Fourier Disentangling of Spectra in Observational Surveys

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Plan of the talk

- Theory and observations
- Disentangling of spectra
  – Fourier and wavelength domain
- Challenges of observational surveys
- Treatment of few-epochs spectra
  – example of 68 u Her

Why to observe stars?

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ASTRONOMIÆ
INSTAURATÆ
MECHANICA

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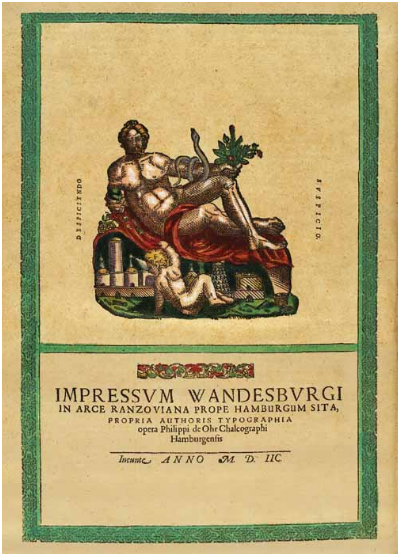

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opera Philippi de Ohr Chalcographi
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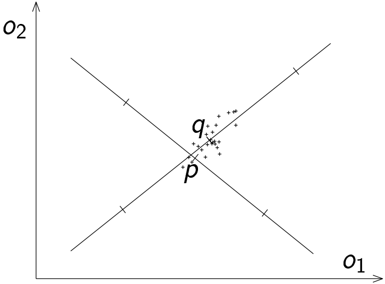
Theory should be inspired and proved by observations

Observation should be motivated and interpreted by theory

Interpretation is biased by model



A more sophisticated model need not be better

Multiple stars

Observations of binaries ⇒ physical parameters of stars

× Proximity effects: tidal, reflection, mass exchange

Roche model: hydrostatic equilibrium ($\nabla P = -\rho \nabla \Phi$)

⇒ homogeneity on equipotentials ⇒ varying g

Von Zeipel's theorem: diffusion approximation

⇒ gravitational darkening ($T_{\mathrm{eff}} \sim g^{0.25}$)

⇒ no hydrostatic equilibrium ⇒ no homogeneity

⇒ meridional + longitudinal circulations

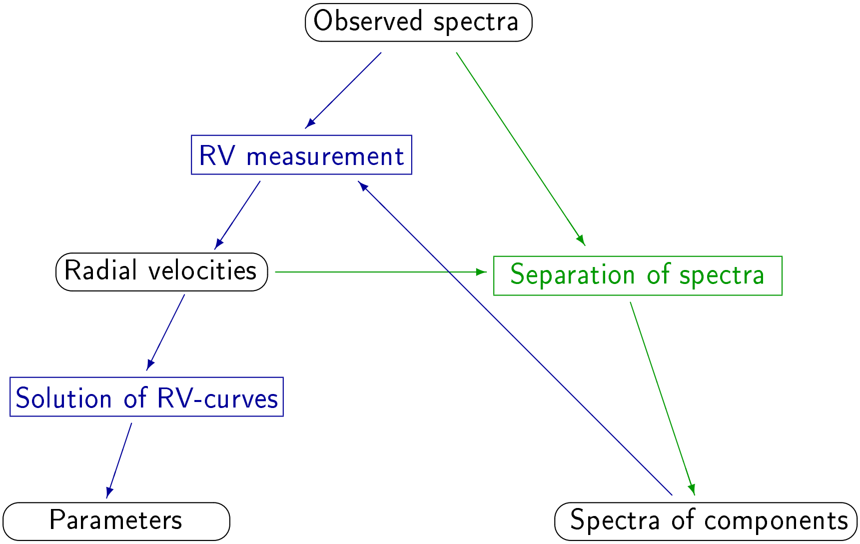
Anisotropic stellar winds – Roche-lobe overflow, asynchronous rotation, pulsations

