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Secular evolution of the young stellar disc in the Galactic Centre

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ABSTRACT
A significant number of early-type stars have been discovered in the innermost parsec of the Milky Way. Roughly one half of those which are orbiting the central supermassive black hole at projected distances $\gtrsim 0.03$ pc appear to form a coherently rotating disc-like structure. A massive molecular torus and an extended cusp of late-type stars have also been detected in this region. Assuming that the stellar disc is initially thin and geometrically circular, we investigate its secular orbital evolution by means of numerical N-body integration. We include the gravitational influence of both the torus and cusp, as well as the self-gravity of the disc. Our calculations show that for a variety of initial configurations, the system evolves to a state compatible with the current observational data within the life-time of the early-type stars. In particular, the core of the disc naturally reaches a perpendicular orientation with respect to the torus. We thus suggest that all the early-type stars may have been born within a single gaseous disc.

Keywords: numerical methods – stellar dynamics – Galactic Centre

1 INTRODUCTION

The centre of the Milky Way harbours, according to recent observations, nearly 200 early-type stars moving on Keplerian orbits around a highly concentrated mass (Allen et al., 1990; Genzel et al., 2003; Ghez et al., 2003, 2005; Paumard et al., 2006; Bartko et al., 2009, 2010), presumably a supermassive black hole (SMBH) of mass $\approx 4 \times 10^6\, M_\odot$ (Ghez et al., 2003; Eisenhauer et al., 2005; Gillessen et al., 2009; Gillessen et al., 2009; Yelda et al., 2011). Most of them are located at projected distance $0.03\ \mathrm{pc} \lesssim r \lesssim 0.5$ pc from the SMBH (Bartko et al., 2009, 2010). Out of these stars, roughly one half form a disc-like structure, the so-called clockwise system (CWS; discovered by Levin and Beloborodov, 2003), while the other half reside on randomly oriented orbits. Observations indicate that all of these stars are coeval and 6 ± 2 Myr old (Paumard et al., 2006). Their origin is, however, rather puzzling. Due to strong tidal field of the SMBH, it is not possible for a star to be formed by any standard star formation mechanism. On the other hand, no transport mechanism is efficient enough to bring them from farther regions, where their formation would be easier, to the observed location within their estimated lifetime. Various hypotheses have, therefore, been suggested in order to explain the origin of these stars.

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In situ fragmentation of a self-gravitating disc is probably the currently most widely accepted formation scenario for the stars of the CWS (Levin and Beloborodov, 2003; Paumard et al., 2006) as this process naturally forms stars in a disc-like structure. It does not, however, explain the origin of the stars observed outside the CWS. Hence, in order to justify the in-disc formation scenario, another mechanism that would force some of the stars to leave the parent disc plane is needed. Šubr et al. (2009) suggested that this might have happened due to gravity of a massive ($\sim 10^6\,M_\odot$) molecular torus, the circumnuclear disc (CND), which is observed between 1.6 pc and 2.0 pc from the SMBH (Christopher et al., 2005). They argue that the CND would cause differential precession of the individual orbits within the parent stellar disc. Consequently, the stars from the outer parts of the disc would be dragged out of the disc plane while the inner parts of the disc would remain undisturbed. This core can be identified as the CWS today.

In this work, we further analyse the mechanism suggested by Šubr et al. (2009). In particular, we focus on the impact of the self-gravity of the parent stellar disc on its orbital evolution in a predefined external potential of the SMBH, CND and a cusp of late-type stars which is also observed in the Galactic Centre (Genzel et al., 2003; Schödel et al., 2007; Do et al., 2009). As the first approximation, we consider the cusp to be spherically symmetric and centred on the SMBH.

2 NUMERICAL MODEL

The gravitational potential induced by the SMBH in the vicinity of the stellar disc can be, to a very high accuracy, considered Keplerian. It is thus natural to describe the stellar orbits in the disc by means of the Keplerian elements: semi-major axis a, eccentricity e, inclination i, longitude of the ascending node Ω and argument of pericentre ω. For sake of definiteness, let us define the z-axis of our reference system as the symmetry axis of the CND, i.e. orbital inclination i is the angle between the symmetry axis of the CND and angular momentum of the star. If the only component of the overall gravitational potential were the gravity of the SMBH, the Keplerian elements of all the individual orbits would be constant in time. On the other hand, inclusion of any additional gravitational potentials may lead to an intricate secular evolution of some of the elements.

