Modelling a nuclear star cluster – II.

Non-spherical shape and the role of interaction with a self-gravitating accretion disc

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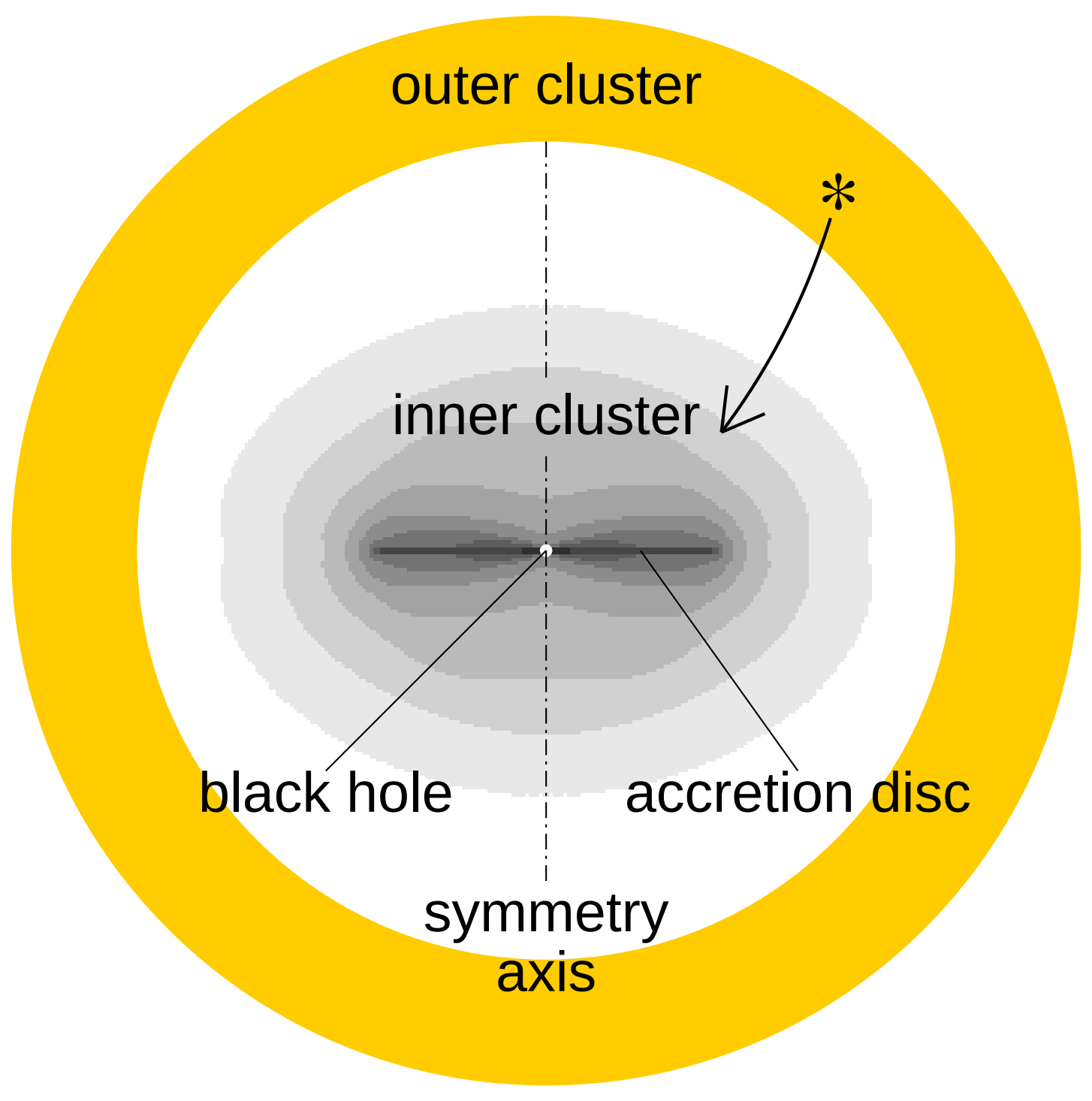
We model the motion of stars and the resulting structure of a central star cluster around a supermassive black hole. The aim of this work is to understand processes that can shape the overall structure of the nuclear star cluster, in particular, we explore the degree of non-sphericity of the cluster that can be expected from the interaction with an embedded accretion disc. This provides a toy model to explore the interplay between the flat population of stars embedded in the disc and the quasi-spherical population of the bulge, to be compared with observational results in the future. We take the interaction with an accretion disc and the effects of the disc disc self-gravity into account. We show that the cluster properties are then determined predominantly by the radial profile of the disc surface density. We develop a simple steady-state model of the central cluster and we estimate the rate at which stars migrate to the centre.

