Spectroscopically and Spatially Resolving the Components of Close Binary Stars
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Doppler Tomography of Binary Stars

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Abstract. The technique of Doppler tomography is now an important tool for astronomers investigating the spectra of close binary stars. The method has proven invaluable in the study of emission lines from accretion disks in cataclysmic variables, and it also plays a central role in the reconstruction (or disentangling) of the component spectra in double-lined spectroscopic binary stars. Here I focus on the latter application and discuss how Doppler tomography can help us study the stellar parameters of individual stars in close binaries. I review some of the results from tomography on unevolved and evolved binaries plus binaries in multiple star systems. I also discuss the application of tomography to the reconstruction of maps of circumstellar emission regions in massive binaries.

1. Introduction

Binary stars provide fundamental data on stellar masses through their orbital motions and light curves, but we also need to learn about their other characteristics (such as effective temperature, gravity, and abundances) in order to investigate stellar evolutionary processes. The analysis of stellar spectra can provide these other parameters if we can successfully extract the spectral features of the individual components. There are a few special cases where the spectral separation can be easily accomplished. These include binaries with hot and cool components with unique spectral patterns, double-lined systems with orbital Doppler shifts much larger than the line widths, and totally eclipsing binaries that reveal only the larger component's spectrum at mid-eclipse. However, most spectroscopic binaries do not possess these optimal qualities, and we require instead a means to separate the spectral components that can ideally use spectra from both separated and blended orbital phases.

Over the last decade a number of new techniques have been developed to tackle this problem of spectral reconstruction, and the methods have been applied to a significant number of astrophysically interesting binary systems (particularly among the hot, early-type stars). Here I will review these new methods (§2) and discuss a few of the particularly exciting results that have emerged using these clever tools (§3). The mathematical problem in the case of the reconstruction of binary star spectra amounts to finding an optimum $2 \times N_\lambda$ solution from a large number N_S of composite spectra of length N_λ wavelength points. A more challenging problem is to reconstruct an image of a velocity field for the circumstellar gas associated with a specific emission line from an interacting binary, for example. Curiously, this more difficult problem was solved first for the emission from accretion disks in cataclysmic variables (CVs; Marsh & Horne 1988; Marsh

2001), and the now well-established schemes to solve this problem are referred to as *Doppler tomography.* I will use the same name for the simpler reconstruction of binary spectra, and I will discuss some of the connections between spectral and velocity map reconstructions in §4.

2. Reconstruction Techniques

Doppler tomography has grown out of a mesh of applications in astronomical and medical imaging. The common thread of these methods is the reconstruction of a spatial object through observations of projections through the object made at differing viewing angles. We can regard the composite spectrum of a spectroscopic binary as such a $2 \times N_\lambda$ object, and observations made at orbital phases of differing Doppler shift are equivalent to projections through the object at differing viewing angles. Thus, it should be possible in principle to apply any number of techniques used in tomographic reconstruction in other fields to the problem of binary star spectrum reconstruction.

The first application of Doppler tomography to the separation of binary star spectra was done by Bagnuolo & Gies (1991) who used an Iterative Least Squares Technique (ILST) to reconstruct the UV spectra of the components of the double-lined binary AO Cas. This method uses the radial velocity curves of both stars and their continuum flux ratio to reconstruct the component spectra based on an iterative scheme that applies partial corrections set by a gain factor (< 1). The algorithm is fast and robust, and the results are insensitive to the starting assumptions about the spectra (usually assumed to be featureless continua), gain factor, and number of iterations.

A second approach was introduced by Simon & Sturm (1994) based upon a singular value decomposition (SVD) of the over-determined matrix equation $Mx = c$, where M has matrix elements corresponding to the Doppler shifts of the stars, x contains the spectra of the two components, and c is a matrix of the observed, composite spectra. Simon & Sturm also considered how the matrix M could be optimized to find or improve upon the assumed orbital elements by minimizing the difference between the observed and model composite spectra. They refer to this combined method of spectral reconstruction and orbital parameter fitting as *spectral disentangling.*

A third and now widely adopted method of spectral disentangling based on Fourier transforms (FT) was developed by Hadrava (1995, 1997). Hadrava showed that the composite spectra can be expressed as convolutions with Fourier transforms that form an elegant system of linear equations. Hadrava also includes a method to optimize the orbital elements directly (and bypass the need for initial radial velocity measurement). His code *KOREL* is available on the internet, and the current version allows up to 5 stellar components, the presence of atmospheric telluric lines, and orbital phase variable flux ratios. An extension of this method by Ilijić et al. (2004a; *FDBinary*) is available on the internet.

