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Modeling Stellar Wind Spectra from Rapidly Rotating Stars

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Abstract

In post-interaction massive binaries (PIMBs) one often finds rapidly rotating objects, e.g., after one component has accreted mass and angular momentum, or after two components merged. Being hot and luminous, such objects drive stellar winds. Models for stellar atmospheres and winds usually adopt spherical symmetry. However, rapid rotation would break this symmetry.

We have developed a version of the Potsdam Wolf–Rayet (PoWR) model atmosphere code which allows to combine two different atmosphere models, e.g., one for the rapid wind over the polar regions, and a second one for the slower wind over the gravity-darkened equatorial zone.

For two examples we will demonstrate that such 1.5-D spectral simulations can explain observed wind-line profiles which otherwise cannot be reproduced.

Keywords: stars: rotation, stars: winds, stars: model atmospheres

1. Introduction

The spectra of stellar winds are routinely modeled under the assumption of spherical symmetry. However, rapid rotation is expected to cause some "gravity darkening" of the equatorial zone due to the centrifugal force (von Zeipel, 1924). Thus, the higher flux of radiation at the poles corresponds to a higher effective temperature and should drive a faster wind, while at the equator the photosphere is less hot and the wind should be slower. In this work we demonstrate the pronounced impact of such non-spherical wind geometries on the most prominent wind line, the UV resonance doublet of C IV at 1548/1550 Å.

2. Method

The modeling of the atmospheres and winds of hot stars is a challenge, in particular because the conditions are far from local thermodynamic equilibrium (LTE). One of the few existing tools for this task is the Potsdam Wolf–Rayet (PoWR) model atmosphere code (Hamann and Gräfener, 2003, and references therein). Such models routinely adopt spherical symmetry.

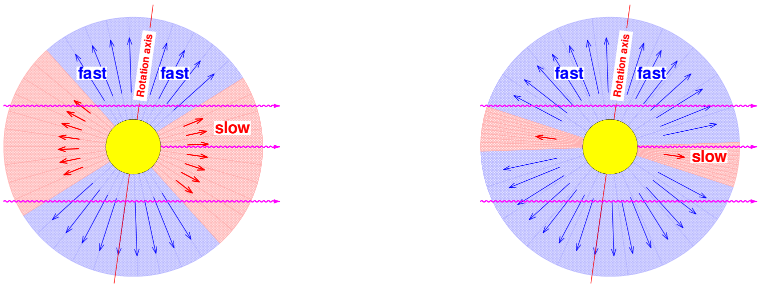

Figure 1: Stellar wind of a rapidly rotating star, schematically composed of a fast wind in the polar double-cone, and a slower wind in the equatorial region. The rays of light travel towards the observer at the right. *(Left)* Broad equatorial zone, covering the whole stellar disk with the slow-wind region. *(Right)* Narrow, disk-like equatorial zone that covers only part of the stellar disk as seen from the observer.

Such non-LTE calculations consist of two subsequent steps. First, the radiative transfer equations in the co-moving frame of reference are solved consistently with the equations of statistical equilibrium (and a few other constraint equations) in order to establish the population numbers of the atomic levels. This is hard to do in more than one dimension.

The second and final step is the calculation of the emergent spectrum in the observer's frame, based on the population numbers that have been established before. In this *formal integral*, more physical details can be taken into account, such as pressure broadening, and the frequency redistribution of photons scattered by free electrons. A three-dimensional treatment of rotating atmospheres has been implemented in PoWR already some time ago (Shenar et al., 2014).

Here we report and test a new feature implemented in PoWR, designed for rapidly rotating stars where the atmosphere and wind deviates from spherical symmetry. As a first approximation, we combine in the formal integral *two* models that have been established before. The first of these models should be adequate for the equatorial zone, and the second model for the polar cones. While the radiative-transfer integral follows a specific ray through the atmosphere; at each point along that ray the opacity, emissivity and projected wind velocity are taken from the respective model, according to the geometrical domain the ray is just passing through.

The geometry is specified by two free parameters: the opening angle of the double-cone and the inclination of the rotation axis with respect to the line-of-sight to the observer (ϑ and i). Figure 1 sketches two examples for different opening angles.