Introduction

Evidence for a moderate degree of non-sphericicity (flattening) of the Galactic centre Nuclear Stellar Cluster (5 pc half-light radius) has been reported recently [7], based on a careful analysis of Spitzer images of the Sagittarius A* central region. Here, we examine the long-term orbital evolution of stars forming a dense stellar cluster surrounding a central black hole with an embedded accretion disc. This configuration is relevant for central regions of active galactic nuclei [2, 6, 9], and it may be applied also to the center of the Milky Way, assuming that rapid accretion took place and a gaseous disc was formed at some stage during its history [5].

The model

We idealise a galactic core as a system consisting of a central black hole, an accretion disc and a dense stellar cluster. The three components interact with each other. Naturally, various approximations need to be imposed [8]. The aim of our model is to examine the structure of a stellar system in the region of black hole gravitational dominance $R_{\rm h}$, including the effects due to gaseous disc. Two regions of the cluster can be distinguished according to the characteristic time-scale of processes dominating the stellar motion (see Figure 1). The outer cluster is assumed to reach a gravitationally relaxed form [1], acting as a reservoir of fresh satellites that are being continuously injected inwards. The inner cluster is defined as a region where star-disc collisions take over.



Fiducial numbers of the model:

- Black hole mass
  $M_\bullet \approx 10^6 – 10^9 M_\odot$
- Accretion disc – surface density, mass and radial size
  $\Sigma_{\rm d} \propto r^s$
  $10^{-3} M_\bullet \lessapprox M_{\rm d} \lessapprox 10^{-2} M_\bullet$
  $R_{\rm d} \approx 10^4 R_{\rm g} \approx 0.1 M_8\,{\rm pc}$
- Outer cluster – number density and velocity dispersion

$$\begin{aligned} n(r) &= n_0 (r/R_{\rm h})^{-7/8} \\ R_{\rm h} &= GM_\bullet/\sigma^2 \approx 10 M_8\,{\rm pc} \\ n_0 &\approx 10^6 – 10^8\,{\rm pc}^{-3} \\ \sigma_{\rm c} &\approx 200\,{\rm km/s} \end{aligned}$$

Fig. 1: Schematic picture of the model: the outer cluster (a reservoir), the inner (flattened) cluster, and an accretion disc. Levels of shading represent the number density of stars in the inner cluster, which is gradually increasing towards the disc plane.

Individual orbits. Stars loose their orbital energy and momentum by means of successive dissipative passages through accretion disc. The overall trend is to circularize orbits and decline them into the plane of the disc. Characteristic time of aligning stellar orbits with the disc is $t_{\rm d}(a) \approx t_0\, M_8\, (\Sigma_*/\Sigma_\odot)^{-1}\, (a_0/R_{\rm g})^{3/2-s}\ {\rm yr}$, where a is semi-major axis and t_0 is a constant, of the order of unity for the standard disc model.

Different modes of radial migration apply to stars in the disc plane, depending whether a star succeeds to open a gap in the disc medium, or whether it remains embedded entirely in the disc medium and proceeds via density waves excitation. We switch between relevant modes in the numerical integration.

Finally, the gravitational field of the disc provides a perturbation that is capable of exciting large fluctations of eccentricity [4, 10]. We therefore compute the gravitational field of the disc and take its effect into account for the long-term orbital decay of stellar trajectories. The effect of eccentricity oscillations is shown in Figure 2.

