Stellar dynamical evidence against a cold disc origin for stars in the Galactic Centre

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Abstract
Observations of massive stars within the central parsec of the Galaxy show that, while most stars orbit within a well-defined disc, a significant fraction have large eccentricities and/or inclinations with respect to the disc plane. Here, we investigate whether this dynamically hot component could have arisen via scattering from an initially cold disc – the expected initial condition if the stars formed from the fragmentation of an accretion disc. Using N-body methods, we evolve a variety of flat, cold, stellar systems, and study the effects of initial disc eccentricity, primordial binaries, very massive stars and intermediate mass black holes. We find, consistent with previous results, that a circular disc does not become eccentric enough unless there is a significant population of undetected 100–1000 M⊙ objects. However, since fragmentation of an eccentric disc can readily yield eccentric stellar orbits, the strongest constraints come from inclinations. We show that none of our initial conditions yield the observed large inclinations, regardless of the initial disc eccentricity or the presence of massive objects. These results imply that the orbits of the young massive stars in the Galactic Centre are largely primordial, and that the stars are unlikely to have formed as a dynamically cold disc.

Key words: stellar dynamics – Galaxy: centre – methods: N-body simulations

1 Introduction
Observations of the Galactic Centre (GC) have revealed a population of young (~5 Myr) massive stars orbiting within a fraction of the MHI ≈ 3 × 10⁶ M⊙, supermassive black hole Sgr A. The existence of any young stars so close to the black hole is a puzzle, since the tidal field would prevent star formation from gas clouds with densities ρ < MHI/[(4π/3)r³]. This critical density is ~ 10¹⁹ cm⁻³ at 0.1 pc, far higher than the densities of normal molecular clouds. The dynamics of the stars are also unusual and interesting. Although the innermost ‘S-stars’ appear to be consistent with isotropic orbits, many of the young stars at a distance of the order of 0.1 pc lie on a single plane (Levin & Beloborodov 2003; Genzel et al. 2003; Paumard et al. 2006; Lu et al. 2006) and rotate clockwise on the sky. The eccentricities of stars in this clockwise disc are significant. The average value is e ≈ 0.35, with the eccentricities of several stars going above 0.5 (Beloborodov et al. 2006; Lu et al. 2006). Moreover, the stars that do not belong to the clockwise disc (which, by definition, have large inclinations that in many cases exceed 90°) have even larger eccentricities, perhaps as large as e = 0.8 for stars on counter-clockwise orbits (Paumard et al. 2006).

Two classes of theories have been advanced to explain the origin of the disc stars. In the first, the stars form in situ from a massive accretion disc in which the density is large enough to exceed the tidal limit (Levin & Beloborodov 2003; Milosavljević & Loeb 2004; Nayakshin & Cuadra 2005; Paumard et al. 2006). Accretion discs at these radii around black holes are known to be vulnerable to fragmentation and star formation provided only that they can cool on a dynamical timescale (Paczynski 1978; Kolykhalov & Sunyaev 1980; Shlosman & Begelman 1989; Gammie 2001; Rice et al. 2003; Goodman 2003). The second model posits that the stars formed outside the GC region but migrated in due to dynamical friction (e.g. Gerhard 2001; Kim & Morris 2003; Kim et al. 2004; Girkan & Rasio 2005; Berukoff & Hansen 2006). Understanding the predicted dynamics of these models in more detail may assist in discriminating between them.

Fragmentation of a thin accretion disc yields, almost by construction, starts with the basic disc-like dynamics observed in the

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1 Note that there is some dispute as to whether there is evidence for a second, counter-clockwise disc of stars. This question is not important for our purposes. We rely on observations only insofar as they demonstrate that there is (at least) one disc, and that some stars have orbits that do not coincide with any suggested disc plane. These aspects are uncontested.
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GC. Within such a model those stellar orbits that do not belong to any well-defined disc have to be generated after the disc fragments, perhaps via scattering. There is, however, only just enough time for significant dynamical evolution to occur [Alexander et al. 2007] found that even with a top-heavy mass function it was hard to attain the large eccentricities observed. This problem can be circumvented if the disc fragments while it is still eccentric [Nayakshin et al. 2007; Alexander et al. 2008], but it is still difficult to explain the high inclinations. Here, we investigate whether stellar dynamical evolution from any plausible cold disc initial conditions (i.e. those for which the local velocity dispersion is small compared to the orbital speed) can explain the observed stars. We consider both circular and eccentric initial conditions, and allow for the possibility of a high primordial binary population and additional scattering from unobserved massive objects (short-lived massive stars, or intermediate mass black holes).

2 NUMERICAL METHOD

We model the stellar dynamics of a disc of stars using the mercury6 code, which is optimized to study systems dominated by a central mass [Chambers 1999]. In order to treat close encounters reliably we adopt the optional Bulirsch–Stoer integrator, in its version for conservative systems.

