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Life at the Extremes — Massive Star Formation and Evolution in the Galactic Centre

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Many galaxies host pronounced (circum)nuclear starbursts, fuelled by infalling gas. Such activity drives the secular evolution of the nucleus and may also generate super winds which enrich the interstellar and intergalactic medium. Given the intense radiation fields and extreme gas densities present within these nuclear regions, star formation may not occur in the same manner as it does in more "quiescent" regions of the galactic disc. To address this uncertainty, we are driven to investigate the only circumnuclear starburst where individual stars and star clusters may be resolved. Its proximity permitting dissection at resolutions a hundred times better than available for M31, the Galactic Centre provides us with a unique laboratory to study both stellar and galactic evolution.

The circumnuclear starburst of the Milky Way

The central few hundred parsecs of the Milky Way host the most vigorous ongoing star formation activity within the Galaxy and, with a rich population of young massive stars and clusters, it appears that this activity has been under way for at least several Myr (see, for example, Figure 1). Raw material for star formation is abundant, with up to 10% of the Galaxy's molecular gas ($2–6 \times 10^7$ $M_{\odot}$; e.g. Bally et al. 2010) found within the Central Molecular Zone (CMZ), spanning -1 to $+1.5$ degrees of Sgr A*. Somewhat counter-intuitively, and despite these extensive molecular reserves, the star formation rate within the CMZ is actually lower than expected based on the analysis of nearby star-forming regions in the quiescent galactic disc. A common assumption is that this is a result of the extreme conditions within the CMZ, where the density, pressure, temperature, velocity dispersion and radiation field are all significantly greater than elsewhere in the Milky Way (Barnes et al., 2017 and references therein).

Revealing the underlying physical reasons for this discrepancy has implications for a number of fields, not least because the conditions present within the CMZ potentially replicate those in starburst galaxies out to redshifts, $z \sim 1–3$, as well as in the circumnuclear regions of local, quiescent systems. As a consequence, the CMZ has been the subject of numerous millimetre- and radio-wavelength studies aimed at constraining the properties of the stellar nurseries hosting the earliest phases of

