Modeling of emission lines in low-ionization winds of B-type stars

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Resumen / En el contexto de la aparición del nuevo material observacional provisto por la misión espacial *Gaia*, y enfocado en estrellas de tipo espectral B peculiares, se desarrolla un modelo para simular el espectro de líneas de elementos una vez ionizados como Ca II y Mg II fuera del equilibrio termodinámico local. El cálculo se realiza para un rango de temperaturas efectivas y gravedades superficiales, para diferentes distribuciones de temperatura y velocidad en el material circunestelar y distintas tasas de pérdida de masa. Los perfiles sintéticos obtenidos son capaces de reproducir los rasgos generales de las líneas espectrales observadas como, por ejemplo, perfiles P Cygni.

Abstract / Motivated by the availability of new observational material provided by *Gaia* mission, and focused on peculiar B-type stars, we develop a model to simulate the non-LTE line profiles of ionized elements such as Ca II and Mg II. The calculation is performed for a range of effective temperature and surface gravity, for different temperature and velocity distributions of the circumstellar material as well as different stellar mass-loss rates. The obtained synthetic profiles are capable of reproducing the general features of the observed spectral lines, such as P Cygni-type profiles.

Keywords / stars: emission-line, Be — circumstellar matter — radiative transfer

1. Introduction

Peculiar B-type stars such as LBVs or B[e]SGs often present Ca II and Mg II lines with P Cygni or emission profiles in the optical and near-infrared (Aret et al., 2012; Cochetti et al., 2020). The Ca II lines are particularly valuable, and the *Gaia* mission provides not only astrometric, photometric and spectroscopic data for an overwhelming amount of stars but also focuses on the IR triplet of calcium (Gaia Collaboration et al., 2016). This triplet is coupled to the Ca II H and K transitions as well as to the [Ca II] lines arising at shorter wavelengths. To understand their formation, a proper treatment of non-LTE line profiles is required.

We develop a stellar atmospheric model which includes the effect of radiation-driven winds with the aim to explain and reproduce the characteristics of the line profiles typically observed in the peculiar B and A spectral type stars. In this way, we explore the conditions under which Ca II and Mg II emission lines are formed.

In the future, the modeling results for the different structures will be compared with spectroscopic observations for a sample of massive peculiar B stars in the visible and IR ranges, acquired by our group with CASLEO or ESO instruments and the Gemini Observatory's spectrographs, respectively. We plan to complement our data with the spectra of the *Gaia* space observatory database.

2. Methods and data

Our stellar atmospheric model describes the circumstellar medium by an expanding, spherically symmetric flow. The line radiative transfer equation is rigorously solved in spherical coordinates and in the comoving fluid frame according to Mihalas & Kunasz (1978). Atomic models of 14 energy levels for Ca II and 15 energy levels for Mg II plus continuum are applied to simultaneously solve the statistical equilibrium equations. The solution is obtained by means of the equivalent two-level atom approach (ETLA).

For this purpose, the code developed by **?** was improved and readjusted to include the Ca II atomic data. Moreover, additional energy levels were incorporated for the computation of Mg II $\lambda 2.1369, 2.1432, 2.4047$ and 2.4131 μm lines.

The calculation is performed for a range of effective temperature ($T_{eff} = 9\,000$ K - $15\,000$ K) and surface gravity ($\log g = 3.0$ and 3.5) representative of intermediate and late B-type stars. Furthermore, different wind temperature (T_0) and velocity distribution parameters (β, v_∞), as well as different stellar mass-loss rates ($\dot{M}$), are considered to determine the conditions under which these emission lines are formed.

The synthetic line profiles are computed in an automated way by scanning a multidimensional space of model parameters.

