

# Resolving the kinematics of the discs around Galactic B[e] supergiants

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Accepted 2018 June 27. Received 2018 June 26; in original form 2018 April 7

## ABSTRACT

B[e] supergiants are luminous evolved massive stars. The mass-loss during this phase creates a complex circumstellar environment with atomic, molecular, and dusty regions usually found in rings or disc-like structures. For a better comprehension of the mechanisms behind the formation of these rings, detailed knowledge about their structure and dynamics is essential. To address that, we obtained high-resolution optical and near-infrared (near-IR) spectra for eight selected Galactic B[e] supergiants, for which CO emission has been detected. Assuming Keplerian rotation for the disc, we combine the kinematics obtained from the CO bands in the near-IR with those obtained by fitting the forbidden emission [O I]  $\lambda$ 5577, [O I]  $\lambda\lambda$ 6300,6363, and [Ca II]  $\lambda\lambda$ 7291,7323 lines in the optical to probe the disc structure. We find that the emission originates from multiple ring structures around all B[e] supergiants, with each one of them displaying a unique combination of rings regardless of whether the object is part of a binary system. The confirmed binaries display spectroscopic variations of their line intensities and profiles as well as photometric variability, whereas the ring structures around the single stars are stable.

**Key words:** circumstellar matter – stars: early-type – stars: massive – supergiants – stars: winds, outflows.

## 1 INTRODUCTION

Massive stars have an exceptionally important impact on their stellar environment and their host galaxies. They lose mass from the start of their lives via strong stellar winds. As stars evolve off the main sequence, they pass through several phases of intense or even episodic mass-loss before they explode as supernovae. Particularly, one such phase is composed by the B[e] supergiants (B[e]SGs, for a review see Kraus 2017).

B[e]SGs are luminous ( $\log L_*/L_\odot \gtrsim 4$ ) B-type stars that do not exhibit significant variability (Lamers et al. 1998). They display complex circumstellar environments (CSEs). The presence of strong stellar winds is indicated by the P Cygni profiles in their Balmer lines. Moreover, their optical spectra are composed by narrow, low-excitation permitted and forbidden emission lines from singly ion-

ized and neutral metals, while their ultraviolet spectra exhibit broad absorption features of higher excitation levels of highly ionized metals. Additionally, they show a strong infrared (IR) excess due to hot circumstellar dust.

The presence of such a complex CSE has been puzzling. Zickgraf et al. (1985) proposed a model consisting of a two-component wind: a low-density, fast, line-driven polar wind, where the emission of high-excitation lines originates; and a high-density, slow, equatorial outflowing disc, in which the line emission of permitted and forbidden low-excitation lines originate, and in which dust is formed further away. Indications for the presence of such dusty discs come from a variety of observational properties, such as the intrinsic polarization and the CO emission in IR spectra (see Kraus 2017 for more details). The best proof has been provided by interferometry, which actually resolved these discs (de Wit, Oudmaijer & Vink 2014, for a review). Contemporaneously, it confirmed the earlier findings by Liermann et al. (2010) that the discs are actually detached from the central star (Domiciano de Souza et al. 2011; Millour et al. 2011; Wheelwright et al. 2012a), and that the discs move

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in Keplerian rotation rather than following the outflowing scenario (e.g. Marchiano et al. 2012; Wheelwright et al. 2012b). Further support comes from high-resolution IR spectroscopy, where CO (e.g. Cidale et al. 2012; Wheelwright et al. 2012b) and SiO (Kraus et al. 2015) emission features have been detected. As CO and SiO form under different physical conditions (temperature and density), the information derived by modelling their features can help us probe the structure of the molecular disc. This method has been extended to optical spectra by modelling forbidden emission lines (e.g. Aret et al. 2012), which has unveiled multiple rings around B[e]SGs (Maravelias et al. 2017), which are not necessary homogeneous (Kraus et al. 2016; Torres et al. 2018).

Even though observations have helped us acquire a more detailed understanding of the B[e]SGs, we still lack a proper description of how their CSE (and consequently the B[e]SGs) form. During the years, a number of models have been proposed that each can explain some of their observed properties. An approach is to create an asymmetric stellar wind in single stars using fast rotation (e.g. Maeder & Desjacques 2001; Kraus 2006), the bi-stability mechanism (e.g. Pelupessy, Lamers & Vink 2000; Petrov, Vink & Gräfener 2016), slow-wind solutions (e.g. Curé 2004; Curé, Rial & Cidale 2005), or the magneto-rotational instability mechanism (e.g. Krtićka, Kurfürst & Krtićková 2015; Kurfürst, Feldmeier & Krtićka 2014). Alternative scenarios with single stars include mass-loss events triggered by non-radial pulsations and/or other instabilities, or the presence of objects (e.g. minor bodies or planets) that clear their paths creating single/multiple stable ring structures (Kraus et al. 2016). A different forming channel is through binaries, either from mass transfer (e.g. Miroshnichenko 2007; Millour et al. 2011; Wheelwright et al. 2012b) or even from mergers (e.g. Podsiadlowski, Morris & Ivanova 2006). Support for the importance of a companion comes from the high fraction of binaries among the OB populations ( $\geq 50$ –70 per cent; Sana et al. 2012, 2013; Dunstall et al. 2015), as well as a significant estimate for the fraction of mergers ( $\sim 8$  per cent; de Mink et al. 2014). Despite that, the number of confirmed binaries among the B[e]SG population is fairly low (6 out of 31 objects; Kraus 2017).

To better understand the B[e]SGs, we need to study in detail their CSEs and how these are formed. To address that, we have initiated a campaign to study the CSEs for a large number of Galactic and Magellanic Cloud B[e]SGs, using high-resolution optical and IR spectroscopy. This work is focusing on a sub-sample of eight selected Galactic B[e]SGs that display CO emission features. For all of these, we have obtained/collected optical spectra and derived their kinematical information from forbidden line modelling.

The paper is structured as follows: In Section 2, we present our sample, the observed and archival spectra obtained, and the data processing we followed. In Section 3, we describe the model we used, and in Section 4 we present our results. We discuss our results in Section 5, and our conclusions are given in Section 6.

## 2 OBSERVATIONS AND DATA PROCESSING

### 2.1 Sample

Our sample consists of eight Galactic B[e]SG sources (out of a total population of 16 Galactic examples; Kraus 2017) that show CO emission features. For these, we have compiled a large collection of high-resolution optical and near-IR spectra, acquired with the same instrument (per band) at different epochs. This enables us to build the most homogeneous data set for these sources at this resolution.

In Table 1, we give some basic properties for our sample: columns 1 and 2 refer to the most usable identifiers, columns 3 and 4 correspond to their coordinates, columns 5–8 provide indicative photometric magnitudes in the optical (*V*) and near-IR (*J*, *H*, *K*), respectively. Column 9 refers to the binarity status of each source, while further details (e.g. eccentricity, orbital period) for each binary are provided in the sections that follow.

### 2.2 Optical data

We used the Fiber-fed Extended Range Optical Spectrograph (FEROS, Kaufer et al. 1999), a bench-mounted echelle spectrograph. FEROS provides high-resolution spectra ( $R \sim 48\,000$ ) with a wide spectral coverage ( $\sim 3600$ – $9200$  Å). The spectrograph was attached to the 1.52-m ESO telescope for observations performed in 1999–2002, and to the 2.2-m MPG telescope later on (both telescopes located at the European Southern Observatory in La Silla, Chile). The targets have been observed systematically during the 2014–2016 period, and they are supplemented with data taken scarcely since 1999, through various programs of our team and the archive.<sup>1</sup> The spectrograph is fed with light from two individual fibers with a 2-arcsec field of view each. We used the Object-Sky (OBJSKY) mode that permits simultaneous acquisition of object and sky spectra. An observing log of the optical observations can be found in Table 2. For each source (column 1), we provide the date of the observation (column 2), the number of exposures and the exposure time (column 3), and the signal-to-noise (S/N) ratio (column 4) as derived from a region around  $7100$  Å in the optical and around  $2.293$   $\mu\text{m}$  in the near-IR spectra. We also give the instrument used (column 5) along with the resolution (column 6) and the wavelength coverage (column 7).

For our work, we used the FEROS pipeline products, which we further processed (using the PYRAF command language). We first remove the barycentric correction applied to the data by the FEROS pipeline, and we combine spectra to obtain higher S/N ratio. To remove the telluric lines, we employ the standard IRAF/TELLURIC task using standard star data, either from observations taken at the same night or using templates whenever standard stars observations were not available (mainly from 1999 and 2000). We subtract the sky from the object spectrum whenever the [OI] sky lines contaminate the emission features of interest – not possible in all cases due to the lack of sky spectra (in those, the lines have been manually removed). After the telluric and sky removal, we correct back all final spectra for the barycentric velocity and their corresponding systematic radial velocities. Since these are unknown, we opted for correcting with the values that center the [OI]  $\lambda 6300$  line. As a last step, we select the spectral lines we are interested in and we normalize their intensity with local continuum (which is calculated at their central wavelength through a linear fit of continuum regions located at the red and blue parts with respect to the lines; Maravelias 2014).

### 2.3 Infrared data

For the IR observations, we have used the CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES; Kaeuffl et al. 2004), equipped on a 8.2-m telescope of ESO-VLT (Paranal, Chile).

<sup>1</sup>The ESO Science Archive Facility, which includes Phase 3 (fully reduced) data for FEROS, found at [http://archive.eso.org/wdb/wdb/adp/phase3.spectral/form?collection\\_name=FEROS](http://archive.eso.org/wdb/wdb/adp/phase3.spectral/form?collection_name=FEROS)

**Table 1.** Sample of stars.

Star (1)	Other common identifiers (2)	RA (J2000) (hh mm ss.s) (3)	Dec. (J2000) (dd mm ss.s) (4)	<i>V</i> (mag) (5)	<i>J</i> (mag) (6)	<i>H</i> (mag) (7)	<i>K</i> (mag) (8)	Binarity status (9)
CPD-52 9243	Hen 3-1138	16 07 02.0	−53 03 45.8	10.25	6.31	5.39	4.44	–
CPD-57 2874	Hen 3-394, WRAY 15-535	10 15 22.0	−57 51 42.7	10.20	5.76	4.96	4.28	–
HD 327083	Hen 3-1359	17 15 15.4	−40 20 06.7	9.67	5.64	4.57	3.69	Yes <sup>1</sup>
HD 62623	3 Puppis, 1 Puppis	07 43 48.5	−28 57 17.4	3.93	3.40	3.07	2.34	Yes <sup>2</sup>
GG Car	HD 94878, CPD-59 2855	10 55 58.9	−60 23 33.4	8.70	6.76	5.94	4.97	Yes <sup>3</sup>
MWC 137	V1380 Ori	06 18 45.5	+15 16 52.3	11.95	8.76	7.84	6.62	–
HD 87643	Hen 3-365, MWC 198	10 04 30.3	−58 39 52.1	9.50	6.22	4.76	3.65	Yes <sup>4</sup>
Hen 3-298	WRAY 15-406	09 36 44.4	−53 28 00.0	11.4	7.85	6.84	5.70	–

*Note.* All data retrieved from Simbad (accessed on March 13, 2017), except for HD 327083 obtained from Miroshnichenko et al. (2003) and the IR data for Hen 3-298 obtained from Cutri et al. (2003). References: <sup>1</sup> – Wheelwright et al. (2012a), <sup>2</sup> – Millour et al. (2011), <sup>3</sup> – Marchiano et al. (2012), <sup>4</sup> – Millour et al. (2009)

This instrument can obtain high-resolution ( $R \sim 50\,000$ ) spectra with a range of  $2.277\text{--}2.325\ \mu\text{m}$  in the *K* band. In order to remove the sky and detector glow, we performed observations with a standard nodding on-slit strategy. Each science target was followed by the observation of a standard star to correct for telluric lines. The ESO/CRIRES pipeline (v2.3.4) was used to reduce the data, and the final spectra were corrected for heliocentric velocity. Due to quality issues, we use only the part of the spectrum around the first CO bandhead. This allows us to derive concrete results regarding the kinematics for the CO region, but not about the temperature and the column density (at least two bandheads are needed; Kraus 2009).

For HD 62623, we present an additional spectrum using the Gemini Near-Infrared Spectrograph (GNIRS) mounted on the 8.1-m Gemini North telescope (Mauna Kea, Hawaii-US). The observations were performed in long-slit (single-order) mode ( $R \sim 18\,000$ ), using the  $1101\text{mm}^{-1}$  grating and the  $0.10\text{-arcsec}$  slit, centered at  $2.318\ \mu\text{m}$ . Observations were taken with an ABBA nod pattern along the slit in order to remove sky emission. All the steps of the reduction process were made using IRAF software package tasks. Reduction steps include AB pairs subtraction, flat-field correction, telluric correction, and wavelength calibration. Each science target was followed by the observation of a standard (B-type) star to correct for telluric lines. After applying the corrections for heliocentric and systemic velocities, the continuum was used to normalize the data, and, finally, it was subtracted to obtain a pure emission spectrum. The observing log for the IR spectra is included in Table 2.

### 3 MODELLING

The various emission features (in the optical and the near-IR) form in regions of different physical conditions (e.g. temperature and density). In the Keplerian rotation scenario, each region will display a different rotational velocity according to its position within the disc. The optical [O I]  $\lambda 5577$ , [O I]  $\lambda\lambda 6300, 6363$ , and [Ca II]  $\lambda\lambda 7291, 7323$  emission lines would form closer to the star than the molecular emission. Moreover, in a standard disc scenario in which density and temperature decrease with distance from the central star, the [Ca II] and the [O I]  $\lambda 5577$  lines occupy similar disc regions close to the star, whereas the [O I] doublet lines form further out (Kraus, Borges Fernandes & de Araújo 2007, 2010; Aret et al. 2012). Hot molecular emission originates from disc regions between the atomic gas and the dust, where the gas temperatures range from 5000 down to 2000 K. In this region, first CO forms, with its first-overtone

band emission ( $\sim 2.29\ \mu\text{m}$ ) tracing the inner edge of the molecular disc (Liermann et al. 2010; Oksala et al. 2013), while SiO forms at slightly lower temperatures hence farther out (first-overtone band emission around  $4\ \mu\text{m}$ ; Kraus et al. 2015). Thus, the kinematical information derived from these emission features can probe the disc's structure.

For the model computations of the first CO bandhead observed in our IR data, we utilize the previously developed code by Kraus et al. (2000). It computes a CO emission spectrum assuming that the material is in local thermodynamic equilibrium and located within a narrow rotating ring ( $v_{\text{rot}}$ ). Depending on our knowledge of the inclination angle of the system, the  $v_{\text{rot}}$  corresponds to the de-projected velocity, else we refer to the line-of-sight velocities that are lower limits of the real rotational velocities. This velocity is convolved with a Gaussian component ( $v_{\text{g}}$ ), which is a combination of a typical thermal velocity ( $v_{\text{thermal}} \sim 1\text{--}2\ \text{km s}^{-1}$ ) and some random internal motion of the gas ( $v_{\text{turbulence}}$  typically  $\sim 1\text{--}2\ \text{km s}^{-1}$ ). The last step of the calculations is another convolution of the model with a single Gaussian component that represents the instrument's spectral resolution ( $R$ ).

To model the optical emission lines, we assume that the atomic gas follows the distribution of the molecular gas, i.e. we consider emission from narrow rotating rings for the [O I]  $\lambda 5577$  and  $\lambda\lambda 6300, 6363$ , and the [Ca II]  $\lambda\lambda 7291, 7323$  lines. We are using the same thermal velocity, as our approach is based purely on the kinematics, but we adjust the instrument's spectral resolution to the optical one ( $R \sim 5.5\text{--}6.5\ \text{km s}^{-1}$ , for FEROS). For some cases in our narrow ring approach, the model required a value for  $v_{\text{turbulence}}$  that was (much) larger than the typical value of  $1\text{--}2\ \text{km s}^{-1}$  that can be associated with turbulence. In these cases, we interpret the extra Gaussian velocity component needed for the fit as indication for rings with finite (extended) width, and we determine the typical ring-width as  $v_{\text{turbulence}} = \sqrt{\langle v_{\text{g}} \rangle^2 - R^2 - v_{\text{thermal}}^2}$ , where  $\langle v_{\text{g}} \rangle$  is the mean value from all measurements corresponding to the same ring from all epochs available. In this case, we convolve the model of the emission line directly with a Gaussian profile that combines the thermal velocity, the turbulence, and the instrument's spectral resolution. This is allowed because the optical forbidden lines are optically thin, in contrast to the (partially) optical thick lines and the line blending in the near-IR region for the CO emission spectrum.

In order to determine the rotational velocities, we follow this strategy:

(i) We first determine the rotational velocity of the CO ring, since the CO emission features are a direct evidence of gas presence.

Table 2. Observing log.