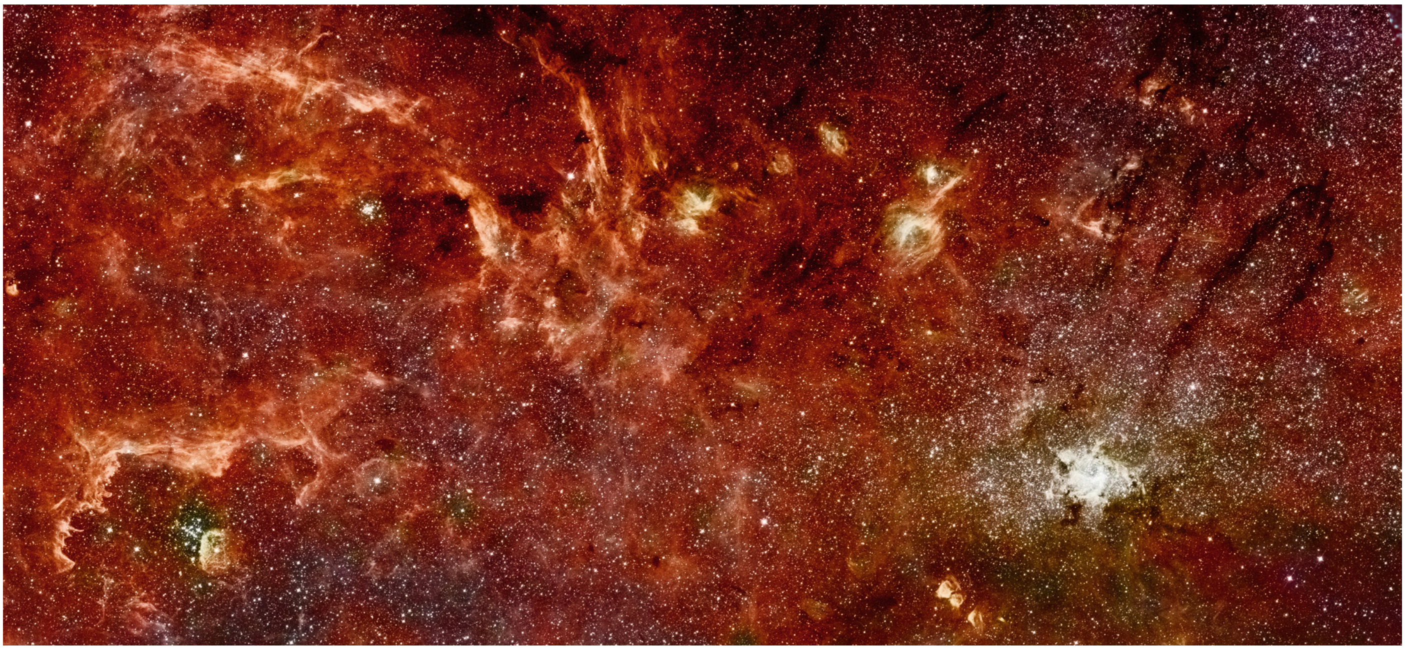

Figure 1. False-colour montage of Hubble Space Telescope (NICMOS) and Spitzer (IRAC) observations of the centre of the Galaxy, spanning ~ 47 pc × 22 pc. Sgr A* and the nuclear star cluster are at the centre of the bright spiral of ionised gas to the bottom right, the Arches cluster is the bright compact source located within the eponymous arcs of emission to the top left and the Quintuplet cluster is centred within the wind-blown bubble to the bottom left, directly adjacent to the compact rectangular ejection nebula associated with the Pistol star (V4647 Sgr).

star formation (for example, Barnes et al., 2017 and Ginsburg et al., 2018). However, such an approach yields an incomplete picture of star formation in the CMZ, since it is not sensitive to the products of this physical process. In particular, one would want to determine the recent star formation history of the CMZ, and whether the initial mass function (IMF) that results from the mode(s) of star formation favoured within the region is consistent with that of the Galactic disc, or alternatively requires a top-heavy IMF biased towards massive stars. These are important questions since massive stars and supernovae play a disproportionate role in secular galactic evolution via the deposition of chemically processed material, and both mechanical and radiative feedback. This, in turn, seeds and initiates the next generation of star formation as well as driving large-scale super winds that enrich the intergalactic medium.

As a consequence, a parallel observational effort to construct a stellar census for the CMZ has been undertaken at infrared wavelengths in order to overcome the significant interstellar extinction towards the Galactic Centre. These efforts have distinguished four components in the population of massive stars within the CMZ (Figure 1). The circumnuclear cluster associated with Sgr A* is the most well studied of these and comprises an extended stellar cusp of predominantly low-mass stars (integrated mass of ~ 3 × 10^7 $M_\odot$ within a half light radius of 3–5 pc) within which is a compact cluster comprising massive OB supergiants and hydrogen-depleted Wolf-Rayet (WR) stars. Extensive observations suggest an age of approximately 4–8 Myr and an integrated mass of > 10^4 $M_\odot$ for this stellar aggregate. Critically, this raises the possibility of a top-heavy or "flat" IMF (for example, Bartko et al., 2011 and references therein).

Two further young massive clusters — the Arches and Quintuplet — are found within the CMZ (Figures 1 and 2). Infrared spectroscopy of the cluster members (see Martins et al., 2008 and Liermann et al., 2009) suggests both aggregates are young (2–5 Myr) and massive (> 10^4 $M_\odot$), with potentially top-heavy IMFs. A final population of apparently isolated massive stars has also been identified throughout the CMZ (for example, Dong et al., 2011), although the properties of this cohort are less well characterised than those of the clusters and it is likely that the current census is highly incomplete.

