Wolf-Rayet Stars
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SOAR Near-Infrared and Optical Survey of OIf* and OIf*/WN Stars in the Periphery of Galactic Massive Star Forming Regions

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In this contribution we present some preliminary results obtained from a SOAR-Goodman optical spectroscopic survey aimed to confirm the OIf* - OIf*/WN nature of a sample of Galactic candidates that were previously confirmed as massive stars based on near-infrared spectra taken with OSIRIS at SOAR. With only a few of such stars known in the Galaxy to date, our study significantly contributes to improve the number of known Galactic O2If* stars, as well as almost doubling the number of known members of the galactic sample of the rare type OIf*/WN.

1 The most massive hydrogen core burning stars

1.1 The earliest O-type stars and the OIf*/WN intermediate type

For a long time the O3 stars were considered to represent the most massive main-sequence stars. However, in the last decades it has become clear that some hydrogen-rich nitrogen sequence Wolf-Rayet stars are in reality extremely massive and luminous main-sequence stars (de Koter, Heap & Hubeny 1997; Schnurr et al. 2008; Smith & Conti 2008; Crowther et al. 2010), which because of their proximity to the Eddington limit present an emission-line spectrum at the beginning of their main-sequence evolution, mimicking the spectral appearance of classical WR stars. From the empirical determination of stellar masses of high-mass binary systems, and the use of state-of-the-art stellar models, it is now clear that such kind of massive stars probably belong to the OIf*/WN and WNH spectral types (Smith & Conti 2008; Crowther et al. 2010). This conclusion is supported by systematic studies of binaries made for example, by Schnurr et al. (2008) for R145 (in 30 Dor), Smith & Conti (2008) for WR25, Roman-Lopes (2013a) for WR22 (both in the Carina Nebula), Schnurr et al. (2009) for NGC3603-A1, Smith & Conti (2008); Bonanos et al. (2004), for WR20a (comprised of two O3If*/WN6-type stars with absolute masses of 83 and 82 $M_\odot$), Roman-Lopes (2012) for WR21a (one WN6ha with an estimated minimum mass of 87 $M_\odot$, and an early O-type secondary with a minimum mass of 53 $M_\odot$), and more recently, Crowther et al. (2010) from the spectroscopic analyses of WNH stars located within the core of NGC 3603 and the 30 Doradus Nebula in the Large Magellanic Cloud. Indeed, some WNH stars in the core of 30 Doradus and NGC 3603 have computed initial masses in the range of 165-320$M_\odot$, and 105-170$M_\odot$, respectively.

The intermediate spectral type O3If*/WN6-A was introduced more than 30 years ago by Rauw et al. (1996) to classify the bright emission line star Sk-67 22 in the LMC, which shows intermediate spectra between those of HD93129A (the prototype of the O2If* class) and WR20aa (O2If*/WN5) (Figure 1). The OIf*/WN type can be distinguished from the OIf* and WNH types by the P-Cygni morphology of the Hβ line, since it is uniquely in absorption for O stars (including OIf* stars) and purely in emission for WN stars (Hadfield et al. 2007). New exemplars of the OIf*/WN spectral type were mainly found in the LMC, always consisting of bright massive objects (for more on this see for example, Walborn & Blades (1997); Melnick (1985); Crowther et al. (2010)). In the Galaxy, Roman-Lopes, Barba & Morrel (2011) and Roman-Lopes (2012, 2013a,b) using low-resolution SOAR-OSIRIS and NTT-SOFI NIR spectra, have identified five new exemplars of the type, whose Galactic sample possibly is still compound by less than 10 known exemplars to date.

1.2 Optical and near-IR spectroscopic classification

The classification of early-type stars has historically relied upon high quality blue visual spectra, to which UV morphological sequences have been added (e.g. Walborn 1982). With the advent of efficient detectors and large ground-based telescopes, the near-IR window has opened up (mainly the K-band) for spectral typing, albeit generally cruder with respect to optical spectroscopy (Gray & Corbaly 2009). This is especially relevant for highly obscured and distant emission line early-type stars, which have been discovered for example from near-IR narrow-band surveys (Crowther et al. 2006; Shara et al. 2009) and near to mid-IR spectral energy distributions (Hadfield et al. 2007).

