Spectroscopically identified intermediate age stars at 0.5–3 pc distance from Sagittarius A*[★]

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ABSTRACT

Context. Nuclear star clusters (NSCs) at the dynamical center of galaxies appear to have a complex star formation history. This suggests repeated star formation, even in the influence of the strong tidal field from supermassive black holes. Although the central region of our Galaxy is an ideal target for studies of the star formation history in the NSCs, most studies in the past have concentrated on a projected distance of $R_{\text{Sgr A}^*} \sim 0.5$ pc from the supermassive black hole Sgr A*.

Aims. In our previous study, we detected 31 so far unknown early-type star candidates throughout the Galactic NSC (at $R_{\text{Sgr A}^*} = 0.5\text{--}3$ pc). They were found via near-infrared (NIR) imaging observations with narrow-band filters which are sensitive to CO absorption lines at $\sim 2.3 \mu\text{m}$, a prominent feature for old, late-type stars. The aim of this study is to confirm the spectral type for the early-type star candidates.

Methods. We have carried out NIR spectroscopic observations of the early-type star candidates using Subaru/IRCS/AO188 and the laser guide star system. K-band spectra for 20 out of the 31 candidates and reference late-type stars were obtained. By determining an equivalent width, EW(CO), of the ^{12}CO absorption feature at $\approx 2.294 \mu\text{m}$, we have derived an effective temperature and a bolometric magnitude for each candidate and late-type star, and then constructed an HR diagram.

Results. No young ($\sim$ Myr) massive stars are included in the 20 candidates we observed; however, 13 candidates are most likely intermediate-age giants (50–500 Myr). Two other sources have ages of ~ 1 Gyr and the remaining five sources are old (> 1 Gyr), late-type giants.

Conclusions. Although none of the early-type star candidates from our previous narrow-band imaging observations can be confirmed as a young star, we find that the photometric technique can distinguish old, late-type giants from young and intermediate-age populations. From the 20 spectroscopically observed candidates, 65% of them are confirmed as being younger than 500 Myr. The intermediate-age stars could be as yet unknown members of a population formed in a starburst ~ 100 Myr ago. Finding no young ($\sim$ a few Myr) stars at $R_{\text{Sgr A}^*} = 0.5\text{--}3$ pc favors the in situ formation scenario for the presence of the young stars at $R_{\text{Sgr A}^*} < 0.5$ pc, although we do not completely exclude the possible existence of unknown young, massive stars in the region from our observations. Furthermore, the different spatial distributions of the young and the intermediate-age stars imply that the Galactic NSC is an aggregate of stars that were born in different places and under a variety of physical conditions.

Key words. Galaxy: center – stars: formation – techniques: spectroscopic

1. Introduction

Most galaxies host luminous nuclear star clusters (NSCs; e.g., Carollo et al. 1998; Côté et al. 2006; Böker 2010; Georgiev & Böker 2014). Many of these NSCs have been found to coexist with supermassive black holes (SMBHs) at the center of the host galaxies (Seth et al. 2008; Graham & Spitler 2009; Neumayer & Walcher 2012). Unlike SMBHs, it is expected that NSCs provide a visible record of gas accretion and star formation at the center of galaxies; therefore studying stellar populations in NSCs can provide clues as to how stars are formed within the strong tidal field of SMBHs.

The NSC at the center of our Galaxy is the only one that can be resolved into individual stars with current instruments, making it an ideal target for studies of stellar populations and star formation history in NSCs. A concentration of young, massive stars at the center of the Milky Way's NSC, within a projected distance of about 0.5 pc of the SMBH Sagittarius A* (Sgr A*), was identified by spectroscopic observations and traces a starburst that occurred a few Myr ago (see, e.g., Paumard et al. 2006; Bartko et al. 2009; Lu et al. 2013; Yelda et al. 2014). However, because of the strong and patchy interstellar extinction toward the Galactic NSC, broadband photometry can hardly be used to distinguish stellar populations (see, however, Schödel et al. 2010). The number of stars is too large to be surveyed with single or multi slit spectrographs. The apparent size of the NSC (half-light radius of ≈ 4.2 pc $\approx 1''.8$; Schödel et al. 2014) is too

* The reduced spectra as FITS files are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/588/A49>

Fig. 1. Spatial distribution of the early-type star candidates found in Nishiyama & Schödel (2013, blue circles and ID numbers from the mentioned work) overplotted on a $2.25\ \mu\text{m}$ narrow-band image (VLT/ISAAC). Spectra for 20 of the candidates were obtained with Subaru/IRCS (green circles). The large cyan circle delimits a region within $0.5\ \text{pc}$ ($12''.9$) in projection from Sgr A*. Spectra for five red giants were also obtained as a reference (red circles). Magenta arrows represent intermediate-age ($50\ \text{Myr}$ – $500\ \text{Myr}$) stars (see Sects. 3 and 4).

large to survey the entire region of the NSC using integral field spectrographs with a typical field of view (FoV) of several arcsec, when operating with angular resolutions on the order of $0''.1$, which is necessary in the crowded field of the Galactic center. Therefore, most of the past observations of stellar populations in the Galactic NSC have been limited to a region within a projected radius of $R_{\text{Sgr A}^*} \sim 0.5\ \text{pc}$ from Sgr A* (see, e.g., Genzel et al. 2003; Paumard et al. 2006; Maness et al. 2007; Do et al. 2009; Bartko et al. 2010; Pfuhl et al. 2011; Do et al. 2013; Lu et al. 2013).

