High-mass stars in the Galactic center Quintuplet cluster*

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Abstract: The Galactic center region is heavily obscured by dust in the ultra-violet and visual. Recently, a catalog with near-infrared K-band spectra of massive stars located in the Quintuplet cluster at about 35 pc projected distance of the GC was presented. Among several O stars the cluster hosts a number of massive stars in their late evolutionary stages, i.e. Wolf-Rayet stars of the nitrogen (WN) and carbon (WC) sequence. Tailored analyses with the Potsdam models for expanding atmospheres (PoWR) are presented for the WN stars. We find that the stars belong to a group of rather cool ($T_* \approx 25 - 36$ kK) but very luminous WNL stars ($\log(L/L_\odot) > 6.0$). The derived stellar parameters are discussed in the context of stellar evolution and it is shown that the stars are descendants from massive stars with initial masses of $M_{\rm init} \geq 60\,M_\odot$.

1 Introduction

With the discovery of three massive star clusters within 35 pc projected distance to the Galactic center (GC), this region turned out to be unique to study star formation and evolution. The clusters host a large fraction of the known Galactic massive stars also in late evolutionary stages, e. g. luminous blue variables (LBVs) and Wolf-Rayet (WR) stars.

While the Arches cluster is found to be the youngest cluster with about 2.5 Ma old (Figer et al. 2002) containing basically OB and WR stars of the nitrogen sequence (WN), the Central cluster and Quintuplet cluster are slightly older with ages of 6 and 4 Ma (Figer et al. 1999a, Paumard et al. 2006) and contain carbon enriched WR stars (WC) as well. For the Quintuplet, the Pistol star LBV (Figer et al. 1999a, b), and further LBV candidates (Geballe et al. 2000, Barniske et al. 2008) are found in the neighborhood of the cluster.

The combination of quantitative spectral analysis and comprehensive stellar model atmospheres allows the stellar parameters to be determined. In comparison of stellar evolution models with the stellar parameters the initial masses and ages of the sample stars can be estimated. Thus, the evolution of the stellar population of massive stars in the Galactic center can be discussed.

*Based on observations with the ESO VLT-SINFONI

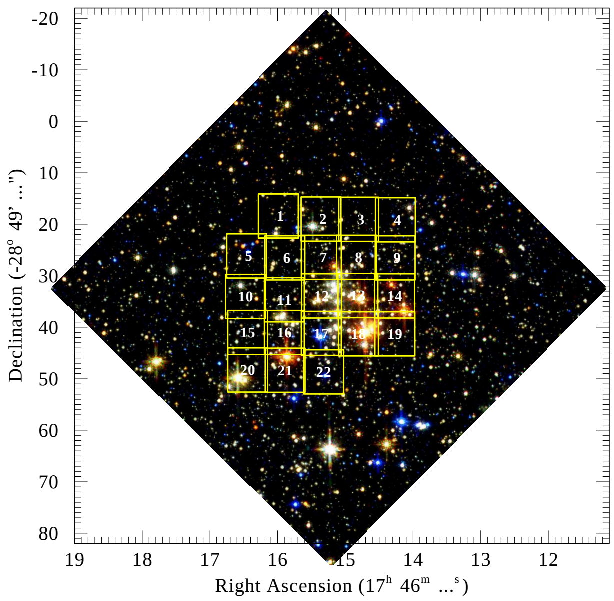

Figure 1: Fields observed with SINFONI in the Quintuplet central regions shown on an HST image (STScI-PRC1999-30b).

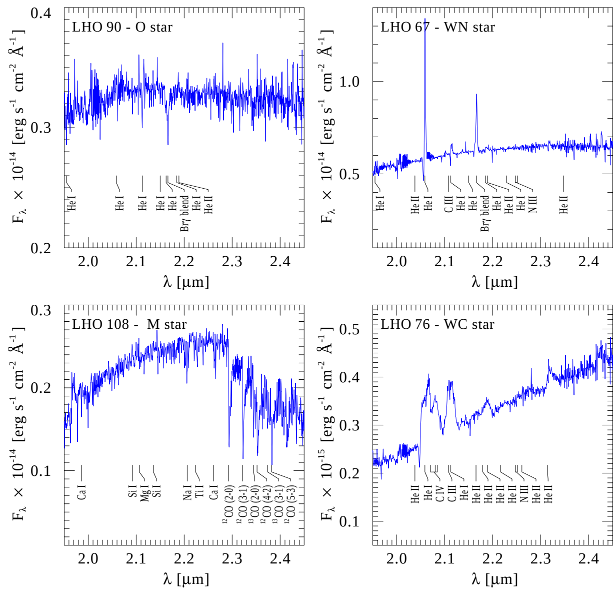

Figure 2: Example spectra from the LHO catalog with line identifications used for spectral classification.

