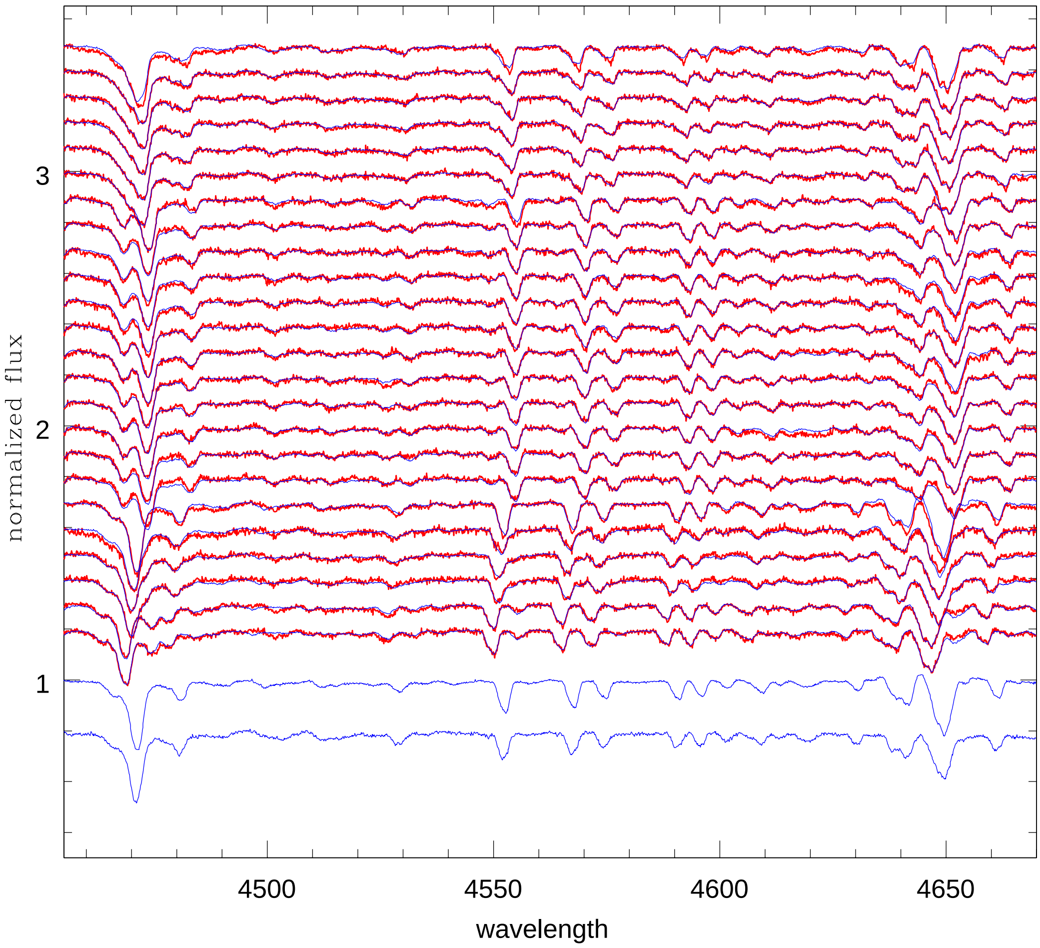

Figure 1: Time series of observed composite spectra (red lines) of the B0 V + B1 V close eclpsing binary system V453 Cyg (Pavlovski & Southworth 2009). This is a portion of échelle spectra secured with the FIES spectrograph at the Nordic Optical Telescope (La Palma). The individual disentangled spectra of the two stars, which have very similar effective temperatures, are shown at the bottom of the plot (blue lines, secondary offset by -0.2) with their correct continuum levels. The disentangled spectra have been adjusted with the appropriate Doppler shifts and relative intensities to reproduce the observed spectra, and are overlaid on them using blue lines.

Detached eclipsing binaries are fundamental objects for obtaining empirical constraints on the structure and evolution of high-mass stars, and are the primary source of directly measured stellar properties. Accurate physical properties are available for fewer than a dozen high-mass binaries, and most have no observational constraints on their chemical composition (Torres, Andersen & Giménez 2010). The aim of our projects is to obtain a sample of high-mass binaries both with accurate parameters and, for the first time, with detailed abundance studies of the individual stars. We aim to gain insight into the chemical evolution of high-mass stars in close binary systems. The close proximity of the components leads to strong tidal forces, which may be an important additional effect on the internal and chemical structure of the stars, beside rotation and magnetic fields.