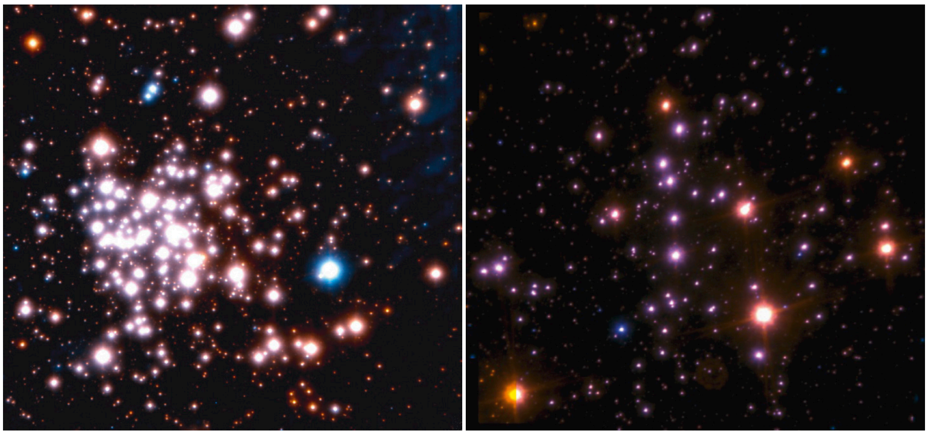

Figure 2. Near-infrared (*H*- and *K*-band) false-colour images of the Arches (left) and Quintuplet (right) clusters. Reproduced here by courtesy of Andrea Stolte.

However, it has recently become apparent that there may be systematic problems with the current estimates of cluster properties. Existing quantitative studies of both clusters are prone to uncertainties in the extinction law, whereby alternative formulations result in differences in the bolometric luminosities of cluster members of up to ~ 0.6 dex. When combined with the effects of differential reddening, this casts considerable doubt on current ages derived from isochrone fitting as well as the construction of mass-luminosity functions from which IMFs are derived (Clark et al., 2018a,b). Secondly, studies to date have been based on single-star evolutionary models, but a combination of observational and theoretical studies over recent years has highlighted the importance of a binary channel. Indeed, motivated by the suggestion of non-coevality for the Arches and Quintuplet, a reinterpretation of existing data by Schneider et al. (2014) suggests that both clusters may host a binary fraction approaching unity and that they are considerably older than has been assumed.

Resolving these issues is important, since the Arches and Quintuplet are (potentially) young and massive enough to have formed stars of >> 100 $M_\odot$ that have not yet undergone core-collapse; Groh et al. (2013) suggest that non-rotating 120 $M_\odot$ stars will experience SNe after 3 Myr. Determining the properties and the formation or evolutionary channels of these stars is vital to understanding the progenitors of both electromagnetic and gravitational-wave transients, as well as quantifying the radiative and mechanical feedback from young massive clusters. Such massive stars must also be the precursors of the black holes inferred to be present within the population of accreting X-ray binaries recently identified within the CMZ by Hailey et al. (2018) as well as the young, highly magnetised neutron star (or magnetar) SGR J1745-29 (Kennea et al., 2013). Moreover, they may provide an explanation for the high-energy emission (> 100 GeV) coincident with the inner 200 pc of the Galactic centre (Aharonian et al., 2006). Whilst exotic explanations such as the annihilation of dark matter have been proposed, a more prosaic explanation in which the emission arises as a result of the production of cosmic rays via either supernovae and/or the collision of the winds of very massive stars may also be viable (for example, Aharonian et al., 2018), assuming there are sufficient stars to support such physical mechanisms.

A VLT and HST survey of the CMZ

Central to these questions is the production of a reliable census of massive stars within the CMZ and the subsequent quantitative characterisation of their physical properties (for example, luminosity, mass-loss rates and initial mass). To achieve this goal we have undertaken multi-epoch near-infrared *H*+*K*-band spectroscopic observations of the Arches, Quintuplet and diffuse massive stellar population of the

CMZ with the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) and the *K*-band Multi-Object Spectrograph (KMOS) on the Very Large Telescope (VLT). The multi-epoch component of our survey, initially focussed on the Arches cluster, serves two purposes: allowing for the identification and characterisation of binary systems; and permitting us to reach deeper into the fainter, lower-mass cohort via the stacking of multiple individual exposures.

Additional spectroscopic data from the ESO archive expanded the temporal baseline of observations, increasing the sensitivity to long period systems, while multi-epoch photometric observations of the Arches cluster with NACO permitted a search for eclipsing systems from which dynamical stellar masses could be extracted. Observations from the NICMOS and WFC3 instruments on the Hubble Space Telescope (HST) enabled the construction of a near-infrared spectral energy distribution for the stars in question which, when combined with spectroscopic data, permits their physical properties to be determined via comparison to synthetic spectra derived from non-local thermal equilibrium model atmospheres. Further details of all observational datasets, reduction techniques and quantitative analysis may be found in Clark et al. (2018 a,b) and Lohr et al. (2018). In this article, we present some of our preliminary results and outline the new questions and consequent future research goals that they inspire.