We simulate stellar discs extending radially from 0.05 to 0.15 pc. The discs are composed of 100 stars randomly distributed following a surface density profile $\Sigma(r) \propto r^{-1}$, roughly as observed in this radial range, with the mass of each star equal to $25 M_\odot = 8.3 \times 10^{-4} M_{\text{BH}}$. In most of our models the stars are initially rotating in circular Keplerian co-planar orbits around the central object, with small random perturbations such that the thickness of the disc is $h/r = 0.01$. The exact value of this perturbation is not important, as the evolution of the disc is initially rapid. We integrate the systems for a time roughly equivalent to 2700 orbits at $r = 0.1$ pc, almost 5 Myr. Since $N$ is rather small, we run three simulations with each set-up to monitor the variance in the outcome.

Our model system includes the number and masses of the observed population of stars in the GC. Although observational evidence favours a top-heavy mass function [Nayakshin & Sunyaev 2005; Paumard et al. 2006] there could still be undetected lower-mass stars in the same region. Low mass stars, however, always act to damp the dispersion of the observed massive stars [Alexander et al. 2007], so in ignoring them our models yield an upper limit to the rms eccentricities and inclinations that result from scattering.

3 SIMULATIONS

3.1 Single stars

To establish a baseline for subsequent comparisons, we first model the evolution of a disc of single stars similar to that considered previously [Alexander et al. 2007]. We also use this simple system to test the numerical convergence of the integrator, by running three sets of models with different integrator tolerances. Each set includes three independent realisations of the initial conditions.

2 Young stars are observed further away, but their density decreases rapidly and their scattering time-scales become longer with radius, so we do not expect the omission of stars at $r > 0.15$ pc to alter our results.

Figure 1 shows the evolution of the rms values of the eccentricity and inclination for each simulation. We find that convergence is obtained for an accuracy parameter specified by accuracy $= 2 \times 10^{-13}$, and that results accurate to the 10% level, adequate for our purposes, can be obtained with accuracy $= 10^{-12}$. We use the latter value for most of our subsequent runs.

As expected theoretically, the eccentricity and inclination rms grow roughly as $t^{1/4}$, with a proportionality $e_{\text{rms}} \approx 2t_{\text{rms}}$ (e.g., Lissauer 1993), where $i$ is measured in radians. To compare quantitatively with previous work, we fit the average eccentricity rms from all nine simulations with the analytical solution,

$$
\frac{dr_e}{dt} = \frac{G^2 N_* M_*^2 \ln \Lambda}{C_1 r \Delta r \sigma_*^3},
$$

where $\sigma_*$ is the velocity dispersion of a stellar disc of $N_*$ stars each of mass $M_*$, orbiting at radius $r$ with radial extension $\Delta r$. The quantity $\ln \Lambda$, is the Coulomb logarithm, $t_{\text{orb}}$, the orbital period at $r$, and $C_1$ a geometrical constant of order unity (e.g., Lissauer 1993). In agreement with prior work, we conclude that an initially circular disc set up to match the numbers and masses of observed stars in the GC attains an rms eccentricity of around 0.2 within a few million years. This is too small to explain the larger eccentricities observed in the GC population.

3.2 Primordial binaries

A small number of binary stars have been identified in the Galactic Centre [Martins et al. 2006; Peeples et al. 2007; Rafelski et al. 2007], and, given our current knowledge of disc fragmentation, it is possible that the primordial binary fraction resulting from a fragmenting disc could be significant. Encounters between stars and hard binaries tend to shrink the binary orbit, releasing energy that
The average here is defined not over stars, but rather over ‘objects’ that with 100 km s$^{-1}$ velocity it had in the binary. Perets et al. (2008), however, showed that even supernovae can also heat the disc, as the surviving companion keeps the system acquiring.

Figure 2. Eccentricity rms values from the nine different simulations of discs of binary stars. The tighter the binaries are initially, the more dispersion the system acquires.

non-aligned case. We also experimented with decreasing the minimum distance below which stars are assumed to merge. A reduction in this scale by a factor of three resulted in slightly smaller eccentricities, but we were unable to demonstrate convergence by evolving systems with even smaller merger radii due to numerical difficulties. Accordingly, we do not attach physical significance to this difference. In reality, the dynamics of any binaries that shrink to such small scales (which are less than an AU) would likely be affected by the presence of circumstellar discs left over from their formation. We cannot model such effects, but it is hard to see how they could increase the overall stellar disc eccentricity.

3.3 Eccentric flat discs

If the stars originated from the fragmentation of a self-gravitating disc, they did not necessarily form in the GC we consider. To study whether binary heating could be significant for the GC we used an idealised model in which the initial binary fraction is 100%. We replace the disc of 100 single stars with one made up of 50 equal mass binaries, whose centres of mass are initially in circular orbits about the black hole. For the fiducial case the binary orientations lie in the disc plane. In each simulation all binaries have the same initial value of semi-major axis, which we vary between 10$^{-3}$ pc and 10$^{-4}$ pc. A binary with semi-major axis 10$^{-1}$ pc is hard (and hence will shrink and give energy back to the system) if the stellar velocity dispersion $\sigma_e \lesssim 20$ km s$^{-1}$, which corresponds to $e \sim 0.1$. For numerical reasons we are only able to track binaries as they shrink down to a minimum size which we set at $3 \times 10^{-6}$ pc. If any stars get closer than this limit, the code merges them into a single object conserving energy and momentum.

