Dynamical evolution of the young stellar disc in the Galactic centre

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Abstract. Origin of several hundreds of young stars in within the distance \( \lesssim 1 \) pc from the Galactic supermassive black hole still represents an open problem of contemporary astrophysics. In this contribution we further investigate the model which assumes their formation in situ via fragmentation of a self-gravitating gaseous disc. We show that currently observed configuration of the system of young stars can be obtained as an outcome of a dynamical evolution of a single, initially very thin stellar disc. Our model assumes the long-term evolution of the stellar disc to be determined by gravitational influence of a distant molecular torus (CND) and mutual resonances of stellar orbits within the disc.

1. Introduction

High resolution observations of the Galactic Centre have brought surprising view of the nuclear star cluster. One of the unexpected discoveries is presence of a numerous population of massive young stars. Current observations distinguish up to \( \sim 200 \) of O and B giants, LBVs and Wolf-Rayet stars within a distance \( \lesssim 1 \) pc form the central supermassive black hole (SMBH), identified as a radio source SgrA*. It has been soon realised (Genzel et al. 2000) that velocity dispersion of the young stars in the Galactic Centre (few tens of them were observed at that times) is strongly anisotropic. Later on, Levin & Beloborodov (2002) have shown that subset of them have coplanar orbits, forming a stellar disc. Nowadays, it is widely accepted that the young stellar disc, so-called clockwise stellar disc (CWS) spans from \( \sim 0.04 \) pc to \( \sim 0.5 \) pc and it consists of \( \gtrsim 50 \) stars. Rest of the stars is on orbits more or less scattered from the CWS plane. Due to lack of reliable knowledge of orbital parameters of individual stars, it is difficult to make strong statements about shape of the structure they form. Some authors (e.g. Genzel et al. 2003, Paumard et al. 2006) suggest presence of two stellar disc, some others (e.g. Bartko et al. 2009) speak about some kind of warped disc(s).

The most surprising fact about these young stars is their location in the vicinity of the SMBH. Standard formation scenario which assumes some kind of (quasi-)spherical collapse through the protostellar phase can hardly work due to strong tidal forces of the SMBH. Well known process of mass segregation that generally transports massive stars towards centres of star clusters acts on much longer time-scales than the life-time of the observed massive stars. Already in the work of Levin & Beloborodov (2002) it has been suggested that the stars may have been formed in situ via fragmentation of a massive gaseous disc. Alternate theories of their origin are based on some transportation mechanism that may have brought them towards the SMBH from more...
distant region where their formation is considered to be less tricky. Both classes of models apparently fail to explain some observed properties of the set of young stars in the Galactic Centre. While the in situ formation scenario naturally places stars into the disc-like structure, it has a difficulty to explain the fact that at most only a half of the observed young stars are orbiting the black hole coherently, while the other half is on apparently randomly oriented orbits. Moreover, observational data indicate that orbits of a substantial fraction of the young stars have moderate or large eccentricities ($e \gtrsim 0.5$) while the model more naturally leads to low eccentricities. The main drawbacks of the ‘transportation’ model is the fact that the parent star cluster would be tidally disrupted already at larger distances from the SMBH, unless it is strongly bound together e.g. via an intermediate-mass black hole. However, observations indicate neither young stars to be present at distances above 1 pc from SgrA*, nor any evidence for an IMBH within the central parsec.

Our work aims to support the hypothesis of star formation in a single thin disc. By means of numerical N-body simulations we show that such a system would evolve into a currently observed state provided it is influenced by a distant massive axisymmetric source of gravity. This setup is justified by an observed gaseous torus (so-called circum-nuclear disc, CND) which orbits the central SMBH at a distance of $\sim 1.5$ pc.

2. Motion in the perturbed Keplerian potential

In our analysis, we consider gravitational field in the central parsec of the Galaxy to be dominated by the supermassive black hole. Hence, on short time-scales, the stellar motions follow Keplerian ellipses. Their shape is described by semi-major axis, $a$, and eccentricity, $e$. Orientation of the orbital plane is determined by two angles – inclination, $i$, with respect to some reference plane and longitude of the ascending node, $\Omega$ (see Fig. 1). One more angle, argument of pericentre, $\omega$, describes orientation of the orbit within its plane and, finally, true anomaly determines position of the body on the orbit.

