3D Simulations of the 180pc Molecular Ring

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Abstract. Understanding the kinematics and morphology of molecular clouds in the Central Molecular Zone (CMZ) is important for studying the mode of star formation in the central region of the Galaxy. A quasi-continuous ring structure with a radius of 180pc, so-called “180-pc molecular ring”, is interpreted as the transition region between the two stable orbits in the bar potential, x1 & x2 [2]. We present, for the first time, 3-D high resolution hydrodynamic simulations of the gas flows in this transition region, and compare the results with previous 2-D studies. We will also see if an m=1 perturbation, which is revealed as a displacement of the CMZ, is responsible for some of the discrepancies between the previous simulations and observations.

1. Introduction
The origin and stability of the “180-pc molecular ring” seen in the center of our galaxy is a long-standing puzzle in galactic center dynamics. In the previous studies, the 180 pc molecular ring feature was considered as an expanding ring [1]. In 1991, Binney et al. [2] suggested that the longitude-velocity (ℓ−v) plot of the 180 pc molecular ring, a parallelogram rather than an ellipse, can be understood as a projection of the innermost stable x1-orbit [3] in a barred potential. They also showed that the locations of the giant molecular clouds at the Galactic Center (GC), such as Sgr B and Sgr C, could be explained by the x2 orbits.

There have been many hydrodynamical simulations to study the structure and kinematics of the GC molecular clouds [4, 5, 6, 7]. These simulations have been successful in reproducing structures of the gas motions on global scales, but they do not resolve some important discrepancies between simulations and observations such as the large asymmetries in positive longitude. According to observations, more molecular clouds are seen at positive longitudes than at negative longitudes in the GC region. Different mechanisms have been proposed to explain the observed lopsidedness of the distribution of molecular gas. One of the possibilities is that an m=1 perturbation may be responsible for the asymmetry.

Here, we try to answer the influence of an m=1 perturbation on the motion of the molecular clouds through smoothed particle hydrodynamics (SPH) simulations. We then make detailed comparisons between the observations and simulations to understand the distribution and kinematics of the GC molecular clouds.

2. Model & methodology
We have studied various types of galactic potential models used in other recent papers and turned several different potentials into numerical codes. Each type of model has some attractive aspects...
in modeling the potential of our galaxy. These models have been successful in reproducing the structure of the gas motions, but several models were incapable of reproducing x1- and x2-type orbits at the desired locations. In our numerical simulations, we represent the galaxy by a fixed potential with three components: an exponential stellar disk, a power-law ellipsoidal bar, and a dark matter (DM) halo. For the density of the dark halo, we use a Navarro-Frenk-White(NFW) model:[8]:

\[ \rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2} \]

Where \(r_s\) and \(\rho_s\) are characteristic scale and density of the halo, respectively. For the disk component, we adopt Freeman’s [9] exponential disk that has the following form,

\[ \Phi(R) = -\pi G \Sigma_0 R [I_0(y) K_1(y) - I_1(y) K_0(y)] \]

where \(y = \frac{R}{R_d}\)

Here, \(R_d\) is the disk scale length, \(\Sigma_0\) is the central surface density, and \(I_n\) and \(K_n\) are modified Bessel functions of the first and second kinds. As for the bar component, we adopt a density/potential pair similar to that of the prolate bar proposed by Binney et al. [2] with a power law logarithmic slope \(\alpha=1.8\) and a normalization constant \(a_0=1.2\) kpc.

\[ \rho(a) = \rho_0 \left( \frac{a}{a_0} \right)^{-\alpha} \]

\[ a = \sqrt{x^2 + (y^2 + z^2)/q_m^2} \]

We find that a good match to the CO data [10] is obtained when \(q_m=0.75\).

The gas particles of the molecular clouds are placed on x1 orbits as an initial condition and are represented by SPH particles. In our simulations, we used the following system of units in which the gravitational constant \(G = 1\), the unit of length is chosen to be \(R = 1\) pc. The total mass of the galaxy within 1 kpc was assumed to be \(M_{10}=7 \times 10^9\) \(M_\odot\). We calculated the simulations to 0.2 Gyr to allow the gas flow to form a ring and to 0.3 Gyr to verify that the ring is stabilized.

All of the simulations in this study were performed with GADGET-2 [11], a new massive parallel TreeSPH code, capable of following a collisionless fluid with the N-body method, and a gas by means of SPH method. The SPH method has the advantage of allowing for a spatially adaptive resolution length. Fluid quantities are approximated by averaging over neighbouring particles. Furthermore, the SPH scheme includes an artificial viscosity to allow for shocks in the simulated gas flow. We assumed that the gas is isothermal and that its temperature is \(10^4\) K since previous numerical simulations of gas motion in disc galaxies [12] show that radiative cooling is very effective for shocked gas and that the gas temperature is maintained at \(10^4\) K.

