Contrib. Astron. Obs. Skalnaté Pleso **55/3**, 340 – 345, (2025)
https://doi.org/10.31577/caosp.2025.55.3.340

Enhanced spectral disentangling techniques for long-period hot subdwarf binaries

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Received: November 14, 2024; Accepted: January 19, 2025

Abstract. Wavelength space binary spectral disentangling is discussed with a data-driven, steepest-descent chi-square minimizing, global fitting procedure that applies stacked synthetic spectra to render composites. With additional constraints such as Gaia distance, mass ratio, orbital period, and separation of the binary members the stellar parameter precision can be improved even for non-eclipsing systems. We follow the orbits of 36 systems of which we discuss JL 277 here.

Key words: composite spectrum binaries

1. Introduction

Composite spectrum binaries are systems where the observed spectrum is a blend of light from two stellar components. These are common among binaries with evolved stars like hot subdwarfs or (low-mass) white dwarfs with cool companions.

The main challenge is disentangling the contributions of each star, which requires robust methods to accurately derive the atmospheric parameters (e.g., temperature, gravity) and flux contributions from the composite spectrum. These entangled parameters in composite spectra lead to serious degeneracies and systematic errors. Overcoming these requires high signal-to-noise, multi-wavelength observations, and various assumptions or constraints on the systems.

Historically, high-precision stellar parameters were obtainable primarily from eclipsing binaries, where light curves provided direct constraints on component sizes and flux ratios. For non-eclipsing systems, the analysis relied heavily on assumptions and models, leading to larger uncertainties.

With the upcoming Gaia DR4 release, the landscape is changing. Spectral decomposition techniques, combined with precise mass ratios and astrometric data like orbital separations, offer a powerful approach to studying non-eclipsing binaries at a level of precision that previously was limited to single stars or eclipsing systems.

Both wavelength-domain (Simon & Sturm, 1994) and Fourier-domain disentangling (Hadrava 1995, Hadrava 1997, also in these proceedings) are designed to simultaneously solve for orbital parameters and to separate component spectra from a set of spectra sufficiently covering the orbital period. Our method of fitting the observed spectra by synthetic templates enables us to determine atmospheric parameters even from a single observation.

2. Spectral disentangling with XTgrid

We fit the observed composite spectrum with a synthetic model, constructed as a linear combination of two single-star synthetic spectra. The method is implemented in the chi-square minimizing, data-driven, global fitting procedure XTgrid (Németh et al., 2012). The fitting process adjusts the atmospheric parameters (e.g., effective temperature, surface gravity, metallicity) and the relative flux contributions iteratively until convergence is achieved. The primary goal is to derive accurate atmospheric parameters for both stars, disentangling their individual contributions from the observed composite spectrum at the given observed or assumed constraints. XTgrid can combine models from various stellar atmosphere codes and synthetic libraries to render composite models. We applied here Tlusty models (Hubeny & Lanz, 2017) for the hot subdwarf and Atlas models extracted from the BOSZ library (Bohlin et al., 2017) for the cool companions.

The observed spectrum is modeled iteratively using synthetic spectra generated for a range of stellar parameters. The synthetic composite spectrum $F_{\rm model}(\lambda)$ is expressed as:

$$F_{\rm model}(\lambda) = w_1 F_1(\lambda(1 - v_1/c)) + w_2 F_2(\lambda(1 - v_2/c)),$$

where $F_1(\lambda(1 - v_1/c))$ and $F_2(\lambda(1 - v_2/c))$ are the radial velocity corrected synthetic spectra of the two components, and w_1, w_2 are the respective weighting factors representing their flux contributions.

We incorporate observed mass ratios as additional constraints during the fitting process. The mass ratio provides a direct link between the stellar masses M_1 and M_2, which we use to limit the surface gravity ratios and the parameter space of the solutions. This helps to significantly reduce the degeneracy in the fit and improves the accuracy of derived stellar properties.

In non-eclipsing systems, the mass ratio obtained from radial velocity measurements gives us valuable information that previously was not fully utilized in spectral decomposition. By integrating this constraint, we effectively reduce the number of free parameters, thereby refining the solution.

The formation of hot subdwarfs is a direct result of the common envelope and/or Roche-lobe overflow evolution channels (Pelisoli et al., 2020), and the precise surface parameters of the components are keys to fine-tuning evolution models.