The Arches cluster

The motivations for studying the Arches are compelling; as the youngest, densest and most massive young massive cluster in the CMZ it provides a unique test of theories of star and cluster formation under extreme physical conditions as well as our understanding of the physics of the most massive stars in our Galaxy. Martins et al. (2008) provided single-epoch VLT/SINFONI spectra of 28 cluster members, which comprise both very luminous H- and N-rich WRs (WN7-9ha) and mid-O supergiants. The analysis suggested that the cluster might not be coeval, although Schneider et al. (2014) found that this conclusion could be avoided if an extreme binary fraction was assumed, with the most luminous objects being the rejuvenated products of binary-driven mass transfer and/or mergers. However neither study fully accounted for the effects of an uncertain reddening law and significant differential extinction across the cluster. Once these are incorporated, the uncertainties in the stellar luminosities become so great that isochrone fitting becomes challenging, as do quantitative conclusions regarding coevality (cf. Martins et al., 2008).

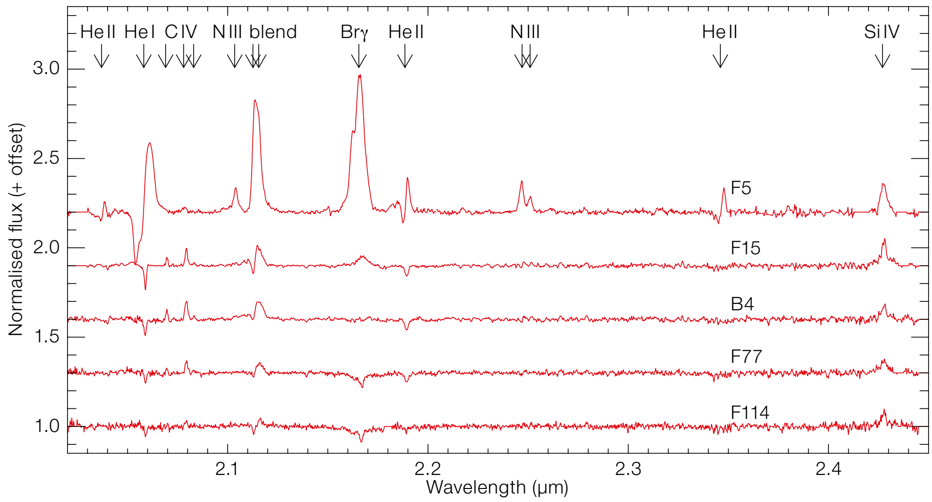

Figure 3. Montage of spectra of Arches cluster members, ranging from WNLha stars (F5) through mid-O hypergiants and supergiants (F15 and B4) and finally to mid-O giants and main sequence stars (F77 and F114); this is the first time such stars have been identified within the cluster.

Our SINFONI and KMOS spectroscopy has enabled us to classify 88 stars within the Arches cluster. This unprecedented census has revealed eight luminous O-type hypergiants — a substantial increase on the two previously identified by Martins et al. (2008) — suggesting a smooth evolutionary progression from the O supergiants through to the H- and N-rich WRs; see Figure 3. WNLh and WNLha are Wolf Rayet stars with spectra dominated by comparatively low excitation lines of H, He and N. The a in WNLha denotes the presence of absorption lines. We do not have to invoke binary interaction to explain the production of WNLh or WNLha stars (cf. Schneider et al., 2014), although some of these stars may still have formed via this route.

Secondly, our stacked observations were sufficiently sensitive to spectroscopically identify both giants and main sequence stars within the cluster for the first time. In particular, the apparent absence of stars earlier than spectral type O5-6 suggests a conservative estimate for the main sequence turnoff mass of ~ 40 $M_{\odot}$ and a likely age of ~ 2–3 Myr for the Arches — a conclusion bolstered by the lack of H-depleted WRs within the cluster (Clark et al., 2018a). This is an important finding since it is not expected that supernovae will have occurred in a cluster of this age (cf. Groh et al., 2013) and hence the most massive stars that formed initially should still be present.