3. \(m=1\) instability

One of the puzzles regarding the distribution of molecular gas toward the GC region is its lopsidedness. Different mechanisms have been proposed to explain the observed feature. One possibility is that an \(m=1\) perturbation may be responsible for the asymmetric distribution of the molecular clouds. We have considered two possible causes for the creation of \(m = 1\) perturbations. One possibility is that a fly-by encounter with a satellite galaxy may provide a perturbing influence which helps to excite an \(m=1\) instability. The other possibility is that an \(m = 1\) excitation is provided by a slight displacement of the center of mass of the dark matter halo with respect to the GC. We tried to answer these effects through N body simulations, First, we have simulated the response of molecular clouds to a perturbation by a fly-by encounter. A Plummer model with \(M_{\text{Plummer}}=10^8\) \(M_\odot\) was chosen for the density of the perturbing object and a hyperbolic orbit for its orbit. Second, the response of molecular clouds to a DM halo that is off centered with respect to the center of the galaxy was investigated. Levine & Sparke [13]
found significant asymmetries in their models to explain lopsidedness of galaxies when the disc lies off centered in the dark matter halo. Viewed in this light, our hypothesis is that an offset between GC and center of mass of the DM halo will be responsible for the $m = 1$ instability.

4. Results
4.1. Simulations without perturbation
Some recent simulations [6, 7] of the molecular clouds in the GC have overlooked some potentially important physical effects such as 3-dimensionality, self-gravity of gas, and so on. We therefore set up 3-dimensional simulations including self-gravity of gas particles. In order to emphasize the important role of an $m = 1$ perturbation concerning gas dynamics, we first present numerical results of a simulation without an $m = 1$ perturbation (Fig. 1). Over the course of a 0.3 Gyr integration, the particles rapidly lose energy and angular momentum, and quickly move onto x2-orbits. Consequently, a small perpendicularly aligned bar of heavily populated x2-orbits develops at the center.

Figure 1. Distribution of the gas particles in the galactic center without perturbation. The length unit is 1 pc.

Figure 2. Longitude-velocity plots for the simulation shown in the left panel. The abscissa gives longitude in degrees and the ordinate gives velocity in km s$^{-1}$.

In spite of the fact that our simulations, that comprise the effects of the self-gravity of the gas and of 3-dimensionality, are more realistic than earlier studies, significant difference to previous results were not found. Therefore, the self-gravity of the gas appears to be negligible because it is insufficient to explain the asymmetry of the molecular gas successfully.

4.2. Simulation of fly-by encounter
The effects of a fly-by encounter on a coplanar orbit that varies with various values for the pericenter and for the core radius of the perturbing object were investigated. If the perturber has a small core radius and close pericenter, the gas particles suffer several instabilities and the perturbation produces a lump of ejected particles. Also, gas from the ring is shown to accrete onto the central core. In an attempt to reduce the perturbation by the Plummer sphere, we
have also tried orbits with large pericenter distances. In this case, there is a smaller deviation in the gas distribution compared to earlier results.

We find that, if the perturber has a core radius of almost 300 pc, and moves on an orbit which has a pericenter of nearly 1 kpc, the result looks similar to the observed lopsidedness in the GC (Fig. 3). Once an \( m = 1 \) perturbation is excited, these models take many orbits to decay. Therefore, molecular clouds are sensitive to the parameters of encounters such as the core radius and pericenter distance of the perturber. An interesting prospect is that it may be possible to detect indirectly the presence of dwarf galaxies from their effect on the molecular clouds at the GC.

4.3. Simulations with an off centered DM halo
In this approach the lopsidedness of molecular clouds is related to a displacement between the center of mass of the DM halo and the GC. For these simulations, we have calculated the period of the DM halo circling around the GC and have modeled it as a fixed potential. We then examined several simulations with an off-centered DM halo at different offset distances. As the offset increases, the instability of gas particles grows and produces a lump of ejected particles. But if the offset distance was taken to be about 300-400 pc, we were able to reproduce the \( \ell-\nu \) map of the lopsided molecular clouds.

5. Summary
- We have performed 3-D SPH simulations of the 180 pc molecular ring in the galactic center.
- The self-gravity of the gas is considered to be a negligible factor since it cannot explain the lopsidedness successfully.
- We have studied the response of molecular clouds to perturbations and the subsequent formation of an \( m = 1 \) instability induced by a fly-by encounter or an off-centered DM halo to try to understand the lopsided distribution of the GC molecular clouds.
In order to understand these \( m = 1 \) instability effects, we have made several calculations. Our simulations show that morphological asymmetries occur during the simulations which are able to reproduce the \(^{12}\text{CO} \ell-u\) plot. However, these simulations are in need of tightly constrained parameters, such as, e.g., a sufficiently close pericenter distance and a small core radius of the perturber during a fly-by encounter.

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