Probing the properties of Be star discs with spectroastrometry and NLTE radiative transfer modelling: \( \beta \) CMi*

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Accepted yyyy Month dd. Received yyyy Month dd; in original form yyyy Month dd

ABSTRACT

While the presence of discs around classical Be stars is well established, their origin is still uncertain. To understand what processes result in the creation of these discs and how angular momentum is transported within them, their physical properties must be constrained. This requires comparing high spatial and spectral resolution data with detailed radiative transfer modelling. We present a high spectral resolution, \( R \sim 80,000 \), sub milli-arcsecond precision, spectroastrometric study of the circumstellar disc around the Be star \( \beta \) CMi. The data are confronted with three-dimensional, NLTE radiative transfer calculations to directly constrain the properties of the disc. Furthermore, we compare the data to disc models featuring two velocity laws; Keplerian, the prediction of the viscous disc model, and angular momentum conserving rotation. It is shown that the observations of \( \beta \) CMi can only be reproduced using Keplerian rotation. The agreement between the model and the observed SED, polarisation and spectroastrometric signature of \( \beta \) CMi confirms that the discs around Be stars are well modelled as viscous decretion discs.

Key words: Physical Data and Processes: polarisation – stars: emission-line, Be – stars individual: \( \beta \) CMi – techniques: high angular resolution – methods: numerical

1 INTRODUCTION

Be stars are non-supergiant stars with a spectral type B that either exhibit H\(\alpha\) Balmer emission lines in their optical spectra or have done so in the past (Collins 1987). It has been thought for some time that this Balmer line emission originates in gaseous disc-like structures (Struve 1931). The presence of rotating, flattened material, i.e. a disc, was initially inferred from the typical double-peaked emission line profile that is exhibited by many Be stars. This has since been confirmed by long-baseline optical and near-infrared interferometry which has resolved small scale discs around several Be stars (see e.g. Quirrenbach et al. 1997). However, despite the progress made in recent years, many questions remain with regard to the origin of these discs (Porter & Rivinius 2003).

Most Be stars rotate rapidly. Indeed, it appears that Be stars preferentially rotate at a significant fraction, \( \approx 80 \) per cent or more, of the critical velocity where the centrifugal force and gravity are balanced (Porter 1996; Rivinius et al. 2006). This rapid rotation may allow material to be lifted off the surface of the star and into orbit, thus forming the gaseous circumstellar disc (Struve 1931). However, this requires the star to rotate perilously close to its critical velocity, and it is not clear whether Be stars rotate this rapidly or not (see e.g. Townsend et al. 2004; Cranmer 2005). Therefore, alternative mechanisms such as non-radial pulsations...
Regardless of how material is ejected into orbit, another mechanism is required to distribute the material throughout the disc. The viscous decretion disc model (VDDM, Lee et al. 1991) features angular momentum (AM) transport by turbulent viscosity to lift material into higher orbits, thereby causing the disc to grow. A necessary result of this model is that material is in Keplerian rotation throughout the disc. Other models, that do not have an AM transport mechanism, such as non-viscously magnetically confined discs and the original wind compressed disc model (Bjorkman & Cassinelli 1993), exhibit angular momentum conserving (AMC) kinematics. Here we directly confront these two fundamental predictions with astrometric data and physical modelling.

Evidence that the discs around Be stars are well modelled as viscous decretion discs is mounting. An example is provided by the work of Carciofi et al. (2009), who modelled the cyclic variability of ζ Tau with perturbations in a viscous disc. The model of Carciofi et al. (2009) reproduces both the VLTI/AMBER observations of ζ Tau and the temporal variations of its Hα and Brγ emission and thus provides strong support for the viscous disc scenario. As another example, Keplerian rotation, a feature of the VDDM, is suggested by many Be emission line profiles (Hummel & Vrancken 2000). As a result, the Keplerian viscous disc is currently the favoured model of Be star discs. However, as noted by Hummel & Vrancken (2000), based on the line profiles alone, it is difficult to conclusively discount alternate velocity laws.

