Our Galactic Center: A laboratory for the feeding of AGNs?

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Abstract.

We demonstrate that our Galactic Center, despite little evidence for the presence of a currently active nucleus, provides insight into the feeding of AGN: The observed velocity field of molecular clouds can be interpreted as tracing out the spiralling inwards of gas in a large accretion flow towards the Galactic Center (Linden et al. 1993, Biermann et al. 1993) in the radial distance range from a few parsec to a few hundred pc. The required effective viscosity corresponds well to the observed turbulent velocities and characteristic length scales. The implied mass influx provides indeed all the material needed to maintain the presently observed star formation rate at distances closer than about 100 pc. We argue that the energy input from supernova explosions due to the high rate of star formation can feed the turbulence of the interstellar medium. This then keeps the effective viscosity high as required to feed the star formation. We suggest that this process leads to limit cycles in star formation, and as a consequence also to limit cycles in the feeding of any activity at the very center.
1. Introduction

The feeding of active galactic nuclei, often of a power that exceeds all of the stars of the surrounding galaxy put together, is one of the major riddles in understanding the energetics of quasars, Seyfert galaxies, BL Lac nuclei and other forms of AGN. It has been argued convincingly that this requires a major mechanism to remove the angular momentum of gas which is already inside several hundred parsec of the nucleus. With the speed of sound at the observed gas temperature and the size of the clouds as scaling for the turbulent viscosity to drive an accretion disk, this does not work; therefore, Shlosman et al. (1989) argued that a stellar bar is required to give the torque which removes angular momentum. While bars are indeed observed in many galaxies, and visibly interact with the gas (e.g. NGC 1300), this is by no means clear for all galaxies that harbor an active nucleus. Also, the bars observed do not easily solve the angular momentum problem on the small length scales required. The problem is actually worse, since many galaxies have an inner region which has a large amount of molecular gas with a large rate of star formation, which also needs to be fed. Shlosman et al. (1990) argue that there is a possibility of “hot accretion”, which would indeed provide larger accretion rates, but their model does not easily yield to a detailed observational check.

Here we will explore our Galactic Center to see what we can learn about the mass influx in an environment where there is little signature of an AGN, and which therefore provides a baseline for which physical concepts can be tested also for inner regions of galaxies that do harbor an active nucleus quite clearly.

Recently we demonstrated (Linden et al. 1993, Biermann et al. 1993) that the observed velocity field of several clouds at distances from the Galactic Center of near 10 pc to $\approx 100$ pc can be interpreted as tracing out a large scale accretion flow. The fit to the observational data implies an effective viscosity for the transport of angular momentum outwards and gas inwards. This effective viscosity in fact matches approximately that value for the transport coefficient implied by the overall velocity dispersion of the clouds and their scale height; this modelling also implies a mass flow inwards, and indeed, the mass flow in turn approximately matches the mass flux required to sustain the presently observed star formation rate.

Moreover, the mass flow rate is in good agreement with what one deduces from observations of the Circumnuclear Disk (CND) inside the region Linden et al. and Biermann et al. were using (Genzel and Townes 1987, Jackson et al. 1993).

We propose that the energy input from supernova explosions due to a high rate of star formation can feed the required turbulence of the interstellar medium. Therefore we specifically ask in this paper whether the star formation rate can uphold the energy dissipation required to maintain the convective turbulence observed, and thus ask, whether the causal loop can be closed between high star formation rate, high excitation of turbulent convection, thus high effective viscosity, thus high mass influx, and then in turn, high star formation rate.
2. The velocity distribution of the clouds

The observations of Zylka (1990) and Zylka et al. (1990) of molecular line emission in the central region of our Galaxy provide the dataset from which we will start to raise our argument. These data allow for the first time to unambiguously discuss the dispersion of the cloud motion and also allow first attempts to actually locate some of the larger clouds, giving the impression of a moderately thick disk-like distribution.

The velocity spread of the cloud motions is about 50 km/s and the scale height of their distribution is of the order of 10 pc. In fact, we can make the following check: Is the cloud velocity dispersion that implied by the known gravitational potential and the z-distribution of clouds, which would support the notion that the cloud motion is basically isotropic? These clouds cannot be moving in an external medium at supersonic speed (referred to the outer medium), because they would be destroyed on dynamical timescales. Therefore, the cloud motions must reflect the motions of a hotter gas, of which the sound speed is at least the velocity of the clouds, and of which the scale height again is at least that of the cloud distribution. In fact, the solar neighborhood suggests that the scale height of the hot ionized medium is indeed several times larger than that of the molecular cloud layer (Garcia-Munoz et al. 1977, Reynolds 1989, 1990).

