Simulations of the Galactic Centre Stellar Discs In a Warped Disc Origin Scenario

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Abstract. The Galactic Center (GC) hosts a population of young stars some of which seem to form a system of mutually inclined warped discs. While the presence of young stars in the close vicinity of the massive black hole is already problematic, their orbital configuration makes the situation even more puzzling. We present a possible warped disc origin scenario for these stars, which assumes an initially flat accretion disc which develops a warp through Pringle instability, or Bardeen-Petterson Effect. By working out the critical radii and the time scales involved, we argue that disc warping is plausible for GC parameters. We construct time evolution models for such discs considering the discs’ self-gravity, and the torques exerted by the surrounding old star cluster. Our simulations suggest that the best agreement for a purely self-gravitating model is obtained for a disc-to-black hole mass ratio of $M_d/M_{bh} \sim 0.001$.

1. Introduction

Our Galactic Centre hosts a supermassive black hole (SMBH), SgrA*, of mass $\sim 4 \times 10^6 M_\odot$ [11, 13, 41, 14]. SgrA* is surrounded by a group of young stars [22, 12, 34, 27, 4, 5] as well as a cluster of old stars [41, 38]. Of the more than 100 young stars observed in the radial range $\sim 0.05$ pc to $\sim 0.5$ pc, nearly 60 populate a disc which rotates clockwise (CW) on the plane of sky [12, 25, 34, 27, 28, 5]. Of the rest, 20 stars seem to form an other counter clockwise (CCW) rotating disc which is highly inclined to the CW one [12, 34, 4, 5] (but also see [27]). Ages of these young stars are a few Myr, suggesting that there has recently been an episode of star formation in the Galactic Centre (GC).

The standard recipe of star formation in terms of the collapse of a molecular cloud seems unlikely to work for the GC environment due to the strong tidal field of the massive black hole. However theoretical studies point to the possibility of fragmentation of accretion discs which become self-gravitating beyond a few tenth of parsec [21, 10, 15, 32, 1]. Simulations of the GC show that such discs might form through the infall [6], or collision [19] of molecular clouds. On the other hand, an open question on the geometrical configuration of the discs remain, since a planar accretion disc, such as that assumed in the above mentioned works, most likely leaves behind a planar distribution of stars when it fragments, but recent observations provide evidence for a gradual 60° warp in the CW disc [4]. Therefore even though the stars might have formed in-situ, their current orbital distribution suggests an origin which is more sophisticated than a simple thin accretion disc [28]. Numerical simulations following the time evolution of such
discs are also in line with this idea, and show that it is unlikely to perturb the stars to the high inclinations they are observed when they form on a cold flat accretion disc [8].

Warped gaseous discs at similar scales are observed in a few nearby AGN, such as NGC4258, NGC1068 and Circinus [18, 17, 16], which suggests that the GC might be representing a particular stage of a cycle during the lifetime of a typical spiral galaxy nucleus [31].

A planar accretion disc could become warped through various processes such as when torqued by a spinning black hole [3, 2, 26, 30], when exposed to radiation from a central source [35, 36, 37], or through vector resonant relaxation [7, 20] if the self-gravity torques do not dominate over the stochastic torques induced by surrounding stellar cusp.

In this work, we propose a scenario for the formation of a warped disc at the Galactic Centre considering radiation instability, and the Bardeen-Petterson Effect as possible warping mechanisms. We assume that when a supposed active phase of the Galactic Center ends, the disc can cool to fragment and form stars. Thereafter, the stellar disc continues its evolution in the gravitational field of the black hole, its self-gravity, and the surrounding old star cluster. We investigate the conditions for which this scenario could work, and we present results from our simulations of warped discs showing that a low mass model such as as inferred from the observations today fits the data reasonably well. A detailed discussion of our results can be found in [43].

2. Warping the Galactic Centre Disc

In this section, we discuss a plausible scenario for the origin of the warp observed in the orbits of the young stars. After assuming the past existence of an accretion disc around the Galactic Centre black hole, we investigate two well studied mechanisms: radiation pressure instability [35, 36, 37] and Bardeen-Petterson Effect [3] for warping the accretion disc. We further assume that the active phase of the GC ends some time, hence the warped disc can cool to form the stars observed today. Thereafter, the evolution of the disc is governed by gravitational torques only. In light of the recent observations presented in [41, 38], we account for the effects of a slightly flattened surrounding star cluster in addition to the disc’s self-gravity.

