Simulations of Nuclear Star-Forming Rings: A Case of the Milky Way

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Abstract. Gas materials in the inner Galactic disk continuously migrate toward the Galactic center (GC) due to interactions with the bar potential, magnetic fields, stars, and other gaseous materials. Those in forms of molecules appear to accumulate around 200 pc from the center (the central molecular zone, CMZ) to form stars there and further inside. The bar potential in the GC is thought to be responsible for such accumulation of molecules and subsequent star formation, which is believed to have been continuous throughout the lifetime of the Galaxy. We present hydrodynamic simulations of gas clouds in the central kpc region of the Milky Way that is modeled with a three-dimensional bar potential. Our simulations consider realistic gas cooling and heating, star formation, and supernova feedback. A torus of dense gas clouds forms as a result of $X_1$–$X_2$ orbit transfer, and its size (∼ 200 pc radius) coincides with the extraordinary reservoir of dense molecular clouds in the inner bulge, the Central Molecular Zone (CMZ). We also present some results from our preliminary simulations for gas transportation from the CMZ to the circumnuclear disk of molecular clouds located at a few parsecs from the GC.

1. Introduction
The CO emission survey along the Galactic plane shows that molecular gas is abundant down to a Galactocentric radius $R_G$ of ∼ 3 kpc. Inside this radius, the gas content is mostly in forms of atoms and there is no noticeable star formation activities. However, a significant amount of molecular gas, as well as various evidences of recent and current star formation, appears again inside a projected $R_g$ of ∼ 200 pc. This distribution of molecular gas is called the Central Molecular Zone (CMZ). The observed longitude-velocity diagram of the molecular emission in the CMZ is generally interpreted as a result of torus-like distribution of molecules with an outer radius of ∼ 200 pc. The total gas mass in the CMZ is estimated to be ∼ $5 \times 10^7$ $M_\odot$ [7].

The gas content in the CMZ is thought to have migrated inward to the current location from the Galactic disk. Serabyn & Morris [11] enumerate mechanisms for the inward transport of gas: shear viscosity due to the differential rotation of gas disk, compression and shocks associated with the elongated or cusped stable orbits in a non-axisymmetric potential, dynamical friction with the field stars, magnetic field viscosity, and the dilution of specific angular momentum by stellar mass loss material from outer bulge [4].

The transition from atomic to molecular status around 200 pc is believed to be responsible for the characteristics of the stable orbits in a bar potential [1]. Bar potentials have several distinct families of stable orbits, among which $X_1$ and $X_2$ orbit families are related to the discussion here: $X_1$, the outermost orbit family, is elongated along the bar’s major axis, whereas $X_2$...
is enlongated along the bar's minor axis at deeper inside the potential. Hydrodynamic effects cause gas particles to generally move along stable orbits, but the innermost $X_1$ orbits are sharply cusped or even self-intersecting at the apocenters. Gas is compressed or even undergoes a shock in these regions, loses its orbital energy, and falls inward to settle onto an $X_2$ orbit inside. Such compression and subsequent cooling will transform the mostly atomic gas to molecular clouds.

Some of the accumulated molecular gas will keep moving inward and reach the CircumNuclear Disk (CND) of molecular clouds at $R_G$ of few parsecs and/or eventually sink to the central supermassive black hole, while some will collapse and form stars in the CMZ. If the nonsphericity of the Galactic potential in the inner bulge has been significant enough to give rise to $X_1$, $X_2$ orbit families for the lifetime of the Galaxy, a fair amount of stars must have formed in the CMZ so far. Serabyn & Morris [11] argue that the sustained star formation in the CMZ has resulted in a cusp in the stellar number density profile with $R_G$ of 100–200 pc.