⇒ 3d - radiation hydrodynamics

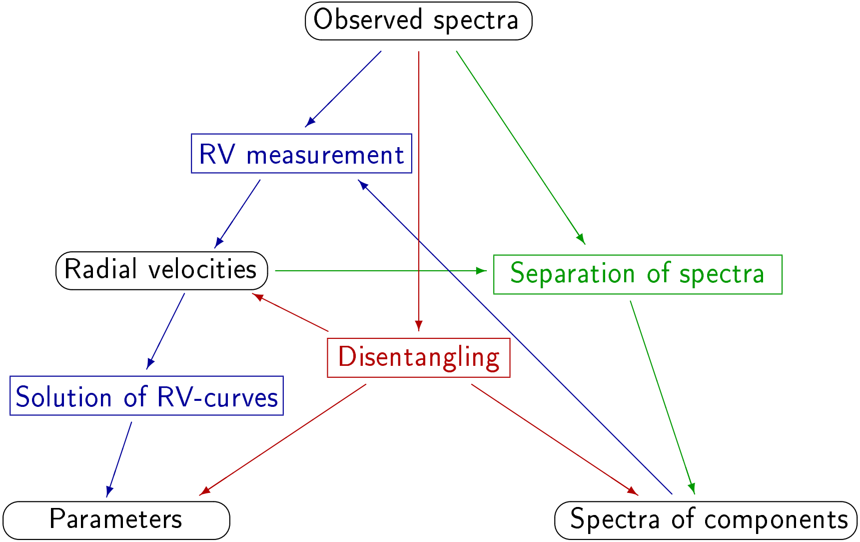
Spectroscopy ⇒ size of the system × blending of components spectra

Disentangling based on simplified model is a tool for spectra interpretation

Disentangling of spectroscopic binaries



Disentangling of spectroscopic binaries



Observed spectra

RV measurement

Radial velocities

Separation of spectra

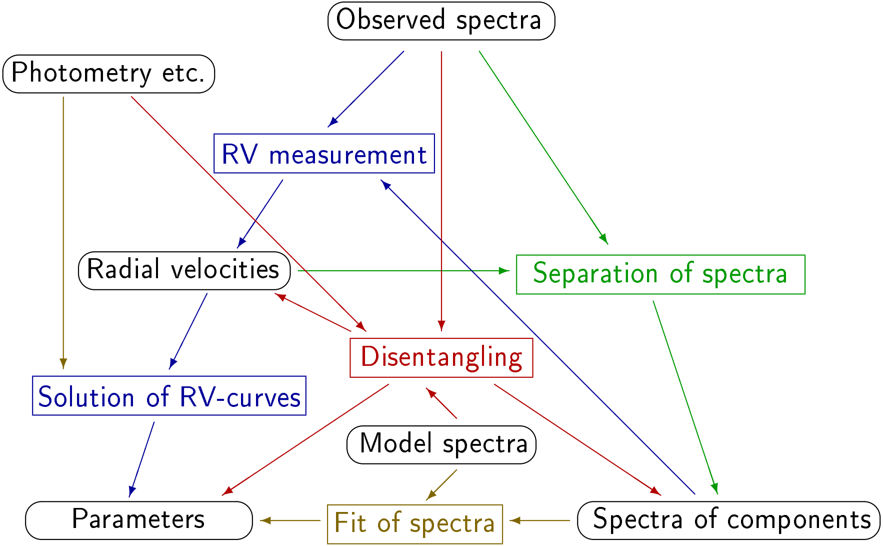
Disentangling

Solution of RV-curves

Parameters

Spectra of components

Disentangling of spectroscopic binaries



Wavelength-domain and Fourier disentangling

1994 K. P. Simon & E. Sturm A&A 281, 286
1995 P. Hadrava A&AS 114, 393

$$I(x,t;p)=\sum_{j=1}^{n} I_j(x-v_j(t;p))\,,\quad x\equiv c\ln(\lambda/\lambda_0)$$

$$I(x,t;p)=\sum_{j=1}^{n} I_j(x)*\Delta_j(x,t;p)\,,\quad \Delta_j(x,t;p)=\delta(x-v_j(t;p))$$

