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Simple hydrodynamical Simulations of the Circumnuclear Disk

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Abstract. The "circumnuclear disk" (CND) is a dense, clumpy, asymmetric ring-like feature centered on Sgr A*. The outer edge of the CND is not distinct but the disk extends for more than 7 pc; the distinct inner edge, at a radius of $\simeq$ 1.5 pc, surrounds the "mini-spiral" of the HII region, Sgr A West. We present simple 3D hydrodynamical models of the formation and evolution of the CND from multiple self-gravitating infalling clouds and compare the results with recent observations. We assume the clouds are initially Bonner-Ebert spheres, in equilibrium with a hot confining inter-cloud medium. We include the gravitational potential due to the point-mass of Sgr A* as well as the extended mass distribution of the underlying stellar population. We also include the effects of the ram pressure due to the stellar winds from the central cluster of early-type stars.

A single spherically symmetric cloud cannot reproduce the clumpy morphology of the CND; multiple clouds on diverse trajectories are required so that cloud-cloud collisions can circularize the clouds' orbits while maintaining a clumpy morphology. Collisions also serve to compress the clouds, delaying tidal disruption while potentially hastening gravitational collapse. Low density clumps are disrupted before reaching the inner CND radius, forming short-lived arcs. The outer parts of more massive clumps get tidally stripped, forming long-lived low-density wide-angle arcs, while their cores potentially undergo gravitational collapse. The fine balance between resisting tidal disruption and preventing gravitational collapse implies that most if not all clumps are not stable for much more than an orbit. Thus, in order for the CND to be a long-lived clumpy object, it must be continually fed by additional in-falling clouds. Clouds that survive to small radii are likely to be the sites of present or future star formation. However, within a few parsecs of Sgr A*, the stellar winds decelerate any in-falling cloud so that the wind-cloud interface becomes Rayleigh-Taylor unstable, potentially disrupting the cloud and inhibiting star formation.

1 Introduction

The proper motions of the young, bright stars in the central parsec of our Galaxy strongly suggest (Genzel et al. 2000; Ghez et al. 2000) that Sgr A*, the stationary, compact, non-thermal radio source (Backer & Sramek 1999; Melia & Falcke 2001) located at the very heart of our Galactic Center (GC), is a $2.6 \pm 0.2 \times 10^6 M_\odot$ dark mass. It is probable that the emission we see is associated with the accretion of matter onto a super-massive black hole (Genzel & Eckart 1999). The 7000 K HII region Sgr A West, known as the Mini-spiral, surrounds Sgr A* and is about 1.5 pc in radius (Roberts & Goss 1993; Ekers et al. 1975). The western edge of the Mini-spiral is coincident with the inner edge of a ring of molecular and atomic gas. This ring is centered on Sgr A* and is known as the Circumnuclear Disk (CND).

Many observations of the CND have been made over the years (e.g., Gatley et al. 1986, Serabyn et al. 1986, Jackson et al. 1993, Wright et al. 2001, Christopher et al. 2002). The CND is asymmetric and very clumpy with a distinct inner edge at a radius of $\sim$ 1.5 pc; its outer edge is less distinct but it extends for more than 7 pc. The mass of the CND is estimated to be $10^{4-5} M_\odot$ with a filling factor of about 0.01. Individual clouds have masses in the range of 1 to $10^3 M_\odot$, sizes of $0.1 - 0.4$ pc, temperatures of more than 100 K, and number densities of 10^{5-6} cm^{-3}. There is evidence that some of the CND clouds are

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on Keplerian trajectories and are stretched perpendicular to their radii towards Sgr A* (Christopher et al. 2002).

