THE STAR FORMATION HISTORY OF THE MILKY WAY’S NUCLEAR STAR CLUSTER

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ABSTRACT

We present spatially resolved imaging and integral field spectroscopy data for 450 cool giant stars within 1 pc from Sgr A*. We use the prominent CO bandheads to derive effective temperatures of individual giants. Additionally, we present the deepest spectroscopic observation of the Galactic center (GC) so far, probing the number of B9/A0 main-sequence stars (2.2–2.8 M⊙) in two deep fields. From spectrophotometry we construct a Hertzsprung–Russell diagram of the red giant population and fit the observed diagram with model populations to derive the star formation history of the nuclear cluster. We find (1) that the average nuclear star formation rate dropped from an initial maximum ~10 Gyr ago to a deep minimum 1–2 Gyr ago and increased again during the last few hundred Myrs, (2) that roughly 80% of the stellar mass formed more than 5 Gyr ago, and (3) that mass estimates within R ~ 1 pc from Sgr A* favor a dominant star formation mode with a “normal” Chabrier/Kroupa initial mass function for the majority of the past star formation in the GC. The bulk stellar mass seems to have formed under conditions significantly different from the young stellar disks, perhaps because at the time of the formation of the nuclear cluster the massive black hole and its sphere of influence were much smaller than today.

Key words: galaxies: star formation – Galaxy: center – Hertzsprung-Russell and C-M diagrams – stars: late-type stars: luminosity function, mass function

Online-only material: color figures

1. INTRODUCTION

The Milky Way nuclear star cluster (NSC) is of special interest since it is the closest galactic nucleus. It offers the unique possibility to resolve the stellar population and to study the composition and dynamics close to a central black hole (BH) at an unrivaled level of detail. The ability to resolve individual stars together with continuous monitoring of the innermost stars has proven the existence of a 4.3 × 10^6 M⊙ supermassive black hole (SMBH; Eisenhauer et al. 2005; Ghez et al. 2008; Gillessen et al. 2009) beyond any reasonable doubt. Surveys of galaxies have found scaling relations between the bulge mass and the mass of the central massive object of a galaxy (Ferrarese et al. 2006). This massive object can be either an NSC or an SMBH, depending on the bulge mass. SMBHs are typically found in massive bulges, while NSCs are common in low-mass bulges. This indicates a mutual evolution of the bulge, the SMBH, and the NSC. The Milky Way with its bulge mass of 10^10 M⊙ falls right in the transition region from galaxies, which are NSC dominated to galaxies, which are SMBH dominated (Graham & Spitzer 2009). For a critical discussion we refer to Seth et al. (2008, 2010). With a radius of 5 pc and a mass of 2–3 × 10^7 M⊙ (Lauhart et al. 2002), the Milky Way NSC is typical. This lucky coincidence makes the Milky Way’s NSC an ideal test case for nuclear co-evolution of galaxies in general. The evolution of a galactic bulge and the central massive object (NSC or SMBH) as well as the physical reason for the scaling relation is however poorly understood. When does an NSC form? Does it evolve simultaneously with the bulge or from a pre-existing bulge? How does the SMBH influence the star formation mode?

In fact, the age of an NSC is the largest uncertainty in the determination of its mass (Ferrarese et al. 2006). Deriving the star formation history from integrated quantities as obtained from distant galaxies is highly model dependent and is especially uncertain for old ages. These limitations can be overcome in the Galactic center (GC) because the stellar populations can be resolved.

Numerous papers have studied the composition of the Milky Way’s NSC. These studies have found that the stellar population can be divided into two classes: the cool and evolved giant stars and the hot and young main-sequence/post-main-sequence stars. The existence of massive young stars is evidence for recent star formation (Forrest et al. 1987; Allen et al. 1990). The most massive stars (WR/O stars) reside in a fairly complex structure, which may be described as a combination of a prominent warped disk, a second disk-like structure highly inclined relative to the main disk, and a more isotropic component (Pavon et al. 2006; Lu et al. 2009; Bartko et al. 2009) at a projected distance of 0.8–12” from the SMBH Sgr A* (1” ≡ 0.04 pc, assuming a GC distance of 8.3 kpc). The GC disk features must have formed in a rapid starburst ~6 Myr ago (Pavon et al. 2006; Bartko et al. 2010), with a highly unusual initial mass function (IMF) that favored the formation of massive stars (dN/dm ∝ m^α; α = −0.45). This extreme IMF deviates significantly from the standard Chabrier/Kroupa IMF with a power-law slope of α = −2.3 (Kroupa 2001; Chabrier 2003) and seems to exist only in the vicinity of the SMBH. A less massive population of ordinary B-stars can be found in the innermost 1”, the so-called S-stars (Eisenhauer et al. 2005; Ghez et al. 2008; Gillessen et al. 2009). The origin of the S-stars is a mystery because the in situ formation in the vicinity of the SMBH is very improbable. Yet, the K-band luminosity function (KLF) of the S-stars is consistent with a canonical Chabrier/Kroupa
IMF. The largest population of the resolved stars, however, are giants with masses between 1 and 2 $M_\odot$. Previous kinematic studies of this population have shown that the cluster dynamics are consistent with a relaxed system, slowly rotating in the plane of the galaxy (Trippe et al. 2008; Schödel et al. 2009). Detailed abundance determinations of luminous cool giants (Carr et al. 2000; Ramírez et al. 2000; Cunha et al. 2007) found a metallicity distribution peaking at [Fe/H] = 0.14 ± 0.16, close to the solar value.

The giant population is well suited for observations in the $K$-band. The giants have typical temperatures between 5100 and 2800 K. In this temperature range, the CO bandheads at 2.29–2.38 $\mu$m are the most prominent spectral lines in the $K$-band. The equivalent width of these lines correlates with temperature (Kleinmann & Hall 1986; Wallace & Hinkle 1996; Förster Schreiber 2000). This allows the determination of individual temperatures for the red giants (RGs). Together with photometric data for the luminosities it is thus possible to construct a Hertzsprung–Russell (H-R) diagram of the GC population and thus to constrain the star formation history in the immediate vicinity of the SMBH. Detailed studies of the giant population of the GC have been performed previously by Blum et al. (2003) and Maness et al. (2007). Using a magnitude-limited sample of 79 asymptotic giant branch (AGB) and supergiant stars (50% complete at $m_K < 10$) within the central 5 pc, Blum et al. (2003) found a variable star formation rate (SFR). They claimed that roughly 75% of the stars are older than 5 Gyr. An intermediate period of low star formation was followed by a recent ($<100$ Myr) period of increased star formation. Maness et al. (2007) used 329 giant stars ($m_K < 15.5$), more than 5 mag deeper than Blum et al. (2003), albeit at the cost of covering only 12% of the total area in the central 1 pc. They found that the giant population is relatively warm, i.e., young. Consequently they favored models with either a top-heavy IMF and a constant SFR, or with a canonical IMF and an increasing SFR during the last few Gyr. The top-heavy IMF scenario was recently challenged by Löckmann et al. (2010) who argued that this would predict an overabundance of stellar remnants resulting in a mass-to-light ratio larger than observed.

The predicted density profile of a relaxed stellar system in the vicinity of an SMBH is a cusp with a radial density profile of $n \sim r^{-\gamma}$, $\gamma \approx 7/4$ (Bahcall–Wolf cusp). Strictly speaking, this is only true for a single stellar mass cusp. In multiple mass configurations, $\gamma$ can range from 1/2 to 11/4. Recent observations have shown that the projected radial distribution of the giant population is actually flat at small radii from Sgr A* (Do et al. 2009; Buchholz et al. 2009; Bartko et al. 2010). There may even be a central hole in the three-dimensional (3D) distribution of late-type stars (Buchholz et al. 2009; Schödel et al. 2009). In either case, the visible distribution seems quite consistent with a Bahcall–Wolf cusp. It is possible that a hidden Bahcall–Wolf cusp is present consisting of stellar remnants or unresolved main-sequence stars. However, this would require the stellar luminosity function to change in the few innermost arcseconds. The bright stars need to be removed by mechanisms acting preferentially close to the SMBH. Collisional stripping of stellar envelopes (Genzel et al. 1996; Alexander 1999) is such a mechanism that keeps stars from reaching their peak luminosity. Tidal stripping close to the SMBH can deplete the giants in a similar way (Davies et al. 2006). Another explanation might be a top-heavy or truncated IMF (Nayakshin & Sunyaev 2005) that produces preferentially massive stars as observed in the young disks. Massive stars quickly become stellar remnants compared to evolved low-mass stars that dominate the KLF. Merritt (2010) argues that the absence of a Bahcall–Wolf cusp can be naturally explained if the stellar population is not relaxed. He finds that the relaxation timescale in the innermost parsec is greater than 5–10 Gyr. The most important question to discriminate between depletion processes and a relaxation time effect is, therefore, whether the system is old enough to be relaxed.

The paper is organized as follows. In Section 2 we present the data and in Section 3 the spectral classification and calibration of spectral indices. In Section 4, we construct the H-R diagram that is then fitted with model populations in Section 5. The star formation history, IMF, and mass composition of the nuclear cluster are presented in Section 6. The results are discussed and compared with other works in Section 7. We conclude in Section 8.

2. OBSERVATIONS AND DATA PROCESSING

This work relies on spectroscopic and imaging data obtained at the Very Large Telescope (VLT) in Cerro Paranal, Chile between 2003 and 2010. The observations were carried out under the program-ids 075.B-0547, 076.B-0259, 077.B-0503, 179.B-0261, and 183.B-0100.

2.1. Imaging and Photometry

The photometric data were obtained with the adaptive optics (AO) camera NACO (Rousset et al. 2003; Hartung et al. 2003) at VLT. The photometric reference images were taken on 2006 April 29 and 2010 March 31. We used the $H$- and $K$-band filter together with a pixel scale of 27 mas pixel$^{-1}$. To each image we applied sky-subtraction, bad-pixel, and flat-field correction (Trippe et al. 2008). All images of good quality obtained during the same night were then combined with a mosaic with a field of view (FOV) of $40'' \times 40''$.

2.1.1. Diffuse Background

In terms of mass, the resolved stellar population represents only the tip of the iceberg. The bulk of the stellar mass is unresolved. Therefore the diffuse background emission of the GC contains valuable information on the cluster composition and its formation. Naturally it is very challenging to estimate the unresolved background in a crowded stellar field. A significant fraction of the background light originates from the uncorrected seeing halos of bright stars. Furthermore, anisoplanatism complicates precise photometry across the FOV when using AO. By using multiple point-spread function (PSF) photometry on NACO images, Schödel (2010) tried to overcome these limitations. The resulting photometry for resolved stars was published in Schödel et al. (2010) and a map containing the unresolved background flux was published in Schödel (2010). We used $H$-band data from both publications to derive the fraction of light contained in the diffuse background. The $H$-band has the advantage that it is least affected by the surrounding nebular emission.

