A spectroscopic modelling method for the detached eclipsing binaries to derive atmospheric parameters

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ABSTRACT

Based on luminosity contributions, we develop a spectroscopic modelling method to derive atmospheric parameters of component stars in binary systems. The method is designed for those spectra of binaries that show double-lined features due to radial-velocity differences between the component stars. We first derive the orbital parameters and the stellar radii by solving the light and radial-velocity curves. Based on luminosity contributions, we develop a spectroscopic modelling method to derive atmospheric parameters of component stars in binary systems. The method is designed for those spectra of binaries that show double-lined features due to radial-velocity differences between the component stars. We first derive the orbital parameters and the stellar radii by solving the light and radial-velocity curves.

Key words. methods: data analysis – binaries: eclipsing – binaries: spectroscopic

1. Introduction

The binary stars play an important role in the study of stellar evolution. Stars always begin their formation in clusters. However, during the main sequence, stars are fractionally in binary systems, depending on their spectral type. Raghavan et al. (2010) find this fraction to be larger than 50% for FGK stars. Duchêne & Kraus (2013) demonstrated that the stellar binarity could be 20% to 80% for different spectral types. By analysing binary stars, stellar structure and evolution can be constrained (Han et al. 2020). For example, Izzard et al. (2009) gave constraints on the masses of stars that undergo an efficient third dredge up by comparing the observed carbon-enhanced metal-poor (CEMP) stars with results from studies of binary population synthesis (BPS). Other important objects are the Type Ia supernovae (SNe Ia). As classical cosmological distance tracers, the formation channels of SNe Ia affect the Hubble constant measurement and related cosmological assumptions and theories. Traditionally, the binary system consisting of a carbon–oxygen white dwarf and a main sequence giant helium donor star was thought to be a progenitor of a SNe Ia (Hoyle & Fowler 1960; Whelan & Iben 1973). During later studies, Iben & Tutukov (1984), Webbink (1984) and Han (1998) proposed the double degenerate scenario whereby two carbon–oxygen white dwarfs merging may also cause the explosion of a SNe Ia. In addition to stellar evolution, the binary interaction can change the galactic spectral energy distribution (SED). Han et al. (2007) found that radiation from hot subdwarfs, which are the evolutionary result of binary interactions, causes the far-ultraviolet excess in the early-type galaxy spectra. Chen et al. (2015) proposed that galactic soft X-ray emission comes from accretion onto the white dwarfs in binary systems. The study of binary stars will also contribute to our understanding of the early evolution of the Universe. For example, re-ionising photons are thought to come from massive single stars, but the photon number is several times less than the required number for the re-ionisation. Due to the high proportion of binarity in massive stars, Götberg et al. (2020) and Secunda et al. (2020) believe that the ionising photons produced by massive binary stars have an important impact on the re-ionisation process in the early Universe.

Depending on whether or not the mass transfer between the component stars has started, binary systems are divided into detached, semi-detached, and contact binaries. The present work concentrates on the detached binaries. The detailed analysis of the characteristics of the component stars at this stage will not only help us to understand the formation of binary stars but will also help us to constrain the later evolution of mass transfer. In addition to mass transfer, the inclination of the orbit is another factor affecting the shape of the light curve. If the inclination of the orbital plane is close to 90°, a binary system is observed as an eclipsing binary star in time domain photometry. Orbital parameters of the eclipsing binaries can be calculated using both the light curve and the radial velocity curve data. And if the orbital period of the binary is shorter than 5 yr, the system can be spectroscopically identified (El-Badry et al. 2018). The orbit of the component stars around each other causes the relative change of radial velocities. The binary spectra therefore show double-peaked features and are called ‘SB2’ spectra. One can fit the profile of a binary spectrum by simply superposing two single-star spectra, but the atmospheric parameters of the component...
stars cannot be correctly derived because of spectral mixing. The spectral mixing affects the profile and strength of both continuum and spectral lines. In different orbital phases, the shifted continuum has varying degrees of impact on line depth. Therefore, when modelling the spectra of binary stars, not only does the intrinsic luminosity contribution of each star need to be taken into account but also the mixing effects in different phases.

The data product of the Medium Resolution Survey of the Large sky Area Multi-Object Spectroscopic Telescope (hereafter LAMOST MRS) includes both the spectra and atmospheric parameters of stars. The resolving power of LAMOST MRS is $R = 7500$, and its wavelength range is 4950–5350 Å in the blue arms and 6300–6800 Å in the red arms. The seventh data release (DR7) of LAMOST published more than 3.8 million MRS spectra, including single-exposure and combined spectra, and stellar parameters of 0.78 million stars with combined spectra. The MRS targeting strategies contain a series of time-domain fields (Liu et al. 2020) and result in a large number of multiple star system spectra, including SB1 (where the spectra lines are single-peaked but the radial velocities vary among different epochs), SB2, and ST (triple-lined spectra of trinary stars) spectra. Li et al. (2021) selected 3175 SB2 and 132 ST candidates using cross-correlation functions between LAMOST MRS spectra and theoretical models. Zhang et al. (2022) used a convolution neural network to develop a distinguishing model and gave a catalogue of 2198 SB2 candidates. Both Li et al. (2021) and Zhang et al. (2022) suggested that the spectra lines of the component stars in a binary system show clear double-peaked features when their radial velocity (RV) differences are larger than 50 km s$^{-1}$ with the LAMOST MRS resolving power of $R \sim 7500$.

It is necessary to build a spectral model to derive atmospheric parameters of component stars for the LAMOST MRS SB2 spectra. The LAMOST Stellar Parameter pipeline (LASP) is the official data-processing pipeline for LAMOST MRS spectra (Wu et al. 2011; Luo et al. 2015). It was designed to derive atmospheric parameters for single stars based on the model-fitting method, but was not suitable for SB2 spectra. Figure 1 shows an example of an SB2 spectrum and the ‘best-fit’ spectrum by LASP. The red lines stand for the LASP automatic masked points, which are not considered in the fitting procedure. Mg I $\lambda 5185$, for example, is a spectral line that shows a clear double-peaked feature, but the peaks are masked. The best-fitting model has significantly broader lines than the component star spectra. The derived parameters of the SB2 spectra cannot reflect the real characteristics of the component stars, and so the LAMOST parameter catalogue does not contain atmospheric parameters of SB2 spectra. It is worth developing a method for deriving parameters from this kind of data.