In our previous paper (Nishiyama & Schödel 2013), we aimed at overcoming these observational limitations by using near-infrared (NIR) imaging observations with narrow-band filters. CO band head absorption features starting at $2.29\ \mu\text{m}$ can be used to distinguish between massive young stars and late-type giants (Buchholz et al. 2009). The absorption features are very

strong for late-type (K and M) stars, becoming weaker for earlier spectral type, and are absent for stars earlier than early-F type (Wallace & Hinkle 1997). So we employed two narrow-band filters, $2.34\ \mu\text{m}$ at, and $2.25\ \mu\text{m}$ just short-ward of, the CO feature, to derive a $[2.25] - [2.34]^1$ color as a proxy of stellar spectral type. In the magnitude range of $9.75 < [2.25] < 12.25$, we thus found 31 so far unknown early-type (Wolf-Rayet (WR), supergiants or early O type) star candidates at $R_{\text{Sgr A}^*} = 0.5$ – $3\ \text{pc}$ from the SMBH Sgr A* (Fig. 1).

To determine spectral types of the early-type star candidates, we carried out adaptive optics (AO) assisted spectroscopic observations using the Subaru telescope² and the infrared camera

¹ $[\lambda]$ denotes a magnitude in a narrow-band filter with the central wavelength of λ .

² Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

Fig. 2. [2.25] vs. [2.25]–[2.34] color magnitude diagram. Red color (positive value) in [2.25]–[2.34] means a weak CO absorption at $2.34\ \mu\text{m}$ which is an indicator for early spectral type stars. A sequence of stars from $([2.25] - [2.34], [2.25]) \sim (-0.2, 9)$ to $(0, 13)$ is the red giant branch (RGB). Blue $\times$ s are the early-type star candidates found in Nishiyama & Schödel (2013) and they are distributed at the red side of the RGB, indicating earlier spectral type. Most of the bright ($[2.25] \leq 11$), very red ($[2.25] - [2.34] \geq 0.1$) sources are already known early-type stars and dust-embedded sources. Light green $\times$ s represents the early-type star candidates whose spectrum is obtained in this study, and red crosses are observed red giants as a spectrum reference.

and spectrometer, IRCS. In this work, we present the results of the observations for 20 of the above mentioned 31 early-type star candidates located outside the central 0.5 pc region.

2. Observations and data reduction

The spectroscopic targets were selected from the early-type star candidates found by Nishiyama & Schödel (2013). Figure 2 shows a [2.25] vs. [2.25]–[2.34] color magnitude diagram of stars in the central $2'5 \times 2'5$ region of our Galaxy (see also Fig. 6 in Nishiyama & Schödel 2013). Red color in [2.25]–[2.34] means a weak CO absorption at $\sim 2.34\ \mu\text{m}$, and the early-type star candidates (blue $\times$ s in Fig. 2) are distributed to the right of the red giant branch (RGB) on the color magnitude diagram. Since most of the stars with very red [2.25]–[2.34] color have already been identified as early-type stars (dark green circles), Pa- α sources (purple thin crosses), or dust embedded sources (purple thick crosses), and there is no clear difference in the [2.25]–[2.34] color among the rest of the candidates, we planned our observations to obtain spectra of as many targets as possible. It means that bright stars with a smaller separation angle from Sgr A* (i.e., observable without a change of natural tip-and-tilt guide stars) have a higher priority in our observations. As a result, we observed 20 early-type star candidates (light green $\times$ s in Fig. 2), and five red giants (red crosses) as a reference. As

shown in Fig. 2, the observed sample does not have a strong bias on the [2.25]–[2.34] color, leading to no clear bias in the sample selection of the observed targets.

The spectroscopic observations were carried out during the nights of 12–13 June and 4–5 August 2012 with the Subaru telescope (Iye et al. 2004) and the infrared camera and spectrometer, IRCS (Kobayashi et al. 2000). The 20 observed stars are indicated by green circles in Fig. 1. The exposure time was 300 s for all the sources except #57 (150 s). The IRCS grism mode provides a spectral resolution of $\lambda/\Delta\lambda \approx 1900$ in the K band with a slit width of $0''.1$.

During our observations in August 2012, we used the Subaru AO system AO188 (Hayano et al. 2008, 2010) and the laser guide star system. Three natural guide stars were used to correct for tip-tilt motions: FJ95-19 (17:45:41.8, $-28:59:31.0$, $V = 15.8$) for #62, FJ95-10 (17:45:39.8, $-29:01:25.7$, $V = 15.4$) for #57 and 63, and USNO-A2.0 0600-28577051 (17:45:40.7, $-29:00:11.2$, $R = 13.7$) for the rest of our candidates. In spite of the low elevation of the candidates at Mauna Kea, the AO system delivers the FWHMs and Strehl ratios of $0''.10$ – $0''.17$ and 0.10 – 0.25 , respectively. In June, since the elevation of the observed candidates (#28, 31, 35, 36, 38, 40) were very low, we did not use the AO system.