It has been estimated that the collisional time-scale of individual CND clouds is more than 1 Myr (Vollmer & Duschl 2001b) but the lifetime of the CND itself may be much shorter since many clouds are tidally unstable and may be disrupted in less than 10^5 yrs (Güsten et al. 1987; Christopher et al. 2002). For comparison, if the clouds in the CND are pressureless and uniform, their gravitational free-fall collapse time would be $\simeq 10^5$ yrs. Also, it appears that some of the Giant Molecular Clouds (GMCs) in the GC are interacting with the outer edge of the CND (Coil & Ho 2000). Clearly, the CND plays a key role in how gas reaches the central pc and Sgr A*; it may also play a critical role in star formation in the GC since many of the young stars of the central parsecs are associated with it. Thus, we have set out to model the formation and evolution of the CND.

Previous investigations of the formation and evolution of the CND have utilized collisional N-body (Vollmer & Duschl 2002) and sticky particle (Sanders 1998) codes. In this work, we use a version of the finite-difference Eulerian code ZEUS3D (Norman 1994) with self-gravity to construct initial simple 3D hydrodynamical models of the CND.

2 The Simple Hydrodynamical Model

The premise of the model is that the CND is formed and maintained by GMCs falling down the Galactic potential well towards Sgr A*. This potential is assumed to be due to a spherical distribution of mass such that within a radius r (in pc) from Sgr A*, the total enclosed mass is given by (see, e.g., Genzel et al. 2000, Fig. 17):

$$M_{\rm enc}(r) = 2.6 \times 10^6 + 1.6 \times 10^6 r^{1.25} M_\odot \ . \qquad (1)$$

The first term in Eq. 1 is due to the point mass of Sgr A* and the second is due to the stellar potential. Interestingly, the stellar potential begins to dominate that of the point mass at a radius of ~ 1.5 pc, the inner radius of the CND. Also, due to the increasing mass of the stellar cluster with radius, there is a shallow minimum in the Keplerian velocity of a circular orbit at ~ 4.5 pc, very close to the average radius of the CND. Thus, one would naturally expect material to collect around 4.5 pc and be potentially disrupted within 1.5 pc.

Each GMC is initially a non-isothermal version of a Bonner-Ebert sphere (Bonner 1956; Ebert 1955); that is, they are in gravitational hydrostatic equilibrium with a hot, confining ISM. We use a canonical adiabatic index $\gamma = 1.1$ since GMCs are generally nearly isothermal. Since in reality there are supersonic motions in GMCs that are on the order of 10s of km s^{-1}, we use an effective central temperature $T_c = 1000$ K. Finally, choosing a central density ρ_c determines the size of the GMC. Note that clouds which have an initial non-zero velocity will not strictly be in equilibrium and, given time, would be expected to collapse perpendicular to their direction of motion. The ISM is assumed to have a temperature $T_{\rm ISM} = 10^6$ K; thus the ISM number density, $n_{\rm ISM}$, is 0.001 times the surface density of the GMC.

In addition to self-gravity and the gravity of the point mass and underlying stellar population, we have included the stellar winds from the central star cluster, IRS 16. To model the winds, we inject a total of $3 \times 10^{-3} M_\odot {\rm yr}^{-1}$ into cells within 0.25 pc of Sgr A*. This gas is given a radially outward velocity of 700 km s^{-1} and a temperature of 10^6 K. We ignore the UV radiation field from the central cluster; the ionization of the illuminated side of a GMC would result in gas from that side being ejected into the ISM and thus a smaller cloud (Vollmer & Duschl 2001a).

3 Specific Simulations

We have constructed two general types of models: single massive GMCs and multiple smaller GMCs. These models have been run with various orbits, resolutions, and cloud sizes. The small GMCs have radii of 0.2 pc, central densities of $\sim 10^6$ cm^{-3}, and masses of $450 M_\odot$. The large GMCs have radii of 2.0 pc, central densities of $\sim 10^4$ cm^{-3}, and masses of $4500 M_\odot$. Most simulations have 256^3 cells.