Therefore, we mainly focus on the LAMOST MRS SB2 spectra and propose a binary-star spectral modelling method to derive the atmospheric parameters for the binary stars. The method synthesises the SB2 spectral model by combining theoretical spectra with the light-curve solutions. The SB2 model is used to fit the observed binary spectra and to derive the stellar parameters of the component stars. Furthermore, the method can be extended to spectroscopic data with a variety of resolutions, as long as the binary system has similar characteristics to our criteria (see details in Sect. 2).

The remainder of this paper is organised as follows. Section 2 introduces the SB2 spectra fitting method, as well as a brief data description. Section 3 gives two examples of atmospheric-parameter derivation. Section 4 summarises our findings. Appendix A provides full procedures and formulae. In Appendix B, we discuss the method performance on the unresolved binary spectra observed in near-eclipsing phases.

2. Method

2.1. Data

The sources in this work are observed by both LAMOST MRS, Kepler mission and Kepler’s second mission (Kepler/K2; Batalha et al. 2010; Caldwell et al. 2010; Koch et al. 2010; Borucki et al. 2011), Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015; Lund et al. 2017; Oelkers & Stassun 2018; Stassun et al. 2018), and targets were chosen that have at

http://dr7.lamost.org/v2.0/doc/mr-data-production-description

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least three SB2 spectra in LAMOST MRS DR7 in order that we may evaluate the self-consistency of our method.

2.2. Double-lined binary spectral model

A binary spectrum contains light from both component stars. The observed spectrum of each binary is affected by the distance to us, the stellar luminosity, and the spectral line profiles. The line profiles are determined based on atmospheric parameters such as effective temperature, surface gravity, metallicity, and so on. The spectroscopic model of the binary star can therefore be explained as follows:

\[ F_{\text{binary}}(\lambda) = F_1(\lambda) + F_2(\lambda), \]

(1)

\[ F_i(\lambda) = C \cdot L_i \cdot P_i(\lambda, T_{\text{eff}i}, \log g_i, [\text{M/H}]), \]

(2)

where \( F_{\text{binary}} \) in Eq. (1) is the flux of the binary; \( F_1 \) and \( F_2 \) are the respective fluxes of the component stars; \( \lambda \) is the observed wavelength; \( L_i \) stands for the shifted wavelength of each component in a specific orbital phase; and \( C \) stands for the relationship between the luminosity and the observed flux. In the shorter wavelength range, \( C \) is considered a constant and depends on the distance of the binary from Earth. Therefore, \( C \) has the same value for each component star. \( L_i \) represents the luminosity of each star. \( P_i \) means the spectral line profiles. In this work, we use \( T_{\text{eff}}, \log g, \) and \( [\text{M/H}] \) to generate the theoretical continuum and line profiles simultaneously. For a binary system, \( T_{\text{eff}} \) and \( \log g \) are derived for each component while the same \( [\text{M/H}] \) is assigned. We omit the projected stellar rotation velocity \( v_{\text{sin}i} \) to generate the line profiles. The degeneration in surface gravity, rotational velocity, line mixing in binary spectra, and line spread function (LSF) of telescopes in line broadening can affect the accurate measurement of \( \log g \). See Sect. 3.2 for more details. In a binary spectrum, the line profiles of one component will be affected by the line mixing and the continuum of the other. The Doppler shifts of the continuum caused by the relative motion in different orbital phases affect the profiles differently.

For spectra without absolute flux calibration, the spectra are pseudo-continuum normalised before deriving stellar parameters, and only the line features are used. After normalisation, the effect of distance can be ignored. The binary star model can be explained as:

\[ f_{\text{binary}}(\lambda) = \frac{L_1}{L_1 + L_2} \cdot P_1(\lambda_1, \text{param}) + \frac{L_2}{L_1 + L_2} \cdot P_2(\lambda_2, \text{param}), \]

(3)

where \( f_{\text{binary}} \) is the normalised binary spectrum. To obtain the luminosity contribution \( \frac{L_i}{L_1 + L_2} \) (\( i = 1 \) or 2) from each star, we choose to model the binary spectra of the detached eclipsing binaries, because the orbital parameters and luminosity contributions of the eclipsing binaries can be derived by combining the light curves and the radial velocity curves. In different phases, the component star in a detached system is not distorted significantly by the gravitation of its companion. When the stars are approximated as spheres, the projected areas of the component stars can be simply regarded as circular surfaces in the modelling.

When the light curve solution is obtained, the binary spectral model with continuum is described as:

\[ F_{\text{binary}}(\lambda) = A_1 \cdot L_1 \cdot P_1(\lambda_1, T_{\text{eff}1}, \log g_1, [\text{M/H}]) + A_2 \cdot L_2 \cdot P_2(\lambda_2, r_1 \cdot T_{\text{eff}1}, \log g_2, [\text{M/H}]), \]

(4)

and then this model spectrum is pseudo-normalised to derive stellar parameters. In this model, the luminosity contribution of each component is determined not only based on its intrinsic brightness \( L_i \) but also on the projection area \( (A_i) \) in a specific phase. \( A_1 \) and \( A_2 \) are calculated using stellar radii \( R_1 \) and \( R_2 \). The radial velocities are obtained by analysing the orbital motion of the binary system. The light curves used in this work are from Kepler/K2 or the TESS mission, and the radial velocity curves are reconstructed using multi-epoch LAMOST MRS SB2 spectra. We use Wilson–Devinney binary star modelling code (WD; Wilson & Devinney 1971; Wilson 1979, 1990, 2008; Wilson & Van Hamme 2014) through a Python UI, PyW2015 (Güzel & Özdarcan 2020), in order to derive the orbital parameters. After analysing the light curve, we get orbital period \( P \), stellar radii \( R_1 \) and \( R_2 \), semi-major axis SMA, orbital inclination \( i \), eccentricity \( e \), periastron longitude \( \omega \), mass ratio \( q \), and \( T_{\text{eff}} \) and \( r_1 \) for the next steps. The observation epoch of the spectrum is folded into phase angle \( \theta \).

