Nuclear Disk Formation by Direct Collisions of Gas Clouds with the Central Black Hole

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ABSTRACT

We simulate clouds in the Galactic Centre (GC) crossing over the black hole in parts and present this as a possible formation mechanism for the observed stellar disks in the GC through the redistribution of angular momentum by colliding material with opposite angular momentum. A parameter study using six high resolution simulations of an isothermal cloud of constant density falling onto the black hole and crossing over it in parts demonstrates that this mechanism is able to reproduce the observed disk properties in the GC. The evolution of the ensuing accretion disks is highly non-linear with the redistribution of the angular momentum through dissipative processes being a dominant effect. We analyse the resulting Toomre unstable, eccentric gaseous disk and show that this already yields a good comparison with the observed stellar disk size and eccentricity in the GC. The best simulation results in an outer radius of 1 pc, a mass of $10^4 M_\odot$ and an eccentricity of 0.24 for the Toomre unstable disk, which compares well with the observations.

Key words: Galaxy: centre – methods: numerical – ISM: clouds – disk formation

1 INTRODUCTION

Observations reveal an interesting feature in our Galactic Centre (GC): two sub-parsec-scale rings of young stars near the radio source SgrA* (Genzel et al. 2003; Puymard et al. 2008; Bartko et al. 2009) which cannot be explained by normal means of star formation due to the hostility of the environment. Tidal forces would disrupt typical molecular clouds in the vicinity of the central black hole, preventing their condensation into stars. There are around 100 young and massive stars distributed in a warped clockwise rotating disk and a second inclined counter-clockwise rotating disk. The outer edge of the system is at around 0.5 pc and the inner edge at around 0.04 pc. The mean eccentricity of the clockwise rotating system is measured to be $0.36 \pm 0.06$.

An alternative and more plausible formation scenario postulates that the stellar rings formed by fragmentation of self-gravitating, eccentric accretion disks (Rice et al. 2005; Alexander et al. 2008 and references therein). Previous studies concentrated mainly on the fragmentation of an already existing accretion disk. The question how these disks formed in the first place has only recently been discussed, e.g. by Wardle & Yusef-Zadeh (2008) and Mapelli et al. (2008). In their models the accretion disks are built up by the rapid deposit of gas around the central black hole through the infall and tidal disruption of a gas cloud. However, here the problem arises that a gas cloud that most likely formed far from the GC where tidal forces are inefficient must be placed on an orbit with a close passage around the black hole.

Furthermore, the cloud should not be disrupted by internal star formation processes before encountering the black hole. Mapelli et al. (2008) and Hobbs & Navakshin (2009) studied the formation of a disk by a cloud or clouds passing the central black hole at some distance larger than the cloud radius. However, Wardle & Yusef-Zadeh (2008) showed that it is very unlikely for a cloud to be captured by the black hole without engulfing it during the encounter, as only a small set of initial parameters would lead to such an event. Thus Wardle & Yusef-Zadeh (2008) proposed a model in which the infalling cloud covers the black hole in parts during its passage. This process efficiently redistributes angular momentum and dissipates kinetic energy through the collision downstream of material with opposite angular momentum streaming around the black hole from both sides, finally resulting in a compact accretion disk.

In this paper we study the direct encounter of a gas cloud with the central black hole in detail using high-resolution numerical simulations. We show that gas disks similar to the observed stellar GC disk can be formed when the infalling clouds cover the black hole in parts. This paper...
is structured as follows. In Section 2 we present a motivation for our model. In Section 3 the numerical method and the initial setup of the model are presented. The main results as a function of varying impact parameters and initial cloud velocities are presented in Section 4. Finally, we summarize and discuss our findings in Section 5.

2 MOTIVATION

In order to motivate our model we start by considering a cloud on an arbitrary Keplerian orbit around the black hole, where the cloud settles into a circular orbit by dissipating kinetic energy into thermal energy. The largest cloud which could form a disk similar to the observed stellar disk of radius $r_{disk} = 0.5$ pc, which at the same time does not cross the black hole during the passage, would be a cloud of exactly the stellar disk radius of 0.5 pc on an initially circular orbit. All clouds with a larger radius will cross over the black hole in parts during the passage. The minimum distance to the black hole must be smaller than $r_{disk}$ for all non-circular orbits if we want to build up a disk of size $r_{disk}$ by energy dissipation because of angular momentum conservation. Thus, the circular case really gives the upper limit for the size of a cloud that does not touch the black hole during the passage.

