

An extraordinary cluster of massive young stars in the Milky Way's nucleus

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The mass distribution of newborn stars (the stellar initial mass function, or IMF) is key to the evolution of galaxies, as it determines whether a galaxy's interstellar medium is funneled predominantly into dim, long-lived, low-mass stars, as is the case in normal galactic disks, or into bright, short-lived, massive stars, as is perhaps the case in "starburst" nuclei^{1,2}. Our own Galactic nucleus is not a full-fledged starburst, but its star-formation rate per volume is nevertheless well above^{3,4} that of the Galactic disk (by a factor of $\sim 10^3$). Even so, the Milky Way's nuclear IMF remains uncertain, because high obscuration and the large background population of bright, elderly giant stars have impeded the detection of normal hydrogen-burning (or "main-sequence") stars. Our high-resolution infrared observations of a compact stellar cluster in the nucleus now reveal the presence of numerous young, massive main sequence stars, several of which may number among the Galaxy's most massive. Dwarfing all other known young Galactic clusters, the "Arches" cluster may in fact be a weaker analog of the "super star-clusters" found in starburst nuclei.

Where best to look for main-sequence stars in the crowded Galactic nucleus? Because of the dense concentration of bright giants (which have finished core H-burning and left the main sequence) in the nucleus, a compact young cluster is the most viable target. Excluding the cluster in our Galaxy's central parsec because of extreme crowding, the most promising target is perhaps the recently discovered "Arches" cluster^{5,6} (G0.121+0.017), a compact concentration of a dozen or so bright stars located (in projection) ≈ 25 pc from the Galactic center. These stars have been tentatively identified as rare Wolf-Rayet (WR) stars^{5,6}, which represent a late phase in the evolution of massive stars, by which time rapid mass-loss has largely stripped the stars of their outer layers. As the brief ($\sim 2 - 5 \times 10^6$ yr⁷) WR phase occurs only in the most massive stars, WR stars are signposts for recent massive star formation. Slightly less massive stars still burning hydrogen can thus be expected in their vicinity.

Because the Milky Way's nucleus is completely obscured by intervening dust at optical wavelengths, near-infrared (NIR) images of the Arches cluster were acquired with the Keck 1 telescope on a night of excellent seeing (0.45" FWHM). Images were acquired at three NIR wavelengths [J ($\lambda = 1.25 \mu\text{m}$), H ($\lambda =$

1.66 μm) and K' ($\lambda = 2.12 \mu\text{m}$)], and combined into the false-color image shown in Fig. 1. This NIR image reveals a very rich stellar cluster, with a substantial overdensity above the surrounding “background” stars. A radius of $\approx 6''$ (or 0.23 pc for a distance¹⁰ of 8 kpc) encompasses most of the stars in the dense cluster core, but a slightly larger radius ($\sim 9''$ sec, or 0.35 pc) is needed to include all of the previously known bright WR-like stars^{5,6}, and so this larger radius may better describe the cluster’s full extent. As seen in Fig. 1 and the inset to Fig. 2, the stars in the compact cluster core show very similar NIR colors, and so share a common distance and extinction. In contrast, the surrounding field stars show a much wider color range (Fig. 1), reflecting a range of extinctions and distances. The average NIR cluster color (Fig. 2) implies¹¹ an average visual extinction of 28.4 mag, fully consistent with a location near the Galactic center.

We address the nature of the Arches stars by means of the cluster’s NIR color-magnitude diagram (Fig. 2) and number counts (Fig. 3). The number counts show a very clear distinction between the populations interior and exterior to a dividing radius of $9''$: the exterior field stars are consistent in number and brightness with the population of cool giants expected for this location¹², while the interior (cluster) number counts extend to much brighter stars. Given this contrast, and the presence in the brightest few bins in Fig. 3 of young WR-like stars^{5,6} (note that Of supergiants resemble WR stars at low spectral resolution¹³, but these would also be young), an old population such as that found in globular clusters is unlikely.

A young cluster is thus indicated, and indeed the NIR fluxes from the Arches stars, when corrected for distance and extinction, are consistent^{14,15} with those of the most massive (O-type) main sequence stars (Fig. 3). In addition, a significant tail extends to even brighter stars, likely blue supergiants and WR-like stars, which no doubt represent the evolved descendants of the most massive and short-lived of the O stars. This scenario receives further support from the cluster’s CMD, in which the stars interior to $6''$ (i.e., the stars most clearly part of the cluster) are largely confined to a very well-defined vertical track (Fig. 2). The ten or so brightest stars (those with line emission characteristic of WR-like stars^{5,6}) follow a slightly sloped track, with the brighter stars being slightly redder, while the bulk of the fainter stars below $K \sim 11$ show a fairly constant color ($H-K \approx 1.75$) down to $K \approx 14.5$ (for $K > 13.5$, the scatter increases due to source confusion), as expected for the upper main sequence^{14,15}. Given the cluster’s fairly uniform extinction, and