The theoretical model is computed using the SPECTRUM (Gray 2015) base on the Kurucz ATLAS9 (Castelli & Kurucz 2003), assuming local thermodynamic equilibrium (LTE) and a plane-parallel atmosphere to generate the flux density spectra. We then use the Payne (Ting et al. 2019) to interpolate the spectra of the component stars. The Payne is a stellar label fitting method that consists of several ingredients. The ‘interpolator’ of the Payne applies neural networks to produce spectral model fluxes for a set of arbitrary labels. The default neural network architectures, which have two hidden layers and ten neurons for each layer, are adopted in this work. The training set of the Payne is the Kurucz model mentioned above and the labels are \( T_{\text{eff}}, \log g, \) and \( [\text{M/H}] \), and the parameter ranges of the training set are: \( 4500 \leq T_{\text{eff}} \leq 8000 \text{K}, 2.0 \leq \log g \leq 5.0 \text{dex}, -2.0 \leq [\text{M/H}] \leq 0.5 \text{dex} \). The ranges cover most of the LAMOST MRS observation data. Figure 2 shows the released stellar parameter distribution of LAMOST MRS DR7 v2.0. We ignore the spectral model with \( T_{\text{eff}} \) lower than 4500 K because the mixing of the molecular bands will be more complicated. After the single star spectra are interpolated by the Payne, we synthesise the SB2 spectra with different RVs for the component stars and the projection areas that are calculated applying the light-curve solution. The pseudo-continuum-normalised SB2 spectra are used to fit the observed spectra with the least square method. The SB2 model generation and the spectral fitting are iterative. In each iteration, we synthesise the SB2 model with a new set of parameters to fit the observed spectra. Both blue and red bands are generated and applied in the fitting. This is unlike the LASP, which uses only the blue band in the fitting procedure. Although the LAMOST blue band contains more information than its red band in parameter deriving (Zhang et al. 2020), the blue band is not sufficiently sensitive to luminosity. Chen et al. (2021) suggested that the red band
should also be used to derive atmospheric parameters, especially \( \log g \).

In Eq. (4), \( \lambda_1 \) and \( \lambda_2 \) are the shifted wavelengths of the component stars caused by their radial velocities \( \text{RV}_1 \) and \( \text{RV}_2 \). The radial velocities are automatically determined in the fitting procedure. \( \text{Teff} \) is the effective temperature of the hotter star and the effective temperature of the cooler star is represented by \( \text{RTeff} \). The initial value of \( \text{RTeff} \) comes from the light-curve solution, and we set it to be variable in the range ±0.1, although the true ratio of \( \text{RTeff} \) is constant. The variation of \( \text{RTeff} \) actually reflects the change in the relative shift of two continua in the SB2 spectra. The application of \( \text{RTeff} \) can limit the spectral interpolation by the light curve characteristics and reduce the iteration times. \( \log g_1 \) and \( \log g_2 \) are the surface gravity of the two stars, respectively. Only one metallicity is derived for each spectrum.

In the non-eclipsing phases, the two component stars contribute all their fluxes to the binary spectrum. The projection area \( A_1 \) is calculated according to the area of the circle. While in the eclipsing phases, eclipsing depth and surface blocking should be considered in luminosity contribution. When judging the relative distance \( d \) of the component stars, the eclipsing area can be calculated simultaneously, and \( d \) can be calculated using Eq. (A.4). Assuming that \( R_1 > R_2 \), the relative positions of the component stars are obtained by comparing the values of \( d, R_1 + R_2, \) and \( R_1 - R_2 \): (a) \( d > (R_1 + R_2) \): the luminosity distribution in non-eclipsing phases is discussed before. (b) \( d < (R_1 - R_2) \): the total eclipsing phase. (c) \((R_1 + R_2) > d > (R_1 - R_2)\): during the partially eclipsing phases, the shielded areas are approximated to the area of a portion of a circle cut by a line segment. The area calculations are described in Appendix A.

We do not consider the reflection effect and the limb-darkening effect in this work, although they should be taken into consideration for the eclipsing phase spectra. Double-lined features in one spectrum indicate that the component stars have similar luminosity. Otherwise, the features of the least luminous star would be veiled by the other. Sometimes, the temperature difference between the primary and secondary star can be large for the situation where the cooler star has a larger radius than the hotter star. In the eclipsing phases, the reflection effect may change the magnitudes and thus the luminosity contributions. Also, in these phases, the limb-darkening effect may reduce the luminosity contribution of the eclipsed star, which increases the difficulty of deriving its atmospheric parameters. For the LAMOST MRS spectra, when \( \Delta \text{RV} \) between the two stars is smaller than 50 km s\(^{-1}\), the stellar parameters derived by fitting the asymmetry of blended lines are quite different from those derived by fitting the double-lined features (see Appendix B). This may be caused by the resolving power or the noise of the spectra. The parameters from the blended lines are excluded in the final results, and the neglect of the reflection effect and the limb-darkening effect is ignored for LAMOST MRS SB2 spectra, but we note that for the data with higher resolution, these effects should be considered more carefully.