Object	Date UT (yyyy-mm-dd)	$N \times t_{\text{exp}}$ (s)	S/N	Instrument/observatory	Resolution	Wavelength range
(1)	(2)	(3)	(4)	(5)	(6)	(7)
CPD-52 9243	1999-04-19	1 × 3600	100	FEROS/ESO-La Silla	48 000	3600–9200 Å
	1999-06-25	1 × 2400	80	FEROS/ESO-La Silla	48 000	3600–9200 Å
	2000-03-28	1 × 1800	50	FEROS/ESO-La Silla	48 000	3600–9200 Å
	2000-06-11	1 × 3600	75	FEROS/ESO-La Silla	48 000	3600–9200 Å
	2005-04-21	1 × 1800, 1 × 300	125	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2010-04-06	2 × 20	140	CRIRES/ESO-Paranal	50 000	2.276–2.326 μm
	2015-05-13	2 × 600	120	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2015-10-11	2 × 700	85	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2016-04-13	2 × 700	120	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2016-08-02	2 × 1000	100	FEROS/MPG-La Silla	48 000	3600–9200 Å
CPD-57 2874	2008-12-22	2 × 1000	100	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2009-12-02	2 × 32	140	CRIRES/ESO-Paranal	50 000	2.276–2.326 μm
	2015-05-13	2 × 600	100	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2016-01-13	2 × 700	90	FEROS/MPG-La Silla	48 000	3600–9200 Å
HD 327083	2016-03-13	2 × 900	60	FEROS/MPG-La Silla	48 000	3600–9200 Å
	1999-06-25	1 × 1800	90	FEROS/ESO-La Silla	48 000	3600–9200 Å
	2010-06-28	20 × 20	280	CRIRES/ESO-Paranal	50 000	2.276–2.326 μm
	2015-05-11	2 × 600	70	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2015-10-12	2 × 500	80	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2015-10-15	2 × 500	80	FEROS/MPG-La Silla	48 000	3600–9200 Å
HD 62623	2016-04-13	2 × 500	75	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2016-07-28	2 × 600	70	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2008-12-21	2 × 120	230	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2009-11-29	2 × 32	100	CRIRES/ESO-Paranal	50 000	2.276–2.326 μm
	2010-05-03	3 × 300	100	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2012-04-06	8 × 10	500	GNIRS/GEMINI-Mauna Kea	18 000	2.28–2.35 μm
	2013-05-09	1 × 120	200	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2014-11-29	2 × 10	90	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2015-05-10	2 × 10	120	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2015-10-12	2 × 20	40	FEROS/MPG-La Silla	48 000	3600–9200 Å
GG Car	1999-04-18	1 × 900	130	FEROS/ESO-La Silla	48 000	3600–9200 Å
	2000-02-23	1 × 1200	100	FEROS/ESO-La Silla	48 000	3600–9200 Å
	2008-12-22	2 × 900	100	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2009-06-09	1 × 810	110	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2009-12-02	2 × 32	100	CRIRES/ESO-Paranal	50 000	2.276–2.326 μm
	2011-03-23	1 × 700	110	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2015-05-13	4 × 120	70	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2015-11-23	4 × 120	75	FEROS/MPG-La Silla	48 000	3600–9200 Å
MWC 137	2015-11-26	4 × 120	70	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2009-11-03	5 × 32	30	CRIRES/ESO-Paranal	50 000	2.276–2.326 μm
	2015-12-05	3 × 1200	70	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2016-02-28	3 × 1000	90	FEROS/MPG-La Silla	48 000	3600–9200 Å
HD 87643	1999-04-18	1 × 1800, 1 × 900, 1 × 360	60	FEROS/ESO-La Silla	48 000	3600–9200 Å
	2000-02-23	1 × 1200	55	FEROS/ESO-La Silla	48 000	3600–9200 Å
	2009-12-02	2 × 32	120	CRIRES/ESO-Paranal	50 000	2.276–2.326 μm
	2015-05-12	7 × 200	10	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2015-10-13	2 × 400	75	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2016-04-13	2 × 400	70	FEROS/MPG-La Silla	48 000	3600–9200 Å
Hen 3-298	2005-04-19	1 × 3600, 1 × 600	60	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2009-12-02	4 × 16	100	CRIRES/ESO-Paranal	50 000	2.276–2.326 μm
	2015-05-11	2 × 1100	20	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2015-11-26	3 × 900	40	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2015-12-06	2 × 1100	60	FEROS/MPG-La Silla	48 000	3600–9200 Å
	2016-01-12	2 × 1300	60	FEROS/MPG-La Silla	48 000	3600–9200 Å

(ii) The rotational velocity (and the Gaussian component) of CO is our first guess for the corresponding model of each optical line. If these initial guesses are not sufficient to reproduce the observed profile, then we adjust their values accordingly.

(iii) A symmetrical broadening of the spectral line is the result of integrating its flux over a complete ring. To account for asymmetries, we calculate the line flux over partial rings (see also Kraus et al.



2016 for the difference between full and partial rings). This indicates the presence of inhomogeneities within these rings.

(iv) It is possible though that a single rotational velocity cannot fit the line. In that case, we add more rings up to the successful fit of the observed profile.

(v) In some cases, we need to combine multiple and partial rings. We do this in order to remain consistent with our approach; however, we point that this could not be the only scenario (see Section 5).

To select the optimum fitting parameters for each line, we create a number of models changing one parameter ( $v_{\text{rot}}$ ,  $v_{\text{g}}$ , and fluxes in multiple ring-models) at a time, and we visually compare them with the observed profiles. During this process, we have implemented a  $\chi^2$  measurement to direct us towards the best solution and help us address degeneracy problems, e.g. selecting among multiple ring options the one with the smallest reduced  $\chi^2$  value. Quoting those values could be rather misleading as due to the combination of high-quality data (very small errorbars), the telluric/sky residuals (although our best effort to correct for these), and the continuum determination (including the presence of some features at the wings of some lines), the reduced  $\chi^2$  values become quite large. The corresponding errors are derived by the maximum and minimum values that provide an acceptable fit.

We point here that the modelling process refers to the line profiles originating from the emitting regions of the CSE, which means that the gaps between the individual rings are due to gas-free or low-density regions. Alternative models have been tested in the past. An outflow scenario can fit the profiles, but it fails to reproduce the spectra of these sources, e.g. the lack of the [O II]  $\lambda 7319$  line (Kraus et al. 2010). A viscous disc scenario underestimates significantly the [O I] line intensities (see Porter 2003; Kraus et al. 2007).

## 4 RESULTS

For each source in our sample, we have obtained spectra from various epochs. This allows us to examine the physical properties of their discs and their variations if present. In the following paragraphs, we describe our results per object, summarized in Table 3. For each source (column 1), we provide the inclination angle (column 2), whenever known to obtain the de-projected velocities, the stellar mass estimates (column 3), the rotational velocities and ring radii (according to mass) of the forming regions for the [O I]  $\lambda 5577$  line (columns 4 and 5), the [Ca II]  $\lambda 7291$  line (columns 6 and 7), the [O I]  $\lambda 6300$  line (columns 8 and 9), the first CO bandhead (columns 10 and 11), and the first SiO bandhead (columns 12 and 13). In the last column (14) of Table 3, we present the systemic radial velocity derived for each source by identifying the necessary shift to center the observed profiles of the [O I]  $\lambda 6300$  line compared to a symmetric model, which is added to the barycentric correction performed by FEROS pipeline. For each star, the rotational velocities are shown in a decreasing order, i.e. as we progressively move away from the star. The rotational velocities of the optical lines are the averaged values over all epochs, and their corresponding errors are the result of error propagation from the individual measurements. We present more detailed information for the fits we have performed for each epoch and star in Appendix A. Considering the near-IR spectra, we have re-processed all original CRIRES data (for which Muratore et al. 2012 presented preliminary fits for some objects), and we provide rotational velocities corrected for the line of sight whenever the inclination angle is known. We present all final fits

for the first CO overtone bandhead emission (at  $\sim 2.3 \mu\text{m}$ ) in Fig. 1, and we discuss these CO features (henceforth) in relation with the results obtained from the optical lines.

### 4.1 CPD-52 9243

The CO emission features have been detected in the near-IR spectra already by the works of Whitelock et al. (1983) and McGregor, Hyland & Hillier (1988). Cidale et al. (2012) using high-resolution spectroscopy and interferometry have found that the CO emission originates from a detached rotating ring at  $36 \text{ km s}^{-1}$  (Fig. 1). Additionally, Kraus et al. (2015) have discovered SiO emission from a rotating ring at  $35.5 \text{ km s}^{-1}$ . Since their velocities are the same, it becomes apparent that the total molecular emission originates from a common region.

In Fig. 2, we present the line profiles of the optical emission lines from all available observations (from 1999 to 2016). We note the absence of [O I]  $\lambda 5577$  in all epochs. While the [Ca II] doublet presents clearly double-peaked profiles, the [O I] displays asymmetries (e.g. stronger blue peaks on 2016-04-13, 2015-05-13, and 2000-06-10).<sup>2</sup> Using the model described in Section 3, we fit each of these lines with a two-ring model (see Fig. 3). To account for the asymmetries of the [O I] line, we need to use partial rings (half-filled), and since these are present only on some epochs (e.g. not on 2016-08-02 or 2000-03-27), they may be indicative of a revolving inhomogeneity of the material. Nevertheless, the rotational velocities derived from the fitting process are similar in all epochs (see Table A1 for more details), and their averaged values are  $30.4 \text{ km s}^{-1}$  and  $48.9 \text{ km s}^{-1}$  for the [Ca II] line and  $32.1 \text{ km s}^{-1}$  and  $51.4 \text{ km s}^{-1}$  for the [O I] line.

The identification of two rings for each line indicates that there are two emitting regions/rotational rings. Moreover, the similar values found for the [Ca II] and [O I] lines indicate that these gases coexist. Given the Keplerian rotation, the ring at  $\sim 31 \text{ km s}^{-1}$  is located further away from the star than the molecular ring (at  $\sim 36 \text{ km s}^{-1}$ ). Since our typical ring-width is  $\sim 9 \text{ km s}^{-1}$ , this ring may not be totally independent from the molecular one. The presence of another ring at a higher velocity (of  $\sim 50 \text{ km s}^{-1}$ ) implies a region that is located closer to the star, and consists mainly of atomic gas (i.e. [Ca II] and [O I]). Thus, in total, we suggest that the circumstellar disc of CPD-52 9242 consists of two to three rings (as the outermost ring could be potentially overlapping with the molecular one). We used the stellar mass estimate by Cidale et al. (2012) of  $17.4\text{--}18.6 M_{\odot}$  to convert these velocities to distance radii from the star (see Table 3). The derived radii at  $\sim 6.7 \text{ au}$  (ring with atomic gas only: [Ca II] and [O I]) and  $\sim 12\text{--}17 \text{ au}$  (combined atomic and molecular gas) are consistent with the results of Cidale et al. (2012), who identified atomic gas at 5 and 12 au.

Apart from the changes in the [O I] profile, there are intensity variations that are systematic for all lines, with the strongest lines present during our latest observations (in 2015 and 2016). The  $H\alpha$  line also displays variability on its blue peak, which is indicative of changes in the wind. It is interesting to note that the profiles of  $H\alpha$  (up to 2005) and [O I]  $\lambda 6300$  (on dates with symmetric profiles) are similar to the ones obtained in 1988 by Zickgraf (2003) (cf. his fig. 1 and 2, at similar resolution of  $R \sim 55\,000$ ), although the big gap between 1988 and 1999 does not allow for any strict conclusions about the variability of the lines.

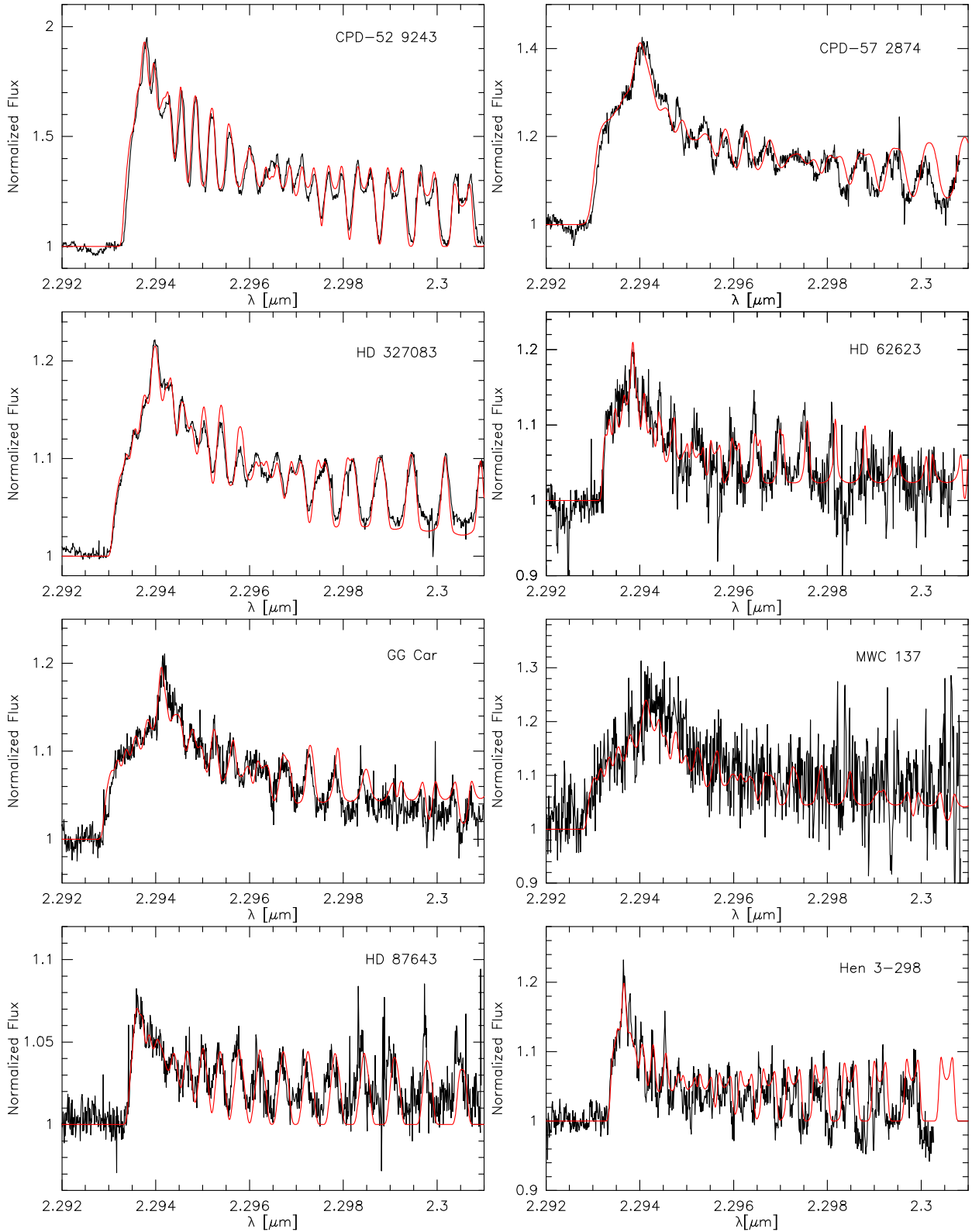
Additionally, there is a small radial velocity offset for the [O I]  $\lambda 6300$  line present in different epochs (up to  $5 \text{ km s}^{-1}$ , larger than

<sup>2</sup>The [O I]  $\lambda 6363$  line suffers from an absorption line on its red wing.

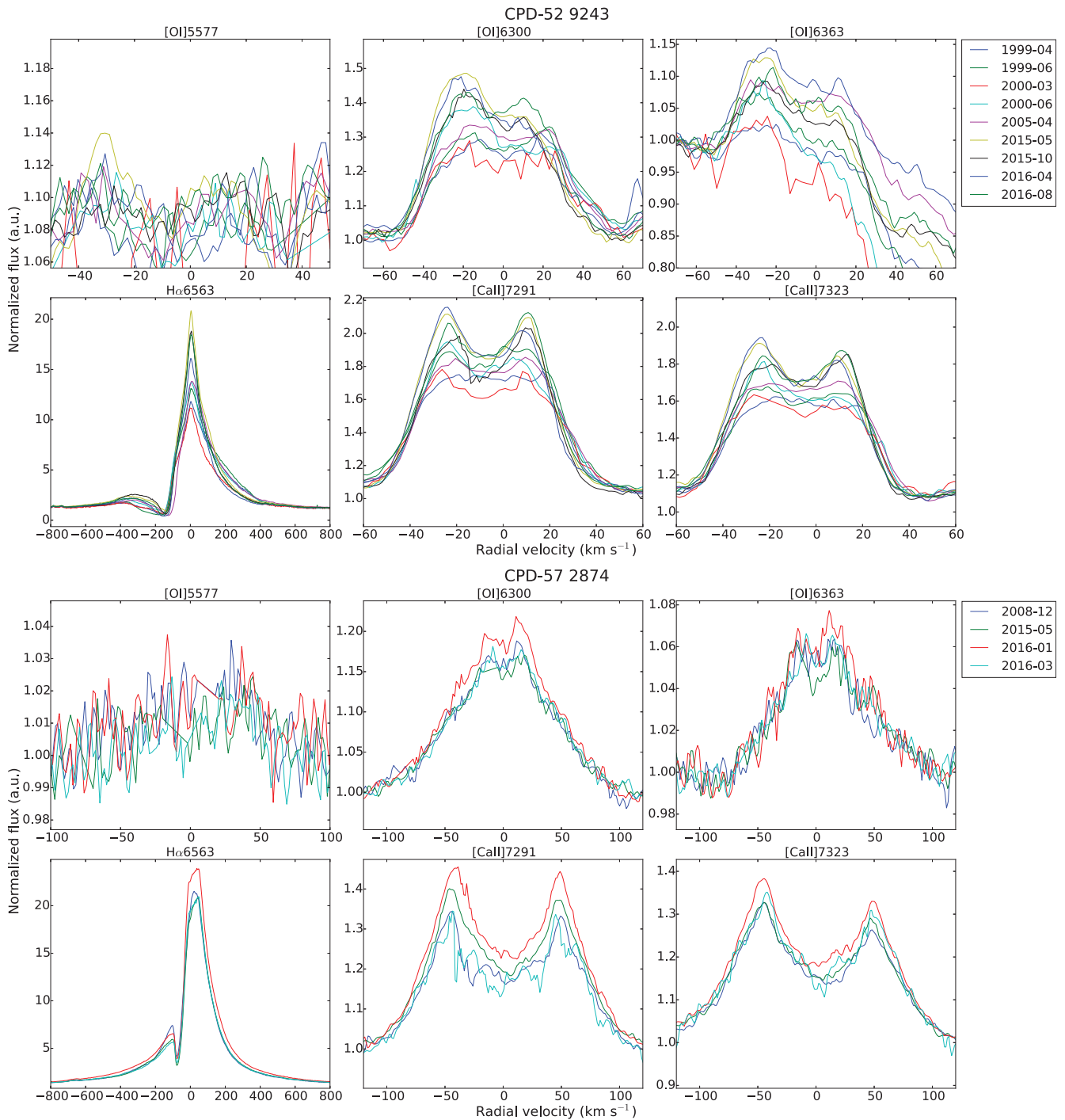
**Table 3.** The summary of the kinematics identified in our sample. For each source, we present the number of identified rings per line as we move further away from the star (i.e. in a decreasing order of rotational velocities).