The reduction process included flat-fielding, sky subtraction, bad pixel correction, cosmic-ray removal, wavelength calibration with an arc lamp, spectrum extraction, and relative flux calibration. Flat field images were provided by obtaining spectra of continuum sources. Interspersed with the observations, we observed a dark cloud located at a few arcmin northwest of the Galactic center to obtain sky measurements. Argon arc frames were used to fit a dispersion solution.

Telluric correction was achieved by dividing each candidate's spectrum by that of one of the early A main-sequence stars HD 126997 (A0-IV), HD 200918 (A0V), or HD 190285 (A0V), which were observed on the same night and at a similar air mass. Prior to division, the Br- γ line was removed from the standard star spectra by interpolating the stellar continua. The systematic influence of the spectral energy distribution of the A-stars was subsequently removed by multiplying with a blackbody spectrum of an appropriate effective temperature. Each spectrum was shifted to rest wavelength by using five or six of the ^{12}CO and ^{13}CO bandhead absorption features (see Fig. 3). We removed the curvature of the stellar continua by dividing the spectra by a third or fourth polynomial function that was fitted to the line-free region of the stellar spectra. The resultant K -band spectra are shown in Fig. 3.

As a control sample, we also observed five stars located on the RGB in the color-magnitude diagram (Fig. 2). The same observational settings were used as for the early-type star candidates.

3. Spectral classification

K -band spectra provide prominent features which can be used for stellar classification. For early-type stars, the Br- γ absorption line is expected; however, no spectrum of our candidates shows the Br- γ absorption. Instead, all of the spectra show clear CO bandhead absorption features, indicative of a spectral type later than $\sim G4$. So none of our 20 observed candidates is confirmed as an early-type star.

Many prominent features in the K -band, such as Na I, Ca I, and CO, have been widely used to investigate stellar parameters. In particular the absorption strength of the $^{12}\text{CO}(2-0)$ bandhead ($\approx 2.294\ \mu\text{m}$) is a good indicator of a stellar effective

Fig. 3. *K*-band spectra of the early-type star candidates (*top*) and RGB stars (*bottom*). Each star is identified above its spectrum with the ID assigned by Nishiyama & Schödel (2013) and Fig. 1. The position of the Br- γ , Na I doublet, Ca I triplet, four band heads of ^{12}CO , and two band heads of ^{13}CO are indicated by the vertical broken lines. The position and width of two narrow-band filters, 2.25 μm (NB2.25) and 2.34 μm (NB2.34), are also indicated by cyan hatched boxes. The spectra are sorted by the strength of the CO absorption feature at $\approx 2.294 \mu\text{m}$ from the top (weak) to the bottom (strong), in each panel.

temperature (T_{eff}). To measure the CO absorption depth, several index definitions have been proposed (see Mármol-Queraltó et al. 2008, and references therein); here we compute the CO index according to the recipe of Frogel et al. (2001). Pfuhl et al. (2011) used this definition to determine T_{eff} of late-type stars in the Galactic NSC, and have found a smaller systematic uncertainty than other definitions used by Blum et al. (2003) and Maness et al. (2007).

The definition by Frogel et al. (2001) uses five narrow bandpasses, four at continuum, and one at the CO bandhead, to estimate the CO absorption depth (see Table 2 in Frogel et al. 2001). In our study, the continuum level $\omega_C(\lambda)$ is determined with a

linear fit to the flux levels in the continuum bandpasses, and the equivalent width $\text{EW}(\text{CO})$ is measured according to

$$\text{EW}(\text{CO}) = \int \frac{\langle \omega_C \rangle - \omega_{\text{CO}}}{\langle \omega_C \rangle} d\lambda, \quad (1)$$

where $\langle \omega_C \rangle$ is the mean of continuum levels measured in the four bandpasses, and $\omega_{\text{CO}}(\lambda)$ is the depth of CO absorption at wavelength λ . The uncertainty of $\text{EW}(\text{CO})$, σ_{CO} , results from the uncertainty of the mean that is derived from the measurement in the four bandpasses. The resultant $\text{EW}(\text{CO})$ and σ_{CO} for the early-type star candidates are shown in Table 1. Note that σ_{CO} only includes the uncertainty in the continuum level and not any

Table 1. Observed candidates and their parameters.

