Molecular Clouds Close to the Galactic Center

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Abstract.

We demonstrate that the accretion disk model for the Galactic Center region by Linden et al (1993a) is applicable for at least one order of magnitude in radius from the Galactic Center (10 ... 100 pc). The viscosity $\nu$ is shown to be weakly dependent on the radius $s$: $\nu \sim s^{0.4}$. Finally, we discuss the influence of the inner boundary on the structure of the inner disk regions.
Introduction

In a recent paper Linden et al. (1993a) (in the following often referred to as LDB) have shown that one can use molecular clouds in the Galactic Center (GC) region as tracers of the large scale mass flow in this area. They demonstrated that their technique allows one to determine the location of the clouds as well as the radial mass flow rate and the viscosity in the disk. While they find large values for the viscosity, they can show that these are in agreement with the observed velocity dispersion and the scale height of the gas distribution.

Additionally, Linden et al. (1993b) (=LBSLD) explained this large viscosity in terms of turbulence that is induced through gravitational instability, subsequent star formation and then actually driven by the ensuing supernova explosions. From the reasoning given there it follows that one has to expect the viscosity \( \nu \) to be smaller for smaller radii from the GC (for stationary accretion disks, \( \nu = \text{const.} \) [see sect. 4; : vertically integrated surface density]; usually, \( \partial / \partial s < 0 \) (\( s \): radial coordinate), i.e. \( \partial \nu / \partial s > 0 \)).

LDB demonstrated their method for one example, namely for one of the best observed molecular clouds close to the GC, M-0.13-0.08. As it turned out that this cloud is located in their model on a ring segment at an almost constant radius of \( \approx 115 \text{ pc} \) from the GC they could not draw any conclusions about the radial variation of the viscosity. In the present paper, we wish to test the validity of the LDB-model and the parameter set as obtained by LDB by analyzing recent observations of molecular clouds with small projected distances on either side of the GC. The results for the H\(_2\)CO observations by Pauls et al. (1993) demonstrate that these are in agreement with the model considerations. In addition to determining the clouds’ geometrical positions to be \( \approx 10 \text{ pc} \) from the GC, this allows even to get information about the gradient of the viscosity between 10 and 100 pc.

In the next section, we give a short description of the model as introduced in LDB and the technique of their analysis that we also use here; in section 3, the observations and our results are compiled. Section 4 is devoted to a discussion of these results, especially of the implications for the radial variation of the viscosity. In the subsequent section, we discuss how our conclusions depend on the physical and numerical modelling of the disk’s inner boundary. The last section, finally, is devoted to a compilation of our conclusions and to an outlook on how we plan to proceed in the analysis of the gas distribution in regions close to the GC.

The model for the gas dynamics close to the Galactic Center

Following LDB we model the gas and its distribution in the innermost \( \approx 200 \text{ pc} \) of the Galaxy as a viscous accretion disk. We assume that the disk extends along the galactic plane. We use the following approximations as is usually done in the context of modelling accretion disks (Weizsäcker, 1943, Lüst, 1952, Shakura and Sunyaev, 1973):

- The disks are geometrically thin in the direction perpendicular to the rotation plane. We take the standard approach and describe the vertical structure in a one zone model.
• The disk evolves in a gravitational potential that is rotationally symmetric in the galactic plane. Despite the fact that our Galaxy might be a barred spiral, the assumption of a rotationally symmetric gravitational potential is reasonable as the length scales of such a potential bar are larger than the ones of the disk that we are discussing (Matsumoto et al., 1982; Blitz and Spergel, 1991; Binney et al., 1991). Consequently, we assume the disk to be also rotationally symmetric. We expect inhomogeneities in the disk flow to cause larger deviations from rotational symmetry than asymmetries in the galaxy’s gravitational potential. Nonetheless, in this first of analysis, we neglect such deviations from axial symmetry.

• We assume the radial mass flow rate, $\dot{M}$, to be constant. Further, we assume that vertical infall into the disk does not play a rôle at any radius. These assumptions will be discussed in Sect. 5.

In contrast to standard $\alpha$-accretion disks we allow for several additional processes:

• Viscosity is generated by processes outside the accretion flow itself. In this respect it is a different type of accretion disk model from the usually discussed $\alpha$-disks (Shakura and Sunyaev, 1973). Details of the viscosity prescription are discussed below.

