The two young star disks in the central parsec of the Galaxy: properties, dynamics, and formation

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Abstract. We report the definite spectroscopic identification of $\approx 40$ OB supergiants, giants and main sequence stars in the central parsec of the Galaxy. Detection of their absorption lines have become possible with the high spatial and spectral resolution and sensitivity of the adaptive optics integral field spectrometer SPIFFI/SINFONI on the ESO VLT. Several of these OB stars appear to be helium and nitrogen rich. Almost all of the $\approx 80$ massive stars now known in the central parsec (central arcsecond excluded) reside in one of two somewhat thick ($\langle |h|/R \rangle \approx 0.14$) rotating disks. These stellar disks have fairly sharp inner edges ($R \approx 1''$) and surface density profiles that scale as $R^{-2}$. We do not detect any OB stars outside the central $0.5 \text{ pc}$. The majority of the stars in the clockwise system appear to be on almost circular orbits, whereas most of those in the ‘counter-clockwise’ disk appear to be on eccentric orbits. Based on its stellar surface density distribution and dynamics we propose that IRS 13E is an extremely dense cluster ($\rho_{\text{core}} \gtrsim 3 \times 10^8 M_{\odot} \text{ pc}^{-3}$), which has formed in the counter-clockwise disk. The stellar contents of both systems are remarkably similar, indicating a common age of $\approx 6 \pm 2 \text{ Myr}$. The K-band luminosity function of the massive stars suggests a top-heavy mass function and limits the total stellar mass contained in both disks to $\lesssim 1.5 \times 10^4 M_{\odot}$. Our data strongly favor in situ star formation from dense gas accretion disks for the two stellar disks. This conclusion is very clear for the clockwise disk and highly plausible for the counter-clockwise system.
1. Introduction

The Galactic Center (GC) is a unique laboratory for studying galactic nuclei. Given its proximity (~8 kpc), processes in the GC can be investigated at resolutions and detail that are not accessible in any other galactic nucleus. The GC has many features that are thought to occur in other nuclei (for reviews, see [1–4]). It contains the densest star cluster in the Milky Way intermixed with a bright H II region (Sgr A West or the ‘mini-spiral’) and hot gas radiating at X-rays. These central components are surrounded by a ~1.5 pc ring/torus of dense molecular gas (the ‘circum-nuclear disk’, CND). At the very center lies a very compact radio source, Sgr A*.

The short orbital period of stars (in particular the B star S2) in the central arcsecond around Sgr A* show that the radio source is a 3–4 × 10⁶M⊙ black hole (BH) beyond any reasonable doubt [5, 6]. The larger Galactic Center region contains three remarkably rich clusters of young, high mass stars: the Quintuplet, the Arches, as well as the parsec-scale cluster around Sgr A* itself [7].

Beyond the scope of pure Galactic Center research, the Galactic Center early-type star cluster gives the opportunity to study the wider interest questions of massive star formation at large as well as starburst galaxies. Of course, this cluster is a signature of mass deposition in the central parsec, and is therefore to be put in the context of fueling and growth of supermassive black holes.

The presence of many high-mass, short-lived stars, in the central parsec shows that massive star formation has occurred at or near the Galactic Center within the last few million years. This is surprising. All obvious routes to creating or bringing massive young stars in(to) the central region face major obstacles. In situ star formation, transport of stars from far out, scattering of stars on highly elliptical orbits and rejuvenation of old stars due to stellar collisions and tidal stripping have all been proposed and considered (for a recent review of the rapidly growing body of literature see [4]). No explanation at this point is the obvious winner (or loser). Perhaps the two most prominent and promising scenarios for explaining the young massive stars outside the central cusp, at radii of 3–10″ from Sgr A*, are

(i) the ‘in situ, accretion disk’ scenario [8–12]. Here the proposal is that stars have formed near where they are found today, very close to the central black hole. However, in situ star formation is impeded by the tidal shear from the central black hole and surrounding dense star cluster. To overcome this shear, gas clouds have to be much denser (~10¹²R⁻³ cm⁻³) than currently observed [13]. The tidal shear can be overcome if the mass accretion was large enough at some point in the past – perhaps as the consequence of the in-fall and cooling of a large interstellar cloud – such that a gravitationally unstable (outside of a critical radius) disk was formed. The stars were formed directly out of the fragmenting disk;