2 Analysis

2.1 Observations

The high extinction in the direction of the GC ($A_V \approx 28$ mag) prohibits observations in the ultraviolet and optical range. Therefore, infrared spectroscopy is the prime tool to study massive stars in this region of the Milky Way. We used the ESO-VLT Spectrograph for INtegral Field Observation in the Near-Infrared (SINFONI) to observe the central parts of the Quintuplet cluster in 22 fields of 8×8 arcsec field of view, see Fig. 1 with a background composite HST image (HST program 7364, PI D. Figer, NICMOS F110W, F160W, and F205W). A spectral catalog of the point sources with 160 flux-calibrated *K*-band spectra was presented by Liermann et al. (2009, hereafter LHO catalog). Example spectra are shown in Fig. 2. For details on data reduction and flux-calibration, please refer to the catalog paper.

Among the 13 WR stars listed in the LHO catalog four are of WN and nine are of WC type. First, we concentrate on the analysis of the WN stars as described in Liermann et al. 2010 (A&A, in press). The sample comprises WR 102d, WR 102i, WR 102hb, and WR 102ea. Additionally, the star LHO 110 was included in the sample, which was classified as Of/WN candidate in the LHO catalog. However, the spectrum of this star strongly resembles spectra of typical WN stars.

2.2 PoWR models

The Potsdam Wolf-Rayet non-LTE model atmospheres (PoWR) are described in a number of publications and we refrain from repeating the details here. For further reading we suggest the reader to have a look in Hamann & Gräfener (2004).

To determine the stellar parameters we fit the spectral energy distribution (SED) of the stars by adjusting the extinction to match the observed 2MASS *J*, *H*, and *K*-band magnitudes (Fig. 3, upper panel). Simultaneously, the model continuum is used to normalize the observed flux-calibrated spectrum which then can be fitted with a synthetic emission line spectrum (Fig. 3, lower panel). To obtain

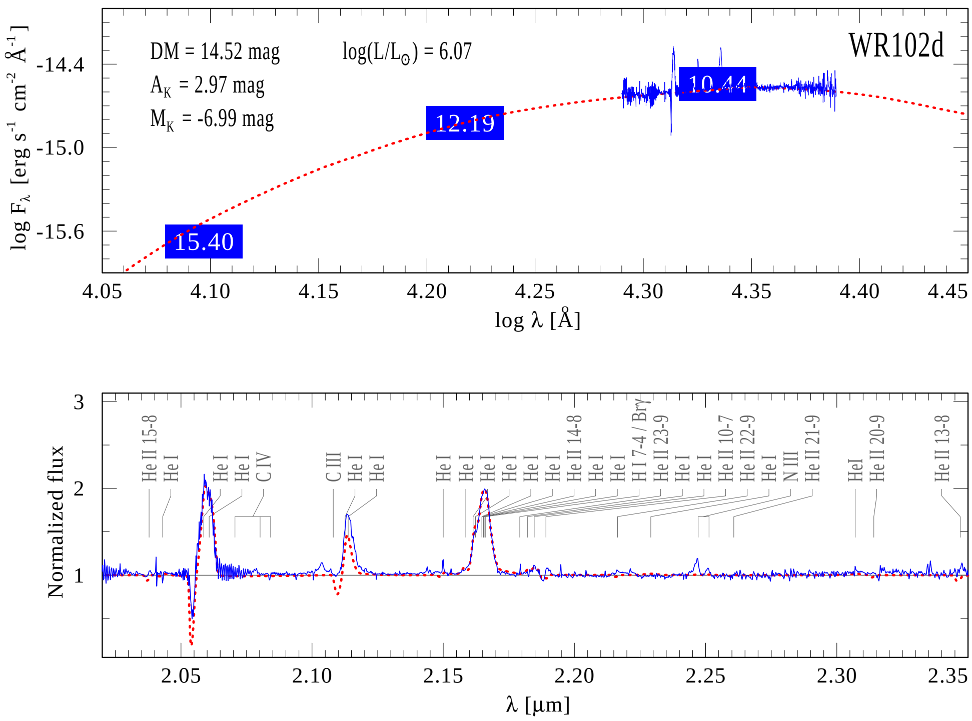

Figure 3: *upper panel*: SED and 2MASS J, H and K-band magnitudes (blue solid line and boxes) fitted with PoWR model (red dotted line) to determine the extinction and luminosity of the star. *lower panel*: Normalized emission line spectrum (blue solid line) and PoWR model (red dotted line) to derive the stellar and wind parameters.

the best fitting model these steps are an iterative process.

