An extraordinary cluster of massive stars near the centre of the Milky Way

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The relative numbers of newborn stars of different masses in a galaxy (the initial mass function) determines whether the galaxy's interstellar gas goes mainly into long-lived low-mass stars, as in the disks of normal spiral galaxies, or into short-lived massive stars, as has been proposed for "starburst" galaxies[1,2]. The centre of the Milky Way is not a fully-fledged starburst region, but its star formation rate per unit volume of space is nevertheless roughly a thousand times that of the disk[3,4]. It is, however, very difficult to study the initial mass function near the centre, because the dust in the gas clouds obscures the starlight, and the relatively rare young stars are mixed with much more numerous older stars[11]. Here we report high-resolution infrared observations of a compact cluster of stars in the central region of our Galaxy. We find approximately 100 young, massive main-sequence stars, several of which seem to be among the most massive in the Galaxy. This cluster may be a weak analogue of the large star clusters in starburst galaxies, which opens the possibility of studying the starburst phenomenon through a local example.

Where best to look for normal main-sequence stars in the crowded Galactic nucleus? Because of the dense concentration of bright giants (which have finished core hydrogen-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 Centre. 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 (~(2–5) × 10^6 yr; ref. 7) 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 (near-IR) images of the Arches cluster were acquired with the Keck I telescope on a night of excellent seeing (0.45″ full-width at half-maximum). Images were acquired at three near-IR wavelengths (J($\lambda = 1.25\,\mu$m), H($\lambda = 1.66\,\mu$m) and K′($\lambda = 2.12\,\mu$m)), and combined into the false-colour image shown in Fig. 1. This near-IR image reveals a very rich stellar cluster, with a substantial overdensity above the surrounding 'background' stars. A radius of ~6″ (or 0.23 pc for a distance[8] of 8 kpc) encompasses most of the stars in the dense cluster core, but a slightly larger radius (~9″, 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 near-IR colours, and so share a common distance and extinction. In contrast, the surrounding field stars show a much wider colour range (Fig. 1), implying a range of extinctions and distances. The average near-IR cluster colour (Fig. 2) implies[9] an average visual extinction of 28.4 mag, fully consistent with a location near the Galactic Centre.

We address the nature of the Arches stars by means of the cluster's near-IR colour–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 location[10], 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] (we note that Of supergiants resemble WR stars at low spectral resolution[11], 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 near-IR fluxes from the Arches stars, when corrected for distance and extinction, are consistent[12,13] with those of the most massive (O-type) main-sequence stars (Fig. 3). In addition, a significant tail extends to even