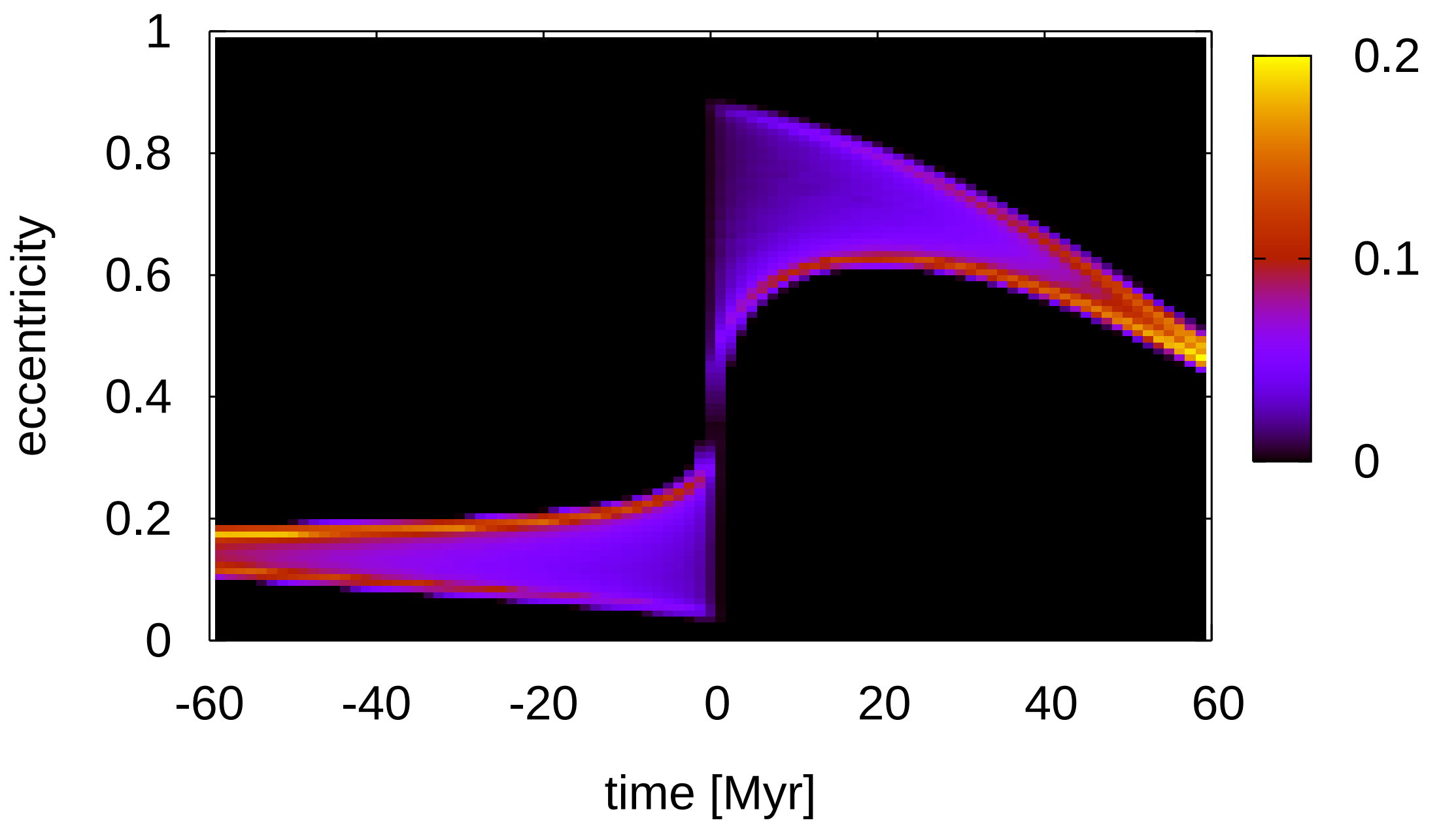


Fig. 2: Occasional jumps toward high eccentricity occur due to the Kozai-type mechanism [4]. These episodes are the effect of the gravitating disc in our model. An example is shown in this figure. Characteristic time-scale $t_{\rm c}$ of the oscillations depends on $M_{\rm d}/M_\bullet$ ratio, and is generally much longer that the dynamical time at corresponding radius (it is of the order of thousand orbital revolutions in our case). Prevailing circularisation is expected because of gradual energy losses and the resulting orbital decay via star-disc collisions, hoever, fraction of highly eccentric orbits persists in the cluster. These orbits bring stars close to the black hole where they can be preferentially captured or destroyed.