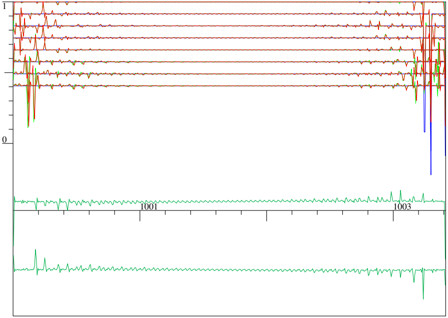
$$\tilde{I}(y,t;p)=\sum_{j=1}^{n} \tilde{I}_j(y)\tilde{\Delta}_j(y,t;p)\,,\quad \tilde{\Delta}_j(y,t;p)=\exp(iyv_j(t;p))$$

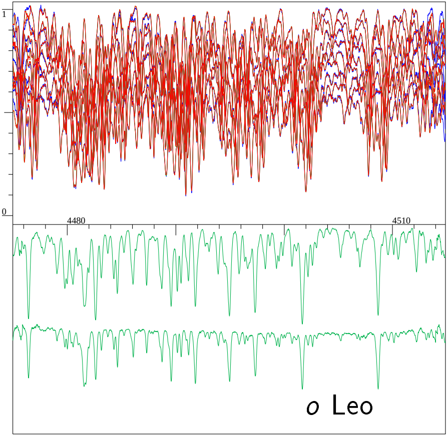
$$0=\delta\sum_{l=1}^{N}\int|I(x,t_l)-\sum_{j=1}^{n} I_j(x)*\Delta_j(x,t_l,p)|^2dx$$

$$0=\delta\sum_{l=1}^{N}\int|\tilde{I}(y,t_l)-\sum_{j=1}^{n} \tilde{I}_j(y)\tilde{\Delta}_j(y,t_l,p)|^2dy$$

Comparison:

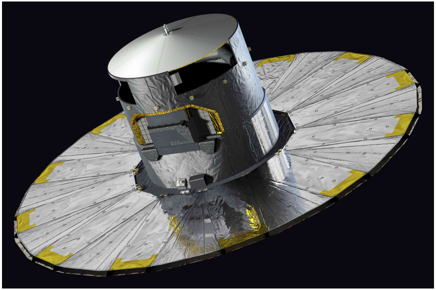
- $\surd$ Numerical efficiency $\Rightarrow$ possibility of generalizations
- $\times$ Need of interpolation into equidistant logarithmic scale
- $\times$ Weighting of pixels – weighting of Fourier modes
- $\surd$ Edge effects

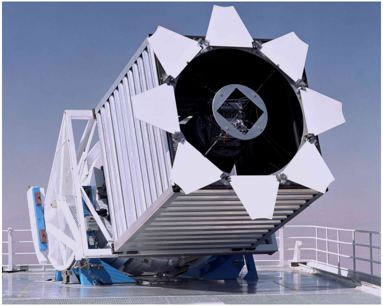


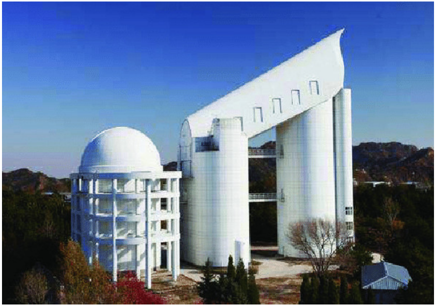


Photometric and astrometric surveys
- spectroscopic follow up

Spectroscopic surveys
- e.g. Gaia, SDSS, LAMOST







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Autonomous disentangling for spectroscopic surveys

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ABSTRACT

A suite of spectroscopic surveys is producing vast sets of stellar spectra with the goal of advancing stellar physics and Galactic evolution by determining their basic physical properties. A substantial fraction of these stars are in binary systems, but almost all large-survey modelling pipelines treat them as single stars. For sets of multi-epoch spectra, spectral disentangling is a powerful technique to recover or constrain the individual components' spectra of a multiple system. So far, this approach has focused on small samples or individual objects, usually with high-resolution ($R \gtrsim 10.000$) spectra and many epochs ($\gtrsim 8$). Here, we present a disentangling implementation that accounts for several aspects of few-epoch spectra from large surveys: that vast sample sizes require automatic determination of starting guesses; that some of the most extensive spectroscopic surveys have a resolution of only ≈ 2000; that few epochs preclude unique orbit fitting; that one needs effective regularization of the disentangled solution to ensure resulting spectra are smooth. We describe the implementation of this code and show with simulated spectra how well spectral recovery can work for hot and cool stars at $R \approx 2000$. Moreover, we verify the code on two established binary systems, the 'Unicorn' and 'Giraffe'. This code can serve to explore new regimes in survey disentangling in search of massive stars with massive dark companions, for example, the $\gtrsim 200\,000$ hot stars of the SDSS-V survey.