Šubr et al. (2009) have investigated the influence of the CND and spherical cusp on the stellar disc with the stars treated as test particles. They found that the CND causes differential precession of the individual stellar orbits in the disc. Furthermore, provided the spherical cusp is massive enough, the first time derivative of Ω, the precession rate, is constant and can be written as

$$\frac{\mathrm{d}\Omega}{\mathrm{d}t} = -\frac{3}{4}\frac{\cos i}{T_\mathrm{K}}\frac{1+\frac{3}{2}e^2}{\sqrt{1-e^2}} \tag{1}$$

with

$$T_\mathrm{K} \equiv \frac{M_\bullet}{M_\mathrm{CND}}\frac{R^3_\mathrm{CND}}{a\sqrt{GM_\bullet a}}\,, \tag{2}$$

where $M_\bullet$ represents the mass of the SMBH, $M_{\rm CND}$ and $R_{\rm CND}$ stand for the mass and radius of the CND, respectively, and G denotes the gravitational constant. It thus appears that the precession rate strongly depends upon the semi-major axis of the orbit. Hence, the outer parts of the disc are more affected by the precession than the inner parts, which results in warping of the disc and, eventually, in its complete dissolution.

Including the gravity of the stars in the disc leads to random variations of the individual orbital elements due to two-body relaxation of the disc. Although these changes are not large enough to have an impact on the overall shape of the disc by themselves (Cuadra et al., 2008), they can, according to formula (1), affect the precession rate of the individual orbits. Let us, therefore, further focus on the combined effects of differential precession and two-body relaxation of the disc.

For this purpose, we model the individual components of the Galactic Centre as follows: (i) the SMBH of mass $M_\bullet = 4 \times 10^6\,M_\odot$ is considered to be a source of the Keplerian potential, (ii) the CND is modelled as a single massive particle of mass $M_{\rm CND}$ orbiting the SMBH on a geometrically circular orbit of radius $R_{\rm CND} = 1.8$ pc, (iii) the spherical cusp is represented by a smooth power-law density profile, $\rho\,(r) \propto r^{-\beta}$, and mass $M_{\rm c}$ within the radius $R_{\rm CND}$, (iv) the stars in the disc are treated as a group of N gravitating particles orbiting the SMBH on orbits that are initially geometrically circular. Their radii are generated randomly between 0.04 pc and 0.4 pc in compliance with relation $\mathrm{d}N \propto a^{-1}\,\mathrm{d}a$. Distribution of masses of the individual stars in the disc follows a power-law mass function $\mathrm{d}N \propto m^{-\alpha}\,\mathrm{d}m$, $m \in [m_{\rm min}, m_{\rm max}]$. Evolution of this system is investigated numerically by means of the N-body integration code NBODY6 (Aarseth, 2003).

3 DISCUSSION OF THE RESULTS

The course of the orbital evolution of the stellar disc depends upon many parameters that describe the overall gravitational potential in the system: $M_{\rm CND}$, $M_{\rm c}$, β, N, $m_{\rm min}$, $m_{\rm max}$, α, initial inclination of the disc with respect to the CND, $i^0_{\rm CWS}$, and its initial half-opening angle, Δ_0. Our calculations show that, for a wide set of these parameters, the system reaches a configuration compatible with the current observational data after $\approx$6 Myr of its orbital evolution (for a detailed discussion, see Haas et al., 2011a).

In particular, it appears that the orbits in the outer parts of the disc are indeed affected by the precession of the ascending node more strongly than those in the inner parts. This leads, in accord with formula (1), to gradual deformation of the disc and, eventually, to disruption of its entire outskirts. Moreover, it turns out that the precession is, on longer time-scales, globally accelerated in the outer parts of the disc, which we attribute to the two-body relaxation of the disc. This acceleration was not observed by Šubr et al. (2009) as they had not considered the self-gravity of the disc.