A number of discs around Be stars have now been directly probed with optical/NIR interferometry (see Vakili et al. 1998; Meilland et al. 2007a,b; Carciofi et al. 2009; Pott et al. 2014; Delaa et al. 2011; Meilland et al. 2011; Kraus et al. 2012; ?). Several of these studies also find evidence for discs in Keplerian rotation. However, there are a few notable exceptions (see Meilland et al. 2007a; Delaa et al. 2011). Therefore, we have yet to arrive at a complete understanding of the properties of Be star discs. Furthermore, many of the earlier studies that employed spectro-interferometric data were limited in terms of spectral resolution and/or had a sparse u, v coverage. These limitations have been overcome in a few cases (see e.g. Kraus et al. 2012). Nonetheless, few studies confront spectrally and spatially resolved data with detailed three-dimensional, NLTE radiative transfer calculations. Here we address this issue and confront unique high spectral resolution, sub milli-arcsecond (mas) precision spectroastrometric data with a detailed model of Be star discs.

Spectroastrometry is a complementary technique to spectro-interferometry that offers a valuable insight into the kinematics of unresolved structures. The technique utilizes the spatial information present in a long-slit spectrum to deliver spatial information with sub-mas precision (see e.g. Bailey 1998, Whelan & Garcia 2008). Spectroastrometry can offer a higher spectral resolution than spectro-interferometry and offers an efficient way to probe circumstellar kinematics on small scales. Therefore, such data are well suited to comparison with model calculations.

We have observed a sample of Be stars with spectroastrometry. Here we present our results on β CMi, a B8 type star located at a distance of 52 pc. The disc around this object was recently resolved with the VLTI and CHARA interferometers as reported by Kraus et al. (2012). Using a kinematical model, these authors show that their observations are best described assuming Keplerian rotation. Here, we fit our high spectral resolution data and photometric and spectro-polarimetric data with a state-of-the-art NLTE radiative transfer model to probe the physical properties of the disc.

2 OBSERVATIONS AND DATA REDUCTION

β CMi was observed on the 9th of December 2008 with the UVES spectrograph (Dekker et al. 2000) mounted on the VLT-UT2. The red arm of the instrument was used as attention was focused upon the Hα line. Observations where conducted using the 600 g/mm grating and the Hα filter. The MIT-LL CCD was employed and the spatial pixel size of 0.16” ensured the seeing, which was ~0.8”, was well sampled. Observations were conducted with a slit width of 0.5”, which resulted in a spectral resolution ~80,000 or 4 km s⁻¹. The spectral range was ~ 6545–6580 Å. Data were obtained at four different slit position angles, 0, 90, 180 and 270°. This is to identify, and eliminate, any systematic artifacts in the spectroastrometric signatures (see e.g. Brannigan et al. 2004). Spectra of a ThAr lamp were used to wavelength calibrate the data.

Data reduction was conducted using IRAF and routines written in IDL. Flat field frames, which were first corrected for the average bias level, were combined. The averaged flat field was then normalised. Finally, raw data were corrected using an average bias frame and the normalised, averaged flat frame. The total intensity long-slit spectra were then extracted in a standard fashion.

Spectroastrometry was performed by fitting Gaussian profiles to the spatial profile of the long-slit spectra at each pixel along the dispersion axis. This allowed the centroid position to be determined as a function of velocity. The continuum position exhibited a trend in the dispersion direction which was removed by fitting a 1-D polynomial function to it. The average positional spectra for anti-parallel position angles were combined to form the average North-South (NS) and East-West (EW) positional spectra. All such spectra were assessed visually to exclude features only present at a single position angle (for details on the spectroastrometric technique see e.g. Oudmaijer et al. 2002, Wheelwright et al. 2011).

The spectroastrometric signature of β CMi is shown in panel d) of Figure 1. As a result of the high SNR, the average positional precision (the rms of the centroid in the continuum) is less than 0.2 mas. A clear spectroastrometric signature is observed and appears as expected for a rotating disc (see e.g. Oudmaijer et al. 2011). The amplitude of the excursions in the EW and NS directions is of order 1 mas, and allows us to derive the Position Angle (PA) traced by the major axis of the disc of 130±5°. This is consistent with the polarisation angle of ~ 45°, as this is expected to perpendicular to the disc. The calculated PA is also essentially consistent with the value of 140 ± 1.7° reported by Kraus et al.
point source catalogue \cite{Cutri2003}, the IRAS point source catalogue \cite{Beichman1988} and Ducati \cite{2002}. The UV spectrum was obtained from the INES database \cite{Wamsteker2000}, and broad-band measurements of the UV and optical flux were taken from Johnson et al. \cite{1966}, Ducati \cite{2002}. Optical spectra were taken from the HPOL data-base mentioned above.

