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# A near infrared spectral sequence of O-type dwarfs

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**Resumen** / El estudio de la morfología espectral es una poderosa herramienta para comprender las propiedades fundamentales de las estrellas. El esquema de clasificación espectral de las estrellas O ha sido revisado en el contexto del *Galactic O-Star Spectroscopic Survey* y se propuso un nuevo conjunto de estrellas estándar espectrales. Dado que la gran mayoría de las estrellas O Galácticas son visibles sólo en el infrarrojo pues se ven sujetas a gran absorción interestelar en el óptico, es necesario extender este trabajo hacia esas longitudes de onda. Estamos trabajando en la construcción de un atlas espectral con observaciones de alta calidad entre 0.85 $\mu$m y 2.5 $\mu$m. Las observaciones de este proyecto datan desde el 2013 y se realizaron con los espectrógrafos GNIRS (Observatorio Gemini, Hawaii) y FIRE (Observatorio Las Campanas, Chile). Presentamos aquí un nuevo lote de resultados, que incluye los espectros de una secuencia de estrellas estándar enanas que van desde O4 a B0 en las bandas $X$, $Y$, $J$, $H$ y $K$ del infrarrojo cercano. Analizamos este conjunto de datos para establecer algunas características espectrales de tales estrellas, con el objetivo de definir criterios de clasificación en el rango del infrarrojo cercano tales como los cocientes entre He I $\lambda$1.700 $\mu$m y He II $\lambda$1.042 $\mu$m y entre He I $\lambda$1.700 $\mu$m y He II $\lambda$1.692 $\mu$m.

**Abstract** / The study of spectral morphology is a powerful tool for understanding the fundamental properties of stars. The spectral classification scheme for O stars has been revised in the context of the *Galactic O-Star Spectroscopic Survey* and a new set of spectral standard stars was proposed. Since the vast majority of the Galactic O stars are visible only in the infrared as they are subject to large interstellar absorption in the optical, it is necessary to extend this work towards those wavelengths. We are working on the construction of a spectral atlas with high quality observations between 0.85 $\mu$m and 2.5 $\mu$m. The first observations for this project date back to 2013 and were made with the GNIRS (Gemini Observatory, Hawaii) and FIRE (Las Campanas Observatory, Chile) spectrographs. We present here a new batch of results, which includes spectra of a sequence of dwarf standard stars with spectral types ranging from O4 to B0 in the $X$, $Y$, $J$, $H$, and $K$ near-infrared bands. We analyze this data set to establish some spectral characteristics of such stars, with the aim of defining classification criteria in the near-infrared range such as the ratios between He I $\lambda$1.700 $\mu$m and He II $\lambda$1.042 $\mu$m and between He I $\lambda$1.700 $\mu$m and He II $\lambda$1.692 $\mu$m.

*Keywords* / atlases — stars: early-type — stars: massive

## 1. Introduction

Despite being rare objects, O stars make a huge contribution to their surroundings. This effect comes from their energy output in form of strong UV radiation, powerful stellar winds, dynamical influence due to their high mass and chemical enrichment via supernova events. But they span a really short lifetime which in addition doesn't allow them to blow away the gas and dust envelope that gave birth to them. Moreover O stars are concentrated towards the Galactic plane, which adds high levels of visual extinction to their lines of sight. These circumstances make observing them in the optical domain quite difficult, so getting data at near infrared wavelengths (NIR) seems a much better approach.

