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Observations and Modeling of Be Stars: β CMi

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Abstract. Be stars are rapidly rotating stars with circumstellar envelopes in the form of outflowing gaseous Keplerian disks, which are responsible for the observed emission in Balmer lines. Matter redistribution in the disk is governed by viscosity. The current models of Be stars suffer from an uncertainty concerning the outer parts of their disks. These parts can be observed only in mid-IR to mm wavelengths due to their free-free and free-bound reprocessing of the stellar radiation. In the near future, we aim to constrain the structure of the outer disk of classical Be star β CMi by obtaining new sub-mm/mm observations and modeling them along with archival spectroscopic, polarimetric and near-IR interferometric observations. For the modeling we use a fully 3D, NLTE, Monte Carlo radiative transfer code HDUST. The compilation of archival data and the modeling procedure are described here.

Introduction

Be stars are rapidly rotating non-supergiant B-type stars that show Balmer emission lines in their spectrum or have done so in the past [*Collins*, 1987]. The characteristic Balmer emission lines originate in a gaseous circumstellar environment in the form of an equatorial disk [*Struve et al.*, 1931]. The disk-like shape of the circumstellar matter has been originally inferred from the typically double-peaked profile of emission lines (Fig. 1). It has since been confirmed independently by spectro-polarimetric observations and interferometric imaging (Fig. 2), that the Be stars' disks are geometrically thin with low opening angles of about 5–15 degrees and that the outer radius of Hα emission is typically 5–10 stellar radii [e.g., *Quirrenbach et al.*, 1997]. The outer radius of the disk can be large ($\approx 100\ R_\star$) when not tidally truncated by, e.g., a binary companion, although the outflow velocity is much lower compared to the disk rotation velocity. The disk rotates in a Keplerian way and matter and angular momentum redistribution is governed by viscosity. Another typical characteristic of Be stars is radiation excess in the infrared and longer wavelengths, created by free-bound and free-free emission in the outer parts of the disk.

Although Be stars rotate very rapidly, the rotation velocity most probably reaches only 70–90 % of the critical value (when gravitational force on the equator is exactly balanced by centrifugal force), therefore rotation alone is not enough to eject matter from the equatorial region to form the disk [*Porter*, 1996; *Yudin et al.*, 2001]. The rotation velocity seems to get progressively closer to the critical value for later type Be stars [*Yudin et al.*, 2001]. As the circumstellar disk is not a remnant of the natal accretion disk, another mechanism has to be responsible for forming it. Non-radial pulsations (NRP) seem to be the most probable candidate, as most of early-type Be stars exhibit line-profile variations indicating their presence [*Rivinius et al.*, 2003]. In later type Be stars, the NRP were seemingly absent, until recently the MOST satellite brought a detection of low-amplitude light variations compatible with NRP in the late Be star β CMi [*Saio et al.*, 2007]. Still, another mechanism is needed to distribute the matter throughout the disk, i.e., to make it grow. Viscous decretion disk model [*Lee, Osaki & Saio*, 1991], in which angular momentum transport by turbulent viscosity is used to lift material to higher orbits, is the most probable mechanism. Unlike other proposed models, e.g., a wind compressed disc model [*Bjorkman & Cassinelli*, 1993], which would exhibit angular momentum

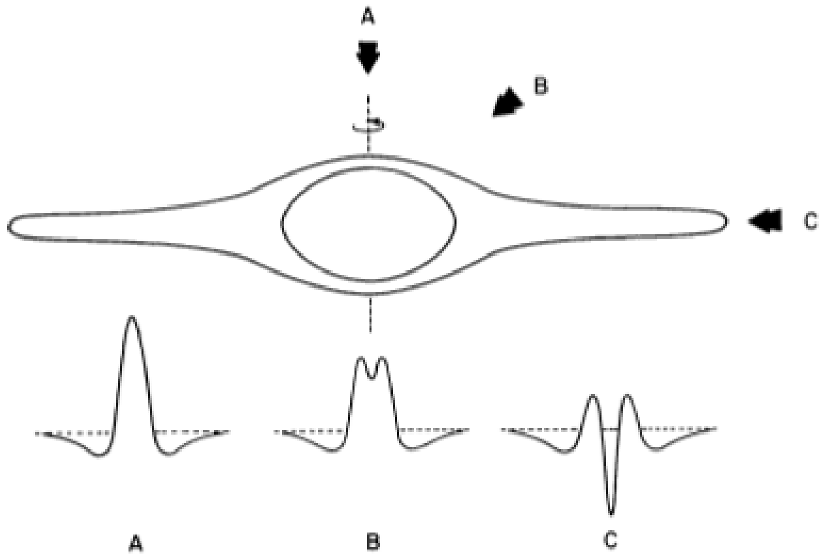

Figure 1. Different shapes of Hα profile depending on the observer position [adopted from *Slettebak*, 1979]. However, other properties of the disk such as the density structure also have an effect on the line profile. For details, see *Silaj et al.* [2010].

