

The physical properties of post-mass-transfer binaries

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ABSTRACT

Aims. We present and analyse the detailed physical properties of six binary stellar systems, originally proposed as possible star-black hole binaries on the basis of radial velocities from Gaia’s third data release, but soon recognised as likely post-mass-transfer binary systems with stripped companions.

Methods. We used multi-epoch high-resolution FEROS spectra and spectral disentangling paired with stellar templates to derive effective temperatures, T_{eff} ; stellar radii, R_* ; and projected rotational velocities, $v \sin i$ for both components in all systems along with the mass ratio, $q = M_{\text{accretor}}/M_{\text{donor}}$ and the components’ flux ratio as a function of wavelength.

Results. Our analysis directly confirms that all systems are post-mass-transfer binaries with two luminous stars, i.e. no black hole companions. Each system contains an A-type accretor component that is rapidly rotating and a cooler very low-mass donor ($\sim 0.25M_{\odot}$) that is overluminous. Five of the systems show no trace of any emission lines, implying that there is no current mass transfer, consistent with our inferred radii, in all cases within the Roche volume. The data are generally consistent with stable case AB mass transfer with β (the fraction of mass lost from the accretor) less than 0.7. While the accretor components rotate rapidly, they rotate well below the critical rotation rate, v_{crit} , even though there must have been enough mass transfer to spin them up to a significant fraction of v_{crit} , according to theoretical models of angular momentum transfer. As neither magnetic braking nor tidal synchronisation should have been effective in spinning down the stars, our results suggest that either mass accretion does not increase the angular momentum of the accretors to their critical values or the systems never reached these values in the first place.

Key words. binaries: spectroscopic – Stars: rotation

1. Introduction

Most massive stars and an appreciable fraction of lower-mass stars are born in binaries (Moe & Di Stefano 2017). The initially more massive star evolves first and expands, potentially leading to mass transfer towards its companion. Such mass transfer fundamentally alters both components and the whole configuration of the system, as the donor loses most of its envelope and becomes a low-mass stripped star, while the accretor gains mass and is spun up by the angular momentum of the accreted material (Packet 1981). The outcome of this interaction depends critically on the initial orbital period, component masses, and the efficiency with which mass and angular momentum are accreted (Packet 1981; Soberman et al. 1997).

For a brief period, the low-mass stripped star can become very luminous, outshining its far more massive (accretor) companion star in the binary. During this phase, the high inferred mass ratios (and thus, large implied secondary mass) and the lack of obvious evidence of a secondary star due to rotationally broadened spectral lines, can make these systems appear as black hole binary ‘impostor’ systems (Shenar et al. 2020; Bodensteiner et al. 2020; El-Badry & Burdge 2022; El-Badry et al. 2022a,b). Immediately after the Gaia data release 3 (DR3) (Gaia Collaboration et al. 2023), El-Badry & Rix (2022) (hereafter EB+22) analysed a sample of Gaia DR3 binaries initially flagged as pos-

sible black hole hosts based on their high mass functions. By modelling their spectral energy distributions (SEDs) and light curves, EB+22 showed that these systems were actually systems containing a stripped donor star and a main-sequence accretor.

These systems containing a relatively hot (~ 9000 K) accretor and a cooler (~ 5000 K), less massive ($\lesssim 0.5 M_{\odot}$) but luminous ($\gtrsim 10 L_{\odot}$) donor, represent an important stage in binary stellar evolution. When seen edge-on, they may appear as Algol-type variables, where paradoxically the less massive component is initially the more luminous of the two (Kopal 1955). This is due to previous mass transfer in the system, which reversed the mass ratio (Kippenhahn & Weigert 1967). While the basic physical picture of how such systems form through mass transfer is understood, many aspects remain poorly constrained empirically. In particular, how conservative mass transfer is (i.e. how much mass is retained in the binary versus lost to the interstellar medium) (e.g. de Mink et al. 2007; Claeys et al. 2011; Deschamps et al. 2013), mass transfer stability (e.g. Hjellming 1989a,b; Deloye & Taam 2010; Ge et al. 2010a,b, 2015, 2023; Ge et al. 2024; Woods & Ivanova 2011; Pavlovskii & Ivanova 2015; Temmink et al. 2023; Ivanova et al. 2024), the mechanisms governing stellar spin during and after mass transfer (e.g. Sun et al. 2024), and the detailed physical properties of stripped donor stars (e.g. Göteborg et al. 2023) constitute some of the biggest uncertainties in binary evolution while tremendously af-

Table 1. Results of the spectral analysis for the donor (don) and accretor (acc) for each system.

Gaia Source ID	Short ID	$T_{\text{eff,don}}^a$ [kK]	$T_{\text{eff,acc}}^a$ [kK]	q^a	$T_{\text{eff,don}}$ [kK]	$T_{\text{eff,acc}}$ [kK]	q_{TODCOR}	$v_{\text{rot,don}}$ [km/s]	$v_{\text{rot,acc}}$ [km/s]
Gaia 2933630927108779776	G-2933	4.4 ± 0.2	9.7 ± 0.3	8.1 ± 1.4	4.75 ± 0.25	9.50 ± 0.25	5.7 ± 1.2	19 ± 1	176 ± 1
Gaia 5694373091078326784	G-5694	4.6 ± 0.2	9.9 ± 0.3	8.8 ± 1.7	4.75 ± 0.25	9.25 ± 0.25	6.5 ± 1.1	21 ± 1	190 ± 1
Gaia 6000420920026118656	G-6000	4.5 ± 0.2	9.5 ± 0.3	11.6 ± 2.1	4.75 ± 0.25	9.00 ± 0.25	5.1 ± 1.2	21 ± 1	156 ± 1
Gaia 5243109471519822720	G-5243	4.6 ± 0.2	9.4 ± 0.3	7.1 ± 1.2	4.75 ± 0.25	8.75 ± 0.25	7.1 ± 2.4	20 ± 1	157 ± 1
Gaia 2966694650501747328	G-2966	4.7 ± 0.1	9.4 ± 0.2	8.7 ± 1.2	5.50 ± 0.25	9.00 ± 0.25	5.4 ± 1.5	20 ± 1	164 ± 1
Gaia 5536105058044762240	G-5536	4.9 ± 0.2	8.4 ± 0.3	8.3 ± 1.7	6.75 ± 0.25	7.25 ± 0.25	2.8 ± 0.7	12 ± 1	285 ± 1

Notes. ^(a) Comparative values from EB+22.

fecting the outcome of binary evolution models (e.g. Marchant & Bodensteiner 2024; Pols 2007).

Here, we present a detailed spectroscopic follow-up study of six systems using multi-epoch high-resolution spectra taken with the Fiber-fed Extended Range Optical Spectrograph (FEROS, Kaufer et al. 1999) instrument. Out of the sample of 14 objects identified by EB+22, six are at declinations inaccessible to FEROS, while of the remaining eight, six were at right ascensions observable by FEROS during the observing period applied for, P112. Thus, these six are the targets analysed in this work, and they are listed in Table 1. For brevity, we refer to them in the text by their first four numbers only (i.e. Gaia 2933630927108779776 is G-2933).

By applying the spectral disentangling method (section 3.1) and employing stellar spectral templates, we derived fundamental parameters (effective temperature, T_{eff} ; stellar radius, R_* ; and projected rotational velocity, $v \sin i$) for both components, along with mass ratios, q ; and wavelength-dependent component flux ratios. This allowed us to constrain the current physical state of these systems and probe their mass transfer history. We build on the work of EB+22, to provide not only spectroscopic stellar parameters but also clarify whether mass transfer is still ongoing, how conservative the mass transfer must have been, and how much rotation the accretor exhibits. To test these expectations and characterise the present-day properties of these systems, we obtained new, multi-epoch, high-resolution spectroscopy, which we describe in the following section.

2. Observations and data reduction

We acquired multi-epoch spectroscopic data ¹ using the FEROS instrument at the MPG/ESO 2.2m telescope at La Silla, Chile. It is located at $29^\circ 15' 28''$ S, $70^\circ 44' 12''$ W, at an altitude of 2375 m. The telescope uses a Ritchey-Chrétien reflector, with the FEROS instrument at Cassegrain focus, covering a wavelength range of $\sim 3500 \text{ \AA}$ to $\sim 9200 \text{ \AA}$ at a resolution of $\sim 48,000$.

Observation details are consolidated in table D.1 in the Appendix. We observed each target about ten times with a one or two nightly cadence, depending on the system's reported periods in EB+22. As all targets have orbital periods of ~ 10 to 20 days, this cadence provides good coverage of the RV dynamical range. We used exposure times of 20-30 min to reach a S/N of about 40-150, depending on the G -band magnitude as reported by Gaia (see Table E.3 in the Appendix).

The FEROS instrument is well-suited to this kind of analysis, as it provides good resolution over a wavelength range that includes the most important Balmer lines, relevant for our analysis of the hotter accretor, as well as many metal lines. We reduced data from FEROS using the *ceres* pipeline (Brahm et al.

2017), which returns spectra in the wavelength range $\sim 3900 \text{ \AA}$ to $\sim 6770 \text{ \AA}$.

After acquisition and reduction of the data, we normalised the observed spectra with a running median filter. *ceres* provides normalised spectra, but we used the unnormalised spectra and performed our own normalisation to ensure the data and model spectra were normalised by the same method. Additionally, we created a set of template spectra by normalising and re-sampling Coelho (2014) model spectra in the relevant temperature, metallicity, and $\log g$ ranges onto the same wavelength grid as the FEROS data. The template spectra were computed assuming local thermal equilibrium and spaced in intervals of 250 K (T_{eff}), and 0.5 ($\log g$). Here, we consider temperatures from 4000 K to 11000 K, and surface gravities from two to four. We assumed solar metallicity and applied rotational broadening with the *RotBroadInt* package by Carvalho & Johns-Krull (2023) from 0 km/s to 300 km/s.

Using these data, our next goal was to derive the stellar and orbital parameters of both components. In the following, we outline the sequence of analyses performed, each building on the results of the previous step.

3. Data modelling and results

We present the methodology and observational results for our sample in this section. This is followed with a comparison of our results with EB+22 and a discussion of the significance for the physical state and history of these systems in the subsequent Section 4.

3.1. Spectral disentangling and determining RVs

As a first step, we disentangled the composite spectra into the individual component spectra. This provided the foundation for all subsequent analyses by yielding both the radial velocities (RVs) and the individual stellar spectra.

In this work we make extensive use of the spectral disentangling pipeline described in Seeburger et al. (2024), based on Simon & Sturm (1994). Spectral disentangling is a data-driven method that seeks to decompose multi-epoch observational spectra of a multiple system into the individual component spectra. By assuming that the component spectra are time invariant in their shape and only change by being red- and blue-shifted, one can construct a matrix that, when multiplied by the two component spectra, reconstructs the observations at each epoch. The values of the matrix elements are determined by the RVs of each component at each epoch. This can be simplified by first determining the primary (donor) velocities and the mass ratio of the system and then computing the secondary (accretor) velocities from these (see Section 2.5 in Seeburger et al. (2024) for details).