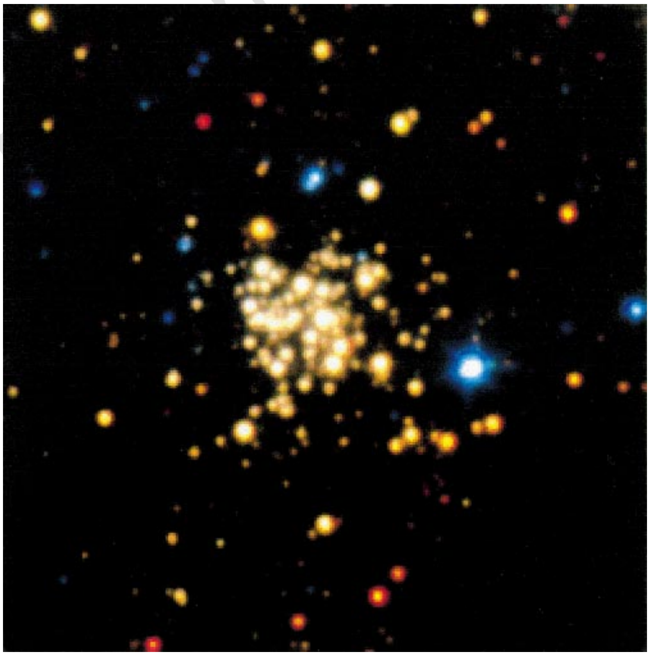

Figure 1 False-colour near-IR image of the Arches cluster constructed from Keck I near-IR camera (NIRC) images acquired on 3 June 1996. Three wavelengths were observed, J ($\lambda = 1.25\,\mu$m), H ($\lambda = 1.66\,\mu$m) and K′ ($\lambda = 2.12\,\mu$m). The K′ passband[22] was used instead of the more standard K band (2.21 μm) 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 centre is roughly at right ascension 17 h 42 min 39.9 s, declination –28° 48′ 13″. North is up and west to the right, and the Galactic plane is orientated at ~30° east of north. NIRC has a 256 × 256 detector array with a plate scale of 0.15″ per pixel, and a field of view of 38.4 × 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 ~1 min each at K′ and H, and 6 min in the J. band which is subject to heavier extinction. The detection limits near the edges of the field were ≈21st, 19th and 18th magnitudes at J, H and K′, respectively. The blue stars are foreground stars, the very red stars are background stars that have been subject to heavy extinction, while the stars making up the cluster all show a very similar intermediate colour (average $H - K' = 1.43$ mag). (We note that a patch of high extinction occupies the south-western corner of the field.) Stars were counted and fluxes measured with IRAF's DAOPHOT subroutine[23], and 343, 714 and 904 stars were found in the J, H and K′ bands.

brighter stars, probably 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 model receives further support from the cluster's colour–magnitude diagram, in which the stars interior to 6″ (that is, 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-band magnitude $K \approx 11$ show a fairly constant colour ($H - K \approx 1.75$) down to $K \approx 14.5$ mag (for $K > 13.5$ mag, the scatter increases due to source confusion), as expected for the upper main sequence[12,13]. Given the cluster's fairly uniform extinction, and the narrow spread in the observed track on the colour–magnitude diagram (± 0.05 mag), the bluer colours seen at $K > 11$ mag indicate that these fainter stars are probably somewhat hotter than the WR-candidates, consistent with temperatures in the O-star range. We also note that increasing the outer cut-off radius for the colour–magnitude diagram to 9″ introduces a known bright, cool giant with CO absorption features[6] ~0.3 mag to the red (right) of the top end of the track in Fig. 2, a location in line with the expected near-IR colour separation between the giant branch and the upper main sequence. Thus, the infrared fluxes and colours of the fainter Arches stars are fully consistent with hot, massive O stars.

Unfortunately, the absolute near-IR 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 broad-band fluxes alone. On the other hand, spectroscopic classification can also be ambiguous for some massive stars[11,14], making a combination of near-IR fluxes and spectra necessary to definitively classify individual stars. Unresolved multiple stars may also mimic brighter single stars, but the strong dependence of near-IR brightness on stellar mass for hot main-sequence stars[13] 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 mag, it is clear from Fig. 3 that the stellar population of the Arches cluster 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 makes a transition 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 solar masses, $20 M_{\odot}$), a dozen of which may have evolved to the WR phase. Even allowing for uncertainties in near-IR fluxes, and in stellar models and ages, $\sim 100 \pm 20$ massive stars remain. This rich cluster thus substantially increases the potential count of exotic, massive stellar types in our Galaxy, making it a prime testing ground 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 found to date for our Galaxy is simply the result of extinction to the interesting neighbourhoods, and specifically toward our Galaxy's nucleus.

The total observed mass in O stars in the Arches cluster is then $(5{,}000 \pm 1{,}000) M_{\odot}$. Extrapolating to include lower-mass stars by means of a standard power-law initial mass function (IMF) of exponent −2.35, the total cluster mass becomes $\sim(1.5\text{–}6) \times 10^4 M_{\odot}$ for lower mass cut-offs in the range $(2\text{–}0.1) M_{\odot}$. Such a mass is comparable to that of a small globular cluster[15]. Similarly, the total cluster luminosity is $\sim 10^8$ times the solar luminosity, 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 Myr if WR stars are indeed present[7]. 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 ~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 NGC3603, the only giant H II region visible from our perspective in the Galaxy[16], and W49A, probably the most luminous star-forming region in the disk[17] (but which is obscured optically), have O-star tallies of ~50, of which most are of subtypes cooler and less massive than O5 (compare Fig. 3). The

