Wolf-Rayet Stars
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The WR population in the Galactic Center

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The Galactic Center (GC) hosts three of the most massive WR rich, resolved young clusters in the Local Group as well as a large number of apparently isolated massive stars. Therefore, it constitutes a test bed to study the star formation history of the region, to probe a possible top-heavy scenario and to address massive star formation (clusters vs isolation) in such a dense and harsh environment. We present results from our ongoing infrared spectroscopic studies of WRs and other massive stars at the Center of the Milky Way.

1 Massive stars in the GC: Clusters vs isolation

Recent studies have revealed the presence of a large number of isolated massive stars (Mauerhan et al. 2010a,b) at the GC which is comparable to the massive star population of each of the clusters (Figer et al. 1999, 2002). Such detection of apparently isolated massive stars in this region has raised a further fundamental issue – whether these "massive field stars" are results of tidal interactions among clusters, are escapees from a disrupted cluster, or represent a new mode of massive star formation in isolation (Dong et al. 2014). Following the numerical dynamical simulations from Harfst et al. (2010), and including the effects of stellar evolution and the orbit of the Arches cluster in the Galactic Center potential, Habibi et al. (2014) investigated the first option and found that models were able to account for ~60% of the isolated sources within the central 100pc as sources drifted away from the center of the clusters. On the other hand radial velocity measurements of a sample of eight objects in the vicinity of the Arches cluster (Dong et al. 2014) suggest that two of them could have been associated with the cluster while two others likely formed in isolation. The latter option was also derived for WR102ka from radial velocity studies and a deep integral-field spectroscopy survey of its surroundings by Oskinova et al. (2013). However, we note that radial velocity estimates of these objects (mainly OIf+ and WNh) may be subject to high uncertainties, as the spectral lines utilized in these studies are severely contaminated by the stellar winds (see below). Thus, further detailed evidence for or against these scenarios is still lacking and awaits precise proper motion measurements (currently underway) providing 3-D velocities of the sources relative to the clusters.

A major step to differentiate among the above scenarios can be achieved through spectroscopic studies of the isolated sources, yielding stellar properties, ages and abundances. Comparison of the results of the quantitative model-atmosphere analysis to theoretical isochrones will allow us to determine if these stars were born in single co-eval cold molecular cloud event or formed over an extended (e.g. 1–10 Myr) period. Obtaining metal abundances from these "field" objects is crucial to understand the metal enrichment history of the GC and to test whether these isolated stars have followed a metal-enrichment scenario different than those in the GC clusters.

The Quintuplet and Arches clusters provide the stellar reference sources to perform such studies. At its current evolutionary phase (age ~4 Myr, Figer et al. 1999), the massive members of the Quintuplet Cluster are currently WN9-10h (plus a WN6), weak lined WC9, OIf+ stars and LBVs (Figer et al. 1999; Liermann et al. 2009), while the massive population of the younger Arches cluster is dominated by WN8-9h and OIf+ stars (Figer et al. 2002; Najarro et al. 2004; Martins et al. 2008). These spectral types basically encompass all the isolated evolved massive stars identified from recent follow-up spectroscopic observations of Paα emission objects in the GC (Mauerhan et al. 2010a,b) which show quite similar spectral morphology to those present in the Quintuplet and some of the brightest Arches members.

Another current hot-topic is whether the IMFs of massive star clusters are top-heavy. In such occurrences the larger number of type II supernovae produce enhanced yields of α-elements, resulting in an increase of α-element vs Fe (the main suppliers of iron are type Ia SNe). Najarro et al. (2004, 2009) have shown that quantitative NIR spectroscopy of high-mass stars may provide estimates of both absolute abundances and abundance ratios, telling us about the global integrated enrichment history up to the present, placing constraints on models of galactic chemical evolution, and acting as clocks by which chemical evolution can be measured. Abundance analyses may thus help to distinguish between top-heavy and standard star formation in the region.