A fourth method was introduced by Harries, Hilditch, & Howarth (2003) who fit composite spectra for two components using a non-linear least-squares (NLLS) algorithm for a given set of orbital parameters. They then use a genetic algorithm to find orbital parameters that minimize the residuals between the observed and model composite spectra. They find that this approach provides reconstructed spectra that are in good agreement with results obtained using the SVD algorithm. They also aid future studies of their target systems by publishing the individual radial velocity shifts determined by the algorithm for each spectrum.

We can be confident that these methods are producing reliable spectral reconstructions. For example, Barai et al. (2004) have recently applied the ILST algorithm to reconstruct the spectra of the eclipsing Algol-type system, RY Persei, and Figure 1 shows a comparison of their reconstructed spectra to a single spectrum obtained during primary eclipse (when the spectrum of the hot star is absent). There is excellent agreement between the reconstructed spectrum of the secondary and its uncontaminated spectrum observed during eclipse (except at Hα which is due to uneclipsed, circumstellar gas emission).

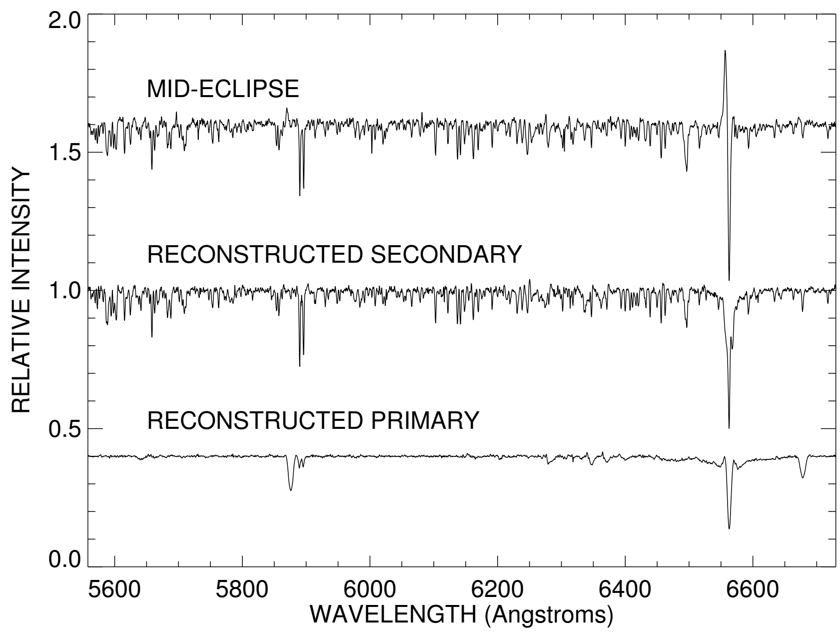

Figure 1. A comparison of the spectral reconstructions of the primary and secondary spectra of RY Per (based upon spectra obtained outside of eclipse) with the a pure secondary spectrum obtained during eclipse.

New users of these methods should be aware of several practical issues. Hynes & Maxted (1998) and Ilijić, Hensberge, & Pavlovski (2001) demonstrate how the signal-to-noise in the reconstructions improves with the number of composite spectra used, and thus, the number of observations has a direct bearing on the detection of faint companion spectra. Many of the codes allow for a flux ratio variation with wavelength and/or with orbital phase (although care must be taken with the inclusion of eclipse phase spectra). Since the reconstructions are based on Doppler shifts, any features which do not reflect orbital motion will have ambiguities in the reconstructions (for example, the P Cygni lines found in the UV spectra of hot stars, where the profile shape and velocity is determined by the stellar wind properties). Furthermore, the methods tacitly assume that the stars emit spectra that are constant, and this assumption fails in systems that display the *Struve-Sahade effect* (where the secondary lines appear stronger during approach; Bagnuolo et al. 1999) and systems with profile variations due to pulsation (De Cat et al. 2004). Nevertheless, the reconstructions can be helpful in these cases in revealing the nature of the time variations.

3. Results on the Components of Binary Systems

Doppler tomographic reconstructions of binary spectra are now available for a diverse group of binaries over a wide range of the electromagnetic spectrum. I have gathered together three tables of investigations that are each arranged in a sequence of decreasing system mass. Table 1 lists studies of unevolved systems. The columns give the names of the authors, the algorithm code used (as given in §2 plus the Doppler differencing [DD] of pairs of spectra introduced by Ferluga et al. 1997), the target name, the spectral classification of the components, and comments. These studies have led to determinations of flux ratio, effective temperatures, surface gravities, projected rotational velocities, and chemical abundances, plus masses, radii, and distance for eclipsing systems. The list contains 16 Galactic systems plus 3 each from the Small and Large Magellanic Clouds. Most of these contain early-type stars, and the masses derived from the eclipsing systems agree with their evolutionary masses (for single stars of the same temperature and gravity) provided a revised, lower effective temperature scale is adopted for O-stars (Gies 2003; Hilditch 2004). The power of these methods is demonstrated in the detection of the faint companion in HD 53975 that contributes only 5% to the composite spectrum (Gies et al. 1994).

