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## Reconstruction and Analysis of Component Spectra of Binary and Multiple Stars

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**Abstract.** In the last two decades about a dozen methods were invented which derive, from a series of composite spectra over the orbit, the spectra of individual components in binary and multiple systems. Reconstructed spectra can then be analyzed with the tools developed for single stars. Eventually this has created the opportunity for chemical composition studies in previously inaccessible components of binary stars, and to follow their chemical evolution, an important aspect in understanding evolution of stellar systems. First, we review new developments in techniques to separate and reconstruct individual spectra, and thereafter concentrate on some applications. In particular, we emphasize the elemental abundance studies for high-mass stars, and present our recent results in probing theoretical evolution models which include effects of rotationally induced mixing.

### 1 Introduction

Shifts of the spectral lines due to the orbital motion of components in binary and multiple systems are essential for determination of stellar masses. Due to the intermingling of several diluted components, spectra of binary and multiple stars are often complex. Typically lines overlap in the course of the orbital cycle, which makes measurements of the radial velocities difficult and less accurate than desired for the determination of reliable stellar masses (Andersen 1991, Torres, Andersen & Giménez 2009), and prevents a straightforward astrophysical analysis of the composite spectra. However, in spite of all difficulties encountered progress has been made, in particular for Algol type systems (c.f. Tomkin 1989).

Tremendous advance in astronomical instrumentation and in efficiency and linearity of detectors have prompted the development of new analysis techniques. These are now able to exploit all the intermingled Doppler shift information present in the spectra. New methods are offering incomparable opportunities, both for deriving precise fundamental stellar quantities and for investigating the chemical evolution of binary and multiple stars.

### 2 Reconstruction techniques

In the last two decades about a dozen methods were invented which derive, from a series of composite spectra over the orbit, the spectra of individual components in binary and multiple systems. Herewith, these reconstruction methods are di-

vided into three basic groups: (i) spectral separation, (ii) spectral disentangling, and (iii) spectroastrometric splitting:

- Spectral separation: The spectra of components are reconstructed from a time series of composite spectra for corresponding radial velocities and light factors of the components.
- Spectral disentangling: Self-consistent solution of a time series of composite spectra which gives individual spectra of components and set of orbital elements. No *a priori* knowledge of RVs is needed.
- Spectroastrometric splitting: Technique which utilises the spatial information present in a longslit spectrum. It can not only be used to detect binary systems, it can also deconvolve the observed spectrum into the individual spectra of its components.

## 2.1 Spectral separation

*Doppler tomography* was the first successful reconstruction of individual spectra of the components from a time series of composite spectra that did not rely on template spectra (Bagnuolo & Gies 1991). The reconstruction is made through an iterative least-squares solution. The radial velocities of the components have to be known and are used as input data. Recently, the 11th paper in the series on tomographic separation was published by Penny, Ouzts & Gies (2008). Further informations on this and other methods, were given in review papers by Gies (2004), and Hensberge & Pavlovski (2007).

*Subtraction procedure* has shown to yield resonable results for systems containing a cool giant and a hotter main-sequence star (Griffin & Griffin 1986). Recently, the authors have published their 15th paper in the series on composite spectra (Griffin & Griffin 2009).

*Doppler differencing* introduced by Ferluga et al. (1997) is the most straightforward method of direct subtracting, in which two spectra of a binary obtained in the phases of opposite extremes of RVs are used. Recently, Lee et al. (2008) revived this method in a successful separation of an extremely interesting quadruple system containing two eclipsing pairs.

## 2.2 Spectral disentangling

*Spectral disentangling in wavelength domain* or *disentangling in velocity-space* was invented by Simon & Sturm (1994). It is based on solving the matrix equation  $Ax = y$ , where in vector  $y$  all observed spectra are stored, and  $x$  contains the spectra of the components. Matrix  $A$  has elements (blocks) corresponding to the Doppler shifts and light factors. The block  $A_{jk}$  for each observed spectrum, where  $k$  identifies the component and  $j$  the time of observation, transfers  $x_k$  into the  $j$ -th subvector of  $y$ .