¹ ID: 112.264Z.001, PI: Seeburger

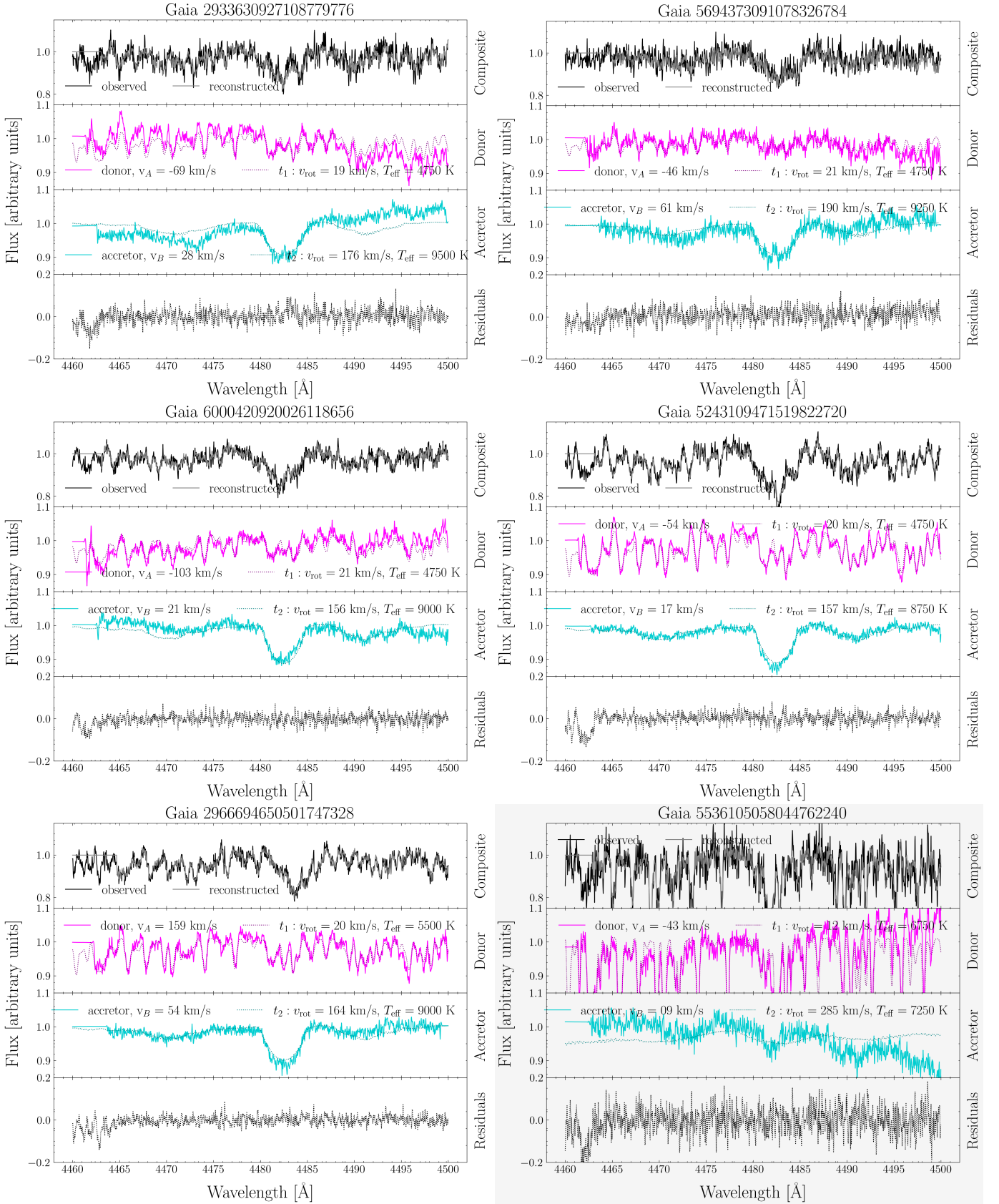


Fig. 1. Observed spectra for one epoch (black line, top row), the two disentangled components (magenta and cyan lines, middle row, shown in the rest frame), their sum (grey line, top row, computed by shifting and co-adding), and the residual (bottom row) for the six targets of this study, centered around the Mg II line as seen clearly in the accretor spectrum. We also show the best-fit template spectra for each disentangled component in the middle rows (dotted lines). In this and following figures, plots showing results for target G-5536 have a light grey background to differentiate them from the other targets, due to the difficulties with the analysis encountered for this object.

Gaia 2966694650501747328

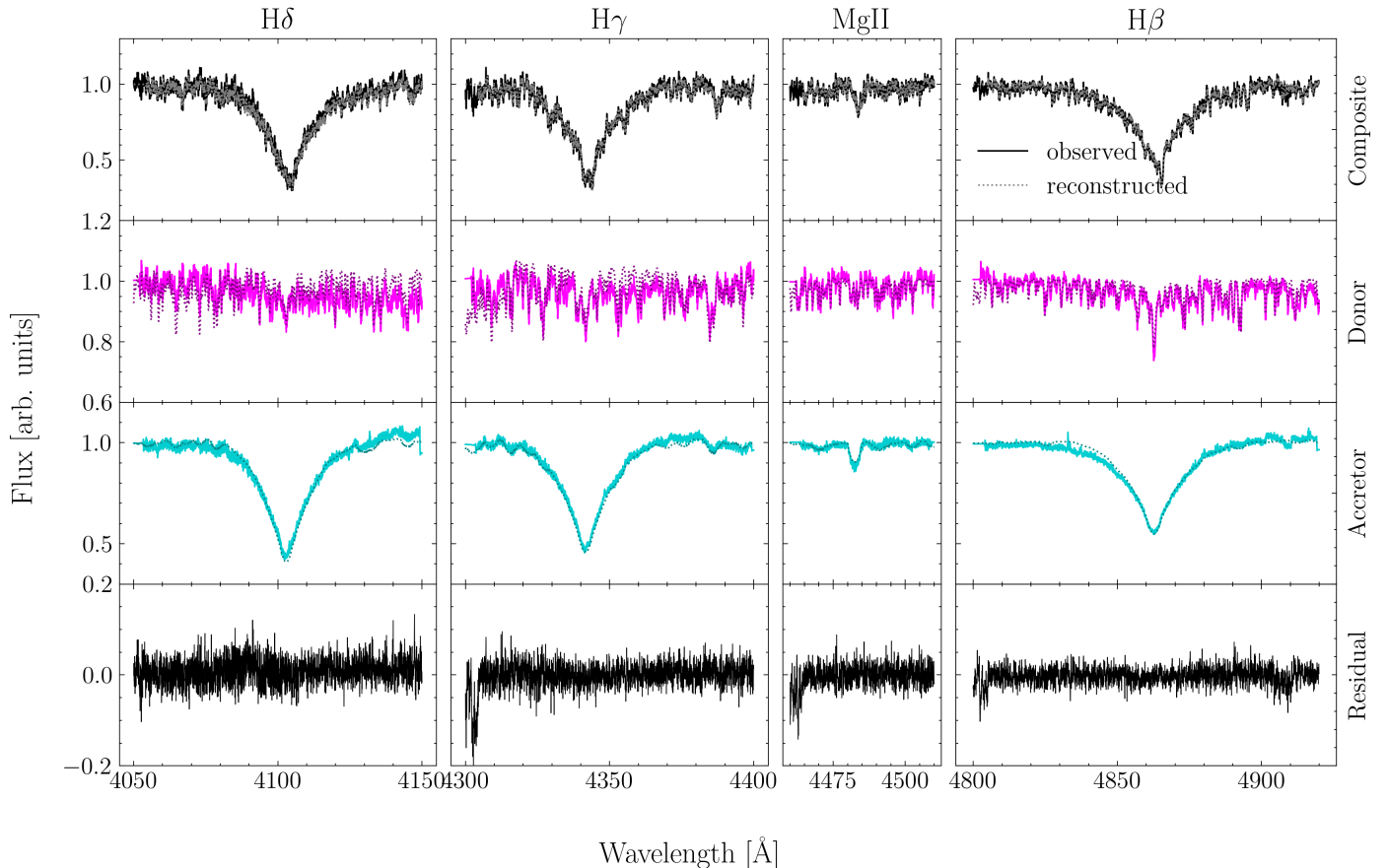


Fig. 2. Observed spectra for one epoch (black line, top row), the two disentangled components (magenta and cyan lines, middle rows), their sum (grey line, top row), and the residual (bottom row) for a number of different wavelength ranges. We also show the best-fit template spectra for each disentangled component in the middle rows (dotted lines). The windows here show the Balmer series and Mg II in the accretor, which is hot and has few lines. Here, we only show the spectra for one object (G-2966), the rest can be found in Figures A.1 and A.2 in the Appendix.

Seeburger et al. (2024) combined this linear algebra problem with a non-linear optimisation step. At each step of the optimiser, a vector of primary RVs and a mass ratio is proposed, the spectra are disentangled, and the residuals between the multi-epoch observations and reconstruction are computed. This residual is taken to be a metric of fit and sought to be minimised by the optimiser, in theory returning the parameter set for which the algorithm could most accurately decompose the spectra, as well as the best-fit component spectra.

In this work, we computed initial guesses for the primary RVs by cross-correlating the observed spectra with our templates. Then, we iteratively optimised the primary velocities and mass ratio by proposing a set of candidate parameters, disentangling and computing the residual for that set, seeking to minimise the residual. We found the region around $H\beta$ to be optimal for this, as both spectra contribute similarly to the total flux, and there are sufficient features in both components (abundant metal lines in the donor, $H\beta$ in the accretor) to perform the disentangling. This is particularly important for the accretor, which is hot and has only a few lines.

The basic result of this analysis are the disentangled spectra for all six systems, with velocities and mass ratio determined via optimisation. These disentangled spectra are shown in Figure 1, for the Mg II wavelength region, where, in all six systems, both components show prominent features. For each of the six panels, the top displays the total spectrum at one epoch, the next two

the two disentangled components (donor and accretor), and the bottom panel shows the residuals. Figure 1 demonstrates that all systems yield well-defined and physically plausible disentangled solutions that leave only small systematic residuals. This immediately confirms that all these systems are indeed SB2 (double-lined spectroscopic binaries, as opposed to SB1s, single lined spectroscopic binaries) binary systems with two luminous components, as surmised by EB+22.

All panels of Figure 1 show that the primary spectrum (magenta, second panel) exhibits an abundance of narrow metal absorption lines, characteristic of cool stars without fast rotation. The secondary spectrum (cyan, third panel) shows far fewer and much broader lines, indicative of a hotter and rapidly rotating star. Qualitatively, this is aligned with the picture where the cool primary star is a low $\log g$ donor, while the hotter secondary star is the spun-up accretor. The nature of the hotter disentangled component is illustrated further in Figure 2 for one of the objects (G-2966): the Figure zooms in on three Balmer line sub-regions ($H\beta$ to $H\alpha$ is not shown due to stationary, telluric lines near the stellar line affecting the disentangling), in addition to the Mg II region shown already in Figure 1. The Balmer lines are the dominant spectral features of the hotter component, indicative of A-type stars with $T_{\text{eff}} \approx 9000$ K. Figure 2 also illustrates that our sample star (G-2966) shows no wings on either side of the $H\beta$ line, indicating little or no $H\beta$ emission. This affirms expectations for a system currently not undergoing mass

transfer. Analogous figures for the other five targets are shown in Figures A.1 and A.2 in the Appendix.

3.2. Stellar parameter determination

Having obtained disentangled spectra for both components, we next determined their effective temperatures and projected rotational velocities. These parameters provide the basis for assessing the physical state of each star and for subsequent comparisons with evolutionary models.

First, we focused on the disentangling result around the red end of the spectrum (4800 - 5700 Å), where the cooler donor dominates the flux, allowing us to fit a template to the disentangled donor spectrum. We did so by considering the template spectra described above, at all available effective temperatures and surface gravities, but only a selection of rotational velocities, as these were determined in a subsequent step. We scaled each template by a set of different light ratios between 0.01 and 100, and performed a least squares fit with the disentangled donor spectrum. We repeated the same procedure in the blue (3950 - 4900 Å) for the hotter accretor. This provided the effective temperatures and surface gravities of each component from the corresponding best-fit template. Additionally, by considering the disentangled spectra around the Mg II line at 4481 Å, we determined the projected rotational velocity of the stars, crucial to understanding the spin-up and/or spin-down that has occurred during mass transfer. We achieved this by selecting the best-fit template in terms of T_{eff} and $\log g$ from the previous step (where we considered only a handful of potential rotational velocities), and considered all rotationally broadened instances thereof, subsequently determining the best-fit rotational velocity via a least-squares fit of the disentangled spectra and broadened templates. We preferred Mg II over one of the (deeper) Balmer lines, as the shape of the Balmer lines is predominantly set by the stellar temperature and surface gravity, and rotation has only a comparatively small effect.