• If the disk becomes gravitationally unstable, i.e., if Toomre’s $Q$ value (Toomre 1964) drops below unity, we allow for star formation to set in. We approximate this by dealing with a two phase medium. The phase of the newly formed stars decouples from the viscous evolution of the gaseous phase, and does not accrete, while it still contributes to the potential.

We describe the disk in a cylindrical coordinate system $\{s, z, \varphi\}$.

In the current model, we do not specify the physical process that determines the viscosity $\nu(s)$ in a self-consistent way but rather choose some prescription for this physical quantity. This means that at this point we specify “only” the efficiency of a process that causes radial transport of mass and angular momentum (i.e., that drives the accretion process). In contrast to Linden et al. (1993a), we do not require $\nu$ to be constant throughout the disk but rather assume a power law dependence on the radius:

$$\nu = \nu_0 \left(\frac{s}{s_\nu}\right)^\beta$$  \hspace{1cm} (1)

$\nu_0$ and $s_\nu$ are scaling variables that have to be chosen such that the resulting flow velocities are compatible with the results for M-0.13-0.08. This requires

$$\nu_0 = 6 \cdot 10^{26} \text{ cm}^2\text{s}^{-1} \quad \text{for} \quad s = s_\nu = 115 \text{ pc}$$  \hspace{1cm} (2)

$\beta$ is the power that has to be determined through our analysis. A meaningful determination of $\beta$ is only possible if the resulting radial distance for the two gas components that we use for the analysis (see next section) is considerably different from the 115 pc as determined for M-0.13-0.08, as otherwise the radial baseline would be too short.

While, formally speaking, this prescription for $\nu$ is introduced artificially into LDB’s accretion disk model, LBSDL have shown that one can very well understand $\nu$ as to be caused by local processes in the region of the disk that are due to the stellar component that is coexisting there (star formation and supernovae stir the gas and thus enhance the turbulence that acts as viscosity in the gas component).
Figure 1. Face-on view onto a cut out of the GC accretion disk. The observer is located at $x = 8.5$ kpc, $y = 0$ pc. The (underlying) theoretical radial velocity field is shown as a gray-scale picture (The definition of the sign of the shown velocity component $v_x$ is given in the text). The two vertical bars represent the observations as discussed in the text. An individual observation consists of a direction, i.e., a vertical bar in the figure at the proper position, and a radial velocity, i.e., a certain shade of gray. In the framework of the model, the location of the cloud components is determined by matching shades of gray.

In this paper, we assume that all other parameters are the same as used by LDB:

- There is a compact mass in the very GC with $M_c = 2 \cdot 10^6 M_\odot$, presumably a black hole.
- The background mass distribution due to the stellar component in the GC region is spherically symmetric and follows the power law $M_b(r) = 1.14 \cdot 10^9 M_\odot (r/100 \text{ pc})^{5/4}$. $M_b(r)$ is the mass enclosed in a sphere of radius $r$.
- The disk’s outer radius is located at 200 pc from the GC.
- The disk’s inner radius is located at 1 pc. In section 5, we shall discuss the influence of this parameter on our solutions, and shall see that in the present context of the standard boundary condition, the resulting positions of the gas clouds are far enough from the disk’s numerical boundary not to be influenced strongly by the boundary condition.
- The disk is stationary with a radial mass flow rate of $10^{24}$ g/s. Star formation does not consume an appreciable fraction of the gas flowing in.
In the framework of these assumptions and parameters, we solve for the radial distribution of surface density and radial and azimuthal velocity in the disk.

It turns out that Toomre's $Q$ value is never smaller than unity. But we would like to remark that this is only a sufficient condition for star formation actually to take place. As is shown in LBSLD (c.f., especially, their sect. 5), about one and a half orders of magnitude lower a surface density might very well be sufficient to sustain star formation under the conditions prevailing in our disks. We shall discuss the consequences of a possible limit cycle behaviour in a subsequent paper (Duschl et al., in preparation).

In principle, additional effects could come from non-stationary disks. We have investigated this possibility and found that – for our currently still very limited sample of observed velocities – this does not lead to an improvement of our solutions. Actually, we have obtained all our solutions by following the time evolution of disks from arbitrarily chosen initial mass distributions until a steady state was reached. While we followed the intermediate models in the course of the disk's evolution, we found that stationary solutions usually accounted for the best representations of the observations.