ID ^a	RA ^b (J2000.0)	Dec ^b (J2000.0)	$R_{\text{Sgr A}^*}$ ^c ["]	H ^d [mag]	K_S ^d [mag]	A_K [mag]	$EW(\text{CO})$ [Å]	σ_{CO} [Å]	T_{eff} [K]	$\sigma_{T_{\text{eff}}}$ [K]	M_{bol} [mag]	$\sigma_{M_{\text{bol}}}$ [mag]
28	17:45:39.375	-29:00:37.21	12.61	13.3	11.0	2.6	8.6	0.5	4665	299	-4.1	0.4
31	17:45:39.616	-29:00:44.46	17.28	12.1	10.2	2.9	16.9	0.3	3921	142	-4.7	0.2
33	17:45:39.339	-29:00:09.22	21.00	14.0	11.8	2.9	8.9	0.2	4638	169	-3.6	0.6
34	17:45:39.475	-29:00:08.12	21.31	14.3	11.5	2.7	15.2	0.3	4105	141	-3.3	0.2
35	17:45:41.114	-29:00:49.62	25.72	13.6	10.9	3.0	16.1	0.6	4015	190	-4.1	0.6
36	17:45:42.052	-29:00:20.02	27.60	13.4	10.6	3.2	19.8	0.5	3527	150	-4.3	0.8
38	17:45:39.603	-29:00:58.80	31.23	13.7	11.7	3.3	12.2	0.6	4366	250	-3.9	0.4
39	17:45:39.880	-28:59:56.49	31.68	13.2	11.2	2.8	10.5	0.3	4503	179	-4.0	0.3
40	17:45:39.416	-29:00:58.78	31.75	13.9	10.7	3.4	23.0	0.3	2931	126	-4.0	1.0
41	17:45:41.117	-28:59:57.27	33.91	13.6	11.4	2.5	12.9	0.2	4305	141	-3.3	1.2
43	17:45:42.266	-29:00:49.47	36.19	14.0	11.4	3.1	19.2	0.2	3624	127	-3.5	0.5
45	17:45:37.436	-29:00:08.73	39.27	13.5	11.3	3.0	9.0	0.3	4634	176	-4.2	0.7
46	17:45:37.122	-29:00:38.29	39.61	13.8	11.5	3.2	12.3	0.4	4361	184	-4.0	0.5
51	17:45:37.616	-28:59:47.42	51.63	13.6	11.1	3.0	15.1	0.3	4114	139	-4.0	0.7
52	17:45:35.917	-29:00:17.02	55.21	12.7	10.7	2.5	23.5	0.3	2809	126	-3.0	0.4
54	17:45:43.872	-29:00:01.32	56.96	13.4	11.2	2.7	24.3	0.2	≤2700	—	—	—
57	17:45:37.013	-29:01:24.71	69.15	13.9	11.2	2.6	14.7	0.3	4146	143	-3.5	1.5
60	17:45:41.819	-28:59:18.38	73.52	13.4	11.0	2.8	17.5	0.3	3847	133	-3.7	1.6
62	17:45:43.062	-28:59:24.95	74.56	14.0	11.3	2.9	24.1	0.2	≤2700	—	—	—
63	17:45:35.700	-29:01:23.08	79.14	12.4	10.3	2.6	22.3	0.3	3081	125	-3.7	1.0

Notes. ^(a) ID from Table 2 in Nishiyama & Schödel (2013). ^(b) Typical positional uncertainty is 0'.1–0'.3. ^(c) Distance from Sgr A*. ^(d) From Nishiyama et al. (2006).

other systematic uncertainties from, e.g., correction of the spectral curvature. So the estimated σ_{CO} shown here are lower limits. However, the expected systematic uncertainty is only on the order of a few percent when we use the definition by Frogel et al. (2001, see also Sect. 4).

For the effective temperature calibration, we use the following $EW(\text{CO})$ – T_{eff} relation derived by Pfuhl et al. (2011):

$$T_{\text{eff}} = 5832 - 208.28 \cdot EW(\text{CO}) + 11.3 \cdot [EW(\text{CO})]^2 - 0.34 \cdot [EW(\text{CO})]^3 \text{ [K]}, \quad (2)$$

where T_{eff} is in the unit of Kelvin. Pfuhl et al. (2011) used the definition of $EW(\text{CO})$ by Frogel et al. (2001) and derived the equation above using 33 red giants with known T_{eff} , spectral type of G0 to M7, and metallicity of $-0.3 < [\text{Fe}/\text{H}] < 0.2$. This $EW(\text{CO})$ – T_{eff} relation holds in the range $3.5 < EW(\text{CO}) < 24$. Two early-type star candidates (#54 and 62) and a reference red giant (RG 46) have a larger $EW(\text{CO})$ than this range, so that we do not determine their T_{eff} . It means that they are likely to be cooler than ~ 2700 K.

To determine the amount of the interstellar extinction, we use the data sets of 1.71 μm and 2.25 μm narrow-band filters taken with VLT/ISAAC (Nishiyama & Schödel 2013). A mean [1.71]–[2.25] color of the 20 nearest stars, $\langle [1.71] - [2.25] \rangle$, was calculated at the position of each target. Assuming that the nearest stars are late-type (K – M) giants with an intrinsic color of $([1.71] - [2.25])_0 = 0.2$, the amount of the interstellar extinction A_K can be estimated with the equation $A_K \approx 1.44(\langle [1.71] - [2.25] \rangle - ([1.71] - [2.25])_0)$ (Nishiyama et al. 2006). The typical uncertainty in A_K determined by RMS of the colors of the nearest stars is 0.68 mag. We note that the intrinsic color difference of K – M giants, ± 0.1 , is small enough to be safely ignored.

To determine bolometric magnitudes, a bolometric correction BC_K is necessary. We follow the equation $BC_K = 2.6 - (T_{\text{eff}} - 3800)/1500$ from Blum et al. (2003). With BC_K and A_K , the bolometric magnitude can be calculated

as $M_{\text{bol}} = K_S - A_K - \text{DM} + BC_K$, where K_S is the observed K_S -band magnitude and DM is a distance modulus of 14.5 at the distance of 8.0 ± 0.15 kpc (Schödel et al. 2010). An uncertainty of DM of 0.04 mag is also quadratically added to the uncertainty of M_{bol} . We ignore the negligible magnitude difference between the K and K_S bands. As a result, we obtain both T_{eff} and M_{bol} , and thus the observed stars can be plotted on an HR diagram (Fig. 4).