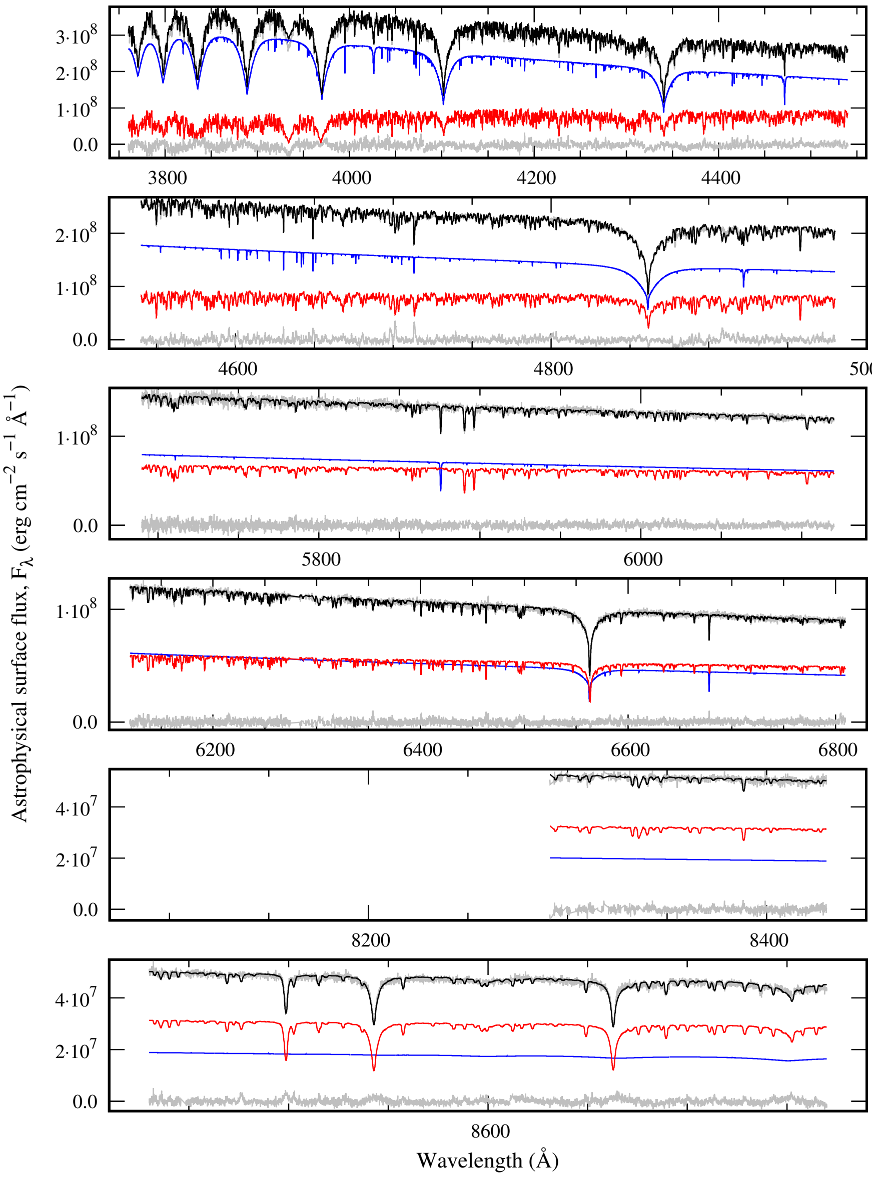

Figure 1. Best-fit XTGRID / TLUSTY+ATLAS composite model for JL 277 shown in *black*. The VLT / UVES observation is in *grey*, the TLUSTY model is in *blue*, and the ATLAS model is shown in *red*. At zero flux we show the fit residuals. The model parameters are available on request.

Figure 1 shows the best-fit spectral model for JL 277, an sdB+F5V type binary. The measured spectral energy distribution from ultraviolet, optical, and infrared measurements is available for many systems (e.g. Simbad VizieR service) and allows the flux contributions from the spectral model to be compared in much broader ranges as demonstrated for JL 277 in Figure 2.

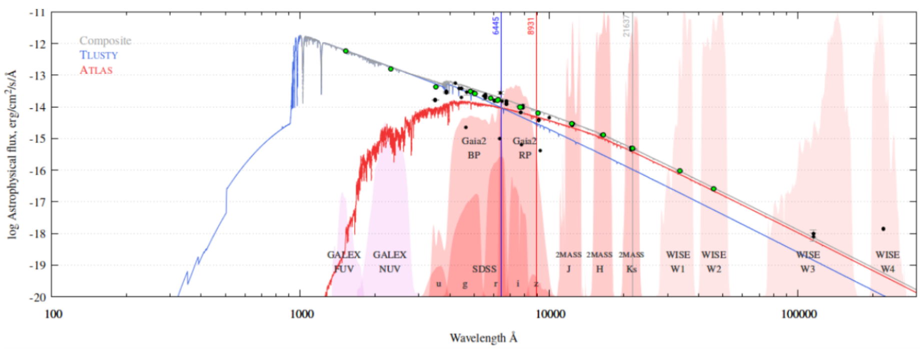

Figure 2. Spectral energy distribution of JL 277. All data points were taken from the VizieR Photometry Viewer service. The photometric data were de-reddened using $E(B-V) = 0.022$ mag (stilism.obspm.fr). The green points were used to match the slope of the passband convolved combined TLUSTY and ATLAS fluxes to the observations and the model was normalized to the observed SED in the 2MASS/K band.