**Observations and results**

To test the model of LDB and to refine the description further, we attempt to include two (components of) gas clouds as observed by Pauls et al. (1993) in H$_2$CO. Out of a large body of observations in different frequencies and for different molecules (e.g., Bally et al., 1987 and 1988; Serabyn et al., 1987; Zylka et al., 1990; Oda et al., private communication), we choose this particular set observations mainly on grounds of the following reasoning. To get meaningful information about the radial gradient of the viscosity, we need a long radial baseline. As the cloud M-0.13-0.08 is located at about 115 pc distance from the GC in a disk with an outer radius of 200 pc, to achieve this long baseline, we need observations of gas that is much closer to the GC than $\approx 100$ pc. Moreover, this choice allows to get information about the physical conditions in the nearer vicinity of the GC than is obtained by working on M-0.13-0.08.

Before attempting to map large areas of the gas distribution in the GC, such a step that confirms the large range applicability of the model seems to us to be mandated.

The two components that we use have projected locations on either side of the GC and both show radial velocities of -188.5 km/s (LSR velocities; negative velocities pointing towards us; velocities radial to the observer, but not to the GC); the one component is located 24" west of the GC (in the following referred to as component W-1), the other one 13" east of it (W-2).

We find that it is indeed possible to explain both observations in the framework of the LDB model, and find that the two components are located about 10 pc from the GC. The result is shown in Fig. 1. There we followed the velocity definition of LDB, i.e., the velocities are counted positive (in the reference system of an accretion disk centered on the GC, a velocity directed towards the GC from negative coordinates, i.e., from “behind” the GC has to be counted positive). Fig. 1 shows the plane of the disk face-on. The observer at Earth is situated at $x = 8,500$ pc, and $y = 0$ pc. The vertical lines correspond
to the observations which give us a direction and a velocity. The velocity is coded by
different shades of grey. The underlying theoretical velocity field as computed from the
accretion disk model is coded in the same way. The location of the clouds is determined
by matching grey shades. The shown velocities are \( v_x \) velocities, i.e., LSR velocities radial
with respect to the observer; this is meant by the expression “geocentric radial velocities”.

When keeping all the other parameters of the LDB model unchanged, we get the best
solutions for a radial dependence of the viscosity \( \nu \sim s^{0.4} \).

In the resulting models, the local galactocentric radial velocities (i.e., the real radial
velocities in the disk with respect to the GC as opposed to the above defined geocentric
ones that are radial with respect to the observer) are of the order of 10\% of the corre-
responding azimuthal (i.e., Keplerian) velocity. Only for radii smaller than \( \approx 3 \) pc our
approximation of a Keplerian, geometrically thin disk break down as then the radial veloc-
ities are no longer small compared to the azimuthal ones. On the other side, in the radius
range of \( \approx 1 \) pc our description becomes unsatisfactory anyway as there boundary effects
will play an important rôle. We address this aspect in Sect. 5.

**Discussion**

Our results are in good agreement with what LDB found: LDB determined a set of pa-
rameters by modelling the cloud M-0.13-0.08 which is located at \( \approx 115 \) pc. We took the
approach of assuming that – with the exception of the viscosity – these parameters are
valid throughout the GC accretion disk. We demonstrated that it is indeed possible to
understand the observed velocities of the \( \text{H}_2\text{CO} \) clouds at \( \approx 10 \) pc from the GC.

On theoretical grounds (e.g., LBSLD) we expected a radial variation of \( \nu \sim s^{\beta} \).
The exponent \( \beta \) itself is determined through our present analysis. It turns out that for
all \( \beta \in [0, 1] \) the velocity of the western component (W-1) can easily be reproduced
in the framework of the LDB-model. But only for \( \beta \lesssim 0.45 \), we succeed to get good
representation for both components. Moreover, we find that for \( \beta \lesssim 0.3 \), the solutions
become meaningless as then the radial velocities at the points of the clouds are no
longer small compared to the azimuthal velocities. Then the approximations of the model
calculations break down. While on the first glance this is mainly a problem of the model’s
assumptions and does not exclude a predominantly radial motion of the gas, one has
to keep in mind that observations clearly indicate that a disk-like structure of the gas is
maintained down to the radius of the molecular ring at 2 pc. This indicates that a value for
\( \beta \approx 0.4 \) is a physically consistent and reasonable result.

This result is also in reasonable agreement with the results of LBSLD. There it was
concluded on the grounds of order of magnitude estimates that \( \nu \) should vary approxi-
mately linearly with the radius. Our results indicate that the radial dependence is somewhat
weaker.