The structure of blocks  $A_{jk}$  is rather simple. These are diagonal matrices with the diagonal shifted according to Doppler shift of component  $k$  at time  $t_j$  and multiplied by a light factor. Their size is determined by the number of bins in the spectral interval and the maximum size of the Doppler shifts. Therefore, vectors  $x_k$  must be somewhat longer than the subvectors  $y_j$ . Solving this matrix equation for  $x$  requires the inverse of  $A$ . Since matrix  $A$  is not a

square matrix, and since it may be rank deficient, a singular value decomposition must be used. The system is an over-determined system of linear equations (more equations than unknowns) when the input consists of more spectra than stellar components, and *least squares solution* is required such that it minimizes the norm of the residuals  $r = \|Ax - y\|$ . Simon & Sturm (1994) were the first who beside reconstruction of individual spectra also optimized a set of orbital elements of a binary system. In this sense *spectral disentangling* was formulated and is distinguished from *spectral separation* techniques (Sect. 2.1)

Wavelength-domain spectral disentangling has several interesting features as emphasized by Ilijić (2004), (i) original sampling of observed spectra can be preserved since the input spectra must not be resampled onto same wavelength grid, (ii) weight can be assigned to each pixel in the observed spectrum, (iii) in consequence of (ii) some parts of observed spectra can be omitted, like interstellar lines and bands, telluric lines, emission lines, blemishes and other technical imperfections which are not cleaned in the reduction of the spectra. An important drawback of the approach in (logarithmic) wavelength-domain, or velocity domain, is the prohibitively large CPU time and memory storage involved, due to the coupling of the huge number of equations ( $N_{\text{obs}} \times N_{\text{pix}}$ ). Therefore, this method should be used only in the gridding mode or in the separation mode with known orbital elements.

*Spectral disentangling in Fourier domain* or *Fourier disentangling* was developed by Hadrava (1995) and resolves elegantly the CPU time overhead of the wavelength-domain approach. The equations for the discrete Fourier transforms of the spectra reduce to a huge number  $((N_{\text{pix}}/2) + 1)$  of small sets of ( $N_{\text{obs}}$ ) complex equations with only few ( $k$ ) unknowns. When dealing with long spectral windows like in the case of échelle spectra this issue is of essential importance. Weights can be given to specific Fourier components (e.g. eliminating the influence of badly constrained low-order components) and to complete spectra, but – nothing comes for free – weight can not be given to pixels. With the cyclic character of finite Fourier transforms, there should be ideally sufficient continuum at the same level at both ends to avoid ‘end-of-range’ effects (Ilijić et al. 2001a,b) from spectral features leaving and entering the data set due to Doppler shifting. An optimization is also performed for the orbital elements, and measurements of RVs are bypassed, as in the method of Simon & Sturm (1994). Detail explanations and mathematical expositions can be found in Hadrava (2004, 2009).

*Iterative Doppler differencing* is a method developed by González & Levato (2006) on some premises used earlier by Marchenko, Moffat & Eenens (1998). This is an iterative scheme, using alternatively the spectrum of one component to predict the spectrum of the other one. In each step, the contribution of one component to the observed spectra is eliminated, RVs are measured for the other component, and applying the related Doppler shifts a new estimate of the spectrum of the other component is obtained.

*Non-linear least-squares fitting* was applied by Harries et al. (2003), and independently by Napiwotzki et al. (2003). The idea is to fit composite spectra for two components for a given set of orbital parameters or RVs. Harries et al. (2003) have used a genetic algorithm for minimization of the residuals between the observed and model composite spectra, while Napiwotzki et al. (2003) in

their code FITSB2 are using Simplex (c.f. Drechsel & Nesslinger, this Volume, for the recent use of this code).

### 2.3 Spectroastrometric splitting

*Spectroastrometric splitting* method is based on the positional measurements, hence its name. Conceptually, the centroid of a flux distribution to a fraction of pixel is measured on a long slit spectrum. The distribution of the light at a specific wavelength in the extraction slit changes locally if one component contributes to a spectral feature stronger than the other component, relative to nearby continuum. The method was developed by Bailey (1998a), Garcia et al. (1999), Takami et al. (2001), and Porter, Oudmaijer & Baines (2004). It proved to be a powerful technique providing information on the flux distribution at milliarcsecond scales. In a recent application of the method of *spectroastrometric splitting* the spectrum of  $\beta$  Cep was split into its constituent spectra by Wheelwright, Oudmaijer & Schnerr (2009), which enabled them to disclose that the fainter secondary exhibits signatures of a classic Be star.

## 3 Spectral disentangling in practice

Even in its first applications for deriving the orbital elements, spectral disentangling (SPD) techniques were found to be superior to other methods (Sturm & Simon 1994, Simon et al. 1995, Harmanec et al. 1997). Recently, Southworth & Clausen (2008) have examined this issue in detail. They measured RVs by fitting double Gaussians, and by calculating 1D and 2D cross-correlation functions (CCF). The derived orbital elements are compared to those derived by SPD in wavelength-domain. It was found that the line blending is a more severe obstacle for cross-correlation. 2D cross-correlation did not improve results, probably due to the spectral similarity of the component stars. It is encouraging that the orbits measured from SPD were the most internally consistent, and did not require any corrections for line blending. However, Southworth & Clausen have found that SPD suffers from the presence of many local maxima (minima) in the parameter space, as is common in non-linear multi-parameter optimization.