Figure 3 shows the results for these simulations, with the blue curves depicting the case of randomly oriented orbits. The typical eccentricity remains fixed at $e \approx 0.5$, while the inclination remains a typical value of 0.1, just as in the circular case (Sect. 3.1). The runs starting with aligned orbits (red curves) have a larger spread in eccentricities (although still $e_{\text{rms}} \approx 0.5$), with approximately

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3 Supernovae can also heat the disc, as the surviving companion keeps the velocity it had in the binary (Perets et al. 2008), however, showed that even with 100 km s$^{-1}$ kicks no significant inclinations are reached.

4 The average here is defined not over stars, but rather over ‘objects’ that could be either bound binaries or single stars. It is very hard to determine whether the observed stars are actually singles or binaries, so the value we are plotting is what can be compared to current observations.
can be formed via scattering of GC. It does not seem likely that a significant non-disc population is as if these very massive stars disappeared a very short time ago. To study the effect of these black holes, we set up simulations in which the stellar disc was initialised as described in Section 3.1. We then added $N$ intermediate mass black holes, with orbits appropriate for an isotropic cluster with number density profile $n(r) \propto r^{-7/4}$ (Bahcall & Wolf 1976) (i.e. drawn from an energy distribution $f(E) \propto E^{1/2}$ with random directions). We consider a model with $N = 5 \times 1000 - M_\odot$ inside 1 pc (similar to the number expected from Portegies Zwart et al. 2006 analysis), together with additional cases that assume $N = 10 \times 500 - M_\odot$ and $N = 20 \times 500 - M_\odot$ intermediate mass black holes.

The resulting $e_{\text{rms}}$ curves are shown in Figure 5. There is a lot of dispersion between the different realisations, since the small numbers of black holes involved mean that in some cases none (or very few) of the massive objects intersect the stellar disc. However, it is clear that the typical effect is rather similar to the case of massive stars discussed previously. Quite large eccentricities are readily produced, but the inclinations ($i_{\text{rms}} \approx \epsilon_{\text{rms}}/2$, not shown in the plot for clarity) remain too small to explain the observed distribution of stars in the Galactic Centre.

5 Note that although Kozai (1962) resonance would allow for the generation of high inclinations, the rapid precession of stellar orbits due to the stellar cusp is likely to destroy this resonance.
4 CONCLUSIONS

In this paper we have studied the dynamical evolution of initially flat cold stellar discs consisting of the massive stars observed today in the GC. We find that these systems do not evolve to match the observed stellar population – which includes significant numbers of stars that are not clearly identified with a well-defined disc plane – even when scattering from plausible (and perhaps not so plausible) additional perturbers is included. It is clear that the most important observational constraints on theoretical models comes from measurements of the orbital inclinations. Although a flat circular disc does not become eccentric enough in 5 Myr to match the observed orbital inclinations, it is possible to create quite eccentric systems either by scattering from eccentric gas discs, or by perturbing circular discs with additional massive objects (short-lived stars, or intermediate mass black holes). However, in no cases that we have considered is it possible to generate enough high inclination or counter-rotating stars within the available time. No physical process we have considered breaks the basic relation \( \epsilon_{\text{rms}} \approx \epsilon_{\text{ini}} \), between the mean eccentricity and inclination and this, coupled with the slow rate of heating at late times (typically \( \propto t^{1/2} \)), precludes formation of a significant non-disc population.

The simplest disc scenario for forming the sub-pc stars in the GC appeals to the fragmentation of a flat gaseous disc into a population of massive stars. Both the tendency of self-gravitating accretion discs at these radii to fragment, and the subsequent formation of a top-heavy mass function, receive at least qualified support from theory (Shlosman & Begelman 1989; Levin & Beloborodov 2003; Nayakshin et al. 2007). However, our results suggest that it is very unlikely that subsequent evolution of a stellar system formed in this manner would yield any substantial population of stars outside of the original disc plane or planes. Possible alternatives are that some or all of the GC stars migrated inward from larger radii (though this model has its own challenges, e.g., Kim et al. 2004; Nayakshin & Sunyaev 2003), that a non-spherical component in the background stellar population, or a second stellar disc (Nayakshin et al. 2006), influences the dynamics of the main stellar disc in ways we have not considered; or that in situ star formation occurs in a very complex geometry. In the latter case the present orbits of stars are expected to trace, to a first approximation, the angular momentum distribution of the star forming gas.

Ideas that would yield dynamically hot initial conditions – such as very strongly warped discs (Nayakshin 2005) or clouds that collapse as they engulf the black hole (Yusef-Zadeh & Wardle 2008), perhaps forming two coeval discs (Genzel et al. 2003) – have been proposed, though whether such scenarios can be analysed in the same framework as the simpler disc models is dubious.

It is to be hoped that better observational data on the stellar orbits, which should confirm or refute the existence of additional clustering in the distribution of orbital vectors, will afford some insight into which models are viable.

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