In spite of the observational progress made during the last years, the number of known Galactic OIf*/WNH stars with studies in both, optical and near-IR domains is very small, only four! (WR20a,

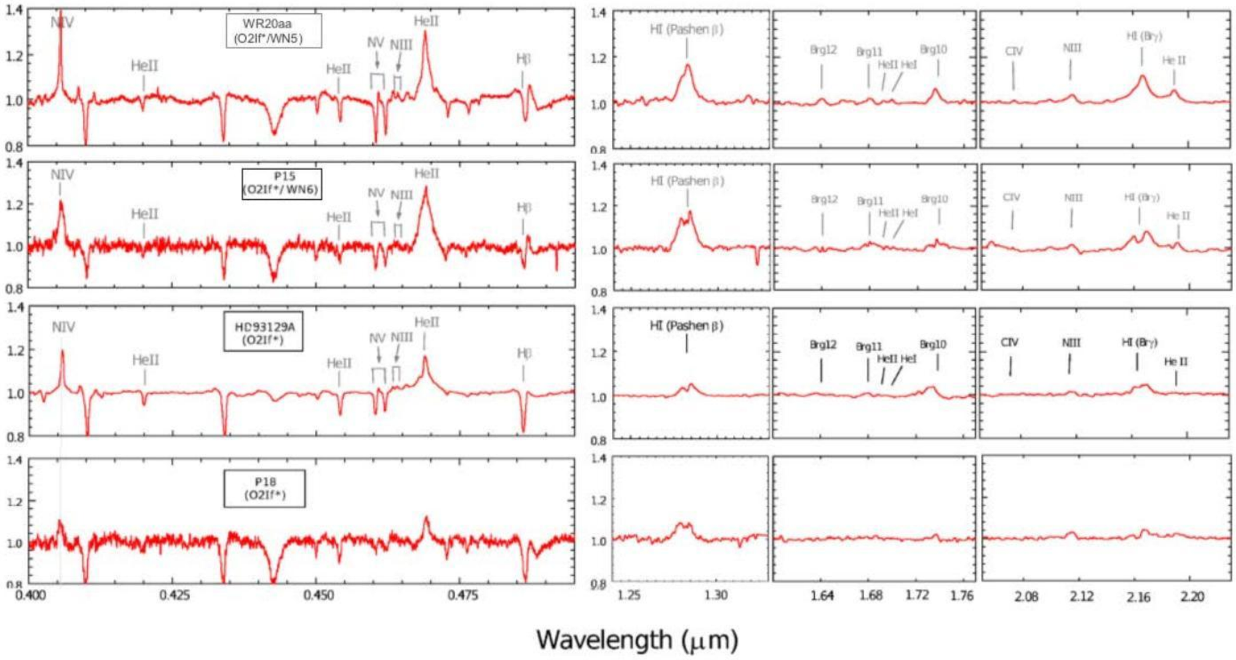

Fig. 1: Goodman and OSIRIS optical-NIR spectra of WR20aa (O2If*/WN5) and HD93129A (O2If*) taken at the SOAR telescope, together with the spectra taken for two (P15 and P18) newly discovered O2If* and O2If*/WN6 Galactic exemplars, with the main spectral lines indicated by labels. Despite the similar morphology, one can notice that the intensity of some key optical and NIR lines are quite different.

WR21a, WR25 - Crowther et al. (2010) and WR20aa - Roman-Lopes, Barba & Morrel (2011)). Considering that most (if not all) of the still unknown members of the OIf*/WNH Galactic population probably are going to be discovered (and properly studied) only from the use of NIR spectroscopic facilities, one relevant questions is, can we properly distinguish between Of, Of/WN and WN stars solely from near-IR spectroscopy? Before we can answer that, it is necessary to improve the number of known Galactic OIf*, OIf*/WNH and WNH stars with high quality optical and near-IR spectra.

2 Results

Here we present some results on our search for massive stars still unknown in the periphery of a sample of Galactic massive star regions. The 2MASS point sources there were studied based on a near-infrared selection criteria and from spectroscopic surveys aimed to determine their corresponding spectral types. From the related surveys, it was possible to successfully identify and classify at least four new Galactic O2If* stars, as well as a similar number of new Galactic exemplars of the intermediate OIf*/WN type.