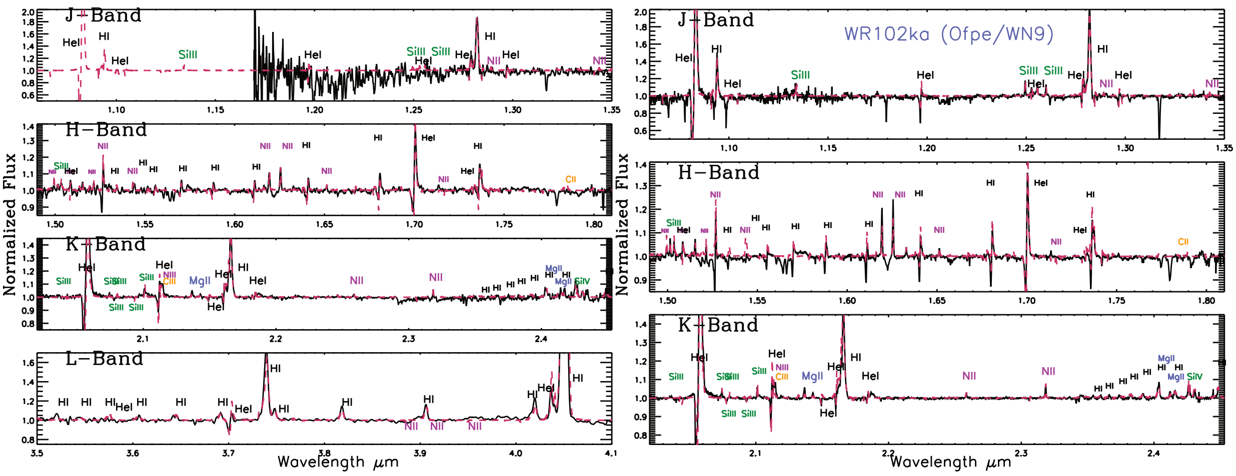

Fig. 1: Breaking the $T_{\rm eff}$ degeneracy in OIfpe/WN9 stars. Previous uncertainties in $T_{\rm eff}$ (±6000 K) due to the lack of He II lines in the spectra, are drastically reduced (±1000 K) by making use of the N II/N III and Si III/Si IV ionization equilibria. **Left)** Q8 in the Quintuplet Cluster. **Right)** The isolated WR102ka star.

2 Observations and preliminary results

We started in 2010 an observing program at GEMINI North (currently ongoing) which has been obtaining high S/N, medium-resolution spectra of the most massive stars in the Quintuplet (including the dusty WCL proper members) as well as isolated massive stars in the inner GC. So far, around 20 massive stars in the Quintuplet cluster and GC inner region have been observed since 2011 with GEMINI NIFS and GNIRS near infrared spectrographs in the H and K bands at medium-resolution (R ∼5000). The brightest targets were also secured at the shorter X and J Bands. We expect to complete our sample by Aug–Sep 2016.

We are currently in the process of modeling the early-type spectra with the CMFGEN code (Hillier & Miller 1998), to obtain physical and chemical properties and present below some results from our ongoing analysis:

We obtain a clear α-element enrichment from the analysis of the Quintuplet WNh stars, consistent with the results derived for the LBVs (Najarro et al. 2009) which denoted a clearly enhanced α/Fe=2 ratio with respect to solar.

Stellar abundances of the isolated objects seem to show a similar trend on average, with the presence of even higher α-element enrichment in some cases.

Our new high S/H spectroscopic J, H and K data provide important diagnostic lines (N II-III, SiII-IV, CII-IV, etc), which are crucial not only for abundance determinations but also to constrain stellar properties. As an example, previously found uncertainties in $T_{\rm eff}$ (±6000 K) for the Ofpe/WN9 objects at the GC (Najarro et al. 1997; Martins et al. 2007) due to the lack of He II lines in the spectra, are drastically reduced (±1000 K)by making use of the N II/N III and Si III/Si IV ionization equilibria. This is shown in Fig. 1, where preliminary fits are displayed for two OIfpe/WN9 stars in our sample (Q8 in the Quintuplet cluster and WR102ka, an object relatively far from the three clusters).

When available the HI and He lines at Pβ, provide an excellent He/H ratio diagnostic, allowing much more accurate He abundance determinations than those performed by means of K-Band spectra. Simple blue (He I) to red (H I) peak ratios may be used (see Q8 and WR102ka Pβ complex in Fig. 1)

Radial velocity estimates, if obtained for OIf+ and WNh stars, require detailed modeling of the observed spectra (Figer et al. 2004). For the OIf+ stars, the He II absorption lines, which are decent diagnostics for OV and for some OI stars with weak-to-moderate stellar winds start to be filled by the stellar wind, producing an effective blue-shift as high as 80–90 km s^{-1}. This may have important consequences when associating the radial velocities of these objects with the nearby gas and clusters. Further, even quantitative modeling may suffer from high uncertainties. Our preliminary fits to WR102ka making use of the full J, H and K band spectra reveal a radial velocity of ∼100 km s^{-1}. This value differs significantly from the 60 km s^{-1} obtained by Oskinova et al. (2013) by means of only K-band spectra and with a slightly (25%) lower spectral resolution.

