Dynamics and origins of the young stars in the Galactic center

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Abstract. The environment near the massive black hole (MBH) in the Galactic center is very hostile for star formation. Nevertheless, many young stars (both O and B stars) are observed close the MBH. The B-stars seem to have an isotropic, continuous distribution between 0.01 pc and up to a pc. The O stars, in contrast, seem to be distributed in a coherent disk like configuration, extending only between \( \sim 0.04 \) pc to \( \sim 0.5 \) pc. Our current understanding favors an in-situ formation origin for the more massive (O and Wolf-Rayet) stars, in gaseous disk and/or streams from an infalling gas clump. The B-stars seem to have a different origin, more likely through a dynamical capture, following binary disruption by the MBH. This scenario could also be able to explain the origin of hypervelocity stars in the Galactic halo. These and other possible origins of the young stars in the Galactic center are briefly reviewed and their possible observational signatures and constraints are detailed.

1. Introduction

High resolution observations have revealed the existence of many apparently normal young OB (including Wolf-Rayet; WR) stars in the galactic center (GC), where tidal forces exerted by the massive black hole (MBH; (Schödel et al. 2002; Ghez et al. 2003)) are likely to inhibit regular star formation in regular molecular clouds. The existence and properties of such stars could give us important clues for understanding of the GC environment (see Alexander 2005, for a review). They could also help constrain the origin and evolution of hypervelocity stars observed in the Galactic outskirts (Hills 1988; Brown et al. 2006; Perets 2009a), which in principle could probe the potential and dark matter component of the Galaxy (Gnedin et al. 2005; Yu & Madau 2007; Perets et al. 2009a).

The young stars observed in the central pc near the MBH, could be divided into two seemingly distinct stellar populations, which differ both in their types (B-stars vs. O or WR stars) and in their kinematic properties. The young B-stars population (\( \sim 7 - 15 M_\odot \); fainter stars can not currently be resolved) includes a few tens of stars with an isotropic distribution extending from \( \sim 0.01 \) pc all through the central pc (Bartko et al. 2010a). For some of these stars, in the central 0.04 pc (so called the ‘S-stars’ or the ‘S-cluster’), full orbital solutions are known, showing them to have relatively high eccentricities (\( 0.3 \leq e \leq 0.95 \)) (Ghez et al. 2003; Eisenhauer et al. 2003), with approximately thermal eccentricity distribution, and random orbital orientations. Although the full kinematic properties of the B-stars outside this region are not known, the available data suggest their distribution is isotropic with similarly relaxed eccentricity distribution.
The other young stars (mostly O and WR stars) reside in a more restricted region, between 0.04 pc to 0.5 pc, in seemingly two coherent structures. Most of these reside in a stellar disk moving clockwise in the gravitational potential of the MBH (Levin & Beloborodov 2003; Genzel et al. 2003; Lu et al. 2006; Paumard et al. 2006; Tanner et al. 2006; Bartko et al. 2009). The second structure is less coherent and its exact nature (and existence) is still unknown and debated. The orbits of the stars in the CW disk have an average eccentricity of ∼ 0.35 and the opening of the disk is h/R ∼ 0.1, where h is the disk height and R is its radius. The disk structure is warped at large angles (65°). Most of the stars outside the CW disk reside in somewhat less coherent structure, between 0.3-0.5 pc from the MBH, and highly inclined with respect to the CW disk. A small fraction of the young O stars do not reside in either of these structures at some intermediate inclinations. The current knowledge on the observed properties of the young stars in the GC are discussed in several recent papers (see e.g. Bartko et al. 2010a). In table 1, we summarize the observed properties of the young stars in the GC, which should be satisfied by models of their origin and evolution.

| Stellar Type | Masses and Lifetime/age | Morphology | Radial (n(r)) Distribution | Eccentricity Distribution |
|--------------|-------------------------|------------|---------------------------|--------------------------|
| B            | 7-15 M⊙ 10-50 Myrs      | Isotropic (spherical) | $r^{-1.1}$ | ~Thermal (c) ~ 0.7 |
| O and WR     | 15-60 M⊙ 4-6 Myrs       | Clockwise warped (65°) disk (H/R ∼ 0.1) + coherent highly inclined disk/stream structure | $r^{-2}$ (in the CW disk) | (c) ~ 0.35 (in the CW disk) |

Table 1. Properties of the GC young stars

In the following we briefly overview suggested scenarios for the origin of the young stars in the Galactic center. Several models suggested these stars to be older stars, which only appear to be young. However, current observations show the young GC stars are apparently normal, genuinely young, and massive stars. We therefore focus on other more favorable scenarios, producing young stars (see Alexander (2005) for an overview of the young stars impostors scenario, as well as some of less recent literature on some of the other models).