Star	$i^a$	Mass	[O I] 5577	[Ca II] 7291	[O I] 6300	CO	SiO	Systemic					
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
	( $^\circ$ )	( $M_\odot$ )	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$R$ (au)	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$R$ (au)	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$R$ (au)	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$R$ (au)	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$R$ (au)	RV <sup>b</sup> ( $\text{km s}^{-1}$ )
CPD-52 9243	46 <sup>c1</sup>	17.4–18.6 <sup>1,c</sup>	–	–	48.9 ± 3.0	6.7 ± 0.8	51.4 ± 4.8	6.0 ± 1.1	–	–	–	–	–49
CPD-57 2874	30 <sup>o3</sup>	15–20 <sup>3,c</sup>	–	–	30.4 ± 2.9	17.3 ± 3.3	32.1 ± 4.6	15.5 ± 4.4	36 ± 1 <sup>1</sup>	12.3 ± 0.7	35.5 ± 1 <sup>2</sup>	12.7 ± 0.7	3
HD 327083	50 <sup>o5</sup>	25 <sup>6</sup>	–	–	210.5 ± 15.0	0.35 ± 0.05	166.3 ± 11.4	0.56 ± 0.08	130 ± 1 <sup>4</sup>	0.92 ± 0.01	110 ± 1 <sup>2</sup>	1.28 ± 0.02	–
HD 62623	52 <sup>o7</sup>	9–10.5 <sup>8,c</sup>	57.1 ± 7.0	2.7 ± 0.7	158.3 ± 6.2	0.62 ± 0.05	120.3 ± 6.2	1.1 ± 0.1	86 ± 1 <sup>4</sup>	3.00 ± 0.07	78 ± 1 <sup>2</sup>	3.65 ± 0.09	–26
GG Car	63 <sup>o ± 9</sup> <sup>o9</sup>	38 <sup>10</sup>	–	–	108.1 ± 8.1	1.3 ± 0.2	88.3 ± 7.1	2.0 ± 0.3	53 ± 1 <sup>4</sup>	3.1 ± 0.1	48 ± 1 <sup>2</sup>	3.8 ± 0.2	27
MWC 137	Unknown	10–15 <sup>11,c</sup>	–	–	–	–	44.5 ± 4.5	7.8 ± 1.6	91.5 ± 7.5 <sup>10</sup>	4.0 ± 0.7	–	–	–22
HD 87643	Unknown	25 <sup>13</sup>	–	–	–	–	74.7 ± 4.3	4.0 ± 0.5	84 ± 2 <sup>12,d</sup>	1.57 ± 0.07	–	–	42
HD 87643 <sup>e</sup>	7.4 <sup>o4</sup>	25 <sup>13</sup>	–	–	10.6 ± 1.3 <sup>d</sup>	173 ± 43	61.0 ± 5.3 <sup>d</sup>	5.2 ± 0.9	11 ± 1 <sup>4,d</sup>	161 ± 29	–	–	–3
Hen 3-298	unknown	20 <sup>14</sup>	23.2 ± 2.7 <sup>d</sup>	33.0 ± 7.7	82.3 ± 10	3.3 ± 0.8	691 ± 70	0.046 ± 0.009	85 ± 8 <sup>4</sup>	3.1 ± 0.6	–	–	81
			21.5 ± 1.1 <sup>d</sup>	38.4 ± 3.9	75 ± 13	3.9 ± 1.4	474 ± 41	0.10 ± 0.02	19 ± 1 <sup>4,d</sup>	49.1 ± 5.2	–	–	
			–	–	218 ± 23	–	28.1 ± 2.9 <sup>d</sup>	24.7 ± 5.1	–	–	–	–	
			–	–	18.7 ± 1.1 <sup>4,d</sup>	–	207 ± 72	207 ± 72	–	–	–	–	

*Notes.* <sup>a</sup> Inclination angle of the system rotation axis with respect to the line of sight ( $i = 90^\circ$  means edge-on view of the disc); <sup>b</sup> The systemic radial velocity for each star, as derived by centering the [O I]  $\lambda 6300$  line; <sup>c</sup> For the sources with a range of stellar mass estimates, we used an average value for the determination of the corresponding ring radii; <sup>d</sup> Rotational velocities as projected to the line of sight; <sup>e</sup> For HD 87643, we present our results for both the line-of-sight velocities and the velocities derived after constraining the inclination angle (see text for more details). References: <sup>1</sup> Cidale et al. (2012); <sup>2</sup> Kraus et al. (2015); <sup>3</sup> Domiciano de Souza et al. (2011); <sup>4</sup> This work; <sup>5</sup> Marchiano et al. (in preparation); <sup>6</sup> Wheelwright et al. (2012a); <sup>7</sup> Millour et al. (2011); <sup>8</sup> Aret, Kraus & Siechta (2016); <sup>9</sup> Marchiano et al. (2012); <sup>10</sup> Kraus et al. (2013); <sup>11</sup> Mehner et al. (2016); <sup>12</sup> Muratore et al. (2015); <sup>13</sup> Oudmaijer et al. (1998); <sup>14</sup> Oksala et al. (2013).



**Figure 1.** The near-IR CRIRES spectra of our sample (black lines), showing the first CO bandhead and their corresponding models (red lines). (See text for more details regarding each source, and Table 2 for observing dates).



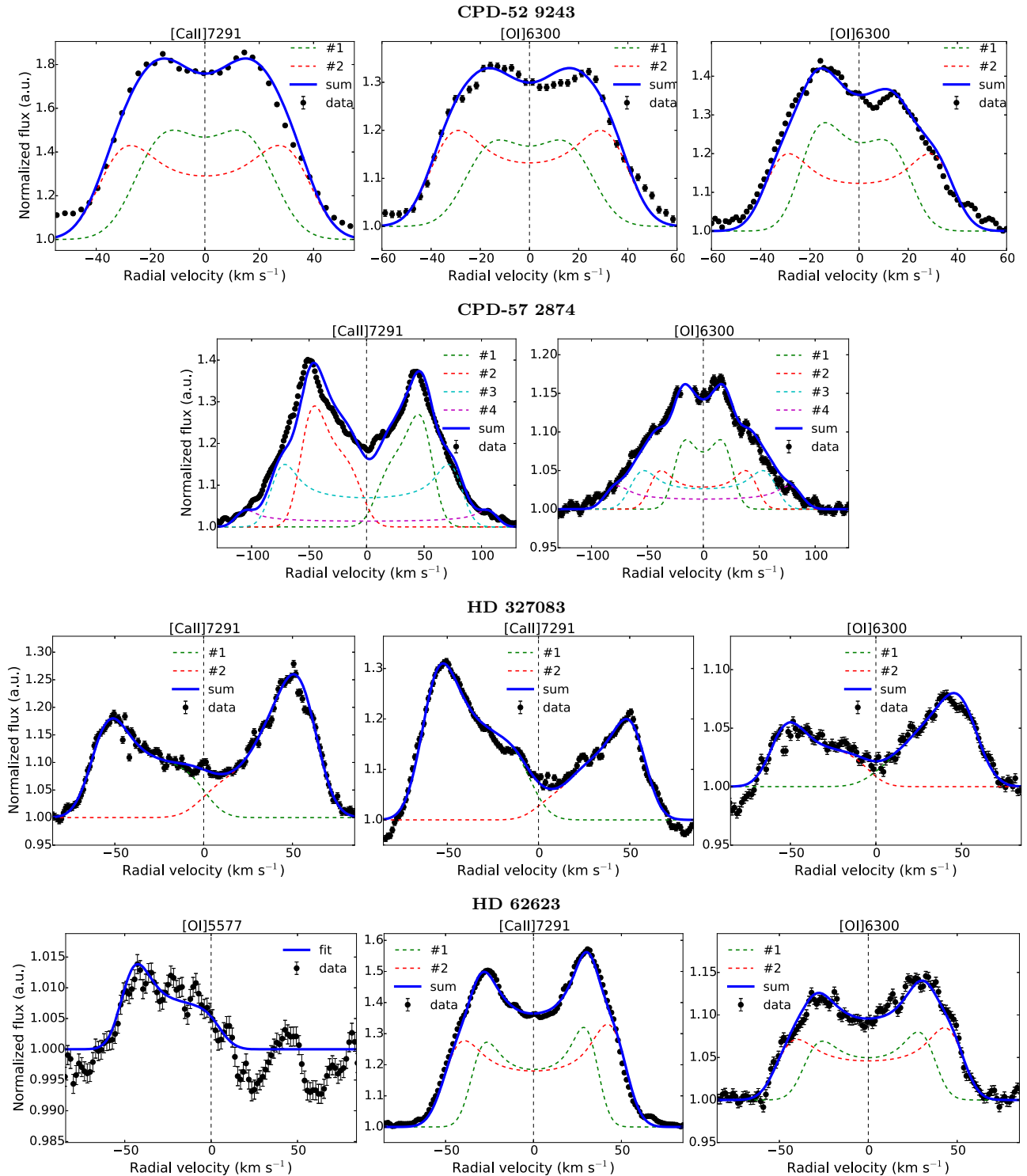
**Figure 2.** Profiles of the [O I]  $\lambda\lambda 5577, 6300, 6363$ , the  $H\alpha$   $\lambda 6563$ , and the [Ca II]  $\lambda\lambda 7291, 7323$  lines as derived from all available FEROS observations for CPD-52 9243 (1999–2016) and CPD-57 2874 (2008–2016). (See text for more details).

our typical calibration error of  $\sim 1 \text{ km s}^{-1}$ ), and between this line and the [Ca II]  $\lambda 7291$  (up to  $8 \text{ km s}^{-1}$ ) line, which may indicate either slight displacements of these rings with respect to each other or more elliptical rings than the circular ones assumed. This is similar to what we see for the elliptical binary GG Car (Marchiano et al. 2012; Kraus et al. 2013; see Section 4.5), which may imply a binary nature for CPD-52 9243 also (as it has been suggested already by Cidale et al. 2012).

#### 4.2 CPD-57 2874

The presence of the CO first overtone bandhead in a near-IR spectrum was first pointed out by McGregor et al. (1988). Muratore et al. (2012) used high-resolution CRIRES spectra to identify the double-peaked features of CO, and a preliminary fit of these data revealed a rotating ring at  $65 \text{ km s}^{-1}$  (line-of-sight velocity). In this work, we reprocessed the original CRIRES data (from 2009-12-02) to derive a more robust conclusion regarding the kinematics of the





**Figure 3.** Examples of fits to the line profiles for our sample. Observations are shown as black dots, while the individual ring models are shown as dashed lines and the reconstructed profile as solid blue lines. From the top to bottom, CPD-52 9243: the first two panels show double-peaked models for the [Ca II]  $\lambda$ 7291 and the [O I]  $\lambda$ 6300 lines from 2005-04-21, while the last one the asymmetric [O I]  $\lambda$ 6300 line from 2015-10-11; CPD-57 2874: the [Ca II] and the [O I] lines from 2015-05-13 along with three- and four-ring models, respectively; HD 327083: the [Ca II] line (from 2015-10-11 and 2016-04-13), and the [O I]  $\lambda$ 6300 line (2015-10-11), respectively, with models of single rings with inhomogeneities; HD 62623: the [O I]  $\lambda$ 5577 (2010-05-03) line modelled with a partially filled ring, as well as the [Ca II]  $\lambda$ 7291 (2015-05-10) and the [O I]  $\lambda$ 6300 (2014-11-29) lines with their corresponding two-ring models with small inhomogeneities. (See text for more details for each source).

CO. Using the first CO bandhead, we find a de-projected rotational velocity of  $130 \text{ km s}^{-1}$  (see Fig. 1). Additionally to CO, Kraus et al. (2015) detected SiO emission, originating from a  $110 \text{ km s}^{-1}$  ring.

In Fig. 2, we present the line profiles for the optical lines as derived from all available observations between 2008 and 2016. There is no sign of the [O I]  $\lambda 5577$  line. The [Ca II]  $\lambda 7291$  displays a deep central depression that demands a multi-ring model to properly fit its highly asymmetric profile. To account for the peaks, we use two partial rings with similar rotational velocities but integrated over different velocity ranges (green and red dashed lines shown in Fig. 3; see Table A2 for more details). Then, we use another set of two (complete) rings that fit the extended wings of the [Ca II] line (cyan and magenta dashed lines in Fig. 3). We interpret these results as three rings where [Ca II] is forming (at  $108.1$ ,  $158.3$ , and  $210.5 \text{ km s}^{-1}$ ), of which the first one is a ring with inhomogeneities, due to either the absence of the gas or because the local conditions are not proper to produce detectable [Ca II] emission. To model the [O I]  $\lambda 6300$  line, we use four (complete) rings (at  $44.5$ ,  $88.3$ ,  $120.3$ , and  $166.3 \text{ km s}^{-1}$ , shown as dashed lines in Fig. 3). If we combine all these velocities, then we see that we get a rather complex and alternate combination of emitting regions. By starting closer to the star (i.e. the largest rotational velocities), we get a [Ca II] ring at  $210.5 \text{ km s}^{-1}$ , a [O I] ring at  $166.3 \text{ km s}^{-1}$ , and a [Ca II] ring at  $158.3 \text{ km s}^{-1}$ . Due to our typical ring width of  $\sim 11 \text{ km s}^{-1}$ , the last two rings actually overlap. Further away from the star, we find the CO ring at  $130 \text{ km s}^{-1}$ , another [O I] ring at  $120.3 \text{ km s}^{-1}$  (perhaps with some overlap with the CO and SiO rings), the SiO ring at  $110 \text{ km s}^{-1}$ , a non-homogeneous [Ca II] ring at  $108.1 \text{ km s}^{-1}$  (overlapping with the SiO ring), and another two [O I] rings at  $88.3$  and  $44.5 \text{ km s}^{-1}$ . It is possible though that the CSE in the case of CPD-57 2874 may not consist of individual rings, but is an inhomogeneous disc with alternate regions of molecular and atomic emission.

Taking into account the stellar mass estimates for CPD-57 2874 of  $15\text{--}20 M_{\odot}$  by Domiciano de Souza et al. (2011), we can calculate the distances of these rings from the central star (see Table 3). The derived ring radii show us that the gas emission extends up to  $\sim 9 \text{ au}$ , which is consistent with the picture we have from the interferometry, as Domiciano de Souza et al. (2011) find a broad near-IR emission region at  $\sim 8.5 \text{ au}$  and the bulk of the dust further away ( $\sim 11\text{--}14 \text{ au}$ ).

In general, the lines do not show significant variability over the observed period of 8 yr. There is only a small intensity increase in the last observation (2016-03-13) for the [O I] and [Ca II] lines, but with identical profiles. Likewise, the  $H\alpha$  line displays a stronger red peak, while its blue peak shows some variability, possible due to changes in the wind. Observations from 1988 at similar resolution ( $R \sim 55000$ ) show that both the  $H\alpha$  and the [O I]  $\lambda 6300$  lines appear similar to our observations (Zickgraf 2003, cf. fig. 1 and 2). Nevertheless, it is hard to argue if there has been any change or not during the 1988–2008 period.

### 4.3 HD 327083

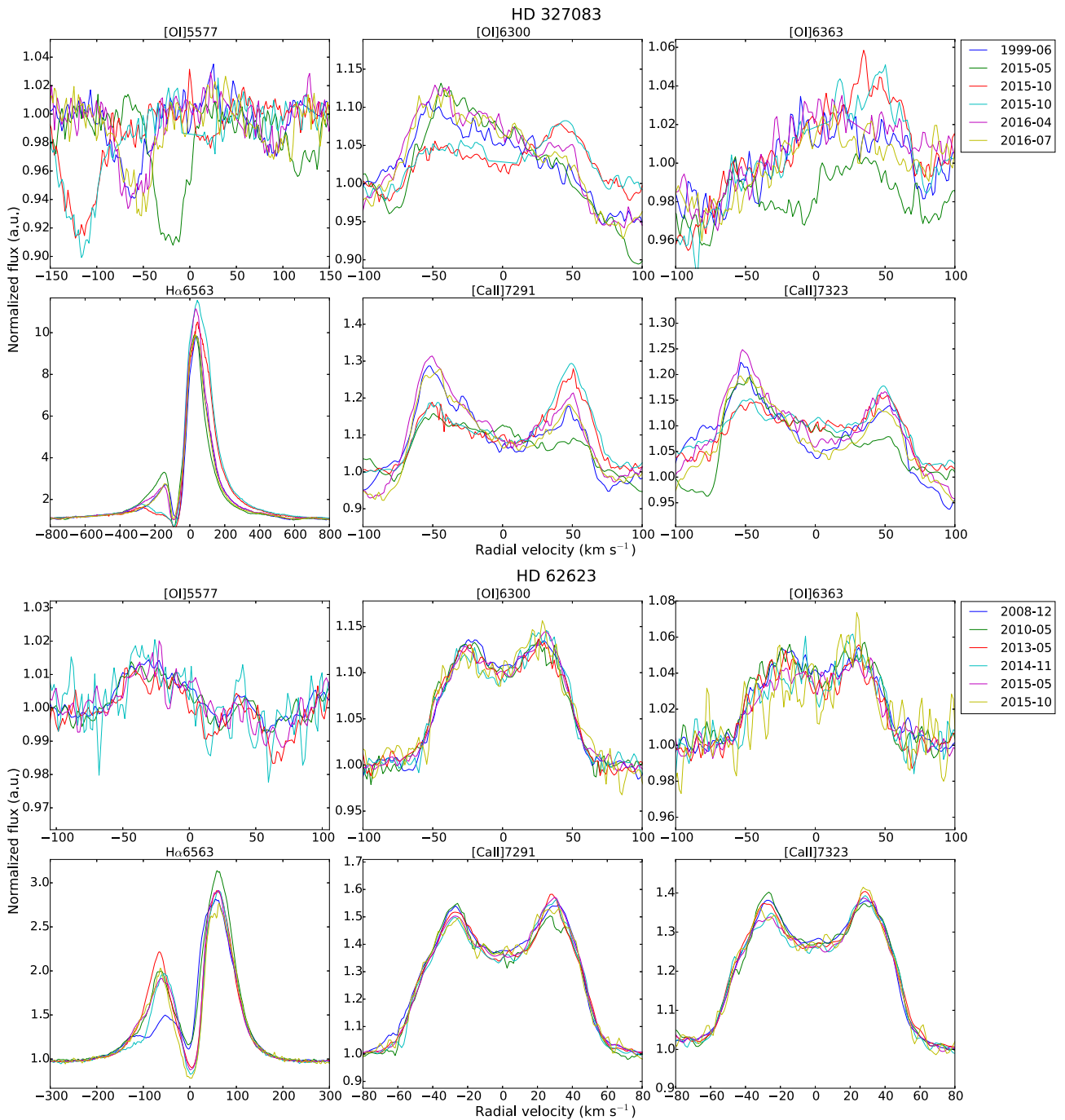
CO emission features have been detected in the near-IR spectra of HD 327083 since the works of Whitelock et al. (1983) and McGregor et al. (1988). A preliminary derivation of the projected rotational velocity for the CO ring at  $55 \pm 1 \text{ km s}^{-1}$  was given by Andruchow et al. (2012), using the Phoenix/Gemini IR spectrometer in May 2010. From our CRILES spectra in June 2010, we obtain a de-projected rotational velocity of  $86 \pm 1 \text{ km s}^{-1}$  (Fig. 1). Additionally, Kraus et al. (2015) detected SiO, originating from a rotating ring at  $78 \text{ km s}^{-1}$ .

Fig. 4 presents the line profiles for the 1999–2016 period, for which there is no sign of the [O I]  $\lambda 5577$  line. The [Ca II] and [O I] doublets display asymmetrical profiles. To properly model the strong central depression of the [Ca II] line, we have to use two partial rings that have similar velocities but different integration ranges (see Fig. 3 and Table A3 for details). We find a range of  $70\text{--}77 \text{ km s}^{-1}$  throughout all epochs. As the typical ring-width is  $10.5 \text{ km s}^{-1}$ , we conclude that the [Ca II] emission line originates actually from a single ring region (with an averaged value of  $75.4 \text{ km s}^{-1}$ ) with inhomogeneities. Alternate profiles on different dates are a possible indication of revolving inhomogeneities.