Table 1 lists the best template temperatures and rotation velocities for both components. Further, these are also shown on the relevant panels of Figures 1 and 2, indicating the stellar parameters of the template (dotted lines) displayed in that panel. All donors show significant but moderate rotational velocities consistent with tidal synchronisation. The accretors rotate more rapidly, but in all cases well below critical rotation, v_{crit} , the surface velocity of the star where its outward centrifugal force is equal to the inward force exerted by gravity, also known as break-up velocity. This can be computed as:

$$v_{\text{crit}} = \sqrt{\frac{GM_*}{R_*}}, \quad (1)$$

where M_* and R_* are the mass and radius of the star in question, and G is Newton's constant. For a detailed discussion, see Section 4. We then used these best templates for subsequent analysis.

3.3. Applying TODCOR for an independent mass ratio estimation

To independently verify and refine the mass ratios inferred from the disentangling procedure, we also applied the Two-Dimensional CORrelation (TODCOR, Zucker & Mazeh 1994) method. The mass ratio is an essential parameter for the mass transfer history analysis in Section 3.7.

We used the best-fit templates for each component with TODCOR to determine the velocities of the two components for each epoch. The primary and secondary velocity (v_A and v_B , respectively) at each epoch were chosen such that they maximised the value of the 2D cross-correlation of the light-ratio-scaled templates with the observed spectrum at that epoch. The primary and secondary velocity are related by

$$v_B = v_{\text{COM}} + \frac{v_{\text{COM}} - v_A}{q}, \quad (2)$$

where v_{COM} is the centre-of-mass velocity. This shows that v_B should be a linear function of v_A with a slope and intercept of

$$\text{slope} = -\frac{1}{q} \quad \text{and} \quad \text{intercept} = v_{\text{COM}} + \frac{v_{\text{COM}}}{q}. \quad (3)$$

We fit this straight line using scipy's `curve_fit` (Virtanen et al. 2020), a non-linear least squares algorithm to fit a function to data, and derived the desired quantities. `curve_fit` also returns the covariance matrix, which allowed us to determine the error on the parameters. Thus, TODCOR provided an independent measurement of the mass ratio and centre-of-mass velocity from the individual epoch velocities.

We illustrate this for two of the objects (G-2966 and G-5536) in the top left and right panels of Figure 3, respectively. The panels show the component velocities, estimated from a range of different wavelength windows. The velocity estimates for the cool, narrow-lined donor component (along the x-axis of Figure 3) are consistent across wavelength windows with very small uncertainties. For the accretor, however, the velocity estimates vary substantially and are inconsistent across the different wavelength windows, and their formal uncertainties are considerably larger than those of the donor velocities. Indeed, these (presumably also systematic) uncertainties made the determination of the mass ratio – from the slope of the best-fit line – difficult for all objects. The different values of the mass ratio and centre-of-mass velocity are shown for the corresponding lines in the bottom panels, illustrating the discrepancies. We discuss further in Section 4. Our best estimates of the dynamical mass ratios, q , are listed in Table 1.

3.4. Finding the light ratio as a function of wavelength

The relative flux contribution of each component carries additional information about the system's configuration. We therefore determined the wavelength-dependent light ratio, linking the spectroscopic analysis with the photometric SED modelling that followed.

To do so, we considered the disentangled spectra across the ceres spectral range, split into 20 wavelength windows. For each window, we wished to ascertain the optimal light ratio between the (previously determined as described in Section 3.2) best-fit donor and accretor templates. To this end, we scaled the donor and accretor templates by a factor

$$l_{\text{don}} = \frac{1}{1+a} = \frac{f_{\text{donor}}}{f_{\text{total}}} \quad \text{and} \quad l_{\text{acc}} = \frac{a}{1+a} = \frac{f_{\text{accretor}}}{f_{\text{total}}} \quad (4)$$

respectively, computing the best fit via least-squares minimisation between the disentangled spectra and the respective scaled templates. This allowed us to determine the optimal light ratio

$$a = \frac{f_{\text{accretor}}}{f_{\text{donor}}}, \quad (5)$$

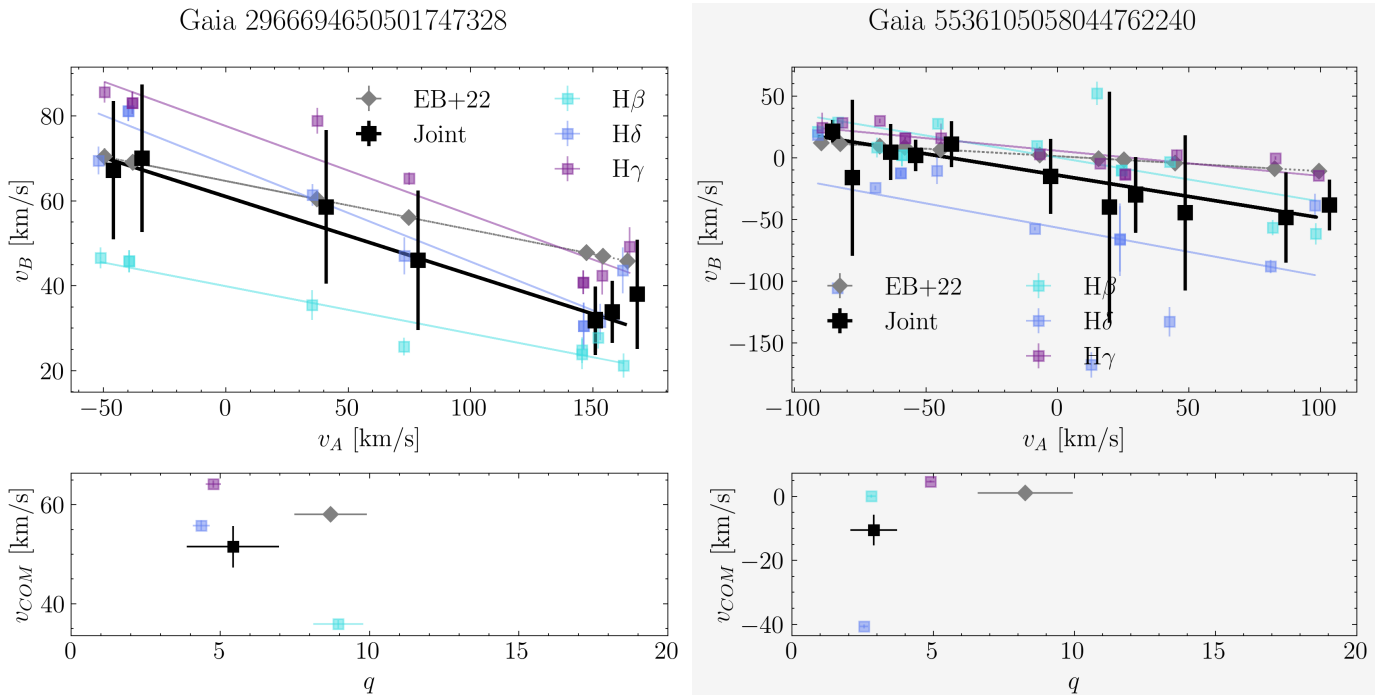


Fig. 3. Results of the TODCOR algorithm applied to two objects. Top panels: RV of the donor and accretor shown on the x- and y-axes, respectively. Markers show the RVs of both components determined for each epoch with different methods and in various wavelength windows, with each marker displaying a different epoch. The lines indicate the linear best-fit to the RVs, as the relationship between donor and accretor RVs is linear. Grey diamonds show the donor RVs from *ceres* (Brahm et al. 2017) on the x-axis, with corresponding accretor RVs on the y-axis. The accretor RVs were computed using the *ceres* donor RVs, the mass ratio from EB+22, centre-of-mass velocity from Gaia, and equation 2. Coloured squares and lines show the results from TODCOR for a number of wavelength windows centered on different lines. Black squares show the unweighted mean for each epoch velocity over the different wavelength windows, offset to higher v_A by a small amount for clarity. The fit labelled ‘Joint’ is then performed to these mean values. From the slope and intercept of the best-fit line, the mass ratio and centre-of-mass velocity can be computed, see equation 3. Bottom panels: Plot of the mass ratio vs the centre-of-mass velocity as determined from each set of data in the top panel, coloured accordingly. The left panel shows target G-2966, while on the right we see object G-5536, with a grey background to highlight the difficulty of the analysis for this object. For G-5336, we see that while there is a big discrepancy between the mass ratio from TODCOR and the one found by EB+22, the quality of the linear fit with TODCOR is not good, calling this result into question.

and, trivially, the relative light contribution of the donor l_{don} for the window in question. Using this method, we got a piece-wise approximation of the light ratio as a function of wavelength, which subsequently provided an additional constraint in our SED fits.

The donor spectrum’s contribution to the total flux, $l_{\text{don}}(\lambda) = f_{\text{donor}}/f_{\text{total}}$ is shown for all objects in the bottom sub-panels of Figure 4 (red line). This Figure shows that in all cases the donor flux contribution increases strongly towards longer wavelengths, as expected from the much cooler temperature of the donor. This also explains why the disentangled donor spectra at short wavelengths in Figure 2 appear so noisy: The total flux at the bluest wavelengths is dominated by the accretor.

3.5. SED fitting

To connect the spectroscopic and photometric constraints and to verify the consistency of the derived parameters, we modelled the SEDs of the systems using multi-band photometry. SED fits were initially used by EB+22 to identify the systems studied here as potential SB2s, without priors on the stellar parameters from spectroscopy. We followed a similar method as the original authors.

We acquired observed photometry for each target from the Wide-field Infrared Survey Explorer (WISE, Wright et al. 2010), SkyMapper (Keller et al. 2007), American Association of Variable Star Observers (AAVSO) All-Sky Photometric Sur-

vey (APASS, Henden et al. 2016), the Galaxy Evolution Explorer (GALEX, Martin et al. 2005) and the Two Micron All Sky Survey (2MASS, Skrutskie et al. 2006), covering a wide wavelength range. For each component of the system, we simulated synthetic spectra with *pystellibs* (Fouesneau 2016), and added them to obtain a composite model SED. Dust attenuation was then performed using the *dustmaps* package (Green 2018) with the 3D dustmap from Edenhofer et al. (2024). We created mock photometry using *pyphot* (Fouesneau 2024). This package contains a library of common photometric filters, including their throughput as a function of wavelength. Then, for a given flux through a filter, the total number of photons, and thus energy flux, can be computed via integration. More detail is provided in the *pyphot* documentation².

Then, using the Markov chain Monte Carlo sampling package *emcee* (Foreman-Mackey et al. 2013), we determined the best set of parameters for each component of the SED to reconstruct the observed photometry. Here, we held the effective temperatures fixed to the values acquired from the spectroscopy and set the surface gravities to the values inferred by EB+22. We placed a Gaussian prior on the parallax based on the Gaia DR3 parallax and its error, and a flat prior on the radii for both components. Thus, we performed a three-parameter fit: the parallax, radius of the donor and radius of the accretor.

