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Quantitative Spectroscopy of Close Binary Stars

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Abstract. The method of spectral disentangling has now created the opportunity for studying the chemical composition in previously inaccessible components of binary and multiple stars. This in turn makes it possible to trace their chemical evolution, a vital aspect in understanding the evolution of stellar systems. We review different ways to reconstruct individual spectra from eclipsing and non-eclipsing systems, and then concentrate on some recent applications to detached binaries with high-mass and intermediate-mass stars, and Algol-type mass-transfer systems.

Keywords. binary stars, spectroscopy, stellar atmospheres, chemical composition

1. Introduction

The structure and evolution of a star is determined by its mass and chemical composition. Hence, the position of the star in the HR diagram is uniquely defined only when its mass and bulk metallicity are known. Eclipsing and double-lined spectroscopic binaries in a detached configuration remain the primary source of directly measured fundamental stellar quantities: mass and radius. Modern observational techniques are currently able to reach precisions of 1–2% in these parameters, a prerequisite for testing theoretical stellar evolutionary models. In their critical survey and compilation of available results, Torres, Andersen & Gimenez (2010) selected 95 detached eclipsing binaries (dEBs) which satisfied a reasonable criterion of 3% in precision for both quantities. The effective temperatures of the component stars cannot be determined directly from the analysis of light or radial velocity curves, making $T_{\rm eff}$ a less well-determined quantity.

The metallicity has been determined for the components of only about 21 of the 95 binaries in the sample of Torres *et al.* (2010). Usually, metallicity is derived from fitting the overall spectrum of the stellar system. Detailed abundance determinations have been accomplished for only *four* binaries: directly from the spectrum of β Aur (Lyubimkov *et al.* 1996) and CV Vel (Yakut *et al.* 2007), and from disentangled component spectra of V578 Mon (Pavlovski & Hensberge 2005) and V453 Cyg (Pavlovski & Southworth 2009).

Tremendous advances in observational stellar spectroscopy, both in spectral resolution, quantum efficiency and detector linearity, allow new opportunities in binary star research. Reconstructing the individual spectra of the components opens a new window on these stars: detailed spectral analysis, atmospheric diagnostics, and determination of atmospheric chemical compositions (Pavlovski 2004, Pavlovski & Hensberge 2005). This enables a fine probing of stellar evolutionary models and proper calibrations of fundamental stellar quantities (Pavlovski & Southworth 2009, Pavlovski *et al.* 2009, 2011). The advantages of analysing disentangled spectra are manifold.

2. Renormalisation of disentangled component spectra

More than a dozen methods have been invented to obtain separate spectra of the components of multiple systems from a series of composite spectra obtained at a range of orbital phase. Pavlovski & Hensberge (2010) divided them into three basic categories: (i) spectral separation; (ii) spectral disentangling; and (iii) spectroastrometric splitting. In all cases, the isolation of individual spectra exploits the variable Doppler shift of the stars.

In *spectral separation* techniques, radial velocities (RVs) are input data obtained from another source (e.g. cross-correlation). The method most widely used in this category is Doppler tomography, developed by Bagnuolo & Gies (1991). The technique of *spectral disentangling* (SPD; Simon & Sturm 1994, Hadrava 1995) refers to the situation where both the individual spectra and the orbital parameters of the components are measured, simultaneously and self-consistently. The *spectroastrometric splitting* method accesses the spatial information present in long-slit spectra of partially resolved components (see Bailey 1998; Wheelwright, Oudmaijer & Schnerr 2009, and references therein).

The principles of these methods are outlined in the review papers by Hadrava (2004, 2009), Hensberge & Pavlovski (2007), and Pavlovski & Hensberge (2010). Without going into details, we record here some new developments by Konacki *et al.* (2010), Folsom *et al.* (2010) and Kolbas & Pavlovski (this Volume).

Spectral disentangling or separation techniques return individual spectra which are either in the common continuum of the system, or on an arbitrary (generic) continuum. The reason for this is a basic principle of SPD: there is no information on the continuum light ratio of the stars if disentangling is performed on spectra where the light ratio is constant. The absolute spectral line depths are then unknown because the continuum level is unknown. The solution is to obtain spectra during eclipse, as information on the continuum level is then available. Spectra during eclipse can be difficult to secure for reasons including the scheduling of observations and the lower brightness of the system at eclipse times. However, the main difficulty lies in the Rossiter-McLaughlin effect. This distorts the line profiles and thus violates a basic assumption of spectral disentangling. The Rossiter-McLaughlin effect can be only avoided by studying totally-eclipsing systems. In practice, we usually have a situation in which the continuum light ratios do not vary between spectra, and SPD has to be performed with arbitrary or generic light dilution factors. Renormalisation then requires light factors from other sources.