If supergiants are included in our targets, we need to use another $EW(\text{CO})$ – T_{eff} relation for them; however, considering their rarity, and the observed magnitudes of our targets ($K_S > 10$), it is safe to assume that no supergiant is included in our targets. In addition, the resultant bolometric magnitudes M_{bol} of the early-type star candidates are fainter than -4.6 mag, even if we use the bolometric correction of $BC_K = 2.6$ (Blum et al. 2003), and intrinsic colors of supergiants for the extinction correction; almost all of the supergiants in the central 5-pc region appear to be brighter than $M_{\text{bol}} \approx -5.0$ (Blum et al. 2003).

Without a proper motion measurement, it is still difficult to remove foreground/background sources completely. A less accurate but common way to remove such sources uses the interstellar extinction. We have constructed a narrow-band ([1.71] and [2.25]) color magnitude diagram for our targets, known early-type stars and red giants, and other sources (Fig. 5). The [1.71]–[2.25] color corresponds to NIR $H - K$, and is more sensitive to the amount of the interstellar extinction than [2.25]–[2.34] used in Fig. 2. We have confirmed that the color spread of stars observed in this work is almost the same as those of known early-type stars and red giants in the NSC, suggesting that our targets are located in the NSC as well.

4. Discussion

4.1. Narrow-band photometry

The main goal of our work is a systematic search for young, massive stars throughout the Galactic NSC. To find candidates

Table 2. Parameters for reference red giants.

ID ^a	RA ^b (J2000.0)	Dec ^b (J2000.0)	H ^c [mag]	K _s ^c [mag]	A _K [mag]	EW(CO) [Å]	σ _{CO} [Å]	T _{eff} [K]	σ _{T_{eff}} [K]	M _{bol} [mag]	σ _{M_{bol}} [mag]
RG35	17:45:41.273	-29:00:49.73	12.7	9.9	3.2	23.2	0.3	2889	127	-4.6	0.8
RG39	17:45:40.389	-29:00:01.41	—	12.4	3.2	23.3	0.4	2851	127	-2.1	0.6
RG43	17:45:42.117	-29:00:49.58	13.9	11.2	3.4	23.8	0.5	2749	130	-3.4	0.5
RG46	17:45:36.488	-29:00:38.14	14.0	11.2	3.2	27.8	0.4	≤2700	—	—	—
RG54	17:45:43.721	-29:00:01.17	13.5	11.1	3.0	23.6	0.2	2790	122	-3.1	0.8

Notes. ^(a) See Fig. 1. ^(b) Typical positional uncertainty is 0'.1–0'.3. ^(c) From Nishiyama et al. (2006).

Fig. 4. HR diagram for the early-type star candidates (green circles) and red giants as a reference (red circles). Overplotted are theoretical isochrones for ages of (from left to right) 50 Myr, 100 Myr, 500 Myr, 1 Gyr, 5 Gyr, and 10 Gyr with solar metallicity using the Padova code (Girardi et al. 2000; Marigo et al. 2008).

of these young, massive stars in this region, we carried out NIR imaging observations using two narrow-band filters, 2.25 μm and 2.34 μm , with filter widths of $\approx 0.03 \mu\text{m}$ (Nishiyama & Schödel 2013). As shown in Fig. 3, the 2.34 μm filter is sensitive to the CO band head absorption at $\approx 2.29 \mu\text{m}$, a typical feature seen in late-type stars; on the other hand, the 2.25 μm filter is just shortward of the CO absorption. When we measure magnitudes of stars in the two filters, [2.25] and [2.34], a redder color in [2.25]–[2.34] means less CO absorption at 2.34 μm , indicating earlier spectral type. Hence the [2.25]–[2.34] color index can be used as a proxy for EW(CO).

Unfortunately, we found strong, systematic [2.25]–[2.34] color trends along the x - and y -axes in the ISAAC FoV (Fig. 4 in Nishiyama & Schödel 2013), making absolute calibrations of [2.25] and [2.34] impossible. To use the [2.25]–[2.34] color to search for early-type stars, we carried out a color correction in the assumption that the average of the intrinsic stellar colors is the same throughout the observed FoV. This assumption is appropriate for our observed field because of the similar intrinsic colors of almost all stellar types around the K band, the dominance of late-type giants in this region, and the restricted

Fig. 5. [2.25] vs. [1.71]–[2.25] color magnitude diagram for sources measured in Nishiyama & Schödel (2013). The observed early-type star candidates in this work are overplotted by light green $\times$ s. Dark green circles and red triangles represent spectroscopically identified early-type stars and late-type giants in the Galactic NSC, respectively.

wavelength range of our observations. Hence what we use to identify the early-type star candidates is a *relative* [2.25]–[2.34] color to the dominant late-type giants (RGB stars), and the color is calibrated to have [2.25]–[2.34] = 0 for the RGB stars. Then we defined stars more than 2σ redder than the RGB as early-type star candidates.