(ii) the ‘in-spiraling star cluster’ scenario [14–19]. Here the idea is that young stars were originally formed outside the hostile central parsec and only transported there later on. Individual transport of stars by two body relaxation and mass segregation from further out takes too long a time (~10⁷–10⁹ years, [4]). Stars in a bound, massive cluster can sink in much more rapidly owing to dynamical friction [14]. To sink from an initial radius of a few parsec or more to a final radius of ≲1 pc within an O star lifetime (a few Myr) requires a cluster mass > 10⁵M⊙. To prevent the final tidal disruption of such a cluster at too large a radius – resulting in the deposition of its stars there – the core of the original star cluster also has to be much denser (> 10⁷M⊙ pc⁻³) and more compact (<1 pc) than any known cluster. However, as a helpful by-product, dynamical processes in such a hypothetical super-dense star cluster may then lead to the formation of a central, intermediate mass black hole (IMBH; [20, 21]). Such a black hole may help to stabilize the cluster core against tidal disruption and lessen the high density requirement somewhat [22].
In the following, we present the data and results we obtained using SINFONI concerning the parsec-scale early-type star cluster around Sgr A*. These results are presented in greater depth in [23]

2. Observations and data analysis

2.1. Observations

SPIFFI [24, 25] is a near-infrared integral field spectrometer providing a 2048 pixel spectrum simultaneously for a contiguous, 64 × 32-pixel field. Its salient features include a reflective image slicer and a grating spectrometer with an overall detective throughput (including pre-optics module and telescope) of ≥ 30%. Its 2048^2-pixel Hawaii II detector covers the J, H and K (1.1 to 2.45 μm) atmospheric bands. In its 2003 version with a smaller 1024^2-pixel detector the spectrometer provided 1024 spectra for a 32^2-pixel field. Spectral resolving powers range from $R = 1000$ to 4000. Three pixel scales (12.5 × 25 square milli-arcseconds (mas), 50 × 100 mas^2 and 125 × 250 mas^2) can be chosen on the fly. In the SINFONI ESO VLT facility, SPIFFI is mated with the MACAO adaptive optics module [26] employing a 60-element wave-front-curvature sensor with avalanche photodiodes. This mode makes it possible to perform spectroscopy at the smallest (diffraction limited) pixel scale.

We have covered a square field of > 2 pc × 2 pc centered on Sgr A* at low spatial resolution as well as various subfields at intermediate or high resolution. We looked for early-type stars by visually inspecting the cubes and line maps around features typical of early-type stars. The main signatures we looked for are essentially lines from Hydrogen (Brγ) and He I. The intrinsically most prominent of these lines (Brγ and He I 2.058 μm) are unfortunately present in the emission from the interstellar medium, which make them hard to use, in particular at lower spatial resolution. There remains however one fairly deep absorption feature in the K-band spectra of OB stars that is not present in the ISM: a compound of 4 He I lines and three N III lines at 2.113 μm. The spectra of the OB candidates so identified were then extracted with the interstellar emission removed by subtracting an off-source spectrum (generally from a ring around each source).

3. Results

3.1. OB stars are finally detected

Our observations have led to the firm detection of 29 OB supergiants, as well as 12 OB stars of luminosity class III and V. In addition we have 18 OB candidates whose identifications we regard as tentative. Those additional stars need to be confirmed. All these detections refer to the region outside the central cusp, with projected radius $p_{SgrA*} ≥ 0.8''$. Our group has already reported 70 mas resolution SINFONI observations of this central cusp [27], with the detection of more than a dozen main sequence B stars, in addition to the late O9/B0 main sequence star S2 (S02) detected earlier by [6].

