Star formation in the central 0.5 pc of the Milky Way

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Abstract. The supermassive black hole candidate at the Galactic Center is surrounded by a parsec-scale star cluster, which contains a number of early type stars. The presence of such stars has been called a “paradox of youth” as star formation in the immediate vicinity of a supermassive black hole seemed difficult, as well as the transport of stars from far out in a massive-star lifetime. I will recall 30 years of technological developments which led to the current understanding of the nuclear cluster stellar population. The number of early type stars known at present is sufficient to access the 3D structure of this population and its dynamics, which in turn allows discriminating between the various possible origins proposed along the years.

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 Minispiral) 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 × 10^6 M☉ black hole (BH) beyond any reasonable doubt [5; 6]. The larger GC 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.

I will first review the historical road leading to the discovery of the nuclear cluster, which is paved with technological advances in the fields of infrared high-resolution imaging and spectroscopy. Having exposed the facts that are currently known about the nuclear cluster, I will present the pending questions and the debate currently taking place on the formation scenario for this cluster.

2. History of Galactic Center Infrared Observations
2.1. The discovery of the massive star population
In the early ’70s, infrared instruments where limited to single-pixel detectors. Two maps of the region, at 2.2 and 10 μm, were published in 1975 [7]. Those maps were obtained by scanning the region with an InSb detector and a 2.5” circular aperture, which represented a two-fold improvement over previous work (e.g. [8]). These maps showed that the infrared emission in
the central parsec was concentrated in a few compact sources. Those sources where numbered and referred to as, e.g., “source 7”. This denomination later evolved into “infrared source 7”, or “IRS 7” for short. These names are still widely used in the literature. These sources can be found on the SIMBAD database by using the less ambiguous acronym “GCIIRS n”, for “Galactic Center Infrared Source”.

The discovery of the point-like radio source at the GC (later called Sgr A*) had just been reported the year before [9]. Quite naturally, the positional agreement between this source and one of the infrared compact source (IRS 16) from Ref. [7] was mentioned there, and the authors suggested that they may be coincident with the position of highest stellar density in the Galaxy. At the same time, it was becoming apparent that the central parsec contained a $\sim 5 \times 10^6 \, M_\odot$ massive object. In 1977, Ref. [10] discussed how natural it is to suspect that the compact radio source “might contain the engine providing the [...] mass required”. Detection of a broad He I emission line at the location of IRS 16 was reported in 1982 [11]. The authors tentatively interpreted their observation as the signature of orbital motion of gas close to the putative black hole.

However, when the first two-dimensional infrared cameras became available (e.g. [12]), providing arcsecond resolution, IRS 16 was resolved into several point sources, none of which was coincident with the radio source. Additional spectroscopic studies (e.g. [13]) have demonstrated that these sources were normal stars: Wolf–Rayet stars (or close to that stage) to be precise, fairly rare in the Galaxy, but not unique and more common in the Magellanic Clouds. Wolf–Rayet stars are evolved, massive, short-lived stars. The presence of many of them in the central parsec (about 30 are currently known [14]) has been challenging to understand: Ref. [15] demonstrates that the standard scenario for star formation was severely inhibited in this environment, mainly due to the very strong tidal forces from the black hole.

### 2.2. Characterizing the massive star population

The first diffraction-limited images of the GC where obtained on the ESO NTT (New Technology Telescope), a 3.5m-aperture facility located at La Silla (Chile), using a speckle imaging technique. A few infrared stars were detected in the central arcsecond around Sgr A* in 1993 [16], but no actual infrared counterpart to the radio source was detected on these data. The same authors were rapidly able to report the first proper motions of GC stars [17], and of these faint stars in the central arcsecond [18]. Approximately at the same time, the Keck telescope delivered its first images. Also using a speckle imaging technique, it permitted detection of accelerations of the same stars, providing an independent estimate of the enclosed mass [19].

In 2002, the adaptive-optics system NAOS coupled with the camera CONICA (forming together NACO) was used on ESO VLT on the GC for the first time, few months after the first light of NACO. Together with the 8 years of NTT data obtained previously, these observations provided the authors of Ref. [5] with a long enough time baseline to constrain the orbit of S2 (a.k.a. S0-2, SIMBAD identifier: [EG97] S2), one of these stars. Its orbital period, $\sim 15.2$ yr, is short enough that, as of writing, it has already been observed for more than one complete orbit.