Genuine early-type stars are expected to have a redder [2.25]–[2.34] color than late-type giants on the RGB, and an almost negligible EW(CO). Fig. 6 shows a plot of the EW(CO) of the observed stars versus their [2.25]–[2.34] color (as given by Nishiyama & Schödel 2013). The latter was adjusted such that the mean color of the RGB stars is 0, as described in the previous paragraph. As shown by green circles in Fig. 6, all of our early-type star candidates have a color of [2.25]–[2.34] $\gtrsim 0.1$, and most of them have EW(CO) of $\lesssim 20$. This agrees well with the fact that most of the early-type star candidates have a smaller EW(CO) than the RGB stars. Contrary to our expectations, however, we do not observe any clear trend of the [2.25]–[2.34] color as a function of EW(CO). This is probably due to relatively large

Fig. 6. Relation between stellar $[2.25]–[2.34]$ color relative to the RGB mean color and $EW(CO)$ for the early-type star candidates (green circles) and late-type giants as a reference (red circles). In the relative $[2.25]–[2.34]$ color, the RGB stars and early-type stars are expected to have a color of $[2.25]–[2.34] \approx 0$ and $[2.25]–[2.34] > 0$, respectively. The right-hand side axis shows the corresponding T_{eff} derived by Eq. (2). The blue arrows represent spectral type in the case of giants (according to the Table 2 in Meyer et al. 1998). The horizontal dashed line represents the upper limit of $EW(CO)$ to determine T_{eff} with Eq. (2).

uncertainties of, and a narrow range in, the $[2.25]–[2.34]$ colors for the early-type star candidates.

4.2. Results of spectroscopic follow-up observations

To further investigate the nature of our target stars, we compared their position in the HR diagram (Fig. 4) with the theoretical isochrones for solar metallicity (Girardi et al. 2000; Marigo et al. 2008). Some of our candidates are likely to be old (age ≥ 5 Gyr) late-type giants; on the other hand, most (13 out of 20) of them are located to the left of the 500-Myr isochrone. They are thus likely to be young giants with a mass in the range $2.5 M_{\odot} < M < 6 M_{\odot}$ and are descendants of main-sequence B-type stars. No young ($\sim \text{Myr}$) massive star is included in the 20 candidates we observed.

The data points in the HR diagram might have a systematic uncertainty. One of the candidates and three of the reference red giants are located clearly to the right and below the oldest theoretical isochrone, taking into consideration the uncertainties shown in the plot. Pfuhl et al. (2011) investigated systematic uncertainties in $EW(CO)$ and T_{eff} due to the differences of a spectral resolution and an amount of the interstellar extinction. They found no measurable impact in the $EW(CO)$ index by Frogel et al. (2001) owing to degrading the resolution from $R \sim 3000$ to 2000, and the resolution in our observations is $R \sim 1900$. Moreover, the Frogel et al. (2001) index is decreased by only less than a few percent due to the uncertainty in the extinction correction applied to the stars studied here, which leads to the combined systematic uncertainty of less than 50 K in T_{eff} .

Our source #33 was observed and its stellar parameters were determined by Maness et al. (2007, source ID 300). Although they use a different definition for $EW(CO)$ and $EW(CO)–T_{\text{eff}}$

Fig. 7. HR diagram (same as Fig. 4) overplotted with theoretical isochrones for ages of (from left to right) 50 Myr, 100 Myr, 500 Myr, 1 Gyr, 5 Gyr, and 10 Gyr with $Z = 0.3 Z_{\odot}$ (blue lines), $Z = Z_{\odot}$ (black dotted lines), and $Z = 3 Z_{\odot}$ (magenta lines), using the PARSEC isochrones (Bressan et al. 2012). The PARSEC isochrones do not include the tip of the AGB, but it can be used to compare isochrones for different metallicities.

relation, their resultant T_{eff} and M_{bol} are 4529 K and -3.58 , respectively; both of them are in very good agreement with ours, $T_{\text{eff}} = 4638 \pm 169$ K and $M_{\text{bol}} = -3.6 \pm 0.2$. This suggests no strong systematic offset in our determination of T_{eff} and M_{bol} and that we have successfully found an intermediate-age population in the Galactic NSC. In any case, we do not think that the possible systematic uncertainties, present in our HR diagram, affect its main features; we can clearly distinguish two populations: an older, cooler one and a younger, hotter one.

Pfuhl et al. (2011) found a significant population of outliers which are distributed to the right and below the oldest isochrone for solar metallicity. They ascribed the presence of the outliers to possible effects such as dust envelopes, variability, high metallicity, or uncertainty in stellar evolutionary models.

Several outliers, distributed to the right and below the 10-Gyr isochrone, are also found in our HR diagram (Fig. 4). We have made a conservative estimate of the uncertainties in A_K (Sect. 3), leading to a typical $\sigma_{M_{\text{bol}}}$ of 0.7 mag. Figure 5 clearly demonstrates that the candidates must be located very close to the Galactic center; even if they are located at 1 kpc from the Galactic center, M_{bol} would change only 0.3 mag, and they are thus still outliers.

The outliers can be potentially explained by their super-solar metallicity. In Fig. 7, we have constructed an HR diagram with isochrones of different metallicities. Here the PARSEC isochrones (Bressan et al. 2012) with $Z = 0.3 Z_{\odot}$ (blue lines), $Z_{\odot}$ (black dotted lines), and $3 Z_{\odot}$ (magenta lines) are used. The diagram implies that most of the outliers are very old (~ 10 Gyr) population with $Z \gtrsim 3 Z_{\odot}$, and this has already been pointed out by Pfuhl et al. (2011). Observational constraints of the metallicity of the outliers are crucial for understanding their true nature.