2.3. Continuum influence and method uncertainty

In this subsection, we analyse the impact of the continuum in detail because the pseudo-normalised spectra are used in the fitting, and the line intensities of the normalised spectra will be significantly affected by the continuum. In an SB2 spectrum, the most luminous star makes the greatest contribution to the continuum and will cause more impact on line intensity after normalisation. The superposition of two continua causes the relative line intensity ratio between two stars in a binary spectrum to be lower than the ratio between the two single star spectra. We synthesised a series of SB2 spectra and fitted the double-peaked lines with the double-Gaussian function to see how the effect caused by luminosity and continuum varies with \( \text{Teff} \) and stellar radius. Figure 3 shows the lines we chose to obtain the line intensity ratios. The upper panel of Fig. 3 shows the gradient of line intensity differences of four \( \text{Teff} \) gaps: 7000–50/100/200/500 K. The differences were calculated after each theoretical spectrum was normalised using the pseudo-continuum. We derived the gradient to find the narrow single lines that are most sensitive to effective temperature changes. If a spectral line is sensitive to changes in \( \text{Teff} \), the gradient shown in the upper panel of Fig. 3 will be higher. The lower panel contains the related theoretical spectra in the LAMOST MRS wavelength and resolving power. Four narrow single spectral lines that are sensitive to changes in \( \text{Teff} \) and are less contaminated by nearby lines were selected, and they are marked by the grey dashed lines. We then generated a series of SB2 spectra using the same model spectra as in our
fitting procedures. The chosen stellar parameter ranges that are commonly contained in the LAMOST MRS DR7 data (Fig. 2) are as follows:

(a) The metallicity is fixed to −0.5 dex to reduce the fitting time.

(b) To analyse the effect from different effective temperatures, we initially set the primary star with $T_{\text{eff}} = 7250$ K ($T_{\text{eff}}$ for an F0 dwarf star) and let the secondary star have a varying $T_{\text{eff}}$ from 5350 K ($T_{\text{eff}}$ for a G9 dwarf star) to 7250 K, with a step of 5 K. We then choose $\log g$ equal to 4.25 dex and 3.80 dex to represent the dwarf star and the subgiant star, respectively. According to the MESA Isochrones and Stellar Tracks (MIST; Dotter 2016; Choi et al. 2016), when the primary star is a 7250 K dwarf, it has a radius of $1.25 R_\odot$, and if the star is a 7250 K subgiant, the radius is set to be $2.2 R_\odot$. As for the secondary star, we also set the radius to $1.2 R_\odot$ and $2.2 R_\odot$ for dwarf stars and subgiant stars, respectively. We fix the radius of the secondary star to reduce the affect of the stellar radius on the luminosity. The setup is not always physical but is reasonable in most cases. Next, we generate the double-lined features with $\Delta RV$ between the two component stars equal to 100 km s$^{-1}$, which is twice the ARV detection limitation of the LAMOST MRS SB2 spectra in order to get better spectral line fitting. The SB2 spectra contain four combinations: dwarf + dwarf, subgiant + subgiant, dwarf + subgiant, and subgiant + dwarf for the primary and the secondary star, respectively. We have 1520 parameter combinations to investigate the affect of varying $T_{\text{eff}}$.

(c) We also generated SB2 spectra with various radii to analyse the effect of the stellar radius. The parameter ranges are also from the MIST, although some specific combinations are not physical. To achieve a more prominent affect, we set the radius of the 7250 K primary star to vary from $1.2 R_\odot$ to $3.7 R_\odot$ with a step of 0.02 $R_\odot$, and the related surface gravity is between 3.5 dex and 4.3 dex. The secondary star has a $T_{\text{eff}}$ of 6000 K (for a G0 dwarf star). The $\log g$ of a dwarf secondary star is 4.25 dex ($R = 1.2 R_\odot$) and of a subgiant secondary is 3.80 dex ($R = 2.2 R_\odot$), the same as in the case where we vary $T_{\text{eff}}$. The combinations to generate binary spectra are 7250 K primary star + dwarf secondary star and 7250 K primary star + giant secondary star. We have 254 parameter combinations for the radius-changing affect.

(d) In different orbital phases, the relative motions between the two component stars cause the continuum of the most luminous star to blue- or redshift in the binary spectra. To analyse whether or not the blue- or redshifted continua have varying effect on the line intensities, the synthesised SB2 spectra have two kinds of radial velocity settings: the primary star has a radial velocity of $-50$ km s$^{-1}$ and +50 km s$^{-1}$. ARV between the two components is 100 km s$^{-1}$. This procedure doubles the SB2 spectral number, and so we finally have 3548 SB2 spectra for the line intensity ratio analysis, including 3040 spectra with various $T_{\text{eff}}$ and 508 with various radii. Figure 4 shows how the line ratios change with different $T_{\text{eff}}$, and Fig. 5 shows the changes with varying radii.

(e) With the same atmospheric parameters and stellar radius, but with ARV varying from 40 km s$^{-1}$ to 120 km s$^{-1}$ randomly, we generated another 3548 SB2 spectra to evaluate the parameter fitting accuracy of our method. Figures 6 and 7 show the differences between the theoretical parameters and the fitting parameters.

In Fig. 4, the line ratios of the different spectral lines with varying $T_{\text{eff}}$ are shown in separate panels. In each panel, different line styles represent different parameter combinations. Grey lines are the line intensity ratios between two spectra of single stars. The blue lines indicate that the 7250 K components are blueshifted in the SB2 spectra, and the orange lines mean the 7250 K components are redshifted. Different line styles stand for different parameter combinations.

Fig. 4. Line intensity ratio between a lower $T_{\text{eff}}$ star and a 7250 K star. The grey lines represent the ratio between two spectra of single stars, and the colourful lines are the ratio between two star components in the binary spectra. The blue lines mean that the 7250 K components are blueshifted in SB2 spectra, and the orange lines mean that the 7250 K components are redshifted. Different line styles stand for different parameter combinations.

Fig. 5. Line intensity ratios change with different radii. The grey lines represent the ratio between two spectra of single stars, and the colourful lines are the ratio between two star components in the binary spectra. The blue lines mean that the 7250 K components are blueshifted in SB2 spectra, and the orange lines mean that the 7250 K components are redshifted. Different line styles stand for different parameter combinations.
Fig. 6. Parameter differences between the measured values and the theoretical values. Blue circles in $\Delta T_{\text{eff}}$ and $\Delta \log g$ panels show the differences between the primary stars, and orange dots show the differences between the secondary stars. One metallicity is fitted for each binary system, so the $\Delta [\text{M/H}]$ panels contain only orange points. All the binaries in this figure have the primary component blueshifted in the SB2 spectra.