Since no completeness map was published by Schödel (2010), we used a superb $H$-band mosaic with Strehl $>20\%$ from the 2010 March 31. We applied StarFinder (Dolaiti et al. 2000) and converted our detections in magnitudes by referencing them to Table A2 of Schödel et al. (2010). To derive the completeness, we applied a common technique of creating and re-detecting artificial stars of various brightness. As a limiting magnitude, separating diffuse background from resolved sources, we used
Using an extinction of \( A_H = 4.65 \pm 0.12 \) (Fritz et al. 2011) and a GC distance of \( R_0 = 8.3 \pm 0.35 \) kpc (Ghez et al. 2008; Gillessen et al. 2009) we obtained an absolute separating magnitude of \( M_{H, \text{cut}} = 0.27 \pm 0.34 \). The error estimate accounts for the absolute photometric uncertainty, the cutoff, extinction, and distance uncertainties. We then subtracted the difference between the stellar flux (up to the limiting magnitude) in our \( H \)-band image and the stellar flux in the Schödel et al. (2010) list from the diffuse background flux. Furthermore, we subtracted the known early-type stars since they dominate the light in the inner 10''.

We find that the diffuse background (\( m_H > 19.45 \pm 0.12 \)) contains \( H_{\text{diff}}/H = 27\% \pm 9\% \) of the total (diffuse + resolved) \( H \)-band flux. The 1\( \sigma \) error contains the variation across the field (6\%) and the uncertainty due to the cutoff between diffuse and resolved light \( M_{H, \text{cut}} \). Taking into account the completeness, we added another 3\% systematic error due to undetected early-type stars.

### 2.1.2 Mass-to-light Ratio

To derive the total \( H \)-band luminosity of the inner 1.2 pc, we used the resolved and unresolved stellar \( H \)-band flux stated in Schödel et al. (2010) and Schödel (2010). To account for the spatially varying extinction of the GC, we used their published extinction map. Unfortunately, the extinction map contains \( H \)-band extinction of \( 0.52 \pm 0.2 \times 10^6 L_{\odot, H} \). Of this value \( 0.52 \pm 0.2 \times 10^6 L_{\odot, H} \) can be attributed to the diffuse background. The dynamical mass enclosed (excluding the SMBH) is \( M(R < 1.2 \text{pc}) = 1.4 \pm 0.7 \times 10^6 \text{M}_\odot \) (Genzel et al. 2010). Thus we derive a total mass-to-light ratio of \( M/H = 0.7 \pm 0.4 \text{M}_\odot/L_{\odot, H} \) and a diffuse mass-to-light ratio of \( M/H_{\text{diff}} = 2.6 \pm 1.7 \text{M}_\odot/L_{\odot, H} \).

By assuming an average intrinsic color of \( m_{H-K} = 0.2 \) we can convert the total \( H \)-band luminosity into a \( K \)-band luminosity of \( K(R < 1.2 \text{pc}) = 3.0 \pm 0.4 \times 10^6 L_{\odot, K} \). The corresponding mass-to-light ratio is \( M/K = 0.5 \pm 0.3 \text{M}_\odot/L_{\odot, K} \). The mass-to-diffuse-light ratio is \( M/K_{\text{diff}} = 1.9 \pm 1.2 \text{M}_\odot/L_{\odot, K} \). The bolometric mass-to-light ratio is \( M/L_{\text{bol}} = 0.7 \pm 0.4 \text{M}_\odot/L_{\odot, \text{bol}} \).

### 2.2 Spectroscopy

Our spectroscopic data were obtained with the adaptive optics assisted integral field spectrograph SINFONI (Eisenhauer et al. 2003; Bonnet et al. 2004). We used all high-quality SINFONI data sets available to us, and took data between 2003 and 2010. In total we used 32 fields with pixel scales between 25 and 100 mas. The data output of SINFONI consists of cubes with two spatial axes and one spectral axis. Depending on the plate scale, an individual cube covers \( 0.8 \times 0.8 \) or \( 3.2 \times 3.2 \); the spectral resolution varies between 2000 and 4000 depending on the chosen bandpass and the FOV. Roughly 70\% of the stars used in this work were observed at a resolution of \( R \approx 2000 \). We used the data reduction SPRED (Schreiber et al. 2004; Abuter et al. 2006), including bad-pixel correction, flat fielding, and sky subtraction. The wavelength scale was calibrated with emission line gas lamps and fine-tuned on the atmospheric OH lines. Finally, we removed the atmospheric absorption features by dividing the spectra through a telluric spectrum obtained on the respective night.

#### 2.2.1 Deep Spectroscopy of the GC

Very good seeing conditions and long integration times on two SINFONI fields allowed us to perform the deepest census of the GC population so far. The two fields cover roughly 18 arcsec\(^2\) and are \( \approx 50\% \) complete down to \( m_K < 18 \). The location of the fields can be seen in Figure 1. Both fields were placed in regions with low extinction and without bright stars in the vicinity. One of the fields (East), at a distance of 7'4, probes the disk region. The second field (North) is located at the outer rim of the disks at 13'5. The richness of faint stars can be seen in Figure 1. The identification of a \( m_K < 17 \) star as late-type requires only two hours of integration on source. The prominent CO bandheads are easy to identify and the multiplicity of the lines helps to rule out misidentifications in noisy spectra. However, the identification of an early-type star is much more challenging. The early-type stars are identified by the hydrogen \( \text{Br}\gamma \) line. Unfortunately, the line is less prominent than the CO bandheads. The identification is further hindered by the surrounding nebular \( \text{Br}\gamma \) emission. This emission is patchy and varies significantly in intensity and velocity on scales of 1''. Depending on the location of the star, this can lead to a wrong background subtraction during the data analysis mocking a stellar line. Because the stellar absorption line in A-stars is a broad Lorentzian, it is clearly different from the narrow Gaussian emission line of the gaseous background. Thus in case of sufficient signal-to-noise ratio (S/N) an identification is possible. To achieve a sufficient S/N an integration time of about five hours on source is required to identify an early-type star as such with \( m_K < 18 \).

#### 2.3 Source Selection

The selection of stars used in the H-R diagram fitting is based on a master list of \( \approx 6000 \) stars at projected radii between \( 0.1 < r < 25'' \) (or \( 4 \times 10^{-3} \) to 1 pc), for which Tripp et al. (2008) derived proper motions as well as \( K \)-band photometry. The list consists of well-isolated stars identified on several images without overlapping neighbors (separation > 130 mas). For our final analysis we retained only those entries in the master list that also had an unambiguous identification in a corresponding SINFONI cube. In total we collected \( \approx 1300 \) spectra. After removing duplicates (due to overlapping fields), roughly 1000 spectra remained. Out of this sample we used only stars with an S/N > 10 and a CO index EW(CO) > 3.5 (i.e., no early-type stars). The S/N was measured in the continuum bands stated in Table 1. This left us with about 800 giants for which we were able to determine individual temperatures and velocities. In order to have a homogeneous and deep sample, we used in the H-R diagram fit only stars contained in fields with a completeness \( > 50\% \) at \( m_K = 15 \) (see next section). The remaining sample consisted of 450 stars with magnitudes between \( 0.5 < M_K < -8 \). The contribution of fore- and background stars is negligible in the GC. The contamination due to stars which are not members of the cluster is of the order 1\% (Buchholz et al. 2009).
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Figure 1. Three-color image of the innermost 1 pc of the Milky Way (K-band: blue; L-band: red). The white cross indicates the position of Sgr A*. The U-shaped nebular emission visible in the L-band, the so-called Mini-Spiral, is powered by the ionizing radiation of the young O/WR stars in the vicinity. The position of the two deep spectroscopic fields is indicated. All photometrically detected stars not confused with neighboring stars are indicated by open circles. The color coding represents the stellar type. Cold giants with confirmed CO bandheads are indicated in red. Hot main-sequence stars identified by Brγ absorption are indicated in blue. Green stars are not identified.

(A color version of this figure is available in the online journal.)

Table 1

| Feature                  | Wavelengths (μm) |
|--------------------------|------------------|
| 12CO(2,0) band          | 2.2910–2.3020    |
| 12CO(2,0) continuum I   | 2.2300–2.2370    |
| 12CO(2,0) continuum II  | 2.2420–2.2580    |
| 12CO(2,0) continuum III | 2.2680–2.2790    |
| 12CO(2,0) continuum IV  | 2.2840–2.2910    |

2.4. Detection Probability

The spectroscopic fields used in this work differ in spatial resolution, covered area, and integration time. The main limitation for spectroscopy in the GC is stellar crowding. This is why we probed most of the inner 1 pc with the small-scale (100, 25 mas) AO-assisted modes of SINFONI. For these observations, we used typically one hour of integration time on source. Two additional cubes (100 mas) are exceptionally deep with integration times of 4.5 and 7.8 hr on source. The spectroscopic completeness of these cubes is >50% at mK < 18. The results of the deep observations are discussed in Section 3.1. The spectroscopic completeness was determined by comparing the total number of stars contained in the master list with the number of stars for which we could extract spectra. The photometric completeness of the images was determined as described in Section 2.1.1. All observed fields and the combined completeness (for mK = 15) are shown in Figure 2. Fields with a high completeness of up to 80% are found at several arcsecond distance from Sgr A*. Further in, the completeness degrades due to stellar crowding. Only the inner one arcsecond is sampled with the smallest pixel scale (25 mas) and reaches a completeness of about 50%.

3. SPECTRAL CLASSIFICATION

The K-band provides two prominent spectral features allowing a spectral classification. Early-type stars (T > 5000 K) can be identified by the presence of a Brγ absorption line. Late-type stars (T < 5000 K) on the other hand show weak or no Brγ absorption but strong absorption line blends known as CO bandheads. The bandheads appear at the spectral type ∼G4 and increase in strength up to M7. The strength also increases with luminosity class from dwarfs to giants and to supergiants. Yet, for this work only giants are of interest. Main-sequence stars with spectral type G4 and cooler are fainter (mK > 20) than the detection limit. Supergiants of the same spectral type on the other hand are extremely bright (mK < 9) and easy to identify (Blum et al. 2003).

