Determining Inclination Angles in Rapidly Rotating Massive Stars via Spectroscopic Analysis

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Rapidly rotating massive stars

A significant feature of massive stars is their fast rotation, which is especially notable in Be stars. The near-critical rotation of these stars leads to **oblate shapes**[1]. This deformation causes a variation in local temperatures and gravity accelerations across the stellar surface, a phenomenon known as **gravity darkening** (GD)[2], as shown in Fig. 1. Recent advancements have refined the original formalism of GD, leading to more accurate approximations than previous models [3].

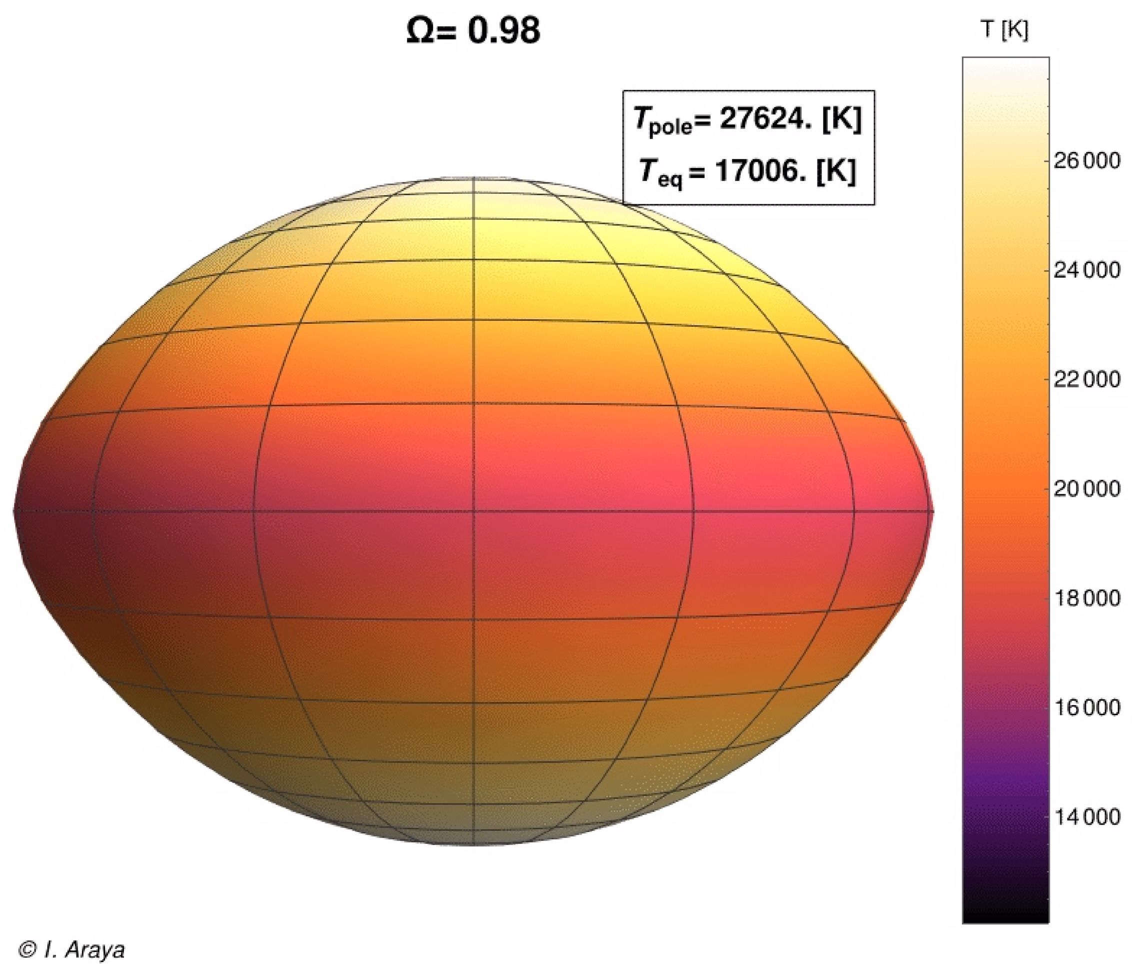

Figure 1: Latitudinal variation of the effective temperature of an oblate star with angular rotation rate Ω=0.98.

The polar/equatorial radius and inclination angle i, are often measured from interferometry, which applies only to a few stars. Now, they can be diagnosed with the aid of GD spectral synthesis code ZPEKTR[4].

Data and Methodology

The spectroscopic data used in this work were obtained from the Be Stars Observation Survey (BeSOS)[5] taken with the PUCHEROS spectrograph, which has a resolution of 17000 with a $S/N = 20$[6].