2. Origins and evolution

2.1. In-situ star-formation from infalling gaseous clumps

It was suggested that the young OB stars in the GC were formed in-situ in the central pc a few million years ago in gaseous disks and/or streams formed from infalling and/or colliding gaseous clumps (Morris 1993). Analytic calculations and simulations (Nayakshin & Cuadra 2005; Levin 2007; Bonnell & Rice 2008; Hobbs & Nayakshin 2009) have shown that stars could form in such fragmenting clumps to form stellar disks and/or other coherent structures, in the region of a few 0.01 pcs up to a few 0.1 pcs from the MBH. These could, in principle, be consistent with the observed young stellar structures (disk and a secondary
inclined structure). This scenario could also explain the radial distribution of OB stars in the disk and possibly also explain their eccentricities. Moreover, some of the models studied produce a top heavy mass function (MF) for the newly formed stars, possibly consistent with observations (Bartko et al. 2010a).

Note, however, that our poor understanding of the initial conditions and the star formation processes in the GC, allows for a wide parameter space to play with, which, naturally, raise difficulties in constraining (or strictly falsifying) such models. Nevertheless, the robustness of producing some sort of star formation in the GC region under a variety of conditions explored in the literature suggest these models as the currently most promising scenarios for the origin of the young stellar disk and stellar structures (although less likely the origin of the isotropic B-stars population, as discussed below).

2.2. In-situ star-formation followed by rapid migration

None of the models for in-situ star formation in the central pc suggests the formation of stars as close to the MBH as the S-stars, or the apparent existence of two distinct young O and B stellar populations. Producing both the disk and isotropic B-stars population in the same scenario (and in particular the inner S-stars) requires a somewhat fine-tuned scenario. One requires a selective process which works differentially on stars of different masses. In any case, an additional process would be required for the migration of stars from the outer to inner regions in the central pc in order to produce the S-stars close to the MBH.

Two-body relaxation processes work, in principle, differentially on stars of different masses, through mass segregation (energy equipartition) processes. For example, such processes in an isolated stellar disk would somewhat segregate the more massive stars into a thinner disk (Alexander et al. 2007; Perets et al. 2008b) producing mass stratified populations. However, this effect is relatively small. Moreover, the most important component for relaxation in the GC is likely to be the stellar black holes population of the stellar cusp, which work through resonant relaxation (Perets et al. 2008b; Löckmann et al. 2009; Perets et al. 2009). Segregation into two different stellar population of different masses regimes is not likely to ensue in this case. Moreover, such scattering of stars could not produce the population of S-stars closer to the MBH (Perets et al. 2008b; also Perets et al., in prep.). Encounter of binary-single stars (Cuadra et al. 2008; Perets et al. 2008a) can also have only a small effect in producing the isotropic B-stars population from a thin stellar disk. Perturbation by massive perturbers (Perets et al. 2007) such as infalling IMBHs (Yu et al. 2007; Gualandris & Merritt 2009) or other stellar disks (Löckmann et al. 2009; also Gualandris et al., in prep.) do not differentiate between stars of different masses either.

Given the lacking suggestion for a mass differentiating process, a different route can be taken. We can suggest that two distinct epochs of in-situ star-formation have occurred. Even two such epochs would still require a migration process of some of the stars from the disk into the inner regions close to the MBH, where stars do not form in-situ. One should mention, in this context, that in some cases different mass function was found for stars formed at different structures in the same simulation (Hobbs & Nayakshin 2009). We can therefore
either suggest two epochs of star formation happening at different times, or a single epoch producing two distinct population. In either case the rapid migration producing the S-stars should affect only one of the stellar populations formed.

Two distinct star formation epochs could naturally produce more massive and less massive stellar populations. Even if both epochs produced stellar population with the same initial mass function, the most massive stars from the first epoch may already end their life, leaving a stellar population of less massive stars. However, comparing the top heavy mass function of the disk stars, as suggested from current observation, with the regular mass function of the isotropic B-stars disfavor this scenario (otherwise much more B-stars should have been observed in the stellar disk).