3.1. Deep Census of the GC Population

The two deep SINFONI fields allowed a deep census of the GC population with 50% completeness down to mK < 18.
Figure 2. AO-assisted SINFONI fields overlaid on a GC image. The color of the fields indicates the combined spectroscopic and photometric completeness for a $m_K = 15$ star. The completeness is mainly driven by the exposure time of the individual fields and the observing conditions of the respective night. (A color version of this figure is available in the online journal.)

3.1.1. A-star Detection

Figure 1 shows the deep fields. Red and blue circles mark stars identified as late-type or early-type. One star was not confirmed as early-type (green circle), but showed no CO bandheads and is therefore deemed to be an early-type candidate. Within the 18 arcsec$^2$ of the two fields, we thus detected five early-type stars and one candidate. Their spectral type was determined by comparison with template spectra of Wallace & Hinkle (1997) and the absolute $K$-band magnitude $M_K$ taken from Cox (2000). Three of them were brighter than $m_K < 17$ and were identified as dwarfs with spectral types between B2 and B8. The two faintest early-type stars identified were B9/A0 dwarfs with $m_K = 17.2$ and $m_K = 17.6$. These stars are the faintest main-sequence stars reported so far in the GC. Stars of that spectral type have main-sequence lifetimes between 360 and 730 Myr and masses between 2.2 and 2.8 $M_\odot$ (Cox 2000). The spectra of the two A-stars are shown in Figure 3. For comparison, two spectra of late-type giants of equal $K$-band luminosity are shown. The candidate is of similar luminosity and falls in the same main-sequence category.

3.1.2. K-band Luminosity Function

The deep census of the GC allowed us to construct a KLF with $12 < m_K < 18$ (Figure 4). The best-fitting slope of the luminosity distribution $d \log N / dm_K = \beta$ is found to be $\beta = 0.33 \pm 0.03$. This is consistent with the results of Buchholz et al. (2009), who determined the slope of stars with a limiting magnitude of $m_K < 15.5$. As already discussed by Alexander & Sternberg (1999), Genzel et al. (2003), and Buchholz et al. (2009), the slope is typical for an old, bulge-like population. This is in good agreement with our H-R diagram fitting (Section 5.1) showing that most of the star formation occurred more than 5 Gyr ago. However, the KLF alone is not sufficient to constrain the star formation history for an old population. The KLF alone cannot constrain the actual formation history and the IMF since the KLF slope is very insensitive to both parameters (Löckmann et al. 2010). For example, the admixture of young and bright
3.1.3. Origin: Disk Members?

One of the observed fields is centered on the disk region, while the second field probes the outer rim of the disks. Thus the early-type stars in the two observed fields are potential disk members. To test for membership, we used the same method as described in Bartko et al. (2010). The 3D velocity and the positions of all five stars are given in Table 2. The last column indicates a likely disk membership. We find that the two A-stars are clearly not disk members. Among the brighter B-stars, only one is consistent with the counter-clockwise disk (CCWS). This supports the results of Bartko et al. (2010) who find a disk IMF skewed toward massive stars. Their disk KLF predicts roughly the same number of stars with $m_K = 14$ as with $m_K = 17$. A Chabrier/Kroupa IMF on the other hand predicts five times more $m_K = 17$ stars. Although the statistical significance of only five early-type stars is limited, it is intriguing that we find one $m_K = 14$ disk member (consistent with the average B-star density) but no fainter disk members. The faint B/A-stars exhibit an isotropic orientation (Bartko et al. 2010) and are most likely the remains of older starbursts.

3.2. Supergiant IRS 7

Two red supergiants are known to reside within 1 pc of Sgr A* (Blum et al. 2003; Paumard et al. 2006). Those supergiants are significantly younger than the rest of the old stellar population. The supergiant IRS 7 is the youngest of this particular luminosity class. Carr et al. (2000) find an initial mass of $20 M_{\odot}$ and stellar age of $\sim 7$ Myr and attribute it to the recent starburst. This is supported by its kinematics (H. Bartko 2010, private communication) placing IRS 7 on the clockwise disk system. We simulated a 6 Myr starburst as found by Paumard et al. (2006) and Bartko et al. (2010) with the IAC-STAR code (see following sections). The predicted ratio of red supergiants ($T_{\text{eff}} < 5000$ K; $m_K < 9$) to blue supergiants ($T_{\text{eff}} > 6000$ K; $9 < m_K < 14$) is between 0.4% and 0.5% (independent of the assumed IMF). This is in good agreement with the observed ratio of 118 blue supergiants with $m_K < 14$ (Bartko et al. 2010) to one supergiant, i.e., a ratio of 0.9%. The second supergiant has an age of a few tens of Myr (Blum et al. 2003) and is thus older than the disks.

3.3. CO Index Definition

The $^{12}$CO(2, 0) bandhead has been widely used as a temperature indicator. This has brought up numerous definitions of CO indices. A detailed comparison of regularly used index definitions was recently performed by Máról-Qeraltó et al. (2008). The analysis showed that some index definitions are systematically more affected by spectral resolution, velocity error, curvature of the spectrum, and S/N than other definitions. In particular, the index definition of Kleinmann & Hall (1986) proved to be very sensitive to those effects. The index measures the continuum and the line flux in two narrow bands in close proximity. A similar index was used in previous studies of the GC population by Maness et al. (2007) and Blum et al. (2003). However, the authors used a wider bandpass than Kleinmann & Hall (1986; 0.015 $\mu$m instead of 0.0052 $\mu$m). In the following the index is referred to as (BL03). Systematic errors in the measurement of the CO strength lead to systematic errors in the temperature estimation. Since the temperature is a tracer of the stellar age, this might lead to a bias in the determination of the star formation history. Indeed, the paucity of cool stars in the GC is the chief constraint which led Maness et al. (2007) to the conclusion of a top-heavy IMF contributed throughout the star formation history of the GC. To estimate the impact of systematics in light of this recent work, we tested the index BL03 against various effects and compared its performance with the alternate index proposed by Frogel et al. (2001, FR01). It uses several narrow bandpasses to estimate the CO continuum with a linear fit (see Table 1). The line and continuum regions for both index definitions can be seen in Figure 5.

3.3.1. Index Computation

Before computing the indices, each stellar spectrum was shifted to rest wavelength. We then divided the spectrum by...
a second-order polynomial fit to remove the curvature of the spectrum. For the continuum fit, we excluded regions with significant absorption lines; the polynomial fit is necessary to account for the large ($A_K \sim 3$) and spatially variable extinction in the GC. We then computed the BL03 index according to the recipe of Blum et al. (2003). The FR01 index was computed in a similar way, with the bandpasses as described in Frogel et al. (2001). The continuum level $w(C(\lambda))$ is estimated with a linear fit to the intervals stated in Table 1. The equivalent width is measured according to

$$\text{EW(CO)} = \int_{\text{band}} \left( \frac{w_C - w_{\text{line}}}{w_C} \right) d\lambda. \quad (1)$$

We tested both indices (BL03, FR01) with template spectra of different resolution. We also reddened the template spectra artificially to determine the impact of extinction.

### 3.3.2. Systematic Error Sources

Reducing the resolution from $R \sim 3000$ to $R \sim 2000$ decreases the BL03 CO index by a factor of $\approx 0.92$. The artificial reddening and the corresponding change of curvature of the spectrum cause a reduction of $\approx 0.94$. Both effects cause the BL03 CO index to be underestimated by a factor between 0.90 and 0.85. The systematic underestimation of the BL03 CO strength leads to an overestimation of the stellar temperatures by $\sim 200$ K. The FR01 index decreased by less than a factor 0.98 due to extinction. Degrading the resolution from $R \sim 3000$ to $R \sim 2000$ shows no measurable impact. We estimate the combined systematic effect to be less than 0.97 (50 K).

The BL03 index suffers also from contamination of the Mg i line contained in the continuum bandpass of the index. The average Mg i line strength of the GC giants is similar to the calibration giants. Thus, the continuum estimation is not biased. Yet the line shows some intrinsic scatter introducing a statistical error in the CO index computation. To minimize the statistical and systematic error sources, we therefore adopted the index definition of FR01. We have to note that the results of Blum et al. (2003) did not suffer from the resolution dependence of their CO index because the bulk of their GC spectra were of the same resolution as the comparison stars.

### 3.4. Temperature Calibration

For the temperature calibration we used stellar spectra of giants with known $T_{\text{eff}}$. In total we used 33 giants with spectral types G0–M7 and metallicities $-0.3 < [\text{Fe}/H] < 0.2$. The spectra were obtained from the NOAO IR library (Wallace & Hinkle 1997) with $R \sim 3000$, the Infrared Telescope Facility (IRTF) library with $R \sim 2000$ (Rayner et al. 2009), and from Förster Schreiber (2000) with $R \sim 2000$. The corresponding temperatures were obtained with the help of the SIMBAD database. The CO–$T_{\text{eff}}$ relation for the template giants can be seen in Figure 6. The best fit to the data is

$$T_{\text{eff}} = 5832^{\pm130} - 208.25^{\pm32.84} \cdot \text{CO} + 11.38^{\pm2.48} \cdot \text{CO}^2 - 0.34^{\pm0.06} \cdot \text{CO}^3. \quad (2)$$

The residual scatter is 119 K. The average metallicity of the calibration stars of $[\text{Fe}/H] = -0.1$ is somewhat below the
average metallicity in the GC of [Fe/H] = 0.14 (Cunha et al. 2007). To account for the metallicity dependence of the CO index computation might be biased on a ~50 K level. More important, however, is the theoretical uncertainty. The Padua and Geneva Isochrones can differ by up to 80 K for the same star. Strictly speaking, this is not an observational uncertainty but in the fitting procedure the theoretical uncertainty must be taken into account. We included the bias by assuming a total systematic uncertainty of 100 K. To visualize the impact of temperature uncertainties, Figure 7 shows the theoretical age versus median temperature relation for red clump (RC) stars (0 < Mbol < 1). Especially for old ages, the age interpretation is very sensitive to temperature changes. Small temperature biases of the order 100 K might change the derived age by several Gyrs. In the star formation history calculation (see Section 5), we did not use only RC stars. However, RC stars make up more than one-third of all observed giants. Thus, the systematic uncertainty of the RC population is representative of the whole giant population.