In parallel to these dynamical studies, spectroscopic studies have been conducted to unveil the nature of all these stars (both within the central arcsecond and at larger radii). Spectro-imaging techniques have been used to disentangle the spectra of the many stars in this extremely dense environment (e.g. [13; 20; 21]). Just like imaging studies, they have benefited from improving spatial resolution, reaching the diffraction limit of 10m-class telescopes with SINFONI on ESO VLT and, more recently, OSIRIS on Keck. The first stars detected in the early infrared studies – in particular the IRS 16 members – were very bright blue supergiants, akin to luminous blue variables (LBVs), presumably in the transitional Ofpe/WN9 stage leading to the Wolf–Rayet state. Then, even more evolved stars (WN and WC stars) have been found, filling the upper part of the initial mass function (IMF). They are much less luminous than the IRS 16 stars,
because they have lost most of their mass already, but exhibit very bright and broad metal emission lines. In 2003, absorption lines were detected in S2 and the star was classified BOV [6; 22]. Finally, using SINFONI, Ref. [14] reported detection of many (about 20) main sequence OB stars, starting to fill the low mass end of the IMF. The conclusions of this paper, in part disputed (notably by Lu et al., see these proceedings), are representative of the state of the art.

3. Current knowledge

Put together, all these studies allow a consistent picture to be depicted. The parsec-scale nuclear cluster consists mainly of old stars. This population is dynamically relaxed. The radiation in the central parsec is however dominated by a younger population, which formed during one (or perhaps two) short event(s) or weak starburst(s) 6 ± 2 Myr ago.

3.1. Stellar disks at the parsec scale

These young stars orbit the black-hole in a coherent fashion. It was already noted in 1996 from the radial velocities alone of ≃ 20 emission line stars [23]. ≃ 40 stars are found to lie on a fairly thin disk, rotating clockwise in projection on the sky, called the clockwise system (CWS) [14; 24–27]. [25] and [14] argue for the existence of a second disk (the counter-clockwise system, CCWS) containing ≃ 15 stars, using two different methods. However, Lu et al. (these proceedings) have developed an independent method for finding disks in the same data set as [14] and testing their significance. They claim that the CCWS found by their predecessors is not statistically significant. Hendrik Bartko et al. (these proceedings) reacted to this criticism, and took two actions to check their previous result: (1) they also developed a more robust statistical approach to determine the significance of their findings, and (2) they improved the quality of their data set, by re-observing stars for which the radial velocities were the least well constrained. They claim to confirm the existence of the CCWS. Some more time is needed to allow the two groups to converge to a common interpretation on this crucial point. Although the existence of the CCWS is still controversial, I give its proposed properties below.

While most stars on the CWS have fairly low eccentricities, the CCWS seems to harbor more eccentric stars (e ≃ 0.8). As the measurement uncertainties decrease, it is also becoming apparent that about half of the early type stars in the GC do not belong to either disk. The two systems are fairly inclined with respect to the Galactic plane and to one-another. They are both 6 ± 2 Myr old, their initial mass function is top heavy and their total mass is around 10^5 M_☉. The disk(s) do not extend down to Sgr A*: they have an inner radius of about 1 arcsecond, inside which the S star cluster resides.

3.2. A relaxed population in the Central arcsecond

In contrast to the disk population, the S stars seem relaxed. They have random eccentricities and orbital planes. There is no clear indication so far of whether these stars were formed at the same time as the disk stars, since none of the most evolved, WR stars belong to the S cluster. The S stars could therefore be somewhat older than the stellar disk population, but not much.

3.3. IRS 13E: a cluster in the cluster

Finally, there are strong claims about a very compact star cluster, about 3" from Sgr A* [28]. Although it has been disputed [29], a conservative statistical analysis has demonstrated that IRS 13E is a physical group of stars, containing at least a dozen of stars, possibly many more [14]. It is made of early-type stars of various initial masses, including Wolf-Rayet stars. If the CCWS exists, IRS 13E presumably belongs to it. It is bright at every wavelength from the submillimetric domain to X-rays. It is a serious candidate for harboring an intermediate mass black hole of 10^3−4 M_☉. However, the X-ray emission originates in the colliding winds from
the hot stars in the cluster rather than from an accretion flow onto this putative black-hole. A conservative lower limit on the cluster mass from its velocity dispersion is $\simeq 10^8$. However, the tidal forces from Sgr A* impose another lower limit to bound the cluster. Depending on its position on the line-of-sight, it may be as high as $10^9 M_\odot$. While it is reasonable to assume the IRS 13E indeed contains $10^5 M_\odot$ in stars, a more massive cluster would require a compact, dark component.