We further assume that, on longer time-scales, the stellar orbits evolve due to

(i) gravity of a spherical cusp of late-type stars
(ii) gravity of a distant gaseous torus (CND) which is modelled by a massive ring
(iii) mutual torques of stellar orbits from the disc.

2.1. External perturbations

Secular evolution of Keplerian orbits under the influence of a distant massive perturber has been extensively studied in the past. Considering the molecular torus of mass $10^5 M_\odot \lesssim M_{\text{CND}} \lesssim$
**Figure 2.** Sinusoidal projection of angular momenta of individual stars. Latitude corresponds to inclination with respect to the CND; longitudinal angle is $\Omega$. Initial angular momenta are confined within the shaded regions with half-opening angle of $5^\circ$ and $2^\circ$ in the left and right panels, respectively. Directions of individual orbits after $\sim 7$ Myr of dynamical evolution are marked with crosses. Main constituents of the gravitational field are the central SMBH of mass $4 \times 10^6 M_\odot$, CND of mass $0.2 M_\star$ and radius 1.6 pc and a spherical cluster of mass $0.1 M_\star$ within $R_{\text{CND}}$, which is modelled by smooth potential. In the left panel, stars are treated as test particles and their mean initial inclination with respect to the CND is $80^\circ$. In the right panel, all stars have equal masses of $M_\star = 40 M_\odot$ and the initial mean inclination is $60^\circ$. The initial stellar disc has a surface density profile $\propto r^{-2}$ within the interval $(0.04 \, \text{pc}, 0.4 \, \text{pc})$.

$10^6 M_\odot$ and typical radius $R_{\text{CND}} \approx 1.6$ pc as the main perturbation to the dominating Keplerian potential of the central SMBH, we may directly apply well established analysis of a hierarchical triple systems as introduced by Kozai (1962) and Lidov (1962). Note that the secular theory of hierarchical triple systems uses averaging technique for description of potential of the outer body, i.e. its outcomes are directly applicable to our case in which the outer body is replaced with a ring of radius $R_{\text{CND}}$ and mass $M_{\text{CND}}$. In general, the star on an orbit with semi-major axis $a \ll R_{\text{CND}}$ would undergo periodic oscillations of inclination and eccentricity, coupled with oscillation or rotation of the argument of pericentre, $\omega$, and monotonic decrease of the longitude of the ascending node, $\Omega$ (angles are measured with respect to the plane of the outer body, i.e. plane of the CND in our model). Characteristic time for the secular evolution is then

$$T_K = \frac{M_\star}{M_{\text{CND}}} \frac{R_{\text{CND}}^3}{a \sqrt{G M_\star a}}. \quad (1)$$

In contrary, an extended spherically symmetric source of perturbation which may be represented by the cusp of late-type stars in the Galactic Centre, leads solely to (negative) pericentre advance (i.e. rotation of the angle $\omega$). It has been shown by various authors that combination of both spherical and axisymmetric perturbations may lead to significant damping of ‘Kozai’ oscillations of eccentricity and inclination. In Šubr & Schovancová (2008) and Šubr et al. (2009) we have shown that under the assumption of massive enough spherical cusp, the only remaining effect of the gravitational influence of the CND upon the orbital planes is monotonic precession around the symmetry axis of the CND with frequency

$$\dot{\Omega} = -\frac{3}{4} \cos i a^{3/2} \sqrt{G M_\star} \frac{M_{\text{CND}}}{R_{\text{CND}}^2 M_\star} \frac{1 + \frac{3}{2} e^2}{\sqrt{1 - e^2}}. \quad (2)$$
Strong dependence of \( \dot{\Omega} \) upon the orbit semi-major axis and inclination with respect to the CND (for \( i \rightarrow 90^\circ \)) led us to formulate a hypothesis that all young stars in the Galactic Centre (except for the S-stars) have been formed in a single gaseous disc. Due to differential precession of individual stellar orbits in the compound gravitational field of the CND and the spherical cusp, the outer and/or less inclined stars have been stripped out of the parent structure. The innermost parts which were less subject to the precession are distinguished as the CWS today. Due to strong dependence of the orbital precession upon the inclination with respect to the CND, this model requires initial inclination of the disc close to 90\(^\circ\). Differential precession than leads to a specific warped structure with angular momenta lying nearly in the plane of the CND (see left panel of Fig. 2).