Although the use of the disentangling gets well-spread in the astronomical community, often RVs are measured afterwards using the component spectra as templates, for use in software combining light curve or astrometric information with spectroscopic information. One should be aware of the fact that calculating the orbital elements from RVs measured in this way will differ somewhat from the ones determined simultaneously with the component spectra. This was shown by Ilijić (2004) who performed numerical experiments with time series of synthetic composite spectra calculated from the two input spectra, and given RVs defined by orbital elements. CCF was performed both with input and disentangled spectra of the components as templates. In no case did CCF return the input pair of RVs. This is due to the limited precision of the orbital elements in the presence of noise in the input spectra, and the noise progression into the disentangled component spectra which *correlates* with the noise in the orbital elements. Therefore, the combination of spectroscopic information with other types of data should no longer be based on RVs but directly on the norm of the residuals in the disentangled algorithms. Existing codes should be adapted

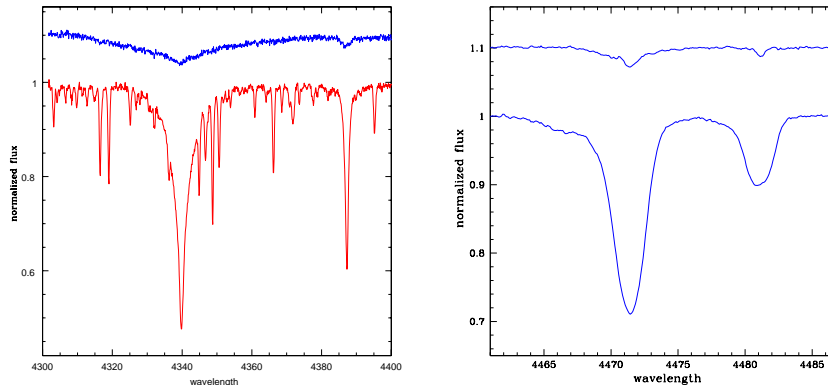


Figure 1. Detection of the faint companions in binary systems by Fourier disentangling, V621 Per in the open cluster h Per (left panel) turns to be SB2 system (Southworth et al. 2009, in preparation), and V380 Cyg (right panel, after Pavlovski et al. 2009). Spectra of the secondary components are shifted arbitrary for clarity.

in this way to ascertain optimal results. Some of these issues were investigated using synthetic data by Hynes & Maxted (1998). This problem deserves further and thorough study.

Undulations or spurious patterns are a long-standing issue. In a comprehensive study, Hensberge et al. (2008) have found a way to remove or reduce these spurious undulations in a self-consistent way. Also, hints are given to reduce quasi-degeneracies by obtaining better-conditioned data sets. Undulations are understood to be due to indeterminacies in the set of equations (low-frequency Fourier components) in the absence of sufficiently strong time-dependent dilution of spectral lines and/or to imperfect normalisation of the input spectra.

SPD has been shown to be capable to detect faint companions. In AR Cas the secondary component, which is about 4 mag fainter than the primary, was detected by Holmgren et al. (1999). Spectroscopic diagnostics were possible on disentangled secondary component of V380 Cyg, which contributes only about 6% of the total light of binary system (Pavlovski et al. 2009). With the application of SPD Southworth et al. (2009, in prep.) have turned the SB1 system V621 Per into an SB2 system. The light ratio is 22 and the detection of the faint component is made in the strong and broad hydrogen lines of the late-B secondary, explaining the failure of Southworth et al. (2004b) to detect it by CCF (Fig. 1). The spectrum of the hot but faint subdwarf in FY CMa was isolated by tomographic separation in Peters et al. (2008). In a detailed study of the prototypical mass-transferring system Algol, Fourier disentangling of more than 80 high-resolution and high S/N spectra (obtained using FIES at the Nordic Optical Telescope) has revealed all three components, of which the K1 giant secondary star contributes less than 2% (Pavlovski, Kolbas & Southworth, this Volume). This is the faintest star ever detected by SPD.