Is this assertion borne out by observations? VLT NACO observations suggest that one of the most intrinsically luminous cluster members — the W8-9ha star F2 — is an eclipsing binary with a period of 10.483 ± 0.002 d (Lohr et al., 2018). Moreover, the light curve reveals the orbit to be slightly eccentric with a pre-contact morphology, indicating that substantive interaction/mass-transfer has yet to occur. Close inspection of the spectra reveals it to be a double-lined system with a O5-6 hypergiant secondary component. Simultaneously modelling both the lightcurves and the radial velocity curves (Figure 4) yields current dynamical masses of 82 ± 12 $M_{\odot}$ and 60 ± 8 $M_{\odot}$, respectively. However, given the age that we infer for the Arches, both components will have lost a large quantity of mass via their powerful stellar winds. Comparison with theoretical predictions suggests an initial mass of >> 120 $M_{\odot}$ for the primary, implying that it was originally one of the

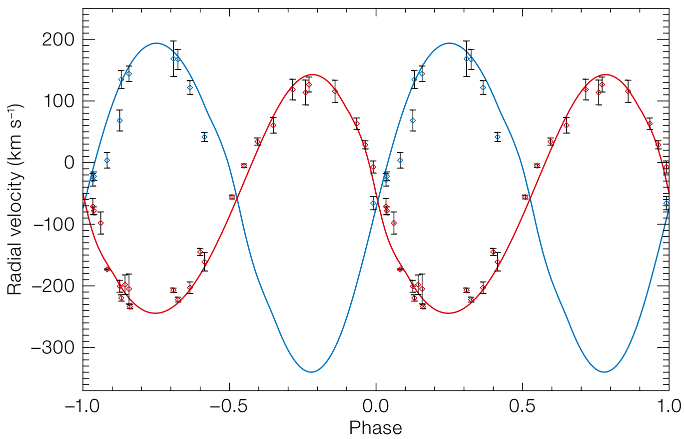

Figure 4. Radial velocity curves for the massive eclipsing binary F2 (WN8-9ha [primary] + O5-6Ia+ [secondary]) phased on the 10.483 ± 0.002 day orbital period. The red and blue points — and best fit lines — correspond to the primary and secondary, respectively.

most massive stars yet identified within the Galaxy, if not the most (Lohr et al., 2018).

Critically, stars with such high initial masses appear mandated by the properties of the coalescing black hole binaries detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO). This immediately begs the question of how many similarly massive binaries are present within the Arches. Prior detections of hard, bright X-ray emission from the eclipsing binary F2 and three further cluster WNLha stars suggests that they may be common, since the most natural explanation for this phenomenon is that all four systems are colliding-wind binaries, whereby the X-rays arise in shocks generated in the wind collision zone (Wang et al., 2006). We can test this assertion via the multi-epoch component of our spectroscopic survey, which is ongoing (ESO Programme ID 0101.D-0141). Preliminary results are suggestive of radial velocity variability in the remaining three X-ray bright sources (F6, F7 and F9), while a number of other objects exhibit substantial radial velocity modulation that is probably induced by binary motion (for example, F15 [O6-7Ia+], F25 [O4-5Ia] and F35 [O4-5Ia]; Lohr et al., in preparation).

The Quintuplet cluster

Results from our Arches survey clearly show that conditions within the CMZ are amenable to the production of very massive binaries that may serve as the progenitors of coalescing black holes. However, this would rely on the retention of sufficient mass at the point of core collapse, and the Arches is too young for stars to have reached this point. Could the Quintuplet serve as an appropriate testbed for this hypothesis, since the literature consensus is that it appears older than the Arches? Once again, uncertain differential reddening casts doubt upon current age estimates, while an additional complication is the possibility of non-coevality, as suggested by the highly diverse nature of possible members (Liermann et al., 2009; Schneider et al., 2014).

In order to address the issue of coevallty we combined our new KMOS spectroscopic dataset with a re-analysis of archival SINFONI data (Liermann et al., 2009); together they yield classifications for 71 stars (Clark et al., 2018b). The most striking finding was that the cluster appears far more homogeneous than previously assumed, dominated by late-O supergiants and the richest population of early-B hypergiants, Luminous Blue Variables (LBVs) and cool N-rich WN9-11h stars within the Galaxy (Figure 5). The presence of H-free and C-rich (WC8-9) WR stars, which are not observed in the Arches cluster, clearly indicates that the Quintuplet is older.

