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Accurate dynamical masses from binaries with extreme brightness ratios

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Abstract. High-resolution cross-correlation techniques are a powerful tool to explore exoplanet atmospheres. We introduce their application to binary stars from the EBLM project. In particular, we focus on eclipsing, high-contrast binaries consisting of a solar-type star and a low mass M-dwarf companion. These binary systems have typical brightness ratios $\sim 0.1\%$ at optical wavelengths and appear as single-lined binaries in optical high-resolution spectra. Since the spectral features of low-mass stars are well known, we can recover the signal of the M-dwarf companion from what otherwise appears as noise, and accurately measure the masses of both stars, turning the system into a double-lined binary. We show that this application is a powerful new tool to not only derive accurate and precise dynamical masses for fully convective stars, but also to extract phase-dependent information. We will furthermore discuss the application to high-resolution infrared spectroscopy to characterise stars at the very bottom of the main-sequence.

Key words: binaries: spectroscopic – stars: fundamental parameters – planets and satellites: atmospheres – stars: low-mass – binaries: eclipsing – techniques: spectroscopic

1. Introduction

Accurate masses and radii of main-sequence stars are crucial to calibrate stellar evolution models which is essential not only to characterise binaries, but also planetary systems as well as their atmospheres. Very low mass main-sequence ($M < 0.35\,\mathrm{M}_\odot$) stars play a special role. A very long standing issue has been the 'radius inflation problem' (e.g. Casagrande et al., 2008; Torres et al., 2010; Spada et al., 2013; Kesseli et al., 2018). Stellar radii from evolutionary models appear to be under-predicted by a few percent. This has also implications for the characterisation of exoplanets of such very low-mass stars. Their parameters crucially depend on the stellar parameters of isolated M-dwarfs which are inferred from stellar models (Dotter et al., 2008; Baraffe et al., 2015).

Eclipsing binaries with F,G, & K-type primaries and very low-mass stellar companions, which we denote as EBLM (eclipsing binary - low mass) are perfect laboratories to characterise the stellar parameters of the low-mass companion. The main goal of the EBLM project (e.g. Triaud et al., 2013; Maxted et al., 2023) is to create an empirical mass-radius-luminosity-metalicity diagram for very low-mass main-sequence stars. While the program targets were initially detected as false positives from surveys for transiting planets such as the WASP survey (Pollacco et al., 2006), the advent of space based photometry as well as an intensive spectroscopic follow up using high-precision spectrographs (Triaud et al., 2017; Martin et al., 2019) led to a large sample of well characterised M-dwarfs with reliable stellar parameters (e.g. von Boetticher et al., 2019; Swayne et al., 2021; Sebastian et al., 2023; Swayne et al., 2024). Due to the high contrast of the binary components, these appear as single-lined binaries, which allows to not only achieve extreme precise measurements of the binary mass function, but also to measure the reflex motion of circumbinary planets (Triaud et al., 2022; Standing et al., 2023).

These high contrast ratios also mean that the masses for the M-dwarf secondaries are derived from stellar parameters of the solar-like primary, which in turn depend on stellar evolution models. Inaccuracies in the parameters of the primary lead to systematic biases for the M-dwarf (Duck et al., 2023). In order to minimise such systematic biases in the EBLM project, Freckelton et al. (2024) presented a homogenous spectroscopic analysis of 179 EBLM primary stars, based on more than 4500 high-resolution spectra. The stellar parameters inferred from this analysis depends on stellar evolution models of F,G, & K-type stars. To verify these we can use the eclipsing configuration of EBLM binaries. Thanks to precision light curves from space and accurate stellar radii from Gaia, the mass of the primary star can be derived directly. This has been shown to be a powerful method to directly verify the accuracy of the primary stellar parameters (Davis et al., 2024). A fully model independent method to verify the accuracy of the EBLM primary parameters are dynamical mass measurements, which are difficult due to the intrinsic contrast of both binary components.

2. Dynamical masses

To measure dynamical masses of these systems, we have to transform high-contrast binaries (single lined) to double-lined binaries. In order to increase the contrast and thus to derive dynamical masses from optical high-resolution spectra, we apply the High-Resolution Cross-Correlation Spectroscopy method (HRCCS; Snellen et al., 2010). This method has been used successfully to detect cross-correlation signals as faint as 10^{-5} and measure atomic and molecular species in exoplanet atmospheres for more than a decade.

This method involves a two step process. First the spectra are detrended to remove telluric or stellar contributions from the host-star. Second the detrended spectra are cross-correlated and combined in the rest-frame of the M-dwarf. The detrending makes use of the fact that a planet signal (i) is buried in the noise of its host star and (ii) is moving significantly (by several $\mathrm{km\,s^{-1}}$) during the observation, which leaves the spectral lines of the exoplanet atmosphere basically unaffected. Both of these requirements are fulfilled for high-contrast binaries.

