Computational Star Formation
Proceedings IAU Symposium No. 270, 2011
J. Alves, B.G. Elmegreen, J. M. Girart & V. Trimble, eds.

doi:10.1017/S1743921311000639

Star Formation in the Central Molecular Zone of the Milky Way

Sungsoo S. Kim,[1,2] **Takayuki R. Saitoh,**[3] **Myoungwon Jeon,**[1,5]
David Merritt,[6] **Donald F. Figer,**[2] **and Keiichi Wada**[4]

[1]Dept. of Astronomt & Space Science, Kyung Hee University, Yongin, Kyungki 446-701, Korea

[2]Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology,
Rochester, NY 14623, USA

[3]Division of Theoretical Astronomy, National Astronomical Observatory of Japan,
Mitaka, Tokyo 181-8588, Japan

[4]Graduate School of Science and Engineering, Kagoshima University,
Kagoshima 890-8580, Japan

[5]Dept. of Astronomy, University of Texas, Austin, TX 78712, USA

[6]Centre for Computational Relativity and Gravitation, Rochester Institute of Technology,
Rochester, NY 14623, USA

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 3-D hydrodynamic simulations of the CMZ that consider self-gravity, radiative cooling, and supernova feedback, and discuss the efficiency and role of the star formation in that region. We find that the gas accumulated in the CMZ by a bar potential of the inner bulge effectively turns into stars, supporting the idea that the stellar cusp inside the central 200 pc is a result of the sustained star formation in the CMZ. The obtained star formation rate in the CMZ, 0.03–0.1 $M_\odot$, is consistent with the recent estimate based on the mid-infrared observations by Yusef-Zadeh *et al.* (2009).

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 are no noticeable star formation activities. However, a significant amount of molecular gas, as well as various evidence 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 $\sim 5 \times 10^7\ M_\odot$ (Pierce-Price *et al.* 2000).

The gas content in the CMZ is thought to have migrated inward to the current location from the Galactic disk. Serabyn & Morris (1996) 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

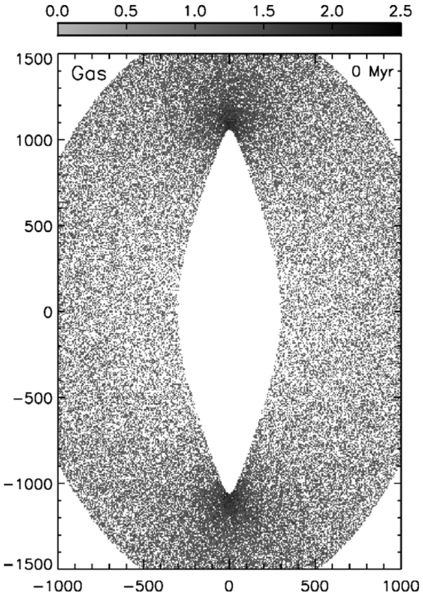

Figure 1. Initial gas particle distribution of our standard run. Length units are in parsecs.

of specific angular momentum by stellar mass loss material from outer bulge (Jenkins & Binney 1994).

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 (Binney *et al.* 1991). 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 elongated along the bar's minor axis 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 Circum Nuclear 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 non-sphericity 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 (1996) 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.

In the present Proceedings 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 $\sim$200 pc can indeed compress gas sufficiently enough to form stars and that the obtained star formation rates are consistent with observations.