3.1 Single Cloud Results

A single GMC with a large impact parameter, b, compared to its radius, gets tidally stripped into large-angle arcs within a few orbits. An example of this is shown in Fig. 1, where a single GMC has entered from the lower left with an upward trajectory. In the figure, the cloud has moved less than an orbit; the core of the cloud is still visible but after a few orbits the entire cloud is smeared out over most of the volume of the simulation. Some of the arcs fall onto Sgr A*, potentially resulting in a mass accretion rate onto the putative black hole of up to $\sim 10^{-3} M_\odot$ yr^{-1}. At no point do repeated collisions of parts of the cloud result in regions denser than the initial cloud's central density (10^4 cm^{-3}). This is in contrast to sticky particle calculations (Sanders 1998) which show arcs of the disrupted GMC colliding with itself, resulting in regions of significantly enhanced density. The IRS 16 winds have a ram pressure of $\simeq 9 \times 10^{-9}/r^2$ dyne cm^{-2}, where r is the distance from Sgr A* in pc. The large GMCs have a gravitational binding energy density of $\simeq 2 \times 10^{-9}$ erg cm^{-3}. Thus, the winds are only dominant within two pc or so of Sgr A* and have little effect on clouds with large impact parameters.

A GMC with an impact parameter smaller than its radius will produce a ring of ejected material. This is shown in Fig. 2, where a cloud with $b = 0$ has been entirely disrupted. Again, large-angle arcs form but no clumps and no regions of high density. After a few 10^5 yrs, the whole structure smoothes out. Interestingly, the energy of the ejected material is comparable to that of a supernova. Since a cloud with $b = 0$ approaches the singularity of the point mass, the detailed structure and evolution depends on the physical resolution of the simulations (the 3D calculations are not converged in resolution). Nonetheless, it appears that the clumpy nature of the CND cannot be reproduced by the disruption of a single GMC. However, turning on the IRS 16 winds in the case of $b = 0$ results in an unstable interface between the cloud and the wind. As shown in Fig. 3, this Rayleigh-Taylor unstable interface clumps up and could potentially result in small dense clouds which match CND observations; this simulation did not have sufficient resolution to follow the development of the instability any further than is shown in Fig. 3.

3.2 Multiple Cloud Results

The multiple GMC models included 24 clouds, each on a Keplerian orbit. In order to mimic a velocity dispersion in the group of clouds, the orbits were perturbed by a Gaussian distribution of random velocity components with a magnitude of $0.25\ v_{\rm Kep}$. These models were intended to investigate how clumps in an existing CND would evolve. As expected, some of the small GMCs merge with each other, some fall inwards towards Sgr A*, some escape the system entirely, and some are directly disrupted into short arcs of gas. This is shown in Fig. 4. Merged GMCs generally have densities which are temporarily enhanced in the azimuthal direction since the chosen initial orbits rarely produce radial collisions. However, after a few orbits ($\sim 10^5$ yrs), all of the clouds are disrupted and dispersed. Before disruption though, these small merged GMCs match the size ($\sim 0.1 - 0.4$ pc), central number density ($\sim 10^6$ cm^{-3}), and morphology (stretched azimuthally) of the observations. Note that with the increased binding energy of the smaller clouds relative to the larger GMCs ($E_{\rm grav} \propto \rho_c^{-1}$ for an EB sphere), the IRS 16 winds are not likely to significantly affect the clouds outside of a pc.

4 Discussion & Conclusions

The preliminary, simple calculations presented here do not include radiative heating or cooling, magnetic fields, phase transitions or possible stellar sources within the GMCs. Nor do they consider rotating or inhomogeneous clouds. Nonetheless, they are the first attempt at 3D hydrodynamical models of the evolution of GMCs in the environment of the central pcs of the Galaxy. In the future, we will run higher resolution multi-material simulations which include radiative heating and cooling. We will also consider non-hydrostatic and rotating clouds.