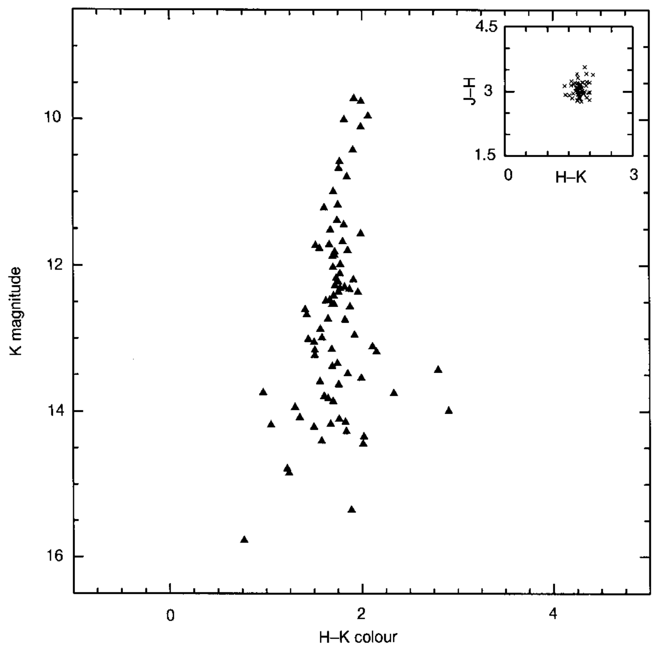

Figure 2 Colour–magnitude diagram for the stars detected at J, H and K′ interior to a radius of 6″. In both this plot and Fig. 3, K′ magnitudes have been converted to K magnitudes using the observed average H-K' colour and the ratio of the H-K and H-K′ wavelength intervals[22], yielding $K = K' - 0.30$. Inset, infrared colour-colour diagram for the Arches cluster stars detected at J, H and K′. The stars shown are limited to those within 6″ of the cluster centre and $K < 13$ mag, the latter to avoid source confusion effects in the cluster core.

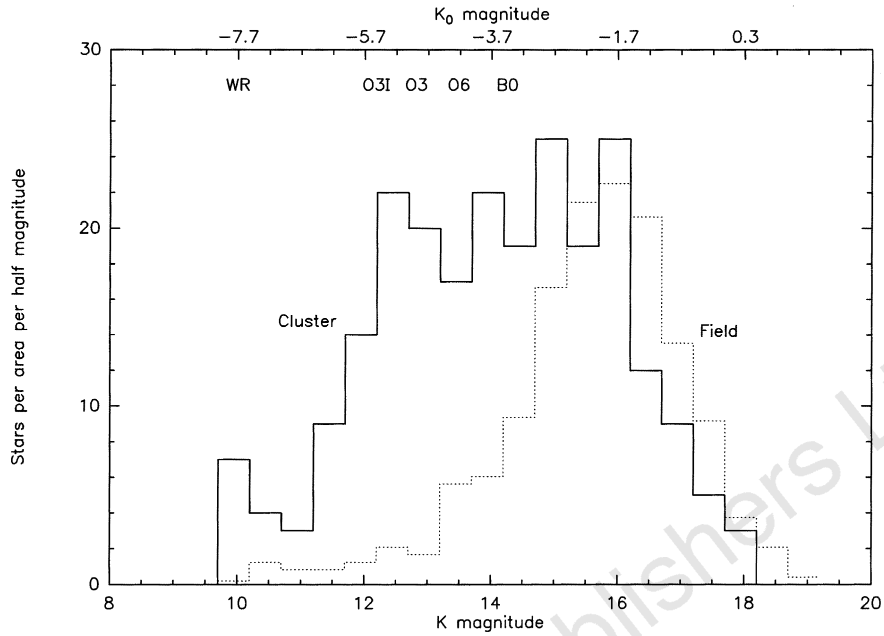

Figure 3 K number counts (per half-magnitude luminosity bin) for the stars inside (solid histogram) and outside (dotted histogram) a 9″ dividing radius. The outer histogram has been rescaled to the same area (81π arcsec^2). The top scale gives the absolute magnitudes, assuming a distance of 8 kpc, and a K-band extinction of 3.2 mag. The main-sequence and supergiant stellar type labels are positioned according to refs 12,13. The WR 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.

assemblage of massive O stars in the Arches cluster is then in fact quite comparable to the recently tabulated O-star population in the rich, young cluster[14] R136 in the spectacular 30 Doradus H II region of the Large Magellanic Cloud. However, the Arches cluster is even more compact: with a radius ($\sim$0.3 pc) only one-third that of R136 ($\sim$1 pc), its average stellar density ($\sim 3 \times 10^5 M_\odot\,\mathrm{pc}^{-3}$) exceeds even that in the core of R136. Furthermore, including also neighbouring star-formation regions such as the Sagittarius A, Sgr A East, Sgr B2, and Quintuplet clusters[18], the star formation activity in our Galaxy's obscured nucleus probably bears a close resemblance to the enormous 30 Dor star-formation complex[19].