We find that all Quintuplet WN stars are of late type (WN9h) still having a significant amount of hydrogen (up to 45%) in their atmospheres, and that they are descendants from initially very massive ($M_{\text{init}} \geq 60\, M_{\odot}$) stars. Further details on the models and the spectral analysis of the individual stars can be found in Liermann et al. 2010 (A&A, in press). In the following, we will focus on the aspect of the initial mass of the sample stars and their position in the HRD compared with Geneva stellar evolution tracks.

3 Discussion

Massive stars with initial masses above $20\, M_{\odot}$ are supposed to pass the WR phase after they left the main sequence. In dependence of the initial stellar mass, different evolutionary scenarios are possible, which might exclude specific phases such as the blue or red supergiant (BSG/RSG) or LBV phase completely, e. g. Crowther (2007) and Maeder et al. (2008). However, in any evolutionary sequence the luminous late-type WN stars (WNL) are an interphase between O stars leaving the main-sequence and WR stars of the carbon sequence (WC), before these massive stars explode as supernova (SN).

As shown in the HRD (Fig. 4) the WNL stars in the Quintuplet form a group of relatively cool but very luminous stars to the right of the zero-age main sequence. Other Galactic WNL stars (open symbols, Hamann, Gräfener & Liermann 2006) and the WNL stars from the Arches cluster (light grey filled symbols, Martins et al. 2008) support the idea of two distinct groups with the hydrogen containing WNL and hydrogen-free WNE stars.

The cool temperatures in combination with the extreme luminosities make it quite difficult to compare the position of the stars with stellar evolution models. Fig. 5 shows the HRD again, with

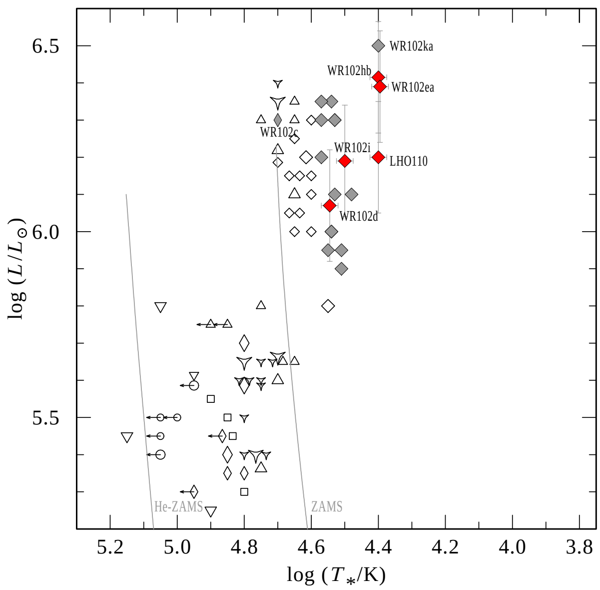

Figure 4: HRD placing the Quintuplet WN stars (red with error bars) in a group of cool but luminous stars: Galactic WN (open symbols, Hamann et al. 2006), Arches WN stars (filled grey, Martins et al. 2008), and WR 102c and WR 102ka (Barniske et al. 2008).