3.4.1. Systematic Temperature Uncertainty

The systematic errors in the derivation of the temperature are the main drivers in the age uncertainty of a giant population (at a given metallicity). As discussed in the previous section, the CO index computation might be biased on a ~50 K level. More important, however, is the theoretical uncertainty. The Padua and Geneva Isochrones can differ by up to 80 K for the same star. Strictly speaking, this is not an observational uncertainty but in the fitting procedure the theoretical uncertainty must be taken into account. We included the bias by assuming a total systematic uncertainty of 100 K. To visualize the impact of temperature uncertainties, Figure 7 shows the theoretical age versus median temperature relation for red clump (RC) stars (0 < Mbol < 1). Especially for old ages, the age interpretation is very sensitive to temperature changes. Small temperature biases of the order 100 K might change the derived age by several Gyrs. In the star formation history calculation (see Section 5), we did not use only RC stars. However, RC stars make up more than one-third of all observed giants. Thus, the systematic uncertainty of the RC population is representative of the whole giant population.

3.4.2. Temperature Estimate from High S/N Spectrum

We compared the median spectrum with available library stars. The template star matching the co-added spectrum most closely is a K3 III giant with a temperature of 4330 K. The agreement of the spectra is impressive. Only the sharpest peaks are slightly smeared out due to a residual velocity error. The 12CO bandheads at 2.294, 2.322, 2.352, and 2.383 μm are well represented. Even the weaker bandheads of 13CO at 2.345 and 2.373 μm match the template (Figure 8). The comparison with colder and warmer giants (Figure 9) shows the sensitivity of the CO bandheads to the stellar temperature. The median temperature of the RC as derived by the stacked spectrum, T eff = 4330 K, agrees very well with the median value (T eff = 4310 K) of the individual low S/N spectra. The Ca i and Na i line blends are moderately sensitive to temperature as well as to the surface gravity log g. The Ca i lines are in good agreement with the template. The same is true for the iron line blends at 2.22 and 2.25 μm as well as Mg i, Si i, and Al i. Unfortunately, almost all of the atomic lines are contaminated with weaker atomic lines and lines of CN. This excludes the possibility of a spectral synthesis fit at the given resolution. However, qualitatively, it is clear that the GC spectrum is closely matched by a solar metallicity spectrum, in agreement with the work of Cunha et al. (2007).
3.5.3. Sodium Line Blend: Potential Evidence for Mixing Processes

The strongest deviation between our average spectrum and the K3 III template is found in the Na\textsc{i} lines. They seem to be intrinsically stronger than in the solar neighborhood. None of the template spectra in the temperature range of the RC can reproduce the Na\textsc{i} strength. An increased Na\textsc{i} strength was reported previously in low-resolution spectra by Blum et al.
The Na\textsc{i} lines are actually blends of a couple of atomic lines and CN lines. The individual contribution depends on the stellar temperature. For temperatures similar to a K3 III giant, sodium is the most important line. Cooler spectra are heavily influenced by Sc and the coolest spectra are dominated by CN. For a detailed analysis of lines in \textit{K}-band spectra see Wallace \& Hinkle (1996). Carr et al. (2000) used high-resolution spectra of IRS 7 to derive abundances. They found that the increased line strength of the Na\textsc{i} complex is mainly caused by stronger CN lines. The CN lines reflect extreme CNO abundances in the atmosphere of IRS 7, which they claim is probably the result of increased rotational mixing.

Cunha et al. (2007) also find CN-cycled material in the atmospheres of three luminous GC giants, although not as deeply mixed as in IRS 7. Increased rotational mixing is predicted for dense stellar clusters, where tidal spin-up can lead to significantly higher rotation speeds of main-sequence stars (Alexander 2005). This might explain the increased CNO material in the outer atmosphere layers of the luminous GC giants. Evidence for increased rotational mixing taking place in a supergiant like IRS 7 with a mass of 20\,\textit{M}_\odot and a lifetime of a few Myrs are hard to transfer to the RC giants of the GC with masses of only 1–2\,\textit{M}_\odot and ages of Gyr. This is especially true since IRS 7 is significantly cooler (3600 K) than the RC.

However, Maeder \& Meynet (2000) note that RGs with masses \textit{M} < 1.5\,\textit{M}_\odot are susceptible to extra mixing and Alexander (2005) notes that tidal spin-up is most effective in long-lived low-mass stars. Thus, the strong sodium lines might indicate that the RC stars have undergone a mixing process different from the solar neighborhood, for example due to tidal spin-up. In principle, the sodium line strength can also reflect a peculiar chemical composition of the GC. With the current knowledge we cannot rule out that possibility. However, rotational mixing provides a convincing explanation for the increased sodium strength. This might provide interesting conclusions on the stellar evolution since fast rotating stars tend to be more luminous and redder and can provide evidence for the existence of an underlying dense stellar cusp of low-mass main-sequence stars (Alexander 2005).

Apart from the Na\textsc{i} lines, the average spectrum shows no peculiarities. Small deviations of the GC spectrum at 2.219 and 2.349\,\textmu m are caused by poorly subtracted nebular emission of the Mini-Spiral. The deviation at 2.317\,\textmu m on the other hand coincides with a telluric line. Overall the agreement is intriguing and validates the method of constructing a median spectrum a posteriori.

4. CONSTRUCTION OF THE H-R DIAGRAM

We constructed an H-R diagram for the GC cluster using the same distance modulus and extinction as described in Section 3.5.1. The H-R diagram is displayed in Figure 10. For comparison, we also included the data of Blum et al. (2003) probing the luminous giants and supergiants in the inner 2.5 pc. The comparison data were rescaled to the updated extinction values used in this work. Although Blum et al. (2003) and this work rely on different temperature calibrations, the overlap regions match very well. The GC population is compared to isochrones (Bertelli et al. 1994) with \( Z = Z_\odot \) and \( Z = 2.5\,Z_\odot \) metallicity (Figure 10, left). The right panel of Figure 10 shows the comparison with a synthetic model population. The model
population represents the case of continuous star formation over 12 Gyr with a GC metallicity of \( Z = 1.5 Z_\odot \) (Cunha et al. 2007).

4.1. Features of the H-R Diagram

The H-R diagram shows several distinct features. The most prominent feature is the RG branch consisting of old (>1 Gyr) stars with masses of the order 1 \( M_\odot \). The GC RC can be identified as an overdensity of stars at a luminosity of \( M_{\text{bol}} = 0.6 \). This agrees very well with the RC in the solar neighborhood measured by Groenewegen (2008). The mean RC temperature derived by individual spectra agrees very well with the estimate based on the high S/N median RC spectrum (Figure 3.5).

A second overdensity can be found at \( M_{\text{bol}} = -0.8 \) and \( T_{\text{eff}} = 3900 \) K. This feature is sometimes referred to as the AGB bump. All aforementioned features are tracers of an old population. The H-R diagram shows a second branch of giants at \( T_{\text{eff}} = 4800 \) K. This warm giant population is bright (\( M_{\text{bol}} < 0 \)) and separated from the cold (old) branch in the same magnitude range. Yet only \( \sim 10\% \) of the giants between \( 0 < M_{\text{bol}} < -4 \) (corresponding to \( 11.5 < m_K < 15.5 \)) can be attributed to the young branch. Similar features are known in globular clusters with multiple stellar populations. The comparison of the GC H-R diagram with Chabrier/Kroupa populations of different ages can be seen in Figure 10 (right). Several obvious features are matched. The RC is well represented in the data. The cool branch of giants with ages greater than 1 Gyr is obvious. The temperature and luminosity of the warm branch are matched by giants younger than 0.5 Gyr. A deficiency of stars with ages of \( \sim 1 \) Gyr can be seen as a gap in the diagram. We do not detect a significant horizontal branch of old and metal-poor giants as would be typical for old globular clusters. This supports the assumption of a predominantly old and metal-rich population.

4.1.1. Outliers

The coolest temperatures we find cannot be reproduced by even the oldest solar metallicity isochrones. Those outliers might be explained by a population of metal-rich stars \( (Z > 2.5 Z_\odot) \). However, this does not contradict the current assumption of a near-solar metallicity in the GC. The cold outliers account for less than \( 8\% \) of the total population. Since metallicity studies in the GC (Ramírez et al. 2000; Cunha et al. 2007) have probed not more than 10 late-type stars, a small metal-rich population might have gone undetected. This can be compared to the situation in the bulge (Baade’s window), where a high-metallicity tail of stars \( (Z > 2.5 Z_\odot) \) makes up about 15\% of the population (Zoccali et al. 2008). Another explanation might involve stellar model uncertainties. Most of the outliers show the same luminosity as bright and cool AGB stars. Stellar models of these stars still suffer from large uncertainties. Model isochrones treat this evolutionary phase in a simplified manner and are thus rather unreliable. Furthermore, stars in these stages are known to pulsate with periods of hundreds of days. During the pulsation, an individual star can change its temperature by up to 500 K (Lancon & Mouchine 2002). All systematic effects considered by us lead to an overestimation rather than an underestimation of the stellar temperature. Yet some of the stars can be heavily dust obscured and thus appear too faint for the given temperature. In the following fitting procedure we ignored stars that were cooler than allowed by the isochrones and the temperature uncertainty. This excludes only a small number of the old stars. Therefore we are confident that the impact on the results is negligible.

4.1.2. The Young Giant Branch

Roughly 10\% of the observed GC giants with magnitudes between \( 0 < M_{\text{bol}} < -4 \) appear to belong to a branch of young \(<500\) Myr) giants. With masses between \( 2.5 M_\odot < M < 6 M_\odot \) those stars are descendants of main-sequence B-stars. They are tracers of an intermediate-age population in the GC. Their stellar age is smaller than the typical non-resonant two-body relaxation time in the GC of the order \( t_{\text{rel}} > 1 \) Gyr. However, close to the SMBH, orbits are near-Keplerian. This causes interactions between stars to build up coherently. The randomization of the angular momentum vectors happens therefore on the fast vector resonant relaxation timescale \( t_{\text{rr}} < \text{few tens of Myr} \) (Hopman & Alexander 2006).

However, the eccentricity and semi-major axis distribution are randomized on the slow scalar resonant timescale \( t_s \) (Hopman & Alexander 2006), comparable to \( t_{\text{rr}} \) for \( r > 0.1 \) pc. The mean stellar mass of the young giants \( (3.2 M_\odot) \) is significantly larger than the average mass of the old giants \( (1 M_\odot) \). The more massive stars tend to sink to the center of a cluster due to dynamical friction exerted through the drag of lighter background objects. The mass segregation timescale in the GC is larger than in normal stellar clusters due to the presence of the SMBH and the corresponding higher velocity dispersion. The mass segregation timescale \( t_s \approx t_{\text{rr}} \) scales with the relaxation time \( t_{\text{rr}} \) but is also a function of the individual stellar mass \( M \) and the mean stellar mass \( \langle M \rangle \) (Alexander 2005). Assuming the mean stellar mass is \( \langle M \rangle \approx 1 M_\odot \), the segregation time is \( t_s \approx \frac{1}{4} t_{\text{rr}} > 1 \) Gyr. This is still significantly larger than the age of the young giants. Thus the radial distribution could not have changed significantly since the stars formed (neither through relaxation nor through mass segregation). Yet the angular momentum vectors (i.e., the orientation of the orbits) will have undergone randomization.