Table 2 lists investigations on 14 Galactic plus 7 SMC binaries that contain evolved components. This is a much more diverse sample of systems (semi-detached, contact, post-Roche lobe overflow, etc.). The short period system HD 115071 consists of an O9.5 V + B0.2 III pair with masses of 11.6 and 6.7 $M_\odot$, respectively (Penny et al. 2002). It is an example of a post-Roche lobe overflow stage (or *hot Algol* system) in which the components are undermassive or overluminous for their spectral types (see also Harries et al. 2003; Hilditch 2004). Plaskett's star (HD 47129) contains a pair of O-supergiants of approximately 51 and 43 $M_\odot$, making it one of the most massive binary systems known in the Galaxy. The more massive component has eluded detection in the past, but Doppler tomographic reconstructions in the UV (Bagnuolo, Gies, & Wiggs 1992) and in the optical (Bagnuolo & Barry 1996) show that the star is a very rapid rotator (with a projected rotational velocity, $V \sin i = 310$ km s^{-1}), possibly the result of prior mass and angular momentum accreted from the companion. A more extreme example is the classical Be star, ϕ Persei. Doppler tomography of UV spectra from the *International Ultraviolet Explorer Satellite (IUE)* (Thaller et al. 1995) and the *Hubble Space Telescope (HST)* (Gies et al. 1998) show that ϕ Persei consists of a B0.5 III-Ve primary orbited by a tiny but hot, sdO secondary star. The hot secondary is the stripped-down remnant of the initially more massive star that transferred most of its mass to the Be star. The accreted mass spun up the Be star to near the critical break-up velocity ($V \sin i = 450$ km s^{-1}).

Table 3 lists studies of 11 triple and quadruple star systems (many discovered through speckle interferometry; Mason et al. 1998), and in some cases spectra were reconstructed for all the components (e.g., 55 UMa; Liu et al. 1997).

Table 1. Spectral Reconstruction Studies of Unevolved Systems

Source	Code	Target	Sp. Type	Comment
Sturm & Simon 1994	SVD	DH Cep	O6 V + O7 V	Optical
Penny et al. 1997	ILST	DH Cep	O6 V + O7 V	UV
Williams et al. 2001	ILST	HD 199579	O6 V((f)) + B1-2 V	Faint sec.
Gies et al. 2002	ILST	HD 101131	O6.5 V((f)) + O8.5 V	IC2944
Gies et al. 1994	ILST	HD 53975	O7.5 V + B3 V	$\Delta m = 3.3$
Hill et al. 1994	ILST	CC Cas	O8.5 III + B0.5 V	Eclipsing
Harries et al. 2003	NLLS	3 stars	OB-type	SMC
Simon et al. 1994	SVD	Y Cyg	B0 V + B0 V	Eclipsing
Hill & Holmgren 1995	ILST	Y Cyg	B0 V + B0 V	Eclipsing
Simon & Sturm 1994	SVD	V453 Cyg	B0.5 V + B0.5 V	Eclipsing
Fitzpatrick et al. 2003	FT	HV 5936	B0.5 V + B2 III	LMC
Holmgren et al. 1997	FT	β Sco A	B0.5 IV-V + B1.5 V	Occn.
Fitzpatrick et al. 2002	FT	HV 982	B1 IV-V + B1 IV-V	LMC
Hensberge et al. 2000	FT	V578 Mon	B1 V + B	NGC2244
Harmanec et al. 1997	FT	V436 Per	B2 V + B2 V	Eclipsing
Janík et al. 2003	FT	V436 Per	B2 V + B2 V	Eclipsing
Ribas et al. 2002	FT	EROS 1044	B2 IV-V + B2 III-IV	LMC
Yakut et al. 2003	FT	V497 Cep	B3 + B	NGC7160
Holmgren et al. 1999	FT	AR Cas	B4V + A6V:	Eclipsing
De Cat et al. 2004	FT	HD 140873	B8 III + A	SPB
De Cat et al. 2004	FT	HD 123515	B9 IV + A	SPB
Hill et al. 1993	ILST	HR 104	A2 V + F0 V	