Regarding the [O I]  $\lambda 6300$  line, we fit the first epoch (1999 June 25) with a single partial ring of  $75 \text{ km s}^{-1}$ . For the next epoch (2015-05-11), we find that a two partial-ring model (with velocities of  $58$  and  $76 \text{ km s}^{-1}$ ) is necessary. In 2015 October, the outermost ring (at  $58 \text{ km s}^{-1}$ ) is not present (probably dissolved or not dense enough). However, we still need two partial rings of similar velocities (at  $70$  and  $74 \text{ km s}^{-1}$ ) to fit the observed profiles, corresponding to a single ring with inhomogeneities. Starting with 2016-04-13, we have an asymmetric profile without any good constraint on its red part (in contrast to its blue part), which makes the fit quite loose. Nevertheless, we need to use a two partial-ring model with rotational velocities of  $66$  and  $80 \text{ km s}^{-1}$ . This is required since a single ring in between those values (e.g.  $\sim 72\text{--}74 \text{ km s}^{-1}$ ) does not fit the observed profile. Similarly for 2016-07-28, we get two rings at  $61$  and  $78.5 \text{ km s}^{-1}$ . The innermost rings (at  $\sim 78\text{--}80 \text{ km s}^{-1}$ ) identified in these two epochs of 2016 are consistent with previous ones. The outermost rings (at  $66\text{--}61 \text{ km s}^{-1}$ ) though are more interesting. Alike the ring at  $58 \text{ km s}^{-1}$  observed in 2015-05-11, these rings may indicate material that left the single ring we see in October 2015 and dissolve further away with time (from  $66$  to  $61 \text{ km s}^{-1}$ ). This would correspond to an extremely fast process, for which we do not have much evidence (such a ring exists only for GG Car). An alternative scenario is that of a relatively tenuous outer ring, which is fragmented to such a degree that only some parts become observable in certain epochs.

Hence, we opt to use two rings for the emitting region of the [O I], one with inhomogeneities (similar to [Ca II]) at an averaged rotational velocity of  $74.1 \text{ km s}^{-1}$  and a tentative fragmented one at  $61.7 \text{ km s}^{-1}$ . The velocities found for the [Ca II] and [O I] forming regions are similar to the SiO ring, which imply a common location for these gases. CO forms (at slightly higher rotational velocity) another ring further closer to the star, although it is possible that due to the typical ring-width of  $10.5 \text{ km s}^{-1}$  it might not be totally separated from the other ring.

A number of stellar mass estimates have been derived in the literature, ranging from  $60 M_{\odot}$  (using non-LTE wind modelling of the Balmer lines; Machado & de Araújo 2003) to  $20 M_{\odot}$  (detection of absorption lines from neutral metals and radial velocity variations; Miroshnichenko et al. 2003) and  $25 M_{\odot}$  (using interferometry; Wheelwright et al. 2012b). The CO ring, which is found closer to the star, is located at a distance of  $7.2$ ,  $2.4$ , or  $3.0 \text{ au}$ , considering the different masses, respectively. In all cases, these radii are larger than the binary separation (at  $\sim 1.7 \text{ au}$ , Wheelwright et al. 2012a) that makes the whole structure circumbinary. We use the latest mass estimate, derived from the interferometric results, to calculate the ring radii in Table 3. Given this mass, the rings (up to  $\sim 4 \text{ au}$ ) are located closer to the source than the dusty disc revealed by Wheelwright et al. (2012a) at  $5.1 \text{ au}$ . We do not detect any other emitting region closer to the source than the CO, although Wheelwright et al. (2012a) observed a more compact



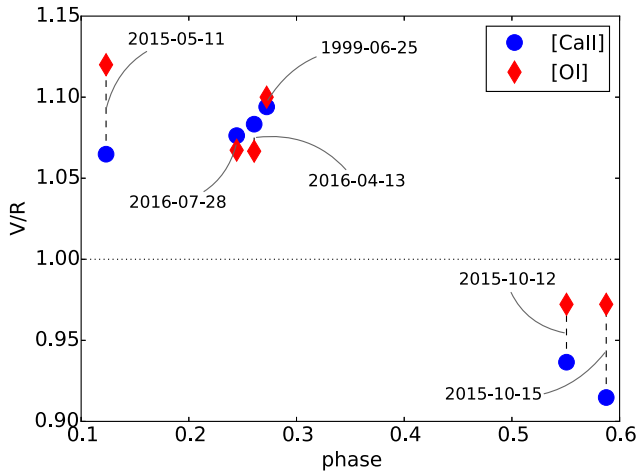
**Figure 4.** Similar to Fig. 2 but for HD 327083 (1999–2016) and HD 62623 (2008–2015, excluding only the [O I]  $\lambda$ 5577 line from 2015-10-12 because of the noise).

region of Br $\gamma$  emission (possible originating from either of the stars in the binary).

In Fig. 5, we present the ratio of the blue to red peak ( $V/R$ ) at each epoch. The  $V/R$  of the [O I] and the [Ca II] lines vary in phase, with  $V/R > 1$  for phases  $< 0.5$  and  $V/R < 1$  for phases  $> 0.5$  (assuming an orbital period of  $\sim 107$  d; Cidale et al., in preparation). However, for the latter case, only observations from October 2015 fall into this phase domain. Given the circumbinary nature of the structure around HD 327083 and the possibility that these rings are not necessarily circular or homogeneous, these asymmetries may be due to the excitation/heating of the gas (hence stronger emission)

at phases when the hotter component is closer to one or the other side of the rotating rings.

The H $\alpha$  line also displays profile changes, especially in 2015 October observations when the blue peak almost disappears. Except for these, H $\alpha$  displays smaller intensity changes. Even though we do not detect any sign of the [O I]  $\lambda$ 5577 line, we do notice the presence of some absorption features (attributed to the cooler companion) that display radial velocity variations. At least partly, this variability could be due to the orbital modulations imposed by the binary inside the circumbinary structure.



**Figure 5.** The  $V/R$  variation for both the  $[\text{Ca II}] \lambda 7291$  and the  $[\text{O I}] \lambda 6300$  lines with respect to the phase for the binary HD 327083. The corresponding pair of spectral features (connected with a dashed line) for each epoch (indicated with an arc) is also shown.

#### 4.4 HD 62623

HD 62623 is the only A[e] supergiant known in the Galaxy (A2.7Ib; Chentsov, Klochkova & Miroshnichenko 2010). Even though it is the brightest source in our sample ( $V = 3.93$  mag) and has been a target of many studies (see the historic overview in Chentsov et al. 2010), CO emission features in the near-IR have remained rather elusive. HD 62623 is the only object for which we have an additional, though slightly lower resolution, near-IR spectrum (from GEMINI/GNIRS; Fig. 6). Despite the time difference of 29 months between the individual observations, we obtained from both spectra the same rotational velocity of  $53 \text{ km s}^{-1}$ , indicating that the molecular ring is stable. In addition, since the GNIRS spectrum also covers the second bandhead, we could determine the temperature ( $T_{\text{CO}} = 1800 \pm 100 \text{ K}$ ) and the column density ( $N_{\text{CO}} = (2.5 \pm 0.5) \times 10^{20} \text{ cm}^{-2}$ ) of the CO-forming region. With the derived velocity, the CO ring resides slightly closer to the star

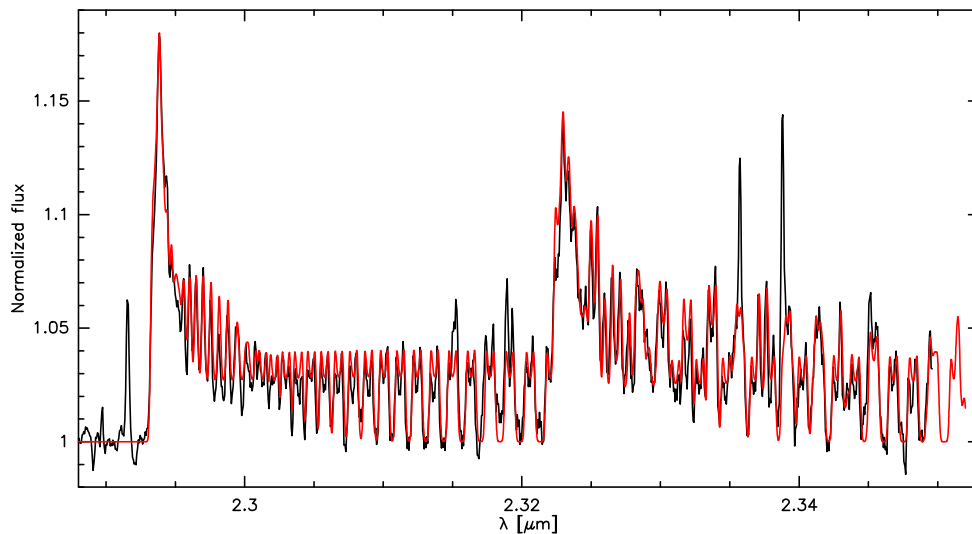
than the SiO ring, for which a velocity of  $48 \text{ km s}^{-1}$  was found (Kraus et al. 2015).

Optical observations cover a period of 7 yr (2008–2015) and they are shown in Fig. 4. In the case of HD 62623, a rather weak signal from  $[\text{O I}] \lambda 5577$  is apparent, displaying always a blue peak. We can model this profile as a single partial ring, which is less than half filled (see Table A4), and with a rotational velocity of  $57.1 \pm 6.3 \text{ km s}^{-1}$ . Due to the large error and the weakness of the (purely blue-shifted) line, we would consider the identification of this emission feature as  $[\text{O I}]$  and hence this ring as rather tentative.

Regarding the  $[\text{Ca II}]$  and  $[\text{O I}]$  doublets, we can fit both with a two ring model at  $\sim 40.7 \text{ km s}^{-1}$  and  $\sim 61.3 \text{ km s}^{-1}$  (see Fig. 3). That means that the two atomic gases coexist in two clearly separated forming regions (as the typical ring-width for HD 62623 is  $\sim 9 \text{ km s}^{-1}$ ). It is interesting to note though observations up to 2013 can be fit with complete rings, while after 2014 we need to insert some inhomogeneity to properly model their slightly asymmetrical profiles. This could be interpreted as the development of inhomogeneities within both rings; however, its simultaneous appearance in both rings may indicate a change in the geometry along the line of sight. In between the rings of atomic gas, we find the molecular rings (CO and SiO). In the innermost rings, we have a common forming region of  $[\text{Ca II}]$  and  $[\text{O I}] \lambda 6300$  lines (at  $\sim 61.3 \text{ km s}^{-1}$ ) and the presence of the (tentative)  $[\text{O I}] \lambda 5577$  line (at  $57.1 \text{ km s}^{-1}$ ).

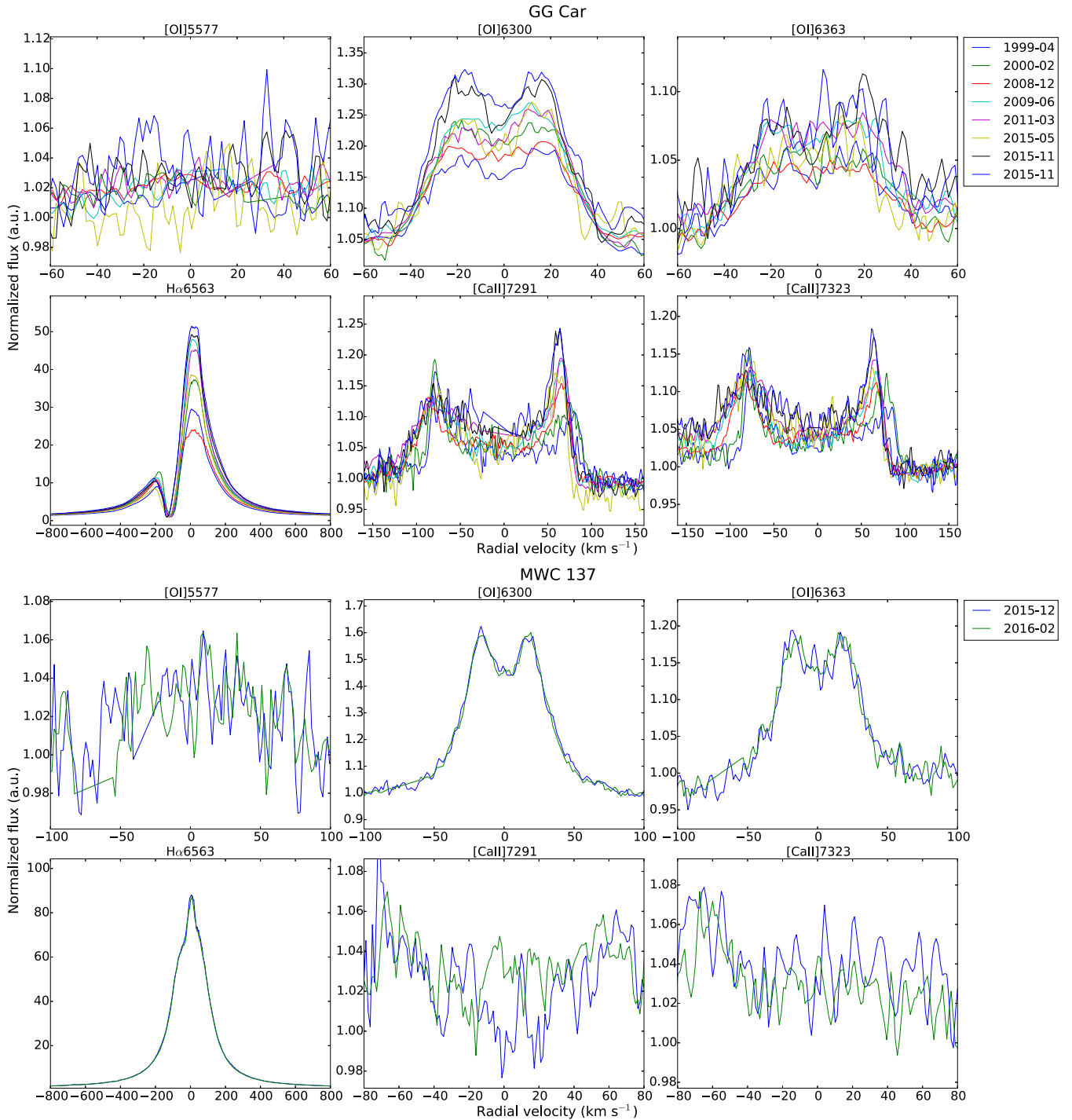
According to the interferometric results by Millour et al. (2011), the equatorial CSE consists of a hot ionized disc close to the star (up to 1.3 au) and a dusty disc further outside (at 4 au). Using the mass range of 9–10.5  $M_{\odot}$  (Aret et al. 2016), we can estimate the ring radii (see Table 3) within the range 2.3–5.0 au, fairly close to the location of the dusty ring. Although not directly detected, a binary scenario has been used to explain the CSE of HD 62623 (Millour et al. 2011). In this case, the maximum possible binary separation (1.2–1.7 au) is smaller than the smallest ring-radius estimate (at 2.3 au), which makes this structure circumbinary (similar to HD 327083).

In general, there are only minor intensity variations in the peaks of  $[\text{Ca II}]$  lines, with the  $[\text{O I}]$  lines being more stable. The most striking change is in the blue peak of  $\text{H}\alpha$ , which is characterized by a sharp increase from 2008 to 2010. From then on, the ratio between the blue and red peak remains almost stable, with a small increase



**Figure 6.** The GNIRS spectrum of HD 62623 (black line), showing the first and the second CO bandheads, and its corresponding model (red line).





**Figure 7.** Similar to Fig. 2 but for GG Car (1999–2015) and MWC 137 (2015–2016).

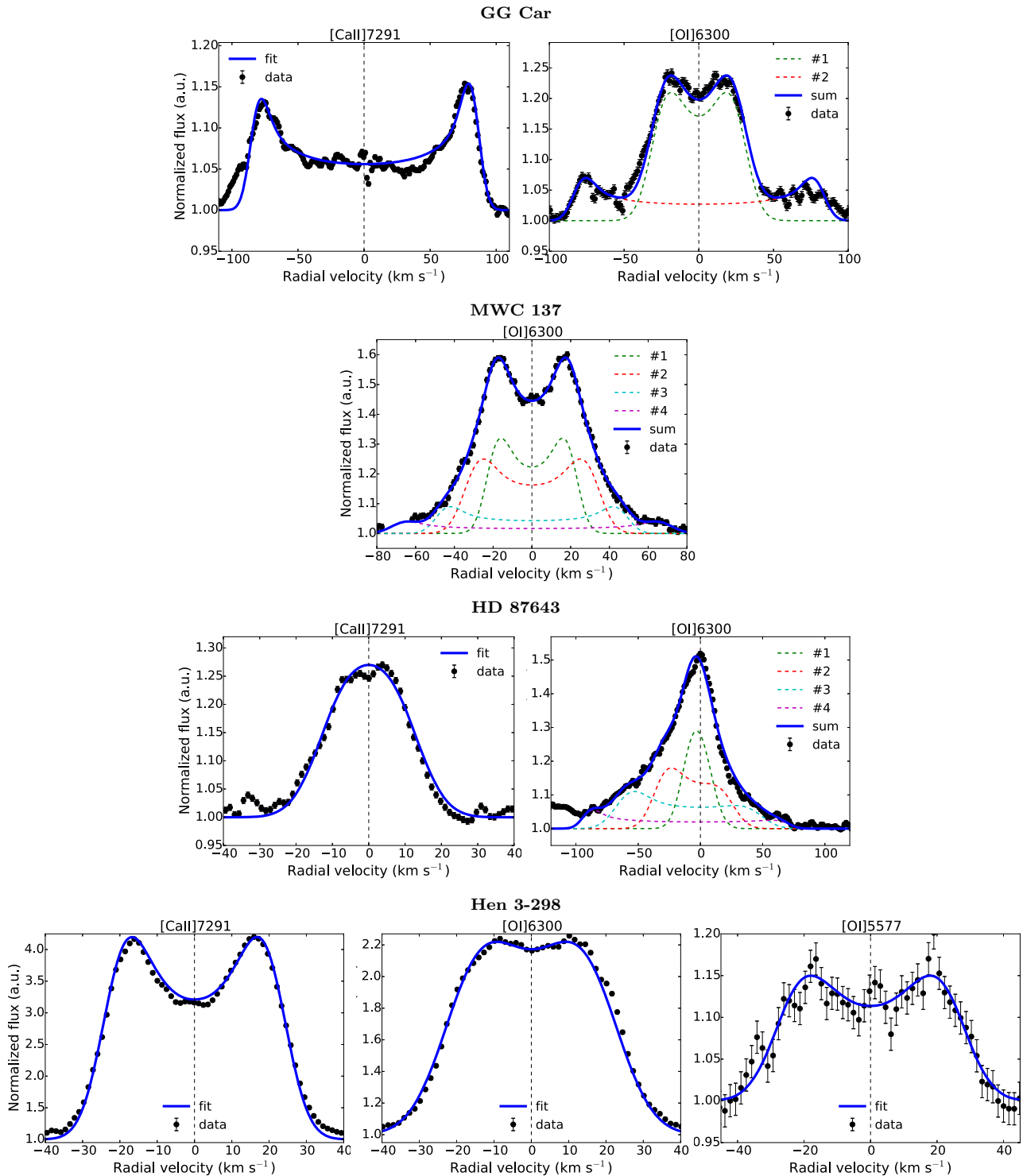
in 2014 and returning back to the previous state in 2015. Given the relative stability of the other lines, this variation in H $\alpha$  may be the result of changes in the wind of the star, which do not affect the circumstellar rings.