4.1.3. Kinematics and Distribution

To assess the dynamical state of the young giants we computed their orbital distribution. We followed the method of Bartko et al. (2009), who used statistical arguments to infer the 3D distribution of a stellar population out of the 3D velocity and projected distance distribution. A coherent motion within a stellar system can be detected as a statistical preference for an angular momentum direction. However, the orbital distribution of the young giants shows no significant excess as would be the case for a disk or a streamer. The orientation of the angular momentum vectors is consistent with being isotropic, as expected due to the fast vector resonant relaxation. The radial distribution of the young giants compared to the cool giant population is shown in Figure 11. Both populations exhibit the same radial density distribution. The density distribution of the total giant population has been described as a core or even a hole close to the SMBH (Buchholz et al. 2009; Bartko et al. 2010; Schödel et al. 2010). In any case, the distribution differs significantly from a Bahcall–Wolf cusp, the predicted final state of a relaxed population. Given the age of the young giants, they must have formed rather close to the SMBH, either in situ or transported in by in-falling clusters. Since the radial density distribution evolves only slowly on timescales of \( \sim \) few Gyr this means that the young giants still contain information on their initial distribution. The 3D velocity of the young giants compared with the cool giants in the same magnitude bin is shown in Figure 12. The 3D velocity was computed assuming a distance of 8.3 kpc to the GC. The maximum 3D velocity \( v_{\text{max}} = \sqrt{\frac{GM_{\odot}}{r}} \).
Figure 11. Ratio of young-to-old giants with magnitudes between 0 < \( M_{\text{bol}} < -4 \) as a function of radius. The average ratio is indicated (dashed line). The errors are the Poisson errors of the young giants in the given radial bin. The ratio is consistent with being flat, indicating that the young giants exhibit the same radial distribution as the old giants.

Figure 12. 3D velocity of the warm giants (red) with magnitudes of 0 < \( M_{\text{bol}} < -4 \) and the cold comparison sample (gray) is shown. The maximum allowed velocity for stars to be bound is indicated: SMBH alone (solid line); SMBH + cluster mass (dashed line).

(A color version of this figure is available in the online journal.)

for stars to be bound is indicated in the figure. The projected distances \( r \) yield a lower limit for the physical 3D distance \( R \). The kinematics of the young population are consistent with the old stars. Using a Kolmogorov–Smirnov test to assess the likelihood that the young giants’ 3D velocities can be drawn from the cold population returns a probability of 70%. The fact that both giant populations share the same radial distribution is surprising. The young giants (\( M_{\text{ZAMS}} \approx 3 M_\odot \)) are three times more massive than their old counterparts with a lifetime too short to experience relaxation and especially to change their angular momentum significantly. However, it renders a radially varying IMF unlikely. The latter is a valid claim although star formation history and IMF are highly degenerate, since one effect would need to cancel the other exactly to emulate a radially constant distribution of young versus old giants.

5. CALCULATION OF THE STAR FORMATION HISTORY

To derive the star formation history, we compared the observed distribution of giants in the H-R diagram to model populations. We restrict our analysis to the \( m_K < 15 \) mag range with >50% completeness. This left us with 450 giants for the fit. We repeated the calculation with a completeness limit of 80%. The results were similar, but with larger uncertainties. Thus we are confident that no bias is introduced due to the completeness limit chosen. The synthetic model populations were created with the IAC-STAR code (Aparicio & Gallart 2004). The code allows a selection of different stellar evolution and bolometric correction libraries for the computation. We chose the Bertelli et al. (1994) stellar evolution library and the Lejeune et al. (1997) bolometric correction library since these are the only libraries with evolutionary tracks of stars with masses >10 \( M_\odot \). The code requires several input parameters such as metallicity, age, and slope of the IMF. Since age and metallicity introduce some degeneracy, we adopted the mean metallicity found by Cunha et al. (2007). Thus, we set up model populations with a metallicity of \( Z = 1.5 Z_\odot \). For the calculation of the star formation history, we applied a method similar to Blum et al. (2003). We defined four age bins (50–200 Myr, 0.2–1 Gyr, 1–5 Gyr, and 5–12 Gyr) with constant SFR within each age bin. The bins were chosen such that the evolutionary tracks are distinct enough to be resolved with the given data quality. The isochrones for stars with ages > a few Gyr are very similar. Therefore, the older age bins were chosen to be wider than the younger age bins. The younger age bins were selected by visual comparison of the model populations with the data. Figure 10 shows the chosen age bins. To study the impact of the IMF, we created models with various IMF slopes between \(-2.7 \leq \alpha \leq -0.45\). Among the models, we included a Chabrier/Kroupa IMF (\( \alpha = -2.3 \)), a top-heavy IMF (\( \alpha = -0.85 \); Maness et al. 2007) and a flat IMF with a slope of \( \alpha = -0.45 \) as was found recently for the young stellar disk (Bartko et al. 2010). We note that the star formation could have proceeded in episodic bursts. Yet, given the quality of the data, it is not possible to distinguish between a burst and continuous formation within an age bin. Therefore the derived SFR is an average across the age bin.

5.1. Fitting Procedure

We added Gaussian noise to the synthetic model populations, representing the statistical errors of \( M_{\text{bol}} \) and \( T_{\text{eff}} \). Then we removed stars from the synthetic populations according to the estimated completeness as a function of \( K \)-band magnitude. The completeness is not a function of temperature, since we used a minimum S/N criterion. We then binned the data and the model populations into an H-R diagram with a bin size of 1.5\( \sigma \) of the typical errors. The data were then fitted as a linear combination of the H-R diagrams of the four model populations (four age bins). For the fit we used the IDL routine TNMIN (Markwardt 2008). As a minimization parameter we used the Poisson maximum likelihood parameter \( \chi^2 = 2 \sum (n_{ii} - n_{ii} \ln(n_{ii}/m_{ii})) \), where \( n_{ii} \) is the number of stars predicted by the model and \( n_{ii} \) is the number of observed stars in the \( i \)th bin of the H-R diagram (Mighell 1999; Dolphin et al. 2002). The contribution of each age bin determines the relative SFR of that bin. The best-fitting SFR for various IMFs is given in Table 3.

5.1.1. Uncertainty and Quality of the Fit

To assess the fit uncertainty we used a method generally referred to as bootstrapping. We constructed 1000 H-R diagrams by drawing random stars out of the data. Each star was allowed to be drawn any number of times. To include the systematic
uncertainty of the data and the theoretical isochrones, we added a random temperature offset with a Gaussian $\sigma$ of 100 K to the whole data set. The constructed H-R diagrams were fitted again with the model populations. The scatter of the derived model populations resulted in a variance diagram. We defined the fit quality as $\chi^2 = (i, m_i) \sum \frac{(m_i - n_i)}{\sigma_i^2}$, where $\sigma_i^2$ is the variance in bin $i$, $m_i$ is again the number of model stars, and $n_i$ is the observed number of stars in bin $i$. The values for $\chi^2$, the number of degrees of freedom, and the corresponding probability that the data can be drawn from the model population are represented in Table 3. The numbers of degrees of freedom are equal to the number of populated bins minus the number of free parameters. Figure 13 illustrates the residuals for various models. Each panel shows the residual model—data weighted by the variance (Dolphin et al. 2002). The color coding indicates bins where the model predicts more stars than observed (bright) and where the model underpredicts the number of stars (dark). The first panel of Figure 13 shows the best-fit model, while the second panel shows a continuous star formation model (both assume a Chabrier IMF). The continuous model predicts too few old (i.e., cold) stars compared to the observations, while it predicts too many young (i.e., warm) stars. The data are well fitted by a mostly old (>5 Gyr) population with an admixture of recently formed stars (< a few 100 Myr) as in the case of the best-fit model. The discrepancy between a continuous formation scenario and a time-varying star formation increases in the case of IMFs favoring the formation of massive stars (right two panels).

### 6. RESULTS

The data fit best a normal Kroupa/Chabrier IMF (49% acceptance probability, see Table 3) but either flatter or steeper IMF can be accommodated within the 2$\sigma$ uncertainties. The distribution in the H-R diagram does not strongly constrain the IMF, in contrast to the diffuse light and dynamical mass discussed in Sections 6.2.1 and 6.2.2. This is not surprising, since the old giant branch contains stars with zero-age main-sequence (ZAMS) masses between $1 M_\odot < M < 1.2 M_\odot$. Thus the mass interval is too small to be significantly affected by changes of the IMF slope. The slope can affect the abundance of young giants, since they cover the mass range 2.5 $M_\odot < M < 6 M_\odot$. However, their abundance depends sensitively on the SFR of the last few hundred Myrs. Furthermore, the bright and massive end of the population suffers from low number statistics. This makes statements on the IMF slope uncertain. In general, the IMF and the SFR as a function of time are largely degenerate. Given the coarse sampling of the age bins, the data are not sufficient to constrain the IMF by the fitting procedure itself. The fit only allows the derivation of relative SFRs for each assumed IMF. However, it is possible to constrain the IMF using the measured dynamical mass. Since each model

| Model       | Age Bin (Gyr) | IMF Slope$^a$ | $\chi^2$/dof(Prob.$^b$) | Absolute SFR ($10^{-4} M_\odot$ yr$^{-1}$) | $\sigma_{\text{SFR}}$ |
|-------------|---------------|---------------|----------------------|---------------------------------|-----------------|
| Model 1     | 12–5          | −2.7 (−1.3)   | 122/94 (3%)          | 3                               | 0.6             |
| Model 2     | 12–5          | −2.3 (−1.3)   | 105/104 (49%)        | 3                               | 0.6             |
| Model 3     | 12–5          | −1.5          | 157/106 (0.1%)       | 13                              | 3               |
| Model 4     | 12–5          | −0.85         | 143/100 (0.3%)       | 126                             | 27              |
| Model 5     | 12–5          | −0.45         | 131/107 (6%)         | 614                             | 124             |
| Continuous  | 12–0.05       | −2.3 (−1.3)   | 178/105 (<0.01%)     | 2                               | ...             |
| Continuous  | 12–0.05       | −1.5          | 181/111 (<0.01%)     | 6                               | ...             |
| Continuous  | 12–0.05       | −0.85         | 176/116 (<0.01%)     | 34                              | ...             |
| Continuous  | 12–0.05       | −0.45         | 211/115 (<0.01%)     | 113                             | ...             |

Notes.