Table 2. Spectral Reconstruction Studies of Evolved Systems

Source	Code	Target	Sp. Type	Comment
Bagnuolo et al. 1992	ILST	HD 47129	O7.5 I + O6 I	UV
Bagnuolo & Barry 1996	ILST	HD 47129	O7.5 I + O6 I	Optical
Penny et al. 1999	ILST	HD 152248	O7 I + O7 I	UV
Bagnuolo et al. 1994	ILST	UW CMa	O7.5 Iab + O9.7 Ib	UV
Bagnuolo et al. 2001	ILST	ι Ori	O9 III + B1 III	Swapped?
Gies et al. 1993	ILST	ι Ori	O9 III + B1 III	Hα
Bagnuolo & Gies 1991	ILST	AO Cas	O9.5 III + O8 V	UV
Penny et al. 2002	ILST	HD 115071	O9.5 V + B0.2 III	Hot-Algol
Harries et al. 2003	NLLS	7 stars	OB-type	SMC
Lorenz et al. 1999	FT	V606 Cen	B0-0.5 V + B2-3 V	Eclipsing
Thaller et al. 1995	ILST	ϕ Per	B0.5 III-Ve + sdO	UV (*IUE*)
Gies et al. 1998	ILST	ϕ Per	B0.5 III-Ve + sdO	UV (*HST*)
Hill et al. 1997	ILST	V360 Lac	B3e + F9 IV	Algol-type
Barai et al. 2004	ILST	RY Per	B4 V + F7 II-II	Algol-type
Hill & Khalesseh 1993	ILST	V1425 Cyg	B5 V + B9 V	Eclipsing
Bisikalo et al. 2000	FT	β Lyr	B6-8II + B	Faint comp.
Ferluga et al. 1997	DD	IZ Per	B8	Algol-type
Griffin 2002	FT	o Leo	F8m + Am	Abundances

Table 3. Spectral Reconstruction Studies of Multiple Systems

Source	Code	Target	Sp. Type	Comment
Harvin 2002	ILST	HD 206267	O6.5 V((f))+B0 V, O8 V	SB2+spkl.
Penny et al. 2001	ILST	δ Cir	O7 III-V+O9.5 V, B0.5	UV
Lorenz et al. 1998	FT	SZ Cam	O9 IV+B0.5 V	Quadruple
Harvin et al. 2002	ILST	δ Ori	O9.5 II+B0.5 III	UV
McSwain 2003	ILST	HD 16429A	O9.5 II, O8 III-V	SB1+spkl.
Ilijić et al. 2004b	FT	AC Vel	B3 IV+B	Eclipsing
Zverko et al. 1997	FT	AR Aur	B9.5 V+A	Eclipsing
Liu et al. 1997	ILST	55 UMa	A1 V+A2 V, A1 V	SB2+spkl.
Koubský et al. 2004	FT	b Per	A2 V	
Frémat et al. 2004	FT	DG Leo	A8 V	
Torres et al. 2004	FT	RV Crt	F8	Eclipsing

4. Emission Line Tomography

The first application of Doppler tomography to binary stars was the reconstruction of emission line flux maps of CVs (Marsh & Horne 1988). Here observations of a single emission line (often Hα) from around the orbit (excluding eclipse phases) are used to build a two-dimensional velocity map of the emission flux (referred to as a *Doppler tomogram*). The basic assumption is that the observer views a velocity distribution that is linked to the spatial distribution of the circumstellar gas, and the emission profile seen at any particular orbital phase is a projection through this velocity map. Since the spatial features often found in CVs (Roche lobe overflow gas stream, hot spot, accretion disk) have distinctive velocity patterns, the Doppler tomogram can be interpreted in terms of these specific structures (Marsh 2001).

Many of the numerical techniques relating to the reconstruction of binary spectra can also be applied to emission line reconstruction problems (and vice-versa). For example, Thaller et al. (2001) used a version of the ILST algorithm to make a back-projection reconstruction of the emission velocity distribution for the O-star binary, HD 149404. This is probably a colliding winds binary, and the tomogram for Hα emission in this system shows evidence of the two winds flowing into the collision zone between the stars.

Tomographic methods are now also being applied to study the circumstellar gas distribution in classical Algol-type binaries (Richards & Albright 1999). The Algol systems present special difficulties because the mass gainers are not small white dwarfs (as in the CVs) but are massive main sequence stars. The bright photosphere of the gainer will occult large portions of the accretion disk at every orbital phase, and the disk itself will cause absorption of the gainer's spectrum where it is seen projected against the gainer star. Barai et al. (2004) have recently introduced a new reconstruction method to map the accretion disk surface density distribution in Algols that accounts for these difficulties. They have applied the technique to Hα spectroscopy of the Algol system RY Persei (B4 V + F7 II-III), and their resulting surface density map bears a strong resemblance to hydrodynamical gas simulations of Algols by Richards & Ratliff

(1998). The gas stream strikes the gainer in RY Persei nearly tangentially at the star's trailing equator, and the favorable torque applied in this case may explain the gainer's rapid rotation ($V \sin i = 213$ km s^{-1}).

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