Key words: techniques: spectroscopic – software: development – binaries: spectroscopic – stars: black holes.

1 INTRODUCTION

The fact that a significant fraction of all stars or stellar remnants is in multiple stellar systems with a period of less than a few years (e.g. Sana et al. 2012; Moe & Di Stefano 2017) fundamentally affects many aspects of astrophysics. It affects the stellar evolution of both components, in some cases already during their main sequence phases, and more often in the evolved phases that will result in compact objects (such as white dwarfs, neutron stars, and black holes); it affects nucleosynthesis, the formation channels of supernovae, and the interpretation of photometric, astrometric, or spectroscopic sky surveys. And massive binaries – or their descendants – are the most prominent and frequent source of gravitational waves so far (e.g. Abbott et al. 2023).

Most of these systems cannot be spatially resolved, with projected separations that often are $\lesssim 1$ mas. However, their orbital velocities make it possible to separate the constituents of such multiple stellar systems in velocity space, especially if spectra at different orbital phases exist. We commonly categorize spectroscopic binaries into SB1 and SB2. Here, SB1 denotes a single-lined spectroscopic binary, where only one of the component spectra is apparent in the observations, and SB2 describes a double-lined spectroscopic binary, where two sets of lines are visible in the observed spectra. The approach of using multi-epoch observations of spectroscopic binaries to determine the components is called *spectral disentangling* (e.g. Bagnuolo Jr & Gies 1991; Simon & Sturm 1994; Hadrava 1995).

In broad terms, spectral disentangling assumes that spectra of a presumed multiple stellar system – when observed at different epochs – can be described as the sum of two (or more) spectra that are invariant in their rest frame, but whose radial velocities (RVs) change as a function time, reflecting orbital motion. The mathematical foundation of spectral disentangling has been established for 30 yr (e.g. Bagnuolo Jr & Gies 1991; Simon & Sturm 1994; Hadrava 1995). End-to-end disentangling requires the simultaneous, or iterative, solution to two problems, (i) reconstructing the rest-frame spectra of each component and (ii) determining the components' RVs at each epoch or, alternatively, the orbital solution of the overall system. If the velocities at all epochs are known, the reconstruction of the disentangled spectra reduces to a linear χ^2-optimization problem, aiming to match the combined spectra at all the different epochs.

However, the application of spectral disentangling to large data sets has some serious practical limitations. First, some literature work has assumed that (a very good guess for) various system parameters can be obtained independently [e.g. Ilijic's (2004) code CRES requires input of both the primary's and the secondary's velocities, shift-and-add as described in Shenar et al. (2020, 2022b) requires input of a few orbital parameters, see Table 1]. If the data are of limited

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- Disentangling suitable for processing of data from spectroscopic surveys
- Problems:
  few epochs
  low resolution
  low S/N
  random phase coverage

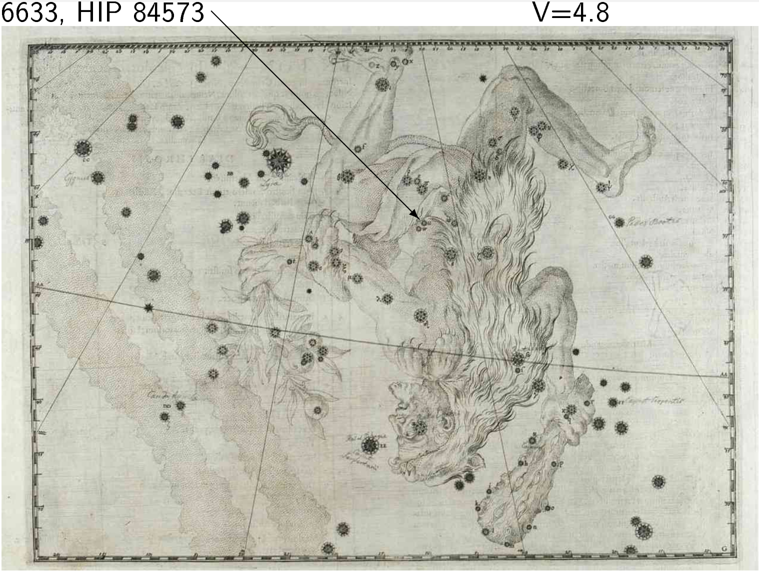
→ RVs instead of parameters
→ wavelength domain
→ cross-correlation with templates