We also identify 30 post main-sequence blue supergiants and Wolf-Rayet stars, adding several stars to the sample already known from previous work [9, 28–30]. Of these, we classify 17 as Ofpe/WN9 and late nitrogen rich WRs (WNL=WN7–9) stars, and 12 as carbon rich WRs (WC) stars. There is one early WN (WNE, WN5/6) star, IRS 16SE2. The Northern Arm bow-shock star IRS 1W, with Brγ in emission and He I λ 2.058 μm in absorption as only features, is perhaps a Be star (see [31] for spectrum and detailed discussion). There is also one additional tentative WC candidate (IRS 7SE2).

More than 100 early-type stars have now been detected in the nuclear star cluster, and this number is expected to grow in the next years. The 90 sure detections are presented on Fig. 1.
3.2. Dynamics
We know the proper motion of most of these stars from our NACO astrometry monitoring program. It is interesting to look at $j$, the projected angular momentum of each star with respect to Sgr A* (Fig 2). It appears that the early-type stars have typically higher $|j|$ values than late type stars, meaning that they are preferentially on more circular orbits. In that we confirm [9]. This previous work as well as others also claim that the early-type stars belong in one or two stellar disks. To check whether our new data confirm this finding, we introduce a new method for finding disk patterns in kinematic data.

Assume that a set of stars with velocities

$$\vec{v}_k = (v_{x,k}, v_{y,k}, v_{z,k}) = ||\vec{v}_k|| (\sin \theta_k \cos \varphi_k, \sin \theta_k \sin \varphi_k, \cos \theta_k)$$

all live in a disk with normal vector

$$\vec{n} = (\sin i \cos \Omega, -\sin i \sin \Omega, -\cos i) .$$

Then for each $k$,

$$0 \quad = \quad \vec{n} \cdot \vec{v}_k$$

$$= \quad \sin i \cos \Omega \sin \theta_k \cos \varphi_k - \sin i \sin \Omega \sin \theta_k \sin \varphi_k - \cos i \cos \theta_k$$

$$\sin i \sin \theta_k \cos(\Omega + \varphi_k) \quad = \quad \cos i \cos \theta_k$$

$$\cotan \theta_k \quad = \quad \tan i \cos(\Omega + \varphi_k) .$$
Therefore, if a given set of stars really constitutes a disk, then the \( \theta \) vs. \( \varphi \) plane must show a telltale cosine pattern. This plane is shown on Fig. 3 for the early-type stars with \( j \simeq +1 \) (hereafter the \textit{clockwise system} [CWS]) as well as for the early-type stars with \( j \simeq -1 \) (hereafter the \textit{counter-clockwise system} [CCWS]). Apart from a few stars with large error bars, the two diagrams exhibit a clear cosine pattern. We therefore conclude that the Galactic Center early-type stars indeed belong in two well defined disks. It is interesting to note that these two disks are at large angle from each other and from the Galactic plane, and that the orbital planes of the S stars as determined by [27] seem to be randomly distributed.

![Figure 3](image3.png)

\textbf{Figure 3.} A cosine pattern is very clear in the \( \cotan \theta \) vs. \( \varphi \) diagram of both the CWS (left) and the CCWS (right). This shows that each system constitutes a disk (see text).
3.3. Physical properties

The two disk systems contain similar fractions of the various subtypes of early-type stars, which is indicative of a common age, within $\simeq 1$ Myr. Both the Hertzsprung–Russel diagram and population synthesis show that the two systems were born $6 \pm 2$ Myr ago.

They also have a very similar stellar density profile with $\Sigma \propto R^{-2}$ down to an inner radius of $\simeq 1''$ for the CWS and $\simeq 2-4''$ for the CCWS. Outside these inner edges, the two profiles are essentially identical not only in slope but also in absolute value. Inside the innermost edge ($1''$) is located the S star cluster, which does not show any preferential orbital plane as already stated above.

Between $1''$ and $4''$ there is a fourth group of early-type stars that shows up on the $j$ vs. $R$ diagram (Fig. 2) as a diagonal feature (DF) running approximately from $(R = 1, j = 0.8)$ to $(R = 4, j = -0.8)$. At this point, we have no satisfying interpretation for these stars. The “diagonal feature” itself may be an artifact made of randomly distributed stars. During the conference, Jessica Lu has shown Keck data for the inner few arcseconds with which she claimed to demonstrate that the CCWS did not exist (these proceedings). It is important to note that this claim is based on data covering only the inner $4''$ radius, and that therefore these observations do not cover the bulk of the CCWS stars, but mostly the DF group.

