Modeling the Ca II forbidden lines arisen from a radiation-driven wind and circumstellar disk

Andrea F. Torres [1,2] Lorena V. Mercanti [1,2] Lydia S. Cidale [1,2] Michaela Kraus [3]

[1]Facultad de Ciencias Astronómicas y Geofísicas, UNLP, Argentina [2]Instituto de Astrofísica de La Plata, CONICET-UNLP, Argentina

[3]Astronomical Institute, Czech Academy of Sciences, Ondřejov, Czech Republic

Abstract

The generally extended envelopes around massive stars in late evolutionary phases account for the episodic or eruptive mass loss processes these objects undergo. Physical and kinematic conditions of these circumstellar shells and their interaction with the stellar radiation determine the observed spectra. Modeling line emission is the primary way to explore these physical properties. In this work, we focus on the forbidden emission lines of ionized calcium ([Ca II] $\lambda\lambda$ 7291, 7324 Å), which are good tracers of the kinematics within the disk of the B[e] supergiants, complementing the information provided by the [O I] emission lines. We model synthetic [Ca II] line profiles, assuming a scenario consisting of a radiation-driven wind and a circumstellar disk in Keplerian rotation. We discuss the potential for probing the formation regions of Ca II forbidden lines in the B[e] supergiant environment.

Introduction

B[e] supergiants are evolved massive stars surrounded by a large amount of circumstellar material composed by atomic and molecular gas and dust. Besides the strong infrared excess emission, numerous emission lines from both forbidden and permitted atomic transitions as well as molecular emission are commonly observed in their spectra at optical and infrared wavelengths. The co-existence of a substantial amount of circumstellar material and a B-supergiant radiation-driven wind indicates that the envelope is not spherically symmetric, but disk-shaped. Results from polarimetric studies (e.g. Magalhães 1992, Melgarejo et al. 2001) support this scenario. However, questions about the structure, geometry and formation mechanism still remain open.

Zickgraf et al. (1985) (also at several other places highlighted) proposed that a slow, high-density equatorial outflow could form a disk. Whether this is the case or not, it is still controversial. So, the study of different tracers that can give information about the density, temperature and kinematics of this circumstellar region is extremely valuable. Emission forbidden lines of O I and Ca II have been investigated to find the physical properties of their forming regions. Kraus et al. (2007, 2010) computed the line luminosity and profile of the emission lines of [O I] $\lambda\lambda$ 6300, 6364 Å for either an outflowing or a Keplerian rotating disk. They obtained reasonably good fits between the synthetic line-profiles for both disk models and found that in the [O I] line-forming region hydrogen is predominantly neutral. Aret et al. (2012) discovered that the [Ca II] $\lambda\lambda$ 7291, 7324 Å can be used as a complementary set of disk tracers. Based on high-resolution optical spectra of a sample of B[e] supergiants, they concluded that the [Ca II] lines originate closer to the star than the [O I] lines, at high density regions. Latest works that derived the kinematics of the atomic gas surrounding B[e] supergiants from [O I] and [Ca II] lines, assuming a Keplerian rotating disk, found a distribution of multiple gaseous rings that is unique for each object (Kraus et al. 2016, Torres et al. 2018, Maravelias et al. 2018).

Our goal is to study if the presence of a radiation-line driven wind and a ring structure in Keplerian rotation could give rise to the intense ionized calcium forbidden emission lines observed in B[e] supergiants.

The code

We adapted the code MULITAS (Brusasco & Cidale 2003, Fernández 2023), that solves the radiative transfer in the comoving frame for the continua and the spectral lines, to compute Ca II lines. To calculate the level population in non-local thermodynamic equilibrium (NLTE), we used the Ca II 13-level atom model given by Mihalas 1973. A disk-like structure in quasi-Keplerian rotation at an inclination angle i is considered. The wind mass outflow in the equatorial plane is an averaged value from a steady, spherical, and isothermal wind (with a temperature $T_{\rm wind}$). We assume a β-law to describe the wind radial velocity field. As the [Ca II] lines arise from a more restricted line-forming region than the permitted ones, we compute the emergent line-profiles originating in a ring structure. In this model, the size of the ring, at a distance $R_{\rm disk}$ from the star, is defined by the free parameter $\Delta v_{\rm rot}$, that represents the range of Keplerian velocities contributing to model the line width. The integration procedure follows the ring model code developed by Kraus et al. (2016).