$^a$ The upper and lower mass cutoff is $0.5 < M < 120$. The models 1 and 2 extend to $0.1 < M < 120$ with a flatter slope between $0.1 < M < 0.5$.

$^b$ Outlier-corrected $\chi^2$ and degrees of freedom. Outliers are bins off by more than 10$\sigma$. The dof corresponds to the number of populated H-R diagram bins (ignoring significant outliers) minus the number of fit parameters. Models 1–5 have four independent fit parameters (age bins), while the continuous models have only one free scaling parameter. In brackets, the acceptance probability is stated.
predicts a certain mass composition of the population, it is possible to distinguish between different models. In any case, no acceptable fit was achieved for continuous star formation scenarios, irrespective of the assumed IMF.

6.1. Star Formation Rate Over Cosmic Time

In the following we only consider the formation scenario with a Chabrier/Kroupa IMF. This is motivated by the slight preference of the fitting, the intriguing total mass prediction of the model matching the dynamical measurements, and the agreement with the observed diffuse background light (see the next sections). We find that the giant population of the GC is old. Figure 14 shows the SFR as function of time (assuming a normal IMF). The formation rate more than 5 Gyr ago was on average $3 \pm 0.6 \times 10^{-5} M_\odot \text{yr}^{-1}$. According to our fit, roughly 80% of the total mass formed more than 5 Gyr ago. The formation period was followed by a period of reduced star formation lasting another 4–5 Gyr. The SFR reached a minimum about 1 Gyr ago. During the last few hundred Myrs, the formation rate increased again. The disk of young stars is part of the increased formation rate. Our results are in excellent agreement with the earlier findings of Blum et al. (2003; compare Figure 14).

The recent period of star formation accounts for about 10% of the total formed mass. Note the recent SFR seems to be higher than several Gyrs ago. However, the bin widths are very different. Each bin represents an average formation rate. The actual formation several Gyrs ago could have happened in short bursts with significantly higher SFRs. The present-day cluster contains roughly 50% of the total processed gas mass in living stars and 10% in remnants. The rest has been lost via stellar winds, explosions, and potentially been swallowed by the SMBH. For simplicity, we set up a simple analytic model that approximates the measured SFR as a function of time (solid line in Figure 14):

$$\text{SFR}(t) = 6.8 \times 10^{-5} M_\odot \text{yr}^{-1} \times e^{t/5.5 \text{Gyr}}$$

$$+ 4.3 \times 10^{-3} M_\odot \text{yr}^{-1} \times e^{-t/0.06 \text{Gyr}}, \quad (3)$$

where $t$ is the look-back time. The integration of the model yields the integrated mass as function of time. As Figure 15 shows, about half of the cluster mass formed before a redshift of one. This suggests that the nuclear cluster formed at a time when the galaxies buildup most of their stellar mass. In that sense, the nuclear cluster formed at the same time, or shortly after, the bulge, about 10 Gyr ago (Zoccali et al. 2008).

6.1.1. Implications from the Faint Main-sequence Population

The two confirmed A-stars and the one candidate (Section 3.1.1) are ideal tracers for star formation during the last few hundred Myrs. Early-type stars with $K$-band magnitudes $17 < m_K < 18$ (assuming $A_K = 2.8$ and $R_0 = 8.3\text{kpc}$) are main-sequence B9/A0 dwarfs with average lifetimes of 500 Myr. Late-type stars in the same magnitude range can only be giants that have already left the main sequence. These giants have ages between 1 and 12 Gyr. Thus the number count ratio of the two populations provides a measure of the star formation efficiency during the last 500 Myr relative to earlier star formation. This ratio is largely independent of systematic uncertainties since it avoids issues like incompleteness and spectroscopic detectability. We included the candidate star in the early-type population. In total we found three (two confirmed) early-type stars and 30 late-type stars in this magnitude bin. We used the IAC-STAR code and found that in the case of continuous star formation over 12 Gyr with a Kroupa IMF, the predicted early-to-late ratio is close to unity. The observed ratio therefore argues for an average SFR during the last 500 Myr of...
Figure 14. Left: star formation rate of the Galactic center as a function of time. The black circles represent the best fit to the H-R diagram with a Chabrier/Kroupa IMF. The mass error is given by the $1\sigma$ error of the fit. The age error is simply the width of the age bin. For comparison, the star formation history derived by Blum et al. (2003) scaled to a radius of 1.2 pc is indicated (green triangles). The star formation rate derived by red supergiants (Genzel et al. 2010) within 1 pc (red square, filled) and within 2.5 pc (red square) and the stellar disks (blue circle; Bartko et al. 2009) are indicated. The star symbol (purple) indicates the recent star formation rate inferred by the early-to-late ratio of faint GC stars (Section 6.1.1). The solid gray line shows a simple exponential model (see the text) of star formation as a function of time. Right: the total mass formed in each age bin is shown. Although star formation occurred at a high rate during the last few hundred Myrs, the total mass contribution is $<10\%$. The bulk of the stellar mass formed more than 5 Gyr ago.

(A color version of this figure is available in the online journal.)

Figure 15. Integrated mass as a function of time as obtained from Equation (3) in Section 6.1 is shown. The dashed curves represent the $1\sigma$ uncertainty. Note today’s cluster mass is only about 50% of the total formed mass. The remaining mass is lost due to stellar evolution.

only about $10\% \pm 6\%$ of the average formation rate 1–12 Gyr ago. To convert the relative formation rate into an absolute rate, we used the SFR inferred in the previous section and calculated an average rate of $2.3 \pm 0.5 \times 10^{-4} M_\odot$ between 1 and 12 Gyr look-back time. Using this value, we obtained an average SFR of $2.3 \pm 2.1 \times 10^{-5} M_\odot$ during the last 500 Myr (see Figure 14). Within the errors this is consistent with the one derived by the H-R fitting. The A-star ratio provides an independent measurement of the relative SFRs. It is another indicator for the early formation of the nuclear cluster.

6.1.2. Comparison with Previous Work

Maness et al. (2007) found that the giant population of the GC is on average warm and thus young. Consequently, they favored models with a normal IMF and an increasing SFR or a top-heavy IMF and continuous formation. Maness et al. (2007) used a CO index that is very sensitive to systematic effects. In particular, their CO index, though widely used, was recently discovered to vary with spectral resolution (Márvez-Queraltó et al. 2008). Since no suitable library was publicly available at the time of writing, they also used template libraries with resolutions between $R \sim 3000$ and 5000 to calibrate their $R \sim 2000$ data. The sum of the effects caused an underestimation of the CO equivalent width and a resulting overestimation of the stellar temperatures. This led to the interpretation of a mostly young giant population. Applying the same methods as Maness et al. (2007) together with a CO index that is less susceptible to systematic effects and using the newly available library of Rayner et al. (2009) with $R \sim 2000$ allowed us to revisit the star formation history of the GC.

6.2. The Mass Composition of the Nuclear Cluster

The present-day mass composition of the NSC depends sensitively on the formation history and the IMF. The mass contribution of stellar remnants and stars as well as the total amount of consumed gas depends on the age and the IMF of a
population. The consumed gas mass is larger than the sum of remnant and stellar mass because a significant mass fraction is lost due to stellar evolution. Since massive stars lose a larger fraction of their initial mass, the gas consumption increases with flatter IMFs for the same total stellar mass. The same is true for the remnant mass. Massive stars have main-sequence lifetimes that are significantly shorter than the age of the galaxy. Therefore many generations of massive stars evolve through time and finally end as remnants. Thus, IMFs that favor massive stars produce more and heavier remnants. As a consequence, the mass contribution of stars still burning hydrogen drops with flatter IMF slopes.