² <https://mfouesneau.github.io/pyphot/photometry.html>

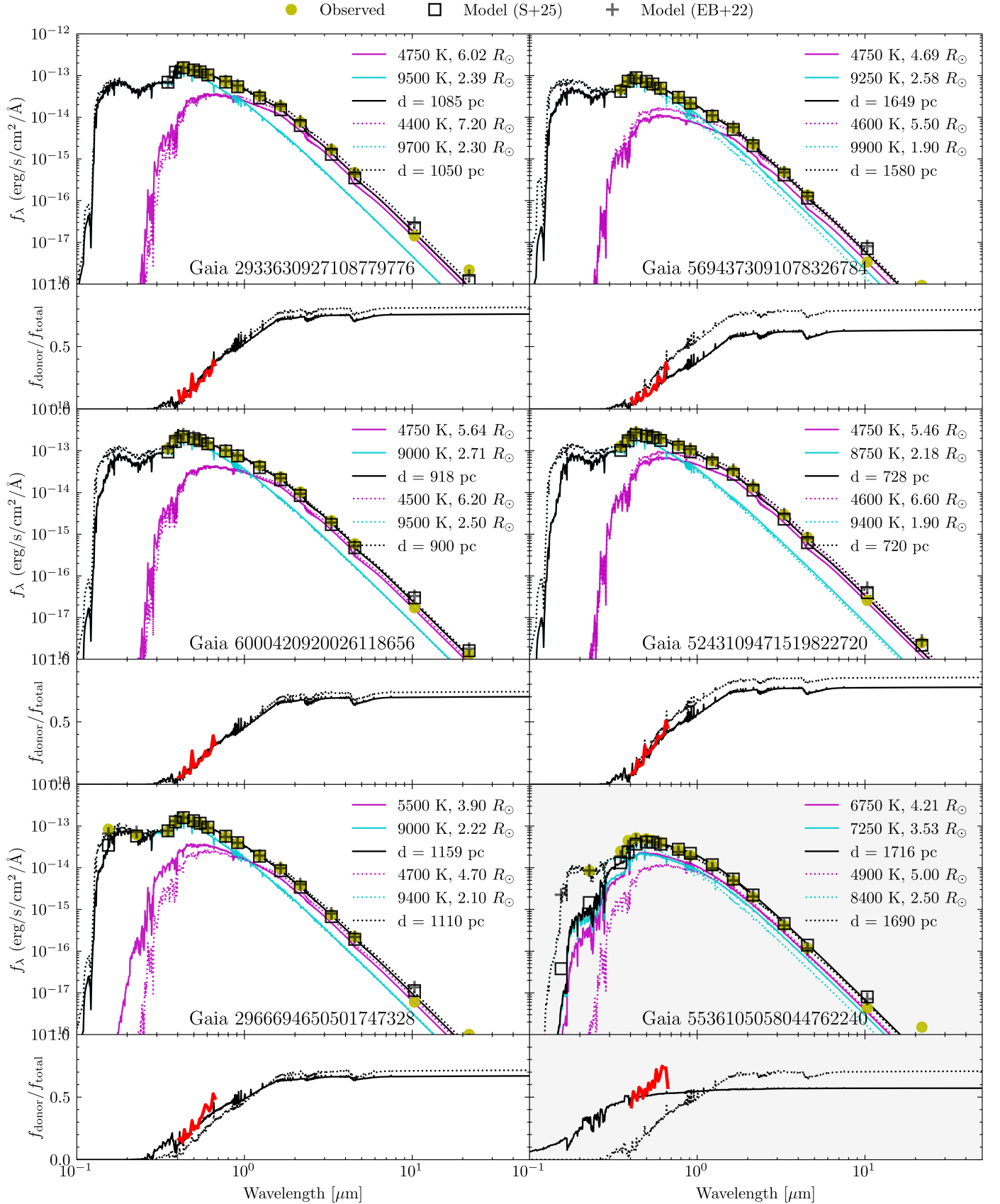


Fig. 4. Spectral energy distribution fits and light ratio as a function of wavelength for each target. In the top plot of each set, we see the donor's (magenta line) and accretor's (cyan line) model SED, as well as sum of the two component models (black line). Solid lines use stellar parameters from this work, and dotted lines the parameters derived in EB+22. We also overplot the observed photometry (lime dots), as well as the mock photometry from this work (black squares) and EB+22 (grey crosses). Subsection 3.5 describes how each of these were obtained/computed. The bottom panel shows the contribution of the donor to the total flux as a function of wavelength. Again, solid indicates this work, dotted EB+22. The red line shows the spectroscopic light ratio derived in this work, providing an additional constraint in the SED fitting process. Target G-5536 is shown with a grey background to highlight the difficulties with its analysis.

We then computed the flux ratio of the two simulated components across the wavelength range covered by the FEROS observations. Comparing it to the spectroscopically determined flux ratio leads to an additional term in our full likelihood function:

$$\mathcal{L} = -0.5 \cdot \left(\frac{f_{\text{model}} - f_{\text{data}}}{f_{\text{error}}} \right)^2 - 0.5 \cdot w \cdot \log_{10} \left(\frac{l_{\text{don,model}} - l_{\text{don,data}}}{\ln(10)} \right)^2. \quad (6)$$

Here, f_{model} is the mock photometry, while f_{data} the observations in the various passbands, and f_{error} their associated errors. $l_{\text{don,model}}$ is the ratio of f_{donor} over f_{total} in the simulated model fluxes, and $l_{\text{don,data}}$ the relative light contribution of the donor as a function of wavelength determined previously. The weight w is chosen to ensure the flux-ratio term does not dominate the likelihood function.

Figure 4 shows the results of the SED fitting, where we overplot the observed photometry (lime dots) with the SEDs corresponding to our spectroscopic temperatures and radius estimates, both for the whole binary system (black line) and for the individual components (magenta and cyan lines). The bottom sub-panel for each object shows the spectroscopically determined donor flux contribution (red line), compared to that implied by the two components' SED.

In Figure 5 (top panels) we summarise information from the spectral fits (effective temperatures) and SEDs (stellar radii) in a Hertzsprung-Russell diagram. In the top left panel, we also include PAdova and TRIeste Stellar Evolution Code (PARSEC, Bressan et al. 2012) isochrones generated using the CMD 3.8 input form³ for stellar logarithmic ages ranging from eight to ten in increments of 0.5, assuming solar metallicity. In the remaining panels, we show the target parameters alongside Modules for Experiments in Stellar Astrophysics (MESA, Paxton et al. 2011, 2013, 2015, 2018, 2019; Jermyn et al. 2023) evolutionary tracks computed by EB+22. Here, the MESA tracks assumed a binary with main sequence (before mass transfer started) masses of $1.5 M_{\odot}$ and $1.1 M_{\odot}$ for the donor and accretor respectively. The initial period was assumed to be 1.3 days. Further details are described in EB+22. The positions of the components are also shown in the $\log g - T_{\text{eff}}$ and $\log(R) - T_{\text{eff}}$ planes (bottom panels). Here, $\log g$ was determined not from our disentangled spectra, but by combining the masses from EB+22 with the radii from our SED fits, as surface gravities from the spectra proved to be poorly constrained.

3.6. Orbital fitting

Having determined reliable RVs for both components in Section 3.1, we then used these to fit orbital solutions for each system. This step linked the spectroscopic results with the systems' dynamical properties and provided the orbital periods required for the mass transfer analysis in Section 3.7.

Similar to Müller-Horn et al. (2025), we used a nested sampling framework to estimate posterior probability distributions for the orbital parameters. Nested sampling is a variation of the commonly used Markov chain Monte Carlo sampling algorithm to sample a posterior distribution (Skilling 2004). Here, we used the UltraNest⁴ package (Buchner 2021), an implementation of the nested sampling algorithm.

³ <https://stev.oapd.inaf.it/cgi-bin/cmd>

⁴ <https://johannesbuchner.github.io/UltraNest/>

The RV curve is described by six parameters: $(K, P, M_0, e, \omega, v_{\text{COM}})$. K represents the RV semi-amplitude of the visible star, P is the orbital period, and $M_0 = \frac{2\pi t_0}{P}$ defines the mean anomaly at a reference time t_0 . The parameters e and ω correspond to the orbital eccentricity and argument of pericentre, while v_{COM} denotes the system's barycentric velocity. Uniform, non-informative prior distributions were adopted for all parameters, with prior ranges set as follows: $K \in [0, 500]$ km/s, $P \in [1, 100]$ d, $M_0, \omega \in [0, 2\pi]$, $e \in [0.0, 0.9]$, and $v_{\text{COM}} \in [-100, 100]$ km/s. The results for these parameters based on the RVs determined in this work are summarised in Table E.3 in the Appendix.

3.7. Mass transfer history

The MESA evolutionary tracks shown in Figure 5 were taken from EB+22. Detailed setup can be found there, but for the purpose of this work we want to highlight the adoption of a fully conservative mass transfer scheme, with mass transfer rates computed using Kolb & Ritter (1990). These assumptions successfully reproduced the observed locations of the components in the Hertzsprung–Russell diagram. In this section, we tested these assumptions by combining our updated orbital parameters and spectroscopic mass ratios to infer the possible mass transfer histories of our targets following the formalism of Soberman et al. (1997).

Using the period from the orbital fit (c.f. with EB+22 and Gaia in Table E.3), and the mass ratio from the disentangling (c.f. with EB+22 in Table 1), we placed constraints on how conservative mass transfer must have been in each system's past. We used equations from Soberman et al. (1997), which relate the period and mass ratio in a mass transferring system subject to the mass transfer parameters α , β and δ . Here, the parameters describe the fraction of the transferred mass lost via various channels.

α is the fraction lost via a wind from the donor, β is the fraction ejected from the accretor, and δ is the fraction retained in a circumbinary ring. α , β and δ are defined as, respectively,

$$\alpha = \frac{\partial m_{\text{wind}}}{\partial m_{\text{don}}} \quad \beta = \frac{\partial m_{\text{iso-r}}}{\partial m_{\text{don}}} \quad \delta = \frac{\partial m_{\text{ring}}}{\partial m_{\text{don}}}. \quad (7)$$

Here, ∂m_{wind} is the mass of stellar wind from the donor, $\partial m_{\text{iso-r}}$ the mass of stellar wind from the accretor (isotropic re-emission) and ∂m_{ring} the mass used in the formation of a ring. ∂m_{don} is the mass lost from the donor. If all these parameters are set to zero, mass transfer is fully conservative, i.e. no mass is lost and 100% of the mass donated by the donor is accreted by the accretor. If these parameters add up to one, then mass transfer is fully non-conservative, meaning all mass ejected by the donor is lost to the surrounding medium; the accretor does not successfully accrete any of it. Functionally, the relative values of α , β , and δ determine the amount of angular momentum carried away by the matter lost from the system, and thus the extent to which the orbit widens or tightens.

For simplicity (following Bodensteiner et al. (2020); El-Badry et al. (2022b)) we assumed $\alpha = \delta = 0$, meaning no mass is lost via wind from the donor or to a circumbinary ring. This scenario is commonly referred to as isotropic re-emission. By varying β , we explored a number of more or less conservative mass transfer scenarios, particularly the evolution of the period with the changing mass ratio. Further, we set a minimum period P_{min} , which is where the donor overflows its Roche lobe on the