3. Radial velocities

Radial velocity measurements of JL 277 were obtained by cross-correlating the observations with RV standard spectra. Figure 3 shows the radial velocity curve. These velocities allowed orbital parameters, semi-amplitudes, and the mass ratio to be determined assuming a Keplerian orbit within the AOTS database system (https://a15.astro.physik.uni-potsdam.de).

4. Future prospects with Gaia DR4

Gaia DR4 is expected to provide precise measurements of orbital separations for a large number of binary systems, including non-eclipsing binaries. This will enable a self-consistent analysis of these systems by combining spectroscopic data (from radial velocity and spectral fitting) with astrometric information. With the orbital size a, period P, and mass ratio q (already included in our fitting process), we can derive absolute masses M_1 and M_2. Consequently, the observed properties of each binary member can be matched to single-star models with commensurable precision.

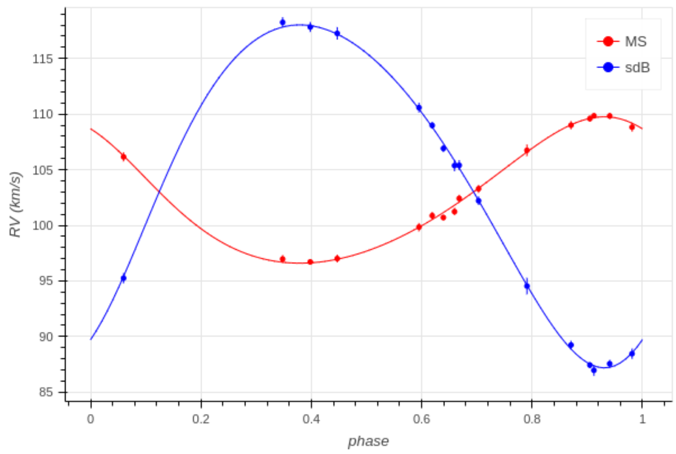

Figure 3. Radial velocity curve of JL 277 from the AOTS system.

Table 1. Orbital parameters of JL 277 extracted from the AOTS system.

Parameter	Value ± Error
P (days)	1090.3 ± 1.5
$T0$ (-2400000)	55827.0 ± 1.5
ω (deg)	3.52 ± 0.10
e	0.086 ± 0.010
K_1 (km/s)	14.470 ± 0.160
K_2 (km/s)	6.528 ± 0.067
q ($M_{\rm sdB}/M_{\rm MS}$)	0.451 ± 0.008

This approach offers a major advantage for the study of non-eclipsing binaries, allowing us to reach precision levels previously achievable only in eclipsing systems. By utilizing observed orbital characteristics, we can fully characterize the binary components, including their evolutionary states and masses, without relying on light curve data.

5. Summary

The inclusion of photometric data and mass ratios as constraints in spectral decomposition significantly enhances the accuracy of derived stellar parameters for non-eclipsing composite spectrum binaries. This methodology opens up new avenues for analyzing these systems with precision previously limited to eclipsing binaries. With the upcoming Gaia DR4 release, we anticipate further improvements in the accuracy of our method, allowing to investigate a wider range of

Table 2. Parameters of the members in JL 277.

Parameter	Primary±1σ	Secondary±1σ
$T_{\rm eff}$ (K)	24200±400	6050±150
$\log g$ (cgs)	5.29±0.09	4.10±0.10
M ($M_\odot$)	0.466±0.020	1.034±0.047
R ($R_\odot$)	0.252±0.003	1.499±0.030
L ($L_\odot$)	19.39±0.77	2.718±0.111
d (pc)	1014.5±20.5	

binaries and better understand their evolutionary stages. This work not only broadens the scope of precise binary star analysis but also has the potential to refine our understanding of binary star evolution, especially in cases involving hot subdwarfs, low-mass white dwarfs, and other evolved stellar components.

Another case study for the quasi Wolf-Rayet (He-rich sdO) and B7V binary HD 45166 is also available in these proceedings.

Acknowledgements. We thank the anonymous referee for their comments and suggestions, which have improved the clarity and quality of this manuscript. This research was supported by the Grant Agency of the Czech Republic (GAČR 22-34467S).

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