As an example, in Figure 2 we have set the current (time zero) values of orbital eccentricity $e(t)$ and seminajor axis $a(t)$ identical as those reported for the S2 star in Sagittarius A*. Therefore, this graph illustrates the expected fluctuations of eccentricity and explains the existence of highly elliptic trajectories, assuming that an accretion disc or a torus was present at the centre of our Galaxy. In this simulation we set $M_\bullet = 4 \times 10^6 M_\odot$ for the central mass. The required mass of the disc was of the order of fraction of percent of the central black hole mass, consistent with the present-day upper limits.

The cluster. Now we construct a steady-state cluster assuming that it is supplied with fresh stars from the reservoir at a rate inversely proportional to the relaxation time. Our computational scheme allows us to further distinguish between two subsamples of the inner cluster: the dragged inner cluster consists of stars on orbits crossing the disc periodically; the embedded inner cluster is formed by stars entirely aligned with the disc. See ref. [8] for details of our approach.

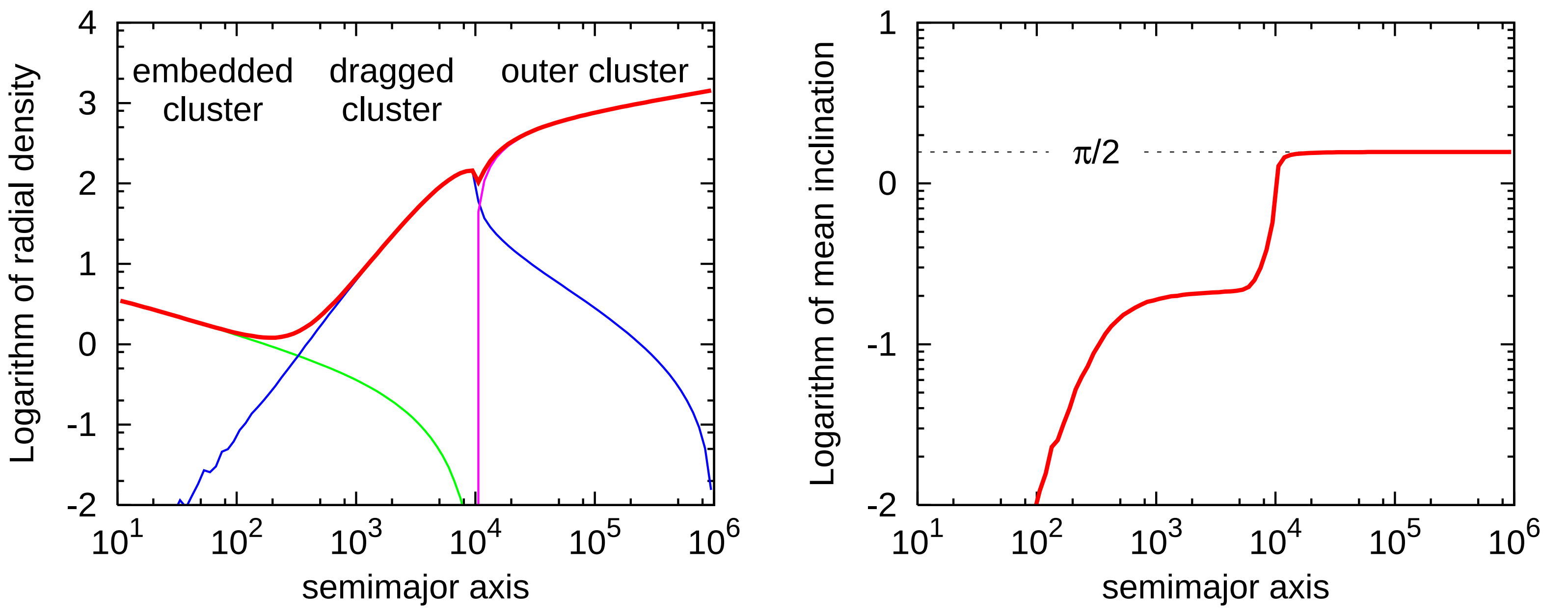


Fig. 3: Left panel: distribution of semi-major axes throughout the stellar cluster, modified by interaction with the gas-pressure dominated standard accretion disc. The broken power-law profile is established by different types of interaction governing different regions of phase space. The three stellar sub-samples are present in our model and they can be easily distinguished in the plot: the outer reservoir (magenta), the inner part of the cluster which is dragged by the disc (blue), and a subsample of stars fully embedded in the disc (green). Right panel: Graph of mean inclination $\langle i \rangle$ in the cluster. The reservoir is spherically symmetric ($\langle i \rangle = \pi/2$), the dragged cluster is somewhat flattened ($0 < \langle i \rangle < \pi/2$), and the embedded population is located in the disc plane ($\langle i \rangle = 0$).