The required mass in the gaseous disk that formed the observed stellar disk is around $10^{4.5}$ $M_\odot$ (Navakshin & Cuadra 2002; Nayakshin et al. 2004). A cloud of radius 0.5 pc with a mass of $10^4$ $M_\odot$ already has a density above $10^5$ cm$^{-3}$ which is the observed upper density limit for molecular clouds in the GC (Güsten & Philipp 2004).

Furthermore, if we can only form a disk of given radius by a cloud losing velocity due to dissipation of energy then all incoming clouds must have an orbit where the shortest distance to the black hole is smaller than the resulting disk radius. In the case of angular momentum redistribution this is no longer necessary. Even clouds on orbits with a point of closest approach much larger than the wanted disk radius can potentially form such a disk if their radius is larger than the minimum distance to the black hole so that angular momentum can be redistributed.

Thus, we conclude that the redistribution of angular momentum must always be included as a mechanism for initiating the formation of such a disk. This will also increase energy dissipation by the formation of colliding flows. The aim of this paper is to show that this mechanism can indeed form a disk similar to the one observed in the GC, which has already been shown for pure energy dissipation by Mapelli et al. (2008) and Bonnell & Rice (2008).

3 MODEL AND NUMERICAL METHOD

The hydrodynamical evolution of the impact of the gas cloud with the central black hole is studied using simulation runs performed with the N-body Smoothed Particle Hydrodynamics (SPH) Code Gadget2 (Springel 2003). The simulations are run with a total number of 10$^6$ SPH particles and a softening length of $\epsilon = 10^{-3}$ pc. The number of neighbours is set to $n_{neigh} = 50 \pm 5$. The black hole is included as a static potential of a point mass of $M_{BH} = 3.5 \times 10^6$ $M_\odot$.

Table 1. Summary of initial conditions for our simulations. The cloud velocity is varied for simulations V01, V02 and V03 and the impact parameter for simulations 101, 102 and V02. C01 is a comparison simulation with the same initial specific angular momentum ($j_{\text{specific}}$) as V03.

| ID | $h$ | $\omega$ | $v_0$ | $b$ | $j_{\text{specific}}$ | $\rho^2_{\text{acc}}$ |
|----|-----|---------|-------|----|----------------------|-----------------|
| I01 | 0.28 | 0.29 | 50 | 1 | 50 |
| I02 | 0.57 | 0.41 | 50 | 2 | 100 |
| V01 | 0.85 | 0.3 | 30 | 3 | 90 |
| V02 | 0.85 | 0.5 | 50 | 3 | 150 |
| V03 | 0.85 | 0.8 | 80 | 3 | 240 |
| C01 | 0.57 | 0.98 | 120 | 2 | 240 |

Genzel et al. (2003) placed at the origin of the coordinate system.

We adopt an isothermal equation of state with a typical cloud temperature of $T_{\text{cloud}} = 50$ K (Güsten & Philipp 2004). This simplification should not strongly affect our results, i.e. the formation of the accretion disk, as the orbital velocities ($v_{\text{orbit}} \sim 100$ km/s) are in general much larger than the cloud sound speed ($c_s \sim 0.45$ km/s). Heating and cooling processes in the disk will however play an important role when investigating its fragmentation and condensation into stars (see e.g. Bonnell & Rice 2008). We postpone this question to the next paper in this series where we will study in detail the thermodynamics of the accretion disk, viscous heating, radiative cooling, star formation and associated feedback processes, as detailed in Johansson et al. (2009).

In this first study we start with a spherical and homogeneous cloud of radius 3.5 pc which is typical for the GC (Miyazaki & Tsuboi 2004, derived from CS(1-0) radio surveys). The $H_2$ gas density is $10^4$ cm$^{-3}$ (Güsten & Philipp 2004, taken from high-resolution surveys of CS and CO in the GC), leading to a cloud mass of $8.81 \times 10^4$ $M_\odot$. The SPH particle mass is then $m_{\text{SPH}} \approx 8.81 \times 10^{-2}$ $M_\odot$ and the corresponding minimum mass that can be resolved is $m_{\text{min}} = n_{\text{neigh}} \times m_{\text{SPH}} = 4.4$ $M_\odot$.

In order for the simulations not to become too time-consuming as a result of very small particle time steps in the vicinity of the black hole we define an accretion radius $r_{\text{acc}}$ within which all SPH particles are considered to be accreted by the black hole and are removed. We want this accretion radius to be larger than the minimum smoothing length of $10^{-3}$ pc and smaller than the observed inner disk edge of $4 \times 10^{-2}$ pc. Test simulations showed that a value of $r_{\text{acc}} = 2 \times 10^{-2}$ pc captures the most relevant accretion physics and disk structure while at the same time allowing us to simulate the encounter until the whole cloud has passed the black hole and an accretion disk has formed.