2.1. Surface Density of the Disc Prior to Fragmentation

In order to determine the plausibly of disc warping prior to star formation, we need to evaluate a few parameters of the gaseous disc, which from the current observations can not be constrained. For those parameters, we mostly make use of the canonical values for AGN discs. However, one parameter, the surface density of the supposed past gaseous disc may be determined by the observations.

When the total number of stars in a stellar system is known, one can determine the total mass in stars by adopting an appropriate initial mass function (IMF), which for the GC discs is shown to be $\xi(M) = \xi_0 M^{-0.45}$ [5]. The total mass in disc stars for the GC reads: $M_s \sim 5360 M_\odot$, translating into a mass ratio of $M_d/M_{bh} = 0.00134$ when the black hole mass is assumed to be $4 \times 10^6 M_\odot$. Once having evaluated the total mass of the current disc, one can then adopt a star formation efficiency, $\epsilon_{SF}$, and determine the gaseous disc mass, and translate this into a surface density for which the warping criteria might be evaluated. The observations of the stellar discs indicate a $1/r^{1.4}$ decline of the surface density [5]. Adopting this, we found for the density of the parent molecular disc $\Sigma_{d,1} = 9.52 \times 10^4 \mu_{5360}^{-1} \epsilon_{SF}^{-1} M_\odot pc^{-2}$, with $\mu_{5360} = (M_s/5360 M_\odot)$ [43].

2.2. Radiation Driven Warping of the Galactic Centre Disc

Warping of accretion discs by radiation is studied in detail by many authors [36, 29, 37, 33]. When an optically thick disc exposed to central radiation absorbs and re-emits the incident photons parallel to the disc local normal, it might acquire a warp if it is slightly distorted. The net torque competes with the $r-z$ stress in the disc, the result of which determines whether
warping will be pronounced or not. The effect of the $r-z$ stress is to force the disc settle onto a plane on a time scale $t_{\nu_2} = 2r^2/\nu_2$, where $\nu_2$ is the coefficient of vertical viscosity. The warp can grow if the settlement time scale is longer than the precession time induced by radiation. This is given as [37]

$$\frac{12\pi \Sigma r^3 \Omega c}{L} \leq \frac{2r^2}{\nu_2},$$

(1)

where $L$ is the luminosity of the central source, $c$ is the speed of light, and $\alpha$ is the Shakura-Sunyaev parameter [39]. For the magnitude of vertical viscosity, we refer to hydrodynamical simulations which give $\eta_\nu = \nu_2/\nu_1 < 3.5/\alpha$, and the radial viscosity coefficient $\nu_1$ can be evaluated using standard equations for accretion discs in steady state [9]. Equation 1 can be rearranged to give the radiation warping critical radius [43]

$$R_{\text{rad}} > \frac{2\eta_\nu^2}{\gamma_{\text{crit}}^2 \epsilon^2} \frac{2GM_{bh}}{c^2} = 9.1 \times 10^{-3} \alpha^{-2} \epsilon_{0.1}^{-2} \text{pc},$$

(2)

where $\gamma_{\text{crit}} \simeq 0.32$ [37], and $\epsilon$ denotes the radiative efficiency. Thus warping the GC disc at the distance of the young stars (0.03-0.5) pc requires $\alpha \sim 0.3$, or $\alpha \sim 0.1$.

2.3. Bardeen-Petterson Effect and the Galactic Centre Disc

When an accretion disc forms around a rotating (Kerr) black hole, its angular momentum might be misaligned with that of the black hole. The parts of the disc close to the hole experience the so-called Lense-Thirring precession [24] which results from the dragging of inertial frames. Since the viscous timescale at these parts of the disc are shorter than those for the outer parts, the inner disc aligns with the black hole spin when the outer parts are still on their original orbits. This way, the disc develops a warp beyond a critical radius $R_{BP}$. The location of this radius is again determined by the competition between alignment timescale, i.e. viscous time scale in the vertical direction, and precession time scale induced by the Bardeen-Petterson Effect. Using steady state disc equations as given in [9], the precession rate given by [23], and solving for the critical radius $R_{BP}$ we found in [43]

$$R_{BP} = 4.22 \times 10^{-4} \left( \frac{a \alpha \Omega \mu_{5360} \epsilon_{SF}}{\eta_{\text{edd}} \epsilon_{SF}} \right)^{1/2.4} \text{pc}$$

