Gas physics and dynamics in the central 50 pc of the Galaxy

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We present models the gas physics and dynamics of the inner 50 pc of the Galaxy. In a first step the gas properties of an isolated clumpy circumnuclear disk were analytically investigated. We took the external UV radiation field, the gravitational potential, and the observed gas temperature into account. The model includes a description of the properties of individual gas clumps on small scales, and a treatment of the circumnuclear disk as a quasi-continuous accretion disk on large scales. In a second step the dynamics of an isolated circumnuclear disk were investigated with the help of a collisional N-body code. The environment of the disk is taken into account in a third step, where we calculated a pro- and a retrograde encounter of an infalling gas cloud with a pre-existing circumnuclear disk. In order to constrain the dynamical model, we used the NIR absorption of the giant molecular clouds located within the inner 50 pc of the Galaxy to reconstruct their line-of-sight distribution.

1 Introduction

During the discussion led by R. Narayan at this conference it became clear that the mass accretion rate onto the central black hole in the Galactic Centre at a radius of <1 pc is ∼ 10−8 M⊙ yr−1. The central black hole is thus extremely sub-Eddington. In order to understand the fueling mechanisms of the central engine, there is an inevitable need for understanding the gas physics and dynamics in the inner ~50 pc of the Galaxy. Gas that flows radially into the Galactic Centre has to pass several barriers. At large scales (<kpc) the gas has to cross the resonance of the inner Lindblad radius. According to the gravitational potential of the Galactic Bulge region, there might be a second inner Lindblad radius that the gas has to overcome. When the gas finally arrives in the inner 200 pc of the Galaxy, it is very clumpy and has a volume filling factor of a few percent (Launhardt et al. 2002). In this environment five different environmental effects determine the structure of the ISM: (i) the stellar radiation field, (ii) stellar winds, (iii) the shear due to differential rotation, (iv) instabilities due to self-gravitation, and (v) supernovae. We modeled analytically the properties of the gas located in the inner 20 pc including the effects (i)–(iv) (Vollmer & Duschl 2001a, 2001b). In a second step we investigated the collision of an external gas cloud falling onto an existing disk structure in the Galactic Centre (Vollmer & Duschl 2002). Finally, the line-of-sight distribution of the giant molecular clouds in the inner 50 pc of the Galaxy were reconstructed using their NIR absorption (Vollmer et al. 2003).

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2 The analytical model (Vollmer & Duschl 2001a, 2001b)

In the inner 20 pc of the galaxy the gas is very clumpy with a volume filling factor of ~1%. These clumps have masses of ~30 M⊙ and sizes of ~0.1 pc (see e.g. Jackson et al. 1993). They are illuminated by the UV radiation field of the central HeI star cluster and form a ring-like structure that is known as the Circumnuclear Disk (CND) (Güstén et al. 1987). Fig. 1 illustrates the situation. The whole CND has a total gas mass of several 10^4 M⊙. The inner edge is located at a radius of ~2 pc where the density of the neutral gas drops by more than an order of magnitude. The gas in the central 4 pc is ionized and forms the giant HII region Sgr A West.

![Fig. 1 Sketch of the inner 15 pc of the Galaxy. The Circumnuclear Disk (CND) consists of small, dense gas clumps that are illuminated by the central HeI star cluster. The dotted line delineates approximately the extension of the HII region Sgr A West.](image)

Our analytical model to describe the gas properties consists of two parts:
(i) Small scale: the gas clumps are described as isothermal spheres that are partially ionized by the UV radiation field (Fig. 2). The gas temperature of the clouds is assumed to be proportional to $R^{-1/2}$.
(ii) Large scale: the properties of clouds located at different distances from the Galactic Centre are determined. The clumpy gas distribution is then smeared out to obtain a quasi-continuous disk structure that is described by the standard set of accretion disk equations with a modified viscosity prescription taking the radiative energy dissipation during clump–clump collisions into account.