Preliminary results

To test the numerical code, we compute synthetic spectral lines of [Ca II] to be compared with those observed in the B[e] supergiant LHA 120-S 73 FEROS spectrum taken in 2005. In Table 1 (rows 1 and 2), we list the stellar and wind parameters that yield the best-fitting of the H_α line profile (see Figure 1), for an isothermal wind with $T_{\rm wind} = 12\,000$ K. In Table 1 (row 3), we give the disk parameters of the best-fitting model to the [Ca II] $\lambda\lambda$ 7291, 7324 Å lines (see Figure 2). However, to model the intensity of the [Ca II] lines, we need to decrease the wind temperature to $T_{\rm wind} = 6\,900$ K, keeping unmodified the rest of the wind parameters. The resulting distance to the [Ca II] ring of LHA 120-S 73 is $R_{\rm disk} = 204$ R_* where $v_{\rm rot}$ is 12 km s^{-1}, for a star of 19 $M_\odot$. The inner edge of the ring is at 90 R_* from the star with an extent of $\sim$700 R_* and a mean electron density $N_e \sim 2\,10^5$ cm^{-3}.

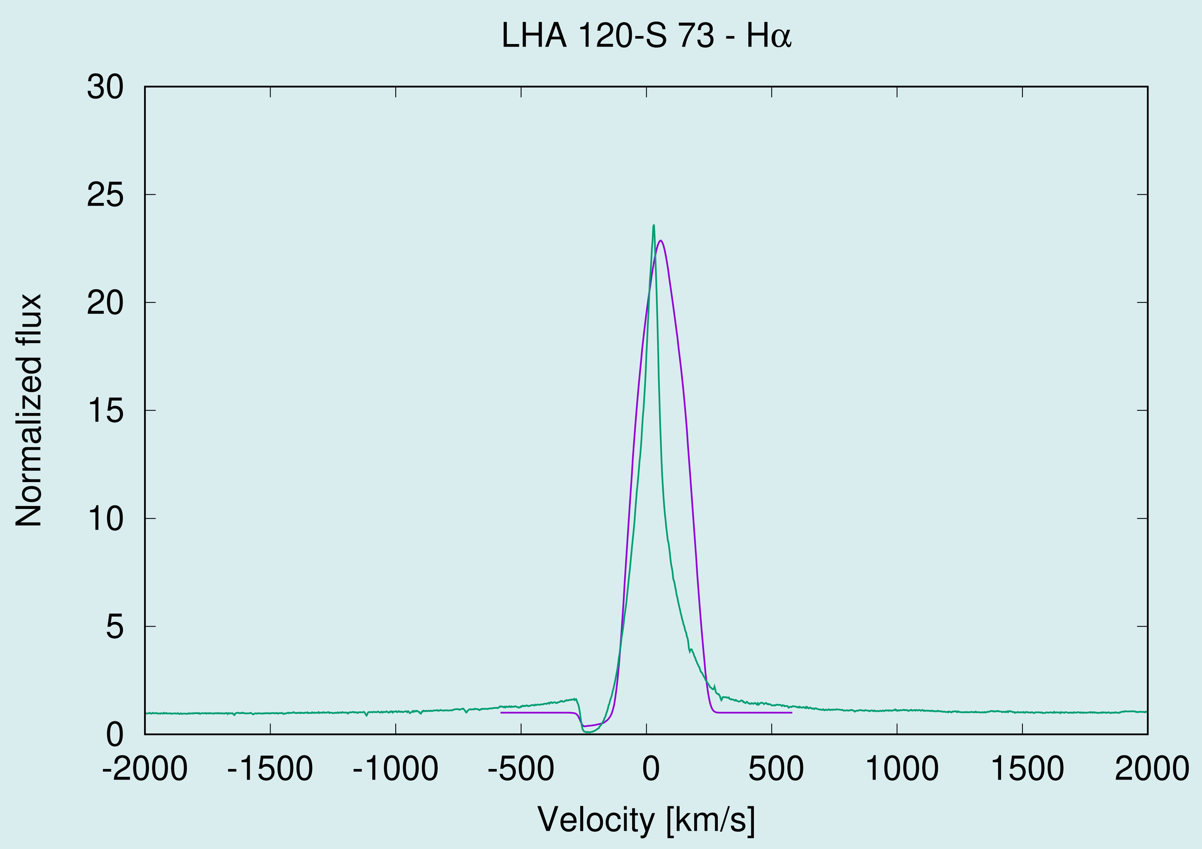

Figure 1. Comparison between the observed H_α line profile (in green) and the synthetic line profile (in violet).