2.1 SOAR observing runs and the OSIRIS and Goodman spectra

The NIR and optical spectroscopic data were obtained with the OSIRIS and Goodman instruments at the SOAR telescope during several runs from 2011 to 2015, with the data being taken on nights that in general presented good seeing conditions.

The NIR raw frames were reduced following standard reduction procedures, which are presented in details in Roman-Lopes (2009). The two-dimensional frames were sky-subtracted for each pair of images taken at two nod positions, followed by division of the resultant image by a master flat. The multiple exposures were combined, and then followed by one-dimensional extraction of the spectra. Also, the effects of the earth atmosphere in the NIR science spectra were corrected using J-, H- and K-band spectra of A-type stars, with the intrinsic hydrogen lines being carefully subtracted by modeling the observed line profiles through the use of Voigt profiles given by the SPLOT task on IRAF. The final NIR spectra were normalized through the fitting to the continuum emission observed in the associated wavelength range. On the other hand, the blue-optical Goodman spectra presented in this work were acquired using the 1.03" long slit with the 930 l/mm (M2 - 385-555nm) grating, which with the mentioned setup provides a maximum resolving power R∼2100 (at 550nm). The reduction of the optical spectra was performed using standard techniques through the use of the packages (beside others) ONEDSPEC, TWODSPEC and APEXTRACT within IRAF. The one-dimensional spectra of the science targets were extracted from the two dimensional frames by summing pixels in the data range and subtracting off the background value for each column. The bad pixels were replaced through a linear interpolation of the removed data range, and the wavelength calibration was performed using Hg(Ar) + Ne lamp spectra. As was made in the case of the NIR spectroscopic observations, the final optical spectra were also normalized through the fitting of the continuum emission in the associated wavelength range.

2.2 Optical and NIR spectra of OIf*, OIf*/WNH and WNH candidates - two template cases

In Figure 1 it is shown the optical and near-infrared spectra of two Galactic stars of the O2If* (HD93129A) and O2If*/WN5 (WR20aa - Roman-Lopes, Barba & Morrel (2011)) types, together with the SOAR spectra taken for two new discoveries (P15 and P18) taken from our sample of new Galactic O2If* and OIf*/WN stars.

Regarding the O2If* sample, HD93129A together with MTT68 (Roman-Lopes 2013b) are probably the only two known Galactic exemplars of the class, with the former being considered the earliest, hottest, most massive and luminous O star in the Galaxy. Indeed, it is an extremely powerful X-ray source that has also an extremely powerful wind with a terminal velocity above 3000 km s^{-1}, and a mass-loss rate above 10^{-5} $M_\odot$ yr^{-1} (Cohen et al. 2011). From a direct comparison of the HD93129A's spectrograms with the optical and NIR SOAR spectra of P18, it is possible to conclude that P18 probably is the third known Galactic exemplar of the rare O2If* type. It is interesting to notice that the optical spectrogram of P18 presents a very intense DIB at 4427Å indicative of heavily optical reddening. In fact, the Goodman blue-optical spectrogram of P18 shown there was generate from the combination of 5 individual exposures of 1800s each, corresponding to about 2.5 hours of integration time at the SOAR telescope. On the other hand, the J-, H- and K-band spectrograms of P18 (also shown in Figure 1) are the results of the combination of 8 individual exposures of 90s each, and if we consider also the standard A0 star observed at the end of the science block (in order to suppress the telluric features imprinted on the original science spectra), the total integration time necessary to get the science + telluric sample corresponds to only 0.4 hours at the same telescope!

Finally in Figure 1 we also present the optical and near-infrared spectra of P15, which present the a very strong NIV 4058Å emission line much much stronger than the NIII emission lines around 4630-40Å , a feature typical of O2If* stars like HD93129A. On the other hand, the presence of a P-cygni profile in the Hβ line indicate that P15 is a new Galactic exemplar of the O2If*/WN6 type.

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Paco Najarro: Could you use the strength of the N IV 9–8 transition to distinguish between O I* and WN spectral class?

Alexandre Roman-Lopes: Thanks for the question. In my opinion, if one can successfully relate the strength of the observed H I Brackett recomlination line (relative to others in the same sequence) with the presence of the N IV emission line, that would probably be an interesting way to distinguish between those two spectral classes.

Geographical distribution of the participant's home institutes