For the first time we have developed a method for determining the eccentricity distribution in each disk. Contrary to the other physical properties discussed above, which are similar in the two disks, the eccentricities are not (Fig. 4). Eccentricities in the CWS are fairly small. The distribution peaks at $e \simeq 0.2$ (although it extends up to fairly high eccentricities). On the contrary, the CCWS is dominated by a high eccentricity ($e \simeq 0.8$) population.

![Figure 4. Eccentricity distribution in the CWS (left) and the CCWS (right). The lines represent the true distributions; the filled histograms are Monte-Carlo simulations showing what our method would give if all stars were on circular orbits, and are representative of the typical error on $e$.](image)

4. IRS 13E: the cluster within

[32] have attracted a lot of attention by showing that the “Helium star” IRS 13E was indeed
a group of at least seven stars, three of which shared a common velocity. They have suggested that an intermediate mass black hole (IMBH) might be necessary to tie this group together. They believed this group was a strong argument in favor of the inspiraling star cluster scenario. On the other hand, [33] have claimed that this group could not be a stable cluster.

In order to assess whether the object was a significant overdensity rather than a chance alignment, we have analyzed a very deep H-band image of the region surrounding IRS 13E (Fig. 5). We find several dozen faint stars in the group. Using careful statistical arguments, we reject by more than 3σ the possibility of a chance alignment. For this reason we believe this cluster has to be somewhat stable, or it would be very unlikely to observe it. However, with the observations at hand, a conservative lower limit for the total cluster mass is only \( \sim 10^3 M_\odot \). The mass in detected stars amounts to roughly half of that, and is only a lower limit to the total stellar mass. We must conclude that, at this point, the case for an IMBH is not strong. More proper motion or radial velocity measurements for individual stars in the cluster are warranted to bring better constraints on the total mass of the group. It is important to note that this cluster seems to belong in the CCWS.

Figure 5. Very deep H-band image of the IRS 13E complex. The arrows and small numbers close to 4 stars give their proper motion and radial velocities. The numbers inside and outside the 0.68\,″ circle give the surface density in these two areas at a limiting magnitude \( m_H = 20.4 \) (19.4).

A very interesting side-result of this study is the determination of a lower limit to the core density of IRS 13E: \( 3 \times 10^8 M_\odot \, \text{pc}^{-3} \). To our knowledge, this is one of the highest cluster core densities known to date, second only to the cusp around Sgr A* itself. Such a high density makes direct star–star collisions likely, which may favor the runaway birth of an IMBH.

5. Summary
From the radial density profile, the mass function and stellar counts, we can safely infer that the total mass contained in each disk \( M_\star < 10^4 M_\odot \). This is one or two orders smaller than the mass required by inspiraling cluster scenarios. For this reason, we strongly feel that our new data finally rule them out. On the other hand, the facts we uncovered, in particular the density profile and inner radii, are well explained by in situ star formation inside a massive accretion disk.

This scenario has two major apparent difficulties, which are quite possible to overcome:

(i) the presence of a massive core (IRS 13E) and high eccentricities in the CCWS: these two properties seem explainable in the context of rapid star formation in a “dispersion ring” rather than a fully circularized accretion disk (note that the timescale for star formation is roughly the same as that needed for circularization);
the presence of two co-eval disks at large angle: the timespan of $\approx 1$ Myr allowed between the two events is sufficient for star formation to remove all gas from the first disk and for a second one to form. The infall of two massive molecular clouds within such a short timescale might be perceived as unlikely. However, they may have been triggered by a single event, such as an interaction with another galaxy.

Finally, we have doubled the number of early-type stars known in the GC, and proved that they are concentrated in two well defined disks. The two systems have probably been born in situ, from massive gaseous accretion disks. However, this explanation fails so far to produce the S star cluster in the innermost arcsecond, for which the “paradox of youth” remains.

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