#### 4.5 GG Car

The IR spectrum of GG Car has been described extensively in previous works (e.g. McGregor et al. 1988; Morris et al. 1996). However, the kinematical properties of the CO emission features

were investigated by Kraus et al. (2013), who identified a detached rotating ring at 91.5 km s<sup>-1</sup> (see in Fig. 1 this model on top the CRIRES spectrum).

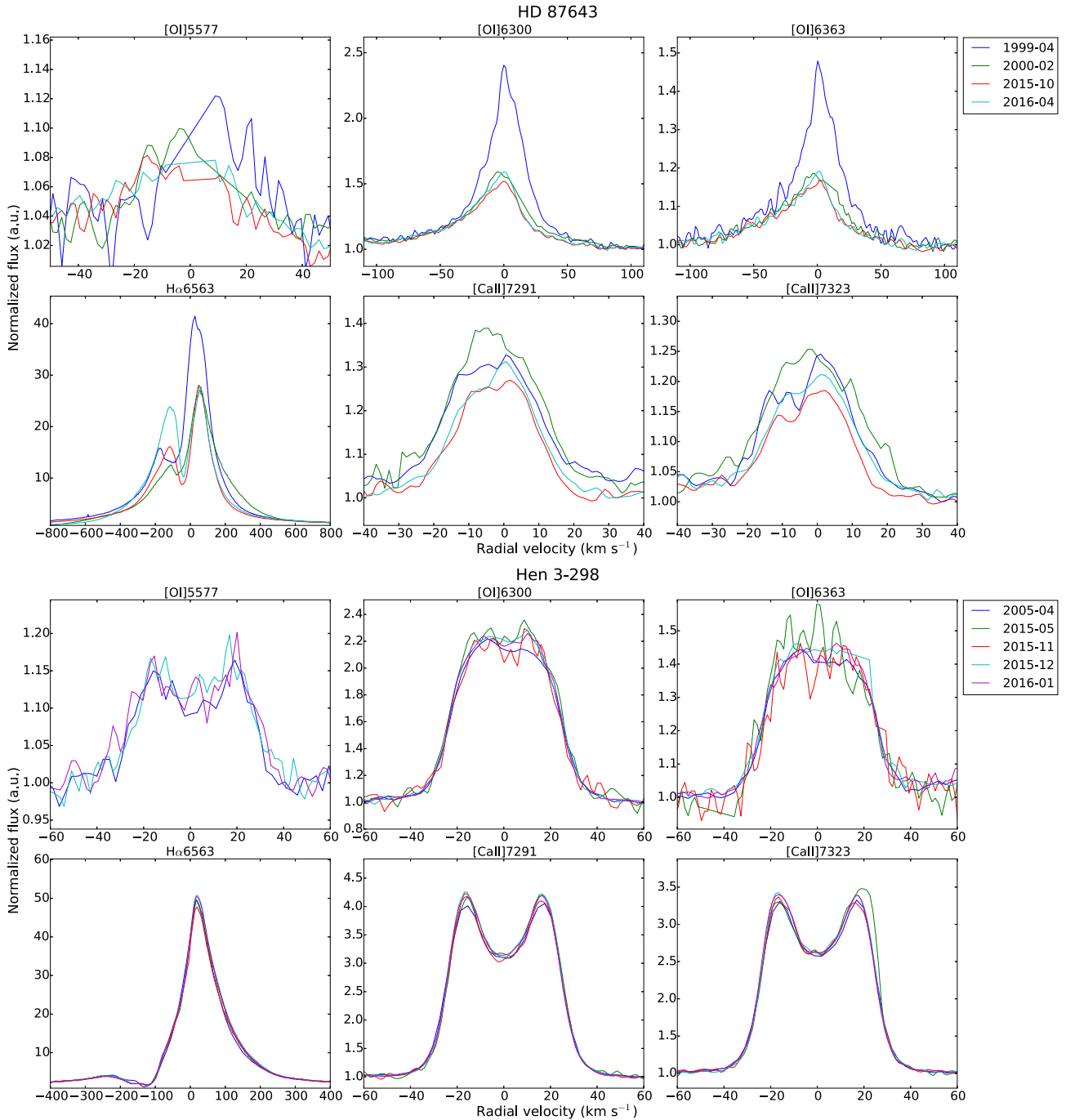
All observations (1999–2015) of GG Car are presented in Fig. 7. There is no sign of the [O I]  $\lambda$ 5577 line, contrary to the doublets of [Ca II] and [O I]. We model the [Ca II]  $\lambda$ 7291 line with a single ring at 95.8 km s<sup>-1</sup>, which implies a stable-forming region throughout all epochs (see Fig. 8) although the profile asymmetries point to inhomogeneous rings. The [O I]  $\lambda$ 6300 line can be modelled with two complete rings throughout all epochs, with velocities ranging



**Figure 8.** Similar to Fig. 3. From the top to bottom, GG Car: the models of a single partial ring and two complete rings for the [Ca II]  $\lambda$ 7291 (2008 December 22) and the [O I]  $\lambda$ 6300 (2000-02-23) lines, respectively; MWC 137: the four-ring model for the [O I]  $\lambda$ 6300 (2016-02-28) line; HD 87643: the complete ring and the four partial-ring models for the [Ca II]  $\lambda$ 7291 and the [O I]  $\lambda$ 6300 lines (from 2015-10-13); Hen 3-298: the [Ca II]  $\lambda$ 7291 (2015-05-10), the [O I]  $\lambda$ 6300 (2016-01-11), and the [O I]  $\lambda$ 5577 (2016-01-11) lines with their corresponding models of single complete rings.

from 91.5–77 to 35.5–28 km s<sup>-1</sup>. However, for the 2008-12-22 line profile, we need to add another (third) ring at 51 km s<sup>-1</sup> located in between the other two. This might imply some movement of gas from a region of high rotational velocity to a low one as it dissolves,

although we note that we do not find this (or any similar) ring later on (even though the next observation is only half a year later, on 2009-06-09; see Table A5). Moreover, it is interesting to point out that after 2009 the velocity found for the innermost ring decreases



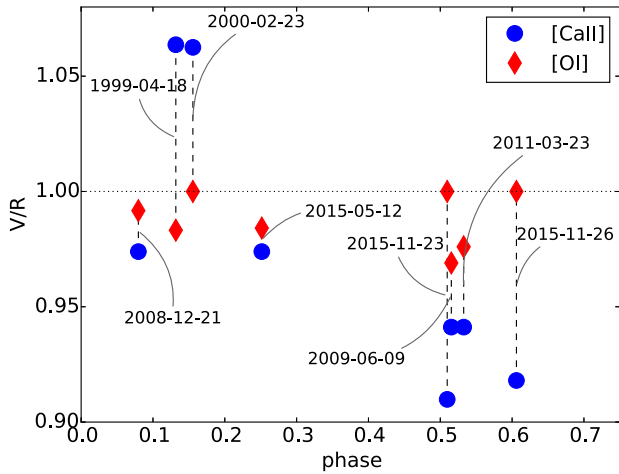
**Figure 9.** Similar to Fig. 2 but for HD 87643 (1999–2016) and Hen 3-298 (2005–2016, excluding the [O I]  $\lambda$ 5577 line from 2015-05-11 and 2015-11-26 because of the noise).

from  $\sim 91 \text{ km s}^{-1}$  to  $\sim 80 \text{ km s}^{-1}$ , and we can only speculate that this may be associated with the formation of the third ring observed in 2008. In contrast, the outermost one has remained stable. Therefore, we opt to describe the forming regions for [O I] with two rings at averaged velocities of  $84.3$  and  $29.9 \text{ km s}^{-1}$ .

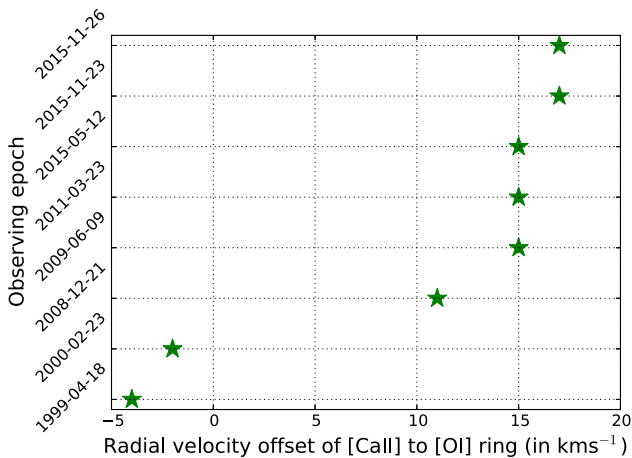
Given our typical ring-width of  $9 \text{ km s}^{-1}$ , we suggest the existence of two distinct rings around GG Car, one close to the star where the atomic gas coexists with CO, and another one further outside where only [O I] emission is excited. Using the stellar mass estimate of  $38 M_{\odot}$  (Kraus et al. 2013), we find ring radii of  $3.7$ – $4.7 \text{ au}$  and  $37.7 \text{ au}$ . GG Car is an eccentric binary system (with a maximum

separation of  $0.83 \text{ au}$ ), and the CO emission originates from a circumbinary ring (Kraus et al. 2013; Marchiano et al. 2012). Since the atomic gas of the innermost ring follows the CO behaviour, we conclude that the whole structure is circumbinary. This is in contrast to the findings of Marchiano et al. (2012), who used a spectral energy distribution fitting to calculate a gaseous envelope located at  $\sim 0.5 \text{ au}$ , lying in between the two components of the binary.

With respect to the intensity variability of the lines, the [O I] line displays the weakest lines in 1999 and 2008, and the strongest ones in November 2015. The [Ca II] line though does not show significant intensity variation, its  $V/R$  varies considerably with respect to



**Figure 10.** Same as Fig. 5, but for GG Car. The [Ca II]  $\lambda 7291$  line displays stronger variation of  $V/R$  than the [O I]  $\lambda 6300$  line.



**Figure 11.** The time evolution of the radial velocity offset of the [Ca II]  $\lambda 7291$  line to the [O I]  $\lambda 6300$  line, for the case of GG Car.

the [O I] line (Fig. 10). Furthermore, we find that the [Ca II] line displays an offset with respect to values measured for the [O I] line, ranging from  $-4$  to  $+17$   $\text{km s}^{-1}$  (on top of the systemic velocity of  $-22$   $\text{km s}^{-1}$ ). In Fig. 11, we show the evolution of this offset with time, which may be indicative of displacements of these rings/lines with respect to each other.

We note also the strong variation in the  $H\alpha$  line. There are significant changes in the intensity of its red peak with a  $V/R$  range of  $\sim 0.2$ – $0.45$  (in 2015 and 2008, respectively). There is also an evolution of the central absorption feature from  $\sim -111$   $\text{km s}^{-1}$  (1999) to  $\sim -135$   $\text{km s}^{-1}$  (2015 November), which may indicate an increase in the expansion of the ionized material, as the  $H\alpha$  line includes much broader regions (e.g. polar wind) than the equatorial disc/rings that give rise to the other observed lines.

#### 4.6 MWC 137

MWC 137 is embedded into a rich CSE (Kraus et al. 2017). Although its nature has been debated, observations favour a post-main-sequence scenario (Mehner et al. 2016), especially with the detection of both  $^{12}\text{CO}$  and  $^{13}\text{CO}$  emission features (Oksala et al. 2013; Muratore et al. 2015). In Fig. 1, we present the, rather noisy,

CRIRES spectrum of MWC 137 with a model for the CO originating from a rotating ring at  $84$   $\text{km s}^{-1}$  (Muratore et al. 2015). Due to the unknown inclination angle, this velocity (as well as the ones derived from the forbidden optical lines) corresponds to the line-of-sight velocities, i.e. they are lower limits of the real rotational velocities.

Fig. 7 shows the optical line profiles from two observations in 2015 and 2016. We do not see any sign of the [O I]  $\lambda 5577$  line, but most striking is the absence of the [Ca II] doublet. We get a strong signal from the [O I] doublet, with a clear symmetrical profile that requires a four-ring model (at 20.3, 31.0, 46.8, and 68.0  $\text{km s}^{-1}$ ; see Fig. 8 and Table A6). Considering the typical ring-width of  $7$   $\text{km s}^{-1}$ , these four rings form distinct regions. As these velocities are smaller than that of the CO ring, their corresponding rings are located further away from the CO ring (with no other emitting region closer to the star). Using a stellar mass estimate of  $10$ – $15$   $M_{\odot}$  (Mehner et al. 2016), we can calculate the ring radii for the CO and the four [O I] rings (see Table 3).

Due to the very short time difference between the two observations (only a few months), there is hardly any difference in the lines. Zickgraf (2003) was able to resolve the [O I]  $\lambda 6300$  line in 1988 (cf. his fig. 2) and, although we cannot really be certain about its wings, the peak separation he found is  $\sim 30$   $\text{km s}^{-1}$  comparable to our observations. Regarding  $H\alpha$ , there are additional spectra from 1986/1988 (Zickgraf 2003) and from 2011/2013 (Kraus et al. 2017), which do not show significant changes. It is interesting to note that Mehner et al. (2016) discovered a jet (better traced in [N II]  $\lambda 6583$ ). They argue that the central position of MWC 137 in the nebula and the jet suggests that it is the origin of both, which is not confirmed by a more detailed analysis of the kinematics of the nebula around MWC 137 (Kraus et al. 2017). In any case, the presence of such a jet is quite puzzling, and if it is actually connected with MWC 137, then it might (most likely) originate from an accretion disc around a compact object, i.e. a hint for a possible binary system like CI Cam (Clark 2006).

#### 4.7 HD 87643

HD 87643 is another source embedded in a reflection nebula (e.g. Crampton 1971; van den Bergh 1972; Surdej & Swings 1983). It has been studied extensively (e.g. Oudmajer et al. 1998; Zickgraf 2003; Millour et al. 2009), but CO emission features have been elusive. In the near-IR survey by McGregor et al. (1988), no clear identification of CO was made (for observations obtained in Jan 1985). In this work, we report for the first time the unequivocal detection of CO band emission, modelled with a rotating ring at  $11 \pm 1$   $\text{km s}^{-1}$  (Fig. 1), corresponding to the line-of-sight velocity due to the unknown inclination angle.

In Fig. 9, we plot the profiles from all observations in the 1999–2015 period. We have excluded the 2015-05-12 spectrum because the exposure has been either compromised or of too low S/N ratio to be useful. There is no emission from [O I]  $\lambda 5577$  line, and the small visible peaks are the residuals of the sky emission line at  $\lambda 5577.3$  due to the imperfect sky subtraction process. We clearly detect though the [Ca II] and the [O I] doublets. To fit the observed profiles of the [Ca II]  $\lambda 7291$  line, we use a single complete ring (see Fig. 8). It is interesting to point out that we see a decrease of the [Ca II] rotational velocity with time from  $\sim 12$  to  $\sim 10$   $\text{km s}^{-1}$  in 1999/2000 and 2015/2016, respectively, which is also obvious from the change in profile widths. This could indicate a movement of gas away from the central source. Nevertheless, we opt to describe the forming region of [Ca II] with a single ring of an averaged rotational



velocity of  $10.6 \text{ km s}^{-1}$ . The [Ca II] velocities are similar to the CO one, which implies that the two gases coexist.

Regarding the [O I]  $\lambda 6300$  line (the intensity changes are discussed further below), the observed profiles can be fit with a model of four half-filled rings. The first two (closer to the star) seem to be stable structures as their corresponding velocities do not change much with time (within the  $\sim 86\text{--}91$  and  $\sim 54\text{--}33 \text{ km s}^{-1}$  range; see Table A7). However, the other two display some differences: from  $\sim 24$  to  $\sim 33 \text{ km s}^{-1}$  for the 1999/2000 and 2015/2016 epochs, and from  $<3 \text{ km s}^{-1}$  in 1999 to  $\sim 9\text{--}10 \text{ km s}^{-1}$  in 2000/2015/2016. Within the proposed scenario of Keplerian rotation, these changes would be interpreted as formation of new emitting [O I] regions (further away from the star), possible after the dissolution of the previous rings. We opt again to describe the HD 87643's disc structure with four rings at (averaged) velocities of 9.7, 28.1, 61.0, and  $89.1 \text{ km s}^{-1}$ . Of these, only one (at  $9.7 \text{ km s}^{-1}$ ) coincides with the [Ca II] and the CO gases, while the other three form closer to the star. Considering our typical ring-width is  $\sim 11 \text{ km s}^{-1}$ , we conclude that the derived rings for the [O I] form distinct regions. The need of partially filled rings shows also a strong asymmetry on the equatorial distribution between the [O I] regions and the complete [Ca II]/CO rings.

Currently, the stellar mass of HD 87643 is not well constrained. Oudmaijer et al. (1998) have used a mass of  $25 M_{\odot}$  for calculations regarding its stellar wind. Using this estimate, our closest (to the star) [O I] ring and the CO ring would have a radius of  $\sim 3 \text{ au}$  and  $\sim 200 \text{ au}$ , respectively. Millour et al. (2009) have resolved HD 87643 to identify a binary system that consists of a primary giant/supergiant hot star with a dusty circumprimary disc and a companion that is much fainter and embedded in its own dusty envelope (with a separation of  $51 \text{ au}$ , at  $1.5 \text{ kpc}$ ), as well as a cooler circumbinary envelope. They find the dusty circumprimary disc at  $\sim 6 \text{ au}$ , and they estimate a radius of  $\sim 2.5\text{--}3.0 \text{ au}$  for the inner gaseous disc. This is fairly consistent with the location of our first [O I] ring, but not with the rest of the structure, as they are found in between the binary and/or further away (coexisting with much cooler dust). Even if we assume that the stellar mass estimate is wrong and we use the smallest mass definition for massive stars ( $8 M_{\odot}$ ), the CO ring is found at  $\sim 59 \text{ au}$ , still an order of magnitude difference and circumbinary. In any case, if the position of the CO ring was really somewhere in between these locations, it would have been easily resolved with interferometry. The fact that this is not what we observe may actually provide a constraint regarding the inclination angle. Assuming that CO originates from the inner rim of the dusty circumprimary disc as found from interferometry ( $3 \text{ au}$  at  $1.5 \text{ kpc}$ ), the mass estimate of  $25 M_{\odot}$ , and the line-of-sight rotational velocity for CO at  $11 \text{ km s}^{-1}$ , we estimate an inclination angle of  $7^{\circ}4$ , which corresponds to a pole-on system. Then, our results are compatible with interferometry as all the [O I] rings are found within the gaseous disc ( $<3 \text{ au}$ ). In Table 3, we present the ring radii derived using both the line-of-sight velocities and the de-projected ones using this inclination angle.<sup>3</sup> The proposed approach has admittedly some issues to explain, for example, how such a nearly pole-on system displays high level of polarization and possibly the photometric variability. Nevertheless, it is a valid

<sup>3</sup>Considering the *GAIA* results to solve the distance uncertainty does not help to put more constraints in HD 87643's nature. The measured parallax of  $6.92 \pm 0.27 \text{ mas}$  (from DR1) and  $0.01 \pm 0.12 \text{ mas}$  (from DR2) corresponds approximately to  $\sim 0.14 \text{ kpc}$  and  $\sim 100 \text{ kpc}$ , respectively. These values are obviously inconsistent, while even the DR2 value alone is highly unreliable.

attempt to construct a common picture derived from both near-IR and optical data. Certainly, higher spectral and angular resolution observations could help to better resolve the CSE.