We selected **ten Be stars** with known *inclination-angles* from the sample of Cochetti et al. 2019[7]. They obtained i through a comparison of geometrical models with interferometric observations with the AMBER instrument installed on the VLTI.

We applied the ZPEKTR code to model the observed spectra of HeI 4471 Å line (same line used in BeSOS) taking into account the effects of fast rotation in the frame of the Espinosa-Lara's formalism. The models are built up using the TLUSTY/SYNSPEC non-LTE models [8][9]. Due to the GD effect, the line profile of the ZPEKTR models changes when the inclination angles vary, as shown in Fig. 2.

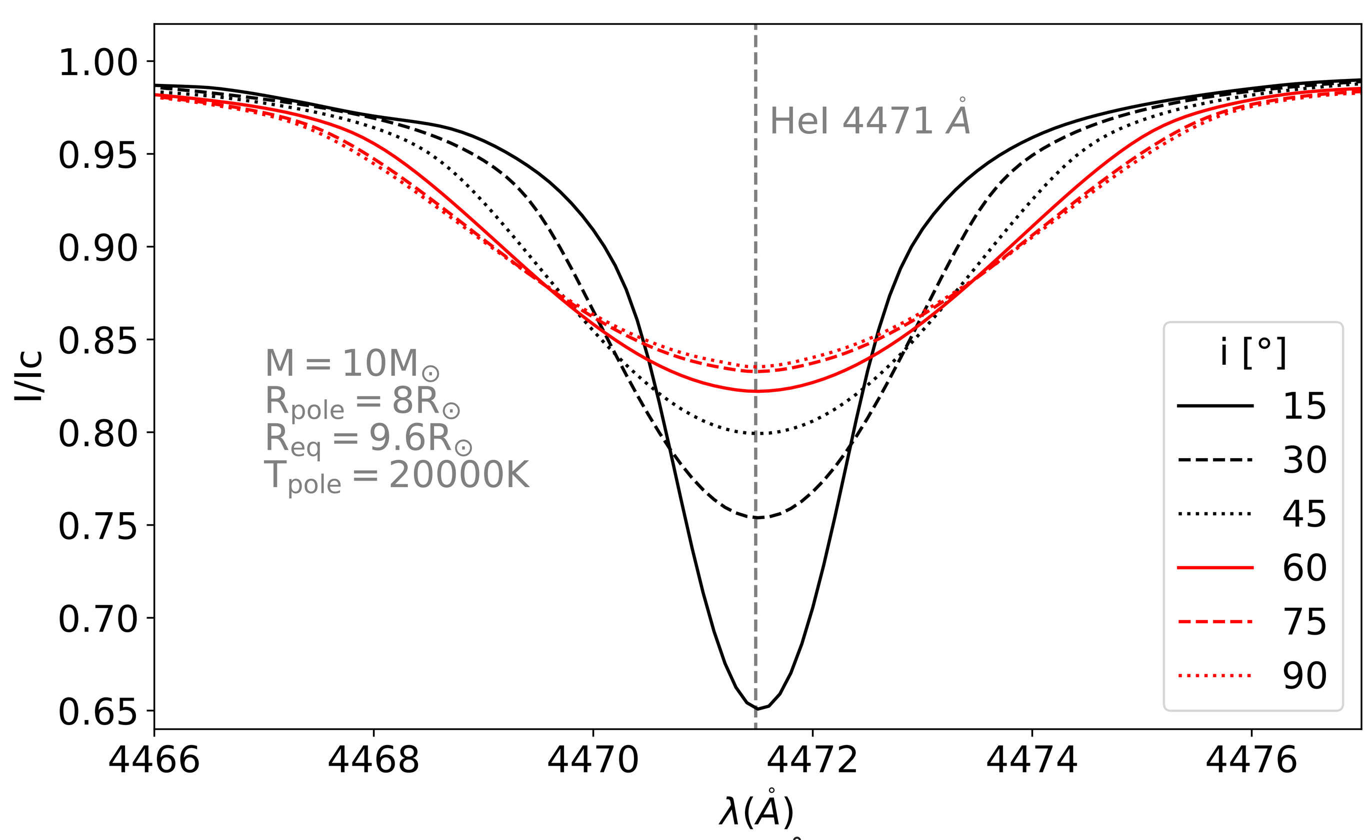

Figure 2: Six ZPEKTR models for the HeI 4471 Å line with the same input parameters (shown on the left of the panel) only changing the inclination angles for a star with rotation rate V/V_c=0.71.

For each star, we created a grid of models and we used the χ^2-test to determine the best fit. We used the best 400 models to present our results with their corresponding errors.

Modeling of HD 212076

For each star, we modeled the HeI 4471 Å line, as shown in Fig. 3 for the star HD 2102076. The parameters obtained from these models are presented in Table 1.