$$P,\ T,\ e,\ \omega,\ K$$

Example of binary 68 u Her

HD 156633, HIP 84573

V=4.8



Johann Bayer 1603, Uranometria

68 u Her

Monthly Notices
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Tracing CNO exposed layers in the Algol-type binary system u Her

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ABSTRACT

The chemical composition of stellar photospheres in mass-transferring binary systems is a precious diagnostic of the nucleosynthesis processes that occur deep within stars, and preserves information on the components' history. The binary system u Her belongs to a group of hot Algols with both components being B stars. We have isolated the individual spectra of the two components by the technique of spectral disentangling of a new series of 43 high-resolution échelle spectra. Augmenting these with an analysis of the *Hipparcos* photometry of the system yields revised stellar quantities for the components of u Her. For the primary component (the mass-gaining star), we find $M_{\rm A} = 7.88 \pm 0.26\,{\rm M}_{\odot}$, $R_{\rm A} = 4.93 \pm 0.15\,{\rm R}_{\odot}$ and $T_{\rm eff,\,A} = 21\,600 \pm 220\,{\rm K}$. For the secondary (the mass-losing star) we find $M_{\rm B} = 2.79 \pm 0.12\,{\rm M}_{\odot}$, $R_{\rm B} = 4.26 \pm 0.06\,{\rm R}_{\odot}$ and $T_{\rm eff,\,B} = 12\,600 \pm 550\,{\rm K}$. A non-local thermodynamic equilibrium analysis of the primary star's atmosphere reveals deviations in the abundances of nitrogen and carbon from the standard cosmic abundance pattern in accord with theoretical expectations for CNO nucleosynthesis processing. From a grid of calculated evolutionary models the best match to the observed properties of the stars in u Her enabled tracing the initial properties and history of this binary system. We confirm that it has evolved according to case A mass transfer. A detailed abundance analysis of the primary star gives C/N = 0.9, which supports the evolutionary calculations and indicates strong mixing in the early evolution of the secondary component, which was originally the more massive of the two. The composition of the secondary component would be a further important constraint on the initial properties of u Her system, but requires spectra of a higher signal-to-noise ratio.

Key words: binaries: eclipsing – binaries: spectroscopic – stars: fundamental parameters – stars: individual: u Her.

1 INTRODUCTION

The evolution of a star in a binary system is affected by the presence of its companion. Only a limited space is allowed for evolution due to the mutual gravitational pool of the components, and the star which was initially more massive will be the first to reach this limiting radius (i.e. the Roche lobe). At this point a rapid phase of mass transfer happens. Most of the more massive component is accreted by its companion, and an Algol-type binary system is formed. The previously more massive star is now a low-mass subgiant filling its Roche lobe, and its companion is now the hotter and more massive component with the characteristics of a main-sequence star. The mass-transfer scenario, first hypothesized by Crawford (1955), is a well-established solution to the Algol paradox (cf. Hilditch 2001).

This evolutionary process causes many observable effects (changes in orbital period, erratic light variability, distorted radial velocity, RV, curves, etc.), but one is particularly important. Up to 80 per cent of the mass of the initially more massive star can be lost, exposing layers which were originally deep within the star and have been altered by thermonuclear fusion during the star's main-sequence evolution. Some of the material transferred to the companion is similarly altered. The surface chemical compositions of both stars are therefore a precious diagnostic of the nucleosynthesis processes that occur deep within stars. The abundance pattern in Algol-type binaries could reveal their past, and would be strong evidence for postulated mass transfer between the components (cf. Sarna & De Greve 1996).