2.1. Application to optical spectroscopy

We, thus, applied the HRCCS method to measure the dynamical masses of the binary EBLM J0608−59, using optical high-resolution spectra obtained with ESPRESSO at the VLT (Pepe et al., 2021). The binary is composed of a solar-type primary component with M-dwarf companion and features an average contrast ratio 0.2 per cent at optical wavelengths. In the following we lay-out the method while the details of this study are described in Sebastian et al. (2024b).

Optical spectra are dominated by the absorption spectrum of the primary star. Telluric contributions can be avoided in the cross-correlation thanks to the wide spectral range of these data. We thus detrend the spectra to effectively remove the absorption spectrum of the primary. This has been achieved by applying a singular value decomposition ((SVD, Kalman, 1996)) to the spectra, which are aligned into the primary's rest-frame. The SVD decomposes the spectra into a sum of components, which are correlated to the primary's rest-frame as well. In this way, the SVD components with largest eigenvectors, contain basically the primary spectral lines and can simply be subtracted. We define the optimal number of components to be removed by the "effective rank", which is based on the entropy of the eigenvectors (Roy & Vetterli, 2007). This estimates the significant number of components needed to describe the correlated signal. In other words, if this number of SVD components are removed, the correlation of the remaining data in the primary's rest-frame is not distinguishable from white noise. In contrast to typical exoplanet applications, which define the optimal number of removed components by optimising the detected cross-correlation peak returned from the planets atmosphere (e.g. Cheverall et al., 2023), this definition is basically based on the noise of the data. A typical spectral Frame before and after the application of the SVD detrending is shown in Fig. 1.

The detection was made by enhancing the M-dwarfs signal (i) by a combination of all detrended spectra in the rest-frame of the M-dwarf and (ii) by performing a cross-correlation with a M-dwarf line list. Such a combination requires the orbital velocity of the M-dwarf, and thus the knowledge of its orbital parameters. In case of EBLM binaries these can be inferred precisely from the orbit of the primary star. The only unknown parameter is the semi-amplitude

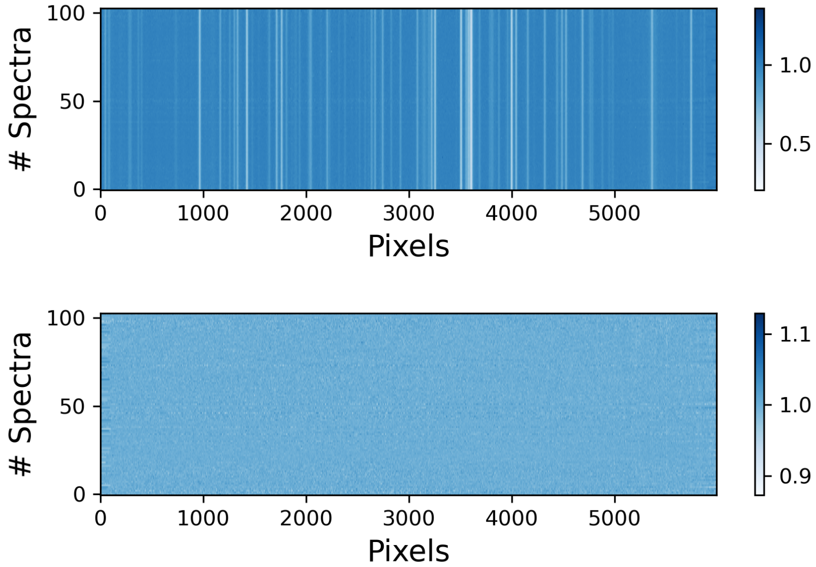

Figure 1. Spectral segment from 103 ESPRESSO spectra of EBLM J0608−59 in the rest-frame of the primary. Upper panel: normalised spectra, Lower panel: Spectra after SVD detrending.

of the M-dwarf. By sampling such combinations over a range of different semi-amplitudes, the M-dwarfs signal gets amplified, once all spectra are combined in the rest-frame of the M-dwarf. In practice, the M-dwarfs semi-amplitude can now be inferred from the maximum amplification of the cross-correlation peak. This method can also be referred to as "K-focusing" (e.g. Sebastian et al., 2024a). Fig. 2 left panel shows the cross correlation to the combined and detrended ESPRESSO spectra sampled for different semi-amplitudes (K_2), as well as the systemic velocity ($V_{\rm rest}$) of the M-dwarf. We used the publicly available *Saltire* model (Sebastian et al., 2024a) to measured the semi-amplitude of the M-dwarf with an uncertainty better than $\sim 500\,{\rm ms}^{-1}$, which allowed us to determine the dynamical masses of both companions with accuracies better than 2 per cent for the primary and better than 1 per cent for the M-dwarf. The well detected CCF signal, as well as the known orbit parameters of the secondary, both allow us to extract the CCF signal in the time domain. We can, thus, measure the phase-dependent CCF contrast, which is a function of the used line list, the individual absorption lines of the M-dwarf, and the contrast of the binary components. Such phase dependent CCF contrast variations do carry information about e.g. reflected light for close in binaries at optical wavelengths. Since the ESPRESSO spectra do cover the full orbital phase of EBLM J0608−59, we can -within the uncertainties- confirm a constant CCF contrast for the M-dwarf (Sebastian et al., 2024b).