We do not include black hole growth in order to speed up the simulations. This growth is anyhow negligible since at most only around one percent of the black hole mass was accreted at the end. Energetic feedback from the accreting black hole might however be important and will be investigated in a subsequent paper. The gravitational forces are purely Newtonian, relativistic effects (frame dragging) would only become important at radii smaller than $r = 10^{-4}$ pc for a $M = 3.5 \times 10^6$ $M_\odot$ black hole which is beyond our accretion radius. The Gadget Code treats grav-
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Figure 1. Logarithmic density in $M_\odot$ in the xy-plane with $z=0$ pc at different times for simulation 102. Velocity is given in km/s with the unit length of the arrow corresponding to 148 km/s. Material with opposite angular momentum collides, a density wave builds up and spirals into the forming disk.

...itational forces as Newtonian up to 2.8 times the smoothing length, which in any case is also beyond our accretion radius for the minimum smoothing length.

Initially, the centre of mass of the cloud is placed at a distance of 5 pc from the origin/black hole on the x-axis (the direction of motion) and an offset $b$ on the y-axis. We have chosen this relatively small distance in order to prevent the cloud from collapsing before it reaches the black hole. The free fall time of a cloud with $n = 10^4 \text{cm}^{-3}$ is only around 0.36 Myrs. For an average infall velocity of 50 km/s the cloud’s centre of mass should reach the black hole after roughly 0.1 Myrs.
The evolution is characterized by the fraction \( \frac{b}{R} \) where \( R \) is the cloud radius and \( b \) is the initial cloud’s centre of mass offset on the \( y \)-axis. \( \frac{b}{R} \) is always smaller than one in our case of a cloud crossing over the black hole.

The initial cloud velocity \( v_c \) in \( x \)-direction is a typical value, taken from the observations presented by Miyazaki & Tsuboi (2000). The evolution is then characterized by the ratio \( \frac{b}{v_c} \) where \( v_c \) is the initial cloud velocity and \( v_c = \frac{2GM_{\text{bh}}}{R} \) is the black hole’s escape velocity at distance \( b \). Table 1 summarizes the initial conditions we used for our parameter study. Three simulations were computed with fixed initial cloud velocities of 50 km/s and varying offsets \( b \), set to 1, 2 and 3 pc, respectively. In addition we did two simulations with \( b \) fixed to 3 pc and varying initial cloud velocities, set to 30 and 80 km/s, respectively. The comparison simulation C01 has the same initial specific angular momentum as simulation V03 but a smaller impact parameter and higher velocity.

The simulations were typically run for an evolutionary time of 0.25 Myrs which corresponds roughly to the situation when all parts of the cloud have crossed the black hole. Only simulation I01 was stopped earlier, that is after 0.2 Myrs. At that time, due to the small impact parameter, the time step became very small making the simulation very time-consuming and too expensive to continue. In this paper we are only interested in the resulting gaseous disk properties and defer the study of star formation to a follow-up paper.

Table 2. The total mass within the accretion radius \( M_{\text{acc,exp}} \) as expected theoretically, assuming angular momentum conservation compared with the result \( M_{\text{acc,exp}} \) from the numerical simulations.

| ID  | \( M_{\text{acc,exp}} \) [10^4 M_⊙] | \( M_{\text{acc,sim}} \) [10^4 M_⊙] |
|-----|-----------------------------------|-----------------------------------|
| I01 | 0.1                               | 4.33                              |
| I02 | 0.08                              | 1.22                              |
| V01 | 0.13                              | 0.68                              |
| V02 | 0.05                              | 0.26                              |
| V03 | 0.03                              | 0.16                              |
| C01 | 0.03                              | 1.12                              |

4 RESULTS

4.1 Density Evolution

Figure 1 shows the time evolution of the cloud for our standard model I02. Density maps and the velocity field in the xy-midplane with \( z=0 \) are plotted. After starting the simulation, the cloud approaches the black hole from the right side along the x-axis. Due to tidal forces the parts closest to the black hole quickly start to form a finger-like extension stretching towards the black hole located at the coordinate origin as seen in Figure 1.