the narrow spread in the observed CMD track (± 0.05 mag), the bluer colors seen at $K > 11$ indicate that these fainter stars are likely somewhat hotter than the WR-candidates, consistent with temperatures in the O-star range. We also note that increasing the outer cutoff radius for the CMD to $9''$ introduces a known bright, cool giant with CO absorption features⁶ ≈ 0.3 mag to the red (right) of the top end of the track in Fig. 2, a location in line with the expected NIR color separation between the giant branch and the upper main sequence. Thus, the infrared fluxes and colors of the fainter Arches stars are fully consistent with hot, massive O stars.

Unfortunately, the absolute NIR fluxes of the brightest main sequence stars and the associated supergiant and WR phases remain observationally and theoretically somewhat uncertain, due both to their scarcity and their high mass-loss rates. Accurate classifications of individual stars are thus not possible from broadband fluxes alone. On the other hand, spectroscopic classification can also be ambiguous for some massive stars^{13,16}, making a combination of NIR fluxes and spectra necessary to definitively classify individual stars. Unresolved multiple stars may also mimic brighter single stars, but the strong dependence of NIR brightness on stellar mass for hot main-sequence stars¹⁵ suggests that this cannot skew our results dramatically unless the number of fainter O stars is itself scaled upward by a similarly large multiplicity factor. This would imply many hundreds of fainter O stars, also a rather extreme result. Thus, even allowing for brightness uncertainties as large as 1 magnitude, it is clear from Fig. 3 that the Arches cluster's stellar population consists of an abundance of hot, massive O-stars, and that the population extends to the brightest, most massive, and rarest O3 stellar type at the very top of the main sequence, where the distribution cuts off as it transitions to more evolved types (O-giants, supergiants, and WR stars). For the theoretical fluxes given in Fig. 3, we find the remarkable total of ≈ 120 massive O stars (mass $> 20 M_{\odot}$), a dozen of which may have evolved to the WR phase. Even allowing for uncertainties in NIR fluxes, and in stellar models and ages, roughly 100 ± 20 massive stars remain. This rich cluster thus substantially increases the potential count of exotic, massive stellar types in our Galaxy, making it a prime astrophysical laboratory for elucidating stellar structure and mass-loss phases near the stellar high-mass instability limit. It is also clear that the relative scarcity of extremely massive stars reported heretofore for our Galaxy is simply the result of extinction to the interesting neighborhoods, and specifically toward our Galaxy's nucleus.

The total observed mass in O stars in the Arches cluster is then $5000 \pm 1000 M_{\odot}$. Extrapolating to include lower mass stars by means of a standard power-law IMF of exponent -2.35 , the total cluster mass becomes $\approx 1.5 - 6 \times 10^4 M_{\odot}$ for lower mass cutoffs in the range 2 to $0.1 M_{\odot}$. Such a mass is comparable to that of a small globular cluster¹⁷. Similarly, the total cluster luminosity is $\approx 10^8 L_{\odot}$, and the ionizing photon flux a few 10^{51} s^{-1} , making this cluster a powerhouse by Galactic standards. The cluster is also quite young, certainly $< 5 \text{ Myr}$ if WR stars are indeed present⁷. However, if O3 stars are present and the WR-candidates are instead high-mass-loss O-supergiants, the cluster could be as young as 1 Myr.

A single Galactic cluster containing approximately 100 massive O stars is indeed remarkable, as the number of O stars in the Arches cluster then dwarfs all other known young clusters in the Milky Way's large-scale disk. In particular, both NGC 3603, the only giant HII region visible from our perspective in the Galaxy¹⁸, and W49A, likely the most luminous star forming region in the disk¹⁹ (but which is obscured optically), have O-star tallies of approximately 50, of which most are of subtypes cooler and less massive than O5 (cf. Fig. 3). The assemblage of massive O-stars in the Arches cluster is then actually quite comparable to the recently tabulated O-star population in the rich, young cluster¹⁶ R 136 in the Large Magellanic Cloud's (LMC's) spectacular 30 Doradus HII region. However, the Arches cluster is even more compact: with a radius ($\sim 0.3 \text{ pc}$) only a third that of R 136 ($\sim 1 \text{ pc}$), its average stellar density, $\sim 3 \times 10^5 M_{\odot} \text{ pc}^{-3}$, exceeds even that in the core of R 136. Furthermore, including also neighboring star-formation regions such as the Sgr A, Sgr A East, Sgr B2, and Quintuplet clusters²⁰, the star formation activity in our Galaxy's obscured nucleus likely bears a close resemblance to the LMC's enormous 30 Dor star-formation complex²¹.

