Boletim da Sociedade Astronômica Brasileira, **37**, no. 1, 15-16

Empirical relations for the determination of effective temperature and chemical abundances of hot stars

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Abstract. This work demonstrates that empirical relations between line ratios and stellar effective temperature (T_{eff}) can provide robust diagnostics for massive stars. Equivalent widths of He I and He II lines show strong correlations with T_{eff} above 25,000 K, enabling the development of new spectral indicators without the need for detailed atmosphere modeling. These calibrations have the potential to significantly reduce computational costs and accelerate the analysis of extragalactic stellar populations.

Resumo. Este trabalho demonstra que relações empíricas entre razões de linhas e temperatura efetiva estelar (T_{eff}) podem fornecer diagnósticos robustos para estrelas massivas. As larguras equivalentes das linhas de He I e He II mostram correlações fortes com T_{eff} acima de 25.000 K, possibilitando o desenvolvimento de novos indicadores espectrais sem a necessidade de modelagem detalhada da atmosfera. Essas calibrações têm o potencial de reduzir significativamente os custos computacionais e acelerar a análise de populações estelares extragalácticas.

Keywords. stars: massive – stars: abundances – stars: fundamental parameters – techniques: spectroscopic – Magellanic Clouds

1. Introduction

Massive stars are key drivers of galactic evolution, playing a crucial role in the chemical enrichment and dynamical feedback processes that shape galaxies over time. Their strong stellar winds and supernova explosions inject energy and momentum into the interstellar medium, triggering or quenching star formation and redistributing heavy elements throughout their environments. Because of this, a detailed understanding of the fundamental parameters of massive stars, particularly the effective temperature (T_{eff}) and surface chemical abundances, is essential for modeling stellar feedback, chemical evolution, and star formation histories in galaxies.

Traditionally, these parameters are derived from detailed spectral modeling, a process that is computationally intensive and requires high-resolution spectra and sophisticated model atmospheres. This approach, while accurate, is not feasible for large stellar samples or distant galaxies where only limited spectral information is available.

This study proposes an empirical method for estimating T_{eff} using helium line ratios in the optical spectra of hot stars. The primary goal is to identify reliable spectroscopic indicators that can replace or complement full atmospheric modeling. By focusing on the equivalent widths (EWs) of He I and He II absorption lines, we aim to construct calibration relations that can be broadly applied across environments with different metallicities.

Our approach leverages data from the XShootU collaboration, which provides high-resolution, high-S/N spectra of OB stars in the Magellanic Clouds. These galaxies offer an ideal testbed for this method, given their well-known distances, relatively low reddening, and metallicity gradients. The results of this work support the development of a robust, physics-informed alternative to traditional analysis, opening the door to automated classification and parameter estimation for large stellar populations in nearby and distant galaxies.

Figure 1. A composite view of the "wing" of the Small Magellanic Cloud (SMC). The image combines data from NASA's three Great Observatories: X-ray observations from Chandra (shown in purple), optical data from Hubble (rendered in red, green, and blue), and infrared emission from Spitzer (also contributing to red tones). The SMC provides a unique opportunity to study stellar evolution in a low-metallicity environment outside the Milky Way. Image credit: NASA/CXC/JPL-Caltech/STScI.

2. Methods and Sample

The sample used in this study is part of the XShootU collaboration, which provides high-resolution spectra of massive stars in the Large and Small Magellanic Clouds (LMC and SMC). A fraction of the sample (~50 stars) has well-determined fundamental parameters obtained from detailed atmospheric modeling by Martins et al. (2024) and Bernini-Peron et al. (2024).

We selected twelve spectral windows covering key He I and He II absorption lines, focusing on those that are strong and isolated in the optical range. For each star, we measured the equivalent widths (EWs) of these lines using an automated Python-based pipeline. After quality control, a subset of reliable measurements was retained for analysis.