(3)

for the GC disc where $a$ is the black hole spin parameter, and $\eta_{\text{edd}} \equiv L/L_{\text{edd}}$, with $L_{\text{edd}}$ the Eddington luminosity. This estimate shows that the Bardeen-Petterson radius for the GC is much below the inner edge of the stellar discs. A comparison of the angular momenta of the disc, and the black hole, in addition to the estimate of the alignment time scale suggests that if the disc fragmented to stars after it was warped through Bardeen-Petterson Effect, $\epsilon_{SF} < 1$, and $\alpha < 0.1$ [43].

3. The Model and The Numerical Setup

In the previous sections we argued that for a range of plausible parameters, an initially flat disc around SgrA* could be warped prior to star formation. After that, the disc evolves gravitationally. To simulate the time evolution of the stellar disc, we model a warped disc as a collection of concentric circular rings which are mutually tilted, and are in gravitational interaction with each other. We also account for the torques induced by the surrounding old star cluster. Each ring around the black hole of mass $M_{bh}$ is characterized by it mass $m$, radius $r$, and the Euler angles $(\psi, \theta, \phi)$. $\psi$ denotes the location of a star on its ring, where $\theta$, and $\phi$ are the inclination and the azimuthal angles of the rings. The equations of motion, and the mutual
Gravity torques for such a system of rings are written as in [42], while for the torque induced by the star cluster, we use equation (2) given in [40].

In our simulations, we use 50 equally spaced rings to model a disc. We adopt two different mass fractions in order to enable our models to be applicable to systems other than the GC. We construct models that involve only the effects of the self-gravity (models SGM), and models which also account for the torques from the surrounding star cluster (models CLM). The indices 1 and 2 in the naming of the models refer to mass fraction of $M_d/M_{bh} = 0.00134$ and $M_d/M_{bh} = 0.0134$ respectively. For models CLM, the parameter controlling the strength of the cluster torque is set such that it could correspond to a mass of $10^6 M_\odot$ and a flattening of 0.9. The initial warp shapes of all the models is such that the disc has an overall warp of about $60^\circ$ going from in-to-out, and the azimuths lie on a straight line. We note that it is justified to assume such high amplitude warps when considering both the radiation and Bardeen-Petterson warping as the driving mechanisms [37, 26].

4. Results

The self-gravity and the star cluster torques will have an effect of forcing the disc precess. The temporal evolution of the disc will then be governed by the relative strengths of both torques.

In figures 1 and 2 we show how the warp profiles, i.e. radius-vs-inclination- of the models SGM1 (left) and SGM2 (right) change throughout the simulations. The red lines depict the warp profiles at the start of the simulation, while the blue lines depict the final configuration. The dense black dots show individual ring inclinations at a particular time $t$. We see that while the warp shape of model SGM1 remains almost unchanged during the evolution, the more massive disc breaks into two pieces. Of these two distinct pieces which precess independently, the inner disc at negative inclinations exhibits an almost planar shape, while the outer one has a warp of about $10^\circ$.

**Figure 1.** Warp profile of model SGM1 throughout the simulation. The inclination of the disc remains unaltered.

**Figure 2.** Warp profile of model SGM2 throughout the simulation. The disc breaks into two pieces.

In figures 3 and 4 we show the warp profiles of models CLM1 (left) and CLM2 (right). We see again that the lighter disc changes its inclination only slightly while the more massive one acquires a warp shape where the middle parts of the disc are pushed to more polar orbits, and the disc has a distorted shape.