In order to estimate the scale height of the gas distribution, we have to specify the gravitational potential in which the disk is situated. The mass inside a spherical radius \( r \) can be approximated (Sanders & Lowinger 1972, Genzel & Townes 1987) as

\[
M_r = M_0 \left( \frac{r}{r_0} \right)^{5/4}
\]

with \( M_0 = 5.8 \times 10^7 M_\odot \) and \( r_0 = 9.2 \) pc, which is exactly 30 lightyears. This implies from hydrostatic equilibrium (assuming the temperature to be constant in \( z \)) a scale for the hot outer gas of

\[
H = 0.61 \text{ pc} \left( \frac{c_s}{10 \text{ km/s}} \right) \left( \frac{s}{r_0} \right)^{7/8}
\]

where \( s \) is the radial distance from the Galactic Center in the disk, and \( c_s \) denotes the sound speed. Using, say, \( s = 50 \) pc and \( H = 10 \) pc from the Zylka et al. data, we obtain an adiabatic speed of sound of 37.3 km/s which corresponds to a temperature of \( 6.1 \times 10^4 \) K. This is surprisingly close to the temperature which characterizes the radiation field of Sgr A* (see the recent discussion by Falcke et al. 1993). We have thus made a consistency check: The cloud velocity dispersion in the \( z \)-direction is to within the errors the same as along the line of sight, and so the cloud velocity distribution is approximately isotropic.

3. The physical cause for the large velocity spread of clouds

3.1 Global gravitational instability

Lin and Pringle (1987a) have argued that in a self-gravitating disk the overall gravitational instability serves to excite motions which lead then to an effective turbulence and to a turbulent...
momentum transport. This mechanism may serve as initial viscosity injection into an interstellar medium where star formation just begins. The gravitational instability in a disk (Toomre 1964) appears if

$$Q = \frac{v_d \kappa}{\pi G \Sigma} < 1$$

Equation 3 translates to

$$v_d = 1.4 \text{ km/s} \left(\frac{s}{r_0}\right)^{-1/8} Q,$$

using already here the radial surface density dependence discussed below.

The gravitational instability leads to the growth of density perturbations and can cause a rotating disk to fragment into clumps. The angular momentum transport is then provided by the shear and viscosity produced by this kind of instability. The viscosity is related to the clouds that form in a gravitationally unstable disk. The instability develops fragments with velocities of the order

$$v_c = \frac{\pi G \Sigma}{\kappa},$$

and length scales

$$\lambda = \frac{2\pi^2 G \Sigma}{\kappa^2}.$$ 

We assume that initially the galactic disk is kept on the border of gravitational instability, creating a cloudy medium with both cloud sizes and separations of order $\lambda$. These clouds should provide the angular momentum transport by a 2-dimensional random walk with step-length $\lambda$ and velocity $v_c$, i.e. the viscosity is given by (Lin and Pringle 1987b)

$$\nu_{\text{eff}} \simeq \lambda v_c \simeq \lambda^2 \Omega(s),$$

where $\Omega(s)$ is the rotation frequency of the disk.

Kennicutt (1989) presented overwhelming evidence, that in 15 disk galaxies the star formation threshold is associated with the onset of gravitational instabilities in the gas disk. His sample shows that for radii smaller than 5 kpc $\Sigma > \Sigma_c$, so that $Q < 1$ and the viscosity may be given by $\nu_{\text{eff}}$.

While this, in principle, could be a viable way of transporting angular momentum and mass, in practice, it turns out not to be efficient enough compared to the observed flow velocities in the innermost few hundred parsec of galactic centers.

### 3.2 Supernovae driven turbulence – the basics

Related to the described scenario is another obvious possibility: General star formation, driven by gravitational instabilities, leads also to the formation of massive stars, which in turn not only have strong winds (e.g. Bieging et al. 1989), but also produce supernova explosions. The energy
input from these supernovae is for massive stars similar to the wind energy input integrated over the lifetime of the star. Both together can put sufficient energy into an interstellar medium not just to stir it, but even to blow it up: This effect is clearly seen in the starburst galaxy M82 (Kronberg et al. 1985, Schaan et al. 1989), where the interstellar medium is blown out to distances of many kpc perpendicular to the central part of the galactic disk (see various reports in Bloemen 1991). A fair number of galaxies are now known to behave similarly. Hence it is evident that massive stars provide a strong stirring. The question here is why the stirring by massive stars would produce larger velocities near to the Galactic Center than in the solar neighborhood. We propose to ask the question in the same framework as the model of McKee and Ostriker (1977) for the interstellar medium in the solar neighborhood. Specifically we aim at a consistency check for the notion proposed, i.e., that the high star formation rate can uphold the high rate of turbulence.

First of all, we wish to demonstrate that the star formation rate is very much higher in the Galactic central region: The star formation rate is observed to be near $0.5 \, M_\odot/\text{yr}$ in the radial range to a few hundred pc (Güsten 1989), which is 300 times the rate of star formation per area over the whole Galaxy, with a hard lower limit at about $0.05 \, M_\odot/\text{yr}$. Since the scale height near 100 pc from the Galactic Center is about 10 times smaller than in the solar neighborhood, the implied supernova rate per unit of time and unit volume is about $3 \times 10^3$ times higher. Thus, scaling the supernova rate with the star formation rate, the supernova rate is about $S_{-13} = 3 \times 10^3$, where $S_{-13}$ is the supernova rate per volume in units of $10^{-13} \, \text{pc}^{-3} \, \text{yr}^{-1}$, an estimate which we will reduce by half an order of magnitude to be conservative. We will use this final estimate below. However, the density of the interstellar medium and thus the pressure is also higher (for a recent investigation of star formation near the Galactic Center, see Morris 1993).