There is clearly a fine balance between gravitational collapse and tidal disruption in the GC. Only those clouds dense enough to be stable against tidal disruption can approach Sgr A* while clouds which are too dense undergo gravitational collapse before they reach the central parsecs. Even rotating clouds can only get to within $\simeq 2$ pc (Vollmer & Duschl 2001b) of Sgr A* before their critical density to resist tidal disruption exceeds their critical density for gravitational collapse. Combined with the observation that the clouds now in the CND are not tidally stable (Christopher et al. 2002), this implies that individual clumps within the CND are short-lived ($\sim 10^5$ yrs) objects and if the CND as a whole is a long-lived clumpy object ($\gtrsim 10^6$ yrs), it must be continually fed by in-falling clouds. Only multiple GMCs can reproduce the characteristics of the CND and even then only for a short time; a single large GMC cannot, even through multiple self-collisions, reproduce the CND's morphology.

If the GMCs presently interacting with the CND (Coil & Ho 2000; Zylka et al. 1990) are any indication, the GMCs that formed the CND came from $\gtrsim 100$ pc out and took $\gtrsim 10^6$ yrs to fall into the central parsecs. Thus, they could have formed stars *while* falling into the GC and the clumps we see today in the CND could be the remnants of their cores. If so, there would likely have been recent star-formation going on in the CND clumps. If these GMCs produced the hot, massive stars such as IRS 16 that pervade the central parsecs, this would resolve the difficulty of how so many young stars exist so near a super-massive black hole.

The role of the stellar winds from the IRS 16 cluster is not clear. Any interface between the hot winds and the GMCs will be unstable; however, it is not clear if the instability would induce collapse and subsequent star formation or if it would completely disrupt the GMC. Higher resolution simulations will help address this issue. Also, the in-falling streamers of stripped GMCs (e.g. Fig. 4) will be ionized by the IRS 16 stars, perhaps producing the Sgr A West HII region.

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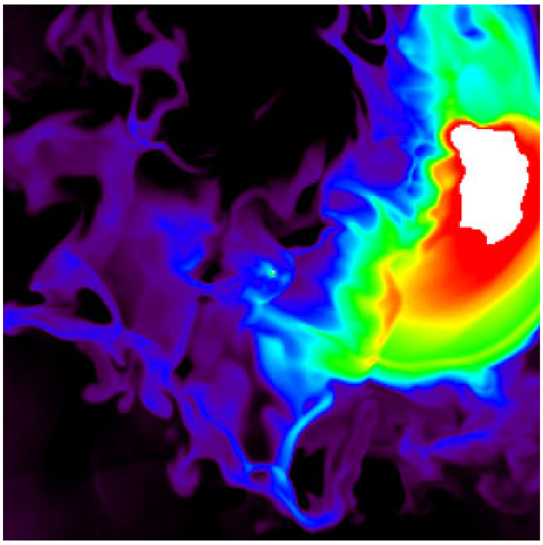

Fig. 1 A log plot of density in the z-plane showing a disrupted large cloud at $t \simeq 10^5$ yrs which had an initial velocity of 100 km s^{-1} and $b = 3$ pc, and was falling towards Sgr A*, located at the center, from the lower left in the figure. Black corresponds to $n \lesssim 10^{-3}$ cm^{-3} and white to $n \gtrsim 10^2$ cm^{-3}. The figure is 15 pc on a side. The IRS 16 winds were not turned on for this simulation.