We tested several combinations of He line ratios to assess their correlation with effective temperature. Among them, the

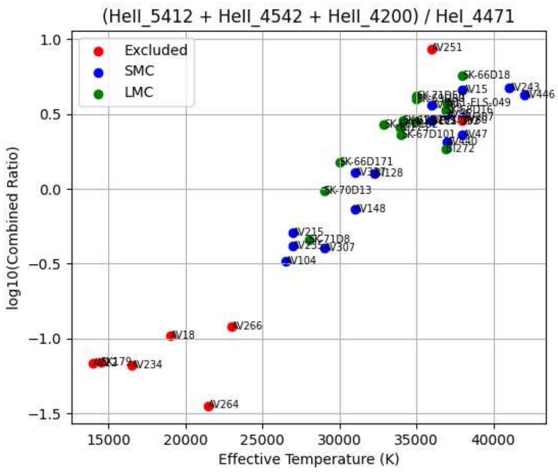

Figure 2. Combined He II/He I line ratio as a function of effective temperature. Each point represents a star, color-coded by galaxy: blue for SMC, green for LMC, and red for excluded objects.

ratio that yielded the strongest and most consistent correlation is the one shown in Figure 2.

3. Key Findings

The analysis of the He line ratios reveals a clear and tight correlation with stellar effective temperature. Figure 3 shows the relation between the combined He II to He I ratio and $T_{\rm eff}$ for stars in the LMC and SMC, with overplotted linear regressions for each galaxy.

The correlation is particularly strong for the SMC sample ($r = 0.95$), likely due to reduced metallicity effects. From this figure there is a hint that the relation between the He lines and the effective temperature might depend on the metallicity. Dividing the trends for the SMC and LMC we find a much better correlation.

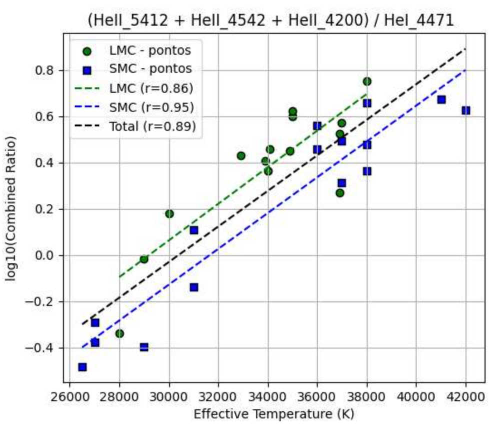

Figure 3. Correlation between the combined He II/He I line ratio and effective temperature for LMC (green) and SMC (blue) stars. Dashed lines show linear regressions for each subset, along with the total sample fit (black).

4. Conclusions

Our analysis confirms that helium line ratios, particularly those combining multiple He II lines over He I $\lambda 4471$, are effective diagnostics for estimating the effective temperature of massive stars. The method works best for stars with $T_{\rm eff} > 25{,}000$ K, where He II absorption remains strong and well-measured.

The following empirical calibrations were derived from the data:

$$\log_{10}(R) = 7.91 \times 10^{-5}\, T_{\rm eff} - 2.310 \quad \text{(Total sample)} \qquad (1)$$

$$\log_{10}(R) = 7.73 \times 10^{-5}\, T_{\rm eff} - 2.449 \quad \text{(LMC)} \qquad (2)$$

$$\log_{10}(R) = 7.70 \times 10^{-5}\, T_{\rm eff} - 2.342 \quad \text{(SMC)} \qquad (3)$$

These relations offer a practical alternative to full spectral modeling for determining $T_{\rm eff}$ in OB-type stars. They are particularly useful for large datasets or studies involving stars in distant galaxies, where quick and robust estimates are essential.

5. Future Directions

The next steps of this study include extending the analysis to a larger set of lines of different elements, particularly those that may be sensitive to surface gravity or metallicity. We also aim to refine the empirical calibrations by including more stars from diverse environments, such as lower-metallicity galaxies and a sample of Milky Way stars.

Additionally, we plan to implement this method in an automated pipeline for stellar classification, enabling its application to massive stellar populations observed in extragalactic surveys. This will help build more accurate models of stellar feedback and galactic evolution based on statistically significant datasets.

Acknowledgements. We thank the XShootU collaboration for providing access to the spectral data used in this study. A.T.S.S. acknowledges support from the Universidade Cidade de São Paulo (UNICID) and the Núcleo de Astrofísica Teórica (NAT). The author also acknowledges financial support from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

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