In the different panels of Fig. 5, we show the $xy$ projections of the 3-dimensional views of the models. The color code depicts the height of the disc ($z$-axis) above the plane. Fig. 5a shows the projection of the models at the start of the simulation. The rest of the figures are
for the final configurations. Fig. 5b is for model SGM1, while the figures 5c, 5d, and 5e are for models SGM2, CLM1, and CLM2 respectively. The precession of the model discs become apparent in these plots, where the self-gravity only model with a low mass fraction is seen to precess the least. The final configuration of this model is very close to its starting configuration. When the disc mass fraction is increased, we see that the coherence between the inner and the outer parts is lost, although these parts remain intact within themselves. When the influence of the surrounding star cluster is taken into account, the model discs precess faster compared to self-gravity only models, which manifests itself with the spiral-like projection of the orbits for the low mass model. When the disc mass is increased, the disc precesses with an even higher rate, and the disc dissolves due to differential precession.

5. Comparison with the Observations
In this section, we will briefly discuss how a comparison of our models with the observations can be made. In our comparison, we use the data presented in [4] which includes 136 stars with measured \((x,y)\) positions, and the Monte Carlo simulated \(z\) positions. The respective space velocities are also given. We start by writing the coordinates of a star on its ring, and the components of the velocities. We then generate a random sample of stars on these rings by dicing the positions of the star on the ring, and obtain the phase space distribution of stars for each instant of time \(t\) [43].

As a next step, we generate the components of local average angular momenta as a function of average projected distance from the black hole, and rotate the data from the simulations successively until the best fit is obtained. Fig. 6 shows the best fitting warp profile which is obtained for model SGM1. The blue dots represent the data, where shaded are shows the region bound by the error bars. The red triangles depict the model. We see that the gradual change in the disc inclination is successfully produced. When the effects of the star cluster are also taken into account, the observed overall warp shape can not be produced by our simulations. This might mean either that the star cluster is nearly spherical, or that its mass is less than the value we assumed here based on the most recent observations reported in [41, 38]. We also note that, none of our simulations lead to a configuration where parts of a broken disc would appear in counter clockwise rotation on the plane of the sky to mimic the CCW disc.
Figure 5. *xy* projections of the 3-dimensional views of the model discs. (a): for the initial configuration, (b): for model SGM1, (c): for model SGM2, (d): for model CLM1, (e): for model CLM2. The disruption of a massive disc under the influence of the star cluster can be clearly seen in Fig. 5e.

Figure 6. The warp profile of the best fitting model (red triangles) and of the CW disc (blue dots) given in [4]. Figure is from [43].
6. Summary

In this work, we have proposed a new origin scenario for the warped stellar discs of young stars at the Galactic Centre (GC). We assumed that the GC had an active phase during which the star formation was delayed until the past accretion disc was warped. In order to test the plausibility of this idea, we considered two warping mechanisms, the Pringle (radiation) instability, and the Bardeen-Petterson Effect. Using simple arguments, we showed that warping of the GC disc is plausible if the star formation efficiency is high, and the viscosity parameter $\alpha \sim 0.1$.

Keeping in view that the activity in the Galactic Centre has ceased some time ago after which the disc is subject to gravitational torques only, we followed the time evolution of warped discs taking into account the discs’ self-gravity in the non-linear regime and the torques exerted by the surrounding old star cluster. In order to let our results be applicable to systems other than the GC, we examined for two different disc-to-black hole mass ratios (mass fractions) the long term temporal behavior of the warped disc models and investigated the interplay between the self-gravity and the cluster torques. We also compared our models with the observations of the warped GC discs. Our findings can be summarized as follows:

i) When the mass fraction is $M_d/M_{bh} \approx 0.001$, the overall inclination of the disc is not grossly altered during the simulations. When only the self-gravity of the disc is considered, the disc precesses as a single body throughout its evolution, while inclusion of the torques from the star cluster cause the rings precess apart.

ii) When the disc mass fraction is $M_d/M_{bh} \approx 0.01$, the disc breaks into two parts precessing independently in the case of a purely self-gravitating disc, and dissolves due to differential precession when the star cluster torques are taken into account.

iii) In our simulations, we do not find a configuration where parts of a broken disc would counter-rotate on the plane of the sky. Comparing our models with the observations, we see that the low mass model taking into account only self-gravity of the disc agrees better with the data. When the torques from the star cluster are also present, the overall warp shape can not be produced. This disagreement might mean either that the old star cluster at the Galactic Centre is nearly spherical, i.e. does not torque the disc, or that the mass of the cluster within the outer edge of the disc is less than the value assumed here based on the most recent observations. Future observations targeting the old star cluster will therefore help a better understanding of the evolution of the stellar discs.