Results

We assumed that the central mass $M_\bullet = 10^8 M_\odot$ is surrounded by the gas-pressure dominated Shakura-Sunyaev disc ($s = -3/4$) with $\dot{M} = 0.1 M_{\rm Edd}$ and viscosity parameter $\alpha = 0.1$. The outer stellar cluster can be characterized by number density $n_0 = 10^6 {\rm pc}^{-3}$ and velocity dispersion $\sigma_{\rm c} = 200\,{\rm km/s}$.

Structure of the cluster modified by the interaction with an accretion disc. Figure 3 shows the density structure of the modified cluster. Majority of stars forming the embedded cluster sink to the centre in the regime of density waves, hence $v_r \propto r^{1/2}$ and $n(a) \propto a^{-1/2}$. In the dragged cluster, the orbital decay leads to the governing index given by $s - 1/2 = -5/4$, and the corresponding number density $n(a) \propto a^{5/4}$. The asymptotic profile $\propto a^{1/4}$ of the outer cluster is determined by the initial distribution. Isotropy of the outer cluster is violated in the inner regions where the mean inclination saturates at ≈ 0.2 (dragged cluster). The influence of the disc manifests itself in different characteristics of the inner cluster. For example, dependence of the drag on size and mass of stars causes gradual segregation of different stellar types present in the cluster.

Figure 4 shows the integrated properties of the cluster that can be compared with observation. We plot the shape of a synthetic spectral line $I(v_z)$, i.e. intensity in the line as a function of line-of-sight velocity v_z near the projected center of the cluster. Local maximum of the line occurs around $v \sim \sin(\xi) v_{\rm K}(R_{\rm d})$. For some values of model parameters, this secondary peak exceeds the central maximum and dominates the predicted profile. High-velocity tails of the line profiles are also noticeably affected in comparison with an uperturbed form of the outer cluster [8].