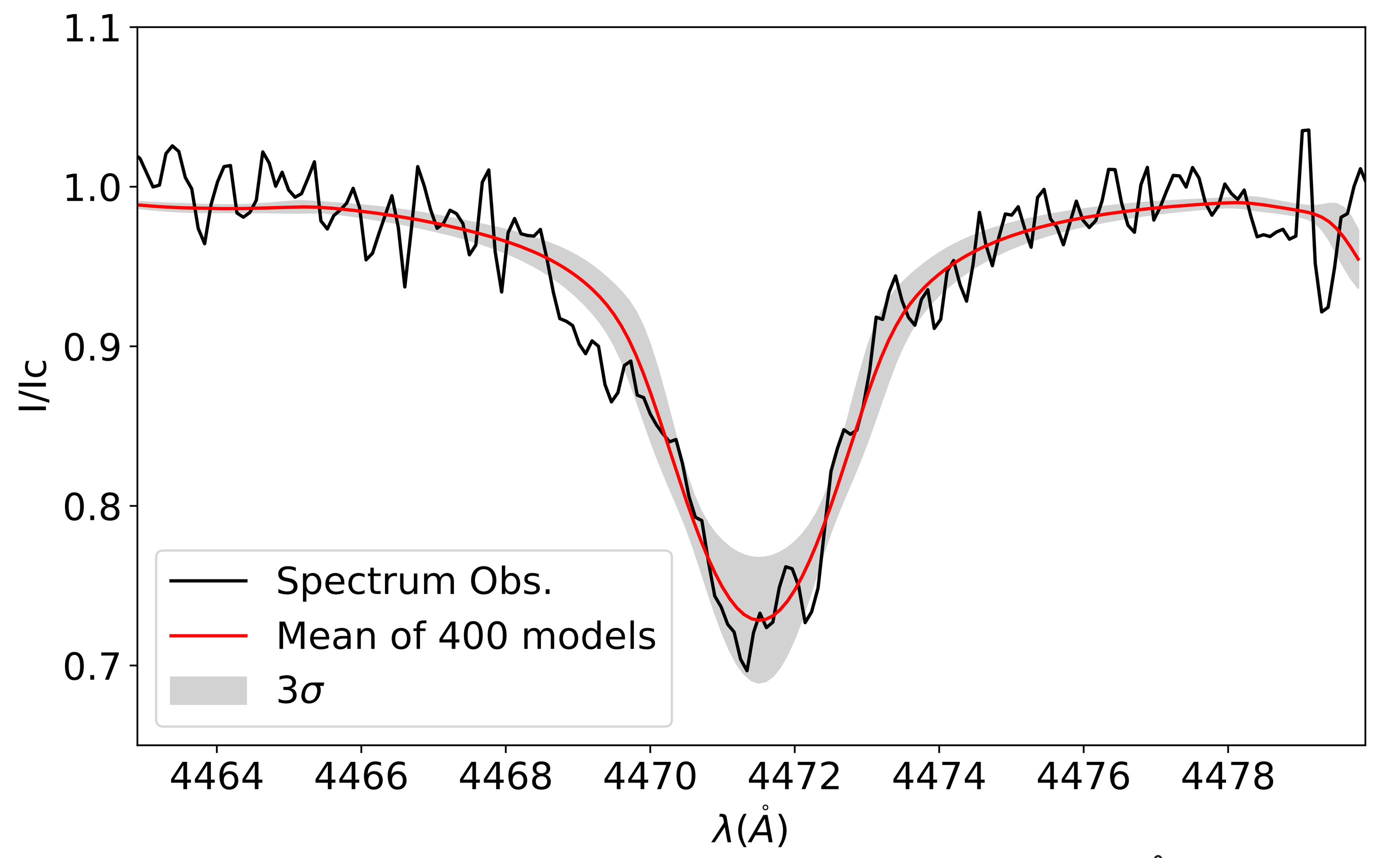

Figure 3: ZPEKTR model for the star HD212076 for the HeI 4471 Å line.

Star	T_{pole} [K]	Ω/Ω_c	$v \sin i$ [km/s]	i [°]
HD 212076	19475 ± 500	0.85 ± 0.02	120 ± 10	22 ± 2

Table 1: Four ZPEKTR parameters for the star HD 212076.

Results

We compared our results of the **inclination angle** with Cochetti et al. 2019[7], fitting a linear function without intercept (shown in Fig. 4), obtaining:

$$y = 0.95(\pm 0.02)\,x,$$

the y-axis is the interferometric measured values of the inclination angles and the x-axis corresponds to the values found in this work, with an R^2 of 0.996.