A few NIR atlases of OB stars spectra have been published by the end of the XX century and the beginning of the XXI century although they suffer from several issues such as being wavelength limited or constructed with low resolution or low signal-to-noise ratio (S/N) spectra or without a complete sample of classification standards (cf. Torres Robledo et al., 2011). In addition, the James Webb Space Telescope (JWST) started its operations and is producing huge amounts of data. This data set already includes numerous star forming regions that are shrouded by dust and gas and now their members became visible thanks to the near- and mid-infrared detectors on board. This fact, along with the existence of a grid of spectroscopic standard stars defined by the Galactic O-Star Spectroscopic Survey (GOSSS; Sota et al., 2011, 2014; Maíz Apellániz et al., 2016) gives rise to the need of a new and improved NIR atlas. This is why we started collecting high S/N and high resolution spectroscopic observations of standard stars with the Gemini North Infrared Spectrograph (GNIRS) and the Folded-port InfraRed Echellette (FIRE) attached to the Magellan Baade telescope at Las Campanas Observatory, Chile. Therefore, the Atlas can be mostly instrumentally homogeneous at each hemisphere.

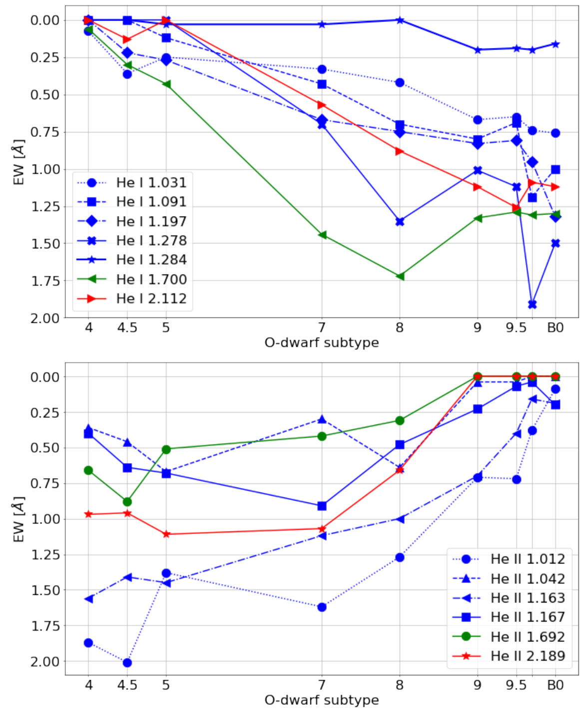


Figure 1: *EW* of He I (upper panel) and He II (lower panel) lines measured in the spectra of standard stars. The lines are colored according to their location in the different bands: *J* (blue), *H* (green) or *K* (red).

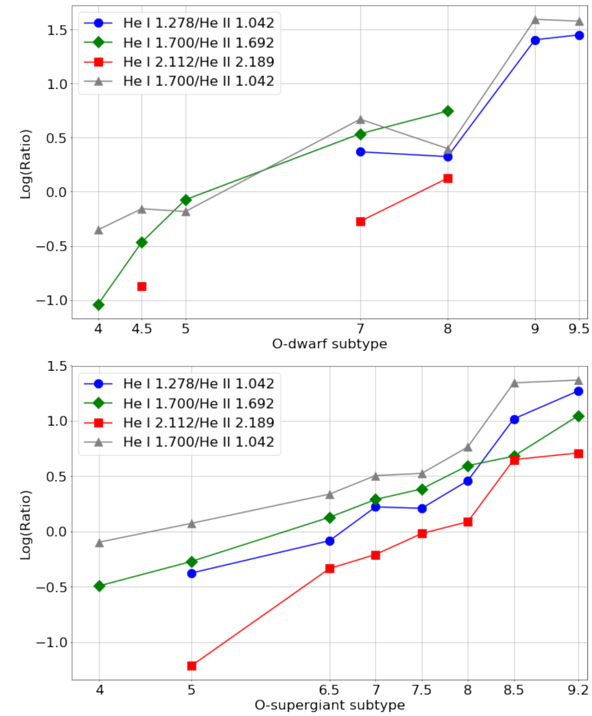


Figure 2: He I to He II ratios in logarithmic scale, corresponding to dwarfs (upper panel) and supergiants (lower panel, adapted from fig. 2 of Giudici Michilini et al. 2021). The colors are as in Fig. 1, and gray corresponds to the He I 1.700/He II 1.042 ratio.