We now consider whether the IMF in our Galactic nucleus is "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 $\sim 20\,M_\odot$, 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 clumps[20] are comparable in mass. Furthermore, given additional young clusters of comparable total mass located nearby (listed above), the formation of massive clusters of the order of $10^4\,M_\odot$ is probably the preferred mode of star formation 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-clusters[21] 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—would thus prove an illuminating link in this hierarchy. □

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Self-organized growth of nanostructure arrays on strain-relief patterns

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The physical and chemical properties of low-dimensional structures depend on their size and shape, and can be very different from those of bulk matter. If such structures have at least one dimension small enough that quantum-mechanical effects prevail, their behaviour can be particularly interesting. In this way, for example, magnetic nanostructures can be made from materials that are non-magnetic in bulk[1], catalytic activity can emerge from traditionally inert elements such as gold[2], and electronic behaviour useful for device technology can be developed[3,4]. The controlled fabrication of ordered metal and semiconductor nanostructures at surfaces remains, however, a difficult challenge. Here we describe the fabrication of highly ordered, two-dimensional nanostructure arrays through nucleation of deposited metal atoms on substrates with periodic patterns defined by dislocations that form to relieve strain. The strain-relief patterns are created spontaneously when a monolayer or two of one material is deposited on a substrate with a different lattice constant. Dislocations often repel adsorbed atoms diffusing over the surface, and so they can serve as templates for the confined nucleation of nanostructures from adatoms. We use this technique to prepare ordered arrays of silver and iron nanostructures on metal substrates.

Arbitrary atomic-scale structures can be assembled with the tip of a scanning tunnelling microscope (STM), either through direct displacement of adsorbed atoms[5], or through tip-assisted decomposition of chemical species[6]. The principal drawback of methods based on scanning probes is their serial character. Approaches where a large number of structures can be created in parallel are self-organized growth—either in the kinetic[7] or in the thermodynamic regime[8–10]—and the controlled deposition of size-selected clusters from the gas phase[11]. Whereas the latter technique produces nanostructures of nearly uniform sizes on surfaces, the self-organized growth suffers from broad size distributions. In addition, both methods yield largely uncorrelated spatial distributions caused by the statistics of deposition and diffusion.

There have been several attempts to improve the spatial order in nanostructure growth. The vertical correlation of island nucleation in sequences of quantum dot and spacer layers yielded improved lateral order[12]. Also, misfit dislocations have been used for nanoscale structuring. Preferred nucleation of Ni at dislocations of the Au(111) reconstruction resulted in ordered islands[13]; for this system, the mechanism was identified as site-specific exchange, a finding that strongly reduces the number of elements suitable for this type of ordering[14]. Also in semiconductors, island accumulation at dislocations has been reported[15]. However, there the bulk-like dislocations were not mobile enough to order into periodic patterns. Due to the attraction towards dislocations, islands were lined up in one dimension but were not periodic in two dimensions.

In heteroepitaxial systems that show strain relief through dislocations, the dislocations quite often arrange into highly ordered periodic patterns. This is due to mutual long-range repulsion and

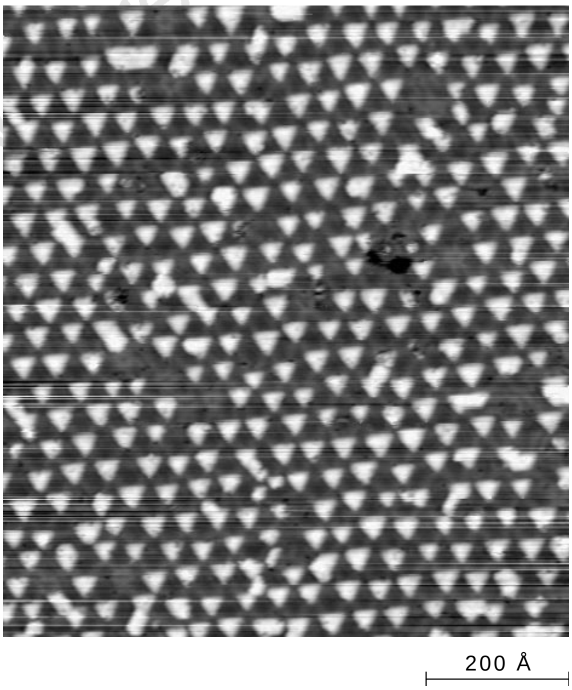

Figure 1 STM image of a periodic array of Fe islands nucleated on the dislocation network of a Cu bilayer on Pt(111) at 250 K.

Figure 2 STM image of periodically ordered versus randomly nucleated islands on a heterogeneous substrate. The islands were grown by deposition of 0.1 ML Ag at 110 K onto a Pt(111) surface pre-covered by 1.5 ML Ag (1 ML is one adsorbed atom per substrate atom).