conserving disk kinematics, the viscous decretion requires Keplerian rotation ($v(r) \propto r^{-0.5}$). The Keplerian rotation of the Be stars' disks as a feature of the viscous decretion disk model has been recently shown to be the right mechanism to explain observational characteristics of the stars ζ Tau and β CMi via NLTE radiative transfer modeling [*Carciofi et al.*, 2009; *Wheelwright et al.*, 2012].

About one third of Be stars show the so-called V/R oscillations in their Hα profiles, i.e., periodic changes in the ratio between violet and red peaks of Hα [*Hanuschik et al.*, 1996]. These oscillations are an effect of propagation of one-armed density waves through the disk. It has been shown by *Okazaki* [1997], that such density waves can propagate only in disks rotating in a Keplerian way.

The goal of our research is to model consistently the circumstellar disk of a classical Be star β CMi using computer code HDUST [*Carciofi & Bjorkman*, 2006] and to compare the model with wealth of existing observations. We focus on the outer parts of the disk observable only in mid-IR to radio wavelengths. Several Be stars had been observed in these wavelengths more than two decades ago [*Taylor et al.*, 1990; *Taylor et al.*, 1991], but no more observations were carried out until recently [*Štefl et al.*, 2012]. Therefore we are proposing new observations to modern sub-mm/mm telescopes CARMA (succesful) and APEX (pending), which are able to measure well the sub-mm/mm fluxes and even their variations for nearby Be stars [*Štefl et al.*, 2012]. We will model the new data in order to study a possible change in the disk geometry in its outer parts and to study possible truncation mechanisms such as the effect of a binary component.

In the following section we summarize the observations used for modeling, in the section after that we describe the modeling procedure and finally we discuss first modeling attempts and the problems faced.

Archival Observations

We have selected the star β CMi (HR 2845, HD 58715; spectral type B8Ve) for our study because of its large and stable disk suitable for detailed analysis. At the distance of 52 pc (corresponding to Hipparcos parallax of 20.17 mas) it is one of the closest and brightest Be stars. The major axis of the Hα emitting disk has been derived by *Quirrenbach et al.* [1997] to

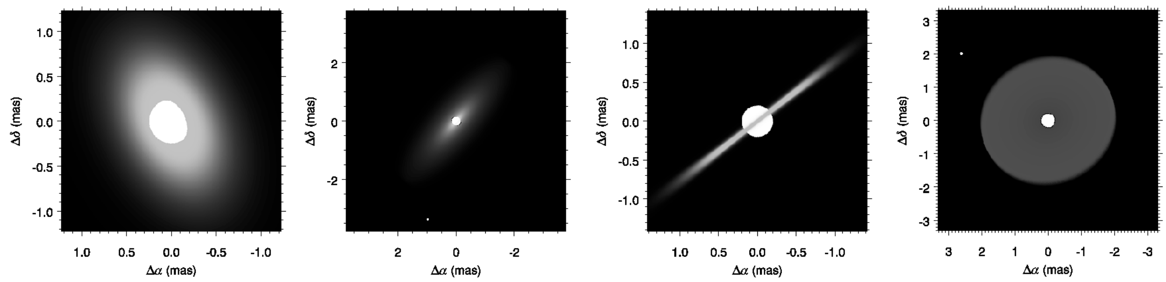

Figure 2. Modeled images using CHARA interferometric data by *Gies et al.* [2007].

2.65 mas. The disk of β CMi has been recently resolved by the VLTI and CHARA near-infrared interferometers [*Kraus et al.*, 2012]. From their spectro-interferometric observations, the disk is confirmed to be in Keplerian rotation, they also calculated the inclination of the system to $(38.5 \pm 1)^\circ$ and the mass of central star to (3.5 ± 0.2) $M_\odot$.