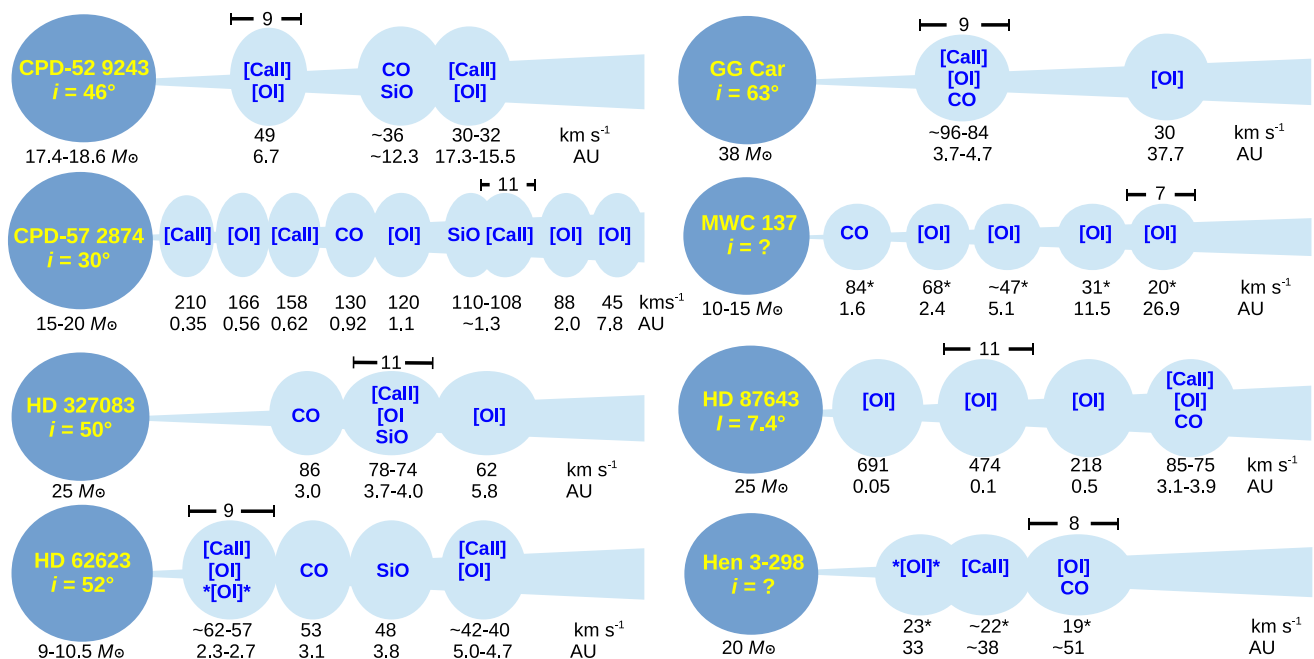
There is a striking change in the intensity of the [O I] doublet and the  $H\alpha$  line between the first epoch (1999-04-18) and others. This is a quite dramatic change especially for the [O I] lines when comparing with the second epoch (2000-02-23), which is only 10 months later. This line has been observed in 1988 by Zickgraf (2003), who shows a profile similar to our observations after 1999 but with a less extended blue wing (cf. his fig. 2). The  $H\alpha$  line exhibits significant changes too. The  $V/R$  is increasing steadily since 1999, from  $\sim 0.4$  to  $\sim 0.8$  in 2016. There are radial velocity changes in the blue peak and the absorption component, but without any significant changes for the red peak. When comparing with the observations by Zickgraf (2003) in 1986 and 1988 (cf. his fig. 1), we see that there are small differences between the two epochs. More importantly, though, the  $V/R$  ratio remains low, similar perhaps to our 1999/2000 observations. Unfortunately, there are no data for the 1988–1999 period to show us if this ratio has been systematically constant or not over this period, hiding any possible periodicity.

#### 4.8 Hen 3-298

CO emission features have been reported previously by a number of works (Miroshnichenko et al. 2005; Muratore et al. 2012; Oksala et al. 2013). From our CRIRES data (2009 December 2), we model the CO emission from a rotating ring at  $19 \pm 1 \text{ km s}^{-1}$  (Fig. 1). This value is in agreement with the  $17.8 \pm 0.4 \text{ km s}^{-1}$  found by Miroshnichenko et al. (2005), by fitting the second CO bandhead (from observations in 2002 December and 2004 May). We note that for Hen 3-298 also the derived rotational velocities are lower limits, corresponding to the line-of-sight velocities.

In Fig. 9, we show the line profiles from observations from 2005 to 2016. We detect all the optical forbidden emission with clear double-peaked profiles. Miroshnichenko et al. (2005) detected the [Ca II] and [O I] doublets (without any reference on the [O I]  $\lambda 5577$  line) as single-peaked, mainly because of the lower resolution ( $R \sim 15000$ ) of their observations. We fit each of the lines using a single and complete emitting ring, with rotating velocities of 23.2, 21.5, and  $18.7 \text{ km s}^{-1}$  for the [O I]  $\lambda 5577$ , the [Ca II]  $\lambda 7291$ , and the [O I]  $\lambda 6300$  lines, respectively (see Fig. 8 and Table A8). From these velocities, we find the [O I]  $\lambda 5577$  closer to the star, the [Ca II] ring further out, and the outermost [O I] (doublet) ring further away, coexisting with the CO emission region. Given the typical ring-width of  $8 \text{ km s}^{-1}$  for Hen 3-298, it is probable that these regions overlap. To calculate the ring radii, we estimate a stellar mass of  $20 M_{\odot}$ , by using the evolutionary track that best fits its position in the Hertzsprung–Russell diagram (see fig. 12 in Oksala et al. 2013).

Over an 11-yr period, Hen 3-298 displays remarkable stability, with only minor changes in the profiles of the [O I] and [Ca II] doublets. The observed  $H\alpha$  line profiles are similar to the profile presented by Miroshnichenko et al. (2005). From their observations in 2002 (cf. their fig. 1d),  $H\alpha$  shows a P-Cygni profile with a strong red peak ( $\sim 55 \text{ km s}^{-1}$ ) and a central absorption at  $\sim -120 \text{ km s}^{-1}$ , similar to our data. Thus, we can conclude that  $H\alpha$  has remained stable over the 2002–2016 period. However, we cannot claim any differences for the metal lines between the 2002 observations by Miroshnichenko et al. (2005) and our first data set (2005) because of the lower resolution of the former work.



**Figure 12.** A cartoon illustration of the disc structures as derived from our analysis. We represent the [O I]  $\lambda 5577$  line as  $*[O I]*$ , the [O I]  $\lambda\lambda 6300, 6363$  doublet as [O I], and the [Ca II]  $\lambda\lambda 7291, 7323$  as [Ca II]. The arrows above the rings symbolize the typical ring-widths and are given in  $\text{km s}^{-1}$ . For more details on the data used and references, see Table 3. Note that the relative structures and sizes are not in scale.

## 5 DISCUSSION

### 5.1 A common picture?

Our main motivation for this work is to discuss the CSE properties of B[e]SGs with a consistent and homogeneous approach (both during the observations and the analysis) in an attempt to investigate whether there is a common description. To better illustrate our results (from Table 3), we have created a cartoon presentation of the disc structures in Fig. 12. We present a section along the disc of each object and on top of this we show the individual ring structures identified.

Regarding our disc tracers, the [O I]  $\lambda 5577$  line is found only in two objects, in the binary HD 62623 and in Hen 3-298. Its position is always located in a single region and very close to the star as expected (Kraus et al. 2007, 2010; Aret et al. 2012). Its presence in a confirmed binary system and a (currently considered) single one does not provide any further constraints regarding its appearance. On the other hand, the [Ca II]  $\lambda\lambda 7291, 7323$  and the [O I]  $\lambda\lambda 6300, 6363$  doublets are detected in all objects, with the exception of MWC 137 in which no [Ca II] is detected. In many cases, we find that the two doublets are formed in the same or near-by regions, and sometimes coexist with the molecular gases (CO and SiO). Our results show that the circumstellar discs around B[e]SGs are far different from the classic picture of homogeneous outflowing structures (Zickgraf et al. 1985). Given the Keplerian rotation of the gas, we find that these discs are a composition of atomic and molecular gases that form local enhancements with the appropriate conditions to give rise to the corresponding lines, a result that seems to be common among sources in the Galaxy and the Magellanic Clouds (Aret et al. 2012; Kraus et al. 2016, 2017; Torres et al. 2018). In all stars, we find distinct, but not necessarily homogeneous, rings, except for CPD-57 2874, where we see a continuous set of rings that points perhaps to an inhomogeneous disc. A visual inspection

of our results, as illustrated in Fig. 12, does not provide a common picture regarding the distribution of the atomic and molecular rings in the CSE. It seems that each source, regardless if it is a binary system with an orbital period of a few tens of days (GG Car, HD 327083) or much longer (HD 87643), a single star (Hen 3-298), or embedded in a nebula (MWC 137, HD 87643), displays a unique combination.

It is appropriate though to also include information about the position of the dust as derived from the interferometric studies. Dust is found to coexist with the rings of atomic ([O I]  $\lambda 6300$  and [Ca II]  $\lambda 7291$  lines) and molecular gas (CO and SiO). In particular, we observe the following:

- (i) In CPD-52 9243, dust is found at  $\sim 15$  au (Cidale et al. 2012) in between the molecular (CO and SiO) and atomic ([O I] and [Ca II]) rings at 12 and 17 au, respectively.
- (ii) In HD 327083, the dust's position at  $\sim 5$  au (Wheelwright et al. 2012b) is very close to the position of the CO ring at 3 au and the [O I], [Ca II], and SiO ring at  $\sim 4$  au.
- (iii) In HD 62623, the dusty disc is located at  $\sim 4$  au (Millour et al. 2011), where we find the SiO ring, in between the CO ring at  $\sim 3$  au and the [O I] and [Ca II] ring at  $\sim 5$  au.
- (iv) In CPD-57 2874, dust is located approximately at 11–14 au (Domiciano de Souza et al. 2011) from mid-IR observations, but they state that they are not able to resolve the near-IR emission (located at  $\sim 8$  au), which is a combination of ionized material and includes the tail of the dust identified in the mid-IR. Our structure extends up to  $\sim 8$  au, so possible we do have some presence of dust coexisting with parts of the inhomogeneous disc, which consists of alternate regions of atomic and molecular gas.
- (v) In order to better correlate our results with interferometry for HD 87643, we have used the position of the CO ring to match the inner rim of the dusty ring (3 au) to derive the possible inclination

angle for this system. Nevertheless, we do find in the same region CO and atomic gas, with dust.

(vi) For GG Car, an estimate of a dusty envelope is made through SED fitting (Marchiano et al. 2012) starting at approximately 34 au. This location coincides with the position of a [O I] (at  $\sim 35$  au), but is further apart than the other ring that combines CO, [O I], and [Ca II] (at  $\sim 4$  au).

(vii) There are no interferometric observations for MWC 137 and Hen 3-298, so no solid conclusions regarding the position of the dust with respect to the identified rings can be made for these objects.

In total, we see that in all objects for which we do have a resolved CSE, excluding MWC 137, Hen 3-298, and possible GG Car, we see that the presence of the dust correlates directly with the presence of atomic and molecular gas. Due to the different conditions of temperature and density for the emission forming regions, it is possible that we see the contribution of different layers in a disc displaying different optical depths for the stellar radiation.<sup>4</sup>

As the B[e] phenomenon occurs in different evolution stages (Lamers et al. 1998), including pre-main-sequence stars that are known to have gaps in their circumstellar discs (e.g. Menu et al. 2015), it would be tempting to claim that the observed differences may be due to the different nature of the objects. However, our sample consists of stars with strong evidence in favour of their supergiant nature. An exception might be HD 87643, which is still considered a pre-main-sequence source, although it does not fully comply with this group (see e.g. Carmona et al. 2011 regarding the lack of H<sub>2</sub> emission lines). Nevertheless, the uniqueness of each CSE shows how the formation mechanisms work in each system. For example, in binary systems, the circumbinary ring formation is connected with the phases of interaction. The length and violence of these phases critically depend on the closeness of the components, their stellar parameters, the eccentricity of the system, etc., resulting in unique sets of rings. In single stars, the situation is more tricky as the degeneracy of their evolutionary state (pre- versus post-RSGs) means that they have experienced different mass-loss episodes. In addition, physical processes like rotation and pulsations may be involved, but to investigate these in more detail is beyond the scope of this paper.

## 5.2 On the CSE formation

Binary interaction is considered as one major channel to form these structures (e.g. Miroshnichenko 2007; Millour et al. 2011; Wheelwright et al. 2012b). Half of our sample is actually confirmed binaries: HD 327083, HD 62623, GG Car, and HD 87643 (excluding CPD-52 9243 which has only been suggested to be a binary; Cidale et al. 2012), but this fraction does not correspond to their total population ( $\sim 20$  per cent, see Kraus 2017). For both HD 327083 and GG Car, we do not find any other emission-forming region closer to the star than the CO ring, while the opposite is true for HD 62623 and HD 87643. This follows our previous result on the uniqueness of the CSE around each B[e]SG. In the cases of HD 327083,

HD 62623, and GG Car, the innermost ring is always larger than the binary separation. The fact that the rings around these binary B[e]SGs are found to be circumbinary can fit well in the binary interaction scenario. None the less, in HD 87643, we actually find a circumpriary structure.

In the absence of any confirmation for binarity in the rest of our sample, we should consider a different mechanism that forms these structures in single stars. It is possible that they are the results of mass-loss triggered by pulsations and/or other instabilities. B[e]SGs may be the successors of Yellow Hypergiants, after passing the Yellow Void (Davies, Oudmaijer & Sahu 2007; Aret et al. 2017). Since the mass-loss in these hypergiants is believed to originate from pulsations (de Jager 1998), it is possible that the CSE in these two phases is the result of a common/similar pulsation mechanism. Indications for such stellar pulsations have been found for the LHA 120-S 73 (Kraus et al. 2016) and LHA 120-S 35 (Torres et al. 2018). Alternative scenarios include either the presence of objects that can clear their paths and stabilize these ring structures similar to shepherd moons (Kraus et al. 2016).

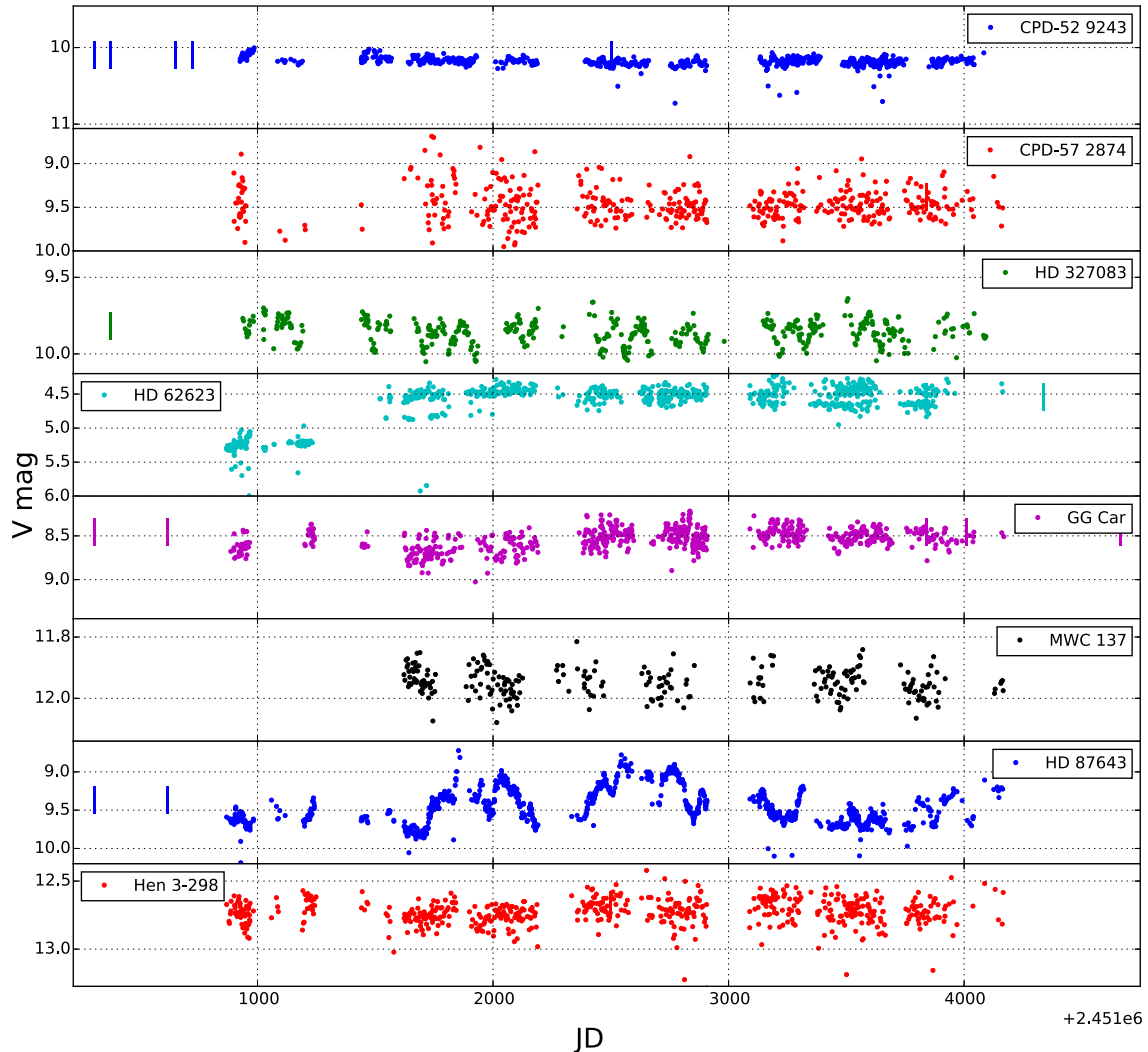
Most observational evidence favour a Keplerian rotation for the discs (e.g. Marchiano et al. 2012; Kraus et al. 2015). Nevertheless, it is possible that these multi-ring structures that we see may be due to a different distribution of the CSE. In an hourglass-like or in a spiral-arm structure, these rings could correspond to density enhancements as the projection along the line of sight. Such a formation could result from wind–wind interactions. For example, Chita et al. (2008) simulate the interaction of an asymmetric wind of a post-RSG B[e]SG, which interacts with the material shed spherically during its RSG phase. To date, it is not known whether B[e]SGs are post- or pre-RSG objects. An indication of their age can be obtained from the ratio <sup>12</sup>CO/<sup>13</sup>CO (which decreases as the star evolves; Kraus 2009), but yet this method is applicable only to objects with detected CO emission and with known rotation speed.