Stars in dense stellar cusps around SMBHs suffer much more close tidal encounters than in normal environments, and

tidal spin-up of stars is expected in the Galactic center region (Alexander & Kumar 2001). The rotation of stars has an impact on the stellar evolution, and isochrones from Ekström et al. (2012) are thus used to understand the effect of the rotation. When the stellar rotation is considered, isochrones are shifted towards a higher luminosity. This cannot explain the existence of the outliers distributed to the right and below the oldest isochrone in Fig. 4.

In the previous paper, we concluded that we found strong candidates for early-type stars (Nishiyama & Schödel 2013). However, as shown in Figs. 3 and 4, no young, massive star is included in our observed candidates; instead, most of these candidates are an intermediate-age (50 Myr–500 Myr) population. We note that precision-photometry in our previous study was limited to the magnitude range of $9.75 < [2.25] < 12.25$. Only WR stars, supergiants, and early O-type stars are distributed in this range as early-type stars, and their expected number is rather small. B-type stars, which may be more frequent, have magnitudes around $K \sim 14$ –16 in the Galactic center. They could not have been found in our seeing-limited ISAAC observations, where the extreme crowding in the NSC severely limits completeness and photometric precision.

In our previous paper, we showed an azimuthally averaged, projected stellar surface density plot as a function of the distance to Sgr A* for the early-type star candidates (Fig. 11 in Nishiyama & Schödel 2013). This shows a continuous profile in the range from $1''.5$ to $60''$ with a power-law index of 1.60. However, again, no young, massive star is included in our observed candidates. It means that the profile we made in the previous paper is not for the early-type, young, and massive stars but for stars younger than ~ 500 Myr. Our results also indicate a lack of young, massive stars outside the central 0.5 pc region from Sgr A*; recently, Støstad et al. (2015) have found a break in the surface density profile of young stars (~ 5 Myr) at 0.52 pc ($\sim 13''$) from Sgr A*. This is consistent with the non-detection of genuine young, massive stars in our spectroscopic follow-up observations.

Although we have not found new young, massive (WR, supergiant, or early O-type) stars, it does not mean that there are no unknown young stars in the $R_{\text{Sgr A}^*} = 0.5$ –3 pc region. As shown in Fig. 2, we misidentified a few, already known early-type stars as RGB stars. In addition, we have not completed spectroscopic observations for the early-type star candidates we have found in the previous work. Therefore we do *not* exclude the possibility of the existence of unknown early-type stars at 0.5–3 pc from the SMBH.

The detection of the intermediate-age population shows that although the technique to measure the CO absorption depth with narrow-band filters cannot distinguish between young and intermediate-age stars, it works well to distinguish them from old, late-type giants. In our previous paper, we have estimated that the contamination rate of the early-type candidates by erroneous identification of late-type giants is about 20% (Nishiyama & Schödel 2013). As shown in Fig. 6, 15 out of the 20 candidates show $T_{\text{eff}} > 3500$ K, and they are clearly hotter than the late-type giants with $T_{\text{eff}} \lesssim 3000$ K, which leads to a contamination rate of 25%. However, we note that we cannot distinguish the young ($\sim$ Myr), massive stars from the intermediate-age (< 500 Myr) stars in our imaging observations. As shown in Fig. 2, no clear difference is seen in the distributions of the spectroscopically confirmed massive, early-type stars and the intermediate-age population. Hence spectroscopic follow-up observation is necessary to discriminate genuine young, massive

Fig. 8. HR diagram (same as Fig. 4) but stars observed by Blum et al. (2003) and Maness et al. (2007) are also plotted with black and blue circles, respectively. Overplotted are theoretical isochrones for ages (from left to right) 50 Myr, 100 Myr, 500 Myr, 1 Gyr, 5 Gyr, and 10 Gyr with solar metallicity using the Padova code (Girardi et al. 2000; Marigo et al. 2008).

stars from the sample selected by our imaging observations with two narrow-band filters.

We present an HR diagram including results of previous works (Blum et al. 2003; Maness et al. 2007) in Fig. 8. Since the observations by Maness et al. (2007) were assisted by AO, their 50% completeness limit is as deep as $K_S \sim 15.5$, about 4-mag deeper than the faintest star we measured here, but were limited to eight relatively small fields ($4''.2 \times 4''.2$ or 0.16×0.16 pc) within a projected distance of 1 pc from Sgr A*. On the other hand, the completeness of Blum et al. (2003), a magnitude-limited survey that encompassed the entire region of our ISAAC survey with a 4-m class telescope, appears to be slightly shallower than ours. This can probably be attributed to the excellent seeing during our ISAAC observations. Our findings also indicate that observations with higher angular resolutions, e.g., with AO, will allow us to reach a deeper limiting magnitude and search for late O and B-type stars via narrow-band imaging.