Visual spectroscopy

We have compiled spectroscopic observations of the Hα profile from the last $\approx$ 12 years. We have at our disposal two spectra from the FEROS spectrograph mounted at a 2.2m telescope at the European Southern Observatory (ESO) site La Silla, a number of spectra from slit spectrograph mounted at the Coude focus of Ondrejov 2-m telescope (new monitoring observations are taking place once a month) and a high resolution spectrum from the UVES spectrograph mounted on the Unit Telescope 2 of the Very Large Telescope at the ESO Paranal Observatory. Recently, thanks to technological progress, bright stars like β CMi have become observable with amateur telescopes, and the observations are regularly deposited at the BeSS database (http://basebe.obspm.fr). We have used a set of high-quality amateur spectra from this database to fill in a several years long gap between the available professional spectra. The Hα profile has not changed significantly in the last 12 years and it does not show any V/R oscillations. The optical SED was taken from the HPOL database (http://www.sal.wisc.edu/HPOL).

Photometry

We have compiled photometric data from the publicly available databases ASAS (http://www.astrouw.edu.pl/asas/), AAVSO (http://www.aavso.org/) as well as data from the Hvar observatory [*Harmanec et al.*, 1997]. Also available are IR fluxes from the Two Micron All Sky Survey (2MASS) and IRAS point source catalogues.

Polarimetry

The polarimetric data were obtained using the Halfwave Polarimeter (HPOL), mounted on the Pine Bluff Observatory telescope. The most precise observation was done in 2000 with a CCD detector and two gratings with wavelength coverage 3400–10500 Å and spectral resolution $\approx$ 10 Å.

Near-IR interferometry

We intend to use high resolution observations made with the VLTI/AMBER instrument, which are available from the ESO archive.

Modeling procedure

We aim to constrain the physical characteristics of the circumstellar disk of β CMi by comparing existing and new observations to radiative transfer code HDUST developed by *Carciofi & Bjorkman* [2006, 2008]. HDUST is a fully 3D, non-local thermodynamic equilibrium (NLTE),

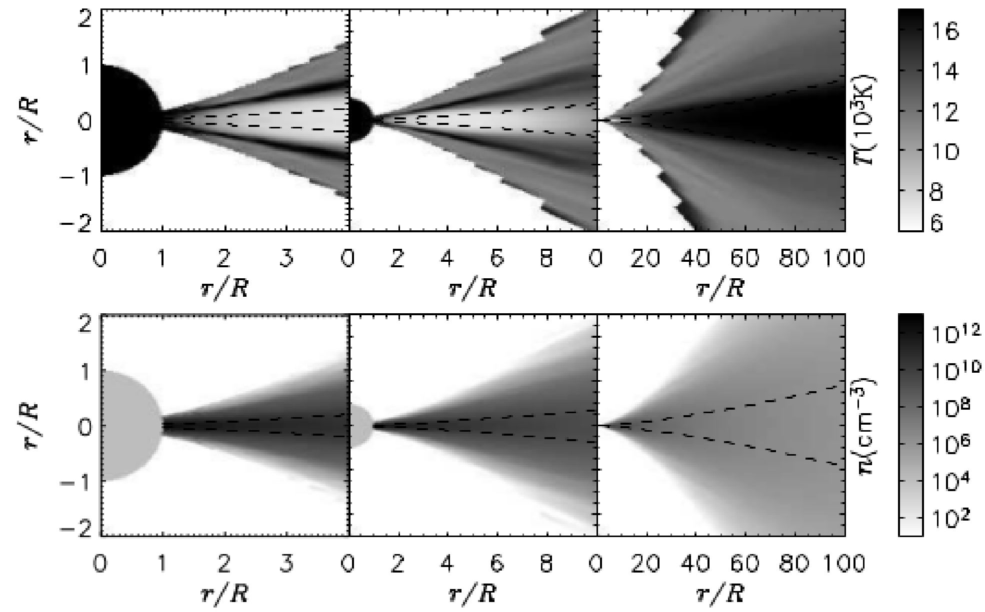

Figure 3. Density and temperature structure of a Be star disk taken from the HDUST modeling of ζ Tau [*Bjorkman & Carciofi*, 2005].

Monte Carlo code which simultaneously solves the problems of radiative transfer, radiative equilibrium and statistical equilibrium for a pre-defined gas density and velocity distributions. We use the code to calculate the temperature structure of the disk and to produce several observables: the optical and IR spectral energy distributions (SEDs), Hα profile and the intrinsic polarisation.

The model includes rotational effects for the central star, such as geometrical deformation and the latitudinal dependence of the stellar radiation resulting from it (gravity darkening). During the Monte Carlo simulation, equal-energy, monochromatic photon packets are emitted from the deformed and gravity darkened star, which is divided into a number of latitude bins, each with different effective temperature, gravity and spectrum given by the corresponding Kurucz model atmosphere assigned to it. Each emitted photon packet travels through the circumstellar envelope, where it may be scattered (it changes direction, Doppler shifts and becomes partially polarized), or absorbed and reemitted locally with a new direction and frequency. We are therefore provided with a direct sampling of all radiative rates and heating of the free electrons, so after an iteration of the simulation is run, the rate equations are solved to update the level populations and electron temperature, until a convergence is reached.