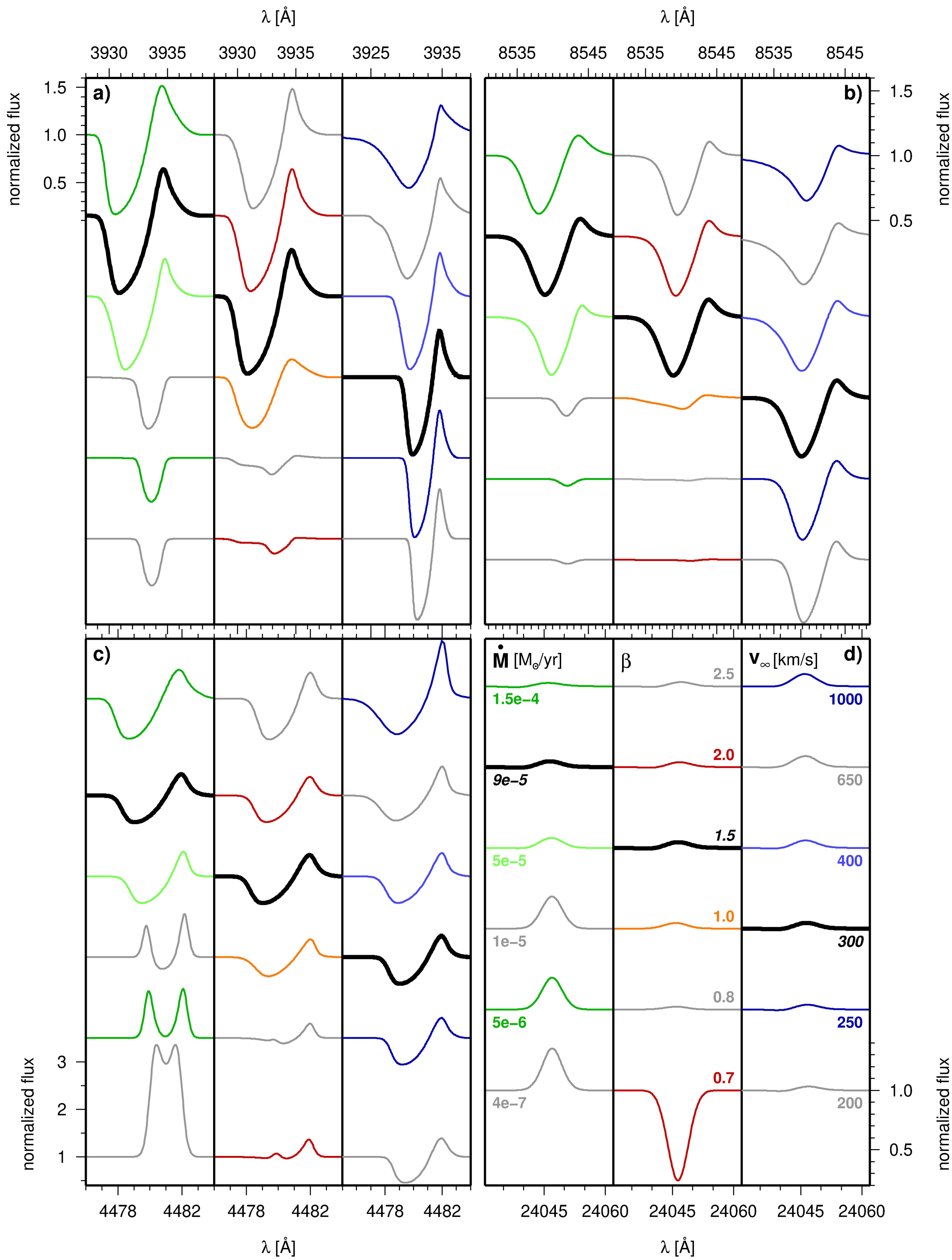

Figure 1: Examples of modeled profiles for four selected lines. a) Ca II λ3930 Å, b) Ca II λ8540 Å, c) Mg II λ4481 Å and d) Mg II λ2.4047 μm. In all shown cases the following values are adopted: $T_{eff} = 12\,000$ K; $\log g = 3.0$; $R_{ph} = 143$ $R_\odot$; electronic temperature of the cool envelope $T_0 = 9\,600$ K. Departing from a reference model (thick black curves; $\dot{M} = 9\times10^{-5}$ $M_\odot\,yr^{-1}$; $\beta = 1.5$; $v_\infty = 300$ km s^{-1}), the values for $\dot{M}$, β and v_∞ are varied as shown in panel d) (identical in all four spectral lines a-d) in order to determine their impact on the line profile shape.

3. Results

The results achieved so far show the dependence of Ca II and Mg II emission lines formation and their respective strengths on the effective temperature, the surface gravity, the radius, and the stellar mass-loss rate. Furthermore, they reveal the relationship between the shape of the line profile and the adopted wind velocity. They allow us to determine the conditions under which the P Cygni profiles are formed.