4 RESULTS

4.1 Modelling procedure and results

The initial step in reproducing the observations was determining the properties of the central star. We estimated the radius of the star and the reddening towards it by reproducing the observed UV and optical SED with an atmospheric model appropriate for the spectral type of $\beta$ CMi (B8Ve, log = 4.0, $T_{\text{eff}} = 12,000$ K). Frémat et al. \cite{2005} report values of $v \sin i = 231$ km s$^{-1}$ and $v_{\text{crit}} = 380$ km s$^{-1}$. Allowing for a ratio $V_{\text{crit}}/v_{\text{crit}} = 0.8$ – 0.85 suggests the inclination is $i \sim 45 – 50^\circ$, in approximate agreement with the results of Tycner et al. \cite{2005} and Kraus et al. \cite{2012}. We assume an inclination of $i = 40 – 45^\circ$.

It was assumed that the star rotates relatively rapidly, at approximately 80–85 per cent of its critical velocity. Gravity darkening effects due to the rapid rotation are taken into account in HDUST using the von Zeipel flux distribution \cite{vonZeipel1924}. The ratio between the equatorial and polar radii and temperature were determined based on the stellar rotation and critical velocity. To conduct the modelling, we explored the available parameter space defined by the ranges above. This was done varying $i$, $V_{\text{crit}}$, $v_{\text{crit}}$ and $R_{\text{max}}$ by hand as the time required to iteratively fit all the observations was prohibitively large. $V_{\text{Turb}}$ and $p_0$ were treated as free parameters. We note that reproducing the photometric, polarimetric and spectroscopic data rules out many parameter combinations that might represent local minima if fewer types of data were considered.

For the Keplerian model, we adopted an inclination of $i = 40^\circ$ and rotation at 85 per cent of the critical velocity as this allows a better match to the observed line profile. This does not produce the best fit to the HPOL SED, but difference between the predicted SED and that observed is within the uncertainty in the flux measurements. The infrared excess of $\beta$ CMi is comparatively small. Reproducing this requires a low disc density, which is consistent with the low polarisation of the star. The best fitting density was defined as the value that reproduced the line-to-continuum ratio of the H$\alpha$ emission. In principle, the central reversal can be recreated by increasing the line-width. However, this increases the line-to-continuum ratio. The density cannot be reduced to compensate without degrading the fit to the IR excess and thus the central reversal cannot be recreated exactly. We also note that the high velocity wings of the H$\alpha$ emission cannot be reproduced. This is attributed to broadening that is not present in the model.

For the AMC model, we adopted a rotation at 80 per

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1 http://sdc.laeff.inta.es/ines/
Table 1. The list of key parameters.

| Parameter | Value\textsubscript{Kep} | Value\textsubscript{AMC} | Notes |
|-----------|----------------|----------------|-------|
| $d$ (pc)  | 52             | 52             | 1     |
| $i$       | 40             | 45             | 2     |
| $V_{\text{rot}}/V_{\text{crit}}$ | 0.85 | 0.8 | 3 |
| $R_e$ ($R_\odot$) | 4.68 | 4.68 | 4 |
| $A_V$     | 0.05           | 0.05           | 4     |
| $T_p$ (K) | 15,000         | 15,000         | 4     |
| $R_{\text{max}}$ ($R_\star$) | 25 | 3.3 | 5 |
| $V_{\text{Turb}}$ (km s$^{-1}$) | 0.1 | 14.5 | 5 |
| $M_e$ ($M_\odot$) | 3.08 | 3.97 | 6 |
| $R_e/R_p$ | 1.32           | 1.27           | 6     |
| $T_p/T_e$ | 1.48           | 1.37           | 6     |
| $\rho_0$ ($\times10^{-12}$g cm$^{-3}$) | 2.9 | 4.6 | 7 |
| $L_e$ ($L_\odot$) | 220 | 220 | 8 |
| $v \sin i$ (km s$^{-1}$) | 182 | 209 | 9 |
| $V_{\text{crit}}$ (km s$^{-1}$) | 333 | 370 | 10 |