This bring us to an interesting very general requirement applicable to any scenario in which the S-stars formed far from their current positions. We can term this the model efficiency. In any such scenario only a fraction, \( f_{\text{mig}} \), of the stars formed in some external region (e.g. the stellar disk, the central pc, or even stars outside the central pc) migrate to become S-stars. For a given number of observed S-stars, \( N_s \), the parent external population should be \( 1/f_{\text{mig}} \) larger to have \( N_{\text{par}} = N_s/f_{\text{mig}} \) stars (compare with similar constraints derived by [Perets 2009a]). Using our efficiency term, more “efficient” models are the ones having larger \( f_{\text{mig}} \). Cases in which \( f_{\text{mig}} \) is small, could be strongly constrained by such requirement. For example, the ’billiard’ model for the origin of the S-stars ([Alexander & Livio 2004] in which stars from the central pc are captured close to the MBH through exchanges with SBHs close to the MBH, is disfavored since the population of similar B-stars in the central pc, are too small to accommodate the required parent population ([Paumard et al. 2006]). Similarly, one can turn to models of a disk origin for the S-stars, such as the Kozai-like perturbations in the two disks scenario ([Löckmann et al. 2009]), the eccentric disk instability model ([Madigan et al. 2009]), or the spiral density wave model ([Griv 2010]). All of these models, irrespective of details, suggest that the S-stars formed as part of a stellar disk, up to a few 0.1 pc away from the MBH. A small fraction of the stars formed in the disk migrated through some process (which works equally on stars of any mass), to later on become the currently observed S-stars. The current number of B-stars inferred in the central 0.5, outside the central 0.04 pc where the S-stars reside, is comparable, and likely somewhat smaller than the total number of S-stars. These models are required to have a very high migration efficiency in order to explain the origin of the S-stars. Putting it differently, a much larger \( f_{\text{mig}} \) than currently suggested by these models is required. We can therefore conclude that (at least) the current formulations of these models, can likely be excluded.

### 2.3. External star-formation followed by rapid migration

Another set of scenarios suggest that the GC young stars formed outside the central pc, where conditions are less hostile for regular star formation. These scenarios try to explain only the origin of the stellar disk, or the origin of the isotropic B-stars, in particular the S-stars, but not both. Note that the extension of S-stars distribution beyond the central 0.04 pc is only a recent observational
development, nevertheless, some of the models suggested for the S-stars origin discussed the possible existence of such extended distribution.

Cluster infall An infall of a young stellar cluster (with or without an intermediate MBH; IMBH) into the central pc was suggested as alternative scenario for the origin of the GC young stars (Gerhard 2001; Kim & Morris 2003; Portegies Zwart et al. 2003; Kim et al. 2004; Levin et al. 2005; Gürkan & Rasio 2005; Berukoff & Hansen 2006; Fujii et al. 2007, 2009). Such dissolving cluster is likely to form a stellar disk like structure, possibly with additional outlying structures and/or isolated stars outside of the main disk, as observed in the GC. It would also produce a bias towards more massive stars to be concentrated in the central region of the GC. These more massive stars, which were originally more segregated in the inner regions of the cluster, would be the last to dissolve from the cluster, i.e. in the central most regions closer to the MBH.

Such inspiraling objects, however, may not be able to inspiral in the appropriate time window for producing the stellar disk (Kim & Morris 2003; Kim et al. 2004). Yu & Madau (2007) and others invoke the existence of an IMBH with mass $>10^4 M_\odot$ which could help produce the current observations. Nevertheless, formation of such an object in a cluster and its infall in the appropriate time window appears difficult (e.g. Kim et al. 2004) and need to be fine tuned to explain the observations. In fact, detailed N-body simulations of stellar clusters, combined with stellar evolution, do not produce IMBH in these clusters (Glebbeek et al. 2009; Vanbeveren et al. 2009). The possibility of an IMBH infall is therefore unfavorable given our current understanding and the lack of evidence for such objects in the central region of the Galaxy.

Apart from the problems posed by requiring the existence of an IMBH, cluster infall models may not be consistent with observations (Paumard et al. 2006). An infalling cluster is likely to leave most of its stars behind during its inspiral as it dissolves, where as very few young stars are observed outside the central 0.5 pc. In a sense, this difficulty is similar to the efficiency problem discussed previously for other models. Note that even the simulations of an infalling cluster hosting an IMBH show that the young stars are stripped from the cluster before the IMBH reaches the central 0.04 pc (see e.g. Levin et al. 2005; Berukoff & Hansen 2006). The young stars closest to the MBH (the S-stars) are therefore not likely to directly originate from such a scenario in any case.