2 Sample and Method

The complexity of the composite spectra of close binaries makes studying the spectra of the individual stars extremely difficult. For this reason there exists very little information on the chemical composition of high-mass stars in close binaries, despite its importance for understanding the evolution of both massive stars and close binaries. A way around this problem exists: spectral disentangling. This technique allows a time-series of composite spectra to be decomposed into their individual components whilst preserving the total signal-to-noise ratio in the input spectra, and without the use of template spectra (Simon & Sturm 1994). An overview of almost a dozen methods for spectral disentangling has been given by Pavlovski & Hensberge (2010). For our work we use the FDBINARY Fourier-space code (Ilijić et al. 2004). Synthetic spectra are generated using ATLAS9 with non-LTE model atoms (see Pavlovski & Southworth 2009 and Pavlovski et al. 2009 for details).

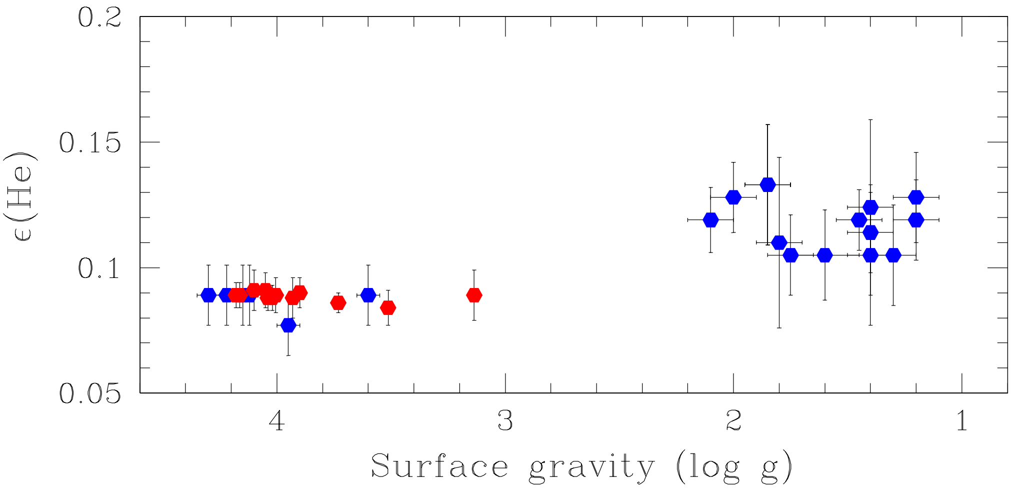

Figure 2: Helium abundances for high-mass stars in close binaries from our sample (red symbols) compared to single sharp-lined B-type main sequence stars and BA supergiants in the Przybilla et al. (2010) sample (blue symbols). ϵ(He) is the fractional helium abundance by number of atoms.

A vital step in a spectroscopic abundance study is precise determination of the stellar atmospheric parameters (effective temperature, surface gravity, microturbulence velocity, etc). When reconstructing the separate spectra of the components their individual light contributions have to be obtained either from the disentangled spectra itself, or from some other source such as a complementary light curve analysis (c.f. Pavlovski & Hensberge 2010).

So far, we have performed detailed abundance studies for 14 components in eight eclipsing binaries. In many cases we have also reanalysed existing or new light curves. Of the systems studied, V380 Cyg (Pavlovski et al. 2009), V453 Cyg (Pavlovski & Southworth 2009, Southworth, Maxted & Smalley 2004a) and V621 Per (Southworth et al. 2004b, 2011 in prep.) are the most informative as their primary components are evolved either close to or beyond the terminal-age main sequence (TAMS). Other binaries studied include V578 Mon (Pavlovski & Hensberge 2005, see also Hensberge, Pavlovski & Verschueren 2000), AH Cep, CW Cep, Y Cyg and V478 Cyg [helium abundances have also been measured from disentangled spectra for DH Cep (Sturm & Simon 1994), Y Cyg (Simon, Sturm & Fiedler 1994) and DW Car (Southworth & Clausen 2007)]. These objects mostly contain stars at the beginning of their main sequence lifetimes, so are important for calibrating theoretical models near their initial conditions.

3 The quest for surface helium enrichment

Theoretical stellar evolutionary models which include rotational mixing predict an enrichment of helium at the stellar surface, even during a star's main sequence lifetime. Extensive observational studies comprising B-type stars in the field (Lyubimkov, Rostophchin & Lambert 2004), and in stellar clusters (Huang & Gies 2006) yield evidence for this enrichment, but with a very large scatter in the individual measurements. An unexpectedly large fraction of both helium-rich, and helium-weak stars were detected by Huang & Gies (2006), who included only three helium lines in their analysis.