Comparing the properties of the post-main sequence cluster members that retain hydrogen in their atmospheres to the simulations of Groh et al. (2014) reveals a spectacular consistency, suggesting that the progenitors of this subpopulation are coeval and likely derive from stars with initial masses of ~ 60 $M_{\odot}$. This would then imply that the H-free WR cohort result from yet more massive stars (>> 80 $M_{\odot}$), although mass-loss due to stellar winds will have rendered the current masses of both cohorts significantly below these values. A cluster age of 3–3.6 Myr is inferred for the Quintuplet and is of considerable interest, since the first supernovae are expected to occur at this time (Groh et al., 2013); as a consequence, their immediate progenitors, derived from the most massive stars

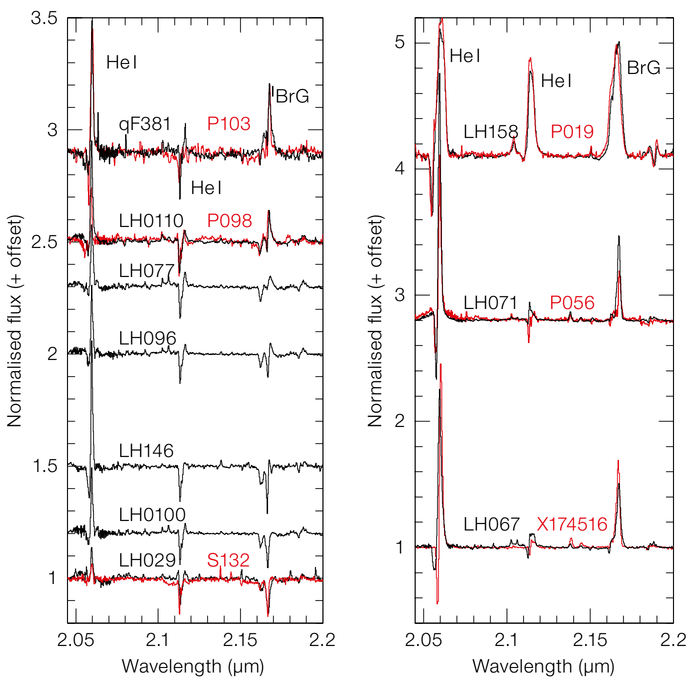

Figure 5. Montage of spectra of early-B hypergiants (left panel) and WN9-11h stars (right panel) with prominent lines indicated. Spectra of members of the Quintuplet cluster are presented in black, while those of the isolated diffuse population of the Galactic centre are in red.

present, should also be identifiable and amenable to analysis.

However, there are two stellar cohorts that do not initially appear to be accommodated by this hypothesis. The first comprises five stars that appear directly comparable to the younger O-type hypergiants and WNLha stars found within the Arches (Figure 6). This doesn't necessarily imply non-coevality for the Quintuplet, as this population could have evolved via a binary channel, whereby they are either secondaries that have been rejuvenated by mass-transfer from the primaries (c.f. Schneider et al., 2014), or else they are the post-interaction primaries viewed after substantial mass loss (cf. Clark et al., 2014). Unfortunately, we currently lack the multi-epoch data to test this hypothesis.

The second, and more challenging, finding is that the properties of the H-free WRs within the cluster are very different from the predictions of Groh et al. (2014, private communication), who suggest they should be comparatively luminous and massive stars with high-excitation spectral features (i.e., WNE, WCE and WO stars). WNE, WCE and WO stars belong to WR spectral subtypes, with spectra dominated by nitrogen, carbon and oxygen, respectively. Our current observations should be sensitive to such WNE and WCE stars, yet none are observed, with WCL WR stars dominating instead. Moreover, modelling one such WCL star suggests that it is substantially less massive than predicted (~ 10–12 *vs* ~ 19–31 $M_{\odot}$; Najarro et al., 2017, Clark et al., 2018b). Given that such stars and their short-lived WO descendants are expected to be the immediate progenitors of supernovae, these observations appear to challenge our understanding of the final phases of massive star evolution, and with it our predictions for the properties of the post-core collapse relativistic remnant.