We detect, for the first time, the WR stellar lines in the NIR SEDs of the dusty WCL proper members in the Quintuplet Cluster (see Fig.2). The deep J band spectra, where the dust contribution weakens, clearly display the presence of the He I-II and

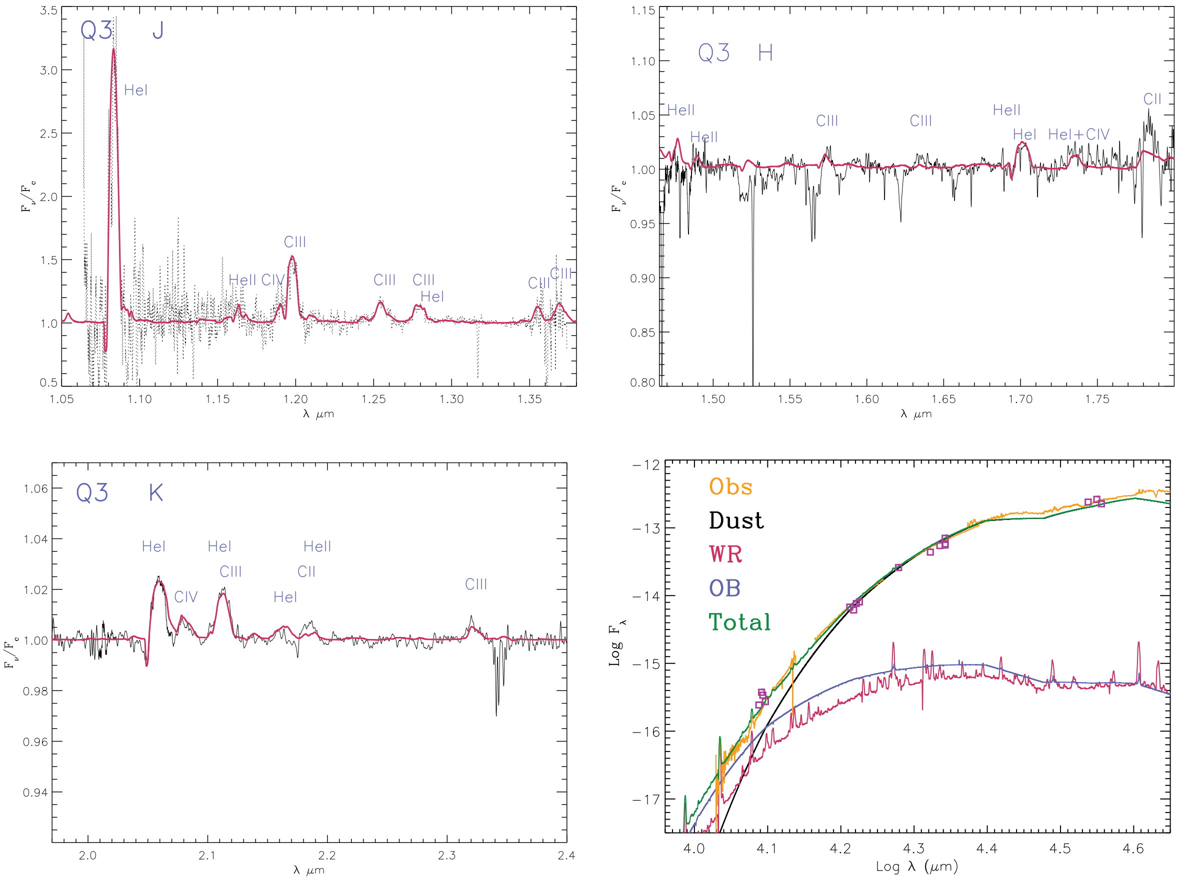

Fig. 2: First detection of stellar lines in the NIR spectra of the dusty WCL proper members of the Quintuplet Cluster. J, H and K band observations and model fits for GCS4 (Q3). Fit to the observed SED (orange) assuming that the total flux (green) is due to the contribution by dust (black), the WR (red) and an OB star (blue).

C III-IV lines of the WC9 component. Further, the huge S/N achieved in the H and K band allows to clearly identify and model the stellar lines which are severely diluted by the dust continuum. Thus, we confirm spectroscopically the WR+OB binary nature of these systems and, fitting spectrophotometric data, derive the individual contributions of the dust, WR and OB components to the total SED of the system (see Fig.2).

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Paul Crowther: Can you say anything about the binary fraction of Galactic center WR stars (beyond dusty WCs)?

Paco Najarro: We lack different spectroscopic epochs for most of the objects. We know that some of the OIfpe/WN9 stars at the GC (16NE and 16SW) are binaries. In the Arches there is an ongoing monitoring campaign looking for binaries led by Simon Clark. For some stars (Pistol, #362, LBV3) we see variability but no traces of binarity.

Gloria Koenigsberger: Are wind velocities and mass-loss rates typical for these types of stars?

Paco Najarro: Yes, the terminal velocities and mass-loss rates we obtain are consistent with those derived for other massive objects with similar spectral types.

Alexandre Roman-Lopes: Have you considered to use the VVV K-band survey in your study of isolated massive stars in the GC region?

Paco Najarro: For those objects which are isolated enough (not contaminated by nearby sources) we certainly could make use of VVV as well.