Hence, second, we wish to demonstrate that the filling factor of the large number of supernova remnants inside the interstellar medium is of order unity, which would imply that the turbulence generated by the supernovae indeed reaches most of the medium. Only for a filling factor of order unity are all the supernovae capable of stirring the interstellar medium fairly completely. The expansion of a supernova shell can be divided into an adiabatic phase until cooling sets in, and then a second phase of constant momentum. The various pieces of the former shell keep expanding to a radius $R_E$, when their kinetic energy approximately matches the average pressure of the medium (Chevalier 1974, McKee and Ostriker 1977). We write the ambient pressure as $P_{0,4k} = 10^{-4} \, P_0 \, \text{dyne}/k$, the supernova energy input as $E_{51} = 10^{-51} \, E_{SN} \, \text{erg}$, and the ambient intercloud density as $n_0 \, \text{particles/cm}^3$; below we will always use $E_{51} = 1$. We then have

$$R_E = 55 \, \text{pc} \, E_{51}^{0.32} \, n_0^{-0.16} \, P_{0,4k}^{-0.20},$$

from a parametrization of Chevalier’s (1974) results given by McKee and Ostriker (1977). The cavity survives until the surrounding gas encroaches upon it, for a time $t_E$, given by

$$t_E = 7 \times 10^6 \, \text{yrs} \, E_{51}^{0.32} \, n_0^{0.34} \, P_{0,4k}^{-0.70}.$$

Here we have to estimate the likely range of the intercloud density and temperature. From the scale height and the known gravitational potential we can estimate the intercloud
temperature to be near $10^6$ K. X-ray data (Blitz et al. 1993, Sunyaev et al. 1993, Markevitch et al. 1993) suggest that the temperature might even be higher, with a range up to about $10^8$ K, at an associated density of the tenuous gas of near 0.05 particles/cm$^3$; however, at such a temperature there has to be a strong wind out of the Galaxy which is not supported by other evidence, and hence we will use the lower estimate for the temperature, a range of $10^6 \pm 1$ K. With an average density of interstellar gas of 240 particles/cm$^3$ out to about 500 pc (Güsten 1989), using an estimated thickness of the cloud layer there of near 30 pc (Zylka et al. 1990), and a filling factor of the clouds of $f_{cl} \lesssim 0.1$, we can estimate a cloud density. We assume approximate pressure equilibrium between clouds, of an observed temperature in the range 40 to 100 K, and intercloud medium. We thus estimate the intercloud density to about 0.01 to 1 $f_{cl}^{-1}$ particles/cm$^3$. From the observed strengths of the magnetic fields (Blitz et al. 1993, Morris 1993) we obtain an independent estimate of the average pressure of order $3 \times 10^6$ in units of dyn/k, which corresponds to an intercloud density of about 1 particles/cm$^3$ at $T = 10^6$ K. In summary there is evidence for a hot intercloud gas with an estimated pressure of $P_{0.4 k} = 300$, and a density in the range of 0.01 to 10 particles/cm$^3$. This leads to a maximum expansion radius in the range of 12 to 40 pc, and a maximum time to caving back in for the bubble in the range of about $3 \times 10^4$ to $3 \times 10^5$ yrs. The chance for a given point to be in a supernova remnant is given by

$$Q_{SNR} = 0.5 \, S_{-13} \, P_{51}^{1.28} \, n_0^{-0.14} \, P_{0.4 k}^{-1.30},$$

while the filling factor is given by

$$f_{SNR} = 1 - e^{-Q_{SNR}}.$$

Putting in our estimates for the possible range of numbers we obtain for $Q_{SNR}$ an estimated range of 0.2 to 0.6, and for the filling factor of supernova remnants 0.2 to 0.5. The uncertainty in our understanding of the interstellar medium near the Sun is substantial and even more so near the Galactic Center, and so these numbers have to be used with some caution. Also, all these numbers should depend on the radial distance $r$; here we just estimated the relevant orders of magnitude and showed that it is actually worthwhile to go through the calculation at all.

We thus conclude that it is possible that Sedov type supernova explosions can indeed reach a sufficient fraction of the interstellar medium even near to the Galactic Center to dominate the turbulent motion.