In pioneering studies, a general trend has been revealed with an underabundance of carbon and an overabundance of nitrogen relative to solar values (Parthasarathy, Lambert & Tomkin 1983; Cugier & Hardorp 1988; Cugier 1989; Tomkin, Lambert & Lemke 1993). This is in line with expectations for the CNO cycle, which is

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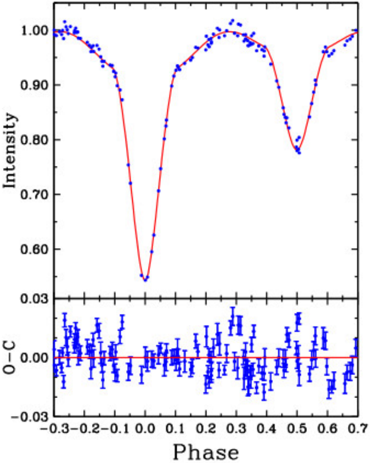
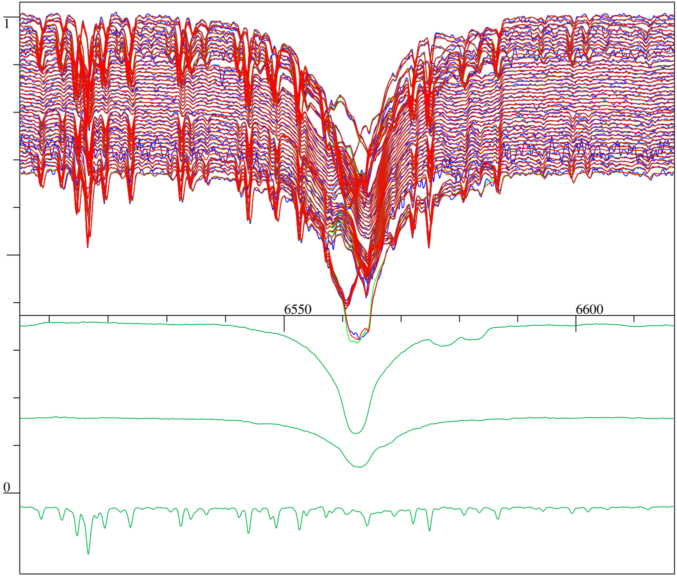
FDBinary
S. Ilijić et al. 2004, ASPCS 318, 111

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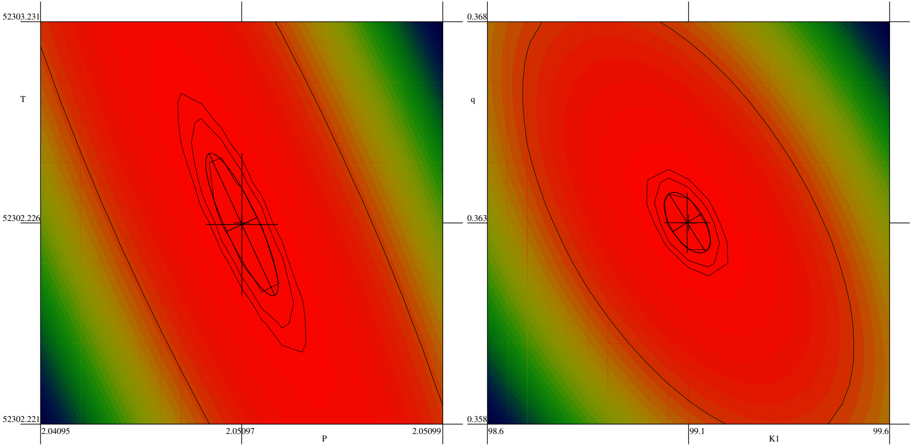
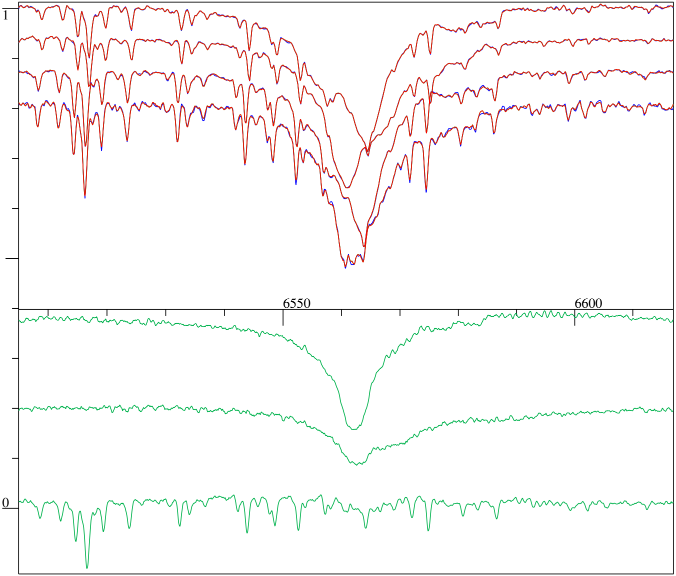