Disentangling was found to be very efficient in detecting new binary stars; for example the survey of the open cluster NGC 2244 by Mahy et al. (2009),

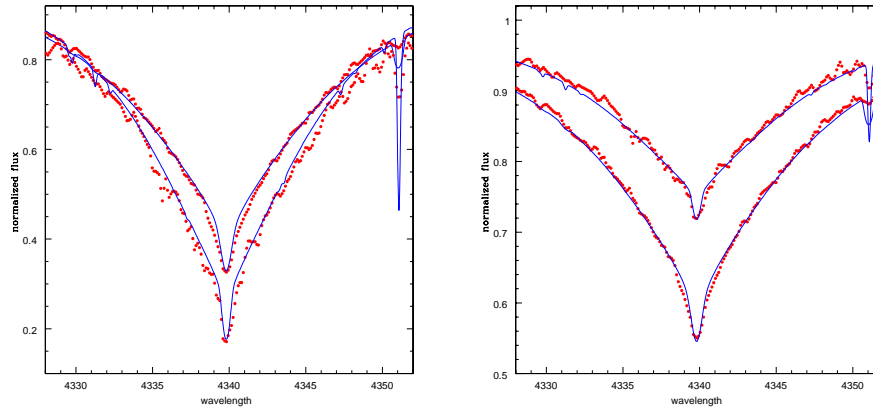


Figure 2. Deriving effective temperatures for the components of V615 Per. Spectra around  $H\gamma$  are renormalised with light factors from the light curve analysis (left panel). Both effective temperatures and light factors are derived by fitting separated (disentangled) profiles (right panel).

X-Mega targets in the Carina nebula by Rauw et al. (2009), and the spectroastrometric survey of PMS stars by Bailey (1998b).

SPD returns the orbital elements of the binary systems with a higher accuracy than achieved by other methods (Holmgren et al. 1999; Hensberge et al. 2000; Southworth & Clausen 2007; Bakiş et al. 2007; Bakiş et al. 2008; Mayer et al. 2008; Pavlovski & Southworth 2009; Pavlovski et al. 2009). Disentangling techniques were successfully applied in the studies of triple systems (Frémat et al. 2005; Bakiş et al. 2008; Hareter et al. 2008), and quadruple systems where different methods were applied (González et al. 2006; Lee et al. 2008; Harmanec et al. 2007). Algol (semidetached) systems were also studied; RY Per by Boyajian et al. (2004),  $\delta$  Lib by Bakiş et al. (2006), u Her by Hilditch (2007), RY Sct by Grundstrom et al. (2007), and Algol itself by Pavlovski, Kolbas & Southworth (this Volume). First applications to chromospherically-active binaries were made by Diaz et al. (2008), Wang et al. (2009), Doğru et al. (2009), and to W UMa-type systems by Özkardeş et al. (2009).

Fourier disentangling made possible the separation of a focussed wind component of the black hole binary X-ray source Cyg X-1 (Yan, Lin & Hadrava 2008). Linder et al. (2008) applied Doppler tomography to produce a Doppler map of Plaskett's star (HD 47129) showing the wind interaction in the system.

SPD is an especially attractive tool for distance measurements, since accurate effective temperatures can be derived from disentangled spectra. An improved accuracy in the distance to the Rosette Nebula cluster NGC 2244 was achieved in the study of the eclipsing and SB2 system V578 Mon (Hensberge et al. 2000). In similar studies distances to the open clusters were provided for the Pleiades (Zwahlen et al. 2004; Groenewegen et al. 2007), NGC 188 (Meibom et al. 2008) and NGC 6791 (Grundahl et al. 2009). SPD of binaries in Local Group galaxies also helps in the proper scaling of cosmological distance ladder (Ribas et al. 2005; Bonanos 2009; North, Gauderon & Royer 2009).

#### 4 Renormalisation of disentangled component spectra

Separate individual spectra of the components of multiple systems are either in the common continuum of the system, or in an arbitrary (generic) mode. If the light factors change significantly between spectra (particularly if eclipse spectra have been obtained) then the separation will directly give individual spectra with correct continuum levels. This requires that the light factors must either be determined from the time-dependent dilution of the spectral lines ('line photometry', Hadrava 1997), or must be estimated from external sources, usually light curves (but see below).

Renormalisation is needed if spectroscopic diagnostics and abundances are to be derived from disentangled spectra. Depending on the nature of the binary/multiple system under consideration, several approaches are possible:

- For eclipsing binaries, light factors may be available from time-independent dilution of spectral lines or from (eclipse) light curves, leading straightforwardly to undiluted disentangled spectra (e.g. Hensberge et al. 2000).
- If the system is not eclipsing, some *physical considerations* still 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. The requirement that the core should not cross the zero-point of any of the component spectra (all of similar spectral type) imposed very strong constraints on the light factors.
- Separated or generic disentangled spectra contain information on the intrinsic spectra. Just as in the way in which information on effective temperatures and surface gravities 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 (2009) applied this idea and found light factors derived from genetic forward modelling of H $\gamma$  in the eclipsing binary V615 Per to be in excellent agreement with those found from light curve analysis (Southworth et al. 2004a). In Fig. 2 (left panel), renormalised spectra of both components of V615 Per are shown. Generic spectra are fitted both for effective temperature and light factor in a constrained mode (sum of light factors equals 1). The fits are shown in Fig. 2 (right panel). Light factors derived from light curve analysis and from line-profile fitting of disentangled spectra agree within 1.5%. That this method gives reliable results is also evident from the study of Pavlovski et al. (2009), who made simultaneous constrained fits of the three Balmer lines for the primary component of V380 Cyg.