The diffuse stellar population of the CMZ

The final CMZ stellar cohort we observed with KMOS was the population of apparently isolated stars. These are important for two reasons: firstly they appear numerous and so any stellar census compiled

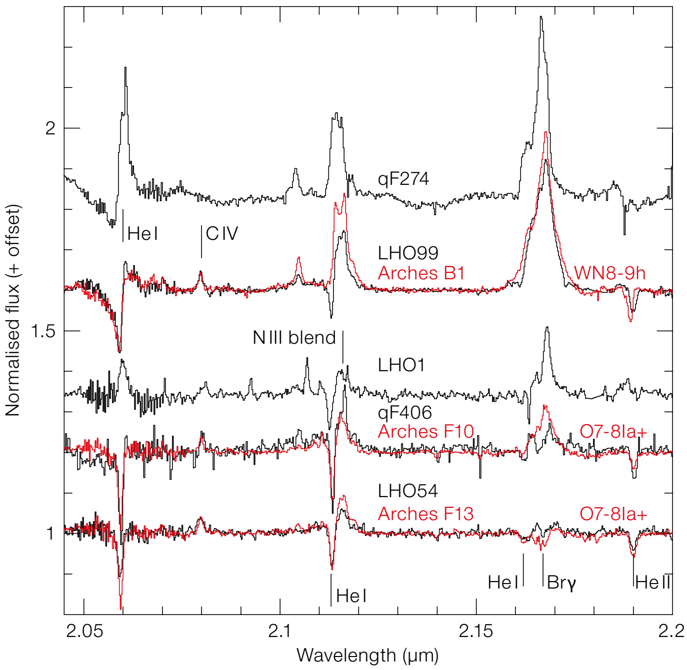

Figure 6. Montage of spectra of WN8-9ha and mid-late O hypergiant stars within the Quintuplet cluster (black) and direct comparators located within the Arches (red).

to quantify the total mechanical and radiative feedback from massive stars in the CMZ must account for them; secondly their origin is highly uncertain — did they form in isolation or were they instead located within a cluster before either being ejected (via a supernova kick or dynamical interaction) or having their natal aggregate dissolve into the field owing to tidal forces? In this regard the 2.8 × 2.8 arcsecond field of view of the KMOS IFUs is invaluable, since it allows us to search for nearby massive companions that might be the remnants of such primordial clusters (c.f. the infrared source GCIRS 13E within the nuclear star cluster).

Analysis of these data is currently underway, but it is already striking that no such remnant aggregates have been detected. A number of new isolated massive stars have been identified with diverse spectral classifications. However, it is notable that a significant proportion have spectral properties entirely consistent with membership of either the Arches or Quintuplet; this is exemplified by comparison of field B hypergiant and WN9-11h stars to those within the Quintuplet (Figure 5). In conjunction with radial velocities determined from these data, proper motions derived from multi-epoch HST observations (Principal Investigator: Lennon, Programme IDs: 13771 and 12915) will help constrain the ultimate origins of these stars and consequently improve our understanding of star and cluster formation (and dissolution) within the extreme environment of the Galactic Centre.

A synthesis of observations and future prospects

In combination with HST photometry, the unique spectroscopic capabilities afforded by SINFONI and KMOS on the VLT have allowed us to make substantial progress in understanding the properties of the massive stars found within the CMZ. The observations outlined here have answered, or are primed to resolve, many of the questions we initially asked, but have also posed many more. At the most fundamental level, a synthesis of spectroscopic and photometric data will allow the quantitative determination of the properties of a statistically significant (> 200) population of very massive (from about 40 to over 120 $M_{\odot}$) stars at every stage of their post-main-sequence evolution.

Critically, this includes the largest ever sample of short-lived hypergiant, LBV and WN9-11h stars — evolutionary phases that have been implicated in transient mass-loss episodes which are so extreme that they define their subsequent evolution. Moreover, the discovery of a rich binary population within the Arches and possible products of interaction within the Quintuplet together emphasise the importance of such an evolutionary channel. Clearly, constraining the binary population of the Quintuplet is a key observational goal in order to facilitate an understanding of the interaction.

