The circumnuclear disk and ionized gas filaments as remnants of tidally disrupted clouds

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**Abstract.** Sticky particle calculations indicate that a coherent structure, a dispersion ring, forms when a cloud on a low angular momentum orbit passes close to the dynamical center of a potential containing a point mass. The cloud is tidally stretched and differentially wrapped, and dissipation in shocks organizes the gas into a precessing off-set elliptical ring which can persist for many rotation periods. The morphology and kinematics of the circumnuclear disk (CND) between 2 and 5 pc and the Northern arm in the inner 1 pc are well-represented by such structures. In the case of the Northern Arm, strong shocks which arise during the formation of the dispersion ring can lead to star formation even in the near tidal field of a massive black hole.

1. The relation between gas flow and periodic orbits

To what extent can the gas structures in the inner few parsecs of the Galaxy be understood in terms of gas flow in a gravitational field? I am referring to the well-studied circumnuclear disk (CND) and the ionized gas filaments within the central cavity of the CND (Morris & Serabyn 1996, Mezger et al. 1996). The morphology and kinematics of the ionized gas filaments have been modeled by motion along Keplerian orbits appropriately projected on the plane of the sky (Serabyn et al. 1988, Herbst et al. 1993, Roberts et al. 1996); the success of such models strongly suggests that the motion is primarily orbital and that other possible mechanisms (e.g., stellar winds, magnetic fields, supernova explosions) do not significantly influence the overall, systematic pattern of flow. But the material is, afterall, gaseous, and how well can gas motion be approximated by orbital motion?

It is obvious that the hydrodynamic equation of motion written in Lagrangian form is the equation of motion of a particle when the pressure gradient and viscous stress terms are omitted. This means that, in a gravitational field, if pressure forces are negligible (including thermal, turbulent, viscous, and magnetic), then gas elements move on orbits. Moreover, for steady state inviscid gas flow in a gravitational field the gas streamlines are non-intersecting periodic orbits. Of course, not all orbits can be streamlines because orbits may loop and there cannot be two values of the fluid velocity at one point.

Fig. 1a shows a typical orbit in a gravitational field resulting from a point mass embedded in an approximate isothermal sphere. This mass distribution is chosen to mimic that implied by stellar kinematics in the inner few parsecs of
the Galaxy, as described by Eckart et al. and Ghez et al. in this volume (the
details are given by Sanders 1998, Paper 1). The orbit is typical of that in a
general axisymmetric potential, but the hard core, the point mass, causes an
abrupt bending of the orbit at closest approach (strong scattering). Now one
might say that such an orbit could not possibly be a gas streamline because
of the loops. However, it is possible to find a rotating frame in which the orbit
appears as in Fig. 1b; this is a possible gas streamline. It was the proposal of
Lindblad (1956, in connection with the problem of spiral structure) that a gas
cloud on such an orbit would disperse to form such a structure which would
precess at a fixed angular velocity, hence the term “dispersion ring”. In this
case, the precession would be counter to the sense of particle motion with an
angular velocity of $-26 \text{ km s}^{-1}\text{pc}^{-1}$.

One could find a set of such orbits covering a range of energy, all of which
precess at about the same rate. Such a configuration is shown in Fig. 1c. For
these orbits the maximum distance to the center varies between 1.7 and 2.2 pc
and the tangential velocity at this point varies between 0.18 and 0.27 times the
circular velocity. It is evident that these “streamlines” crowd at the point of
closest approach to the point mass and this would cause a density enhancement
there (in spite of the higher velocities). It is actually impossible to maintain
this structure forever because the outermost orbits precess (or rather, regress) a
bit faster than the inner most orbits (remember, nearer the center the potential
is closer to Keplerian). So after several orbital periods we might expect the
configuration to appear as it does in Fig. 1d. Here we see that the orbits have
crowded on the leading edge which would give the appearance of a one-arm
spiral. In fact, the orbits have begun to cross which means that dissipative
forces (shocks) will intervene and the orbits can no longer represent streamlines.
This will cause a loss of energy and the gas will settle, on some timescale, to a
circular ring at a radius appropriate to the specific angular momentum.

2. The fate of clouds on low angular momentum orbits

Of course I can create a structure like this artificially by loading gas on such
streamlines, and it would persist for much longer than a characteristic orbital
period. But how might such a structure arise naturally? In particular, how
might it arise in the inner few parsecs of the Galaxy? Let us consider the fate
of a gas cloud launched on a low angular momentum orbit– an orbit which will
carry the cloud near the central point mass. We will look at two cases: 1) A
clumpy cloud initially between five and ten parsecs from the center on an orbit
which will carry it to within one or two parsecs of the center (initial tangential
velocity, $V_t$, is 0.4 of the circular velocity, $V_c$). 2) A small cloud in a very low
angular momentum orbit; i.e., initially between two and three parsecs on an
orbit which takes it to within 0.1 to 0.2 pc of the center ($V_t = 0.2V_c$). The first
case may be relevant to the circumnuclear disk (CND) and the second to the
Northern Arm.