There have been a few hydrodynamic studies on the gas inflow in the inner bulge of galaxies. Jenkins & Binney [4] were the first who numerically examined the idea of Binner et al. [1] with 2-D sticky particle simulations and confirmed that the transition of gas motion from $X_1$ to $X_2$ orbits indeed takes place in a bar potential. Englmaier & Gerhard [2] were able to observe the same phenomenon in their larger-scale, 2-D SPH simulations of gas dynamics in the Milky Way. [8] explored a large parameter space to determine whether and at what radius a nuclear ring of gas forms with 2-D, grid-based simulations. Rodriguez-Fernandez & Combes [9] performed 2-D hydrodynamic simulations (particle motions were followed in 3-D, though) of the inner Galaxy to study the gas dynamics in that region with a secondary bar taken into account. All of these studies primarily concentrated on the gas flows and did not consider star formation in their simulations.

In the presentProceedings paper, we present 3-D hydrodynamic simulations of gas particles in the inner bulge of the Galaxy that consider the effects of star formation, supernova feedback, and realistic gas cooling and heating. We will show that a bar potential that has a $X_1$–$X_2$ transition at ~200 pc can indeed compress gas sufficiently enough to form stars and that the obtained star formation rates are consistent with observations. We also present some results from our preliminary simulations for gas transportation from the CMZ to the circumnuclear disk of molecular clouds located at a few parsecs from the GC.\footnote{The first half of this Proceedings paper (the CMZ simulations) has been published as a Letter \cite{5}.}

### 2. Simulations

We use a parallel tree SPH code ASURA (Saitoh, in preparation) that can utilize the special-purpose hardware GRAPE or an optimally-tuned gravity calculation library, PhantomGRAPE.\footnote{The library can be obtained at \url{http://grape.mtk.nao.ac.jp/~nitadori/phantom/}.} We use an opening angle of $\theta = 0.5$ for a cell opening criterion, and the kernel size of an SPH particle is determined by imposing the number of neighbors to be 32 ± 2. We use a cooling function by [12] for gas with the solar metallicity for a temperature range of 10–10$^8$ K. A uniform heating from far-UV radiation is considered with a value observed in the Solar neighborhood [14].

A star particle is spawned when a gas particle satisfies all three following conditions: 1) the hydrogen number density is larger than a threshold value ($n_H > n_{th}$), 2) the temperature is lower than a threshold value ($T < T_{th}$), and 3) the flow is converging ($\nabla \cdot v < 0$). We adopt $n_{th} = 100 \text{ cm}^{-3}$ and $T_{th} = 100 \text{ K}$. The effect of supernova feedback is implemented in a probabilistic manner. We assume that stars more massive than 8 $M_\odot$ explode as Type II supernovae and that each explosion outputs 10$^{51}$ ergs of thermal energy into the surrounding 32 SPH particles. Detailed discussion on the choice of $n_{th}$ and $T_{th}$, spawning of star particles, and supernova feedback is given in [10].
Figure 1. Distribution of gas (left) and star (right) particles in our standard run at $T = 390$ Myr. Length units are in parsecs. Stars are predominantly formed in the central 200 pc.

For the Galactic potential, we adopt a power-law density distribution with an $m = 2$ bar for the bulge,

$$
\rho = \rho_0 \left( \frac{r}{r_0} \right)^{-\alpha} \left[ 1 + b_{22} P_{22}(\cos \theta) \cos 2\phi \right],
$$

where $P$ is the associated Legendre function. Our standard run has the following parameters: $\alpha = 1.65$, $b_{22} = 0.1$, $\rho_0 = 40 \, M_\odot \, pc^{-3}$, $r_0 = 100$ pc, $M_d = 4 \times 10^{10} \, M_\odot$, $R_d = 3.5$ kpc, and $z_d = 40$ pc.

Initially, the simulation has gas particles only. Our standard run has the following initial distribution of particles: They are on one of the $X_1$ orbits whose semi-minor axes range from 300 to 1200 pc. The number of particles on each orbit is proportional to the length of the orbit, and on a given orbit, the particles are spaced over the same time-interval. The vertical distribution follows a Gaussian function with a scale height of 40 pc. The standard run has $10^5$ gas particles, and the total gas mass is $5 \times 10^7 \, M_\odot$, thus each gas particle initially has a mass of $500 \, M_\odot$.

