Mem. S.A.It. Vol. 79, 1100

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Dynamical evolution of the young stars in the Galactic center

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Abstract. Recent observations of the Galactic center revealed a nuclear disk of young OB stars near the massive black hole (MBH), in addition to many similar outlying stars with higher eccentricities and/or high inclinations relative to the disk (some of them possibly belonging to a second disk). In addition, observations show the existence of young B stars (the 'S-cluster') in an isotropic distribution in the close vicinity of the MBH (< 0.04 pc). We use extended N-body simulations to probe the dynamical evolution of these two populations. We show that the stellar disk could have evolved to its currently observed state from a thin disk of stars formed in a gaseous disk, and that the dominant component in its evolution is the interaction with stars in the cusp around the MBH. We also show that the currently observed distribution of the S-stars could be consistent with a capture origin through 3-body binary-MBH interactions. In this scenario the stars are captured at highly eccentric orbits, but scattering by stellar black holes could change their eccentricity distribution to be consistent with current observations.

Key words. Stars: kinematics – Galaxy: nucleus – Stars: simulations

1. Introduction

High resolution observations have revealed the existence of many young OB stars in the galactic center (GC). Accurate measurements of the orbital parameters of these stars give strong evidence for the existence of a massive black hole (MBH) which govern the dynamics in the GC (Schödel et al. 2002; Ghez et al. 2003). Most of the young stars are observed in the central 0.5 pc around the MBH. The young stars population in the inner 0.04 pc (the 'S-stars' or the 'S-cluster') contain only young B-stars, in apparently isotropic distribution around the MBH, with relatively high eccentricities ($0.3 \leq e \leq 0.95$) (Ghez et al. 2003; Eisenhauer et al. 2005). The young stars outside this region contain many O-stars residing 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). The orbits of the stars in this disk have average eccentricity of ~ 0.35 and the opening of the disk is $h/R \sim 0.1$, where h is the disk height and R is its radius. Paumard et al. (2006) and Tanner et al. (2006) suggested the existence of another stellar disk rotating counter clockwise and almost perpendicular to the CW disk. This disk is currently debated as many of the young stars are have intermediate inclinations, and are possibly just outliers that do not form a coherent disk structure (Lu et al. 2006).

Here we briefly report on our study of the dynamical evolution of the young stars in the GC, both in the stellar disk and in the S-cluster. We use extensive N-body simulation runs on the RIT Grape cluster with realistic number of stars (10^3 – 10^5), that allow us to probe the dynamics of the stars near the MBH and their stellar environment. We study two basic issues: (1) the long term evolution of the S-stars up to their lifetime of a few 10^7 yrs, including their dynamical interaction with stars in the vicinity of the MBH; (2) The evolution of a realistic stellar disk, taking into account both the effects of non-equal mass stars, as studied earlier, and more importantly the effect of the interactions of disk stars with the stellar cusp around the MBH. As we show, the latter component proves to be more important than the other components discussed in previous studies. A detailed report of our complete set of out simulations (not shown here), in addition to analytic calculations will be presented in upcoming papers (Perets et al., in preparation)

2. Formation and/or migration origin

Analytic calculations and simulations have shown that a young stars could have formed and grown over short times of thousands to millions of years in a gaseous disk around the MBH (e.g. (Nayakshin & Cuadra 2005; Levin 2007)). Such stars could then form the stellar disk currently observed in the GC. It was suggested that the 'S-stars' with their very different properties migrated from the stellar disk through a planetary migration like process (Levin 2007). This interesting possibility has not yet been studied quantitatively, but would suggest that the migrating stars should have relatively low eccentricities. Another possibility is that these stars have a different origin, possibly from the disruption of young binaries and the following capture of one of their components (Gould & Quillen 2003). It was recently shown that such a scenario could be consistent with the current knowledge regarding the number of the observed 'S-stars' (Perets et al. 2007). The initial eccentricity of the captured stars should then be very high (> 0.96) in this scenario. We note that other scenarios were suggested for the origin of the young stars in the GC, but seem to be disfavored by current observations (see e.g. Alexander (2005) and Paumard et al. (2006)).

