The Arches cluster – evidence for a truncated MF in the GC?

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Abstract. The Arches cluster serves as an indicator for star formation and cluster evolution in the dense GC environment. A high-resolution adaptive optics study of the starburst suggests a present-day mass function (MF) that deviates significantly from the standard IMF in the intermediate-mass regime. A turn-over is observed around $6 \sim 7\,M_\odot$, below which the MF appears to decline. Above $\sim 10\,M_\odot$, the integrated MF in the cluster center, $r < 0.4\,pc$, displays a moderately flattened slope of $\Gamma = -0.9 \pm 0.15$, close to the Orion IMF with $\Gamma = -1.1$ [8]. In particular in the cluster core, $r < 0.2\,pc$, a pronounced peak is visible at $7\,M_\odot$, while a weaker change in the MF slope is found in the annulus, $0.2 < r < 0.4\,pc$. We compare the Arches cluster to the starburst cluster NGC 3603 in the Carina spiral arm, which displays a moderately flattened present-day MF with $\Gamma = -0.9$ all the way down to subsolar masses. The deviation in the Arches MF can be caused by accelerated dynamical evolution due to tidal disruption of the cluster in the GC potential, or can be the cause of a deviating initial mass function in the Galactic Center. Theoretical arguments for a potentially deviating IMF in a dense environment are recalled.

1. Introduction

The Arches cluster is with an estimated total mass of $M \sim 10^4\,M_\odot$ and a core density of $3 \times 10^5\,M_\odot\,pc^{-3}$ one of the most massive starburst clusters in the Milky Way [3, 4]. The cluster is very compact with a core radius of 0.2 pc [15], but due to it’s projected distance of only 25 pc from the GC, it is expected to be rapidly disrupted in the GC tidal field. Due to its young age of only 2 Myr, the cluster has preserved its central compactness, and thus provides us with a unique testbed for a single-age starburst population evolving close to the GC, and thus for the stellar mass function in the GC environment. This is particularly important as the nuclear cluster itself is comprised of mixed age populations likely formed during different cycles of star formation and possibly at different galactocentric radii, complicating the derivation of the stellar mass function close to the GC and especially conclusions on the initial MF.

The sample of resolved starburst clusters in the Milky Way consists of only a few clusters, such that conclusions on the differences in the starburst MF close to the GC and in the outer Galaxy suffer from statistics. A starburst showing very similar characteristics to the Arches is NGC 3603 in the Carina spiral arm. NGC 3603 has an estimated total mass of 7000$M_\odot$, a core density of $\sim 10^5\,M_\odot\,pc^{-3}$, and is with an age of 1 Myr in a comparable stage of stellar and dynamical evolution. We therefore chose NGC 3603 for a direct comparison with Arches.
Figure 1. High-angular resolution VLT/NAOS-CONICA \(HK\) composite image of the Arches cluster at a resolution of 84 milliarcseconds. The full extent of the image is approximately 1 pc. Note the large number of bright, high-mass cluster members.

Figure 2. Seeing-limited VLT/ISAAC \(JHK\) composite image of the starburst NGC 3603 in the Carina arm at a resolution of 0.4″. This ISAAC excerpt covers approximately 2 pc, about twice the radial extent of the Arches image.

Figure 3. NGC 3603 (left, adapted from Stolte et al. 2006 [14]) and Arches (right, adapted from Stolte et al. 2005 [13]) colour-magnitude diagrams. The brightness is shown on the left axis, while the right axis displays mass estimates derived from the isochrones used to calculate mass functions (see text for details). Magnitudes and colours in the Arches CMD are corrected for a systematic radial extinction variation observed in the cluster field [16]. Main sequence and pre-main sequence isochrones are overlaid for NGC 3603, while for Arches only the main sequence enters the MF. The dark grey lines in the Arches CMD envelope the colour selection of likely cluster members. Note that below \(K = 18\) mag, bulge contamination is expected to dominate the stellar population in the direction towards Arches.

2. Starburst Cluster Mass Functions

The MFs were created from the colour-magnitude diagrams (Fig. 3) using Geneva main sequence models to transform magnitudes into stellar masses [6]. In the case of the Arches cluster, a systematic radial increase in visual extinction was corrected, and a red and blue colour cut was
Figure 4. Present-day mass function of NGC 3603. The dashed line shows a linear least-squares fit to the incompleteness corrected MF (dash-dotted line). The MF is consistent with a single slope between 20 and 0.4 $M_\odot$, the 50% completeness limit. The irregularity around $M \sim 2 - 3 M_\odot$ is due to the transition between main sequence and pre-main sequence, where the CMD is very scattered and the evolutionary status of stars is ambiguous.