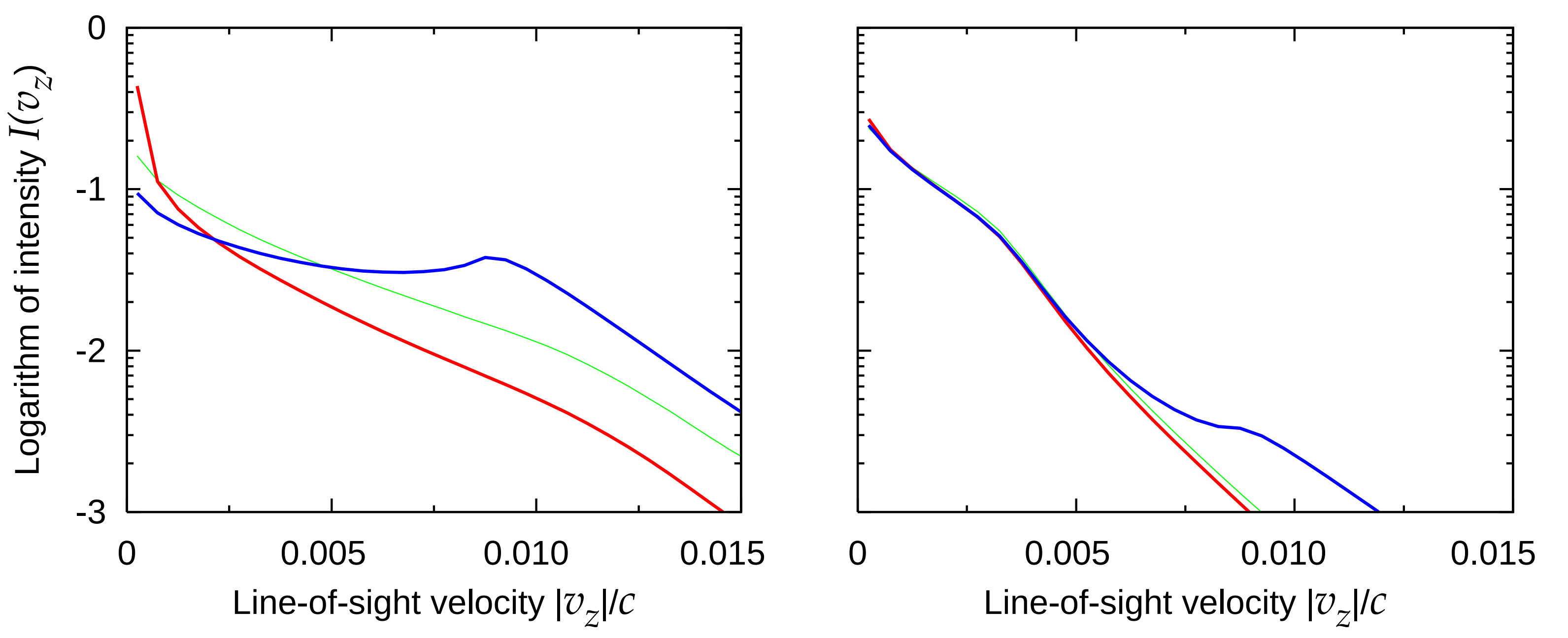


Fig. 4: Velocity profile along line of sight of the inner cluster, integrated across a column of cross-sectional radius $R_{\rm s} = 10^4 R_{\rm g}$ (left panel) and $R_{\rm s} = 10^5 R_{\rm g}$ (right panel). Blue/red lines represent different view angles of the observer: $\xi = 0^\circ$ and 60°, respectively. Growing anisotropy of the modified cluster produces the dependence of measured line profile on ξ, i.e. $I \equiv I(v_z; \xi)$. The green line is for the referential Bahcall–Wolf distribution, which exhibits spherical symmetry.

Oblateness of the cluster. Figure 5 shows different two-dimensional sections of the cluster arranged in four columns. One can clearly observe the impact that star–disc collisions have on the cluster structure, namely, an increasing oblateness of the stellar population in the core and, in some cases, the tendency to form an annulus of stars. The reason for different structures is the continuous crashing of stars on the disc plane. Furthermore, in case of stars embedded in the disc, different modes of star-disc interaction occur and facilitate their radial transport to the central hole.