3. The S-stars

The dynamical evolution of the S-stars since their capture/formation has not been studied before. Here we present the results of N-body simulations dedicated to study such evolution. In order to do so we modeled a small isotropic cusp of 1200 stars, with masses of $3\,M_{\odot}$ (200 stars) and $10\,M_{\odot}$(1000) around a MBH of $3.6\times 10^6\,M_{\odot}$. We used a power law radial distribution of $r^{-\alpha}$ extending from $0.001-0.05$ pc near the MBH, with $\alpha = 2$ for the more massive stars and $\alpha = 1.5$ for the lower mass stars. The more massive stars correspond to the many stellar black holes (SBHs) thought to exist in this region, whereas the lower mass stars correspond to the S-stars in the same region. Since some of the S-stars may have higher masses of $\sim 10\,M_{\odot}$, the higher mass stars in the simulation could also be treated as S-stars. We did not see any major differences in the evolution of the more massive and the less massive stars, and we discuss the evolution of both together.

We studied two evolutionary scenarios for the S-stars. In the first we assumed that the S-stars were captured through a binary disruption scenario by the MBH (Gould & Quillen 2003; Perets et al. 2007) and therefore have initially highly eccentric orbit (> 0.96) and they evolve for few 10^7 yrs. In the second scenario we assumed the S-stars formed in a gaseous disk and migrated to their current position, and therefore have low eccentricities (< 0.3) and they evolved for 5 Myrs (the lifetime of the observed stellar disk. In order to check both scenarios we followed the evolution of those stars in our simulation with highly eccentric initial orbits (the first scenario) and those with low eccentricities (the second scenario) for the appropriate time scales. In Fig. (1) we show the final eccentricity distribution of the S-stars in both scenarios, as compared to the the orbits of the observed S-stars (taken from Gillessen et al.). These results suggest that, given the small statistics (16 S-stars with known orbits), the

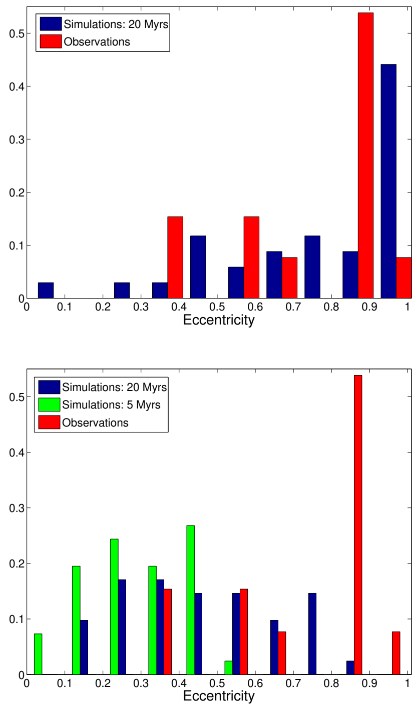

Fig. 1. The eccentricities of observed and simulated S-stars from the binary disruption scenario (after 5 Myrs; upper figure) and from the disk migration scenario (after 5 and 20 Myrs; lower figure).

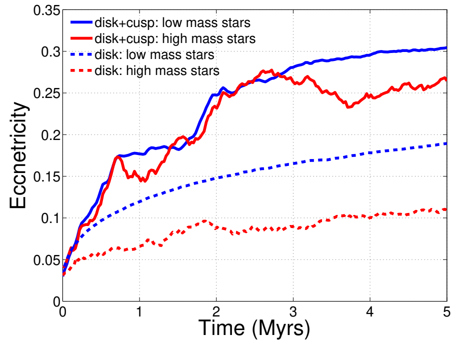

Fig. 2. The evolution of the mean eccentricity of the disk stars (both low mass, $M < 15\,M_{\odot}$ and high mass stars, $M > 15\,M_{\odot}$) with and without interactions with the stellar cusp around the MBH.

first scenario is much favored since it could explain the currently observed orbits of the S-stars, i.e. stars on highly eccentric orbits could be scattered by other stars or SBHs to smaller, and even much smaller eccentricities during their lifetimes. The second scenario, however, seems to be excluded (for the given assumptions), since it has major difficulties in explaining the large number of eccentric orbits in the S-stars observations vs. the bias towards low eccentricity orbits seen in the N-body simulations simulations. This is clearly seen both after 5 Myrs of evolution, and even after longer evolution, if these stars formed in an earlier epoch of star formation in a disk (not currently observed) 20 Myrs ago.