Better defining both single and binary star evolutionary channels is also central to understanding the nature of the final post-core-collapse end points of massive stars. This is especially important given the apparent discrepancy between theoretical predictions and observations of the Quintuplet regarding the nature of supernova progenitors. Specifically, if all of the most evolved stars within the cluster, which must have evolved from very massive (>> 100 $M_\odot$) progenitors, are of masses similar to that of Q3 (10–12 $M_\odot$; Najarro et al., 2017) then it is difficult to see how black holes of masses comparable to those implicated in GW150914 (35 + 30 $M_\odot$) could form in high-metallicity conditions such as those inferred for the CMZ.

Finally, considering the CMZ as a coherent physical entity, the completion of our census and subsequent modelling will quantify feedback from the massive star cohort and hence determine whether it could be responsible for the high energy (> 100 GeV) emission associated with the CMZ (Aharonian et al. 2006), amongst other phenomena. We will determine cluster ages and IMFs (and the location of a high-mass cut-off to the IMF if present), and consequently ascertain whether star formation in such extreme conditions is biased to the formation of high-mass rather than low-mass stars. When combined with data on the isolated stellar component, we will be able to build a detailed picture of the mode(s) and results of star formation in the CMZ over the recent past; an unobtainable goal for any other circumnuclear starburst.

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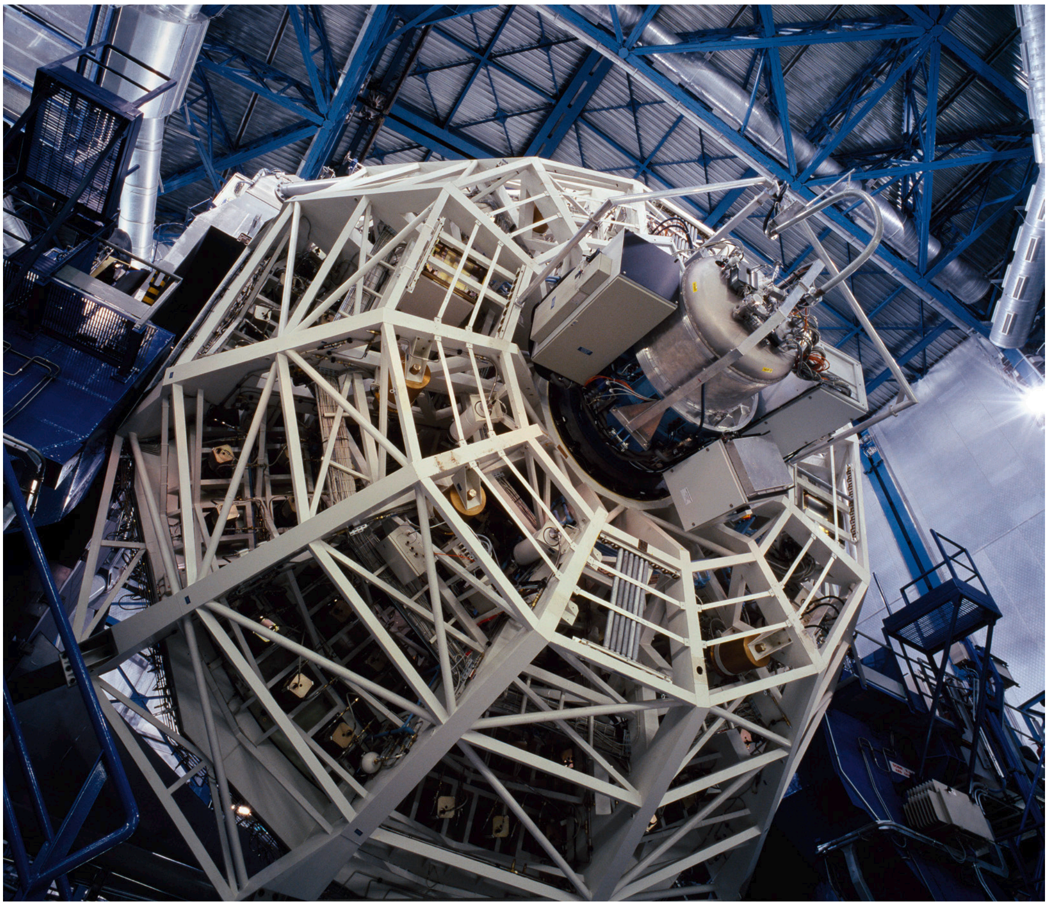

The SINFONI integral-field telescope is mounted on Yepun, the fourth VLT Unit Telescope.