2.2. Mutual torques of stellar orbits

The above formulated hypothesis of the origin and subsequent orbital evolution of young stars in the Galactic Centre is based on an assumption of negligible mutual interaction of stars which are treated as test particles moving in the external gravitational field. Consequently, their inclination with respect to the CND remains unchanged which leads to a specific pattern of projection of their angular momenta on the sphere. A natural step forward is to consider mutual gravitational interaction of stars from within the disc. In Haas et al. (2011b) we have introduced a set of equations describing secular evolution of two interacting circular orbits in the external field of a distant ring and a spherical cusp. Underlying perturbative Hamiltonian theory is a straightforward variation of the approach of Kozai (1962) and Lidov (1962) mentioned above. We have shown that initially coplanar orbits may interact in two qualitatively different regimes:

(i) In the case of weak interaction, the orbits precess independently around the symmetry axis with frequencies \( \dot{\Omega}(a) \) and \( \dot{\Omega}(a') \). On time-scale \( 2\pi/|\dot{\Omega}(a) - \dot{\Omega}(a')| \), they periodically exchange angular momentum which leads to oscillations of their inclinations.

(ii) Strong interaction regime may occur if mass of the stars is large and/or their orbits are close enough. In this case, they also exchange periodically some part of their angular momentum, but the inclination oscillations have generally smaller amplitudes and their precession is locked together.

Fig. 3 shows examples of evolution of two interacting stellar orbits in the external perturbative field of the CND. In two upper panels we plot evolution of inclinations and longitudes of ascending nodes for orbits interacting in the strong regime, while lower panels show weakly interacting system. Difference between the two cases are just masses of the interacting stars, while other parameters are kept unchanged.

We have further generalised our semi-analytical treatment to larger number of interacting stars. It appears that the two basic modes of interaction can be still found in the evolution of the N-body system. In particular, groups of stars interacting within the strong regime keep close values of \( i \) and \( \Omega \) (i.e. orientations of their orbits). On the other hand, several, internally strongly interacting, groups of stars may interact in the weak regime with each other which leads to secular change of their orientation – see Fig. 4 for an example with four stars.

We argue that mutual torques among orbits played an important role in evolution of the young stellar system in the Galactic Centre. The denser inner part of the disc may have survived differential torque from the CND even for moderate initial inclinations. Moreover, due to the weak regime interaction with the outer parts, the surviving inner disc gradually changed its orientation towards higher inclination with respect to the CND which is in accord with present-day mutual orientation of the CND and the CWS. Right panel of Fig. 2 demonstrates this behaviour in terms of projections of angular momenta of the stellar orbits. The system presented here was integrated by means direct N-body integrator NBODY6 with the central SMBH being represented by an external Keplerian potential. The spherical stellar cusp was
Figure 3. Temporal evolution of inclination and longitude of the ascending node for two mutually interacting stars in a perturbative gravitational field of a massive ring (CND). Upper panels describe to stars in the strong interacting regime (coupled precession) while the bottom ones correspond to weakly interacting orbits. Common parameters are: mass of the central SMBH $M_\bullet = 4 \times 10^6 M_\odot$, $M_{\text{CND}} = 0.3 M_\bullet$ and $R_{\text{CND}} = 1.6$ pc. Semi-major axis of the inner orbit (solid lines) is $a' = 0.04 R_{\text{CND}}$, while the outer one (dashed lines) is at $a = 0.05 R_{\text{CND}}$. Masses of stars are $M = M' = 36 M_\odot$ and $M = M' = 20 M_\odot$ in the upper and lower panels respectively.