Figure 5. Arches present-day mass function. The slope of $\Gamma = -0.4$ between 4 and 12 $M_\odot$ appears shallower than the slope at the high-mass end, where $\Gamma = -0.9$. The flattened slopes with respect to a Salpeter IMF indicate an overdensity of intermediate- to high-mass stars, which is particularly pronounced in the range $4 < M/M_\odot < 12$. Due to the onset of severe field contamination below 4 $M_\odot$, the low-mass MF does not represent the cluster anymore.

applied to reject background and foreground stars to avoid field contamination. The colour selection of likely cluster members includes sources along the line of sight which by chance have colours similar to Arches main sequence stars. As the field star contribution increases with decreasing luminosity and mass, the remaining field contamination is expected to steepen the present-day MF. The flat MF derived for Arches is therefore a conservative estimate providing an upper limit to the slope of the MF in the cluster center.

In NGC 3603, stars were individually dereddened, and the field star contamination was subtracted statistically. The hydrogen burning turn-on in NGC 3603 occurs at 4 $M_\odot$, and for lower masses a Palla & Stahler 1 Myr pre-main sequence isochrone was employed [10]. A secondary sequence observed at the high-mass end in NGC 3603 was modelled as equal-mass binaries, and a comparable statistical binary contribution of 30% equal-mass systems was assumed to be hidden in the low-mass PMS population.

The core of both clusters shows a heavy bias to high-mass stars (see Fig. 1), while the outer cluster regions appear closer to a standard Salpeter (1955) IMF. The integrated MFs for NGC 3603 and Arches are shown in Figs. 4 and 5, respectively. These MFs are radially limited to 1 pc in NGC 3603 and 0.4 pc in Arches both due to increasing field contamination, which is more severe in the GC environment. The present-day MF in NGC 3603 displays a slightly flattened, remarkably continuous power-law from the highest to the lowest masses (note that saturation limits us to $M < 20 M_\odot$) with a slope of $\Gamma = -0.9 \pm 0.1$ for $4 < M < 20 M_\odot$, influenced by the high-mass core causing the integrated slope to flatten.

The Arches MF displays the same slope of $-0.9 \pm 0.15$ at the high-mass end, $10 < M < 65 M_\odot$. This consistency is surprising given the different derivation methods used for both clusters and the different mass regimes covered. However, below 10 $M_\odot$, the Arches MF flattens to $\Gamma = -0.4$, indicating a lack of intermediate-mass stars. Below $\log M/M_\odot = 0.4$ or $2.5 M_\odot$, the binned MF
rises due to increasing field contamination by bulge stars, and does not represent the cluster population any more.

To investigate the behaviour further and reduce the effect of binning on the derived MF slope, we have created bin-scanned MFs. Bin-scanned MFs were calculated by shifting the starting point of the first mass bin by one-tenth of the bin width or log $M/M_\odot = 0.02$ while keeping the bin width fixed to log $M/M_\odot = 0.2$. This scanning corresponds to a small-step move down the colour-magnitude diagram, thus providing a better idea of the changes with decreasing stellar mass. However, note that this also implies that individual points are not statistically independent anymore, and the formal fitting error underestimates the true uncertainty in the MF slope (see [13] for a more detailed discussion of the bin-scan method). The bin-scanned integrated MF of the Arches cluster within a radius of 0.4 pc is shown in Fig. 6. In the mass range $6 < M < 60 M_\odot$, the MF slope of $-0.86 \pm 0.1$ is in very good agreement with the fit derived from the single-bin MF in Fig. 5. At the high-mass end, the steepening in the slope is most likely caused by statistical truncation when binning the CMD along the few very brightest stars. This is consistent with random sampling of a standard MF at the high-mass end. At the low-mass end, the onset of field contamination now becomes much more obvious at $4 M_\odot$ (log $M/M_\odot = 0.6$). Note that the details in the entire regime between 2 and $10 M_\odot$ were completely wiped out when only one set of mass bins was used. In the bin-scanned MF, a peak appears at $6 M_\odot$ (log $M/M_\odot = 0.8$), and the MF appears to decline between 4 and $6 M_\odot$, before field contamination dilutes the cluster population.