It is expected that the most reliable light dilution factors come from analysis of the light curves of dEBs. This is true, but it depends on particular cases, as discussed below. When eclipses do not occur, or observational data do not cover them, we must rely on information contained in the disentangled spectra themselves. Here, we list several different approaches recorded in the literature:

- For eclipsing binaries, light factors may be available from the time-independent dilution of spectral lines or from light curves (e.g. Hensberge, Pavlovski & Verschueren 2000). The quality of the photometry, the configuration and geometry of the binary system, or the presence of a third star, could make the light factors uncertain.
- The light factors can be determined from the time-dependent dilution of the spectral lines as additional free parameters in SPD calculations (*line photometry*; Hadrava 1997). Any intrinsic line profile changes (pulsations, spots, Rossiter-McLaughlin effect, etc.) violate a basic assumption of spectral disentangling, and can cause erroneous results.
- If the system is not eclipsing, some *physical considerations* can be used to renormalise individual disentangled spectra. In the study of the non-eclipsing triple system DG Leo, Frémat *et al.* (2005) successfully used the very deep Ca II K line profiles. The requirement that the core should not dip below zero flux for any of the component

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spectra (in this particular case all components are of similar spectral type) imposed very strong constraints on the light factors. Light dilution factors can also be estimated from line depths, or equivalent width ratios, once the atmospheric characteristics are fixed (c.f. Mahy *et al.* 2011). Use of line depth or line intensity ratios require chemical abundances to be specified *a priori*, making this option somewhat uncertain.

• Separated or generic disentangled spectra contain information on the intrinsic spectra. Just as in the way in which information on effective temperature ($T_{\rm eff}$) and surface gravity ($\log g$) are extracted from renormalised spectra, it is possible to recover also light factors by constrained multi-parameter line-profile fitting of both disentangled spectra. Tamajo, Pavlovski & Southworth (2011) have implemented this idea in the code GENFITT. Simulations using synthetic spectra showed that for a reasonable signal-to-noise ratio of S/N $\geqslant$ 100 *constrained genetic fitting* returns reliable $T_{\rm eff}$ and $\log g$ for each star, plus their light factor. It is so called because the optimal fitting is constrained by requiring the sum of the light factors to be unity. $\log g$ can be derived for the stars in close binaries with precisions of 0.01 dex, a crucial advantage in breaking the degeneracy between $T_{\rm eff}$ and $\log g$ for Balmer line profiles. Comparison of the light factors derived by constrained genetic fitting and from light curve analyses is given by Pavlovski *et al.* (2009), Tamajo *et al.* (2011), and Southworth *et al.* (2011b) for some real-world cases.

• The procedure described in the previous item could be generalised in the way that part or whole of the disentangled spectrum is fitted by theoretical spectra. Tkachenko, Lehmann & Mkrtichian (2009, 2010) have used this idea and fitted a large portion of spectra by gridding with precomputed theoretical spectra for a large range of $T_{\rm eff}$, $\log g$ and metallicity. A similar technique has been applied by Torres *et al.* (2011) but with restriction to solar abundances only.

3. Chemical composition from reconstructed spectra

To determine the chemical composition of a stellar atmosphere, it is first neccessary to specify an appropriate model atmosphere. The model is described by $T_{\rm eff}$, $\log g$, and metallicity ([M/H]). For most eclipsing binaries, $\log g$ can be determined from the analysis of light and velocity curves, with a precision and accuracy up to an order of magnitude larger than for single stars. This considerably facilitates the determination of $T_{\rm eff}$, and side-steps the degeneracy between $T_{\rm eff}$ and $\log g$ for hot stars. Moreover, a reliable estimate of $T_{\rm eff}$ is possible directly from *constrained fitting* when the light factors are not well-determined from external sources (Pavlovski *et al.* 2009, Tamajo *et al.* 2011). This also makes it possible to estimate $T_{\rm eff}$ and $\log g$ for non-eclipsing binaries, and stipulate additional constraints in complementary solutions with interferometric observations. The first estimate of $T_{\rm eff}$ can be used in an iterative cycle for fine-tuning light curve and SPD solutions, as was described by Hensberge *et al.* (2000) and further elaborated by Clausen *et al.* (2008).

Detailed abundance work makes possible further improvements in $T_{\rm eff}$ determination through ionisation balance. We have successfully employed the Si II / Si III ionisation balance in high-mass binaries (Pavlovski & Southworth 2009), and the Fe I / Fe II balance in intermediate-mass binaries (work in preparation). Such an improvement in determination of $T_{\rm eff}$ is an important ingredient if one wants to use binaries for distance determination, in particular for galaxies in the Local Group (e.g. Harries *et al.* 2003, North *et al.* 2011).

3.1. *Detached binary stars*

High-mass stars. Despite considerable theoretical and observational efforts, some important pieces of the jigsaw of stellar structure and evolution remain unclear or missing. Meynet & Maeder (2000) and Heger & Langer (2000) found that rotationally-induced

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mixing and magnetic fields could cause substantial changes in theoretical predictions. Some of these concern evolutionary changes in the chemical composition of stellar atmopsheres. In close binaries, tidal effects further complicate this picture (De Mink *et al.* 2009), and pose a big challenge for observational confirmation.