Fig. 7. Parameter differences between the measured values and the theoretical values. Colours and symbols have the same meaning as in Fig. 6. All the binaries in this figure have the primary component redshifted in the SB2 spectra.

Although the line intensities of the least luminous star are significantly reduced in the binary spectra, the blue and orange lines that have the same line styles in Figs. 4 and 5 show that the line intensity decrease does not vary significantly in different orbital phases. The atmospheric parameters derived in different phases (and with various $\Delta RV$) should be consistent as long as the components can be detected. Figure 6 shows the atmospheric parameter differences of the synthetic SB2 spectra when the primary stars are in blueshifted phases, and Fig. 7 shows the parameter differences when the primary stars are at redshifted phases. Each panel contains the parameter from the fitting results of both the primary and the secondary star. The figures show that if the stellar radius and luminosity contribution are known, the fitting results will have very low-level uncertainties for spectra without noise. We therefore do not consider the method uncertainties in the application on the observed SB2 spectra.

3. Examples: Atmospheric parameters of two SB2 eclipsing systems

In this section, we give two observation examples of eclipsing binaries in order to demonstrate the ability of our method. The examples are chosen randomly because the method is designed for binary stars that match our criteria in Sect. 2. Both of the binaries have at least three SB2 spectra in LAMOST MRS DR7 and have light curves from Kepler/K2 or TESS.

3.1. TIC 63209649

TIC 63209649 (also known as KIC 8301013, but TESS light curves are used in this work, so we give the TIC number) is a detached eclipsing binary system with nine successful epochs of spectra in the LAMOST MRS DR7. Figures 8–10 show the

Fig. 8. Normalised TESS light curve of TIC 63209649.

Fig. 9. Pseudo-continuum normalised LAMOST MRS multi-epoch spectra of TIC 63209649. The spectra are shown in the same order in which they were observed.
velocities of each star. We then use our binary spectral model to fit each binary spectrum. The Payne shows the radial velocities of component stars in phase view. In time in UTC format is shown in the upper right corner. Figure 10 normalised LAMOST MRS spectra of nine epochs. The observation data. Figure 8 is the normalised TESS light curve. The cooler one are the measured RVs. The three dots are set manually to be 0, 0.5, and 1, other dots in Fig. 10 are the measured RVs. The three dots are set manually to be γ. Lines are the reconstructed curves. Blue represents the higher mass star and orange represents the lower mass star.

Fig. 10. Reconstructed radial velocity curves of TIC 63209649. Dots are the RVs measured by the spectra except for three dots in the phases 0, 0.5, and 1, which are set manually to γ. Lines are the reconstructed curves. Blue represents the higher mass star and orange represents the lower mass star.

Fig. 11. WD fitting result of the TIC 63209649 light curve. Black dots in the upper panel are the observed data and the red line is the best fitting model. The lower panel shows the fitting residuals.

observation data. Figure 8 is the normalised TESS light curve. This system has a period of about 4.43 days. Figure 9 shows the normalised LAMOST MRS spectra of nine epochs. The spectra are listed in the observed time sequence, and the observation time in UTC format is shown in the upper right corner. Figure 10 shows the radial velocities of component stars in phase view. In order to reconstruct the RV curve, we firstly use the Payne and our binary spectral model to fit each binary spectrum. The centres of strong lines can be fitted correctly to obtain the radial velocities of each star. We then use \( q = \frac{RV_1}{RV_2} \) to fit \( q \) and \( \gamma \). Here, \( RV_1 \) and \( RV_2 \) are the radial velocities of the primary star and the secondary star folded in the phase order, respectively. In addition to the three dots in phases 0, 0.5, and 1, other dots in Fig. 10 are the measured RVs. The three dots are set manually to be γ. Finally, we reconstruct the RV curve using cosine functions. The standard deviation between the measured RVs and the best fitting lines is 5.08 km s\(^{-1}\) for RV1 and 6.66 km s\(^{-1}\) for RV2. We note that the fitting may be rough at the near-eclipsing phases. Combining the light curve and the radial-velocity curves, we derived the orbital parameters using the WD modelling. Figure 11 is the WD fitting result. Black dots in the upper panel represent the folded light curve, and the red line is the best fitting model.

Table 1. Orbital parameters of TIC 63209649.

| Parameter | Primary | System | Secondary |
|-----------|---------|--------|-----------|
| \( t_{\text{conj}} \) (days) | 2458685.7373 | 4.4275 | 16.11±0.053 |
| \( P \) (days) | 4.4275 | 87.44±0.03 | 0.9700 |
| \( q \) | 0.8403 | 0.0929±0.0177 | 0.22 |
| \( a \sin i \) \( (R_\odot) \) | 16.11±0.053 | 90.25±0.22 | 1.5093 |
| \( i \) (°) | 87.44±0.03 | 90.25±0.22 | 1.2297 |
| \( e \) | 0.9700 | 1.2016 | 1.4305 |
| \( \omega \) (°) | 0.22 | 1.4305 | 4.24 |
| \( R \) \( (R_\odot) \) | 1.5093 | 1.2297 | 4.34 |
| \( M \) \( (M_\odot) \) | 1.2297 | 1.2016 | 4.34 |
| \( \log g \) (dex) | 4.24 | 1.2016 | 4.34 |

Dots in the lower panel are the residuals. The orbital parameters from the light-curve solution are listed in Table 1. Combining the orbital parameters, we generated the synthetic SB2 model spectra according to Eq. (4), and fitted seven multi-epoch SB2 spectra of TIC 63209649. Figure 12 shows the best fitting result of one of the SB2 epochs. Black lines are the observed spectra of blue (upper panel) and red (lower panel) bands, and the red lines represent the best fitting spectra. Grey dots indicate the percentage of the residual in the observed data. Most of the residuals are below 10% of the observed spectra, except for residuals of some strong lines, such as the Mg I triplet, \( \lambda5167, 72 \), and 83 and the H\( \alpha \) line. In wavebands with dense spectral lines, for example, \( \lambda5175 \sim 5180 \) and \( \lambda5280 \sim 5285 \), line mixing causes the fitting residuals to become a slightly higher than the relatively lineless waveband. Two of the nine epochs were observed near eclipsing phases and did not show clear double-lined features. We present the spectral fitting results in Appendix B and give a brief discussion.