Both models are connected via the central density of the clumps that is proportional to the central density of the disk: $\rho_{cl} = \Phi_V^{-1} \rho_{disk}$, where $\Phi_V = 0.01$ is the volume filling factor. In addition, the clump properties influence the disk viscosity via the local energy dissipation rate. The main results of this modelling are:
(i) There are two solutions for our set of equations that correspond to two stable clump regimes: the observed heavy clumps ~10 M⊙ and the stripped cores of the heavy clouds with masses between 10^{-5} and 10^{-4} M⊙.
(ii) Within the disk, the number of collisions between clouds is very low ($n_{coll} \sim 10^{-4}$ yr^{-1} for about 500 clouds).
(iii) The inferred mass accretion rate for the isolated CND is $\dot{M} \approx 10^{-4}$ M⊙ yr^{-1}.
(iv) The CND is much more stable and has a much longer lifetime (~ 10^7 yr) than previously assumed.

The disk clouds are exposed to strong stellar winds, the central UV radiation field, and strong tidal shear. We show that stellar winds shape the clouds, but do not affect their other properties. In order to resist the strong shear due to differential rotation each cloud’s central densities must increase with decreasing distance to the Galactic Centre. Its outer radius is determined by the UV radiation field at the illuminated side and by the external gas pressure at the shadowed side opposite to the direction of the Galactic Centre. We show analytically that for a temperature gradient of the form $T \propto R^{-2}$ the radius of the massive clouds are constant irrespective of their location in the disk. Thus, clouds that can resist
Fig. 2 Illustration of the partially ionized globule model described in the text. The UV radiation comes from the direction of the Galactic Centre. The boundary opposite to the Galactic Centre is determined by the gas pressure of the surrounding ionized low density gas.

Tidal shear will become more and more massive when approaching the Galactic Centre. Finally, they will collapse when their masses exceed the Jeans limit. We suggest that the cloud distribution within the CND reflects two selection effects. First, the clouds have to be dense enough to resist tidal shear and second, the clouds that are too massive collapse and will form stars. Magnetic fields and rotation stabilize otherwise gravitationally unstable clouds. This mechanism naturally explains the existence of the inner edge of the CND. Fig. 3 shows the central density of the heavy clouds versus the distance from the Galactic Centre. The limits for gravitational collapse and tidal disruption cross at $R \sim 2$ pc. The dashed surface represents the range of densities where clouds are gravitationally and tidally stable.

Fig. 3 Central density of the heavy clouds versus the distance to the Galactic Centre. Dashed line: maximum central density above which gravitational collapse occurs. Solid line: minimum density in order to resist tidal shear. Dashed surface: range of densities where clouds are gravitationally and tidally stable.
3 The numerical model (Vollmer & Duschl 2002)

In a next step, we use our knowledge acquired with the analytical model to build a realistic dynamical model in order to investigate the gas dynamics in the inner 50 pc of the Galaxy. Since a circumnuclear disk (CND) consisting of small clumps with a tiny volume-filling factor can be long-lived (several Myr, see Sect.2), we study the scenario where a part of a giant molecular cloud falls onto a pre-existing CND. We use a collisional N-body code where each particle represents a gas clump with a certain mass and radius. The infalling gas cloud also consists of a number of small subclumps. These clumps have masses around the observed value of \(30 \, M_\odot\). When a clump approaches the Galactic Centre closer than 2 pc, it is assumed to be destroyed by tidal forces or by gravitational collapse (see Sect.2). These clumps are counted as accreted.

The collisional N-body code yields a realistic cloud collision rate that depends on the cloud radius, density, and dispersion velocity. A realistic simulation of an isolated CND shows the observed disk structure. This simulation yields a mean collision time scale of \(t_{\text{coll}} \sim 2\) Myr and a mass accretion rate of \(10^{-4} \, M_\odot \, \text{yr}^{-1} \leq \dot{M} \leq 10^{-3} \, M_\odot \, \text{yr}^{-1}\). The infalling cloud, which has a mass of several \(10^4 \, M_\odot\), is assumed to be on (i) a prograde orbit and (ii) a retrograde orbit with respect to this CND. We study the resulting cloud–cloud collision rate and the mass accretion rate using different loss rates of the kinetic energy during a collision. Fig.4 shows a prograde (left side) and a retrograde (right side) encounter with a loss of 10% of the kinetic energy of the clumps during a collision. The main difference between the two simulations is that the CND is destroyed 3-4 Myr after the first encounter with the external cloud in the
case of a retrograde encounter. Its mass is mainly accreted onto the Galactic Centre. At the end of the simulation a second CND has formed that has approximately the angular momentum of the infalling cloud, but there is still a counter-rotating core visible, which represents the remnant of the former CND. In the case of a prograde encounter, the infalling mass is partly added to the pre-existing one. The outcome of this simulation is a warped CND that is more massive than the pre-existing CND. Within our scenario of an encounter between an infalling molecular cloud and a CND, it is possible that the observed He II star cluster in the Galactic Centre has been formed by a retrograde encounter of a cloud with the CND ∼7 Myr ago. The cloud that formed the He II star cluster has been destroyed by tidal forces and can presently no longer be distinguished as a single kinematical entity.