This material passes the black hole on orbits corresponding to its initial angular momentum. 8000 yrs later (Figure 1b), this material collides with gas from the opposite side. A density wave forms (green area) which thickens and moves around the disk as seen in the figures 1c,d,e. The simulation was stopped after 0.25 Myrs when the cloud had passed around the black hole. An inner, relaxed equilibrium disk has formed at that time while the outer region represents a 1-armed infalling spiral in the disk plane. This evolutionary state is shown in Figure 1 and Figure 2. Note also the narrow yellow high-density line along the negative x-axis in Figure 1c, and Figure 1d which results from the collimation of material, initially located above and below the z=0 plane which after passing the black hole is redirected towards the negative x-axis.

In all simulations, the SPH particles in the inner 0.1 pc reach the minimum smoothing length so that we are limited by numerics in this region and the physics is not resolved anymore due to strong smoothing over the forces and thus we cannot make any reliable predictions for the size of the inner disk radius.

4.2 Disk Surface Density Distribution

The resulting disk surface density distribution at the end of the simulations (at \( t = 0.25 \) Myrs for all simulations, except I01 which stopped at \( t = 0.2 \) Myrs) are shown in Figure 3. The surface density was calculated by integrating the density in the \( z \)-direction from \( -10^{-2} \) to \( -10^{-2} \) pc in order to capture only gas within the thin disk. The vertical black line in Figure 3 indicates the radius of 2 x \( 10^{-2} \) pc within which SPH particles were removed from the simulation and are considered “accreted” onto the black hole.

The green (dashed) line shows the expected surface density if we just redistribute material according to its initial angular momentum in a circular Keplerian disk. Given in red (solid line) is the resulting surface density from the last
time step of our simulations. Without angular momentum redistribution we would expect that the total accreted mass (accretion will be discussed in detail in subsection 4.3) is equal to the mass within the accretion radius, given by the surface density distribution according to the green curve.

In Table we compare the accreted mass expected from this simple model to the actual accreted mass at the end of our simulations, which take angular momentum redistribution realistically into account. The simulations result in values that are a factor of 5-40 larger than naively expected.
Figure 4. Plot of all grid cells with a Toomre parameter smaller than one. Each grid cell has a size of 0.02×0.02 pc.
from redistributing material in a circular Keplerian disk according to the initial angular momentum which demonstrates the highly non-linear evolution of the accretion disk, the importance of dissipative processes and the redistribution of angular momentum.

To analyse disk stability we calculate the Toomre parameter $Q = \frac{c_s^2}{\pi G m_r}$ on a 250×250 grid applied to an area of 5×5 pc in the xy-plane. Figure 2 shows the resulting disks defined by all grid points with a Toomre parameter smaller than one ($Q < 1$). We compare the properties of the unstable disks defined in this way to the observed stellar disk.

### 4.3 Accretion

Accretion rates are calculated from material which falls below our accretion radius of $r_{acc} = 2 \times 10^{-2}$ pc. This does not necessarily mean black hole accretion since the formation of a small and hot black hole accretion disk evolving viscously is beyond the resolution limit and outside the scope of our current simulation. Nevertheless, it is interesting to compare our accretion rates for all simulations to the Eddington rate of the black hole which is shown in Figure 3. The Eddington mass accretion rate is defined as $\dot{M}_{edd} = \frac{\sigma_T}{\epsilon_T} \frac{m_r}{c_s^2}$, with $m_r$ being the proton mass, $\epsilon$ the accretion efficiency and $\sigma_T$ the Thompson scattering cross-section. From this we get an Eddington rate of $\dot{M}_{edd} = 0.0775 \frac{M_\odot}{M_{BH}}$ using an accretion efficiency of 10% and a 3.5 × 10^6 M_\odot black hole.

Note that the y-axis is scaled differently for different simulations due to the large range of accretion rates we get. At the end of all simulations we reach very low accretion rates indicating that we have reached a nearly stationary state. The low impact parameter simulation I01 accreted almost the same mass as a test case we did with $\frac{v_0}{c_s} = 0$. For the $\frac{v_0}{c_s} = 0$ case all cloud material has zero net angular momentum and the complete cloud is accreted in a small stream onto the black hole. The evolution of this test-case can be seen in Figure 4 together with a close-up of the accretion back-flow. The accretion rates of the large impact parameter simulations V02 and V03 stay below the Eddington rate at all times.

A comparison of the simulations I01, I02 and V02 in Table 2 shows that the impact parameter plays the most important role in determining the final accreted mass while the cloud velocity has a much smaller effect (compare V01, V02 and V03). In all simulations we still have accretion at the end of the runs, however at very low rates, thus the values shown in Table 2 would only increase slightly if the simulations were continued longer.