4.3. Implications for star formation at the Galactic center

Finding no WR, early O main-sequence and O supergiant stars at the $R_{\text{Sgr A}^*} = 0.5$ –3 pc region disfavors the cluster infalling scenario for the presence of young stars in the central 0.5 pc region (e.g., Gerhard 2001; Kim & Morris 2003). This scenario proposed the formation of a massive cluster at more than several parsec distance from Sgr A*, where the tidal field from the SMBH is weak enough to form stars, followed by an infall of the cluster toward the central parsec. Since the star cluster migrates to the center via dynamical friction, a presence of some very massive stars at $R_{\text{Sgr A}^*} > 0.5$ pc, which escaped from the cluster, is expected (e.g., Fujii et al. 2010), but no such stars have

been found in our observations and only two young, massive star candidates have been found in the recent HST Pa α survey (#38 and #133 in the list of Dong et al. 2011, but #38 is likely to be a foreground O4-6I star (Mauerhan et al. 2010, star #7)). Considering the sensitivity for the Pa α emission (from evolved massive stars with strong wind) of the HST survey, and the sensitivity for the CO absorption in our observations, the results described above provide further evidence to support the in situ formation scenario.

However, we emphasize that we cannot exclude the cluster infall scenario in general. A migration of stellar clusters to the center is a natural consequence if clusters are formed in the Galactic center region. Massive stars tend to be carried very close to the center after migration, because massive stars sink to the cluster center due to the mass segregation, and stars at the outer region of the cluster become unbound easily (Fujii et al. 2010). The lifetime of the intermediate-age population stars we found, i.e., more than 50 Myr, is long enough for clusters to migrate from a few tens parsec distance to the central few parsec region (e.g., Gürkan & Rasio 2005). Hence the intermediate-age population we found may be due to either in situ formation or cluster infall. In the latter case, measuring the kinematics of the intermediate-age stars may give some clue as to their origin, given that the two-body relaxation time at their location is expected to be at least an order of magnitude longer than their lifetimes (Alexander 2005).

A large part of our intermediate-age population might have been formed in a starburst about 100 Myr ago. From the detection of a fairly large number (~ 10) of moderately luminous late-type stars, a starburst of 100 Myr ago was suggested within a projected distance of 0.5 pc from Sgr A* (Krabbe et al. 1995). Further spectroscopic observations confirmed the presence of such stars inside (Maness et al. 2007) and outside (Blum et al. 2003) the central 0.5 pc region. The best-fit model for the star formation history of the Galactic NSC by Pfuhl et al. (2011, their Fig. 14) suggests that the star formation rate reached a minimum ~ 1 Gyr ago and then rose again ~ 100 Myr ago. Hence the intermediate-age stars discovered by us may represent as yet unknown members of the population that formed ~ 100 Myr ago.

The different spatial distribution between the young (a few Myr) and intermediate-age population stars is intriguing. Most of the young stars are concentrated in the central 0.5 pc region (e.g., Eckart et al. 1995; Genzel et al. 2000; Paumard et al. 2006; Do et al. 2013), while the intermediate-age stars are distributed throughout the NSC (Haller & Rieke 1989; Blum et al. 1996, 2003). Our observations further confirm the widespread distribution of the intermediate-age stars compared to the young massive stars. It is unlikely that the widespread distribution results from dynamical scattering of stars formed in the central 0.5 pc because the intermediate-age stars are relatively heavy ($M \gtrsim 2.5 M_{\odot}$). The two-body relaxation and mass segregation timescales in the NSC are on the order of 10^9 yr (Alexander 2005), i.e., we can expect the kinematics and distribution of the intermediate-age stars to still bear the fingerprint of their origin. With regard to the origin of these young stars, it is not difficult for star clusters to reach the central few parsec region from a few tens parsec distance within ~ 100 Myr via dynamical friction. Alternatively, the stars might have been formed in the circumnuclear disk (Yusef-Zadeh et al. 2008). In any case, our results imply several paths of the star formation in the Galactic NSC, i.e., stars in the NSC have been formed in different places and under a variety of physical conditions.

5. Summary

We have carried out spectroscopic observations of 20 out of 31 early-type star candidates in the NSC at the center of our Galaxy, which were identified in the imaging survey by Nishiyama & Schödel (2013). We have found that 65% of the candidates probably belong to an intermediate-age (50–500 Myr) population and that the rest of them are late-type giants older than ~ 1 Gyr. The intermediate-age population stars are likely to have formed in a starburst about 100 Myr ago. None of the stars is as young as the few million year old stars within a projected radius of $R_{\text{Sgr A}^*} = 0.5$ pc of Sgr A*. We can thus conclude that the most recent star formation episode in the NSC was confined to the immediate environment of Sgr A*, at least as far as the most massive stars are concerned. Thus, our findings also support the in situ formation of the O/WR stars near Sgr A* and speak against the cluster-infall scenario. In the latter case, we would have expected to observe at least a few O/WR stars in the region beyond $R_{\text{Sgr A}^*} = 0.5$ pc. We show that narrow-band imaging observations can be an efficient means to distinguish younger (< 500 Myr) stars from very old giants; however, our results also suggest that the kind of seeing-limited photometry with only two filters that we used in our previous work is not sufficient to discriminate young (< 10 Myr), massive stars from the intermediate-age (10–500 Myr) ones. Spectroscopic follow-up observations still play an important role in the separation. The clearly different distribution of the young and intermediate-age stars in the Milky Way's NSC may indicate different formation scenarios for the two populations.

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