6.2.1. Constraints from the Dynamical Mass

Various models have been fitted to the data (Section 5.1). Each model yields the SFR as function of time under the assumption of a certain IMF. To derive the absolute mass contribution, it is necessary to scale the models according to the actual star counts. To get a representative number for the nuclear cluster we used the stellar surface density from Schödel et al. (2007). As discussed in Section 1 the radial extent of the NSC is \( \sim 5 \) pc. Our data, however, probed only the inner 30′ (1.2 pc). Therefore we restricted ourselves to that radius. By assuming 30′ as a sharp edge, the surface density from Schödel et al. (2007, their Figure 12) yields \( \sim 18,200 \) stars with \( m_K < 17.75 \) within a projected radius of 30′ from Sgr A*. Between 45% and 55% of the projected stars are also contained within a 3D distance of 30′, depending on the radial density profile derived by Schödel et al. (2007). Thus, we assumed a total of 9100 stars with \( R_{\text{3D}} < 1.2 \) pc to scale the remnant, stellar, and total gas mass for each model. Table 3 shows the derived SFR for each model IMF. Figure 16 shows the mass composition for the models derived in Section 5.1. The model predictions have to be compared with the dynamical mass estimates of the nuclear cluster (see Figure 16). The total mass enclosed within 30′ is \( 5.7 \pm 0.9 \times 10^6 \) M⊙. The SMBH contributes \( 4.3 \pm 0.5 \times 10^6 \) M⊙ (Ghez et al. 2008; Gillessen et al. 2009), while the remaining 1.4±0.7×10⁶ M⊙ (Genzel et al. 1996, 2010; Trippe et al. 2008; Schödel et al. 2009) are contained in stars and stellar remnants. Numerical simulations of Freitag et al. (2006) have shown that during 10 Gyr about \( 4 \times 10^5 \) M⊙ stellar and \( 1 \times 10^5 \) M⊙ remnant mass is removed from the cluster by the SMBH through tidal disruption and inspiral. The cluster composition is scaled to match the observed number of giants. Thus, the inferred stellar mass intrinsically accounts for stars lost to the SMBH because giants and giant progenitors are equally likely to be disrupted as unresolved main-sequence stars constituting the bulk of stellar mass. The situation for remnants, however, is different. The main remnant contribution comes from stellar BHs dominating the mass density in the inner 0.1 pc. Due to their mass (\( \sim 10 \) M⊙) they are significantly affected by mass segregation and more likely to inspiral into the SMBH. Consequently, the inspiral of stellar BHs has to be taken into account in the mass budget. We simply added \( 10^5 \) M⊙ with an uncertainty factor two to the observed dynamical mass to constrain the IMF. We took the value determined by Freitag et al. (2006) as being constant with IMF. This might be the weak point in the line of argument, since Freitag et al. (2006) assumed a Chabrier/Kroupa IMF in their simulations. As Figure 16 shows, the cluster composition depends sensitively on the assumed IMF. For flatter IMFs, the number of stellar BHs increases, but the mean mass increases accordingly making mass segregation less efficient. Thus the actual mass transfer between the cluster and the SMBH as function of IMF can only be addressed by further simulations. Keeping the limitations in mind, the dynamical mass plus the removed mass therefore make IMFs with a slope flatter than \( \alpha = -1.1 \) unlikely. Even if the transferred mass is significantly higher, models flatter than \( \alpha = -0.8 \) violate the total enclosed mass (SMBH + cluster). Mechanisms that expel remnants or stars are very inefficient. One mechanism is the evaporation of stars from the nuclear cluster. However, for the GC the timescale is greater than a Hubble time (Alexander 2005). Mass segregation is another mechanism for removing stars. This mechanism moves low-mass constituents outward, and high-mass constituents inward, without changing the radial density profile significantly. Miralda-Escudé & Gould (2000) suggest that inward migration of a considerable number of bulge stellar BHs can remove low-mass stars from the nuclear cluster. According to their model, the low-mass stars are supposed to form a core with a radius of 1–2 pc. Observations, however, find a core radius of about 0.3 pc (Schödel et al. 2007). If the observed core is related to mass segregation, then the effect is smaller than predicted. Our constraints on the IMF are however not weakened by potential mass segregation. Our models use the number of observed stars as a scaling for the total processed mass (and remnants produced). Therefore if low-mass stars are removed from the inner region, our scaling underestimates the remnant mass. The inferred stellar mass, however, is not changed because giants and unresolved main-sequence stars have very similar masses (\( \sim 1 \) M⊙). Thus the total predicted mass will grow if we take into account that low-mass stars are removed due to mass segregation. This makes our statement on the IMF constraints...
even more significant. In general, it is very hard to remove mass in the form of stars and remnants from a nuclear cluster (an SMBH binary, however, is able to remove stars efficiently). The processed gas mass, unlike stars and remnants, can be expelled from the nuclear cluster due to supernovae or active galactic nucleus activity in the distant past of the SMBH. Stellar winds are also able to remove gas from the cluster. While the low-mass main-sequence stars and giants have wind speeds significantly lower ($v_{\text{wind}} \sim$ a few tens of km s$^{-1}$) than the escape velocity of the NSC, the most massive stars ($v_{\text{wind}} \sim 1000$ km s$^{-1}$) can efficiently remove gas from the cluster (McLaughlin et al. 2006; Martins et al. 2007). Therefore, the processed gas mass cannot constrain the IMF although flat IMFs require a factor hundred greater gas masses than Kroupa-like IMFs. Summarizing the arguments, we can say that IMFs flatter than $\alpha > -1.1$ violate the observed cluster mass. IMFs flatter than $\alpha > -0.8$ exceed even the total mass (SMBH + cluster).

6.2.2. Constraints from the Diffuse H-band Background

As discussed in Section 2.1.1, depending on the IMF and star formation history the diffuse background light from faint unresolved stars may probe the bulk of the stellar population. We find that the diffuse background contributes $H_{\text{diff}}/H = 27\% \pm 9\%$ to the total $H$-band flux. Furthermore, we derived a mass-to-diffuse-light ratio of $M_{\text{dyn}}/H_{\text{diff}} = 2.6 \pm 1.5 M_\odot/L_{H,\odot}$. In the following we used the inverse ratio $H_{\text{diff}}/M_{\text{dyn}}$ for convenience. We compared both quantities to our best-fit models (Section 5.1). To show how $H_{\text{diff}}/H$ and $H_{\text{diff}}/M$ depend on the IMF slope and overall star formation history, we used the population synthesis code STARS (Sternberg 1998) to compute these ratios for a range of IMFs and star formation timescales $t_0$ for simple histories $\text{SFR}(t) \propto e^{-t/t_0}$. We considered a Kroupa IMF, and also three power-law IMFs, $dN/dm \propto m^{-\alpha}$, with $\alpha$ equal to $-1.5$, $-1.35$, and $-0.85$. All of the IMFs range from 0.01 to 120 $M_\odot$. We used Geneva evolutionary tracks for solar metallicity stars, combined with empirical colors and bolometric corrections for dwarfs, giants, and supergiants. For low-mass stars ($< 0.8 M_\odot$), we computed the $H$-band luminosities along the lower main sequence using the calibrations of Henry & McCarthy (1993). We considered exponentially decaying ($t_0 = 3$ Gyr), continuous ($t_0 = \infty$), and exponentially increasing ($t_0 = -3$ Gyr) SFRs, for an assumed cluster age $t = 13$ Gyr, and fixed dynamical mass $M_{\text{dyn}} = 1.5 \times 10^6 M_\odot$. The results are displayed in Figure 17 in the $H_{\text{diff}}/M$ versus $H_{\text{diff}}/H$ plane. The gray areas indicate the measurement including the $1\sigma$ uncertainty. Figure 17 shows that $H_{\text{diff}}/M$ and $H_{\text{diff}}/H$ both decrease for flatter IMFs. This behavior is due to the relative increase in remnant mass from massive stars, and the reduction in the relative fraction of diffuse light from low-mass stars. For a given IMF, $H_{\text{diff}}/M$ decreases but $H_{\text{diff}}/H$ increases, as the history is altered from increasing, to steady, to declining star formation, because the total luminosity for fixed mass is reduced for this sequence of histories, while the fraction of light produced by the accumulating long-lived low-mass stars is increased. In Figure 17 we also indicate the positions of the “best-fit” models discussed in Section 5.1 and listed in Table 3. Figure 17 shows that the observed $H_{\text{diff}}/M$ and $H_{\text{diff}}/H$ ratios require steep (canonical) IMFs and continuous or mildly decaying star formation. In particular, flat IMFs with $\alpha > -1.5$ are inconsistent with the observations.

Our measurements of the diffuse $H$-band background can be compared to the findings of L"ockmann et al. (2010), who used the diffuse $K$-band background together with the dynamical mass to derive $M/K_{\text{diff}} = 1.4_{-0.7}^{+1.4} M_\odot/L_{\odot}$, which was then compared with model predictions. Their mass-to-diffuse-light ratio is somewhat lower than our value ($M/K_{\text{diff}} = 1.9 \pm 1.2 M_\odot/L_{\odot}$), although consistent within the errors. The difference originates from the assumed extinction value. L"ockmann et al. (2010) used $A_K = 3.3$ published by Buchholz et al. (2009). However, this value is 0.5 mag (factor 1.6) higher than the most recent one published by Sch"odel et al. (2010) and Fritz et al. (2011). Correcting for this difference removes the discrepancy between their finding and ours. Their analysis favored an IMF steeper than $\alpha = -1.3$ together with a continuous SFR or an increasing SFR. Our analysis confirms their finding of a steep IMF. Taking into account the revised extinction our finding of an early star formation is also consistent with the findings of L"ockmann et al. (2010). However, we additionally used the ratio of diffuse light to total light to constrain the star formation history even further.

7. DISCUSSION

All statements concerning the star formation history of the NSC have been made under the assumption that the traced population is representative for the whole cluster. The radial extent of the cluster is ~5 pc, i.e., larger than the radii probed by our SINFONI observations. However, the inner 1.2 pc contain already $6 \times 10^6 M_\odot$ of the total $30 \times 10^6 M_\odot$. Thus we cover about 20% of the total cluster mass and this gives us confidence that our results are somewhat representative of the whole cluster.
7.1. Initial Mass Function in the GC

We find that the old giant population must have formed with an IMF steeper than $\alpha \leq -1.3$, probably with a normal Chabrier/Kroupa IMF. In any case, the IMF must have been significantly different from the IMF observed in the young stellar disks. Paumard et al. (2006) and Bartko et al. (2010) found that the young stellar disks in the GC have formed preferentially massive stars. They favored an almost flat IMF with $dN/dm \sim m^{-0.45}$ (Bartko et al. 2010). This indicates that the environmental conditions at the time of formation were different in the past. The nuclear cluster probably formed at a time when the SMBH itself was younger and less massive. With the radius of influence smaller than today, the gravitational potential resembled more a normal cluster. Consequently the IMF was closer to the universal one. The nuclear cluster might also have been contaminated by inspiraling clusters that had formed outside of the GC. Depending on their mass, clusters within several 10–100 pc can spiral into the NSC during a Hubble time (Agarwal & Milosavljevic 2011). Both effects lead to an IMF significantly steeper than the one observed in the young stellar disks today.

7.2. Star Formation in the Vicinity of the GC

The GC region shows star formation at all ages. The massive Arches and Quintuplet clusters at distances of a few tens of pc were formed 2 and 4 Myr ago (Figer et al. 2002, 1999). The stellar disk in the central cluster was formed about 6 Myr ago (Paumard et al. 2006; Bartko et al. 2009) and at roughly 50 pc distance the Sgr B2 cloud harbors several massive star cluster in the making. Figer et al. (2004) used Hubble Space Telescope photometry of several fields within 100 pc of the center to derive the star formation history. They find a continuous star formation in their FOV. Genzel et al. (2003) and Buchholz et al. (2009) used AO-assisted photometry of the nuclear cluster and found that the KLF is well matched by a bulge-like (8–10 Gyr) population with an admixture of young main-sequence stars. Blum et al. (2003) used spectroscopic data of the most luminous giants within 2.5 pc from Sgr A*. Our work confirms their favored formation scenario. The star formation happened predominantly at old times. An intermediate period showed a reduced star formation, while during the last few 100 Myr the SFR was increasing. This is also consistent with findings based on the stellar disks and the number of red supergiants. Roughly 75%–90% of the mass contained in the central cluster formed 5–12 Gyr ago. The formation of the cluster might coincide with the formation of the bulge around 10 ± 2.5 Gyr ago (Zoccali et al. 2008). The $\alpha$-element ratios require the bulge to have formed on a short timescale (∼1 Gyr). Whether this is also true for the GC cannot be answered with the given uncertainty of the data. The fact that Buchholz et al. (2009) do not find a young giant population is not surprising, since those stars make up only ∼10% of the number counts. The KLF fitting is not sensitive enough and since the young giants are rather warm and bright, they might be attributed to the admixture of young main-sequence stars. The same is true if the results are compared to Figer et al. (2004). They, however, find a continuous SFR within 100 pc. This does not contradict our findings and is consistent with the idea of recurrent episodic star formation in the greater GC region (Serabyn & Morris 1996). The star formation events themselves happen on spatial scales of <1 pc (e.g., central, Arches, and Quintuplet clusters). If one assumes that the individual star formation events happen incoherently, then one would naturally expect a continuous star formation history on scales >1 pc. Thus Figer et al. (2004) find a star formation history that is smoothed across many episodic single events.