### 4.4 Disk Properties

Finally, we study the masses and eccentricities of our resulting disks from section 4.2. Simple elliptical fits were made to the disks and the masses were calculated by counting gas which is unstable according to the Toomre criterion. The results are summarized in Table 3.

When comparing the disk masses in the simulations I01, I02 and V02 (fixed velocity, variable impact parameter) with the simulations V01, V02 and V03 (fixed impact parameter, variable velocity) we note that in contrast to the accretion rates, for which the impact parameter was the dominating factor, the cloud velocity is the most important factor in determining the disk masses.

Comparing V03 with C01 we see that the initial specific angular momentum does not determine the final disk properties. According to the data from Paumard et al. (2006) the stars in the observed disks have specific angular momentum reaching from roughly 30 to 70. I01 is within this range and V01 close to it, but these simulations do not reproduce the properties of the observed disks as well as V03 which has a rather large initial specific angular momentum, which again demonstrates the highly nonlinear evolution of a cloud crossing over the black hole.

On average we find disk eccentricities of order $e = 0.4$ and an outer radius of $r = 1.35$ pc. The observed eccentricities of the stellar rings in the GC are $e = 0.34 \pm 0.06$ (Bartko et al. 2009), the estimated mass of the gaseous disk that formed the stars is expected to be around $M \sim 10^{4-5} M_\odot$ (Nayakshin & Cuadra 2005; Nayakshin et al. 2006). The observed outer radius of the disk is roughly $r = 0.5$ pc (Genzel et al. 2003), with the observed disk size still increasing due to the addition of newly observed stars belonging to the disk structure.

These properties are very similar to our gaseous disks, which have a bit too large radii but already show the same low eccentricity as the stellar disks and the required mass in gas to form the observed stellar disk.

### 5 SUMMARY AND DISCUSSION

We have performed simulations of a gas cloud colliding with a massive black hole with parts of the cloud crossing directly over the black hole during the process. Despite the fact that the impact velocity of the cloud and its initial distance is large, sub parsec-scale gas disks form due to angular momentum redistribution and through the efficient dissipation of kinetic energy by the collision of gas flowing around opposite sides of the black hole.

For non-zero impact parameters the net angular momentum generates an eccentric gas disk with global properties that are similar to the observed stellar rings detected in the GC. We get low eccentricities in the range of $e = 0.24 - 0.51$, disk sizes from $r = 1 - 1.7$ pc and masses of the unstable disk region from $M = 0.7 - 6.95 \times 10^4 M_\odot$. The impact parameter is the dominant factor in determining the accretion rates, for which the impact parameter was the dominating factor.
Figure 5. The red (solid) line shows the accretion rate in $M_\odot$ yr$^{-1}$ (left y-axis). The dashed green line shows the Eddington limit of a $3.5 \times 10^6 M_\odot$ black hole at 10% accretion efficiency. Also plotted is the total accreted mass in blue (dotted line) in $M_\odot$ (right y-axis). The low impact parameter simulations accrete at super-Eddington rates, whereas the high impact parameter simulations stay below Eddington accretion at all times.

The accretion rates, from sub-Eddington accretion rates for large impact parameters to super-Eddington accretion for small impact parameters. The cloud velocity is the most important factor in determining the final Toomre unstable disk mass fraction, with a high mass for low velocity clouds and a low mass for high velocity clouds.

Clearly, there is a lot of additional physics that must be included, which will be explored in a subsequent paper. Firstly, we did not investigate the thermodynamics (heat-
Figure 6. Logarithmic density in \( \frac{M_\odot}{\text{pc}^3} \) in the xy-plane with z=0 at different times for the test-case \( \frac{b}{R} = 0 \). (d) is a close-up of the accretion flow visible in panel (c). The velocity is given in km/s. The whole cloud collapses into the black hole since the net angular momentum is zero.

ing/cooling) of the disk as well as its fragmentation and star formation which is necessary to directly compare the simulations with the observations. Secondly, a more realistic cloud model should be used since observations clearly indicate that GC clouds are highly turbulent (Güsten & Philipp 2004). Finally, black hole and stellar feedback will also play an important role in the formation process.

Still our results are very encouraging, we have shown that redistribution of angular momentum must be taken into account when a cloud falls onto the GC black hole and our simulations show that this mechanism can indeed produce eccentric, Toomre unstable disks with properties similar to the ones observed in the GC.

From all the simulations we have performed, simulation V03 shows the most promising features such as low eccentricity of around \( e = 0.24 \), a disk mass of roughly \( M = 10^4 M_\odot \), a size of \( r = 1.0 \text{ pc} \) with sub-Eddington mass accretion at all times.

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