Furthermore, our results show that the mean inclination of the orbits in the outer parts of the disc is decreasing. On the other hand, it grows up and saturates at $\approx 90^\circ$ in the inner parts. We further find that the evolution of the mean values of both the inclination and longitude of the ascending node is similar for all the orbits in the inner parts of the disc. The core of the disc thus remains undisturbed and coherently changes its orientation towards perpendicular with respect to the CND. This effect can be seen in the left panel

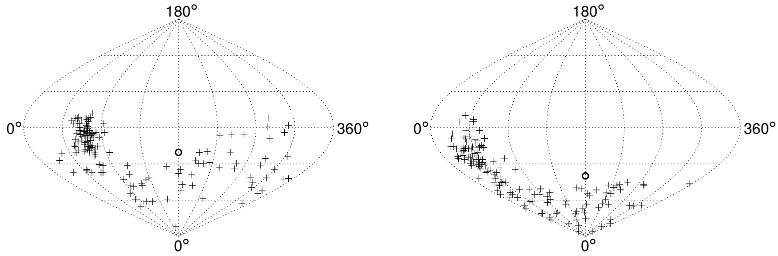

Figure 1. Angular momenta of individual stars in the disc in sinusoidal projection after 6 Myr of orbital evolution. The initial state is denoted by an empty circle. Latitude on the plots corresponds to i while longitude is related to Ω. *Left*: One realization of a model with $i^0_{\rm CWS} = 70°$. *Right*: $i^0_{\rm CWS} = 50°$. The other parameters are set to their canonical values for both panels. For a more convenient comparison with the currently available observational data which suggest that the early-type stars are massive, only stars with $m \geq 12\,M_\odot$ are displayed. The less massive stars with $m = 4$–$12\,M_\odot$ have been included in our calculations since it is likely that a number of them exist undetected in the Galactic Centre.

of Fig. 1 which shows the directions of the individual angular momenta of the stars in sinusoidal projection for one of the realizations of the 'canonical' model: $M_{\rm CND} = 0.3\,M_\bullet$, $M_{\rm c} = 0.03\,M_\bullet$, $m \in [4\,M_\odot, 120\,M_\odot]$, $N = 200$, $\alpha = 1$, $\beta = 7/4$, $i^0_{\rm CWS} = 70°$, $\Delta_0 = 2.5°$. Our results suggest that the compact group of stars at inclination $\approx 90°$ is formed by the stars from the inner parts of the disc, while the stars scattered all around the bottom half of the plot represent the disrupted outer parts. Hence, we see that it is possible to reconstruct the currently observed configuration of the studied early-type stars in the Galactic Centre from a single and initially thin stellar disc. In particular, its compact core can represent the CWS observed today while the stars from the dismembered outer parts can be identified with the stars observed off the CWS plane.

In order to compare our findings with the observations more thoroughly, let us define the CWS within our data as follows. As the zeroth step, the CWS is taken equivalent to a fixed number of the innermost stars from the initial disc. In the next step, we exclude all the stars whose angular momenta deviate from the mean angular momentum of the CWS by more than 20°. On the other hand, the stars initially from outside the CWS, which do not fulfil the latter condition, are included into the CWS. Then, we recalculate the mean angular momentum of the CWS and repeat the whole procedure iteratively until there are no changes of the CWS between two subsequent steps.

Observations indicate that the CWS harbours roughly one half of all the early-type stars between 0.03 pc and 0.5 pc from the SMBH (Paumard et al., 2006; Bartko et al., 2009, 2010). In order to confront this feature, we investigate the evolution of the relative number $N/N_{\rm CWS}$ of the stars belonging to the CWS within our calculations. As can be seen in the top left panel of Fig. 2, this number reaches for the canonical model ≈ 0.5 after 6 Myr of orbital evolution. Observations further suggest that the CWS is roughly perpendicular to the CND (Paumard et al., 2006). We thus follow in our calculations the inclination $i_{\rm CWS}$ of the CWS with respect to the CND. The top right panel of Fig. 2 shows that our results are in agreement even with this observational constraint as $i_{\rm CWS} \approx 90°$ at $t = 6$ Myr.