Derived atmospheric parameters of all the SB2 spectra of TIC 63209649 are listed in Table 2 in order of observation time. The orbital phases are shown in the second column. \( T_{\text{eff}} \) and \( \log g \) are the parameters of the hotter star, and the parameters of the cooler one are \( T_{\text{eff}} \) and \( \log g \). The metallicity of the binary system is \( [\text{M/H}] \). The parameters of the first four epochs show good consistency, but the results of the last three epochs are different, and they are labelled with asterisks in the first column. We checked the spectra of these three epochs and found that a poor signal-to-noise ratio might be the reason for this inconsistency. Figure 13 shows the fitting result of the last spectrum (MJD = 58 645) in Table 2. The noise in this spectrum is higher compared with that in Fig. 12. We therefore excluded this spectrum as well as the two previous noisy spectra before parameter averaging. Atmospheric parameters in the last row of Table 2 are the mean values of the adopted epoch results. We take the standard deviations as the measurement errors and list them in the parentheses. The errors are at the same level as the errors of the LASP parameters of the single stars (Chen et al. 2021).

3.2. EPIC 247529791

The K2 target EPIC 247529791 is also a detached eclipsing binary with a nearly circular orbit. Figure 14 is the normalised K2 light curve. The orbital period is 3.94 days. Figure 15 shows LAMOST MRS spectra of five epochs in time sequence. The latest spectrum has a poor signal-to-noise ratio, and so we excluded it from the fitting procedures. Figure 16 shows the reconstructed
Fig. 12. Best fitting example of the TIC 63209649 SB2 spectrum. Black lines are the LAMOST MRS spectra and red lines are the best fitting synthetic SB2 model. Grey dots represent the fitting residuals.

Table 2. Atmospheric parameters of the TIC 63209649 component stars.

| MJD  | Phase | $T_{\text{eff}1}$ (K) | $\log g_1$ (dex) | $T_{\text{eff}2}$ (K) | $\log g_2$ (dex) | [M/H] (dex) |
|------|-------|------------------------|-----------------|------------------------|-----------------|------------|
| 58 024 | 0.2702 | 6724.98 | 4.18 | 5946.48 | 3.78 | -0.34 |
| 58 262 | 0.0885 | 6596.99 | 4.08 | 5962.63 | 3.83 | -0.97 |
| 58 267 | 0.2126 | 6614.74 | 3.94 | 5880.60 | 3.73 | -0.37 |
| 58 269 | 0.6659 | 6636.17 | 4.30 | 5879.86 | 3.79 | -0.14 |
| 58 624 | 0.8481 | 6386.38 | 3.56 | 5966.20 | 4.45 | 0.10 |
| 58 643 | 0.1308 | 6232.98 | 3.69 | 5678.84 | 4.25 | -0.28 |
| 58 645 | 0.5858 | 6140.11 | 3.58 | 5817.86 | 3.56 | -0.25 |
| Mean(Std) | – | 6643.22(49.20) | 4.13(0.13) | 5917.39(37.60) | 3.78(0.04) | -0.23(0.13) |

Notes. Lines with asterisks are excluded before deriving the final parameters because of the low signal-to-noise ratios.

Fig. 13. Fitting example of a TIC 63209649 spectrum with a low signal-to-noise ratio. Colours and symbols have the same meaning as in Fig. 12.
most prominent line features in the LAMOST MRS spectra are the Mg I triplet, λ5167, 72, 83 lines in the blue band, and the Hα line in the red band. The Mg I triplet lines are not sensitive enough to luminosity (Guinan & Smith 1984), and their line profiles are easily influenced when ΔRV between component stars gets larger. Although combining the red band in the fitting procedure can improve the log g derivation (Chen et al. 2021), Figs. 11–12), the wings of the Hα line are also significantly affected by the mixing of two components.

The atmospheric parameters of component stars in the EPIC 247529791 system were also derived by (Traven et al. 2020, hereafter Traven 2020). The GALAH DR2 specID of this binary is 17013100180129. The authors of this latter work used photometry data to reconstruct the SED of the binaries and then applied the Bayesian inference and a Monte Carlo Markov chain sampler (Gregory 2005; Hogg et al. 2010; Foreman-Mackey et al. 2013; Sharma 2017) to derive atmospheric parameters. The Traven 2020 parameters are listed in Table 5. Metallicities of the system derived in our work and by Traven 2020 show good consistency. For the warmer component star, our method gets higher $T_{\text{eff}}$ than that of Traven 2020, while for the cooler star, our $T_{\text{eff}}$ is lower than that of Traven 2020. The log g of the warmer star obtained by the two methods is similar. The log g of the cooler star in our results is lower than that found by Traven 2020. Furthermore, both log g of the cooler star derived in the two works is lower than that in the light curve solution in Table 3.

Different resolving power and fitting methods may cause the inconsistency of the derived parameters. (1) The LAMOST MRS with $R \sim 7500$ has a lower resolution than GALAH ($R \sim 28000$). Line mixing caused by the Doppler shift of the component stars makes recognising features of the fainter star more difficult, and makes deriving atmospheric parameters imprecise in the lower resolution spectra. (2) We use the Kurucz theoretical
Fig. 18. Best fitting example of the EPIC 247529791 SB2 spectrum. Black lines are the LAMOST MRS spectra and red lines are the best fitting synthetic SB2 model. Grey dots represent the fitting residuals.

