Massive Stars Near and Far
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3D effects of rotation on spectroscopic observables

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Abstract. When a star is rapidly rotating, it deviates from spherical symmetry causing non-uniform distributions of the surface gravity and temperature across the surface. These three-dimensional effects lead to an inclination dependence of many observable spectroscopic parameters, however this is often neglected when analyzing rapidly rotating systems. Using SPAMMS, we generate synthetic spectra that account for the 3D geometry of the system and fit them with 1D models to investigate how much the 3D effects can change the derived stellar parameters. We show that these 3D effects can lead to observed temperature differences of thousands of kelvin for the same star viewed at different inclinations, and a systematic underestimation of the helium abundance.

Keywords. stars: rotation, stars: fundamental parameters, stars: abundances, techniques: spectroscopic

1. The problem

Rapid rotation is common among massive stars, and can play a crucial roll in massive star evolution (e.g., Maeder 1987; Brott et al. 2011; Langer 2012). A key aspect of rapid rotation is a deviation from spherical symmetry, which in turn leads to non-uniform surface gravity and surface temperature distributions across the surface of rapidly rotating stars (von Zeipel 1924). The temperature distribution can then lead to a change in the ionization balance across the surface, meaning that different regions of the star will show certain species while others may not. Unfortunately however, these 3D effects are often neglected in spectroscopic analyses of massive rotating systems.

The radiative transfer codes available for the analysis of massive stars are mostly 1D due to the computationally intensive NLTE calculations required in this temperature regime (e.g., Hillier & Miller 1998; Gräfener et al. 2002; Puls et al. 2005). The synthetic spectra generated are then convolved with a rotation kernel to mimic rotational broadening, but this treats all of the lines in the same way and does not account for the temperature and ionization balance distributions across the surface. Neglecting these effects may bias our measurements for these systems, and could have a large impact on our understanding of physical processes like internal mixing efficiencies.

2. How can we address this?

In order to quantify the impact that these 3D effects have on observed stellar parameters, we use the SPAMMS code (Abdul-Masih et al. 2020), which allows us to model the distorted surface geometry and the subsequent surface parameter distributions for these stars. SPAMMS combines the advanced 3D mesh triangulation capabilities of the PHOEBE

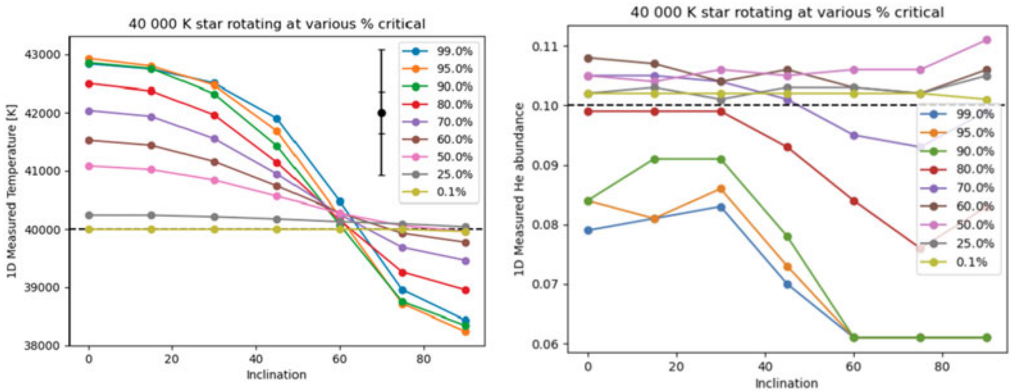

Figure 1. Left: 1D measured temperature as a function of inclination for a 40kK star rotating at different percentages of critical (indicated by the colors). The dashed horizontal line represents the real input temperature of the system. A representative 1σ and 3σ error bar are plotted in black assuming a SNR of 300. Right: 1D measured helium abundance as a function of inclination for the same star.

II code (Prša et al. 2016) with the NLTE radiative transfer code FASTWIND (Puls et al. 2005) to create a surface patch model. Given a set of stellar parameters, SPAMMS generates a mesh that represents the 3D geometry of the photosphere, and based on the local conditions of each mesh triangle, assigns a FASTWIND model. Integrating over the visible surface returns the final synthetic spectrum.

Using SPAMMS, we generate a small grid of synthetic models, where we only vary the rotation rate and the inclination. The rest of the parameters ($T_{\rm eff} = 40$kK, $r_{\rm pole} = 6.0\mathrm{R}_{\odot}$, $M = 25\mathrm{M}_{\odot}$) are left constant. We then fit each of these synthetic 3D models with 1D models to see how the observed parameters change when accounting for the 3D geometry.

3. Are these effects important?

We find a strong correlation between the 1D measured temperature and the inclination, with lower inclinations corresponding to higher temperatures and vice versa (Abdul-Masih 2022 in prep; see Fig. 1). The effect can be seen at rotation rates as low as 50%, but gets stronger as the rotation rate increases. We also find a strong deviation between the input and the 1D measured helium abundance. This effect only begins to appear at rotation rates of greater than 70% critical, but once above this, the helium abundance seems to be systematically underestimated via the 1D fits at this temperature (Fig. 1).

Our findings demonstrate that failing to account for the 3D geometry can lead to incorrect measurements of $\mathrm{T}_{\rm eff}$, abundances and presumably many other parameters. This can have a large impact on our understanding of rapidly rotating massive stars and can affect our calibrations of their internal processes such as rotational mixing efficiency.

Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S1743921322002411.

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