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References

[1] Alexander R D, Armitage P J, Cuadra J and Begelman M C 2008 ApJ 674 927
[2] Armitage P J and Natarajan P 1999 ApJ 525 909
[3] Bardeen J M and Petterson J A 1975 ApJ 195 L65+
[4] Bartko H et al 2009 ApJ 697 1741
[5] Bartko H et al 2010 ApJ 708 834
[6] Bonnell I A and Rice W K M 2008 Science 321 1060
[7] Bregman M and Alexander T 2009 ApJ 700 L192
[8] Cuadra J, Armitage P J and Alexander R D 2008 MNRAS 388 L64
[9] Frank J, King A and Raine D J 2002 Accretion Power in Astrophysics by Julian Frank and Andrew King and Derek Raine p 398 (Cambridge, UK: Cambridge University Press) February 2002
[10] Gammie C F 2001 ApJ 553 174
[11] Genzel R, Pichon C, Eckart A, Gerhard O E and Ott T 2000 MNRAS 317 348
[12] Genzel R et al 2003 ApJ 594 812
[13] Ghez A M, Salim S, Hornstein S D, Tanner A, Lu J R, Morris M, Becklin E E and Duchêne G 2005 ApJ 620 744
[14] Gillessen S, Eisenhauer F, Trippe S, Alexander T, Genzel R, Martins F and Ott T 2009 ApJ 692 1075
[15] Goodman J 2003 MNRAS 339 937
[16] Greenhill L J, Booth R S, Ellingsen S P, Herrnstein J R, Jauncey D L, McCulloch P M, Moran J M, Norris R P, Reynolds J E and Tzioumis A K 2003 ApJ 590 162
[17] Greenhill L J and Gwinn C R 1997 Astrophysics and Space Science 248 261
[18] Herrnstein J R, Greenhill L J and Moran J M 1996 ApJ 468 L17+
[19] Hobbs A and Nayakshin S 2009 MNRAS 394 191
[20] Kocsis B and Tremaine S 2011 MNRAS 412 187
[21] Kolykhalov P I and Syunyaev R A 1980 Soviet Astronomy Letters 6 357
[22] Krabbe A et al 1995 ApJ 447 L95+
[23] Kumar S and Pringle J E 1985 MNRAS 213 435
[24] Lense J and Thirring H 1918 Physikalische Zeitschrift 19 156
[25] Levin Y and Beloborodov A M 2003 ApJ 590 L33
[26] Lodato G and Pringle J E 2007 MNRAS 381 1287
[27] Lu J R, Ghez A M, Hornstein S D, Morris M, Matthews K, Thompson D J and Becklin E E 2006 Journal of Physics Conference Series 54 279
[28] Lu J R, Ghez A M, Hornstein S D, Morris M R, Becklin E E and Matthews K 2009 ApJ 690 1463
[29] Maloney P R, Begelman M C and Pringle J E 1996 ApJ 472 582
[30] Martin R G 2008 MNRAS 387 830
[31] Milosavljević M and Loeb A 2004 ApJ 604 L45
[32] Nayakshin S, Dehnen W, Cuadra J and Genzel R 2006 MNRAS 366 1410
[33] Ogilvie G I and Dubus G 2001 MNRAS 320 485
[34] Paumard T et al 2006 ApJ 643 1011
[35] Petterson J A 1977 ApJ 216 827
[36] Pringle J E 1996 MNRAS 281 357
[37] Pringle J E 1997 MNRAS 292 136
[38] Schödel R, Merritt D and Eckart A 2009 A&A 502 91
[39] Shakura N I and Syunyaev R A 1973 A&A 24 337
[40] Sparke L S 1986 MNRAS 219 657
[41] Trippe S, Gillessen S, Gerhard O E et al 2008 A&A 492 419
[42] Ulubay-Siddiki A, Gerhard O and Arnaboldi M 2009 MNRAS 398 535
[43] Ulubay-Siddiki A, Bartko H and Gerhard O 2012 MNRAS submitted