Is the IMF in our Galactic nucleus then "normal"? The detection of numerous normal O stars accompanying the Arches cluster's previously known WR-like stars clearly removes the need for an overtly bizarre stellar population. However, as our observations do not yet reach stars below about $20 M_{\odot}$, it is premature to reach conclusions regarding the nature of the Arches' IMF, especially as a large number of high-mass stars can arise simply from the rapid production of a large total number of stars with a normal IMF. The most robust result at present is thus the total stellar mass generated in the "burst", a quantity which is relatively insensitive to the addition of lower mass stars. One clear implication of a very compact, massive ($\sim 10^4 - 10^5$

M_{\odot}) young cluster is the need for very efficient conversion of natal molecular cloud material into new stars, as nearby molecular cloud clumps²² are comparable in mass. Furthermore, given additional young clusters of comparable total mass located nearby (listed above), the formation of massive clusters of order $10^4 M_{\odot}$ is likely the norm in the nuclear environment. Given the proximity of these clusters to each other, some degree of synchronization or common triggering may be suspected. All of this suggests that nuclear star formation may be triggered by large-scale shock compression of the interstellar medium. If correct, shock-induced star formation may be the unifying mechanism linking young clusters in galactic spiral arms (of total mass $10^2 - 10^3 M_{\odot}$), young clusters in quiescent galactic nuclei (masses $\sim 10^4 - 10^5 M_{\odot}$), and super star-clusters²³ in colliding and starburst galaxies (masses $\sim 10^5 - 10^8 M_{\odot}$), the different mass scales then being attributable to the widely different mass accumulation rates in the three environments. Determination of the shape of the Arches cluster IMF at lower masses, which can be pursued at higher resolution both with the Hubble space telescope and adaptive optics on large ground-based telescopes, will thus prove an illuminating link in this hierarchy.

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Figure Captions

Fig. 1. False color near-infrared image of the Arches cluster constructed from Keck I near-infrared camera (NIRC) images acquired on 3 June 1996. Three wavelengths were observed, J ($\lambda = 1.25 \mu\text{m}$), H ($\lambda = 1.66 \mu\text{m}$) and K' ($\lambda = 2.12 \mu\text{m}$). The K' passband⁸ was used instead of the more standard K band ($2.21 \mu\text{m}$), because the former is somewhat narrower, which helps to avoid saturation on the brightest stars. In the image, blue corresponds to J, yellow to H, and K' to red. The field center is roughly at 17:42:39.9, -28:48:13. North is up and West to the right, and the Galactic plane is oriented at ≈ 30 degrees E of N. NIRC has a 256×256 detector array with a plate scale of $0.15''$ per pixel, and a field of view of $38.4 \times 38.4''$. Several slightly offset individual exposures were taken, and the final image also occupies 256×256 pixels. Flux calibration was relative to UKIRT faint standard star 34. Data reduction was carried out with the IRAF package, and sky subtraction, flat fielding and the masking of bad pixels were treated in standard fashion. The integration times were roughly 1 min each at K' and H, and 6 min in the more heavily extinguished J band. The detection limits near the edges of the field were $\approx 21\text{st}$, 19th , and 18th magnitudes at J, H, and K', respectively. The blue stars are foreground stars, the very red stars are heavily extinguished background stars, while the stars making up the cluster all show a very similar intermediate color (average $H-K' = 1.43$ mag). (Note that a patch of high extinction occupies the SW corner of the field.) Stars were counted and fluxes measured with IRAF's DAOPHOT subroutine⁹, and 343, 714, and 904 stars were found in the J, H and K' bands.

Fig. 2. CMD for the stars detected at J, H and K' interior to a radius of $6''$. In both this plot and Fig. 3, K' magnitudes have been converted to K magnitudes using the observed average $H-K'$ color and the ratio of the $H-K$ and $H-K'$ wavelength intervals⁸, yielding $K = K' - 0.30$. Inset. Infrared color-color diagram for the Arches cluster stars detected at J, H and K'. The stars shown are limited to those within $6''$ of the cluster center and $K < 13$, the latter to avoid source confusion effects in the cluster core,

Fig. 3. K number counts (per half magnitude luminosity bin) for the stars inside (solid histogram) and outside (dotted histogram) a $9''$ dividing radius. The outer histogram has been rescaled to the same area (81π square arc seconds). The top scale gives the absolute magnitudes, assuming a distance of 8 kpc,

and a K-band extinction of 3.2 mag. The main-sequence and supergiant stellar type labels are positioned according to refs. 14 and 15. The WR label is arbitrarily located on the brightest bin, as these stars may be of this type^{5,6}. Derivation of an accurate IMF slope is not possible from this data set, as blending in the cluster core remains a problem: identification of stars in restricted magnitude intervals indicates that the stellar counts in the cluster core suffer from incompleteness at K magnitudes as bright as 13.