Solution	Kolbas+	43 spectra	4 spectra
P	2.05102685(68)	2.050966(4)	2.050933(11)
T	47611.5007(15)	52302.226(2)	52302.227(3)
K_1	94.6±2.3	99.10(6)	97.98(16)
K_2	267.4±3.3	273.16	268.99
$q = K_1 / K_2$	0.354	0.363(8)	0.364(2)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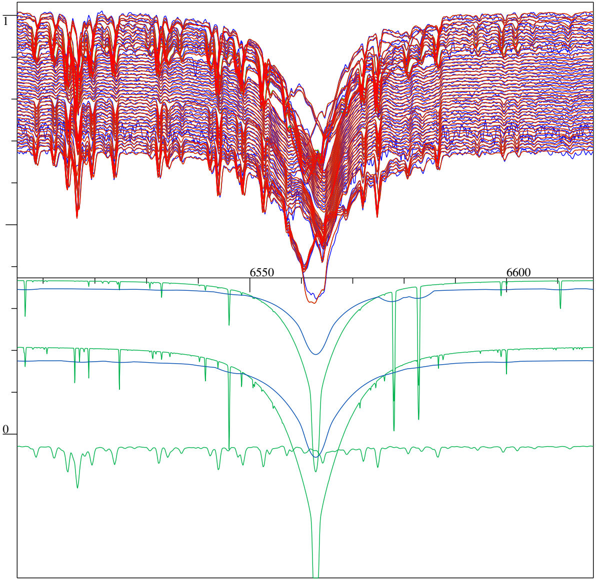
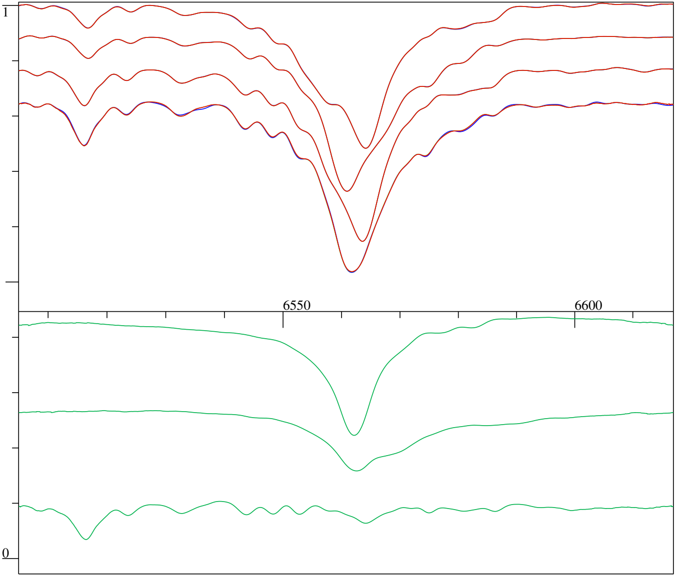


$T_1 = 21350\,\mathrm{K}$

$T_2 = 11090\,\mathrm{K}$



$R \sim 2000$

Conclusion

- Disentangling is a useful tool for interpretation of data from spectroscopic surveys
- Disentangling of orbital parameters is preferable to disentangling of RVs
- It is desirable to combine the disentangling of spectra with light-curve solution of data from photometric surveys

Thank you for your attention