We evolve the system without cooling for the first 50 Myr to have a relaxed particle distribution.

3. Results

Figure 1 shows our standard run at $T = 390$ Myr. About a half of the gas particles that were initially on $X_1$ orbits have migrated inward to the CMZ, and the majority of newly formed stars remain in the central 200 pc. This implies that if gas has been supplied down to the inner bulge
Evolution of the masses in gas and stars for two different radial zones are plotted for our standard run in Figure 2. The evolutionary aspects of the masses do not change much after $T = 200$ Myr: the gas mass inside 250 pc (denoted by $X_2$) and the stellar mass outside 250 pc (denoted by $X_1$) are nearly constant while the gas mass outside 250 pc and the stellar mass inside 250 pc increase or decrease quite linearly. The (nearly) constant amount of gas in the CMZ implies that there is a threshold gas mass in the CMZ above which star formation becomes very efficient. On the other hand, the significantly suppressed star formation rate outside CMZ at later stages is probably a consequence of insufficient gas in that region.

Figure 3 shows the evolution of overall star formation rate (SFR) in our standard run. The SFR increases rather steeply during the first 200 Myr because there are not yet many supernova explosions that increase the temperature of nearby gas particles. During the later half of the simulation, most of the star formation takes place in the CMZ, thus the obtained SFR values of $0.04-0.06\, M_\odot\, yr^{-1}$ can be regarded as the SFR in the CMZ. These values are very close to the recent SFR estimated from mid-infrared observations by [13], $0.04-0.08\, M_\odot\, yr^{-1}$.

region from the disk throughout the lifetime of the Galaxy, then indeed a significant amount of stars would have been born in the CMZ and a resulting stellar population would form a central cusp that is distinctive from the larger bulge.

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Figure 4. Distribution of gas (left) and star (right) particles in our double-bar simulation at $T = 400$ Myr. Length units are in parsecs.

4. From CMZ to CND
Some of the accumulated gas in the CMZ will keep migrating inward and reach the CircumNuclear Disk (CND) of molecular clouds at $r = 2–5$ pc, and a part of it will sink further to form stars in the central parsec or feed the central supermassive black hole. One possible way to transfer gas from the CMZ to the CND would be a nested bar, as examined by [6]. We have performed a simple simulation of gas flow in double-bar potential as a toy model. Figure 4 shows a snapshot at $T = 400$ Myr from our double-bar simulation, which has an inner bar that is modeled with a $n = 1$ Ferrers density profile [3],

$$\rho = \rho_0 \left( 1 - \frac{x^2}{a} - \frac{y^2}{b} - \frac{z^2}{c} \right)^n,$$

where $a = 180, b = 60, c = 60$ pc, and the total mass of the bar is $10^8 M_\odot$ (the inner bar is rotating at the same pattern speed with the main bar with an angular separation of 0 degrees). Two inner rings form at $r \sim 50$ pc and $\sim 10$ pc, and the smaller inner ring would correspond to the CND. There is no known observed features that would correspond to our larger inner ring, but it would be not easy to observationally identify such a ring in that region if the density of the ring is much lower than the CMZ.

5. Summary
We performed 3-D hydrodynamic simulations of the CMZ in a bar potential with consideration of self-gravity, radiative cooling, and supernova feedback. Important findings are 1) that gas
particles are efficiently transported from $X_1$ to $X_2$ orbits, 2) that stars are formed predominantly in the central 200 pc, 3) that the star formation rates obtained from our simulations are consistent with the recent estimates from mid-infrared observations by [13]. These results strongly support the idea that star formation has taken place in the CMZ throughout the lifetime of the Galaxy, and the resulting stellar population is the stellar cusp at the central 100-200 pc region of the Galaxy. We also find that a significant mass of gas can be transported to the CND region by the existence of an inner bar.

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