Our observational project on the chemical evolution of high-mass stars in close binaries is directed toward tracing predicted changes in the photospheric abundance pattern due to rotational mixing. In Pavlovski *et al.* (in preparation), we summarise our results for fourteen high-mass stars in eight dEBs, plus some additional high-mass stars in binaries studied from disentangled spectra (Simon *et al.* 1994, Sturm & Simon 1994, Southworth & Clausen 2007). Of these, V380 Cyg (Pavlovski *et al.* 2009), V621 Per (Southworth *et al.* 2004), and V453 Cyg (Pavlovski & Southworth 2009) are the most informative as their primary components are evolved either close to or beyond the terminal-age main sequence. No abundance changes relative to unevolved MS stars of the same mass have been detected for these components, probably due to their relatively long orbital periods (De Mink *et al.* 2009). The study of HD 48099, an O5.5 V((f)) + 09 V binary system, by Mahy *et al.* (2010) reveals a nitrogen enhancement in the primary star, but a solar abundance for the secondary. The estimated masses are 55 and 19 $M_{\odot}$ for the primary and secondary component, respectively. Determination of chemical composition from disentangled spectra is an important way to constrain theoretical models.

Intermediate-mass and solar type stars. We have recently constructed detailed abundance studies of late-B and A-type stars in the close dEBs AS Cam and YZ Cas (work in preparation). Abundances are also available for the δ Scuti pulsating components in the binaries DG Leo (Frémat *et al.* 2005) and HD 61199 (Harater *et al.* 2008).

Systematic research in FGK stars in binaries, concerning also their chemical composition and an empirial evaluation of their metallicity, was initialized by the late Jens Viggo Clausen and collaborators. A comprehensive study of three F-type binaries has shown the full power of testing and comparing recent stellar evolutionary models using eclipsing binaries, provided their abundances are known (Clausen *et al.* 2008). The same methodology was extended to the solar-type binary systems V636 Cen (Clausen *et al.* 2009) and NGC 6791 V20 (Grundahl *et al.* 2008; Brogaard *et al.*, 2011).

3.2. *Algol systems*

One of the many consequences of the first and rapid phase of mass transfer in close binary systems, and the eventual mass reversal and formation of Algols, is the change in chemical composition of the stars involved. In fact, Algols offer an unique opportunity to probe into stellar interiors since detailed abundance studies of the layers which were once deep inside the star can give important information on the thermonuclear and mixing processes taking place during core hydrogen burning (Sarna & De Greve 1996). Carbon should be depleted in the CNO cycle even during a star's MS lifetime, and observational studies have aimed at testing these predictions (c.f. Tomkin 1981 and references therein).

We have started a new observational programme with the aim of deriving detailed abundances from high-resolution and high-S/N Échelle spectra using the SPD technique. We intend to substantially extend both the number of the elements studied, and the number of lines for each element.

Algol (β Per) is the prototype of the class of binary systems in a semidetached configuration, where the initially more massive and more evolved component fills its inner Roche lobe and transfers material to its now more-massive companion. Algol is one of the most frequently studied objects in the sky, and has been observed at wavelengths ranging from X-rays to radio (c.f. Richards et al. 1988). However, due to difficulties in

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ground-based observations of such a bright object, and a lack of modern high-resolution spectroscopy, its stellar and orbital parameters were somewhat uncertain.

Since 2007, we have secured 140 high-S/N Échelle spectra of Algol using the FIES spectrograph at the Nordic Optical Telescope and BOES at Bohyunsan Optical Astronomy Observatory in Korea. The available light curves are not on their own sufficient to allow the precise quantification of the contribution of the third component to the total light, which is needed for proper reconstruction of the disentangled spectra of the components. Therefore, we rely only on spectroscopic information. Abundances are derived for 15 elements, and are generally close to solar (Kolbas *et al.*, this volume). We are currently undertaking non-LTE calculations for helium and the CNO elements. We corroborate the weakness of the Ca II lines in the spectrum of the third component, and a slight underabundance of scandium, both classical indicators of a metallic-lined star. We will be performing a detailed abundance of our disentangled spectrum for this candidate Am star.

The importance of an abundance study for understanding stellar evolution in binary systems is nicely shown by Mahy *et al.* (2011) in a study of the semidetached system LZ Cep, an O9 III + ON9.7 V binary. They have found the secondary component, now the less massive star in the system, to be chemically more evolved than the primary, which barely shows any sign of CNO processing. Also, considerable changes in the chemical composition which corroborate predictions have been found for the components of Plaskett's star (54 + 56 $M_{\odot}$) by Linder *et al.* (2008). Plaskett's star is in a post-case-A Roche lobe overflow stage.

Cool Algols. The chemical composition of the primaries of two oEA stars, TW Dra and RZ Cas, have been derived by Tkachenko, Lehmann & Mkrtichian (2009, 2010). This subclass of Algols is known for cooler A-type primaries which are pulsating with δ Scuti characteristics (Mkrtichian *et al.* 2002). Their analyses of disentangled spectra have shown that these stars are normal A-stars with a chemical composition close to solar. Understanding the chemical composition of the pulsating components in close binaries is an important condition for proper asteroseismologic diagnostics. In combination with precise stellar parameters derived from complementary photometric and spectroscopic observations (c.f. Southworth *et al.* 2011a), this is a very powerful way for probing modern models of stellar structure and evolution.

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