Table 4. Atmospheric parameters of the EPIC 247529791 component stars.

| MJD   | Phase | $T_{\text{eff}}$ (K) | log $g$ (dex) | $T_{\text{eff}}$ (K) | log $g$ (dex) | [M/H] (dex) |
|-------|-------|----------------------|--------------|----------------------|--------------|-------------|
| 58086 | 0.8963| 6949.89              | 3.58         | 6180.68              | 3.73         | –0.46       |
| 58091 | 0.1634| 6969.50              | 3.47         | 6166.86              | 3.00         | –0.43       |
| 58408 | 0.7257| 6989.81              | 3.62         | 6092.99              | 3.44         | –0.48       |
| Mean  | –     | 6969.73 (16.30)      | 3.56 (0.06)  | 6146.84 (38.50)      | 3.39 (0.30)  | –0.46 (0.02) |

Table 5. Atmospheric parameters of the EPIC 247529791 derived by Traven2020.

| Parameter           | Value     |
|---------------------|-----------|
| $R_1$ ($R_\odot$)   | 1.65      |
| $T_{\text{eff}}$ (K) | 6729.99   |
| log $g_1$ (dex)     | 3.67      |
| $R_2$ ($R_\odot$)   | 2.77      |
| $T_{\text{eff}}$ (K) | 6431.46   |
| log $g_2$ (dex)     | 3.80      |
| [M/H] (dex)         | –0.42     |

spectra as our fitting model, while Traven 2020 adopted a series of observed spectra as the fitting template, which is the same as in the GALAH official pipeline (Kos et al. 2017). (3) The binary spectra models are produced in different ways. In our work, we synthesise the binary spectra with the light-curve-derived radii and the phase-based projection areas. The luminosity contribution depends on the real size and $T_{\text{eff}}$ ratio of the component stars. Traven 2020 generated the synthetic SED of two single stars using the Kurucz ATLAS9 models and produced the SED of the binary system taking the component star radii as the independent variables. The generated binary SED and the radii were restricted by the apparent magnitudes from AAVSO Photometric All-Sky Survey (APASS; Henden et al. 2016), Gaia DR2 (Evans et al. 2018), Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), and Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010).

Except for the difference between the two methods, we suggest two other factors that may cause the inconsistency. These two factors may also represent disadvantages to deriving atmospheric parameters using SB2 spectra. Firstly, the effect of mixing and continuum contamination on the line depth influence the measurement of $T_{\text{eff}}$. Theoretically, the prime criteria used to derive the effective temperature for a main sequence F-type star are the strength and profiles of the hydrogen lines (Gray & Corbally 2009). But the LAMOST MRS waveband contains only the H$\alpha$ line. Due to its depth and broad width, the H$\alpha$ line is easily influenced by the mixing of two spectra. In this case, the metal lines become the main features used to derive $T_{\text{eff}}$. But metal lines are shallower than the H$\alpha$ lines; the absolute strength is more easily affected by the continuum. Furthermore, the relative line intensity ratio is constrained by the luminosity contribution. When fitting the SB2 spectrum, the most luminous star component occupies more weight in fitting the best model. This makes the measured $T_{\text{eff}}$ of the hotter star higher than the real value. These two factors, that is the relative line intensity change and the higher measured $T_{\text{eff}}$ of the hotter star, cause the $T_{\text{eff}}$ ratio to get smaller in the fitting iteration, which causes the $T_{\text{eff}}$ measurement of the cooler star to be lower. Absolute flux calibration may help to reduce continuum contamination.
Secondly, the surface gravity of the component stars found by fitting the SB2 spectra are underestimated. As the most prominent spectral lines in the LAMOST MRS waveband are the MgI triplet λλ 5167, 72, 83 and the Hr, the surface gravity of most of the A- to G-type main-sequence stars cannot be derived precisely (Chen et al. 2021). The wings of the hydrogen lines are sensitive to luminosity for early A-type stars, as is the MgII triplet for late G- to mid-K-type stars (Guinan & Smith 1984). Furthermore, the micro-turbulent velocity plays an important role in determining surface gravity for the F-, G-, and even K-type stars. For the mid-F-type dwarfs, a micro-turbulent velocity of about 1.2 km s⁻¹ affects the luminosity criteria (Gray et al. 2001). The spectral lines in a single star spectrum are broader and stronger due to the micro-turbulence. In an SB2 spectrum, Doppler shift and line mixing cause the double-peak lines to be broader and stronger than the lines in a single-star spectrum. Under the joint influence of the micro-turbulence and the line mixing, deriving log g directly from the SB2 spectra usually overestimates the results. Although Traven 2020 accounted for the micro-turbulent velocity, the spectral line mixing still makes sense, resulting in log g measurements that are smaller than the light curve solution.

4. Summary

We provide a method to model the binary star spectra with double-lined features. The antecedent information of a detached eclipsing binary system is derived by solving the light curves and radial velocity curves. We synthesise the SB2 model spectra by superposing single star spectra according to the luminosity contribution of the component stars. The synthetic spectra are then used to fit the observation spectra using the least square method and to derive atmospheric parameters of the component stars. The method provides the radial velocities, effective temperatures, and surface gravity of each star, and metallicity for the binary system. We generate model spectra for different phases according to the change of the relative position of the component stars. The atmospheric parameters derived from the multi-epoch SB2 spectra have similar values, which indicates the robustness of our method.

Our method provides a way to calculate effective projection areas of component stars in both eclipsing and non-eclipsing phases. However, in the fitting experiments shown in Sect. 3, we find that the LAMOST MRS SB2 spectra were observed mostly in the non-eclipsing phases. With a resolution of 7500, LAMOST MRS cannot resolve double-lined features in nearly eclipsing phases. Therefore, the LAMOST MRS SB2 spectra contain fluxes from the whole system of stars.

This method can also be applied to partially eclipsing spectra as long as the resolution is high enough to resolve binary features. In addition, with increasing resolution, the influence of the limb-darkening effect, the reflection between two stars, and the microturbulence on the spectral line begin to appear and should be considered in determining atmospheric parameters.