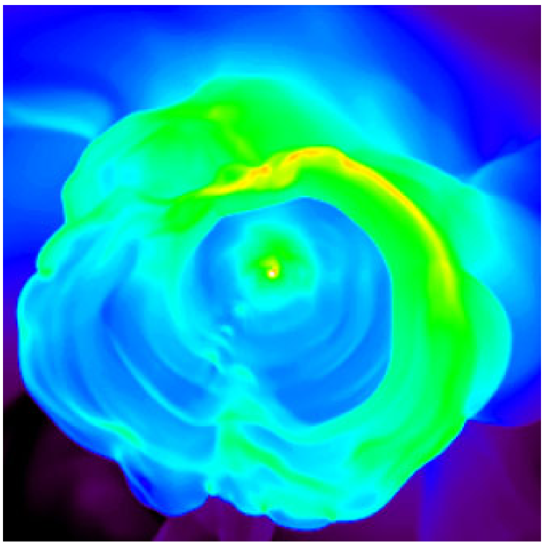

Fig. 2 A log plot of density in the z-plane showing a disrupted large cloud at $t \simeq 8 \times 10^4$ yrs which had a small initial velocity, $b = 0$, and was falling towards Sgr A*, located at the center, from below in the figure. Black corresponds to $n \lesssim 10^{-2}$ cm^{-3} and white to $n \gtrsim 10^3$ cm^{-3}. The figure is 15 pc on a side. The IRS 16 winds were not turned on for this simulation.

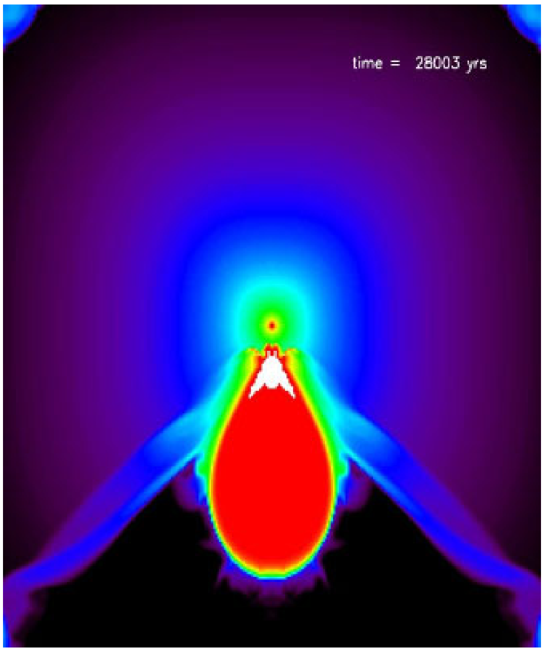

Fig. 3 A log plot of density in the z-plane showing a disrupted large cloud like that in Fig. 2. Black corresponds to $n \lesssim 10^{-1}$ cm^{-3} and white to $n \gtrsim 10^{3}$ cm^{-3}. The figure is 15 pc on a side. The IRS 16 winds were turned on for this simulation.

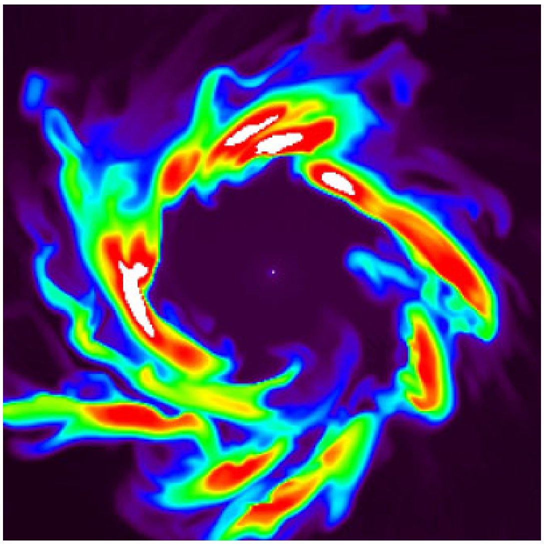

Fig. 4 A log plot of density in the z-plane for 24 small orbiting clouds with perturbed orbits at $t \simeq 10^5$ yrs. Black corresponds to $n \lesssim 10^{-1}$ cm^{-3} and white to $n \gtrsim 10^{3}$ cm^{-3}. The figure is 15 pc on a side. The IRS 16 winds were not turned on for this simulation.