Clearly, this two-zonal approach is only a first approximation and neglects the radiative interaction between the polar and equatorial zones, as well as the stellar oblateness caused by the rapid rotation.

3. Application to Observed Spectra

In this first study, we investigate for two rapidly rotating early-type stars whether the wind lines are noticeably affected by the deviation from spherical symmetry, and whether our approach can lead to a better spectral fit to the observations. We focus on the resonance doublet of C IV in the UV at 1548/1550 Å, which is often the strongest wind signature in the spectra of hot stars.

3.1. SK 190

SK 190, alias SMCSGS-FS 310, located in the wing of the Small Magellanic Cloud, has the spectral type O7.5 In(f)p. Its spectra have been analyzed by Ramachandran et al. (2019) and reveal rapid rotation with $v \sin i = 300\,\mathrm{km\,s^{-1}}$.

The C IV resonance doublet shows a P-Cygni profile which looks quite peculiar at closer inspection: the absorption trough is surprisingly narrow, while the emission part is comparably broad (cf. Fig. 2). When modeling this profile with a terminal wind velocity of $1700\,\mathrm{km\,s^{-1}}$, the width of the absorption trough is largely overpredicted as demonstrated in panel (a) of Fig. 2. In order to fit that small width, a terminal wind velocity as low as $400\,\mathrm{km\,s^{-1}}$ is required, but then the emission part is predicted to be much narrower than observed – cf. panel (b).

This contradiction can be resolved with the two-zonal model, as demonstrated in panel (c). With an opening angle of the polar cone $\vartheta \approx 60^\circ$, the observer sees the stellar disk entirely through the slow equatorial wind and the maximum blueshift of the absorption is correspondingly moderate (see left panel in Fig. 1). The emission part of the P-Cygni profile, however, comprises photons that are scattered in the fast polar wind, which implies that high projected velocities occur on rays which are passing far from the stellar photosphere.

3.2. ζ Oph

As our second test case we select the Galactic star ζ Oph, a nearby and hence very bright object with spectral type O9.2 IVnn. This runaway star shows phases of disk emission, qualifying it as a member of the "Be" class, albeit having a late O-subtype. It rotates with a projected equatorial velocity of $v \sin i = 400\,\mathrm{km\,s^{-1}}$ (e.g., Britavskiy et al., 2023). No binarity can be detected, but pulsations have been found (Walker et al., 2005). The rapid rotation might cause a decretion disk, which is occasionally fed with the help of pulsations. It is not clear if this object presents a *wind-compressed disk* as predicted theoretically by Bjorkman and Cassinelli (1993), but only occasionally confirmed observationally (e.g., Bjorkman et al., 1994).

Due to the lower stellar temperature and the higher (Galactic) metallicity compared to SK 190, the C IV resonance doublet at 1548/1550 Å is immersed in a pseudo-continuum of weak lines (mainly from iron) smeared due to the rapid rotation. Spherically symmetric wind models cannot reproduce the absorption at the line-center wavelengths, as highlighted by the pink area in Fig. 3, panel (a). Any slow-wind component that would obscure the whole stellar photosphere from the observer's view would cause a deep, saturated absorption, unless the wind density is fine-tuned. However, an inclined, geometrically thin equatorial wind necessarily covers only