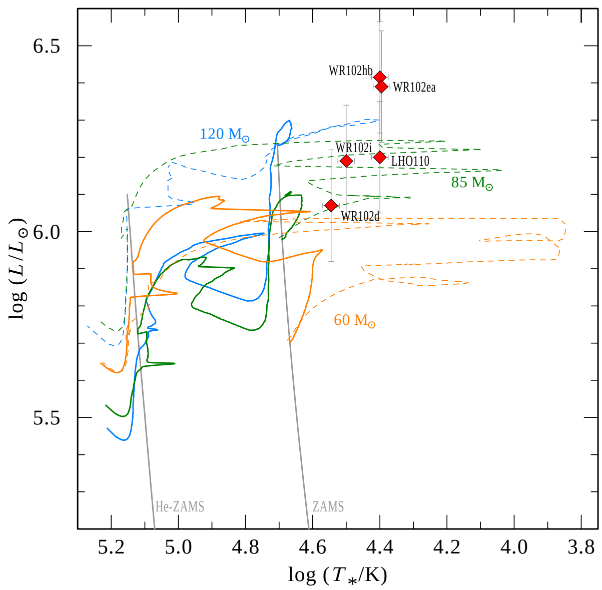

Figure 5: Similar to Fig. 4, the Quintuplet WN stars are shown in comparison with stellar evolution models (Meynet & Maeder 2003). Tracks are for initial masses of 60, 85, and 120 $M_\odot$ and include for the effects of rotation (solid) or not (dashed).

tracks including the effects of rotation (solid lines) and without (dashed lines) by Meynet & Maeder (2003, Geneva tracks). The tracks were calculated for solar metallicity and different initial masses. It can clearly be seen, that the tracks with rotation don't reach into the cool domain the stars are located in and that only the very high-mass tracks $\geq 60\,M_\odot$ initial stellar mass can be considered for their origin. As already noticed by Hamann, Gräfener & Liermann (2006) stellar evolution tracks without rotation extend further into the cool domain and thus fit better to the HRD positions of the stars. This might only imply that the initial equatorial rotational velocity might be lower than the 300 km/s assumed in the stellar evolution models.

The stars WR 102d, WR 102i and LHO 110 fall in the domain of the tracks with initial masses of $60\,M_\odot$ and $85\,M_\odot$. We assume a range of luminosities and stellar temperature for each star according to the error margins (see Liermann et al. 2010, A&A in press) to determine present-day masses and ages for the stars. Additionally, we keep an eye on the surface hydrogen abundance and mass-loss rate to be comparable to the one we derived with the PoWR models; this helps to overcome the slight degeneracy that, within their error margins, most of the sample stars can be assigned to either of the two tracks. In the corresponding part of the Geneva tracks, the models are still the the phase of central hydrogen burning.

But WR 102hb and WR 102ea lie far above the track with the highest initial mass of $120\,M_\odot$. Since we cannot apply the Geneva models, their position in the HRD is compared with stellar evolution tracks by Langer et al. (1994) shown by Figer et al. (1998, Fig. 15a). This leads to an initial mass of > 100 and $150\,M_\odot$ with an age estimate of > 1.9 and 2.1 million years for WR 102ea and WR 102hb, respectively.

We obtained present-day stellar masses from comparison with the Geneva tracks for the three stars of "lower" initial mass in our sample, WR 102d, WR 102i and LHO 110, see Table 1. But we cannot easily provide the numbers for the two most-luminous stars of our sample, WR102hb and WR102ea. However, we notice that the mass-luminosity-relation by Langer (1989), which was actually calcu-

Table 1: Age, initial mass ($M_{\rm init}$), and present-day mass ($M^{\rm Geneva}_{\rm present}$) for the Quintuplet WN stars determined from the Geneva tracks (Meynet & Maeder 2003). The last column lists masses derived with the mass-luminosity relation by Langer (1989, $M^{\rm Langer}_{\rm present}$).

star	age [Ma]	$M_{\rm initial}$ [$M_\odot$]	$M^{\rm Geneva}_{\rm present}$ [$M_\odot$]	$M^{\rm Langer}_{\rm present}$ [$M_\odot$]
WR102hb	2.1	150	-	61
WR102ea	>1.9	>100	-	58
WR102i	3.1	85	45	43
WR102d	3.6	60	28	36
LHO 110	3.1	85	43	44

lated for core-helium-burning stars, yields similar values for the three stars for which we had obtained $M^{\rm Geneva}_{\rm present}$ from the tracks; although our stars have hydrogen abundances up to 45% left in their atmospheres. Thus, we use the Langer relation as a proxy to estimate the present-day masses of WR 102hb and WR 102ea (Table 1, last column).

4 Conclusion

We analyzed the WNL stars in the Quintuplet cluster by means of stellar atmosphere models (PoWR) and determined their fundamental parameters. In the cases where the stars could be properly assigned to evolutionary tracks, they show ages older than 3 million years which is in agreement with the cluster age of 4 million years. In addition, they are most likely still hydrogen-burning objects and their derived present-day masses reveal that the stars have already lost up to 50 % of their initial mass. This strongly emphasizes the importance of the mass loss for the stellar evolution.

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