The results of our detailed abundance determinations in the sample of 14 components of close binary stars are shown in Fig. 2 (red symbols). The results of a recent study of helium abundances in the sample of sharp-lined main sequence and BA supergiants (Przybilla et al. 2010) are also plotted (blue symbols). It is interesting that no helium abundance enrichment has been detected in these studies, either for single stars (Przybilla et al. 2010) or the components of close binaries (this work). The studies therefore do not support a large spread in helium abundance, as found by other authors, with the caveat that the sample of main sequence stars studied is limited.

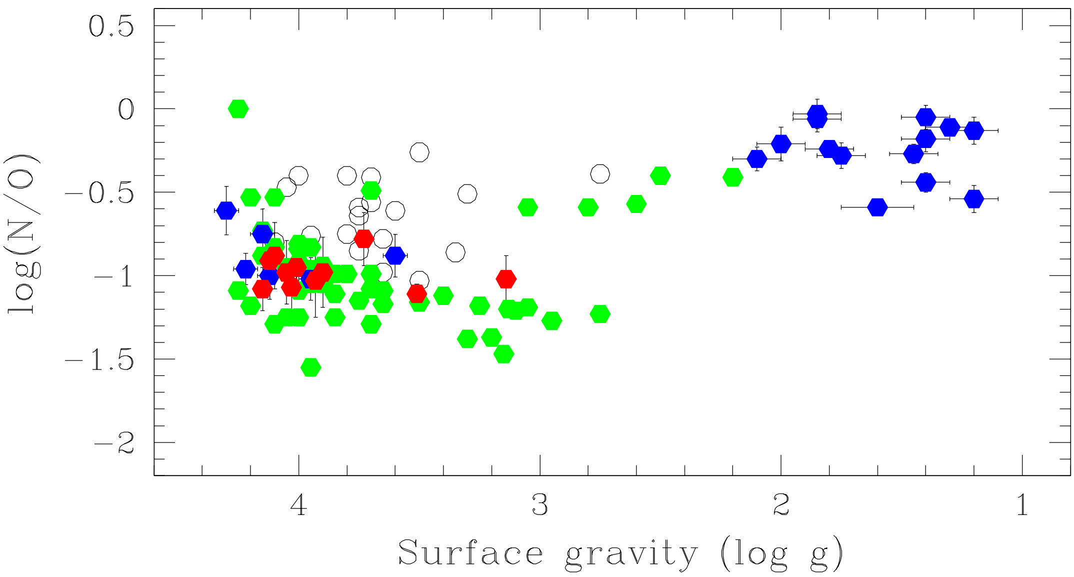

Figure 3: Evolution of nitrogen in high-mass MS stars to supergiants. The close binary systems in our sample are represented by red symbols. Other symbols represent single stars as follows: blue symbols the VLT/FLAMES survey of B stars in Milky Way (Hunter et al. 2009); green symbols the results of an abundance study for a sample of B stars with detected magnetic fields (Morel et al. 2008); and open symbols a study of sharp-lined stars (Przybilla et al. 2010).

4 The evolution of nitrogen in high-mass binaries

In close binary stars, both fast rotation and tidal forces due to the proximity of the components play an important role in stellar evolution. Tides spin up (or spin down) the stars until their rotation period synchronises with the orbital period. The effects of tides, rotational mixing and magnetic fields were studied by de Mink et al. (2009). Their model calculations indicate a significant dependence of the surface helium and nitrogen abundances for short-period systems ($P < 2$ days) for a considerable fraction of their MS lifetime. The best candidates for testing these concepts contain more massive components, in advanced phases of the core hydrogen-burning phase, with significantly less massive and less evolved companions. V380 Cyg, V621 Per and V453 Cyg fit this bill well, but have longer orbital periods (3.9 d to 25.5 d) so are not predicted to show significant abundance enhancements. This is illustrated in Fig. 3 in which the abundance ratio N/O is plotted against $\log g$, which is a good indicator of evolutionary stage. The N/O ratios for the evolved stars in our sample are consistent with ZAMS values, like many of the stars in the VLT/FLAMES sample of Hunter et al. (2009). The evolutionary enhancement of nitrogen is only clearly present in the sample of supergiants observed by Przybilla et al. (2010). On average the magnetic B-type stars (Morel et al. 2008) have large nitrogen abundances, but definitive conclusions on the role of magnetic fields on nitrogen enrichment are still not possible (Morel 2011). The large spread in nitrogen abundances for MS stars is obvious.

Since the enhancements of helium and nitrogen are larger at lower metallicity, the best candidates for detailed study would be close binaries in the Magellanic Clouds. However, these are challenging objects for accurate abundance determination due to their high rotational velocities (resulting in line blending) and relative faintness.

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