I have done these calculations by means of a sticky particle code (Paper 1)
in which the motion of 4000 particles is computed in the gravitational potential
described above. The effects of dissipation are included by allowing particles to
interact: two particles exert a force on one another proportional to their velocity

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Figure 1. a. An orbit in the gravitational field of an isothermal sphere containing a point mass. The initial distance from the center is 1.8 pc and the tangential velocity is 20% of that required for a circular orbit. Distance is in parsecs. b. The same orbit in a frame rotating counter to the sense of particle motion with $\Omega_p = -26$ km s$^{-1}$ pc$^{-1}$. c. A collection of such orbits in the rotating frame which could serve as gas streamlines for a persisting oval structure in the Galactic Center. d. The same structure after several orbital periods; the appearance has changed due to differential precession. In all cases here the sense of particle motion is counter-clockwise and the precession is clockwise.
difference, but only if they are approaching. The procedure is similar to SPH codes but ordinary gas pressure forces are neglected; this mimics a bulk viscosity which is only effective if the flow is converging. Similar schemes have been used in simulations of accretion disks (e.g., Syer & Clark 1992); the rationale is that dissipation in strong shocks is the only important gas dynamical effect if the flow is highly supersonic (as it is).

In the first case (the “CND” cloud), the time evolution is described in Paper 1. After several rotation periods, the material from the disrupted cloud has formed an offset asymmetric ring with an extended arm. The entire structure is precessing at a mean rate of about -12 km s\(^{-1}\) pc\(^{-1}\) (counter to the sense of rotation). Gradually, on a timescale of two to three million years the structure circularizes and the cavity shrinks. The reason for this circularization over a timescale of about 10 rotation periods, is differential precession. Over the rather large range in radius covered by the cloud, the outer parts precess more slowly than the inner parts leading to crossing of streamlines and strong dissipation in shocks. Non-the-less, the structure, as it appears 0.85 to 1 million years after the initial passage, does bear a strong resemblance to the CND, both in morphology and kinematics. This is shown in Fig. 2 as a particle plot with proper motion vectors projected onto the plane of the sky. Note the asymmetric central cavity; because the streamlines crowd on the side nearest the point mass, the highest gas density is observed there (north-western side). On the opposite side the ring is quite tenuous just as observed in the actual CND (Güsten et al. 1987).

The dispersion ring model is not entirely relevant to this model for the CND; there is just too much differential precession over the width of the ring. However, the structure does persist considerably longer than a characteristic rotation period (2.5 \times 10^5 years at r = 3.5 pc). The important point is that the tidal stretching and differential wrapping of an initially clumpy cloud is consistent with the observed kinematics and morphology of the CND.

The dispersion ring model maybe more relevant to the ionized filaments within the central cavity of the CND. In Fig. 3 we see the results of the second calculation: that of a small cloud, initially 2.0 to 2.8 pc from the center, on a very low angular momentum orbit (\(V_t = 0.2V_c\)) which carries it within 0.2 pc of the center. The cloud is initially tidally stretched into a very long filament which repeatedly collides with itself. By an epoch of 1.5 \times 10^5 years, a clear dispersion ring is formed. This coherent and relatively long-lived structure precesses at an angular speed of -26 km s\(^{-1}\) pc\(^{-1}\). It is longer-lived than the CND model in terms of orbit times because there is less differential precession due to the smaller initial size of the cloud. In the eighth frame of Fig. 3 (t = 1.75 \times 10^5 years), the cloud is well-described by the dispersion orbits shown in Fig. 1d. Note in particular the much higher density of gas on the side where the material is approaching the center due to the differential precession of streamlines, just as in Fig. 1d. This could explain why the Northern Arm is not observed to be a complete ring.

When this structure as it appears in the eighth frame is appropriately projected onto the plane of the sky (for this projection the orbital plane almost coincides with that of the CND cloud), the morphology and distribution of radial velocity again bears a strong resemblance to that observed for the Northern Arm (Gezari et al. 1996, Herbst et al. 1993, Roberts & Goss 1993). In Fig. 4
Figure 2. The projected CND model (from Paper 1) $8.5 \times 10^5$ years (three orbital periods) after launching the clumpy cloud on its low angular momentum orbit. The orbital plane is inclined 60 degrees with respect to the plane of the sky and the position angle of the line-of-nodes (solid line) is 35 degrees. The north-western side (upper right) is the near side in this projection. Units are in arc seconds offset from the dynamical center, presumably Sgr A*. This is a particle plot where the arrows at the location of the particles indicate the sense and magnitude of proper motion. The asymmetric central cavity and the higher gas density on the side nearest the dynamical center, observed characteristics of the CND, are model-independent properties of a dispersion ring.
Figure 3. Time evolution of a small cloud (from Paper 1), initially at a mean distance of 2.4 pc from the center, on a very low angular momentum orbit ($V_t = 0.2V_c$). The distance is in units of parsecs and the time since beginning of the infall is given above each frame in units of one-million years.
we see the morphology and the projection of the velocity vectors of on the plane of the sky. The sense of proper motion agrees with that recently observed by Yusef-Sadeh et al. (1998) and by Zhao & Goss (1998).