This can be understood if we loosen LBSLD’s assumption of an inversely linear radial
dependence of but rather take a more general approach. The continuity equation \( \dot{M} =
2\pi s v_s \), together with the approximation \( v_s \approx s/\tau_{\text{visc}} \approx \nu/s \) gives for stationary accretion
disks \( \nu = \text{const.} \). (\( v_s \): radial velocity of matter in the accretion disk; \( \tau_{\text{visc}} \) viscosity time
scale characterizing the typical time scale for matter motion in the accretion disk from $s$ to the disk's inner edge). Additionally, $\nu \sim h c_s$. If we now again follow LBSLD, we get a selfconsistent solution with $c_s \sim s^{-0.17}$, $v_\varphi \sim s^{1/8}$, and $h \sim s^{1.04}$, and find that $\nu \sim s^{0.54}$ and $\sim s^{-0.54}$ which is in good agreement with the value for $\beta$ that we deduced from observations ($c_s$: (isothermal) sound velocity; $v_\varphi$: azimuthal (Keplerian) velocity in the disk; $h$: vertical (half-)thickness of the disk). It is important to note that the above analytical derivation for $\beta$ and the numerical determination are fully independent of each other. Thus this is not only a pleasing matching of numbers but a very strong indication that the physical mechanism of supernova driven turbulence as discussed by LBSLD indeed can reproduce what is going on in the GC region.

**Physics and numerics of the disk’s inner boundary**

We have placed the (numerical) inner radius of the disk at $1\, \text{pc}$. There we applied the standard accretion disk boundary condition that matter leaving the Keplerian disk in inward direction keeps all its angular momentum and thus takes it away from the disk. This also means that this matter keeps its orbital kinetic energy.

This approximation is known to be numerically a problematic one (as it leads to a singularity at the boundary itself) and physically an oversimplification (Duschl and Tscharnuter, 1991). On the other hand it is known that it leads to serious problems only at radii close to the inner radius (i.e., in our case, for $s \gg 10\, \text{pc}$). To ensure that our results are not dominated by the numerical boundary condition, we repeated our calculations for an inner radius of the disk of $0.01\, \text{pc}$. The results were only slightly influenced at the radii where the two clouds are located.

While this is a sufficient numerical justification in the context of the questions discussed in this paper, this kind of a physically and numerically doubtful boundary condition is a conceptual problem for the entire description. We shall address this problem in a forthcoming paper (Duschl et al., in preparation). There, from the formal point of view, we will take the approach of assuming that only a fraction $\zeta \in [0, 1]$ of the angular momentum of the innermost orbit is transported away. From the physical point of view, we will demonstrate that under the conditions prevailing in this radial range from the GC, it is even very likely that the matter will leave as much angular momentum as possible in the disk. The maximum will be mainly determined by the fact that – in addition to conservation of angular momentum – also energy conservation influences the global disk structure. For the present context, it is important to note that the location of the disk’s numerical inner boundary at $1\, \text{pc}$ does not influence the results very much.

In the present paper, we follow LDB and assume that the mass flow rate reaching the disk radially in the rotational plane ($\dot{M}$) does not vary with time, and that the vertical mass infall into the disk is negligible at all radii (cf. Sect. 2). Within the framework of our approximations, the latter means that the integral of vertical mass infall over the relevant disk surface area is always considerably smaller than the radial mass flow $\dot{M}$. We assumed $\dot{M}$ to be a constant as, in the present context, we were mainly interested in investigating the radial variations of the viscosity. In a later phase of our analysis of the gas dynamics
in the vicinity of the GC region, this approximation has to be loosened. This then could lead to non-stationary accretion disk models.

Conclusions

We have demonstrated that the accretion disk model for the gas flow in the GC region by LDB is valid over at least an order of magnitude in radius from the GC if one allows for a (weak) radial variation of the viscosity. We also show that the deduced radial variation of the effective turbulent viscosity is compatible with the scenario of a supernova driven turbulence as proposed by LBSLD.

These results make it worthwhile to attempt to construct a map of the distribution of molecular gas in the innermost ≈ 200 pc around the GC. For radii of the order of 10 pc or even smaller, the question of a proper (numerical) inner boundary condition becomes of importance. The standard boundary condition of accretion disk theory is – as in almost all other cases where accretion disks play a role – not very well suited. In the case of the GC the existence of a (comparatively sharp) inner edge of the disk at ≈ 2 pc gives an important constraint.

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