4 The LOS distribution of the GMCs (Vollmer et al. 2003)

The fueling of the central black hole in the future depends mainly on the present dynamics of the gas in the inner 50 pc of the Galaxy. Within this region the gas is heavily clumped and mainly in the form of giant molecular clouds. Following Zylka et al. (1990) three main giant molecular cloud complexes can be distinguished: (i) Sgr A East Core, a compact giant molecular cloud with a gas mass of several 10^5 M_☉ located north–east of Sgr A*. (ii) The giant molecular cloud M-0.02-0.07 located to the east of Sgr A*. Since its mean radial velocity is ∼50 km s^{-1}, it is also called the 50 km s^{-1} cloud. (iii) The GMC complex M-0.13-0.08 located south of Sgr A*. Since its mean radial velocity is ∼20 km s^{-1}, it is also called the 20 km s^{-1} cloud. The Sgr A East core is part of the 50 km s^{-1} cloud complex, thus we will treat these features as a single structure. Fig. 5 shows a sketch of the inner 30 pc of the Galaxy, where the main features are indicated (Minispiral, CND, 20 km s^{-1} cloud, 50 km s^{-1} cloud). If one wants to understand

![Fig. 5 Sketch of the inner 30 pc of the Galaxy. The central black dot represents the He II star cluster surrounded by the Minispiral and the CND (where only the high velocity lobes are shown). Most of the mass is located at negative b.](image_url)

the gas dynamics in the central 50 pc of the Galaxy, it is of crucial importance to know the line-of-sight distribution of the giant molecular clouds (20 and 50 km s^{-1} clouds) located in this region.

We reconstruct the line-of-sight distribution assuming (i) an axis-symmetric stellar distribution and (ii) that the clouds are optically thick and have an area filling factor ∼1, i.e. that they entirely block the light from the stars located behind them. Fig. 6 shows the reconstructed LOS distribution of the giant molecular clouds in colors. The IRAM 30m 1.2 mm observations of Zylka et al. (1998) are overlayed as contours. Due to the method of reconstruction, LOS distances close to Sgr A* (<10 pc) have a small uncertainty, whereas larger LOS distances might be located up to a factor 2 farther away from Sgr A*. The relative distances are robust results. We found that:

All structures seen in the 1.2 mm observations (Zylka et al. 1998) and CS(2-1) observations (Güsten et al. in prep.) are present in absorption.

The 50 km s^{-1} cloud complex is located between 0 pc and -5 pc, i.e. in front of Sgr A*. It has a small LOS distance gradient.

The 20 km s^{-1} cloud complex is located in front of the 50 km s^{-1} cloud complex. The subclump of
strongest absorption has a LOS distance between -40 pc and -20 pc. The CND is not seen in absorption. This gives an upper limit to the cloud sizes within the CND of $\sim$0.06 pc. The combination of the LOS distribution of the gas and its kinematics will help to unravel the dynamics of the gas in the inner 50 pc of the Galaxy, which represents the future fueling of the central black hole.

5 Outlook

From the present modeling of the gas in the inner 50 pc of the Galaxy we have learned about crucial aspects of the gas physics and dynamics. We found that the mass accretion rate into the central parsec is highly variable and a period of almost no mass accretion is conceivable. This period of starvation might last about $10^4$ yr, which is the cloud–cloud collision time within the CND.

We are now in the position to use the acquired knowledge to determine the temporal behaviour of the mass accretion rate in the past and how it might change in the future. Remaining questions are: Can we find clear signs of past interactions of an external cloud with a pre-existing circumnuclear disk? Will the accreted mass exclusively come from the CND in the near future? Will there be a major accretion event in the near future, when a part of a massive giant molecular cloud interacts with the CND? We already have the keys in our hand to unravel the exciting history and future of the gas dynamics in the Galactic Centre.

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