3.3. Supernovae driven turbulence – the details

Consider the explosion of a star into a homogeneous interstellar medium (Cox 1972) of density $n_0$. The explosion of a star into the interstellar medium can be modified strongly by cloud evaporation and many other effects, discussed in detail by McKee and Ostriker (1977). However, kinematic investigations of the supernova remnants Tycho (Strom et al. 1982), Kepler (Dickel et al. 1988), and SN1006 (Long et al. 1988) show that while there are deviations from the ideal $d \log r / d \log t = 2/5$ law, they are not substantial. Therefore, we shall adopt the simple Sedov expansion as our model. The adiabatic Sedov expansion begins to be modified when cooling sets in. Allowing for time dependent cooling and new atomic rates, Schmutzler and
Tscharnuter (1993) demonstrate that the approximation used by Cox for the cooling coefficient
\[ \Lambda = 10^{-22} \text{erg cm}^3/\text{s} \ n_0^2 = \frac{L}{n_0^2} \] is sufficient for our purposes; in fact, their calculations show that this cooling coefficient is good to within a factor of 2 in the temperature range from \(10^6\) to \(5 \times 10^6\) K and even a fair approximation at lower temperatures above \(2 \times 10^4\) K. So we have for the radius of the supernova shell \(r_{SN,cool}\) at the point when cooling begins to affect the shell
\[ r_{SN,cool} = 20.9 \text{ pc} \ E_{51}^{3/11} \left(10^{22} L\right)^{-2/11} n_0^{-5/11}, \]
where \(E_{51}\) is the explosion energy in units of \(10^{51}\) erg. The velocity of expansion at that point is given by
\[ v_{SN,cool} = 281 \text{ km/s} \ E_{51}^{1/11} \left(10^{22} L\right)^{3/11} n_0^{-2/11}. \]

Already the statistical work of Berkhuijsen (1986) has demonstrated that the dependence on the environmental density \(n_0\) is one of the overriding effects in supernova expansion and leads to strong selection effects.

Here we note that the expansion begins to be affected by cooling and still shows a fairly high velocity of expansion at a radius which is only weakly influenced by the environmental density, so that the higher density in the hotter medium outside the clouds near the Galactic Center as compared to the solar neighborhood has only a moderate influence. It appears reasonable to suppose that the velocity at which the interstellar medium turbulence gets fed, is the velocity at which the supernova shells abruptly start cooling, because then these shells become unstable, disrupt and fly apart in various cloud fragments. We note again, that the expansion will actually continue much further, with the various parts of the shell coming to rest when the expansion slows down to the average characteristic velocity of the medium, the effective speed of sound.

In McKee&Ostriker’s picture, the expansion is limited by reaching the local speed of sound which is assumed to be given. Here, in contrast, we assume that the expansion sets the speed of sound in the tenuous environment and that the limiting condition is rather given by the dissipation requirement (see sect. 5, and, especially, eq. 29).

Let us suppose, that this is the case and identify the velocity of the supernova shell with the velocity dispersion of clouds to within some factor \(f_{dis}\), left unspecified for the moment, but expected to be much less than unity (otherwise, there would not be any shock). We also suppose that the intercloud medium is in pressure equilibrium with the internal cloud pressure. Güsten (1989) gives the integrated surface density out to 500 pc as in the range \(100 \ M_\odot \text{pc}^{-2}\) to \(400 \ M_\odot \text{pc}^{-2}\). Since there are ununderstood discrepancies with \(\gamma\)-ray emission (Lebrun et al. 1983, Bloemen et al. 1984, Güsten 1989) we prefer to err on the cautious side and will use the lower limit in the following. Observations show that the gas surface density decreases with distance from the Galactic Center, and we adopt here somewhat arbitrarily an \(s^{-1}\) law. We will show further below that a moderately steep powerlaw like this is a natural dependence. All this then means that we adopt in the following
\[ \Sigma = 2.5 \times 10^{23} \text{ atoms/cm}^2 (s/r_0)^{-1}. \]

Then we have the following relations: First the relation between the column density, the scaleheight and the average density – dominated by the clouds. This average density, being
equal to the cloud density to within a volume filling factor \( f_{\text{cl}} \), say, of order 0.1, then by pressure equilibrium gives an intercloud density, which in turn enters the expansion law for the shell, which again gives a characteristic velocity which we then – and this closes the loop – set proportional to (but \( \gg \) than) the intercloud speed of sound and the velocity dispersion of the clouds. Hence the first relation is

\[
n_{\text{cloud}} = 2.5 \times 10^{23} \text{ atoms/cm}^3 f_{\text{cl}}^{-1} H^{-1} (s/r_0)^{-1}.
\]

Pressure equilibrium gives the second relation

\[
n_{\text{intercloud}} = (25/21) c_s^{-2} n_{\text{cloud}} c_{s,\text{cloud}}^2
\]

where we use the appropriate adiabatic constant for the two atomic molecular and the single atomic gas. We identify here \( c_s \) with the intercloud speed of sound, and the intercloud density with \( n_0 \), on the grounds that supernova expansion into the intercloud medium alone can excite overall turbulence, while an explosion into a dense cloud is quickly stifled. We assume – and this has little consequence – that the speed of sound inside the clouds is of order 0.76 km/s, corresponding to an adopted temperature inside the cloud of 100 K. The final relation to close the loop is

\[
c_s = v_{\text{SN,cool}} f_{\text{dis}},
\]

where we have to use the intercloud density in the expression for the expansion. Surely, this factor \( f_{\text{dis}} \) is small, since the fragment velocities get further dissipated, say, to \( f_{\text{dis}} \) of order 0.1. Combining all these equations yields a relation for the radial behaviour of the implied speed of sound and its value, which we can then again compare with observations

\[
c_s = 56 \text{ km/s} C (s/r_0)^{-15/68}
\]

with

\[
C = E_{51}^{1/17} (10^{22} L)^{3/17} (f_{\text{dis}}/0.1)^{11/17} (f_{\text{cl}}/0.1)^{-2/17} \times (c_{s,\text{cloud}}/0.76 \text{ km s}^{-1})^{4/17}.
\]