3.4. Ongoing star formation in the central parsec?

So far, very little observations support the idea that there could be current star formation in the central parsec. Just north of IRS 13E, there is a group of very red point sources (IRS 13N), which have been tentatively interpreted as young stellar objects [30; 31], although with caution. Further investigations are required to decide on this matter.

4. Star formation scenarios

4.1. Adiabatic Cloud Collapse

It has been demonstrated that the standard scenario for star formation, adiabatic cloud collapse, is heavily suppressed in the central parsec (see Ref. [15] for a thorough discussion). Tidal forces are such that a cloud cannot be gravitationally bound unless its density is in excess of $10^7$ cm$^{-3}$[1.6 pc/$R_{gc}$]$^{1.8}$ where $R_{gc}$ is the distance to the Galactic nucleus [32]. Such densities are very hard to achieve, and require an external trigger, for instance cloud collisions, strong winds, or supernova shocks. Ref. [15] argues that the magnetic field in the GC clouds has milligauss strength. In the central parsec this is supported by polarization observations [33; 34]. Therefore, magnetic pressure is probably sufficient to support these clouds.

4.2. In-falling cluster scenario

If producing stars seems very difficult in the central parsec, it makes sense to try and externalize the star forming region. This alternative in-falling star cluster scenario speculates that the GC early-type stars were formed as a massive star cluster reasonably far from Sgr A*, were tidal forces are not so much an issue, and then migrated towards their present location, loosing angular momentum through dynamical friction. Several authors investigated this possibility [35–40]. Their collective conclusion is that this scenario can work, but requires a very high initial mass ($> 10^5 M_\odot$) and a very dense core ($> 10^7 M_\odot$pc$^{-3}$). When the core density reaches this level, star–star collisions become likely and can lead to runaway formation of an intermediate mass black-hole, which helps the in-fall of the cluster towards the central parsec. During the infall, the cluster undergoes mass-segregation and looses many lower-mass stars. These elements provide a few predictions which can be checked against the observations:

- residual core: since the cluster core ends up very tight, it may be able to survive for a long time in the central parsec. IRS 13E provides a natural candidate for having originated as the cluster core;
- total mass: the observed cluster contains only $\simeq 10^4 M_\odot$, an order of magnitude below the predictions;
- strong mass segregation and low mass stars lost at large radii: there is currently no indication of mass segregation in the early-type nuclear cluster. However, the statistics for OB stars at large ($> 0.5$pc) are still low, and no lower-mass star (e.g. spectral type later than A) has been detected so far.

Overall, this scenario works qualitatively rather reasonably but so far fails to reproduce the facts quantitatively.
4.3. Self-gravitating disk scenario
While outsourcing star formation did not work quite as well as hoped, other authors worked at improving the in situ scenario. It has been demonstrated earlier that an initially spherical cloud in the central parsec will not be able to contract adiabatically under its own gravity. Instead, it will orbit Sgr A* and be sheared by the tidal forces. After the material on the shortest orbits completes one orbit, it will collide with the slowest parts of the cloud, forming a dispersion ring. This shock in itself has been proposed as being able to compress the material enough to form stars, but it seems difficult to form $10^4 M_\odot$ of stars with this localized trigger. Instead, the ring will evolve into a disk by getting more circular, flatter, geometrically thinner, and denser. More clouds may then come into the central region and merge with this disk, which can thus build-up a considerable mass. A disk configuration provides confinement where shearing cannot act against density anymore. Circularization means that neighboring particles acquire similar velocities. When the disk reaches a critical density, the disk can become self-gravitating. At that point, numerical simulations show that star formation proceeds very quickly and efficiently. Most of the gas can actually participate in star formation, which leaves very little material for accretion onto the black hole: this actually is a problem for other galactic nuclei where starbursts cohabit with a luminous black-hole. This is not an issue in the GC though, since Sgr A* is known to be very underluminous. [26; 42]

5. Open question: Forming the S stars
There is one issue that none of the star formation scenarios proposed above addresses satisfactorily: the presence of the S stars in the innermost arcsecond. For them, the “paradox of youth” is even more pronounced. Forming stars so close to the black hole is deemed nearly impossible. Two alternative approaches have been studied to explain the observations: rejuvenation of old stars and capture of eccentric stars.