## 5.3 On the variability

We have described the observed spectral variability for each source individually in Section 4, so in this section we discuss all sources globally.

Among all sources, the line profiles of Hen 3-298 and CPD-57 2874 remain almost constant throughout all epochs, spanning 11 yr (2005–2016) and 8 yr (2008–2016), respectively. The [O I] and [Ca II] lines of the binary HD 62623 are stable, in contrast to the variable H $\alpha$  line (over the 2008–2015 period). CPD-52 9243 and the binary HD 87643 display more evident variability in their line intensities (with these changes being much stronger in the second source), over a similar time period (1999–2016). The binaries GG Car and HD 327083 exhibit the most drastic changes regarding both their line intensities and their profiles (over the 1999–2016 period). Assuming that the observed variability could be attributed at least partly to the binary interaction, we could argue that binaries display a more variable CSE (for GG Car, HD 327083, HD 87643, and HD 62623 – albeit only in H $\alpha$ ). Interestingly, CPD-52 9243 exhibits some variability, and following that trend we could suggest potential binarity, further supporting previous indications (Cidale et al. 2012). We cannot comment on the variability of MWC 137 for which we have obtained only two data sets very close in time ( $\sim 3$  months) and there is hardly any difference.

<sup>4</sup>The coexistence of the atomic gases is not unphysical, since the corresponding excitation energies are similar. In particular, for the [O I]  $\lambda 5577$  line, the [O I]  $\lambda \lambda 6300, 6363$  doublet, and the [Ca II]  $\lambda \lambda 7291, 7323$  doublet, these are 2.23, 1.97, and 1.70 eV, respectively (data derived from the National Institute of Standards and Technology (NIST) Atomic Spectra Database Levels Form, at [https://physics.nist.gov/PhysRefData/ASD/levels\\_form.html](https://physics.nist.gov/PhysRefData/ASD/levels_form.html), accessed on February, 7, 2018).



**Figure 13.** The ASAS  $V$ -band light curves for our objects, covering approximately the period November 2000–2009 (dots). We also indicate the dates of our optical spectroscopic observations as vertical lines. (See text for a discussion on the variability and the derived periods for each source).

To further explore the correlation of binaries with variability, we examine the light curves obtained from the ASAS survey<sup>5</sup>, since it is more suitable for the relatively bright sources of our sample (which saturate in OGLE). In Fig. 13, we show the  $V$ -band photometry covering approximately the 2000 November to 2009 November period (9 yr). We used the most reliable measurements (flagged with a quality grade of A or B) for which we calculated an average magnitude from all five apertures accompanied by an error estimated as the square root of all errors. Along with the photometric points, we also show the dates of our optical spectroscopic observations (vertical lines). Unfortunately, the overlap between the photometric and the spectroscopic observations is scarce, so we cannot derive any conclusion with respect to this correlation. From Fig. 13, the variability of the confirmed binaries HD 327083 and HD 87643 is prominent, while for GG Car and HD 62623 it is much less evident (the latter one also displays a brightening event after the start of the observations at  $V \sim 5.5$  to  $\sim 4.5$  mag, but care should be taken in total since it may well be saturated even for ASAS). For the rest, the variability may be stochastic or not. To further investigate this,

we obtained the Lomb–Scargle periodograms (Lomb 1976; Scargle 1982) for the entire light curves as well as for a number of individual data sets (e.g. one or more consequent years) of continuous coverage. The last step was performed in order to exclude periods that do not persist throughout the data and may arise from data sampling of the full light curves. Then, we identify all potential periods above the 99 per cent confidence level, which was estimated by simulating light curves based on the noise characteristics of the data and repeating the analysis for each simulated light curve. The results are presented in Table 4.

We can identify the previously derived periods for GG Car and HD 62623, as well as the period of  $\sim 107$  d for HD 327083, which is also found by Cidale et al. (in preparation). We note here the identification of some periods for HD 87643, although its orbital period is considered to be of several decades (Millour et al. 2009), well beyond the baseline of this data set. Similar with the spectral variability, we see that all the four confirmed binaries do display numerous periods. CPD-52 9243’s behaviour is again similar to the other binaries. For the least variable objects CPD-57 2874 and MWC 137, we have identified only one (and rather weak) period. For Hen 3-298, we cannot detect any significant period (even at the

<sup>5</sup><http://www.astrouw.edu.pl/asas/> (Pojmanski 1997).



**Table 4.** Detected periods at 99 per cent confidence level.

Object	Periods (d)	
	This work	Previous
CPD-52 9243	24.7, 66.3, 174.2	–
CPD-57 2874	21.5	–
HD 327083	20.0, 23.9, 53.8, 82.3, 93.4, 107.9, 118.4, 152.6, 171.6	107.687 <sup>1</sup>
HD 62623	136.9, 162.0, 237.1, 276.6 308.8, 349.4, 414.8	138.5, 161.3 <sup>2</sup>
GG Car	31.0, 33.8	31.033 <sup>3</sup>
MWC 137	332.4	–
HD 87643	104.8, 117.1, 147.1, 172.7, 192.7	–
Hen 3-298	none <sup>a</sup>	–

Notes. <sup>a</sup> No period detection even at the 90 per cent confidence level.

1 – Cidale et al., in preparation; 2 – Plets, Waelkens & Trams (1995); 3 – Marchiano et al. (2012).

90 per cent confidence level). We point though that the current, not exhausting, analysis of these light curves does solve for the nature of these periods, as some may not be related to the binaries but to other causes (e.g. disc activity, stellar pulsations).

## 6 CONCLUSION

With this work we present our results obtained from high-resolution optical (FEROS) and IR (CRIRES) spectroscopy for eight Galactic B[e]SGs with CO emission. Our goal is to understand the structure of the discs around the B[e]SGs. Assuming that CO emission originates from a Keplerian-rotating disc and that the atomic gas of the circumstellar environment follows this distribution, we modelled the [O I]  $\lambda$ 5577,  $\lambda$ 6300, and [Ca II] 7291 lines as emission from rotating rings. Their derived kinematics correspond to certain distances that allow us to probe the structure of their discs. We find that all B[e]SGs of our sample are surrounded by multiple ring-like structures. The distribution of these gas rings is unique for each object, without any particular preference or dependance on binarity. This interpretation is based on the Keplerian rotation of the disc but alternative scenarios, e.g. an hourglass or spiral-arm distribution, can result in local enhancements similar to the observed structures.

Multiple epochs of spectroscopic observations help us to investigate the variability and the stability of these structures over time. We have identified the trend that binaries display the largest intensity and profile variability of their optical lines. This is further supported by a preliminary analysis of ASAS optical light curves, from which we have detected a number of periods for binaries. However, to date, there is no consensus on whether binarity causes the formation of the ring structures, in particular since not all studied objects have a companion. Alternative scenarios such as (quasi-)periodic mass ejections triggered by pulsations or other instabilities are worth being studied in more detail.

## ACKNOWLEDGEMENTS

The authors would like to thank the anonymous referee for their constructive feedback. GM acknowledges support from CONICYT, Programa de Astronomía/PCI, FONDO ALMA 2014, Proyecto No 31140024, and GA ČR under grant number 14-21373S. He also thanks Theodoros Bitsakis and Alexandros Maragkoudakis for fruitful discussions during the project. MK acknowledges financial support from GA ČR (grant number 17-02337S). The Astronomi-

cal Institute Ondřejov is supported by the project RVO:67985815. This research was also supported by the European Union European Regional Development Fund, project ‘Benefits for Estonian Society from Space Research and Application’ (KOMEET, 2014 - 2020. 4. 01. 16 - 0029) and by the institutional research funding IUT40-1 of the Estonian Ministry of Education and Research. Parts of the observations obtained with the MPG 2.2-m telescope were supported by the Ministry of Education, Youth and Sports project – LG14013 (Tycho Brahe: Supporting Ground-based Astronomical Observations). We would like to thank the observers (S. Ehlerova, P. Kabath, A. Kawka, and S. Vennes) for obtaining the data. LSC thanks financial support from the Agencia de Promoción Científica y Tecnológica (Préstamo BID PICT 2016/1971), CONICET (PIP 0177), and the Universidad Nacional de La Plata (Programa de Incentivos G11/137), Argentina. LSC and MC thank the support from the project CONICYT and PAI/Atracción de capital humano avanzado del extranjero (folio PAI80160057). MC acknowledges support from Centro de Astrofísica de Valparaíso.

This research has made use of NASA’s Astrophysics Data System, and of the SIMBAD database, operated at CDS, Strasbourg, France. It has used MATPLOTLIB, a PYTHON library for publication quality graphics (Hunter 2007), Astropy, a community-developed CORE PYTHON package for Astronomy (Astropy Collaboration et al. 2013), and NUMPY (Van Der Walt, Colbert & Varoquaux 2011). IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation (Tody 1993). PYRAF is a product of the Space Telescope Science Institute, which is operated by AURA for NASA. This research has made use of the services of the ESO Science Archive Facility. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (<https://www.cosmos.esa.int/gaia>), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

This study is based on observations under the ESO proposals: 384.D-0613(A) and 385.D-0513(A) for CRIRES, 075.D-0177(A), 082.A-9209(A), 085.D-0185(A), 094.A-9029(D), 095.A-9032(A), 096.A-9024(A), 096.A-9030(A), 096.A-9039(A), 097.A-9024(A), and 097.A-9039(C) for FEROS, and is based on observations done with the 1.52-m and 2.2-m telescopes at the European Southern Observatory (La Silla, Chile), under agreements ESO-Observatório Nacional/MCTIC and MPI-Observatório Nacional/MCTIC. This study is based on data obtained from the ESO Science Archive Facility under request numbers: 301274, 302259, 302651 (from ESO proposals: 091.D-0221(A), 096.A-9014(A)), and is based, in part, on observations obtained at the Gemini Observatory (GN-2012A-Q-21 for GNIRS), which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the National Research Council (Canada), CONICYT (Chile), Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina), and Ministério da Ciência, Tecnologia e Inovação (Brazil).

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## APPENDIX A: DETAILS ON THE INDIVIDUAL FITS

In this Appendix, we give the detailed information for each object regarding our fits for each line per epoch. For each fit, we provide the corresponding velocities, i.e. the rotational velocity ( $v_{\text{rot}}$ ) and the Gaussian component ( $v_g$ ), as well as the range of integrating angles and possible rotational velocities.

During the fit process, we integrate the line flux over a range of angles that are arbitrary selected. A starting angle of  $0^\circ$  is set at the right (red) part of the circle along the line of sight, and then

**Table A1.** Fitting the kinematics of CPD-52 9243.

Date (UT)	[Ca II] $\lambda$ 7291				[O I] $\lambda$ 6300			
	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$v_g$ ( $\text{km s}^{-1}$ )	Ring	Range ( $\text{km s}^{-1}$ )	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$v_g$ ( $\text{km s}^{-1}$ )	Ring	Range ( $\text{km s}^{-1}$ )
1999-04-19	$30.0 \pm 1.0$	$14.0 \pm 1.0$	Complete	[−30.0,30.0]	$33.0 \pm 1.0$	$12.0 \pm 1.0$	Complete	[−33.0,33.0]
	$49.0 \pm 1.0$	$9.0 \pm 1.0$	Complete	[−49.0,49.0]	$55.0 \pm 1.0$	$10.0 \pm 1.0$	Complete	[−55.0,55.0]
1999-06-25	$30.0 \pm 1.0$	$12.0 \pm 1.0$	Complete	[−30.0,30.0]	$34.0 \pm 1.0$	$12.0 \pm 1.0$	Complete	[−34.0,34.0]
	$49.0 \pm 1.0$	$10.0 \pm 1.0$	Complete	[−49.0,49.0]	$55.0 \pm 1.0$	$10.0 \pm 1.0$	Complete	[−55.0,55.0]
2000-03-28	$32.0 \pm 1.0$	$9.0 \pm 0.5$	Complete	[−32.0,32.0]	$35.0 \pm 3.0$	$11.5 \pm 2.5$	Complete	[−35.0,35.0]
	$52.0 \pm 1.0$	$10.0 \pm 1.0$	Complete	[−52.0,52.0]	$56.0 \pm 3.0$	$10.5 \pm 1.5$	Complete	[−56.0,56.0]
2000-06-11	$31.0 \pm 1.0$	$10.0 \pm 1.0$	0°–160°	[[31.0],  −29.1 ]	$31.0 \pm 2.0^b$	$11.0 \pm 1.0$	0°–125°	[[31.0],  −17.8 ]
	$48.0 \pm 1.0$	$10.0 \pm 1.0$	Complete	[−48.0,48.0]	$48.0 \pm 1.0$	$11.0 \pm 1.0$	Complete	[−48.0,48.0]
2005-04-21	$29.0 \pm 1.0$	$13.0 \pm 0.5$	Complete	[−29.0,29.0]	$29.5 \pm 1.5$	$13.0 \pm 1.0$	Complete	[−29.5,29.5]
	$48.0 \pm 1.0$	$12.0 \pm 1.0$	Complete	[−48.0,48.0]	$50.0 \pm 2.0$	$12.0 \pm 1.0$	Complete	[−50.0,50.0]
2015-05-13	$30.0 \pm 1.0$	$9.0 \pm 0.5$	Complete	[−30.0,30.0]	$36.0 \pm 1.0$	$11.0 \pm 1.0$	0°–145°	[[36.0],  −29.5 ]
	$48.0 \pm 1.0$	$9.0 \pm 1.0$	Complete	[−48.0,48.0]	$50.0 \pm 2.0$	$12.0 \pm 1.0$	Complete	[−50.0,50.0]
2015-10-11	$30.0 \pm 1.0$	$8.0 \pm 0.5$	Complete	[−30.0,30.0]	$28.0 \pm 1.0$	$10.0 \pm 1.0$	0°–160°	[[28.0],  −26.3 ]
	$48.0 \pm 1.0$	$10.0 \pm 1.0$	Complete	[−48.0,48.0]	$48.0 \pm 1.0$	$10.0 \pm 1.0$	Complete	[−48.0,48.0]
2016-04-13	$31.0 \pm 0.5$	$8.5 \pm 0.5$	0°–165°	[[31.0],  −29.9 ]	$33.0 \pm 1.0$	$11.0 \pm 1.0$	0°–140°	[[33.0],  −25.3 ]
	$48.0 \pm 1.0$	$10.0 \pm 1.0$	Complete	[−48.0,48.0]	$50.0 \pm 1.0$	$11.0 \pm 1.0$	Complete	[−50.0,50.0]
2016-08-02	$31.0 \pm 1.0^g$	$9.0 \pm 0.5$	30°–360°	[[26.8],  31.0 ]	$29.0 \pm 1.0$	$11.0 \pm 1.0$	Complete	[−29.0,29.0]
	$50.0 \pm 1.0$	$11.0 \pm 1.0$	Complete	[−50.0,50.0]	$51.0 \pm 1.0$	$11.5 \pm 0.5$	Complete	[−51.0,51.0]

**Table A2.** Fitting the kinematics of CPD-57 2874.

Date (UT)	[Ca II] $\lambda$ 7291				[O I] $\lambda$ 6300			
	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$v_g$ ( $\text{km s}^{-1}$ )	Ring	Range ( $\text{km s}^{-1}$ )	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$v_g$ ( $\text{km s}^{-1}$ )	Ring	Range ( $\text{km s}^{-1}$ )
2008-12-22	$110.0 \pm 3.0$	$14.0 \pm 1.0$	100°–260°	[[−19.1],  −19.1 ]	$42.0 \pm 2.0$	$12.0 \pm 1.0$	Complete	[−42.0,42.0]
	$109.0 \pm 3.0$	$14.0 \pm 1.0$	0°–90°	[[109],0]	$88.0 \pm 3.0$	$11.0 \pm 1.0$	Complete	[−88.0,88.0]
	$161.0 \pm 3.0$	$13.0 \pm 1.0$	Complete	[−161.0,161.0]	$120.0 \pm 2.0$	$12.0 \pm 1.0$	Complete	[−120.0,120.0]
	$208.0 \pm 8.0$	$10.0 \pm 2.0$	Complete	[−208.0,208.0]	$165.0 \pm 7.0$	$12.0 \pm 2.0$	Complete	[−165.0,165.0]
2015-05-13	$105.0 \pm 3.0$	$13.0 \pm 1.0$	100°–260°	[[−18.2],  −18.2 ]	$44.5 \pm 2.5$	$11.0 \pm 1.0$	Complete	[−44.5,44.5]
	$105.0 \pm 3.0$	$13.0 \pm 1.0$	0°–85°	[[105],  9.2 ]	$88.0 \pm 4.0$	$11.0 \pm 2.0$	Complete	[−88.0,88.0]
	$157.0 \pm 3.0$	$13.0 \pm 1.0$	Complete	[−157.0,157.0]	$121.0 \pm 3.0$	$13.0 \pm 2.0$	Complete	[−121.0,121.0]
	$220.0 \pm 5.0$	$10.0 \pm 2.0$	Complete	[−220.0,220.0]	$167.0 \pm 6.0$	$12.0 \pm 2.0$	Complete	[−167.0,167.0]
2016-01-13	$107.0 \pm 2.0$	$13.0 \pm 1.0$	100°–260°	[[−18.6],  −18.6 ]	$48.0 \pm 2.0$	$12.0 \pm 1.0$	Complete	[−48.0,48.0]
	$108.0 \pm 1.0$	$14.0 \pm 1.0$	0°–88°	[[108],  3.8 ]	$90.0 \pm 3.0$	$11.0 \pm 1.0$	Complete	[−90.0,90.0]
	$160.0 \pm 2.0$	$13.0 \pm 1.0$	Complete	[−160.0,160.0]	$123.0 \pm 4.0$	$13.0 \pm 2.0$	Complete	[−123.0,123.0]
	$213.0 \pm 5.0$	$12.0 \pm 2.0$	Complete	[−213.0,213.0]	$166.0 \pm 6.0$	$12.0 \pm 2.0$	Complete	[−166.0,166.0]
2016-03-13	$111.0 \pm 4.0$	$14.0 \pm 1.0$	100°–260°	[[−19.3],  −19.3 ]	$44.5 \pm 2.5$	$12.0 \pm 1.0$	Complete	[−44.5,44.5]
	$110.0 \pm 3.0^c$	$13.0 \pm 1.0$	0°–88°	[[110],  3.8 ]	$87.0 \pm 4.0$	$11.0 \pm 2.0$	Complete	[−87.0,87.0]
	$155.0 \pm 4.0$	$12.0 \pm 1.0$	Complete	[−155.0,155.0]	$117.0 \pm 3.0$	$13.0 \pm 1.0$	Complete	[−117.0,117.0]
	$201.0 \pm 11.0$	$12.0 \pm 2.0$	Complete	[−201.0,201.0]	$167.0 \pm 3.0$	$12.0 \pm 2.0$	Complete	[−167.0,167.0]