We note that the result depends only with the power 2/17 on the cloud temperature. We emphasize that the parameters \( f_{\text{dis}} \) and \( f_{\text{cl}} \) have been chosen to be of order 0.1. In reality, their value could be different, e.g., smaller, and obviously, their value likely depends on radial distance \( r \) in the Galaxy. However, the dependence of the parameter \( C \) is only rather weak on these two parameters; for \( f_{\text{dis}} = 0.03 \) we still get a value for \( C \) only a factor of 2 lower, and for \( f_{\text{cl}} = 0.01 \) we get a value of \( C = 1.3 \) times larger. To test it with \( f_{\text{dis}} = 0.1 \) and \( f_{\text{cl}} = 0.1 \) we calculate first the value that this relation gives for a radius in the disk of 50 pc, which is 39.4 \( C \) km/s, which is to be compared with the implied speed of sound from the scale height of 37.3 km/s and the observed dispersion of about 50 km/s. For \( C \approx 1 \), the agreement is better than can reasonably be expected from our crude estimates. For plausible values of our parameters the turbulence excited by the large rate of supernovae can indeed excite all the turbulence observed on the one hand, and required by the effective viscosity deduced from our
modelling of the cloud velocities on the other hand. This is a consistency check, not a proof. We conclude that this mechanism may explain the observed cloud velocity dispersion.

4. The accretion rate in our Galactic Center

The characteristic velocities ($v_{\text{turb}}$) and the length scale $s$ ($l_{\text{turb}}$) then provide the scales for the exchange of momentum, here angular momentum, and so define a turbulent viscosity by the product of thickness of distribution (twice the scale height) and turbulent velocity of order

$$\nu_t = 300 \text{ pc km/s}.$$  \hspace{1cm} (20)

In order to be an effective viscosity, this turbulence must tap the momentum in the interstellar medium, and that is concentrated in the clouds. This is achieved by noting, that it is long known (Mathewson and Ford 1970, Appenzeller 1971) that magnetic fields permeate the interstellar medium, from cloud to intercloud medium and so effectively couple both phases. In the following, we assume the magnetic field to play an important rôle only in this respect. Our results (Linden et al. 1993, Biermann et al. 1993) are in good agreement with the assumption that for the large scale dynamics in the range between about ten and a few hundred parsec, the magnetic field does not play the dominant rôle. Thus, in the following, we neglect its effect on the large scale accretion flow.

The physics of such an accretion disk are better thought of in the original accretion disk theory developed first by Lüst (1952) than in the picture of Shakura and Sunyaev’s (1973) $\alpha$ disk models. A (not necessarily constant) $\alpha$ value corresponds to a certain radial variation of the effective viscosity that is directly coupled to the thermal structure of the disk. This means that in $\alpha$ disk models, the chosen value of $\alpha$ determines the thermal and mechanical structure of the disk in the fashion of a closed system (with the only coupling to the outside through radiative losses) while in our models we envisage the value of the effective viscosity to be determined by processes other than simple gas and/or dust friction in an inherently turbulent shearing media (see sect. 3). These processes themselves then are not necessarily directly coupled to the accretion flow. In $\alpha$ disks, there is a limiting value for $\alpha$ of the order of 1 (the exact value depends on the averaging procedure for the vertical structure). Larger values correspond to either supersonic (i.e., $v_{\text{turb}} > c_s$) or to anisotropic turbulence ($l_{\text{turb}} > H$), both of which are excluded in a standard $\alpha$ disk. For our effective viscosity that is determined from processes outside the closed gas/dust disk system, such a limit for the viscosity does not apply as the driving process does not know about $c_s$ and $H$ directly.

Given this viscosity the accretion velocity can be deduced from the conservation of angular momentum and the assumption of hydrodynamic equilibrium in vertical direction:

$$v_r = -x \frac{\nu_t}{s}$$  \hspace{1cm} (21)

$x$ is a quantity of order 1; its actual value again depends on details of the averaging procedure in vertical direction; for our estimates assuming $x = 1$ suffices. We reach the limit of validity of the accretion disk picture when this implied radial velocity approaches a noticeable fraction of the circular velocity, say $1/3 v_\phi$. This limit is reached at a radius of
where $v_{\phi,0}$ is the circular velocity at radius $r_0$. Using the parameters adopted we obtain for the critical radius 5.8 pc, very close to the inner ring observed near 2 pc. Again within the framework of our approximations this is a good agreement as we have to realize that we have deduced $r_{\text{crit}}$ neglecting any effects from the disk's inner boundary (Duschl and Tscharnuter, 1991). For $\Sigma \sim s^{-1}$ and $M \sim r^{5/4}$, we find that effects due to the disk’s inner boundary scale $\sim s^{-7/8}$, i.e., become small only for radii $\gtrsim 10$ pc.