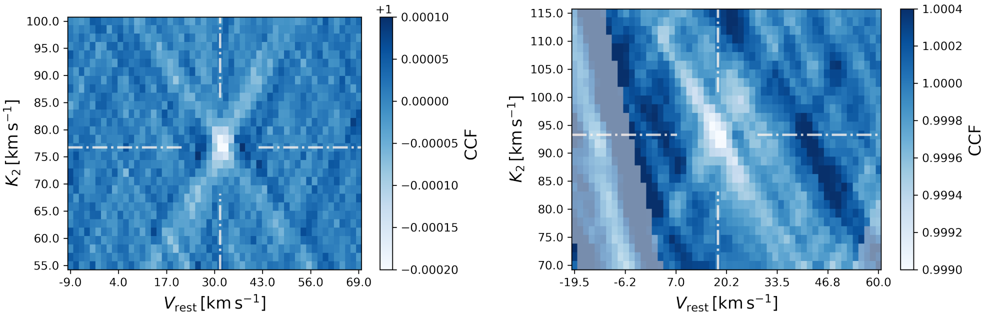

Figure 2. $K_2 - V_{\rm rest}$ mapping as a result from the K-focusing. Left panel: EBLM J0608−59 ($M_2 \sim 0.3\,M_\odot$), using 103 optical ESPRESSO spectra, Right panel: EBLM J0040+01 ($M_2 \sim 0.1\,M_\odot$), using 15 infrared CRIRES$^+$ spectra. Dashed lines mark the expected semi-amplitude and rest velocities of the M-dwarf. Shaded areas: Positions of artefacts from SVD detrending.

2.2. Application to infrared spectroscopy

We showed the power of the HRCCS method to derive dynamical masses from high-contrast binaries. Nevertheless, the majority of the targets from the EBLM project have been observed with optical spectrographs. The contrast ratios of these allow us to derive dynamical masses with the HRCCS method for M-dwarfs down to $\sim 0.2\,M_\odot$.

To allow the dynamical mass measurement of M-dwarfs at the bottom of the main-sequence, we can make use of the decreased contrast ratio at near infrared wavelengths due to the late-type secondary star. This has successfully been shown for EBLM J0113+31 ($M_2 \sim 0.2\,M_\odot$) using high-resolution near infrared SPIRou spectra (Maxted et al., 2022).

In an ongoing survey, we focus on EBLM binaries with M-dwarf companions $\sim 0.1\,M_\odot$ which are observed in the K-band using CRIRES$^+$ on the ESO 8.2-m VLT (Kaeufl et al., 2004). We adopt the full HRCCS frame work, to these infrared observations, including SVD detrending and fitting the M-dwarfs semi-amplitude using the *Saltire* model. In a first part of this survey, we observed the binaries EBLM J0040+01 (15 spectra) and EBLM J1219−39 (9 spectra). Both have orbital periods ~ 7 d. As opposed to the situation in the optical, these data are now dominated not only by the primary's absorption spectrum, but also by significant telluric contributions. Before SVD detrending, we thus fit and clean the spectra from telluric features using the ESO molecfit pipeline (Smette et al., 2015). For both binaries, we successfully detect the M-dwarf components and estimate their dynamical masses. Due to the relatively small number of spectra, the detrended data show residuals of the primary star. We use the *Saltire* model to estimate the areas of the CCF map, affected by artefacts from the primary component. These are finally masked, when we measure the M-dwarfs signal position. The right panel of Fig. 2 shows the detection of the M-dwarf of EBLM J0040+01 on a 3 sigma level with only 15 infrared spectra. In a preliminary analysis, we achieved a precision on the M-dwarf masses (both ~ 0.1 $M_\odot$) of better than 3 per cent for EBLM J0040+01 and better than 7 per cent for EBLM J1219−39.

This demonstrates the power of the HRCCS method, for high-precision infrared spectra, to measure dynamical masses at the very bottom of the main-sequence. Since these binaries are transiting, their radii are well determined and metallicities are well known from the primary star. The full analysis from this survey will be published in Sebastian et al. (2025). We expect to improve the accuracy on the dynamical masses by including more spectra, as well an improved removal of telluric contributions.

3. Summary

In this contribution, we introduced the HRCCS method as a powerful tool to derive precise dynamical masses for high-contrast binaries. Although this method has been in use to detect and analyse exoplanet atmospheres for more than a decade, this is the first time it is applied to spectra of high-contrast binaries. It's application to optical spectra allows us to validate previous, model dependent mass-measurements from the EBLM project and to turn them into benchmark targets for a precise mass-radius diagram for fully convective low-mass stars. We introduce our survey to extend our abilities to measure dynamical masses of EBLM binaries down to the lowest mass star on the main-sequence.

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