Unfortunately, no field data are yet available at comparable resolution, such that the cluster MF below $4 M_\odot$ is presently unknown. An upper limit to the field was estimated from the very edges of our NACO field of view, which however is still as close as 0.5 pc to the cluster center and may contain a large fraction of low-mass cluster members in the case of dynamical mass segregation. This field estimate is included in Fig. 6, and suggests that as much as 50% of the stars below $4 M_\odot$ may be bulge stars.

In Fig. 7, we show the bin-scanned core MF vs. the annulus MF within $0.2 < r < 0.4$ pc. At the high-mass end, $12 < M < 60 M_\odot$, the slope of $\Gamma = -0.3 \pm 0.15$ suggests a strong bias to high-mass stars in the cluster core, and thus strong mass segregation, which can be either a primordial or dynamical concentration of high-mass stars in the cluster core. Towards lower masses, the MF displays a pronounced peak at $7 M_\odot$. In the core, the stellar population below $4 M_\odot$ is intriguingly similar to the outer field at radii beyond 0.5 pc, which can be comprised of both contaminating background stars in the dense GC field as well as dynamically stripped cluster members. This either implies that the core lacks a large number of low-mass stars, or that the low-mass cluster population does not change with radius, while the intermediate- and high-mass stars are added to the core MF. In any event, the large number of high-mass stars in the cluster core, followed by a strong peak at $7 M_\odot$ and a decline towards lower masses, does not resemble a standard MF power law.

In the subsequent annulus, $0.2 < r < 0.4$ pc, the deviation in the MF is not as extreme as in the core. The low number of high-mass stars in this bin causes irregularities at the high-mass end, such that the fit becomes more uncertain. The turn-over at $6 M_\odot$ is still present, but the increased contamination of “field” stars below $4 M_\odot$ renders the interpretation of the MF between 4 and $6 M_\odot$ very difficult. The flattening in this regime to a slope of essentially $\Gamma = 0$ suggests a lack of intermediate-mass stars comparable to, but not as severe, as in the cluster core. It is clear that a reliable field estimate and subtraction is required at this point before a final conclusion on the cluster initial mass function can be made.

3. Observational evidence for a low-mass depleted MF in the GC
Why should the MF in the GC environment be biased to high-mass stars? The effect of the extreme conditions close to the GC can be estimated from the physical properties of
Figure 6. Bin-scanned, integrated MF in the inner 0.4 pc of the Arches cluster. The upper, dotted line is corrected for incompleteness, while the lower, dash-dotted line represents an upper limit to the field contribution derived from the edge of the NACO field of view, $R > 0.52$ pc, scaled to the same area (see Fig. 1). The MF slope, $\Gamma_{\text{NACO}}$, is derived from a linear least-squares fit between 6 and 60 $M_\odot$.

Figure 7. Radial MFs in the cluster center. The dash-dotted line is an upper limit to the field estimate scaled to the respective areas. Left: Core MF inside 0.2 pc ($R < 5''$). A least-squares fit yields a flat core MF between 10 and 60 $M_\odot$. Right: Annulus MF between 0.2 and 0.4 pc ($5'' < R < 10''$). The MF was fitted in two sections, both of which indicate a steeper slope than the core. Note that the high-mass end of the MF becomes irregular due to the lack of high-mass stars in the annulus.

molecular clouds in the central molecular zone. Enhanced temperatures of 70 K in GC cores vs. 10 K observed in local star-forming cores [7], as well as increased hydrogen densities causing higher thermal pressure could explain a higher characteristic mass than in the solar environment. The characteristic mass can be approximated as the Bonnor-Ebert mass, $m_{BE} = 0.35(T_{\text{core}}/10K)^2(n_{H_2}T_{\text{cloud}}/10^6\text{erg cm}^{-3})^{-1/2}$ [1]. In the solar neighbourhood, with $T_{\text{core}} = 10$ K, $T_{\text{cloud}} = 100$ K, $n_{H_2} = 10^{-4}\text{cm}^{-3}$ this yields the well-known characteristic mass of 0.3 $M_\odot$, consistent with the turn-over in a standard IMF [5], e.g. as observed in the Trapezium cluster [8]. With $T_{\text{core}} = 70$ K and a thermal pressure elevated by a factor of 10 this mass increases to...
$5M_\odot$. A similarly high characteristic mass is also suggested with enhanced GC cloud magnetic fields of $100\mu$G [7] following the formulation of Shu [12]. Thus, theoretical arguments support an increased characteristic stellar mass emerging from the star formation process in density and temperature enhanced environments.