8. CONCLUSION

We used several methods to constrain the star formation history of the Milky Way nuclear cluster. This is the only nuclear cluster in which individual stars can be resolved and reliable age estimates can be made. For this purpose, we used 450 K-band spectra of late-type giants to derive individual stellar temperatures. By using a CO index that is insensitive to systematic effects, such as reddening or instrument resolution, together with the new stellar library of Rayner et al. (2009) we improved the temperature calibration for the RGs in the GC. Together with K-band photometry we were able to construct a detailed H-R diagram of the giant population. The comparison of the observed H-R diagram with model populations allowed us to infer the star formation history of the GC. Our results are as follows.

1. The bulk of the nuclear cluster is old. Roughly 80% of the stellar mass formed more than 5 Gyr ago. It might have formed at the same time as the galactic bulge at a redshift of 1–2.

2. After the bulk of the cluster had formed, a period of reduced star formation followed between 1 and 5 Gyr ago. The star formation reached a minimum ∼1 Gyr ago. Our inferred star formation history confirms the earlier findings of Blum et al. (2003).

3. Only during the last 200–300 Myr has star formation set in at a significant level. A population of intermediate-age giants are tracers of that period. Making up only 10% of the number counts, the intermediate-age population is hardly traceable with the KLF. However, they can be clearly identified in an H-R diagram due to their high temperatures. The spatial distribution and kinematics of those giants resemble those of the old giant population.

4. We report the first detection of main-sequence B9/A0 stars with magnitudes 17 < $m_K$ < 18 in the GC. They are the faintest early-type stars to be found in the GC so far. With these stars we probe the mass regime between 2.2 and 2.8 $M_\odot$, and main-sequence lifetimes of 360–750 Myr.

5. The ratio of late-type to early-type stars in the magnitude bin 17 < $m_K$ < 18 yields an independent estimate of the SFR during the last 500 Myr. We find that the average rate during the last 500 Myr must have been a factor 10 lower than the average rate between 1 and 12 Gyr ago. This finding supports the claim of an old cluster population.

6. We find that the bulk of the stellar mass must have formed with an IMF steeper than $dN/dm \sim m^{-\alpha}; \alpha < -1.5$. Otherwise, the required remnant and stellar mass violates the observed dynamical mass and diffuse background. Thus, the bulk of the old stars formed with an IMF significantly steeper than the one observed in the young stellar disk. We suggest that this apparent discrepancy can be naturally explained if the stars formed at a time when the SMBH itself was much younger and less massive. Consequently the sphere of influence was significantly smaller. Without the extreme environment of an SMBH, the stars formed with an IMF close to the universal one. The SMBH was fed by gas including stellar mass loss (Freitag...
et al. 2006) and dominated the inner few pc over time. With the growing size of influence, the IMF became flatter and reached the value observed in the young disk.

7. The deep census of the GC using integral field spectroscopy yields a late-type KLF between 12 < m_K < 18 with a slope of \( d \log N/dm_K = 0.33 \pm 0.03 \). This confirms the previous findings of Genzel et al. (2003) and Buchholz et al. (2009). The slope is consistent with an old bulge-like KLF (Alexander 1999).

Taking into account systematic effects leads to an improved age estimate of the nuclear cluster. To improve the age estimate further, however, requires a technical leap. The main difficulty is that >5Gyr old isochrones are spaced by only a few tens of K. The necessary temperature accuracy can hardly be achieved by spectral analysis. The most promising way is to detect a turnoff of the main-sequence population. This requires the spectroscopic identification of stars with magnitudes of \( m_K \approx 19 \). For example, the confirmation of late-type giants only 1 mag fainter than the current limit can unambiguously confirm the presence of stars with ages of >10 Gyr. Yet the required telescope time which is needed for the spectroscopic identification of those stars is tremendous. Furthermore, these faint stars are significantly affected by stellar crowding. Thus further progress will require the resolving power of a new generation of telescopes like the European Extremely Large Telescope (E-ELT) or Thirty Meter Telescope (TMT). The same is true to derive a model-free measurement of the IMF in the vicinity of the SMBH.

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REFERENCES

Abuter, R., Schreiber, J., Eisenhauer, F., et al. 2006, New Astron. Rev., 50, 398
Agarwal, M., & Milosavljevic, M. 2011, ApJ, 729, 35
Alexander, T. 1999, ApJ, 527, 835
Alexander, T. 2005, Phys. Rep., 419, 65A
Alexander, T., & Sternberg, A. 1999, ApJ, 520, 137

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Diolaiti, E., Bendinelli, O., Bonacini, D., et al. 2000, A&AS, 147, 335
Do, T., Ghez, A. M., Morris, M. R., et al. 2009, ApJ, 703, 1323
Dolphin, A. E. 2002, MNRAS, 332, 91
Eisenhauer, F., Abuter, R., Bickert, K., et al. 2003, Proc. SPIE, 4841, 1548
Eisenhauer, F., Genzel, R., Alexander, T., et al. 2005, ApJ, 628, 246
Ferrarese, L., Côté, P., Dalla Bontà, E., et al. 2006, ApJ, 644, L21
Figer, D. F., McLean, I. S., & Morris, M. 1999, ApJ, 514, 202
Figer, D. F., Najarro, F., Gilmore, D., et al. 2002, ApJ, 581, 258
Figer, D. F., Rich, R. M., Kim, S., Morris, M., & Serabyn, E. 2004, ApJ, 601, 319
Forrest, W. J., Shure, M. A., Pipher, J. L., & Woodward, C. E. 1987, in AIP Conf. Proc. 155, The Galactic Center, ed. C. H. Townes & D. C. Backer (Melville, NY: AIP), 153
Förster Schreiber, N. 2000, AJ, 120, 2089
Freitag, M., Amaro-Seoane, P., & Kolagera, V. 2006, ApJ, 649, 91
Fritz, T. K., Gillessen, S., Dodds-Eden, K., et al. 2011, ApJ, 737, 73
Frogel, J. A., Stephens, A., Ramirez, S., & DePoy, D. L. 2001, AJ, 122, 1896
Genzel, R., Eisenhauer, F., & Gillessen, S. 2010, Rev. Mod. Phys., 82, 3211
Genzel, R., Schödel, R., Ott, T., et al. 2003, ApJ, 594, 812G
Genzel, R., Thaddeus, N., Krabbe, A., Kroker, H., & Tacconi-Garman, L. E. 1996, ApJ, 472, 153
Ghez, A. M., Salim, S., Weinberg, N. N., et al. 2008, ApJ, 689, 1044
Gillessen, S., Eisenhauer, F., Tripe, S., et al. 2009, ApJ, 692, 1075
Graham, A. W., & Spitzer, L. R. 2009, MNRAS, 397, 2148G
Groenewegen, M. A. T. 2008, A&A, 488, 935
Hartung, M., Lenzen, R., Hofmann, K., et al. 2003, Proc. SPIE, 4841, 425
Henry, T., & McCarthy, D. W. 1993, AJ, 106, 773
Hopman, C., & Alexander, T. 2006, ApJ, 645, 1152H
Kleiman, S. G., & Hall, D. B. N. 1986, ApJS, 62, 501
Kroupa, P. 2001, MNRAS, 322, 231
Lacon, A., & Mouchine, M. 2002, A&A, 393, 167L
Launhardt, R., Zylka, R., & Mezger, P. G. 2002, A&A, 384, 112
Lejeune, Th., Cuisinier, F., & Buser, R. 1997, A&A, 125, 229
Lockmann, U., Baumann, H., & Kroupa, P. 2010, MNRAS, 402, 519
Lu, J. R., Ghez, A. M., Horning, S. D., et al. 2009, ApJ, 690, 1463
Maeder, A., & Meynet, G. 2000, ARA&A, 38, 143M
Maness, H., Martins, F., Tripe, S., et al. 2007, ApJ, 669, 1024
Markwardt, C. B. 2008, in XVIII ASP Conf. Ser. 411, Astronomical Data Analysis Software and Systems, ed. D. A. Bohlender, D. Durand, & P. Dowler (San Francisco, CA: ASP), 251
Marmol-Queraltó, E., Cardiel, N., Cenarro, A. J., et al. 2008, A&A, 489, 885
Martins, F., Genzel, R., Hillier, D. J., et al. 2007, A&A, 468, 233
McLaughlin, D. E., King, A. R., & Nayakshin, S. N. 2006, ApJ, 650, L37
Merritt, D. 2010, ApJ, 718, 739
Mighell, K. J. 1999, ApJ, 518, 330
Miralda-Escudé, J., & Gould, A. 2000, ApJ, 545, 847
Nayakshin, S., & Sunyaev, R. 2005, MNRAS, 364, L23
Paumard, T., Genzel, R., Martins, F., et al. 2006, ApJ, 643, 1011
Ramírez, S. V., Sellgren, K., Carr, J. S., et al. 2000, ApJ, 537, 205
Rayner, J. T., Cushing, M. C., & Vacca, W. D. 2009, ApJS, 185, 289R
Rousset, G., Lacombe, F., Puget, P., et al. 2003, Proc. SPIE, 4839, 140
Schödel, R. 2010, A&A, 509, 55
Schödel, R., Eckart, A., Alexander, T., et al. 2007, A&A, 469, 125S
Schödel, R., Merritt, D., & Eckart, A. 2009, A&A, 502, 91
Schödel, R., Najarro, F., Muzic, K., & Eckart, A. 2010, A&A, 511, A18
Schreiber, J., Thaddeus, N., Eisenhauer, F., et al. 2004, in ASP Conf. Ser. 314, Astronomical Data Analysis Software and Systems (ADASS) XIII, ed. F. Ochsenbein, M. G. Allen, & D. Egret (San Francisco, CA: ASP), 380
Serabyn, E., & Morris, M. 1996, Nature, 382, 602
Seth, A., Agüeros, M., Lee, D., & Basu-Zych, A. 2008, ApJ, 678, 116
Seth, A., Cappellari, M., Neumayer, N., et al. 2010, ApJ, 714, 713
Sternberg, A. 1998, ApJ, 506, 721
Tripe, S., Gillessen, S., Gerhard, O. E., et al. 2008, A&A, 492, 419
Wallace, L., & Hinkle, K. 1996, ApJS, 107, 312
Wallace, L., & Hinkle, K. 1997, ApJS, 111, 445
Zoccali, M., Hill, V., Recurrence, A., et al. 2008, A&A, 486, 177

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