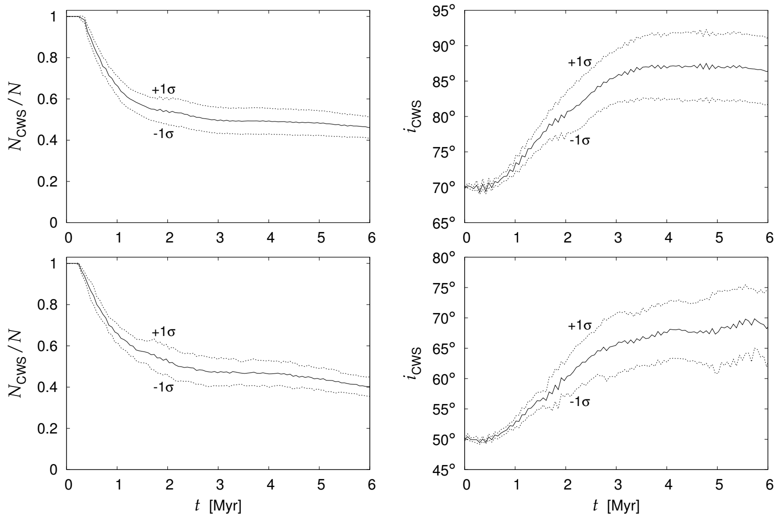

Figure 2. Evolution of the CWS for a model with $i^0_{\rm CWS} = 70°$ (top panels) and $i^0_{\rm CWS} = 50°$ (bottom panels). The other parameters are set to their canonical values in both cases. Only properties of the stars with $m \geq 12\,M_\odot$ are displayed. The dotted lines denote standard deviation for the set of 12 included realizations. *Left*: Number of stars within the CWS (i.e. with angular momentum deviating from the mean angular momentum of the CWS by less than 20°). *Right*: Inclination of the CWS with respect to the CND.

In order to illustrate the dependence of the discovered processes upon the initial parameters, we also show our results for a model with $i^0_{\rm CWS} = 50°$. The other parameters remain set to their canonical values. As we can learn from the right panel of Fig. 1 and the bottom panels of Fig. 2, in this case, the CWS contains at $t = 6$ Myr only $\approx 40\,\%$ of the stars and its inclination reaches only $\approx 70°$. The evolution on longer time-scales proves that even though the inclination of the CWS continues to increase, the number of the stars within the CWS further decreases. Hence, the parent stellar disc is too severely damaged by the differential precession before its core can reach the perpendicular orientation, and, therefore, the observational criteria are not fulfilled for this model. Our results suggest that the studied system evolves after ≈ 6 Myr to a state which accommodates the observational constraints if $i^0_{\rm CWS} \gtrsim 60°$. A more detailed discussion of the remaining parameters can be found in Haas et al. (2011a).

3.1 Physical background

As we have shown in Haas et al. (2011b) by means of standard perturbation methods of celestial mechanics, the dynamical processes described in previous paragraphs are a consequence of preservation of integrals of motion in the considered gravitational potential. In particular, beside the total energy and z-component of the total angular momentum of the stars in the disc, the potential energy which corresponds to their mutual interaction in the field of the CND is also preserved if averaged over one revolution of the stars around the

SMBH. Depending on the strengthens of this interaction, two modes of orbital evolution are possible. Either the stellar orbits interact strongly and, under such circumstances, they become dynamically coupled, precessing coherently in the potential of the CND. Or, if their mutual interaction is weaker, the orbits precess independently, interchanging periodically their angular momentum, which results in oscillations of inclinations. Hence, the dense core of the stellar disc, where the interaction of the orbits is strong enough, is not disrupted by the differential precession. On the other hand, the weakly interacting orbits from the outer parts can not overcome the disturbing influence of the CND and, therefore, the outskirts of the disc are entirely dismembered.

Moreover, the core of the disc inevitably changes its inclination towards higher values due to interaction with the outer parts of the disc as a whole, similarly to the case of two interacting orbits.

4 CONCLUSIONS

We have investigated the secular evolution of an initially thin and geometrically circular self-gravitating stellar disc around a dominating central mass. In accord with the observations of the Galactic Centre, we have included the perturbative gravitational potential of the CND and the cusp of late-type stars. Our results show that the CND causes differential precession of the stellar orbits in the disc which leads to gradual dissolution of its outer parts. On the other hand, the core of the disc remains, due to stronger mutual interaction of its stars, untouched forming the CWS. Simultaneously, the CWS changes coherently its orientation towards perpendicular with respect to the CND which is indeed the configuration observed in the Galactic Centre. We further find that these processes lead to a configuration compatible with the currently available observational data for a wide set of system parameters. Hence, we suggest that all the early-type stars observed at projected distances 0.03–0.5 pc from the SMBH may have been formed within a single gaseous disc and, subsequently, brought to their present location by the combined effects of differential precession and two-body relaxation.

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