Very recently, observational support to a low-mass depleted IMF was also found in the central parsec. From the amount of X-ray sources and integrated light observed in the central parsec, Nayakshin & Sunyaev suggest a lack of low-mass YSOs in the GC [9] (see also Nayakshin, this volume). This depletion is concluded from the fact that young, low-mass stars with $M < 3M_\odot$ are strong X-ray emitters (as known e.g. from the COUP survey [2]). Nayakshin & Sunyaev investigate the possibility that the massive YSOs in the GC are the remnants of an inspiraling cluster, but conclude that this is unlikely, as such a cluster requires a total mass of $M_{\text{initial}} > 10^6M_\odot$ to survive long enough to channel stars all the way into the center of the Galaxy. The authors arrive at the conclusion that in-situ star formation with a top-heavy IMF that concentrates 99% of its total mass in stars with $M > 10M_\odot$ can explain the observed YSO population and X-ray constraints. This estimate is surprisingly consistent with a turn-over at $\sim 7M_\odot$ as observed in the Arches MF.

Nevertheless, one should keep in mind that the Arches MF is a present-day mass function, and no claim can be made from these data alone to reconstruct the initial MF. The two largest uncertainties in the MF are first, the unknown contribution of field stars towards lower masses, and second, the rapid dynamical evolution of the cluster in the GC tidal field, which has likely stripped a significant amount of stars from the cluster potential, which are missing in the present-day MF when compared to the IMF.

4. Conclusions

The present-day MF in the Arches cluster displays an irregular behaviour for masses below $\sim 10M_\odot$, with a turn-over at $6 - 7M_\odot$ particularly pronounced in the cluster core, but also evident in an annulus outside the core. A similar behaviour is not observed in the starburst cluster NGC3603 in the Carina spiral arm, suggesting that star formation and cluster evolution of the Arches cluster are influenced by the GC environment. From the present data, we cannot distinguish dynamical evolution from deviations in the initial MF, and no meaningful field subtraction is available at the low-mass end. Although there is observational evidence for missing low-mass stars in the central parsec in addition to the apparent lack of low-mass stars in the Arches MF, a larger area around the Arches cluster has to be investigated before conclusions on the initial MF in the GC starburst and on the outcome of the star formation process in the GC in general can be drawn.

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References

[1] Elmegreen, B. G. 2000, MNRAS, 311, L5
[2] Feigelson, E. D., Getman, K., Townsley, L. et al. 2005, ApJS, 160, 379
[3] Figer, D. F., Kim, S. S., Morris, M., et al. 1999, ApJ, 525, 750
[4] Figer, D. F., Najarro, F., Gilmore, Diane, et al. 2002, ApJ, 581, 258
[5] Kroupa, P. 2001, MNRAS, 322, 231
[6] Lejeune, T., Schaerer, D. 2001, A&A, 366, 538
[7] Morris, M., Serabyn, E. 1996, ARAA, 34, 645
[8] Muench, A. A., Lada, E. A., Lada, C. J., Alves, J. 2002, ApJ, 573, 366
[9] Nayakshin, S., Sunyaev, R. 2005, MNRAS Letters, 364, 23
[10] Palla, F., & Stahler, F. W. 1999, ApJ, 525, 772
[11] Salpeter, E. E. 1955, ApJ, 121, 161
[12] Shu, F. H., Zhi-Yun, L., Allen, A. 2004, ApJ, 601, 930
[13] Stolte, A., Brandner, W., Grebel, E. K., Lenzen, R., Lagrange, A.-M. 2005, ApJL, 628, 113
[14] Stolte, A., Brandner, W., Brandl, B., Zinnecker, H. 2006, AJ, 132, 253
[15] Stolte, A. 2003, PhD thesis, Mass functions and mass segregation in young starburst clusters, University of Heidelberg (http://www.uni-heidelberg.de/archiv/3611)
[16] Stolte, A., Grebel, E. K., Brandner, W., Figer, D. F. 2002, A&A, 394, 459