**Table A3.** Fitting the kinematics of HD 327083.

Date (UT)	[Ca II] $\lambda$ 7291				[O I] $\lambda$ 6300			
	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$v_g$ ( $\text{km s}^{-1}$ )	Ring	Range ( $\text{km s}^{-1}$ )	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$v_g$ ( $\text{km s}^{-1}$ )	Ring	Range ( $\text{km s}^{-1}$ )
1999-06-25	$76.0 \pm 1.0$	$11.0 \pm 1.0$	0°–80°	[[76.0],  13.2 ]	$75.0 \pm 1.0$	$14.0 \pm 1.0$	0°–122°	[[75.0],  13.0 ]
	$75.0 \pm 1.0$	$8.0 \pm 1.0$	90°–270°	[0,0]				
2015-05-11	$76.0 \pm 1.0$	$12.0 \pm 1.0$	0°–110°	[[76.0],  −26.0 ]	$58.0 \pm 2.0$	$11.0 \pm 1.0$	0°–110°	[[58.0],  −19.8 ]
	$77.0 \pm 1.0$	$12.0 \pm 2.0$	40°–270°	[[59.0],0]	$76.0 \pm 2.0$	$9.0 \pm 1.0$	0°–140°	[[76.0],  −58.2 ]
2015-10-12	$76.0 \pm 1.0$	$12.5 \pm 0.5$	0°–90°	[[76.0],0]	$70.0 \pm 2.0$	$14.0 \pm 1.0$	110°–270°	[[−23.9],0]
	$76.0 \pm 1.0$	$13.5 \pm 0.5$	120°–270°	[[−38.0],0]	$74.0 \pm 2.0$	$12.0 \pm 1.0$	0°–85°	[[74.0],  6.4 ]
2015-10-15	$76.0 \pm 1.0$	$13.0 \pm 1.0$	0°–90°	[[76.0],0]	$70.0 \pm 1.0$	$14.0 \pm 1.0$	110°–270°	[[−23.9],0]
	$76.5 \pm 1.0$	$12.5 \pm 0.5$	120°–270°	[[−38.5],0]	$74.0 \pm 1.0$	$14.0 \pm 1.0$	0°–90°	[[74.0],0]
2016-04-13	$77.0 \pm 1.0$	$12.0 \pm 0.5$	0°–85°	[[77.0],  6.7 ]	$66.0 \pm 2.0$	$8.0 \pm 1.0$	90°–270°	[0,0]
	$71.0 \pm 1.0$	$11.0 \pm 1.0$	110°–270°	[[−24.3],0]	$80.0 \pm 1.0$	$13.0 \pm 1.0$	0°–105°	[[80],  −20.7 ]
2016-07-28	$76.0 \pm 1.0$	$12.0 \pm 1.0$	0°–85°	[[77.0],  6.7 ]	$61.0 \pm 3.0$	$9.0 \pm 1.0$	90°–270°	[0,0]
	$72.0 \pm 1.0$	$10.5 \pm 1.5$	110°–270°	[[−24.6],0]	$78.5 \pm 1.5$	$13.0 \pm 1.0$	0°–106°	[[78.5],  −21.6 ]

Note. The fit of the [O I]  $\lambda$ 6300 line for the 2016-04-13 epoch is not well-constrained due to the extended red wing it displays.

**Table A4.** Fitting the kinematics of HD 62623.

Date (UT)	[O I] $\lambda 5577$				[Ca II] $\lambda 7291$				[O I] $\lambda 6300$			
	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$v_g$ ( $\text{km s}^{-1}$ )	Ring	Range ( $\text{km s}^{-1}$ )	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$v_g$ ( $\text{km s}^{-1}$ )	Ring	Range ( $\text{km s}^{-1}$ )	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$v_g$ ( $\text{km s}^{-1}$ )	Ring	Range ( $\text{km s}^{-1}$ )
2008-12-21	$57.5 \pm 1.5$	$13.0 \pm 2.0$	$0^\circ\text{--}95^\circ$	[[57.5],  −5.0 ]	$41.0 \pm 2.0$	$9.5 \pm 0.5$	Complete	[−41.0,41.0]	$37.0 \pm 1.0$	$11.0 \pm 1.0$	Complete	[−37.0,37.0]
2010-05-03	$61.0 \pm 2.0$	$10.0 \pm 1.0$	$0^\circ\text{--}95^\circ$	[[61.0],  −5.3 ]	$60.5 \pm 0.5$	$11.0 \pm 1.0$	Complete	[−60.5,60.5]	$60.0 \pm 1.0$	$12.0 \pm 2.0$	Complete	[−60.0,60.0]
2013-05-09	$57.0 \pm 3.0$	$8.5 \pm 1.5$	$0^\circ\text{--}95^\circ$	[[57.0],  −5.0 ]	$41.0 \pm 0.5$	$7.5 \pm 0.5$	$20^\circ\text{--}360^\circ$	[[38.5],  41.0 ]	$38.0 \pm 1.0$	$11.5 \pm 0.5$	Complete	[−38.0,38.0]
2014-11-29	$55.0 \pm 5.0$	$11.0 \pm 2.0$	$0^\circ\text{--}95^\circ$	[[55.0],  −4.8 ]	$60.0 \pm 1.0$	$11.0 \pm 1.0$	Complete	[−60.0,60.0]	$62.0 \pm 1.0$	$12.0 \pm 1.0$	Complete	[−62.0,62.0]
2015-05-10	$55.0 \pm 3.0$	$11.0 \pm 1.0$	$0^\circ\text{--}95^\circ$	[[55.0],  −4.8 ]	$42.0 \pm 1.0$	$8.5 \pm 0.5$	$20^\circ\text{--}360^\circ$	[[39.5],  42.0 ]	$43.0 \pm 2.0$	$10.0 \pm 1.0$	$20^\circ\text{--}360^\circ$	[[40.4],  43.0 ]
2015-10-12		Too noisy – not used			$61.0 \pm 1.0$	$10.0 \pm 0.5$	$20^\circ\text{--}360^\circ$	[[57.3],  61.0 ]	$62.5 \pm 1.5$	$11.0 \pm 1.0$	$20^\circ\text{--}360^\circ$	[[58.7],  62.5 ]
					$42.5 \pm 0.5$	$8.5 \pm 0.5$	$20^\circ\text{--}360^\circ$	[[39.9],  42.5 ]	$41.5 \pm 1.5$	$11.5 \pm 0.5$	$20^\circ\text{--}360^\circ$	[[39.0],  41.5 ]
					$61.5 \pm 0.5$	$11.0 \pm 1.0$	$20^\circ\text{--}360^\circ$	[[57.8],  61.5 ]	$60.0 \pm 1.0$	$13.0 \pm 1.0$	$20^\circ\text{--}360^\circ$	[[56.4],  60.0 ]
					$44.0 \pm 1.0$	$11.0 \pm 1.0$	$20^\circ\text{--}360^\circ$	[[41.3],  44.0 ]	$40.0 \pm 3.0$	$11.5 \pm 1.5$	$20^\circ\text{--}360^\circ$	[[37.6],  40.0 ]
					$62.0 \pm 1.5$	$11.0 \pm 1.0$	$20^\circ\text{--}360^\circ$	[[58.3],  62.0 ]	$64.0 \pm 2.0$	$13.0 \pm 1.0$	$20^\circ\text{--}360^\circ$	[[60.1],  64.0 ]

**Table A5.** Fitting the kinematics of GG Car.

Date (UT)	[Ca II] $\lambda 7291$				[O I] $\lambda 6300$			
	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$v_g$ ( $\text{km s}^{-1}$ )	Ring	Range ( $\text{km s}^{-1}$ )	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$v_g$ ( $\text{km s}^{-1}$ )	Ring	Range ( $\text{km s}^{-1}$ )
1999-04-18	$96.0 \pm 2.0$	$6.5 \pm 0.5$	$0^\circ\text{--}165^\circ$	[[96.0],  −92.7 ]	$35.5 \pm 1.5$	$12.0 \pm 2.0$	Complete	[−35.5,35.5]
2000-02-23	$96.0 \pm 2.0$	$6.5 \pm 0.5$	$0^\circ\text{--}165^\circ$	[[96.0],  −92.7 ]	$91.5 \pm 3.5$	$9.0 \pm 2.0$	Complete	[−91.5,91.5]
2008-12-22	$94.0 \pm 2.0$	$8.5 \pm 1.0$	$5^\circ\text{--}180^\circ$	[[93.6],  −94 ]	$30.0 \pm 1.5$	$13.0 \pm 1.0$	Complete	[−30.0,30.0]
2009-06-09	$97.0 \pm 1.0$	$8.5 \pm 1.5$	$15^\circ\text{--}180^\circ$	[[93.7],  −97 ]	$90.5 \pm 2.5$	$9.0 \pm 2.0$	Complete	[−90.5,90.5]
2011-03-23	$97.0 \pm 2.0$	$8.0 \pm 1.0$	$15^\circ\text{--}180^\circ$	[[93.7],  −97 ]	$29.0 \pm 1.0$	$13.0 \pm 1.0$	Complete	[−29.0,29.0]
2015-05-13	$92.5 \pm 2.5$	$8.5 \pm 1.5$	$10^\circ\text{--}180^\circ$	[[91.1],  −92.5 ]	$51.0 \pm 3.0$	$14.0 \pm 2.0$	Complete	[−51.0,51.0]
2015-11-23	$97.0 \pm 2.0$	$8.0 \pm 1.0$	$20^\circ\text{--}180^\circ$	[[91.2],  −97 ]	$91.5 \pm 8.5$	$12.0 \pm 2.0$	Complete	[−91.5,91.5]
2015-11-26	$96.5 \pm 1.5$	$9.5 \pm 1.5$	$20^\circ\text{--}180^\circ$	[[90.7],  −97 ]	$28.5 \pm 1.5$	$13.0 \pm 1.0$	Complete	[−28.5,28.5]
					$79.0 \pm 5.0$	$12.0 \pm 2.0$	Complete	[−79.0,79.0]
					$30.0 \pm 1.0$	$13.0 \pm 1.0$	Complete	[−30.0,30.0]
					$82.0 \pm 2.0$	$12.0 \pm 2.0$	Complete	[−82.0,82.0]
					$29.0 \pm 1.0$	$13.0 \pm 1.0$	Complete	[−29.0,29.0]
					$82.5 \pm 7.5$	$14.0 \pm 2.0$	Complete	[−82.5,82.5]
					$28.0 \pm 1.0$	$13.0 \pm 1.0$	Complete	[−28.0,28.0]
					$77.0 \pm 8.0$	$14.0 \pm 2.0$	Complete	[−77.0,77.0]
					$29.0 \pm 1.0$	$13.0 \pm 1.0$	Complete	[−29.0,29.0]
					$80.0 \pm 5.0$	$14.0 \pm 2.0$	Complete	[−80.0,80.0]

**Table A6.** Fitting the kinematics of MWC 137.

Date (UT)	[O I] $\lambda 6300$			
	$v_{\text{rot}}$ ( $\text{km s}^{-1}$ )	$v_g$ ( $\text{km s}^{-1}$ )	Ring	Range ( $\text{km s}^{-1}$ )
2015-12-05	$20.0 \pm 0.5$	$7.5 \pm 0.5$	Complete	[−20.0,20.0]
	$31.0 \pm 1.0$	$10.0 \pm 1.0$	Complete	[−31.0,31.0]
	$47.0 \pm 1.0$	$7.0 \pm 1.0$	Complete	[−47.0,47.0]
	$67.0 \pm 2.0$	$15.0 \pm 2.0$	Complete	[−67.0,67.0]
2016-02-28	$20.5 \pm 0.5$	$7.5 \pm 0.5$	Complete	[−20.5,20.5]
	$31.0 \pm 1.0$	$10.0 \pm 1.0$	Complete	[−31.0,31.0]
	$46.5 \pm 1.0$	$8.0 \pm 1.0$	Complete	[−46.5,46.5]
	$69.0 \pm 2.0$	$9.0 \pm 2.0$	Complete	[−69.0,69.0]

the integration continues by going behind the star, coming in front of it from the left (blue) part to reach the initial position again (corresponding to a complete ring – in case of partial rings we adjust these angles accordingly). This introduces a direction of the

ring rotation which is arbitrary. To overcome this, we convert these angles to a range of possible velocities. For complete rings, the range is given as  $[-v_{\text{rot}}, +v_{\text{rot}}]$ , while for partial rings it is defined as  $[|\cos(\text{angle}_{\text{min}}) \times v_{\text{rot}}|, |\cos(\text{angle}_{\text{max}}) \times v_{\text{rot}}|]$ .



**Table A7.** Fitting the kinematics of HD 87643.

Date (UT)	[Ca II] $\lambda$ 7291				[O I] $\lambda$ 6300			
	$v_{\text{rot}}$ (km s $^{-1}$ )	$v_g$ (km s $^{-1}$ )	Ring	Range (km s $^{-1}$ )	$v_{\text{rot}}$ (km s $^{-1}$ )	$v_g$ (km s $^{-1}$ )	Ring	Range (km s $^{-1}$ )
1999-04-18	$12.0 \pm 0.5$	$11.0 \pm 1.0$	Complete	[-12.0,12.0]	<3*	$12.0 \pm 1.0$	0°–155°	[[3],  –2.7 ]
					$23.0 \pm 1.0$	$16.0 \pm 2.0$	0°–155°	[[23.0],  –20.8 ]
					$62.0 \pm 4.0$	$16.0 \pm 2.0$	0°–155°	[[62.0],  –56.2 ]
					$90.0 \pm 5.0$	$9.0 \pm 2.0$	0°–155°	[[90.0],  –81.6 ]
2000-02-23	$11.0 \pm 1.0$	$12.0 \pm 2.0$	Complete	[-11.0,11.0]	$9.0 \pm 1.0$	$9.0 \pm 2.0$	0°–150°	[[9],  –7.8 ]
					$24.5 \pm 1.5$	$15.5 \pm 2.5$	0°–150°	[[24.5],  –21.2 ]
					$54.0 \pm 2.0$	$16.0 \pm 2.0$	0°–150°	[[54.0],  –46.8 ]
					$85.5 \pm 2.5$	$9.0 \pm 2.0$	0°–150°	[[85.5],  –74.0 ]
2015-05-12			Data of too low S/N ratio or compromised – not used					
2015-10-13	$10.0 \pm 0.5$	$10.0 \pm 2.0$	Complete	[-10.0,10.0]	$10.0 \pm 1.0$	$12.0 \pm 1.0$	0°–140°	[[10.0],  –7.7 ]
					$32.0 \pm 2.0$	$14.0 \pm 2.0$	0°–140°	[[32.0],  –24.5 ]
					$62.0 \pm 2.0$	$16.0 \pm 2.0$	0°–140°	[[62.0],  –47.5 ]
					$91.0 \pm 5.0$	$9.0 \pm 2.0$	0°–140°	[[91.0],  –69.7 ]
2016-04-13	$9.5 \pm 0.5$	$10.0 \pm 1.0$	Complete	[-9.5,9.5]	$10.0 \pm 1.0$	$12.0 \pm 1.0$	0°–140°	[[10.0],  –7.7 ]
					$33.0 \pm 1.0$	$14.0 \pm 2.0$	0°–140°	[[33.0],  –25.3 ]
					$66.0 \pm 2.0$	$16.0 \pm 2.0$	0°–140°	[[66.0],  –50.6 ]
					$90.0 \pm 5.0$	$9.0 \pm 2.0$	0°–140°	[[90.0],  –68.9 ]

*Note.* <sup>a</sup> We are not certain about the existence of this ring as it is at the limit of what we can fit. It could also be due to the presence of the sky emission line (at  $\lambda$ 6300.3). Unfortunately, there is no sky spectrum available to help us remove or identify the contribution of the sky line.

**Table A8.** Fitting the kinematics of Hen 3-298.

Date (UT)	[O I] $\lambda$ 5577			[Ca II] $\lambda$ 7291			[O I] $\lambda$ 6300		
	$v_{\text{rot}}$ (km s $^{-1}$ )	$v_g$ (km s $^{-1}$ )	Range (km s $^{-1}$ )	$v_{\text{rot}}$ (km s $^{-1}$ )	$v_g$ (km s $^{-1}$ )	Range (km s $^{-1}$ )	$v_{\text{rot}}$ (km s $^{-1}$ )	$v_g$ (km s $^{-1}$ )	Range (km s $^{-1}$ )
2005-04-19	$22.5 \pm 1.5$	$8 \pm 1.5$	[-22.5, 22.5]	$22.0 \pm 0.5$	$8.0 \pm 0.5$	[-22.0,22.0]	$19.0 \pm 0.5$	$12.0 \pm 0.5$	[-19.0,19.0]
2015-05-11	Too noisy – not used			$21.5 \pm 0.5$	$7.75 \pm 0.5$	[-21.5,21.5]	$19.0 \pm 0.5$	$12.0 \pm 1.0$	[-19.0,19.0]
2015-11-26	Too noisy – not used			$21.0 \pm 0.5$	$7.0 \pm 0.5$	[-21.0,21.0]	$18.5 \pm 0.5$	$12.0 \pm 1.0$	[-18.5,18.5]
2015-12-06	$22.5 \pm 1.0$	$10.5 \pm 1.5$	[-22.5, 22.5]	$21.5 \pm 0.5$	$7.25 \pm 0.25$	[-21.5,21.5]	$18.5 \pm 0.5$	$12.5 \pm 0.5$	[-18.5,18.5]
2016-01-12	$24.5 \pm 2.0$	$10.5 \pm 1.5$	[-24.5, 24.5]	$21.5 \pm 0.5$	$7.75 \pm 0.25$	[-21.5,21.5]	$18.5 \pm 0.5$	$12.25 \pm 0.25$	[-18.5,18.5]

*Note.* All rings are complete rings.

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