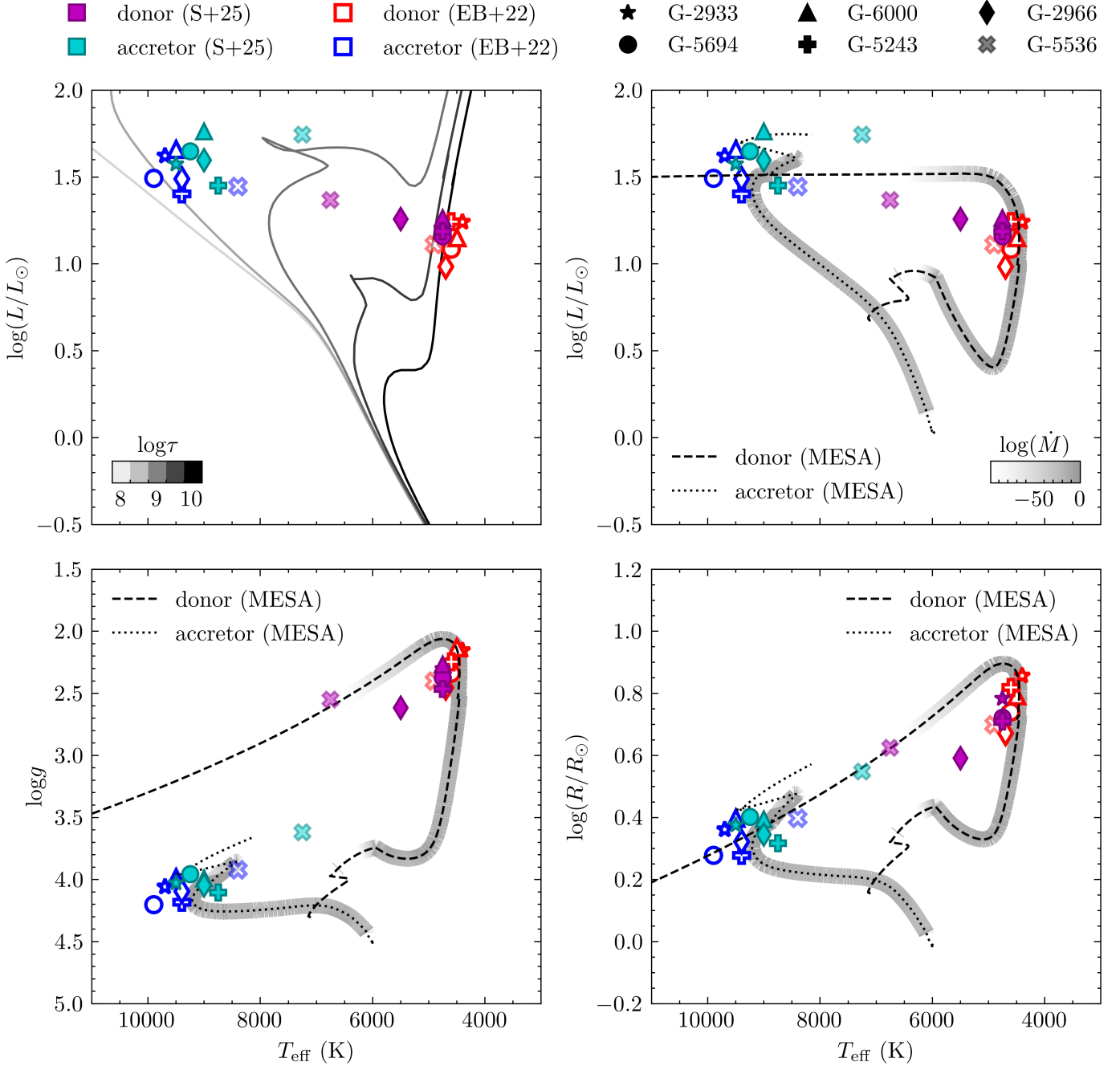


Fig. 5. Parameters of both components of each system as determined in this work (S+25) and EB+22. Findings from S+25 are shown with filled symbols in magenta (donor) and cyan (accretor), while those from EB+22 are empty, outlined in red (donor) and blue (accretor). Different symbols have been chosen to represent the six different systems, with the problematic system (G-5536) shown as more transparent than the rest. The top left panel shows a Hertzsprung-Russel diagram, including PARSEC isochrones spanning a range of ages (Bressan et al. 2012). The top right panel shows the same parameter space, but with possible MESA evolutionary paths for the donor (dashed line) and accretor (dotted line) included, as computed by EB+22. The bottom two panels show $\log g$ vs. T_{eff} and $\log R$ vs T_{eff} respectively, as well as including the aforementioned MESA tracks. The grey shading behind each line indicates the amount of mass transfer in the MESA model at that evolutionary stage.

main sequence (Eggleton 1983). The argument here is that we assume the binary was detached at some point in its evolution. If the mass transfer was too non-conservative (i.e. $\beta \gtrsim 0.7$), the past orbit would have been too tight, and the donor would not have fit. For an in-depth analysis of binary contact tracing, see Henneco et al. (2024).

Figure 6 shows the past evolution of the period as the system underwent mass transfer, for different β values. At q equal to one, the mass ratio is flipped, and the (initially) more massive donor is

now the less massive star of the binary. The coloured lines show how the past period depends on the assumed β . Some, but not all, of these lines dip below the minimum period (grey gradient, with darker colours corresponding to higher, and lighter colours to lower main sequence masses). Below this minimum period, the radius of the donor’s progenitor on the main sequence would have exceeded its Roche lobe, calculated using Eggleton (1983). These reflect values of β excluded by the data.

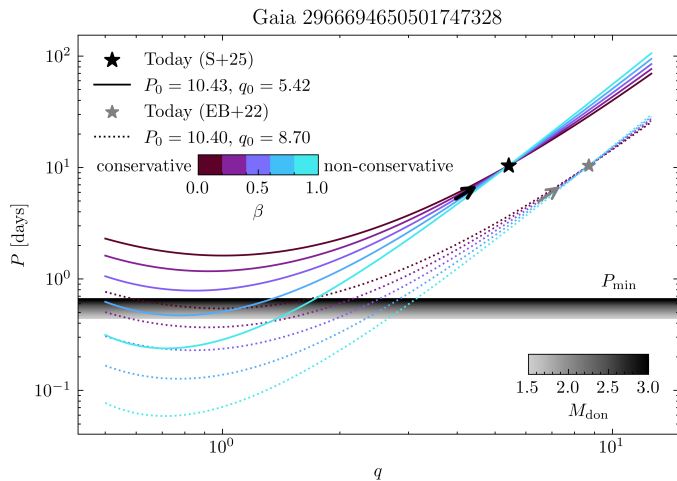


Fig. 6. Period vs mass ratio for one of the targets (G-2966), showing the evolution of the period as mass is transferred from the donor to the accretor. Solid lines use present-day parameters found in this work (S+25), while dotted lines use the results from EB+22. The present-day locations of the systems in the P - q plane are marked with black (this work) and grey (EB+22) stars. Arrows indicate the direction of evolution as mass is transferred from the donor onto the accretor. The minimum Period is shown as a grey horizontal stripe, with colours indicating the donor mass on the main-sequence. We see that the higher mass ratio from EB+22 places a much tighter constraint on the how conservative mass transfer was, than the lower estimates found in this work. For this object in particular, the present-day mass ratio and Period from EB+22 require almost fully conservative mass transfer to avoid a merger.

In Figure 6, the solid lines reflect the possible $P(q)$ for our determination of the present day mass ratio and period, while the dashed lines reflect the $P(q)$ implied by EB+22. This illustrates the importance of the q determination, as it immediately translates into constraints on the mass transfer ‘physics’, especially β . Analogous plots for the other systems are found in Figures C.1 and C.2 in the Appendix.

The inferred range of β values is broadly consistent with the conservative mass transfer prescriptions assumed in the MESA models shown in Figure 5. Consequently, our results do not require significant adjustments to the evolutionary tracks adopted by EB+22.

Our findings therefore support the EB+22 conclusion that mass transfer in these systems must have been relatively conservative, with $\beta \lesssim 0.7$, as for larger β (i.e. more mass loss), the period would be too short at some point during the binary’s evolution. This affirms the conclusions of Bodensteiner et al. (2020), EB+22 and Lechien et al. (2025) that mass transfer has to be quite conservative, and is consistent with the MESA evolutionary paths in Figure 5.

4. Discussion

Having derived the key stellar, orbital, and flux parameters, we now discuss their implications for the current evolutionary state of these binaries and for the physics of mass transfer and angular momentum evolution. Taken together, our spectroscopic analysis showed and confirmed that all these systems have all expected signatures of post-mass-transfer binaries. Spectral disentangling revealed a cool, synchronously rotating donor and a hot, rapidly rotating accretor. The systems show no emission lines (except for object G-2933), indicating that there is no significant mass transfer at present.

More quantitatively, our analysis provided four new pieces of information on each system. These are a measure of the temperatures, T_{eff} , using the two best-fitting templates, independent from those computed by EB+22; the wavelength-dependent flux ratio of both components; their projected rotation velocities, $v \sin i$; and the kinematically determined mass ratio, q .

We illustrate the first two aspects in Figure 4. The SEDs with the parameters inferred by EB+22 are shown as dotted lines in the top sub-panels for each object, while those using parameters determined in this work are shown as solid lines. Comparing our spectroscopic constraints with the SED constraints from EB+22 shows broad consistency. For all objects, we find spectroscopic donor temperatures that are slightly higher than those in EB+22. Similarly, four of the six accretors also show higher temperatures than those found by EB+22. It must be noted, however, that the accretor temperatures lie in the regime of $T_{\text{eff}} \approx 9000$ K. Here, spectral modelling assuming local thermal equilibrium (Coelho 2014; Xiang et al. 2022), including ours, has difficulty matching the spectra, especially the very strong Balmer lines. The net effect of the smaller temperature difference among the components is a more gradual change in the component flux ratio with wavelength in our results, compared to EB+22.

Figure 4 shows that the SEDs predicted by our spectroscopic temperatures match the observed photometry almost as well as the SED fits in EB+22, after finding the best fitting stellar radii. This presumably reflects the uncertainties and covariances inherent in multiparameter photometry fits, which can be mitigated with our spectroscopic temperatures and component flux ratio estimates.

The Hertzsprung-Russell diagram in Figure 5 (top panels) illustrates the nature of the systems, as well as the similarities and differences among them. We show our results (magenta and cyan filled symbols for the donor and accretor, respectively) and compare them to those from EB+22 (red and blue empty symbols for the donor and accretor, respectively). For context, we show single-star PARSEC isochrones (Bressan et al. 2012) of various ages in the top left panel and pertinent MESA (Paxton et al. 2011, 2013, 2015, 2018, 2019; Jermyn et al. 2023) stellar evolution tracks for the donor and accretor computed by EB+22 in the top right. Analogously, we show the positions of all components in the $\log g$ - T_{eff} and $\log R$ - T_{eff} planes (bottom panels), along with the aforementioned MESA tracks.

Overall, we see qualitatively good agreement between the two works, with the exception of object G-5536. This is reassuring, as the parameters for the systems were determined via fundamentally different pathways, increasing our confidence in the congruent results. Small discrepancies in the determined effective temperatures of the stellar component may be attributed to the degeneracies in the SED fitting process employed by EB+22, which are lifted in this work using spectroscopic temperatures from disentangled spectra.

We also note that the accretors are consistent with much younger (single-star) isochrones than the donors, an expected outcome of mass transfer onto the accretor and the resulting rejuvenation. Both sets of results are also roughly consistent with the fiducial MESA tracks from EB+22, which we did not try to optimise for all the individual systems.

Note that our sample contains one system where all these analysis steps do not work as well (G-5536), starting with a poor spectral disentangling result (see Figure 1, which we attribute – at least in part – to the observations’ lower signal-to-noise ratio. This is also encapsulated in the less good fit of the model flux ratio (bottom panel, black line) to the observed spectroscopic flux ratio (red line).

We originally anticipated that our high-resolution multi-epoch spectra should enable tight constraints on the systems' mass ratio, q . But using TODCOR (Zucker & Mazeh 1994) with our best-fitting templates still faced serious difficulties, manifested, for example, as inconsistent velocity estimates when using different wavelength windows to derive them. We attribute this to several compounding factors. First, the accretors are rapidly rotating, which severely broadens their lines, and have few strong lines beyond the inherently broad Balmer series. Second, the spectra in some of our systems (especially object G-2933, showing an emission signature) are unusual. This may lead to rather imperfect template match and in turn may cause systematic problems in TODCOR. This is exacerbated by the fact that the five to ten times more massive accretor has both far smaller velocity variations, and no sharp spectral lines. As the accretor contributes more at the shortest wavelengths, we deemed the q estimates based on H γ and H δ more reliable, compared to H β . We also explored whether the Mg I and Mg II lines present in the accretor spectrum worked better, but found that this was not the case.

For most objects, our kinematic mass ratios are somewhat smaller than those in EB+22, consistent with our smaller temperature difference between the donor and accretor components. Considering Figure 3, the significant scatter in the secondary velocities and resulting large uncertainty in the mass ratio (and systemic velocity) might call this result into question relative to EB+22. Indeed, we have found the determination of the mass ratio to be very sensitive to the templates chosen for both components, with lower-temperature donor templates leading to larger implied dynamical mass ratios. Best-fit templates are determined in a specific wavelength region, which is distinct from the windows used here with TODCOR. As such, a different template might produce a better fit in the window in question, but we found it more important to use the same template consistently for all wavelength windows.

Despite some issues with the template match and the difficulties due to broad accretor lines, we point out that this work represents a much more direct measurement of the mass ratio, which has the distinct advantage of not requiring assumptions about the Roche Lobe filling factor or orbital inclination of the system, as in EB+22. Future work using spectral templates that incorporate a scheme that does not assume local thermal equilibrium may lead to more accurate and reliable results, especially considering the effective temperatures of the accretors.