## 2. Observations

The NIR spectra of this set of O-type dwarf stars were obtained using GNIRS⋆ ($R$=18000) and FIRE ($R$=6000). In both cases, spectra of telluric standard stars were also taken for flux calibration and telluric absorption correction. Ar (GNIRS) and ThAr (FIRE) lamp spectra were taken for wavelength calibration. Additional details can be found in Giudici Michilini et al. (2021).

The GNIRS data reduction was performed with the IRAF⋆⋆ tasks provided by Gemini Observatory. The FIRE data were reduced using the IDL pipeline FIREHOSE provided by the instrument developer (Simcoe et al., 2013). Additional information about the data reductions can be found in Giudici Michilini et al. (2020)

## 3. Results

We obtained the NIR spectra of the following standard stars from Maíz Apellániz et al. (2016): HD 46223 (O4 V(f)), HD 303308 (O4.5 V(fc)), HDE 319699 (O5 V(fc)), HD 93222 AB (O7 V(fc)), HD 97848 (O8 V), 10 Lac (O9 V), AE Aur (O9.5 V), $\upsilon$ Ori (O9.7 V), and $\tau$ Sco (B0), which represent a temperature sequence among O-type dwarfs.

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⋆⋆IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

We measured the equivalent widths (EW) of several lines that are present in most spectra, and also were identified in the spectra of the supergiant standard stars (see Giudici Michilini et al., 2021). EWs were measured with the SPLOT routine within IRAF software. The behaviour of the EW measurements along the temperature sequence is depicted in Fig. 1 and some chosen line ratios, in Fig. 2. The spectra obtained are shown in Fig. 3.

As for the temperature sequence, in general the He I lines become clearly stronger as the temperature decreases and on the other hand the He II lines get weaker, as expected. Contrary to what was seen in the supergiant sequence (where EWs do not show a notable progression, Giudici Michilini et al., 2021), most He II features are quite sensitive to temperature. Nevertheless we can notice some odd behaviors that need to be investigated such as the decrease of the EW of He I $\lambda 1.700$ $\mu$m after its maximum at the O8 sub-type. Other He I lines do not show a monotonic change with temperature either.

In Fig. 2, we show the He I to He II line ratios at each luminosity class in a logarithmic scale. The numerous blank spots at the dwarf ratios are due to zero values for the EW of the corresponding line in those spectral types. This happens specially in the $K$-band, where the dwarfs present measurable helium features in only 3 subtypes. This issue gives rise to the need to search for other features in order to solve this problem and to define a reliable classification criterion.