	LHA 120-S 73			
Stellar parameters	$T_{\rm eff}$ [10^3 K]	$\log g$ [dex]	R_* [$R_\odot$]	M_* [$M_\odot$]
	15	2.5	122	19
Wind parameters	$T_{\rm wind}$ [10^3 K]	β	v_∞ [km s^{-1}]	$\dot{M}$ [10^{-5} $M_\odot$ yr^{-1}]
	12	2.5	200	1.95
Disk parameters	N_e [cm^{-3}]	$R_{\rm disk}$ [R_*]	$\Delta v_{\rm rot}$ [km s^{-1}]	i [°]
	1.78 10^5	204	6	28

Table 1. Model parameters of the best line-profile fittings.

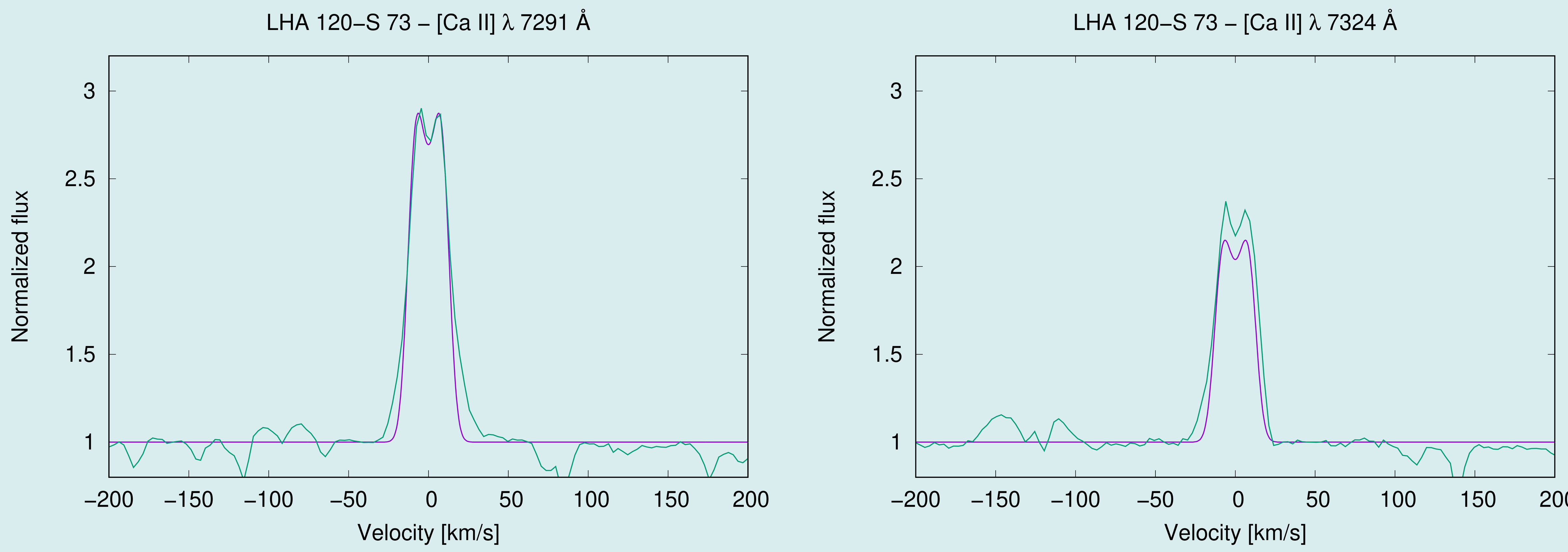

Figure 2. The FEROS spectrum and the best synthetic line profiles are shown in green and violet, respectively.

Our approach reproduces the observed line profiles reasonably well, but we note that the wings of the observed lines are broader than predicted by our model.

Future work

We have obtained the first preliminary results that encourage us to continue developing and improving the code. We plan to incorporate a better description of the physical properties of the wind, considering a temperature law that decreases with the radial distance to the star. In addition, we plan to modify the model to include multiple-ring structures to compare the properties of the rings with those obtained by the LTE [Ca II] calculations performed by Kraus et al. (2016).

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 atorres@fcaglp.unlp.edu.ar