Binary disruption A close pass of a binary star near a MBH results in an exchange interaction, in which one star is ejected at high velocity, while its companion is captured by the MBH and is left bound to it (Hills 1988). Such interaction occurs because of the tidal forces exerted by the MBH on the binary components. A young binary star could therefore be formed outside the central region and later be scattered onto the MBH on a highly radial orbit leading to its disruption. Such a scenario was suggested by Gould & Quillen (2003) to explain the origin of the star S2. In order for the capture rate of such stars to explain the current observation of all the GC B-stars, rapid relaxation processes are required for the binaries to be scattered onto the MBH. Such a model, suggested by Perets et al. (2007), which takes into account scattering by massive perturbers outside the central 1.5 pc (such as giant molecular clouds and clumps observed in
the GC region and other galactic nuclei; Perets et al. 2007; Perets & Alexander 2008) could account for the observed number of B-stars. Note that this scenario, like the disk origin models for the S-stars discussed above, can be constrained by observations of the parent population from which the S-stars originate. Current observations do not exclude this model (Perets et al. 2007; Perets 2009a). Future observation looking for young stars in these regions should, in principle, give better constraints. Nevertheless, other observational signatures may be more easily verified or refuted. We discuss these in the following.

The binary disruption scenario leaves the captured stars on highly eccentric orbits ($\sim 0.94$), and further dynamical evolution is required in order to explain their currently observed eccentricity distribution. Study of their evolution, which is driven by resonant relaxation processes (Rauch & Tremaine 1996), suggest that indeed the more relaxed, almost thermal eccentricity distribution of the S-stars (Perets et al. 2009b) could be consistent with their evolution from much higher initial eccentricity. It is interesting to note, however, that the resonance relaxation time scales in the GC increase with distance from the MBH (Hopman & Alexander 2006). Therefore stars captured further away from the MBH are likely to have less relaxed eccentricity distribution, i.e. this scenario produce a correlated eccentricity-distance, with stars more distant from the MBH expected to have higher eccentricities. Stars captured further than 0.5 pc, for example, are likely to be highly eccentric ($\sim 0.94$) in this scenario.

Typically, a binary is disrupted when it crosses the tidal radius of the MBH (see e.g. Perets et al. 2009b for details). One of the binary components is typically captured at a close orbit near the MBH (Gould & Quillen 2003), and its companion is ejected at high velocities (Hills 1988). The semi-major axis of the captured star around the MBH is linearly related to its original binary progenitor separation (Hills 1991). The radial distribution of captured stars therefore maps the distribution of the binaries separations. The distribution of semi-major axis of massive binaries in the Solar-neighborhood follows a log-constant distribution. The radial distribution of captured stars in the GC should therefore be log-constant, or $n(r) \sim r^{-1}$, if the GC binaries have similar properties.

The mass function of captured stars is likely to be regular, i.e. reflecting the mass function of stars far from the MBH, where regular star-formation could occur. A small contribution from Kozai induced merger of stars, induced by Kozai resonances near the MBH, may contribute a small fraction of more massive stars (Antonini et al. 2009; Perets 2009b; Perets & Fabrycky 2009). In addition, longer living stars captured at earlier times may have a higher probability of being disrupted by the MBH during their dynamical evolution (Perets et al. 2009b). Taken together, the observed mass function (MF) of captured B-stars is likely be quite regular, although possibly more top heavy closer to the MBH, where disruption and merger occur, than a regular MF expected for stars captured further away.

3. Summary

In these proceedings we have shortly reviewed the origin and evolution of the young stars in the Galactic center. These stars which could be divided into two distinct stellar populations likely originated from two different processes.
The young stellar disk which contains mostly O and WR stars likely originated from an in-situ star formation through fragmentation of an infalling gaseous clumps. The population of young B-stars isotropically distributed throughout the central pc around the MBH likely have a different origin. Such stars were not likely to have been produced like the O-stars, and then migrated to their current positions, since a much larger parent population of B-stars should have been observed in the central pc. A binary disruption scenario, in which binaries which formed outside the central pc were scattered onto the MBH, could still be consistent with current observations. Such a scenario have specific predictions regarding the kinematic properties of the GC B-stars. We have reviewed these predictions which could be tested through direct observations in the coming few years.

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