approximated by an additional external potential corresponding to the Bahcall & Wolf (1976) radial density profile $\rho(r) \propto r^{-7/4}$ with total mass $0.1 M_\bullet$ within $R_{\text{CND}}$. In accord with the findings of the perturbative Hamiltonian theory, we modelled the CND by a single massive particle orbiting the SMBH on a circular orbit of radius $R_{\text{CND}} = 1.6$ pc. Finally stellar disc was set up as 200 gravitating particles of equal mass $M_\star = 40 M_\odot$ which were generated randomly on circular orbits with semi-major axis distribution $n(a) \propto 1/a$ within the interval $[0.04$ pc, $0.4$ pc]. Half-opening angle of the disc was $2^\circ$ and it was inclined $60^\circ$ with respect to the CND. Right panel of Fig. 2 shows both the initial state and a snapshot at $t = 7$ Myr. Approximately one half of the stars still forms a coherently rotating structure which changed its orientation to nearly perpendicular with the CND. Second half was stripped from the parent structure. Hence, considering mutual gravitational influence of stars from the disc leads to the state compatible with the observations for much wider range of initial conditions than the model in which the stars are treated as test particles (left panel of Fig. 2). In the latter case, the parent disc has to start from orientation close to perpendicular with respect to the CND as its inclination does not change in time. Moreover, disc of test particles is much more vulnerable to destruction through differential precession which is stronger for lower inclinations.
Figure 4. Evolution of elements, $i$ and $\Omega$, determining orientation of orbits of four mutually interacting stars. Parameters of the system are identical to the lower panel of Fig. 3 except for masses of the stars which are all equal to $10 M_\odot$ and radii of their orbits which are set to $a_1 = 0.0373 R_{\text{CND}}$, $a_2 = 0.0408 R_{\text{CND}}$, $a_3 = 0.0478 R_{\text{CND}}$ and $a_4 = 0.0511 R_{\text{CND}}$. Pairs of close stars interact in the strong regime, forming two couples which are mutually in the weak interaction regime.

2.3. Two-body relaxation

The mutual orbit interaction described in the previous section operates on time-scales much longer than the orbital period. In the rare case of random close encounters, it ceases to be valid. Two-body stellar relaxation within the sphere of influence has been already discussed in the literature (Rauch & Tremaine 1996, Hopman & Alexander 2006). A general outcome for this kind of systems is that so called resonant relaxation which leads to change of orbital orientation and angular momentum is more efficient than classical two-body relaxation which, in addition, changes energy of stars. However, this generic statement was formulated under the consideration of spherical symmetry. The situation is different in the case of coherently rotating stellar disc. Our N-body simulations show (see also Haas & Šubr 2012) that energy of the stars from the disc may change significantly. This is definitely due to large stellar densities, exceeding by several orders of magnitude stellar density of the spherical cusp. Fig. 5 shows the effect of two-body relaxation by means of change of eccentricity and semi-major axis distributions for the model of stellar disc evolving under the influence of spherical cusp and the CND. Complementary work of Haas & Šubr (2012) shows that identical result is obtained without both perturbations to the central Keplerian potential, i.e. it is solely a consequence of the intrinsic relaxation of the stellar disc.

3. Conclusions

We have set up a model of stellar disc in the Galactic Centre which assumes its origin in a single thin coherently rotating structure. We argue that such an initial configuration may lead to a state comparable to the currently observed system of young stars in the Galactic Centre. The important agents which are capable to transform the initial state into the final one within $\sim 7$ Myr are the massive molecular torus, which, on one hand, leads to partial destruction of the parent disc (i.e. it pushes some stars from the disc to randomly oriented orbits on which they are observed now). On the other hand, together with mutual torques of stellar orbits, the CND leads to secular evolution of the orientation of the surviving disc towards nearly perpendicular which is in accord with the observations. The spherical stellar cusp plays an important role in damping the Kozai oscillations induced by the CND, i.e. preventing the stellar disc from
complete destruction within its life-time. Two-body relaxation among the stellar disc orbits may lead to modification of the initial semi-major axis distribution and is also capable of pushing some stars to moderate or high eccentricities.

Current orbital state of the young stars in the Galactic Centre is, up to several exceptions, still not known exactly. This uncertainty naturally propagates back to the time of their formation. As a final remark let us note that regardless of the model of their origin, dynamical evolution during the life-time of the young stars has to be taken into account in order to establish correct relation between (current) observations and the initial state. We have shown that realistic external sources of gravity may play crucial role in the dynamical evolution of the young stars. Hence, good knowledge of parameters of the CND and cusp of late-type stars is important for proper answer to the question of the origin of young stars in the Galactic Centre.

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Figure 5. Initial (dashed) and final (solid lines) counts of eccentricities and semi-major axes for the self-gravitating stellar disc evolving under the influence of the CND (corresponds to the model in the right panel of Fig. 2.)