The determination of the mass ratio has a large knock-on effect on the constraints on how conservative mass transfer was (the β parameter in the Soberman et al. (1997) equations). In Figure 6, we see that the updated mass ratio in this work relative to EB+22 leads to different constraints on the maximum fraction of mass lost by the accretor. Generally, the lower mass ratios found in this work lead to more relaxed constraints. As these constraints represent upper limits on the mass loss, our results are consistent with the tighter limits found by using parameters from EB+22. In a few cases (G-5694, G-5536), parameters from EB+22 imply mass transfer histories that are inconsistent with anything but almost fully conservative mass transfer ($\beta \lesssim 0.2$), and for G-6004, the modern period and mass ratio determined by EB+22 are inconsistent with the assumption of a system which was detached in the past, even with fully conservative mass transfer (see Figures C.1 and C.2 in the appendix).

For object G-5536, the mass ratio found here is close to one (depending on the wavelength range used). However, as can be seen in the top right panel of Figure 3, the quality of the individual straight-line fits (which give mass ratio, q and systemic

velocity, v_{COM} , see bottom right panel of Figure 3), is not very good. This can be explained by reconsidering the disentangled spectra (Figure 1): the disentangled components for object G-5536 are noisy, making selecting the correct template difficult. This is partially due to the fact that object G-5536 is fainter than the rest of the sample, but was observed for a similar amount of total time, leading to a lower S/N overall. Additionally, object G-5536 is likely further evolved, since the independent template fits suggest a higher effective temperature for the donor than found in EB+22. The puffed-up stripped star has likely started contracting and heating up again. This can also be seen in Figure 5: Specifically, we note that the G-5536 components lie further along their respective MESA evolution tracks in all three panels that include them.

This further evolution of object G-5536 results in more similar temperatures of the donor and accretor, and thus a more similar spectral signature. Especially in the Balmer series, the higher donor temperature leads to wider and deeper lines, more similar to those of the accretor. This causes difficulties in the disentangling and subsequent TODCOR analysis.

Stellar rotation As a final point of discussion, we now turn to the level of rotation in the accretors that we determined from our disentangled spectra. These provide additional insights into the angular momentum evolution during and after mass transfer.

We see projected rotational velocities between 150 ~ 200 km/s (see Table 1), a novel measurement not performed by EB+22. While this is clearly rapid rotation, as expected for an accretor, these velocities are well below the critical velocities that are expected to be $\gtrsim 350$ km/s (from $v_{\text{crit}} = \frac{G \cdot M_*}{R_*}$) for these systems, assuming masses and radii from EB+22. Following Packet (1981), Ghodla et al. (2023) and Henneco et al. (2024), we expect a star to have to accrete only about two to ten per cent of its initial mass to spin up to critical rotation. As our analysis suggests the accretors approximately doubled their mass through mass transfer, they should have easily achieved critical rotation.

This discrepancy between expected and observed rotational velocities is unlikely due to mere projection effects; EB+22 found the inclinations of the systems to lie mostly around 65°, which would reduce the velocities only by about ten per cent. Significantly larger inclinations are ruled out as they would produce eclipses, while significantly smaller inclinations are inconsistent with observed accretor parameters. Part of this disagreement may stem from equatorial gravity darkening: due to the reduced gravity at the equator and the Von Zeipel effect (von Zeipel 1924), there is less flux coming from the equator, and the star appears to rotate less rapidly (Townsend et al. 2004). However, as the observed discrepancy between observed and expected rotational velocity is large (of order factor two), it is likely that some mechanism has slowed the accretor's rotation. Mass transfer likely ended only recently, as the donors are still in the short-lived 'puffed-up' stage (see also Bodensteiner et al. 2020; Villaseñor et al. 2023). This implies that the spin-down mechanism must have been fairly efficient. Tides are likely in effect, as demonstrated by the donor rotating at tidally synchronous velocities and suggested by the short periods. However, tidal synchronisation following Zahn (2008) is significantly less efficient than required to reproduce the observed rotational velocities. Assuming parameters of a star representative of the accretors in our sample, we expect the tidal synchronisation timescale, $t_{\text{sync}} \approx 10^{10}$ years. As we know, mass transfer only ceased recently (evidenced by the donors still being in the short-lived bloated stage) it is unlikely that tidal forces alone were suffi-

cient to slow down the rotation of the accretor. Further, the accretors are too hot for magnetic braking (Kraft 1967). If star-accretion disk interactions, such as described by Popham & Narayan (1991) and Paczynski (1991), are in effect, it is possible that these are, or were, slowing down the accretor. The mechanism allows for outward angular momentum transport at the same time as inward mass flow onto the star. These interactions may pose an alternative spin-up mechanism, as the conventional picture suggesting spin up to critical and then cessation of accretion leads to relatively low mass transfer efficiencies (e.g. Henneco et al. 2024).

5. Conclusions

In this work we have obtained and analysed multi-epoch spectra of six targets, identified by EB+22 as likely post-mass-transfer binaries with a puffed-up donor and hot, rapidly rotating accretor. Our data and analysis yield component temperatures and sizes, and mass ratios for all systems, confirming this initial assessment. Only for one of the systems (G-2933) we found clear $H\beta$ emission, suggesting that mass transfer is still ongoing.

To better understand the physical state of the components of each system, we used the spectral disentangling approach by Seeburger et al. (2024) to determine the effective temperatures and rotational velocities from the spectral features of each component. We found slightly higher temperatures (see Table 1) for the donors than EB+22 determined from SED fits. SED fits with the spectroscopic temperatures are still consistent with the observed photometry.

We determined the dynamical mass ratios (Table 1) of the targets using TODCOR (Zucker & Mazeh 1994), finding somewhat lower mass ratios than EB+22. This is consistent with our finding of warmer donors, as warmer donors are likely more massive, reducing q . Combining the current orbital periods and mass ratios, we assessed the mass transfer history, following Soberman et al. (1997), and found that the mass transfer had to have been fairly conservative ($\beta \lesssim 0.7$) to produce the observed systems.

Finally, we determined that all accretors are rotating rapidly, but – importantly – considerably more slowly than the critical rotation velocity. This implies some mechanism must have slowed down rotation efficiently after mass transfer halted. Magnetic braking is unlikely to have been effective to slow down rotation, given that the $T_{\text{eff}} \sim 9,000$ K of the accretors is well above the ‘Kraft-break’ (Kraft 1967). Given that we know the radii, masses and the orbit of the stars, the tidal spin-down prescriptions developed by Zahn (2008) imply slow-down timescales far in excess of the system ages.

One target (G-5536) was consistently difficult to analyse, due to comparatively lower signal-to-noise data and higher similarity of the donor and accretor spectra and subsequently more degeneracies in the disentangling. For this target, additional epochs at higher signal-to-noise ratios might help shed more light on its nature.

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(Perez & Granger 2007), `SciPy` (Virtanen et al. 2020), `AstroPy` (The Astropy Collaboration et al. 2013, 2018, 2022) `SpectRes` (Carnall 2017) and `SpectResC` (Lam 2024)

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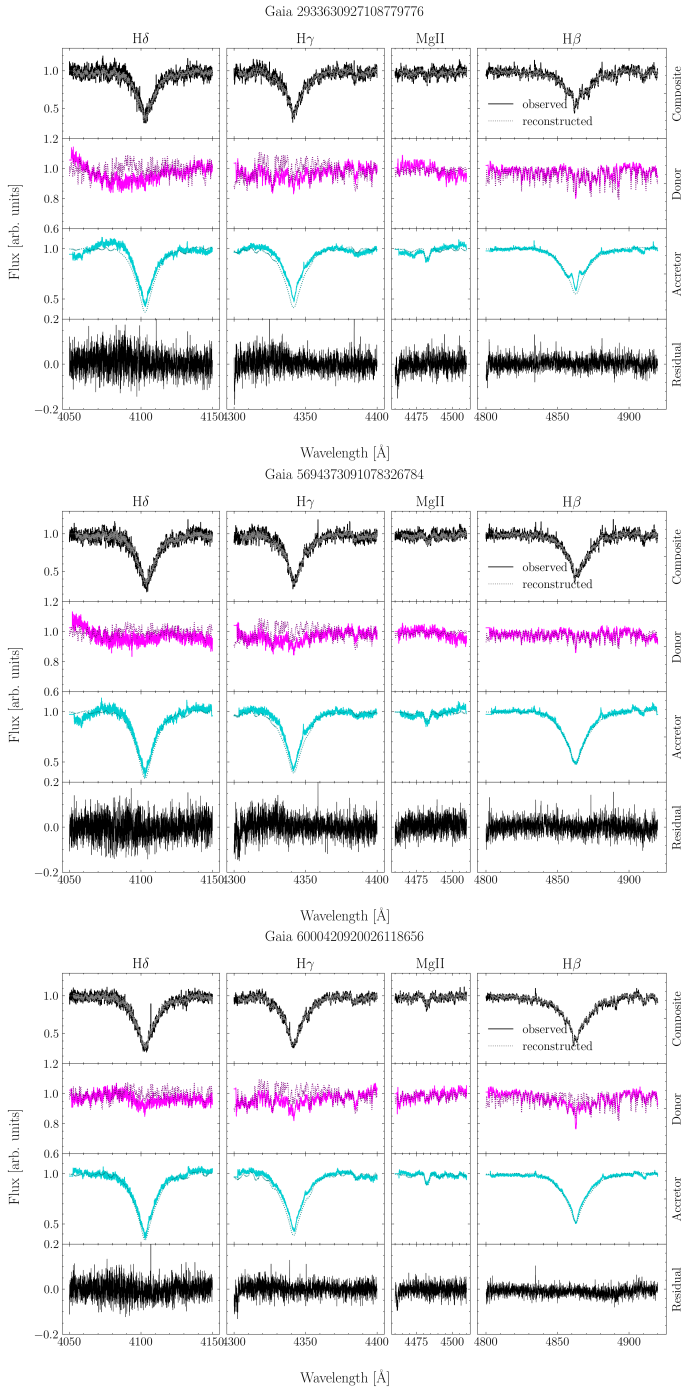


Fig. A.1. Disentangled spectra in different wavelength regions for three of the targets considered in this work, analogous to Figure 2. This demonstrates that one target, G-2933, does indeed show wings on either side of the $H\beta$ line, indicative of $H\beta$ emission and suggesting ongoing mass transfer.

Appendix A: Disentangled spectra

Figures A.1 and A.2 show the disentangled spectra for the remaining targets not displayed in the main text. Each panel illustrates the observed composite spectrum, the separated donor and accretor spectra in their rest frames, the best-fitting template spectra, and the residuals. These figures complement Figures 1 and 2, confirming that all six systems are double-lined spectroscopic binaries with two luminous components and demonstrat-

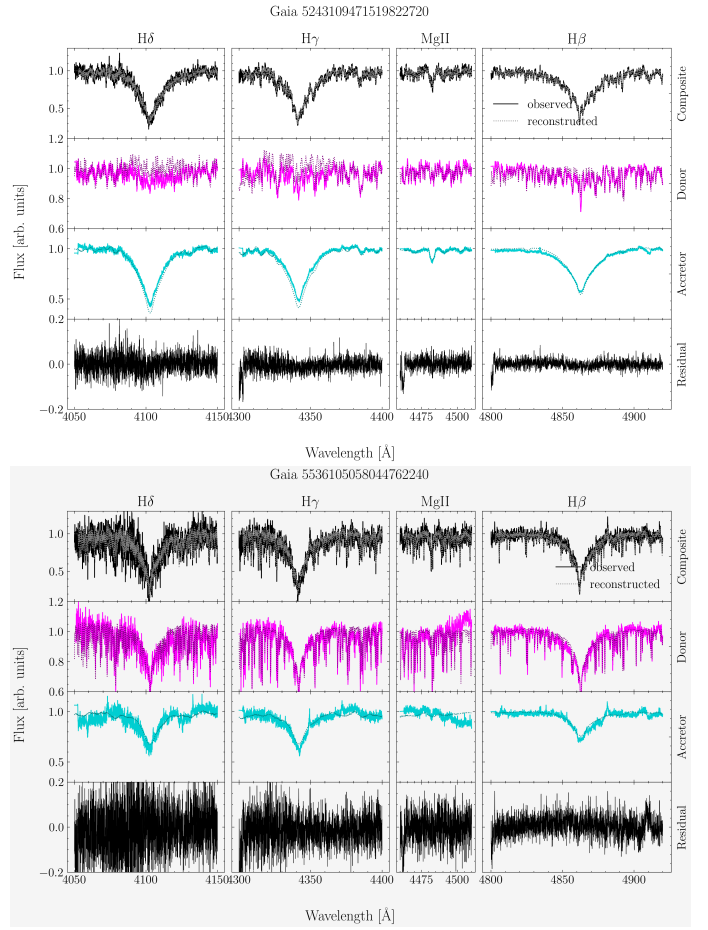


Fig. A.2. Disentangled spectra in different wavelength regions for two of the targets considered in this work, analogous to Figure 2. The background for the panel showing target G-5536 is shown in grey to highlight the difficulties with its analysis.

ing the quality of the disentangling across several wavelength regions.