Renormalised disentangled spectra are suitable for spectroscopic analysis by the tools and methods developed for single stars. Components of different spectral types and physical characteristics have been analysed. Here is a taste of some recent studies based on SPD. Plaskett's famous star was investigated in detail by Linder et al. (2008). In both disentangled components were disclosed strong abundance anomalies which globally corroborate the predictions for evolved, fast-rotating high-mass stars. B-type stars are being systematically studied in the series of papers described in some detail in Sect. 5. In the field of

A-type stars Hareter et al. (2008) have accomplished a comprehensive study of the triple system HD 61199, which photometry from the MOST satellite revealed to contain a multi-mode  $\delta$  Scuti star. In absence of eclipses, the luminosity contributions of the components were derived by fitting synthetic spectra to the disentangled spectra assuming a solar composition. An important contribution in the study of F-type stars in binary systems has been presented by Clausen et al. (2008).

## 5 Chemical evolution of high-mass close binary stars

In the last decade theoretical stellar evolutionary models, particularly for higher masses, were improved considerably with the inclusion of rotation and magnetic fields. These effects have caused substantial changes in the resulting predictions (c.f. recent reviews by Langer et al. 2008 and Meynet et al. 2009). 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, and some are depleted, like carbon and to a lesser extent oxygen. Rotational mixing is predicted to act so efficient that changes in the atmospheric composition should be identifiable whilst the star is still on the main sequence (MS).

Empirical constraints on these processes remain hard to come by. Analysis of detached eclipsing binaries (dEBs) is vital for specifying empirical constraints on the properties of high-mass stars, since they are the primary source of directly measured stellar properties (Andersen 1991; Torres, Andersen & Giménez 2009).

In Pavlovski & Hensberge (2005), it was shown that properly renormalised disentangled spectra yield abundance measurements comparable in accuracy to those derived for single stars. In a series of papers we aim to calibrate the abundance patterns and chemical evolution of high-mass stars by analysing dEBs (Pavlovski & Southworth 2009, Pavlovski et al. 2009). The core of our analysis is *spectral disentangling*, which reveals the individual spectra of the components. The resulting disentangled spectra also have a much higher S/N than the original observations, so are well suited to chemical abundance analysis. Also, the strong degeneracy between effective temperature and surface gravity is not a problem for dEBs because surface gravities can be measured directly and to high accuracy (0.01 dex or better), which is not possible for single stars.

Binaries studied so far include V578 Mon (Pavlovski & Hensberge 2005), V453 Cyg (Pavlovski & Southworth 2009), and V380 Cyg (Pavlovski et al. 2009, see also Pavlovski et al. this Volume). The components of these binaries have masses in the range 8–15  $M_{\odot}$ , and effective temperatures in the range 22–30 kK, thus are all early B-type stars. From evolutionary considerations, we find that they are spread throughout MS, from positions close to ZAMS up to TAMS, like the primary component of V380 Cyg. The latter star is an excellent candidate for probing rotational evolutionary models. Abundance analysis has shown that all stars in the binaries studied so far cluster around normal abundances, including the evolved component in V380 Cyg that has reached already the end of the core H-burning phase. This goes against the expectations from rotational models for the low-end of the high-mass range (Ekström et al. 2008). Both an increase in rotational velocity, and changes in helium and CNO elements, are



predicted by the models. Recent calculations of the chemical evolution of stars in close binaries by De Mink et al. (2009) have shown that, contrary to the short period binaries, surface abundance changes should be small for the relatively long orbital period of V380 Cyg (12.4 d). We are currently engaged in extending the sample of close binaries for which such comparisons can be made.

## 6 Conclusion

SPD techniques make possible improvement in deriving empirical data from binary and multiple systems. Moreover, renormalised reconstructed spectra can be further analysed and eventually photospheric elemental abundances can be derived. A new window has opened for probing stellar evolutionary models by studying the chemical evolution of the components of binary and multiple stars. To paraphrase the subtitle in Clausen et al. (2008) ‘*a new standard has been set*’ in the study of binary and multiple stars.

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