Since the critical radius very nearly scales linearly with the turbulent viscosity, we might argue that the presence of this ring implies that the turbulent viscosity is approximately a factor of 3 smaller than used above near the radius of this ring. Using then our first estimate for the turbulent viscosity again of 300 pc km/s the accretion time scale

$$\tau_{\text{acc}} = \frac{r^2}{\nu_t}$$

amounts to $2.8 \times 10^5$ yrs at $r_0$ and $3.2 \times 10^7$ yrs at 100 pc.

A check can be made on the concept of overall accretion: The accretion flow, a tight spiral, influences cloud motion. In fact, clouds can be used as tracers of the flow field. In Linden et al. (1993) we have followed one of the biggest clouds, M-0.13-0.08 and its vicinity, using it as a tracer, and were able to verify that this accretion disk flow gives an excellent overall fit to the velocity field of this large cloud and also implies independently, by the fit, a turbulent viscosity of similar order of magnitude as derived here (about 2000 pc km/s). The fit gives a distance of the cloud, at 115 pc from the Galactic Center.

All these arguments suggest that the turbulent viscosity rises with radius in an approximately linear fashion, from somewhere near 100 pc km/s near 2 pc to about 2000 pc km/s near 100 pc. It follows that the ratio of radial velocity $v_r$ to circular velocity $v_{\phi}$ is nearly independent of radial distance $r$ in the disk, i.e. $s$. The structure of the accretion flow is thus approximately self-similar with the surface indeed going as $1/s$ asymptotically. In this simplified model our earlier assumption of $\Sigma \sim 1/s$ is thus justified. Elsewhere we derived the radial dependence of the effective viscosity from the observations of Zylka (1990) and Pauls et al. (1993) and compared it with a simple analytical model, where surface density and the supernova excitation are checked self-consistently (Biermann et al. 1993).

We note in passing, that a turbulent viscosity of similar order of magnitude is also implied at larger distances from the center in our Galaxy, where the cloud motions are smaller, but the cloud distribution scale height is larger; in the solar neighborhood the implied turbulent viscosity is of order 700 pc km/s. This implies that even on scales of order kpc, the accretion time scale is still of order $10^9$ yrs, comparable to the timescale of galactic evolution and reaching the Hubble time near at least several kpc. On more conceptual grounds, this has been argued already by Silk and Norman (1981), Lin and Pringle (1987a, b), and Yoshii and Sommer-Larsen (1989). Lin and Pringle (1987b) argue that self-gravity is the motor. A detailed new calculation of galactic evolution in a viscous disk allowing for the possibility of a central mass concentration was performed by Diewald (1992). This in turn implies that somewhere between 100 pc and a few kpc the turbulent viscosity may reach a maximum and then decrease again.
The observed star formation inside 500 pc is in the range 0.3 to 0.6 $M_\odot$ yr\(^{-1}\) (Güsten 1989); with the assumption again, that the surface density scales approximately with 1/s, we thus obtain for the observed star formation rate within 100 pc 0.06 to 0.12 $M_\odot$ yr\(^{-1}\). We note that the implied molecular gas consumption time scale is to within a factor of 2 uncertainty given by 3.10\(^8\) yr, consistent with the estimate of 8.10\(^8\) yr for the inner disk of the galaxy M33 (Wilson et al. 1991). Using the estimated surface density of the gas in the central region given earlier the accretion rate implied is of order 1/3 $M_\odot$/yr, which matches easily the requirement that the observed star formation be fed.

5. The energetics of driving both turbulence and star formation

Using the above analysis we can make another consistency check, and ask, whether the hot intercloud medium can actually be held at its temperature by the steady energy input by supernovae. We note first that with our approximations [from eqs. (16) and (18)]

$$n_{\text{intercloud}} = 52 \text{ cm}^{-3} C^{-3} (f_{\text{cl}}/0.1)^{-1} (s/r_0)^{-1.21},$$

and [from (2) and (18)]

$$H = 1.110^{19} \text{ cm } C (s/r_0)^{0.65}.$$  

The cooling in energy emitted per unit of time and area of the disk then is given by

$$\begin{align*}
(1 - f_{\text{cl}}) (10^{22} L) n_{\text{intercloud}}^2 H &= 2.7 \times 10^{37} \text{ erg/s/pc}^2 \\
C^{-5} (1 - f_{\text{cl}}) (f_{\text{cl}}/0.1)^{-2} (s/r_0)^{-1.77}.
\end{align*}$$

This has to be balanced by the energy input from supernova explosions in our model. This we estimate by calculating the star formation rate from the surface density with a time scale of star formation proportional to the accretion (to within a factor $\epsilon$), and using the entire galaxy with an estimated supernova rate of one per 30 years and a star formation rate of 10 $M_\odot$/year as reference point (Cox and Mezger, 1987). This leads then from the adopted surface density law to an energy input of

$$1.3 \times 10^{39} \text{ erg/s/pc}^2 \epsilon^{-1} C^2 (s/r_0)^{-2.57}.$$  

This demonstrates first, that the energy dissipation in the intercloud medium can be balanced by the supernova activity. Second, it also shows, that there is an outer radius, where the energy balance fails. This cutoff radius $s_*/r_0$ is at

$$s_*/r_0 = \frac{29 \cdot \left(f_{\text{cl}}/0.1\right)^{1.26}}{1 - f_{\text{cl}}} C^{8.82} \epsilon^{-1.26} (310^{21} L)^{-1.26}.$$  