Notes: 1: Hipparcos parallax (Perryman et al. 1997), 2: Tyen et al. (2003) & Kraus et al. (2012), 3: fit SED and line profile, 4: fit SED, 5: fit line profile, 6: Based on $R_p$ and $V_{\text{crit}}$, 7: fit line flux and polarisation, 8: set, 9: c.f. 230 ± 16 km s$^{-1}$ Frémat et al. (2005) and 210 ± ∼ 20 km s$^{-1}$ Abt et al. (2002), 10: see e.g. Frémat et al. (2005).

cent of the critical velocity and an inclination of $i = 45^\circ$ as this allowed the Hα line profile to be reproduced. Since the velocity in the disc decreases more rapidly with radius than in the Keplerian case, the outer radius of the disc has to be significantly reduced to recreate the observed double-peaked line profile. To match the observed line-to-continuum ratio, the line-width also had to be increased. In this case, this resulted in a good fit to the central reversal. The final model line profiles, polarisation signatures, SEDs and spectroastrometric signatures are presented in Figure 1 and the associated parameters are listed in Table 1. It is clear that both scenarios are consistent with the entire polarimetric, photometric (including the IR photometry which is not shown) and spectroscopic data-set, preventing differentiation between the two velocity laws on this basis alone.

4.2 Spectroastrometric results

The crucial constraint on the disc properties is provided by the spectroastrometric data. The spectroastrometric signatures of the best fitting Keplerian and AMC models are presented in panel d) of Figure 1. The amplitude of the spectroastrometric signature of the AMC disc is smaller than that of the Keplerian model; due to the smaller size of the AMC disc. On the contrary, the signature of the Keplerian model reproduces the observed signature well ($\chi^2$ ~1.5 versus ~5). We emphasise that the model astrometric signatures were predicted by the models that best reproduce the observed SED, polarisation and line profile. The spectroastrometric signatures were not fit in any way. Since only the Keplerian model recreates the observed spectroastrometric signature, the AMC scenario can be discarded. Therefore, we confirm that the kinematical structure of $\beta$ CMi’s disc is consistent with Keplerian rotation.

5 DISCUSSION AND CONCLUSION

We present a comparison between photometric, polarimetric and spectroastrometric observations of the Be star $\beta$ CMi and HDUST, a NLTE radiative transfer code developed to model Be stars and discs. Currently, the favoured model of the discs around Be stars is the viscous decretion disc model. We confront this model with spectrally resolved sub-mas precision observations which yield direct evidence of the kinematic structure of the disc around $\beta$ CMi and provide a unique test of the viscous disc scenario.
We show that both Keplerian (the prediction of the VDDM) and AMC scenarios can reproduce the spectroscopic, photometric and polarimetric data-set. However, we were able to subject the disc kinematics to a critical test via spectroastrometry which yields velocity resolved spatial information with sub-mas precision. Due to the rapid reduction in rotational velocity with radius, the AMC disc that recreates the spectroastrometric signature observed and the Keplerian disc. Consequently, only the Keplerian disc reproduces the spectroastrometric signature observed and the AMC scenario can be discounted.

That the disc around β CMi can be modelled as a viscous disc in Keplerian rotation indicates that the transport of angular momentum within it is governed by turbulent viscosity. This addresses one of the two key questions regarding the discs of Be stars: how is material injected into the disc and how is angular momentum transported within it? Although we address the latter question, this does not constrain the disc formation mechanism. It has been suggested that the disc around β CMi is related to the non-radial pulsations this object exhibits \cite[Saio et al. 2007]{Saio2007}. These data cannot directly assess this possibility. However, our modelling does yield the physical properties of the disc which may provide useful constraints to future models of disc formation.

We conclude by emphasising that the comparison between our extensive data-set and NLTE radiative transfer modelling provides a stringent test of the properties and kinematics of the disc of β CMi. The agreement between the model and observations in both the spectral and spatial domains clearly demonstrates that the discs around Be stars can be well modelled as viscous decretion discs.

**ACKNOWLEDGMENTS**

HEW acknowledges the financial support of the Science and Technology Facilities Council (STFC) of the UK and the MPIFR. RDO is grateful for the support of the Leverhulme Trust via the award of a Research Fellowship.

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