In the upper panel of Fig. 2 can be clearly seen that

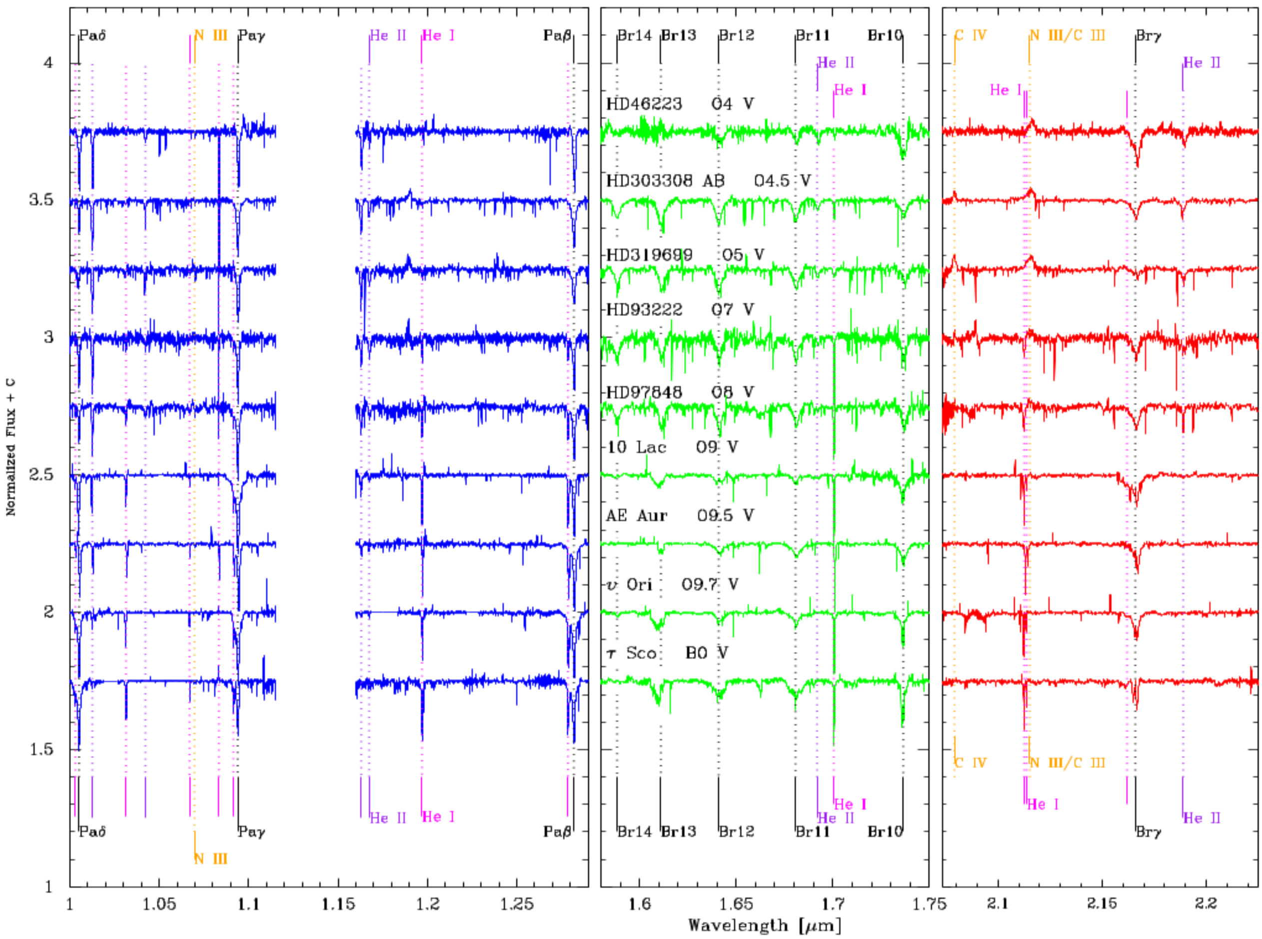


Figure 3: NIR sequence of standard O-type dwarf stars. The lines of He I and He II are labeled with pink and violet, respectively.

the ratio between He I $\lambda1.700$ $\mu$m and He II $\lambda1.042$ $\mu$m is appropriate to differentiate between the subtypes 4 through 9.5. In addition, the ratio between He I $\lambda1.700$ $\mu$m and He II $\lambda1.692$ $\mu$m (both in H-band) shows a steady growth and therefore can be taken as a robust classification criterion for subtypes 4 to 8.

## 4. Conclusions

We obtained high-resolution NIR spectra of a set of O-type classification standard dwarf stars to analyze the effects of temperature on this luminosity class. As expected, the He I lines become stronger as the temperature decreases, and the He II lines behave in the opposite way. Despite some problematic ratios in the three bands, two useful line ratios were identified, the one between He I $\lambda1.700$ $\mu$m and He II $\lambda1.042$ $\mu$m and the other between He I $\lambda1.700$ $\mu$m and He II $\lambda1.692$ $\mu$m.

We will continue to build a high-resolution atlas for spectral classification of O-type stars in the NIR. We also plan to compare the classification criteria in the optical and NIR.

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