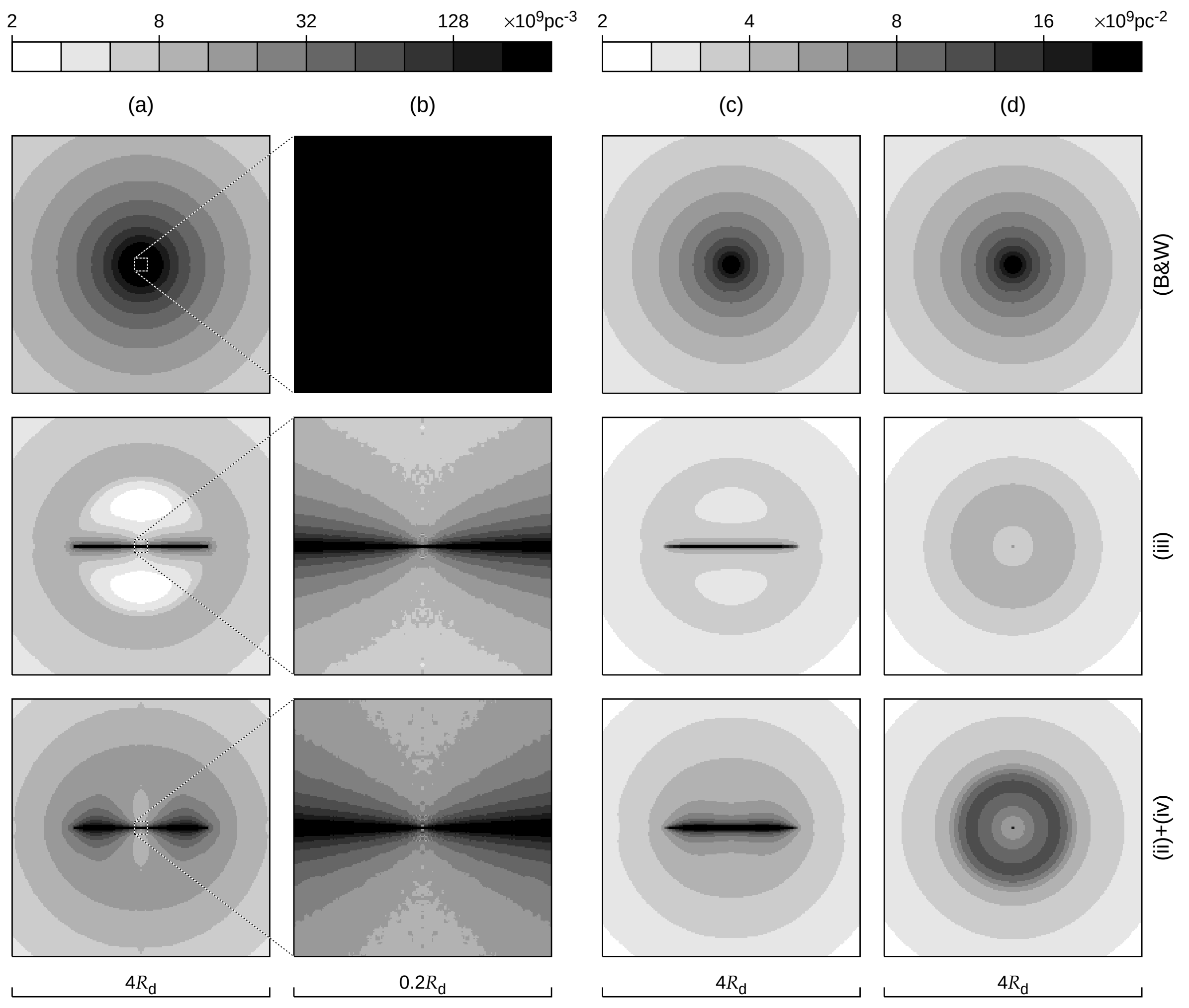


Fig. 5: The spatial density $n_*(r)$ and the corresponding projected density of the cluster are shown using logarithmically spaced levels of shading. Columns (a) and (b) represent the meridional section at two different scales, namely, $4R_{\rm d}$ and $0.2R_{\rm d}$ across (radii are expressed in terms of the disc outer radius, $R_{\rm d}$). Next columns are the edge-on (c) and the face-on (d) projections of the cluster. Across columns, the upper row shows the referential cluster [1] ($n_* \propto r^{-7/4}$). In subsequent rows, the system has been already modified via the interaction with two types of discs, case (iii) and case (ii)+(iv), as discussed in ref. [8].

Conclusions

The orbits are aligned and circularized at typical radii of $10^2 \div 10^3 R_{\rm g}$, spiraling further on nearly circular orbits towards the centre. This provides limits on gravitational waves emerging from the cluster. The rate of the capture events can be estimated as

$$\dot{M}_{\rm s} \approx 10^{-2} M_8^{5/4} \left(\frac{n_0}{10^6\,{\rm pc}^{-3}} \right)^2 \left(\frac{M_*}{M_\odot} \right)^2 \left(\frac{R_{\rm d}}{10^4 R_{\rm g}} \right) M_\odot\,{\rm yr}^{-1}\,.$$

The total accretion rate onto the black hole is a sum of $\dot{M}_{\rm s}$ (which involves massive stars in the cluster), and the accretion rate $\dot{M}$ (gas in the disc). Although the above-described model is intended mainly for active galactic nuclei with a relatively dense accretion disc or a dusty torus, the problem of stars crashing on a gaseous disc may be relevant also for the centre of our Galaxy. The modified cluster structure is relevant for estimating the rate of black-hole feeding and, vice-versa, for the issue of feedback that a super-massive black hole exhibits on the the host galaxy. Furthermore, the orbital decay of stars near a black hole is relevant for forthcoming gravitational wave experiments, because the gas-dynamical drag should be taken into account with sufficient accuracy. For further details see paper [3, 8].