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Appendix A: Projection area calculation

1. Basic assumptions: spherical component stars.

2. Initial data.

2.1 Fit RV curves and mass ratio q using spectra radial velocities.

2.2 Period (P), eccentricity (e), inclination (i), argument of periastron (ω), time of periastron passage $t_{per}$, semi major axis (SMA), radii of component stars (suppose $R_1 > R_2$).

3. Projection areas.

Figure A.1 is a schematic of the projection areas during shallow partial eclipse. The specific calculation is as follows:

3.1 At the observation time $t$ of an SB2 spectrum, the mean anomaly $M$, the eccentric anomaly $E$, and the true anomaly $\nu$ of the binary system are calculated as follows:

$$M = 2\pi \frac{t - t_{per}}{P},$$

$$E - e \sin E = M,$$

$$\tan \frac{E}{2} = \sqrt{\frac{1 - e}{1 + e} \tan \frac{\nu}{2}}.$$  (A.1)

3.2 Projection distance $d$ between the component stars onto the plane-of-sky:

$$d = S M A \frac{1 - e^2}{1 + e \cos \nu} \left[1 - \sin^2(\omega + \nu) \sin^2 i\right]^{1/2}.$$  (A.4)

3.3 Projection areas during different phases:

3.3.1 No eclipse ($d > R_1 + R_2$):

$$A_{1ini} = \pi \cdot R_1^2,$$

$$A_{2ini} = \pi \cdot R_2^2.$$  (A.5)

3.3.2 Total and annular eclipse ($d < R_1 - R_2$): When the larger star is in front (total eclipse):

$$A_1 = A_{1ini},$$

$$A_2 = 0.$$  (A.6)

When the smaller star is in front (annular eclipse):

$$A_1 = A_{1ini} - A_{2ini},$$

$$A_2 = A_{2ini}.$$  (A.7)

3.3.3 Partial eclipse:

a. Shallow partial eclipse ($d > \sqrt{R_1^2 - R_2^2}$): Larger star in front:

$$A_1 = A_{1ini},$$

$$A_2 = A_{2ini} - \Delta A_1 - \Delta A_2.$$  (A.8)

Smaller star in front:

$$A_1 = A_{1ini} - \Delta A_1 - \Delta A_2,$$

$$A_2 = A_{2ini}.$$  (A.9)

b. Deep partial eclipse ($\sqrt{R_1^2 - R_2^2} > d > R_1 - R_2$): Larger star in front:

$$A_1 = A_{1ini},$$

$$A_2 = \Delta A_2 - \Delta A_1.$$  (A.10)

Appendix B: Fitting spectra from near-eclipsing phases

At the near-eclipsing phases, although the double-line features cannot be recognised in the LAMOST MRS resolution, the asymmetry of lines is caused when $\Delta RV < 50 \text{km s}^{-1}$. We present the spectral fitting results of two near-eclipsing spectra. Figure B.1 shows the best fitting model of a TIC 63209649 spectrum. The black lines are the LAMOST MRS spectra, the red dashed lines are the best fitting model, and the grey dotted lines represent the residuals. Although the spectrum can be fitted by a synthetic binary spectrum with the help of the orbital results, the atmospheric parameters are quite different from the results of the SB2 spectra. The best fitting parameters of Figure B.1 are: $T_{eff1} = 6263.63$ K, log $g_1 = 3.75$ dex for the primary star, $T_{eff2} = 6220.43$ K, log $g_2 = 4.44$ dex for the secondary star, and [M/H] = -0.48 dex for the binary system. But the mean parameters of the SB2 spectral fitting are: $T_{eff1} = 6643.22 \pm 49.20$ K, log $g_1 = 4.13 \pm 0.13$ dex for the primary star, $T_{eff2} = 5917.39 \pm 37.60$ K, log $g_2 = 3.78 \pm 0.04$ dex for the secondary star, and [M/H] = -0.23 ± 0.13 dex for the binary system (Table 2). In Sect. 2.3, we find the atmospheric
parameters derived in different phases should not vary significantly if the contributions of the component stars are detected correctly. Therefore, the fitting results in the figure are likely to be inconsistent with the real situation. We suggest that the real signal-to-noise ratio (S/N) of the near-eclipsing spectrum is not high enough to recognise the line asymmetry correctly, despite the announced S/N of this spectrum being 60.42 for the blue band and 94.05 for the red band in the LAMOST MRS catalogue.

Figure B.2 is the near-eclipsing phase fitting result of EPIC 247529791. The atmospheric parameters fitted from these spectra are also different from the parameters from the SB2 spectra. The best fitting parameters of Figure B.2 are: $T_{\text{eff}1} = 6905.15$ K, $\log g_1 = 3.60$ dex for the primary star, $T_{\text{eff}2} = 6367.69$ K, $\log g_2 = 3.32$ dex for the secondary star, and $[\text{M/}H] = -0.31$ dex for the binary system. But the mean parameters of the SB2 spectral fitting are: $T_{\text{eff}1} = 6969.73 \pm 16.30$ K, $\log g_1 = 3.56 \pm 0.06$ dex for the primary star, $T_{\text{eff}2} = 6146.84 \pm 38.50$ K, $\log g_2 = 3.39 \pm 0.30$ dex for the secondary star, and $[\text{M/}H] = -0.46 \pm 0.02$ dex for the binary system (Table 4). We do not use the parameters of the near-eclipsing spectra to calculate the final parameters in this work, but we note that our method has the ability to deal with the line-asymmetry spectra with more precise orbital parameters and high-S/N spectra.
**Fig. B.1.** Best fitting result of TIC 63209649 at the near-eclipsing phase. Lines and colours have the same meaning as in Figure 12. This spectrum is also the fifth from the top in Figure 9. The orbital phase of this spectrum is 0.9931.

**Fig. B.2.** Best fitting result of EPIC 247529791 at the near-eclipsing phase. Lines and colours have the same meaning as in Figure B.1. This spectrum is also the fourth from the top in Figure 15. The orbital phase of this spectrum is 0.0260.