For the parameters $f_{\text{dis}}$ and $f_{\text{cl}}$, the dependence is

$$\frac{s_*}{r_0} \sim \frac{f_{\text{dis}}^{5.70} f_{\text{cl}}^{1.48}}{(1 - f_{\text{cl}})^{1.26}}.$$
Here we have to check several things: First, the parameter $f_{\text{dis}}$ has to be small compared to unity, since otherwise there would not be any shock; we adopt $f_{\text{dis}} = 0.1$. Second, the parameter $f_{\text{cl}}$, the cloud volume filling parameter, could be nearly anything $< 1$; the data analysis of the cloud motions suggests that the high effective viscosity disk extends to at least 115 pc, and so within our parameter range this is indeed consistent with $f_{\text{cl}} \sim 0.1$. Third, we have adjusted the cooling function to the higher value valid near temperatures just below $10^5$ K.

Here, we can then ask again, whether the filling factor of the medium can actually reach unity, i.e. whether the filling factor of the intercloud medium depends only weakly on radial distance $r$ and remains near unity over the radial range we consider. With the expressions introduced above we have to add an expression for the radial dependence of the star formation rate; we assume that the radial dependence of the star formation rate is given by the gas surface density divided by the accretion time scale to within a factor of order unity, since the accretion provides the fresh material for star formation. Since the time scales may very well be a function of the radius, this does not imply that we assume the star formation rate to be linearly proportional to the surface density $\Sigma$. We rather replace the time derivative $\Sigma_{\text{SF}}$ by the difference quotient $\Sigma / \tau_{\text{acc}}$.

It is then easily seen that the filling factor indeed remains near unity over the radial range considered; for a star formation rate which is more weakly dependent on $r$, the radial dependence of the filling factor is even weaker. Hence we have shown, that there is a self-consistent mode of highly excited star formation.

The observations demonstrate that the Toomre criterion is not marginally fulfilled, and the theoretical analysis above suggests that we have two limiting physical states of such a disk, one in which the Toomre instability starts clumping and thus can initiate star formation, and then a higher level of activity when the turbulence is supernova driven, thus providing for a high effective viscosity, thus a high accretion rate, thus sufficient material for further star formation and a sustained high rate of supernovae. This higher state of activity may exhaust the available supply of gas provided from further out, and so may lead to an extreme limit cycle of star formation activity in the inner region of galactic disks with a consequent extreme limit cycle in the supply of gas to the innermost regions. We have made several consistency checks on this concept.
6. The feeding of AGN in analogy to our Galactic Center

If, as seems rather likely, the inner regions of galaxies, which in observable contrast to our Galactic Center do harbor an active nucleus, show at least all those complications that our Galactic Center demonstrates, then such an accretion rate is clearly sufficient to fuel also nuclear activity. Since the observation that the FIR/mm spectrum of radioweak active galactic nuclei (Chini et al. 1989a, 1989b; Sanders et al. 1989; Lawrence et al. 1991) is in all likelihood dominated by dust emission on radial scales up to about 100 pc, we also know that molecular clouds do exist – this also has been confirmed in a number of examples (Sanders & Scoville 1988, Barvainis & Antonucci 1989, Barvainis et al. 1989) – and so that sufficient gas is available for accretion.

All our above estimates and checks do not depend on properties that are characteristic of our Galactic Center only. Thus the above deduced limit cycle is most likely working in all galactic centers, especially in active ones.

7. Conclusion and outlook

In many galaxies, bars are prominent features, and their action may very well be the dominant mechanism to remove angular momentum from material that is many hundreds of pc to a few kpc from the galactic center. This will allow the material to be accreted into regions closer to the center. But our investigations demonstrate that, on length scales of the order of tens to a few hundreds of pc, supernovae driven turbulence is capable of inducing a sufficiently large viscosity that allows for accretion of large amounts of matter even in the absence of a bar.

It is interesting to speculate that the other transport coefficients important for a galaxy and its evolution might be related to the transport coefficient for angular momentum: The transport coefficient that determines the leakage of Cosmic Rays from a galaxy, as well as the transport coefficient that enters the dynamo mechanism in order to produce the rather strong magnetic fields which we observe. Apart from arguments about the numerical value of these transport coefficients one first consequence would be that we ought to seriously consider the possibility that these other transport coefficients are strong functions of radial distance in a galaxy. It is also likely that any theory for, say, a dynamo working in a galaxy cannot be separated from the overall accretion flow (see Chiba and Lesch 1993), since both mechanisms depend on closely related microphysics.