3. Star formation in strong shocks

While the dispersion ring is forming, the tidally stretched cloud collides with itself near the point mass (Fig. 3, fourth and fifth frames). The collision velocities exceed 100 km/s. Assuming highly efficient radiation of the thermal energy, which is likely in the molecular gas, the resulting strong shocks will lead to significant compression of the gas and high gas densities; indeed the gas densities might well exceed the Roche limit ($10^{13}$ to $10^{14}$ particles cm$^{-3}$) in the tidal field of a $2.5 \times 10^{6}$ M$_\odot$ point mass at a distance of 0.1 pc (Phinney 1989). Such a mechanism might very well be the explanation for the young stars observed within a few tenths of a parsec of Sgr $A^*$, the putative massive black hole at the Galactic Center (Allen et al. 1990, Eckart et al. 1993, Krabbe et al. 1995).

The sticky particle algorithm applied here allows one to determine the local value of the compression at the location of a particle ($-\nabla \cdot \mathbf{V}$). This may then be used as a criterion for star formation. If the compression exceeds some arbitrary threshold (in this case 2000 km s$^{-1}$pc$^{-1}$), that particular particle is re-tagged as a star; thereafter, there are no “viscous” interactions with other particles, and the particle’s motion is determined only by gravity.

The results of such a calculation are shown in Fig. 6 where we see both the gas and star distribution after roughly one and two precession periods of the dispersion ring. We see that the gaseous dispersion ring resembling the Northern Arm can easily persist for two precession periods or roughly 10 to 20 characteristic orbital periods; there is no need for this structure to be a highly transient manifestation of a tidally disrupting cloud on the first passage by the black hole. Basically, the dispersion ring appears as an “attractor” in the phase space of the system—a well-known phenomenon in dissipative systems. The stars, on the other hand, without any such mechanism for self-organization, slowly diffuse throughout the available phase space.

4. Comments

We may conclude that the tidal disruption of a small cloud in a potential containing a point mass will lead to a long-lived gas structure—a dispersion ring—which precesses counter to the sense of gas rotation. Such objects resemble, morphologically and kinematically, the gaseous structures seen in the inner few parsecs of the Galaxy—the CND and, within the central cavity of the CND, the Northern Arm. While forming a dispersion ring, a low angular momentum cloud (passing near the central point mass), is stretched into a long filament which collides with itself several times. The resulting strong shocks lead to high compression and can be the sites of star-formation, even in the near tidal field of the black hole. This may explain the presence of massive stars less than several million years old within 0.1 pc of Sgr A*.

Of course, I have not dealt with the problem of initial conditions. How are clouds launched on such orbits to begin with? We know from a number of obser-
Figure 4. The Northern Arm model as seen in the eighth frame of Fig. 3 (1.75 × 10^5 years) projected onto the plane of the sky (from Paper 1). This is a particle plot where the arrows indicate the sense and magnitude of the proper motion. Coordinates are offsets in arc seconds from the dynamical center. Here again the north-western side (upper right) is the near side; the plane of the Northern Arm model coincides with the plane of the CND model to within 10 degrees. The model matches the observed morphology and kinematics of the Northern Arm. Note in particular the higher density on the western side (due to orbit crowding as in Fig. 1d); this gives the appearance of an incomplete ring.
Figure 5.  a,b) Gas and star distributions at \( t = 3 \times 10^5 \) years corresponding to more than one complete precession of the dispersion ring.  
  c,d) Gas and star distributions at \( t = 5.5 \times 10^5 \) years or almost one precession time later. Distance is in units of pc. This figure is from Paper 1.
vations (Morris & Serabyn 1996) that the interstellar medium in the inner 200 pc of the Galaxy is highly inhomogeneous and very turbulent– most of the gas is found in massive molecular clouds and the random velocities of these clouds are a considerable fraction of the circular velocity. The decay of supersonic turbulence occurs through cloud-cloud collisions so occasionally, through this process, a low angular momentum cloud will be created. Bursts of star formation or the occasional flaring of the black hole are possible mechanisms for maintaining the turbulence.

Such a scenario might have general relevance to accretion onto massive black holes in active and normal galactic nuclei. Accretion may proceed via a series of such tidal disruptions of clouds on low angular momentum orbits. If this were true, we would expect accretion to be highly episodic but also highly inefficient with most gas disappearing into star formation.

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