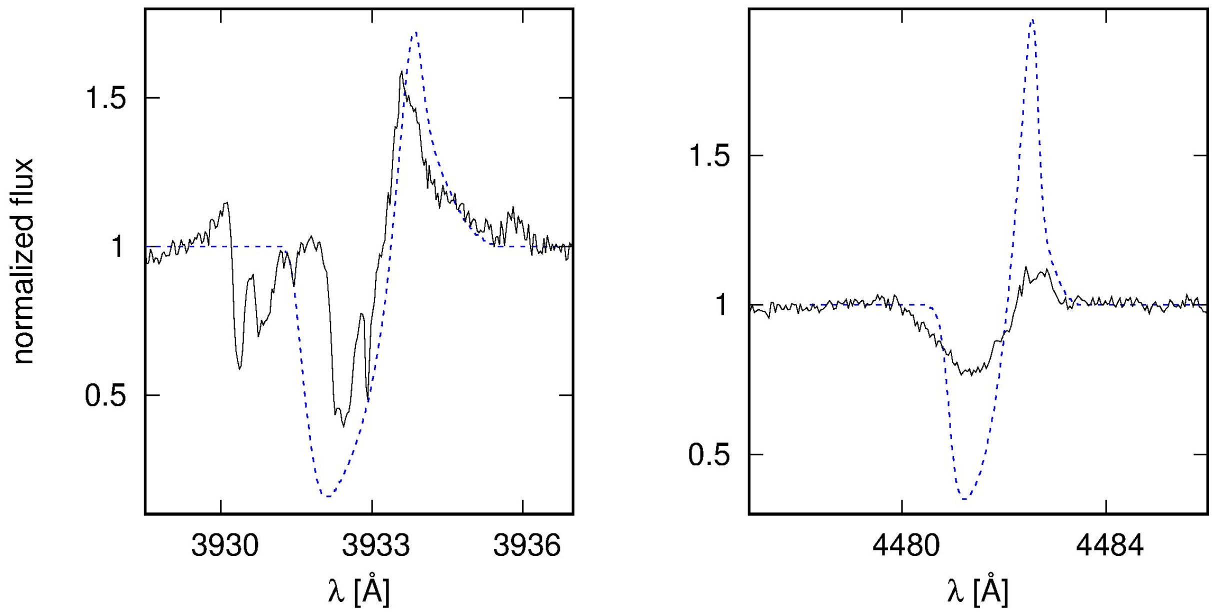

Figure 2: Ca II λ3933 Å and Mg II λ4481 Å line profiles observed in LHA 120-S 73. To illustrate the results, the observed lines (in black) are compared with non-rotating synthetic profiles (in blue) computed for: $T_{eff} = 12\,000$ K; $\log g = 3.0$; $R_{ph} = 134$ R$_\odot$; $T_0 = 9\,600$ K; $\dot{M} = 3 \times 10^{-5}$ M$_\odot$ yr^{-1}; $\beta = 1.5$; $v_\infty = 150$ km s^{-1}; microturbulence and macroturbulence velocity $v_{mic} = v_{mac} = 15$ km s^{-1}. These parameters are within the interval of values tested to build Fig. 1 and are expected values for the star and the wind (cf. Kraus et al., 2016).

Figure 1 shows an example of the modeling results. In the case of the Ca II λ3930 Å line (Fig. 1a, left column), P Cygni profiles emerge from absorption lines as the mass-loss rate increases. A slight profile asymmetry obtained for high velocity gradients ($\beta \approx 0.8$; Fig. 1a, center column) evolves also into P Cygni profiles as β is increased. The profile's width extends with increasing terminal velocities (v_∞; Fig. 1a, right column).

For the Ca II λ8540 Å line (as an example for the triplet components; Fig. 1b) we do not obtain appreciable lines for low mass-loss rates and β values. P Cygni profiles form, via an asymmetric absorption, when increasing either of both parameters.

A different behaviour is obtained for the Mg II λ4481 Å line (Fig. 1c). This line changes from a two-peak profile, through a shell, to a P Cygni profile with increasing mass-loss rate. Low β values generate a profile asymmetry. For Mg II λ2.4047 μm (Fig. 1d) our modeling suggests emission, except for low β values which produce an intense absorption.

4. Discussion and outlook

Figure 2 presents, as an example, the Ca II λ3933 Å and Mg II λ4481 Å line profiles observed in the spectrum of the B[e]SG LHA 120-S 73. This spectrum was taken with the FEROS spectrograph ($R = 55\,000$) mounted at the MPG/ESO 2.2-m telescope in La Silla, Chile, under programme 076.D-0609(A). These observed profiles are compared with the synthetic ones computed with a possible set of parameters suggested for this star (cf. Kraus et al., 2016).

This preliminary comparison is promising. It suggests that our general model setup is capable of reproducing the characteristic features of observed line profiles. The parameter grid still needs to be refined to improve the fit with the observations. In a future stage, we will take into account the presence of a circumstellar disk, which might help explaining the complexity of the observed lines in B[e]SGs (Fig. 2). Furthermore, we plan to include additional chemical elements (such as Fe II) and to increase the intervals and the resolution of the parameter values. Finally, the theoretical spectra will be compared with the observed data for a number of stellar objects of our interest.

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