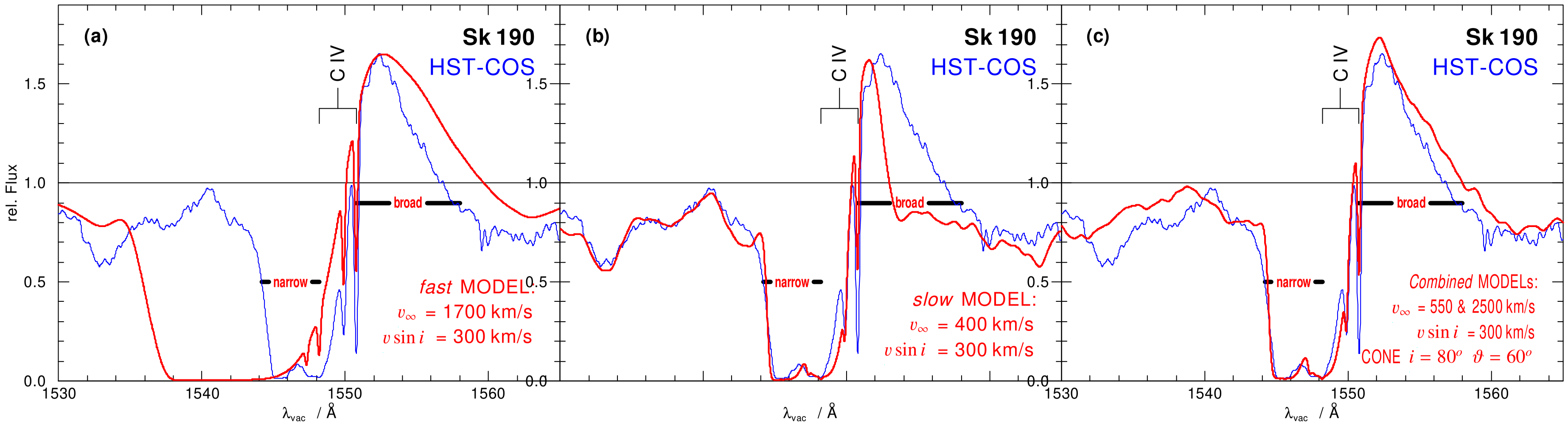

Figure 2: The wind-formed C IV resonance doublet at 1548/1550 Å in the UV spectrum of SK 190. The observation (blue) shows a narrow absorption trough and a comparably wide emission part of the P-Cygni profile. *(a)* Spherical model with a fast wind (1700 km s^{-1}); *(b)* Spherical model with a slow wind (400 km s^{-1}); *(c)* Two-zonal model composed of a fast polar wind (2500 km s^{-1}) and a slow wind in the equatorial zone. The model profiles are in red. See text for more details.

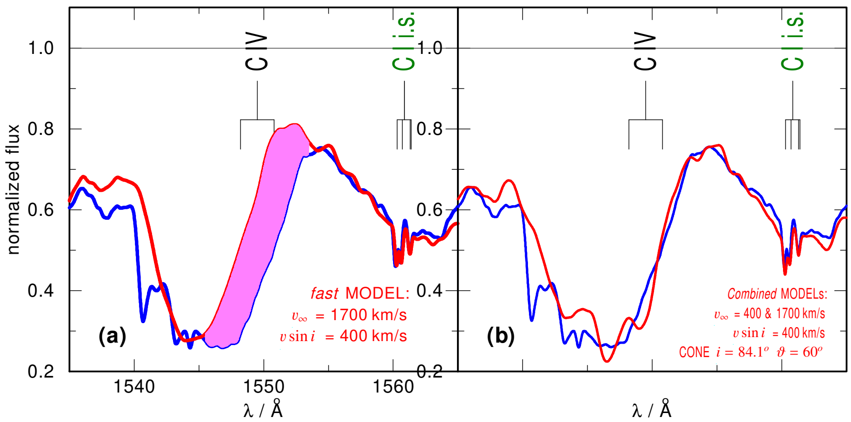

Figure 3: The wind-formed C IV resonance doublet at 1548/1550 Å in the spectrum of ζ Oph. In the observation (blue), there is additional absorption close to the line center that is not reproduced by the spherical model – the difference is highlighted by the pink area in panel (a). In the two-zonal model shown in panel (b) this additional absorption is reproduced due to the slow equatorial wind or disk. The model profiles are in red. See text for more details.

about half of the stellar photosphere as seen from the observer, thus causing the unsaturated profile in the flux as observed.

4. Conclusions

Winds from rapidly rotating stars can deviate noticeably from spherical symmetry. For such stars, the profiles of spectral lines which form in the wind cannot be well reproduced with spherically symmetric models. Much better fits are obtained by combining two models for calculating the emergent spectrum: one model for the polar cones, and one for the equatorial zone.

Further Information

Author contributions

W.-R.H. is the main developer of the Potsdam Wolf–Rayet (PoWR) model atmosphere code. L.S. contributed to implementing the combination of two models as applied in this paper and did some of the model calculations presented here. H.T. is a co-author and experienced user of the PoWR code and cares about its maintenance.

Conflicts of interest

The authors declare that there is no conflict of interest.

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