4. The disk stars

Alexander et al. (2007) and Cuadra et al. (2008) explored the dynamical evolution of a single stellar disk using small N-body simulations ($\sim$ 100 stars), where they studied the effects of massive stars in the disk (the mass function), and the structure of the disk (eccentric vs. circular). Cuadra et al. (2008) also studied the role of wide binaries following Perets et al. (2008) who suggested binaries could have an important role in the evolution of the disk, somewhat similar to their role in stellar clusters (Heggie 1975) and in the ejection of OB runaway stars. These studies showed that although the different components contribute to the disk evolution, it is difficult to explain the current eccentricities of the observed stars and the thickness of the disk, with only these components.

We studied a single disk of $\sim 5000\,M_{\odot}$, composed of either 5000 equal mass stars, or $\sim$ 2500 stars with a Salpeter mass function between $0.6 - 50\,M_{\odot}$. The initial conditions are of a thin disk ($H/R \sim 0.01$) with a surface density of r^{-2}, with all stars on circular orbits ($e \lesssim 0.01$). In addition we studied the evolution of such disks both with and without an isotropic stellar cusp component around the MBH in which the stellar disk is embedded in. The region of the GC disk is thought to contain a few 10^5 up to 10^6stars; simulating such a larger number of stars in orbits close to a MBH, even with a GRAPE cluster is currently difficult. However, the dynamics and relaxation processes close to the MBH are dominated mostly by the much smaller number of SBHs in this region (a few 10^3 up to 10^4 SBHs are though to exist in the GC disk region ;Miralda-Escudé & Gould 2000; Hopman & Alexander 2006; Freitag et al. 2006). Simulating only this SBHs component could therefore be more efficient in running time and at the same time capture most of the important relaxation processes effecting the the dynamics of the disk. In our simulations we put 1.6×10^4 SBHs (of $10\,M_\odot$ each) with an isotropic power law distribution ($n \propto r^{-2}$), between $0.01 - 0.8$ pc.

The evolution of the mean eccentricity of the disk stars is shown in Fig. (2), both for low mass stars ($< 15\,M_\odot$) and high mass stars ($M \geq 15\,M_\odot$, i.e. such as the observed disk stars in the GC). The evolution of a stellar disk embedded in a cusp of SBHs, is compared with that of an isolated stellar disk with a Salpeter mass function between $0.6 - 80\,M_\odot$ (i.e. higher mass cutoff than used in the disk+cusp simulation, to allow for the disk heating by more massive stars, as discussed in Alexander et al. 2007). The results show that the SBHs cusp component has an important contribution to the disk evolution. Although one disk has a lower mass cutoff than the other, it is heated much more rapidly, due to the contribution of the cusp stars. More importantly, the high mass stars corresponding to the stars that are actually observed in the GC disk, have relatively low eccentricities in the isolated disk, and would present difficulty to our understanding of the disk evolution, as discussed by Alexander et al. 2007; Cuadra et al. 2008. Adding the cusp component solves the problem, as even the eccentricities of the higher mass stars are high in this case and comparable with the observed eccentricities of the disk stars in the GC. We note that these simulations did not take into account the contribution of low mass disk stars (i.e. not the SBHs in the cusp) which will further accelerate the heating of the stellar disk.

5. Summary

The dynamical evolution of the young stars in the GC both in the stellar disk(s) and in the inner S-cluster is not yet understood. We used N-body simulations to study the dynamics and origin of these stars. We found that the S-stars close to the MBH in the GC could be stars that were captured following a binary disruption by the MBH, and later on dynamically evolved due to scattering by other stars, or stellar black holes, to obtain their currently observed orbits. We also show the the young stellar disk could have formed as a cold (thin) circular disk and evolve to its currently observed thick (hot) disk, mostly due to scattering by cusp stars, whereas self relaxation of the disk plays a more minor role, especially in regard to the more massive stars seen in observations.

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