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Mon. Not. R. Astron. Soc. **354,** 1177–1188 (2004) doi:10.1111/j.1365-2966.2004.08276.x

Star–disc interactions in a galactic centre and oblateness of the inner stellar cluster

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Accepted 2004 August 1. Received 2004 July 16; in original form 2004 March 26

ABSTRACT

The structure of a quasi-stationary stellar cluster is modelled assuming that it is embedded in the gravitational field of a supermassive black hole. The gradual orbital decay of stellar trajectories is caused by the dissipative interaction with an accretion disc. The gravitational field of the disc is constructed and its effect on the cluster structure is taken into account as an axially symmetric perturbation. Attention is focused on a circumnuclear region ($r \lesssim 10^4$ gravitational radii) where the effects of the central black hole and the disc dominate over the influence of an outer galaxy. It is shown how the stellar system becomes gradually flattened towards the disc plane. For certain combinations of the model parameters, a toroidal structure is formed by a fraction of stars. Growing anisotropy of stellar velocities as well as their segregation occur. The mass function of the inner cluster is modified and it progressively departs from the asymptotic form assumed in the outer cluster. A new stationary distribution can be characterized in terms of velocity dispersion of the stellar sample in the central region of the modified cluster.

Key words: accretion, accretion discs – stellar dynamics – galaxies: active – galaxies: nuclei.

1 INTRODUCTION

We discuss the impact of the gaseous environment on the long-term stellar motion in central regions of active galactic nuclei (AGN). We adopt the view of galactic nuclei as composite systems with stars surrounding a supermassive black hole (with a typical mass of $10^6\,{\rm M}_\odot \lesssim M_\bullet \lesssim 10^9\,{\rm M}_\odot$) and forming a rather dense cluster (Begelman & Rees 1978; Norman & Silk 1983). The central number density of the cluster stands as one of the model parameters that can reach values of the order of $n_* \sim 10^6$–$10^7\,{\rm pc}^{-3}$. We consider the stars of the cluster as satellites orbiting the central black hole. We also take into account the influence that the diluted interstellar environment has on the motion of stars on time-scales exceeding 10^4 dynamical periods. This allows us to address the important question of whether or not the presence of such a medium could increase the concentration of stars in certain regions of the nucleus.

Although we consider the region of direct gravitational influence, where the gravity of the central black hole dominates over non-gravitational forces, one should not neglect the impact of perturbing effects on individual stellar trajectories and the overall cluster structure. We assume that it is the gas in an accretion disc which acts as the main perturbation. The disc medium affects the motion of stars either directly by collisions between stars and gas particles at the point of transition through the disc slab (the case of inclined trajectories), or vicariously, via coupling between the stars and the disc medium (embedded trajectories). These processes will be discussed in combination with the effects of disc gravity.

Our present contribution follows a previous paper (Vokrouhlický & Karas 1998) where the long-term evolution of stellar orbits was studied, including the case of an axially symmetric perturbation imposed on the gravitational field to mimic the presence of a disc. It was shown that the orbits experience abrupt changes of eccentricity and inclination even if the disc mass is a tiny fraction of the central mass, $M_{\rm d} \lesssim 10^{-3} M_\bullet$. In that paper properties of individual orbits were investigated. A simplified approach to the evolution of the central cluster was adopted by Rauch (1999) and Karas, Šubr & Šlechta (2002). Stellar encounters were explored in this context by Vilkoviskij & Czerny (2002), using a semi-analytical approach to the dense and flattened cluster. Here we add an astrophysically more realistic description of the self-gravitating disc, especially of its gravitational field that is superimposed on the central field, and we study the dynamics of the cluster in terms of its overall characteristics (the shape and velocity dispersion).

The main new ingredients of the present investigation are threefold. First, a more elaborate description of the disc accounts for different processes and corresponding time-scales that dominate the system evolution at different distances from the core. The behaviour

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7 Years in Chile: The Accomplishments and Goals of Czech Astronomers at ESO. Villa Lanna, Prague, 14–16 April 2014.

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