Our Galactic Center demonstrates that accretion via angular momentum transport through turbulent viscosity is sufficiently large to provide all the gas necessary in our Galactic Center to drive the star formation, and, in analogy, to drive the accretion towards a central compact object in active galactic nuclei. The physical mechanism which we propose to drive the turbulence – supernovae – naturally leads to extreme limit cycles in the accretion rate.
References

References
Appenzeller I., 1971, A&A 12, 313
Barvainis R., Alloin D., Antonucci R., 1989, ApJ 337, L69
Barvainis R., Antonucci R., 1989, ApJS 70, 257
Berkhuijsen E.M., 1986, A&A 166, 257
Bieging J.H., Abbott D.C., Churchwell E.B., 1989, ApJ 340, 518
Biermann P.L., Duschl W.J., Linden S.v., 1993, A&A (in press)
Blitz, L., Binney, J., Lo, K.Y., Bally, J., Ho, P.T.P., 1993, Nature 361, 417
Bloemen H. (ed.), 1991, The interstellar disk-halo connection (IAU-Symp. 144)
Bloemen J.B.G.M., Blitz L., Hermsen W., 1984, ApJ 279, 136
Chevalier, R., 1974, ApJ 188, 501
Chiba, M., Lesch, H., 1993, A&A (submitted)
Chini R., Kreysa E., Biermann P.L., 1989a, A&A 219, 87
Chini R., Biermann P.L., Kreysa E., Gemünder H.-P., 1989b, A&A 221, L3
Cox D.P., 1972, ApJ 178, 159
Cox P. and Mezger P.G., 1987, in: Star formation in galaxies (ed.: C.J. Lonsdale Perrson), NASA Conf. Publ. No. 2466, p.23
Dickel, J.R., Sault, R., Arendt, R.G., Matsui, Y., Korista, K.T., 1988, ApJ 330, 254
Diewald M., 1992, Masters Thesis, University of Bonn
Duschl W.J., Tschammuter W.M., 1991, A&A 241, 153
Falcke H., Biermann P.L., Duschl W.J., Mezger P.G., 1993, A&A 270, 102
Garcia-Munoz M., Mason G.M., Simpson J.A., 1977, ApJ 217, 859
Genzel R., Townes C.H., 1987, ARA&A 25, 377
Güsten R., 1989, in: The Center of the Galaxy, IAU Symposium No. 136, Ed. M. Morris, Kluwer, Dordrecht, p. 89
Jackson J.M., Geis N., Genzel R., Harris A.L., Madden S.C., Poglitsch A., Stacey G.J., Townes C.H., 1993, ApJ 402, 173
Kronberg P.P., Biermann P., Schwab F.R., 1985, ApJ 291, 693
Lawrence A., Rowan-Robinson M., Efstathiou A., Ward M.J., Elvis M., Smith M.G., Duncan W.D., Robson E.I., 1991. MNRAS, 248, 91
Lebrun F. et al., 1983, ApJ 274, 231
Lin D.N.C., Pringle J.E., 1987a, ApJ 320, L87
Lin D.N.C., Pringle J.E., 1987b, MNRAS 225, 607
Linden S.v., Duschl W.J., Biermann P.L., 1993, A&A 269, 169
Long, K.S., Blair, W.P., Van den Bergh, S., 1988, ApJ 333, 749
Lüst R, 1952, Zeitschr. f. Naturf. 7a, 87
Markevitch M., Sunyaev R.A., Pavlinsky, M., 1993, Nature 364, 40
Mathewson D.S., Ford V.L., 1970, MNRAS 74, 139
McKee C.F. and Ostriker J.P., 1977, ApJ 218, 148
Morris M., 1993, ApJ 403, 496
Pauls T., Johnston K.J., Wilson T.L., Marr J.M., Rudolph A., 1993, ApJ 403, L13
Reynolds R.J., 1989, ApJ 339, L29
Reynolds R.J., 1990, ApJ 349, L17
Sanders D.B., Scoville N.Z., Soifer B.T., 1988, ApJ 335, L1
Sanders D.B., Phinney E.S., Neugebauer G., Soifer B.T., Matthews K., 1989, ApJ 347, 29
Sanders R.H., Lowinger T., 1972 AJ 77, 292
Schaaf R., Pietsch W., Biermann P.L., Kronberg P.P., Schmutzler T., 1989, ApJ 336, 722
Schmutzler T., Tscharnuter W.M., 1993, A&A 273,318
Shlosman I., Begelman M.C., Frank J., 1990, Nature 345, 679
Shlosman I., Begelman M.C., Frank J., 1990, Nature 345, 679
Shlosman I., Frank J., Begelman M.C., 1989, Nature 338, 45
Shakura N.I., Sunyaev R.A., 1973, A&A 24, 337
Silk J., Norman C., 1981, ApJ 247, 59
Smith L.F., Biermann P., Mezger P.G., 1978, A&A 66, 65
Strom, R.G., Goss, W.M., Shaver, P.A., 1982, MNRAS 200, 473
Sunyaev, R.A., Markevitch, M., Pavlinsky, M., 1993, ApJ 407, 606
Toomre A., 1964, ApJ 139, 1217
Wilson C.D., Scoville N., Rice W., 1991, AJ 101, 1293
Yoshii Y., Sommer-Larsen J., 1989, MNRAS 236, 779
Zylka R., 1990, Ph.D. Thesis, University of Bonn
Zylka R., Mezger P.G., Wink J.E., 1990, A&A 234, 133