The self-consistent solution of the disk structure requires solving the equations of hydrostatic equilibrium in the vertical direction of the disk and equations of viscous decretion in the radial direction in non-isothermal conditions. As the intrinsic polarisation of β CMi is low, its disk seems to have a low density. The Hα profile being stable also justifies the quazi-steady state approximation for the disk. It has been shown by *Carciofi & Bjorkman* [2008] that the density structure of a quazi-steady, low-density disk can be well approximated by an analytic prescription, namely Gaussian distribution in the vertical direction and power-law dependence in the radial direction, which allows us to significantly decrease the required computation time. The index n in the radial structure dependence $\rho \propto r^{-n}$ is usually $2 < n < 4$. The adopted value $n = 3.5$ stands for an isothermal disk. Although we calculate with an isothermal density structure of the disk, the disk itself is not isothermal, causing a slight inconsistency in the adopted model. An example of the density and temperature structure resulting from HDUST modeling of the Be star ζ Tau can be seen in Fig. 3. The temperature of the disk initially drops like a flat (infinitesimally thin) black-body reprocessing disk, but when the disk becomes optically thin

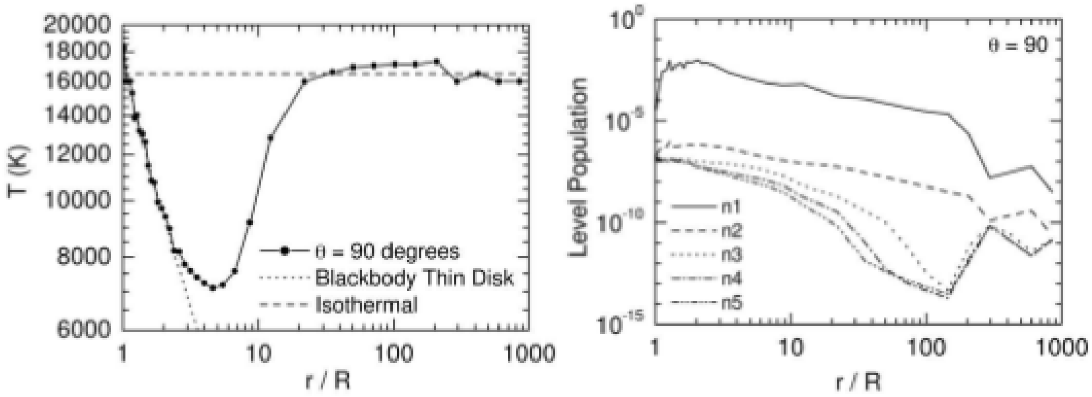

Figure 4. Temperature and level populations structure along the midplane taken from the HDUST modeling of ζ Tau [*Bjorkman & Carciofi*, 2005]. The disk is almost completely ionised.

vertically, the temperature then begins to depart from it, passes through a minimum and rises back to the isothermal value. The temperature and hydrogen level populations structure along the midplane is shown in Fig. 4.

After obtaining the density, temperature and level populations structure, another set of simulations can be run in selected wavelength ranges in order to compute observables such as the SEDs, detailed line profiles and intrinsic polarization.

Discussion

My modeling is going to be the first HDUST application to a late type (B5-B10) Be star and it has revealed problems with the HDUST Monte Carlo solution. The main problem is a bad sampling of ultraviolet (UV) photons caused by a low fraction of radiation being emitted in the UV by cooler stars. The UV radiation is responsible for photoionisation and therefore setting the hydrogen level populations, so an enhancement of its sampling is necessary for a correct solution. Despite the problems, we managed to get preliminary results using a very high number of photon packets, although these results are not yet presentable. After the sub-mm/mm fluxes are obtained, we will focus on modeling the outer disk with the emphasis on studying effects of the disk truncation. The model will be used as a starting point for the ALMA proposal aiming to image the disk directly.

Conclusions

We have compiled archival spectroscopic, photometric, polarimetric and interferometric observations of the B8Ve star β CMi. In order to observationally constrain the outer parts, we are proposing for new sub-mm/mm observations. Observing proposals were submitted in the last period for the CARMA and APEX observatories. The Monte Carlo radiative transfer code HDUST is being used to reproduce the observations and to constrain the physical properties of the disk, such as the electron temperature and level hydrogen level populations structure. The resulting detailed model of β CMi and its disk will be used for the ALMA proposal aiming at direct imaging of the outer disk.

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