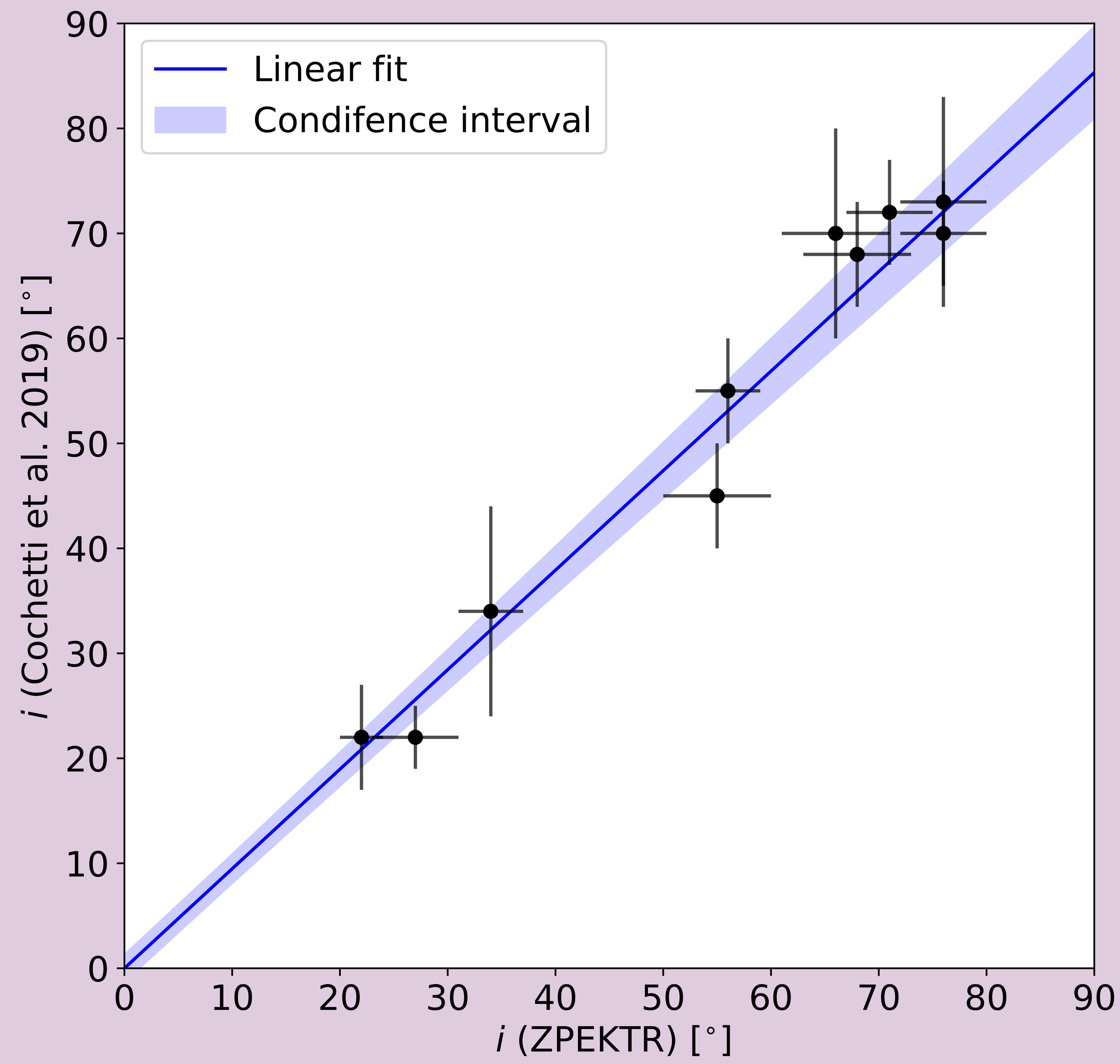

Figure 4: Linear fit between the inclination angle obtained with ZPEKTR and the values provided in Cochetti et al. 2019 for the ten Be stars (Turis-Gallo in prep 2024).

Conclusions and Future Work

- We were able to estimate inclination angles for the massive stars in our sample with high accuracy, aligning well with the direct interferometric measurements performed by Cochetti et al. 2019[7].
- To improve our results, we are currently implementing a Bayesian Neural Network using the ZPEKTR models to obtain a distribution of each output parameter, including errors.

KEY REFERENCES

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ACKNOWLEDGEMENT AND PARTNERS

DT acknowledges support from ANID BECAS/DOCTORADO NACIONAL/2024-21240465. MC, CA & IA thanks Fondecyt project 1230131. This project has received funding from the European Union's Framework Programme for Research and Innovation Horizon 2020 (2014-2020) under the Marie Skłodowska-Curie Grant Agreement No. 823734.