5.1. Rejuvenation of young stars
The basic idea here is that the blue, hot stars in the central arcsecond are not what they seem. They really are old stars that have had plenty of time to sink into the depth of the potential well. They look young because something happened to them which makes their photosphere take the size and temperature of a massive star's:

- envelope stripping: the S stars would be red giants whose envelope has been ripped off during a close encounter with Sgr A*, only their hot core remaining [43; 44];
- tidal heating: Ref. [45] proposes that there exist squeezer, stars on very eccentric orbits around Sgr A* which are heated by tidal interactions with the massive black hole;
- mergers: the S-stars could be the product of several constructive collisions of low-mass stars, building up mass to that of a B star [25].

All these scenarios seem to fail at the quantitative level. In particular, since they have been proposed, precise spectroscopic information has been obtained for the S stars. It is fairly easy to produce the right color for the stars since they are in the Rayleigh-Jeans regime at K-band. On the contrary, it seems quite unnatural that such exotic scenarios should produce so normal-looking stars.

5.2. Capture of stars on eccentric orbits
The other idea is that the S-stars really are normal B stars. They have been formed further out, and moved into the central arcsecond. The scenarios proposed above to bring the entire central parsec early-type star population are hardly able produce the S-stars, although Ref. [46] claim that it is possible using an in-falling star cluster with intermediate mass black hole, and
resorting to moderate envelope stripping to explain the lack of Wolf-Rayet stars in the innermost region. An additional process helps in bringing some B stars from the central few parsecs to the central arcsecond. Overall, this class of scenarios uses three ingredients:

- a reservoir of B stars at reasonable distance from Sgr A*;
- a process to put them on very eccentric orbits, so that they pass close to Sgr A*, crossing the central arcsecond;
- a process to trap the very eccentric, B stars in the central arcsecond.

In Ref. [47], the B star is hypothesized to initially be the lower mass component of a binary system. The trapping process is exchange capture: when the binary comes close to Sgr A* on an eccentric orbit, the higher mass component (\( \approx 60 \, M_\odot \)) is ejected while the lower mass star remains on a tightly bound orbit around the supermassive black hole. However, this process is very inefficient: perhaps only \( \approx 0.5\% \) of massive stars passing within \( \approx 130 \, \text{AU} \) will inject lighter companions into S-star-like orbits. Although the paper concentrates mostly on the trapping process, it does provide a proposal of a reservoir: the binaries would come from in-falling star clusters as described in the preceding section. However, the authors have to speculate that it is reasonable for such clusters to form on eccentric orbits.

In Ref. [48], the trapping process is reversed. Here, the basic idea is that Sgr A* is surrounded by a cluster of stellar mass black holes. Each time a star of similar mass passes through this cluster, there is a chance that the stellar mass black hole is ejected and replaced by the star. They model the reservoir as ongoing star formation at the parsec scale, which in itself does not match the observations beyond the fact that there has been indeed star formation recently. They also have to remains somewhat speculative about how to put many B stars on very eccentric orbits within their lifetime.

6. Conclusion

Over thirty years of technological developments in infrared astronomy have allowed to resolve the nuclear star cluster at the GC to an unequaled level. It is composed of a spheroidal component of late-type stars and an organized population of early-type stars. Of order \( 10^4 \, M_\odot \) of stars have been formed \( 6 \pm 2 \, \text{Myr} \) ago. They are currently concentrated in one or perhaps two disks spanning the central parsec. There is a tight cluster of early type stars, 3.5” from Sgr A* in projection. There is no evidence of ongoing star formation in the region. In addition, the central arcsecond contains several B stars on random orbits.

Although it has been difficult to understand how massive, short-lived stars could ever be observed so close to a supermassive black hole, there exists now several scenarios to explain the parsec-scale disk(s) of stars in an essentially satisfactory manner. However, the existence of the S star cluster in the central arcsecond is still to be considered a “paradox of youth”.

We can already foresee that several types of observations could help in resolving the current issues. First of all, continuing observations with the current techniques will allow detecting accelerations for more and more stars at larger and larger radii from Sgr A*. This will bring new insight to the three-dimensional structure of the early-type star population. It could confirm or rule out the second disk. It could also make apparent older disks, starting to dissolve in the relaxed, late-type star cluster.

Secondly, there are several ways in which the future generations of instrumentation will improve the situation. The GRAVITY experiment [49], approved by ESO as a second generation instrument for the Very Large Telescope Interferometer, will be able to put tighter constraints on the mass profile in the central arcsecond [50]. This will be valuable inputs for the exchange capture scenarios in the preceding section. A spectro-imager with a large field-of-view on an extremely large telescope would allow investigating the density profile of early-type stars at large radii from Sgr A*. This would allow testing the in-falling star cluster scenario.
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