Appendix B: Additional TODCOR results

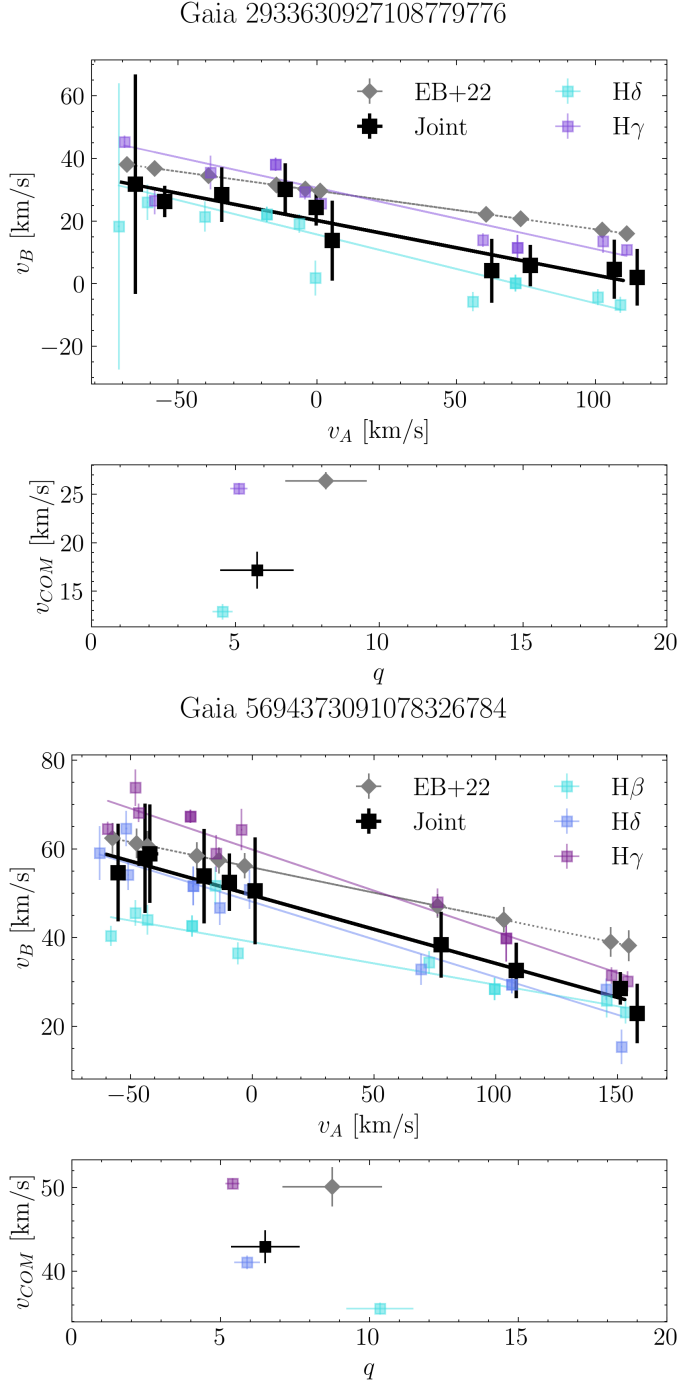


Fig. B.1. Results of the TODCOR (Zucker & Mazeh 1994) algorithm applied to two of the targets considered in this work, analogous to Figure 3

This appendix presents the results of the TODCOR analysis described in Section 3.3 for the remaining targets not shown in the main text. For each binary, Figures B.1 and B.2 show the velocity-velocity diagrams of the donor and accretor components across multiple epochs and wavelength windows, together with the best-fitting linear relations used to determine the mass ratio and systemic velocity. The lower panels display the corresponding distributions of derived mass ratios, q ; and centre-of-mass velocities, v_{COM} ; from individual wavelength intervals, compared to fiducial results from Gaia and EB+22. These plots

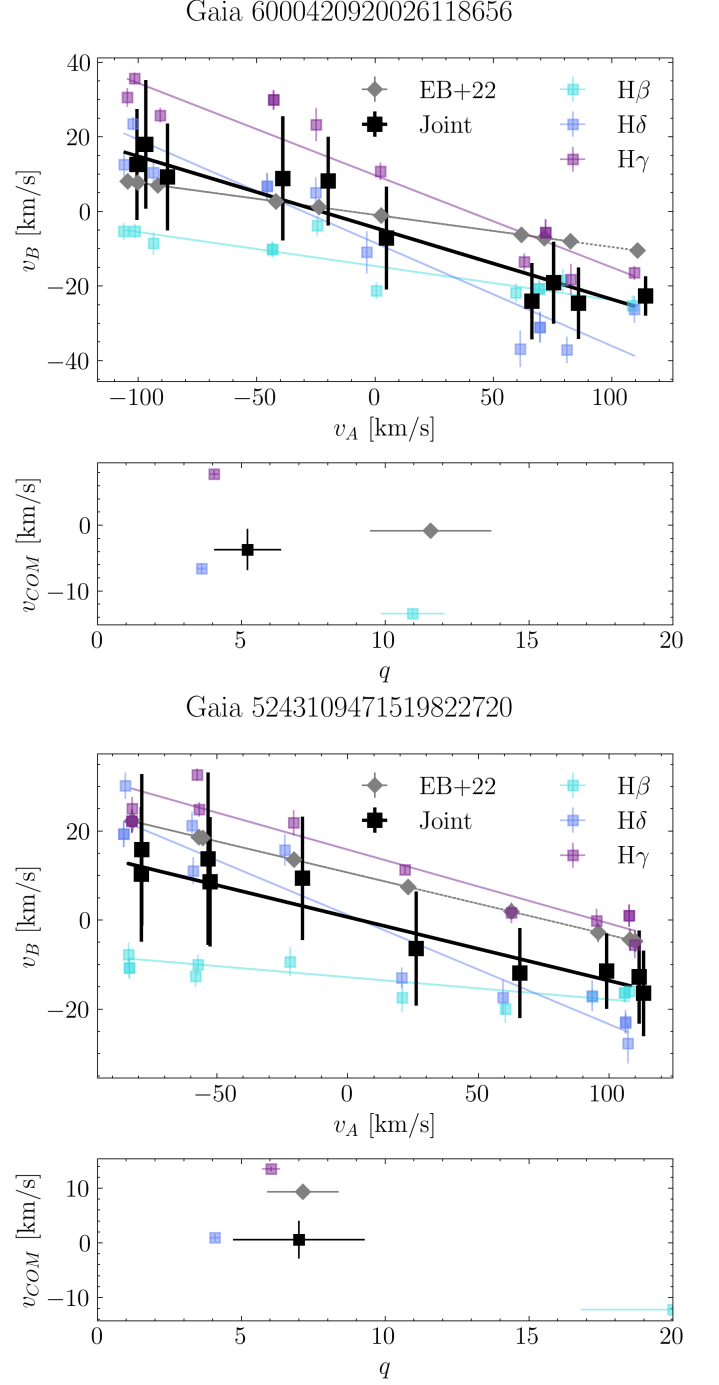


Fig. B.2. Results of the TODCOR (Zucker & Mazeh 1994) algorithm applied to two of the targets considered in this work, analogous to Figure 3

illustrate both the consistency and scatter of the TODCOR solutions.

Appendix C: Mass transfer histories

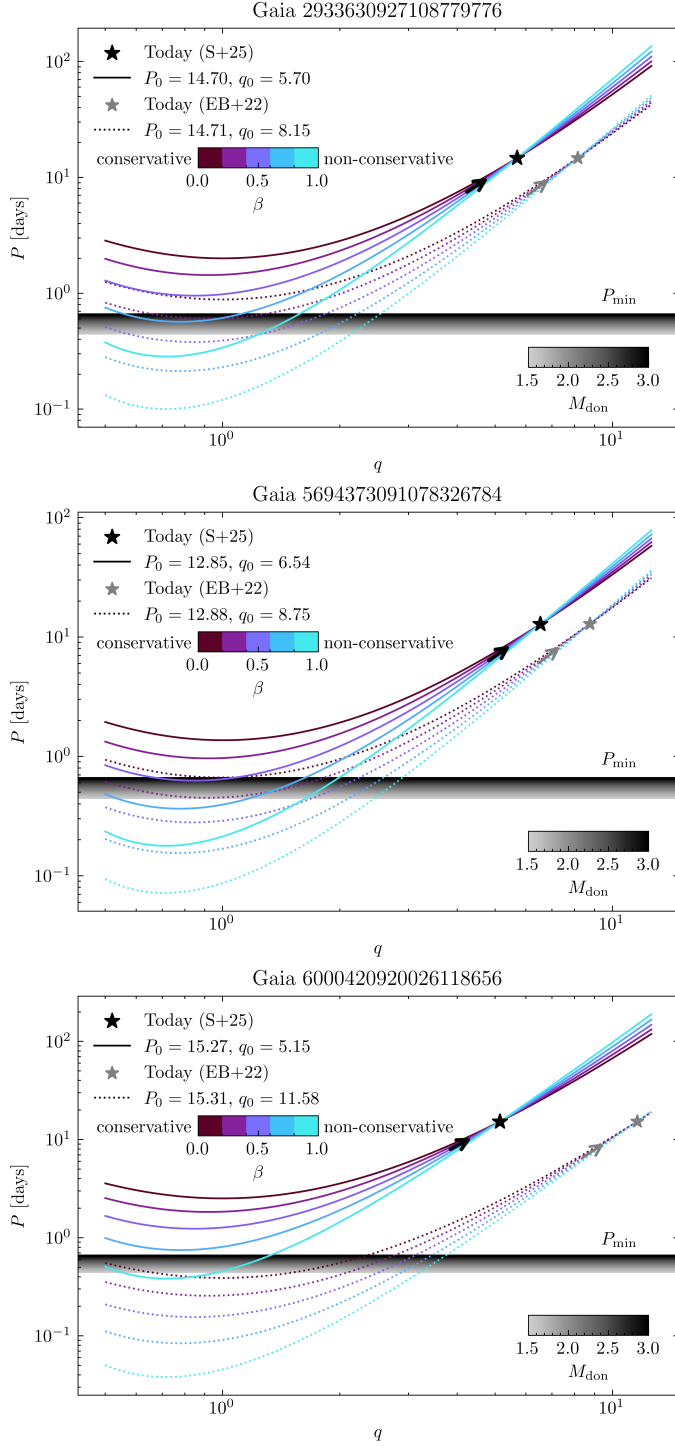


Fig. C.1. Evolution of $P(q)$, subject to the value of β , for three of the targets, analogous to Figure 6.

Figures C.1 and C.2 display the period-mass ratio ($P(q)$) evolution for each binary not shown in the main text, computed using the formalism of Soberman et al. (1997). For each system, we plot the orbital period as a function of mass ratio for different assumptions of the mass-loss parameter β , assuming $\alpha = \delta = 0$ (isotropic re-emission). The grey region marks the minimum orbital period at which the donor would fill its Roche lobe on the main sequence, depending on the assumptions of the

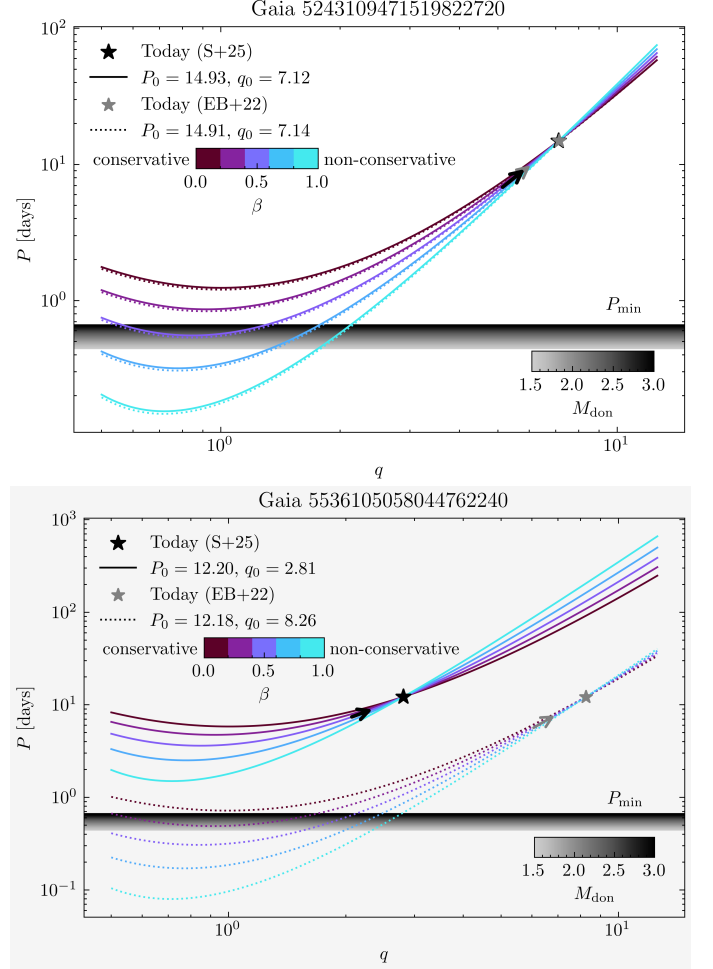


Fig. C.2. Evolution of $P(q)$, subject to the value of β , for two of the targets, analogous to Figure 6. The panel for target G-5536 has a light grey background to highlight the difficulties with its analysis.

initial donor mass. In our systems, the observed parameters are consistent with relatively conservative mass transfer ($\beta \lesssim 0.7$), in agreement with the conclusions drawn from Section 3.7.

Appendix D: Observation overview

Table D.1 summarises the FEROS observations obtained at the MPG/ESO 2.2 m telescope. For each target and epoch, we list the observing date (MJD), exposure time, and average signal-to-noise ratio per pixel over the observed range, as well as RVs determined by the *ceres* pipeline. The cadence of typically one to two nights ensured full orbital-phase coverage for systems with periods of approximately ten to twenty days, providing sufficient phase sampling for reliable RV determination and spectral disentangling.

Table D.1. Observational details for the spectra used in this work.

Target	MJD	SNR	Exp Time [s]	ceres RV [km/s]	Target	MJD	SNR	Exp Time [s]	ceres RV [km/s]
G-2933	60333.1173	103	1200	-14.70	G-6000	60346.3350	83	1800	-23.63
G-2933	60335.1193	89	1200	60.77	G-6000	60348.3673	96	1800	61.90
G-2933	60337.1396	103	1200	111.29	G-5243	60333.2109	127	1200	107.99
G-2933	60339.1458	100	1200	102.51	G-5243	60335.2253	136	1200	95.94
G-2933	60340.2156	102	1200	73.13	G-5243	60337.2772	112	1200	23.12
G-2933	60340.2156	102	1200	73.13	G-5243	60339.2632	126	1200	-56.96
G-2933	60342.1963	100	1200	-4.27	G-5243	60340.2855	135	1200	-82.51
G-2933	60343.2107	83	1200	-39.12	G-5243	60340.2855	135	1200	-82.51
G-2933	60345.1923	83	2000	-68.34	G-5243	60342.2528	146	1200	-82.41
G-2933	60346.2437	65	1200	-58.39	G-5243	60343.3313	111	1200	-55.51
G-2933	60348.2717	97	1800	1.08	G-5243	60344.2825	111	1800	-20.56
G-5694	60333.1980	67	1200	-22.72	G-5243	60346.3153	99	1200	62.68
G-5694	60335.2101	73	1200	76.11	G-5243	60348.3431	105	1800	110.10
G-5694	60337.2528	76	1200	154.57	G-2966	60333.0756	102	1200	147.27
G-5694	60339.1288	71	1200	147.19	G-2966	60335.0842	85	1200	154.11
G-5694	60340.2551	76	1200	103.21	G-2966	60337.0896	96	1200	37.28
G-5694	60340.2551	76	1200	103.21	G-2966	60339.0920	99	1200	-49.52
G-5694	60342.2734	73	1200	-3.20	G-2966	60340.1468	115	1200	-38.02
G-5694	60343.3177	64	1200	-42.97	G-2966	60340.1468	115	1200	-38.02
G-5694	60344.2647	61	1200	-57.35	G-2966	60342.1784	100	1200	74.68
G-5694	60345.2591	73	2200	-47.54	G-2966	60345.1183	112	2000	164.18
G-5694	60346.2986	55	1800	-13.72	G-5536	60333.1322	61	1200	25.33
G-5694	60348.3221	52	1800	86.65	G-5536	60335.1721	65	1200	99.42
G-6000	60333.3195	123	1200	71.51	G-5536	60337.1216	56	1200	82.56
G-6000	60335.3090	96	1300	110.85	G-5536	60339.1087	62	1200	-6.74
G-6000	60337.3417	77	1500	82.47	G-5536	60340.2340	80	1800	-57.97
G-6000	60339.3156	91	1200	2.62	G-5536	60340.2340	80	1800	-57.97
G-6000	60340.3175	112	1200	-41.79	G-5536	60342.2330	82	1800	-89.79
G-6000	60340.3175	112	1200	-41.79	G-5536	60343.2784	68	1800	-67.48
G-6000	60342.3582	136	1200	-100.28	G-5536	60346.2630	41	1800	68.21
G-6000	60343.3470	108	1200	-104.52	G-5536	60348.2958	45	1800	103.22
G-6000	60344.3429	74	2000	-91.75					

Appendix E: Stellar and system parameters

Table E.1 compiles the stellar parameters derived from the disentangled spectra and template fitting described in Section 3.2, as well as the radii and distance determined using SED fits as outlined in Section 3.5. For each system, we report the stellar masses (M , taken from EB+22), radii (R), effective temperature (T_{eff}), for both the donor and accretor, as well as the distance from the system.

Table E.2 shows the corresponding values as determined by EB+22 and is included for easy comparison of the two works, showing broad consistency of the results.

Table E.3 compiles the orbital and stellar parameters derived in this work. For each system, we provide the velocity semi-amplitude of the primary, K_1 ; orbital period, P ; mean anomaly, M_0 ; eccentricity, e ; argument of pericentre, ω ; and systemic velocity, v_{COM} ; obtained from the nested-sampling orbital fits described in Section 3.6. These periods combined with the mass ratios obtained using TODCOR in Section 3.3 form the quantitative basis for the discussion of the system's mass transfer history presented in Section 3.7 and 4.

Table E.1. Stellar parameters for each system from this work

Short ID	M_{don}^a [$M_{\odot}$]	M_{acc}^a [$M_{\odot}$]	R_{don} [$R_{\odot}$]	R_{acc} [$R_{\odot}$]	$T_{\text{eff,don}}$ [kK]	$T_{\text{eff,acc}}$ [kK]	d [kpc]
G-2933	0.27 ± 0.04	2.2 ± 0.2	6.02 ± 0.14	2.39 ± 0.05	4.75 ± 0.25	9.50 ± 0.25	1.09 ± 0.06
G-5694	0.24 ± 0.04	2.1 ± 0.2	4.69 ± 0.07	2.58 ± 0.02	4.75 ± 0.25	9.25 ± 0.25	1.65 ± 0.11
G-6000	0.19 ± 0.03	2.2 ± 0.2	5.64 ± 0.04	2.71 ± 0.03	4.75 ± 0.25	9.00 ± 0.25	0.92 ± 0.07
G-5243	0.28 ± 0.04	2.0 ± 0.2	5.46 ± 0.13	2.18 ± 0.01	4.75 ± 0.25	8.75 ± 0.25	0.73 ± 0.04
G-2966	0.23 ± 0.03	2.0 ± 0.1	3.90 ± 0.02	2.22 ± 0.01	5.50 ± 0.25	9.00 ± 0.25	1.16 ± 0.04
G-5536	0.23 ± 0.04	1.9 ± 0.2	4.21 ± 0.02	3.53 ± 0.02	6.75 ± 0.25	7.25 ± 0.25	1.72 ± 0.04

Notes. ^(a) Stellar masses from EB+22.**Table E.2.** Stellar parameters for each system from EB+22.

Short ID	M_{don} [$M_{\odot}$]	M_{acc} [$M_{\odot}$]	R_{don} [$R_{\odot}$]	R_{acc} [$R_{\odot}$]	$T_{\text{eff,don}}$ [kK]	$T_{\text{eff,acc}}$ [kK]	d [kpc]
G-2933	0.27 ± 0.04	2.2 ± 0.2	7.2 ± 0.2	2.3 ± 0.2	4.4 ± 0.2	9.7 ± 0.3	1.09 ± 0.02
G-5694	0.24 ± 0.04	2.1 ± 0.2	5.5 ± 0.2	1.9 ± 0.2	4.6 ± 0.2	9.9 ± 0.3	1.70 ± 0.06
G-6000	0.19 ± 0.03	2.2 ± 0.2	6.2 ± 0.2	2.5 ± 0.2	4.5 ± 0.2	9.5 ± 0.3	0.92 ± 0.03
G-5243	0.28 ± 0.04	2.0 ± 0.2	6.6 ± 0.2	1.9 ± 0.2	4.6 ± 0.2	9.4 ± 0.3	0.73 ± 0.01
G-2966	0.23 ± 0.03	2.0 ± 0.1	4.7 ± 0.1	2.1 ± 0.1	4.7 ± 0.1	9.4 ± 0.2	1.16 ± 0.03
G-5536	0.23 ± 0.04	1.9 ± 0.2	5.0 ± 0.2	2.5 ± 0.2	4.9 ± 0.2	8.4 ± 0.3	1.77 ± 0.05

Table E.3. System and orbital parameters for each system as determined in this work.

Short ID	Gaia G mag ^a [mag]	Gaia parallax ^a [mas]	P_{orb}^b [days]	K1 [km/s]	P_{orb} [days]	M_0 [rad]	e	ω [rad]	v_{COM} [km/s]
G-2933	11.07	0.92	14.71	92.1	14.70	2.75	0.01	1.76	23.9
G-5694	11.91	0.59	12.88	109.6	12.85	2.54	0.02	2.39	52.6
G-6000	10.73	1.08	15.31	107.6	15.27	3.27	0.01	3.25	3.7
G-5243	10.45	1.37	14.91	101.4	14.93	3.77	0.01	2.34	10.0
G-2966	11.20	0.86	10.40	110.4	10.43	3.64	0.02	2.09	59.5
G-5536	12.15	0.57	12.18	97.9	12.20	3.00	0.02	3.28	6.7

Notes. ^(a) G-band magnitudes and Gaia DR3 parallaxes from Gaia Collaboration et al. (2023). ^(b) Comparative orbital periods from EB+22.