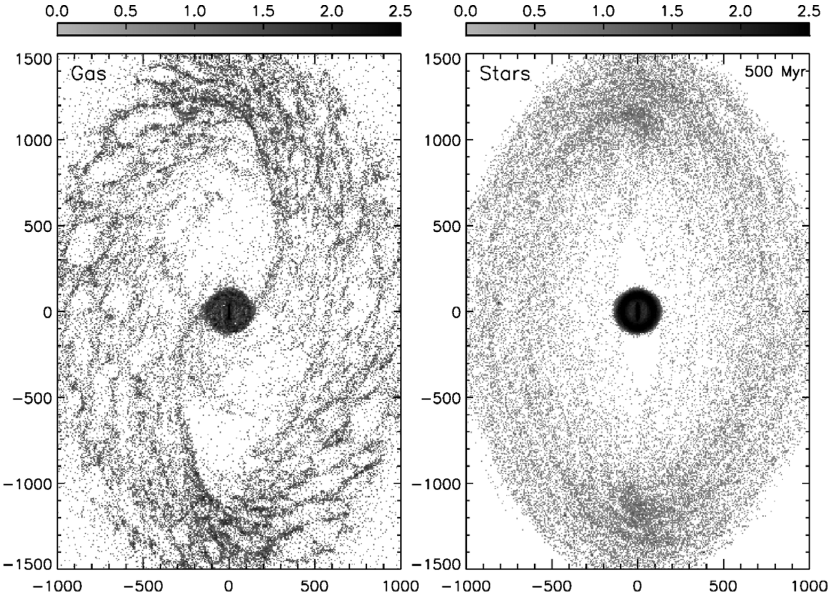

Figure 2. Distribution of gas (*left*) and star (*right*) particles in our standard run at $T = 500$ Myr. Length units are in parsecs. Stars are predominantly formed in the central 200 pc.

2. The 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, Phantom-GRAPE. 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 Spaans & Norman (1997) 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 (Wolfire *et al.* 1995).

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 $n_{th} = 100$ cm^{-3} and $T_{th} = 100$ K. The effect of supernova feedback is implemented in a probabilistic manner. We assume that stars more massive than $8\,\mathrm{M}_\odot$ 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 Saitoh *et al.* (2008).

For the Galactic potential, we adopt a power-law density distribution with a slope of -1.75 and a nonaxisymmetry of $m = 2$ for the bulge, and a Miyamoto-Nagai model for the disk.

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 (see Fig. 1). The vertical distribution follows a Gaussian function with a

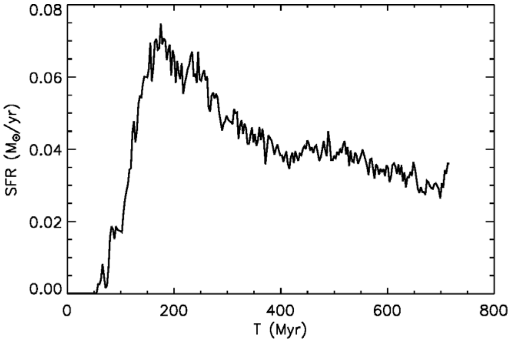

Figure 3. Star formation rate in our standard run. The obtained SFRs are very similar to the values estimated from mid-infrared observations by Yusef-Zadeh *et al.* (2009), 0.04–0.08 $M_{\odot}$ yr^{-1}.

scale height of 40 pc. The standard run has 10^5 gas particles, and the total gas mass is 5×10^7 $M_{\odot}$, 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 2 shows our standard run at $T = 500$ 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 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.

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 0.03–0.04 $M_{\odot}$ 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 Yusef-Zadeh *et al.* (2009), 0.04–0.08 $M_{\odot}$ yr^{-1}.

References

Binney, J., Gerhard, O. E., Stark, A. A., Bally, J., & Uchida, K. I. 1991, *MNRAS*, 252, 210

Jenkins, A., & Binney, J. 1994, *MNRAS*, 270, 703

Pierce-Price, D., Richer, J. S., Greaves, J. S., Holland, W. S., Jenness, T., Lasenby, A. N., White, G. J., Matthews, H. E., Ward-Thompson, D., Dent, W. R. F., Zylka, R., Mezger, P., Hasegawa, T., Oka, T., Omont, A., & Gilmore, G. 2000, *ApJ*, 545, L121

Saitoh, T. R., Daisaka, H., Kokubo, E., Makino, J., Okamoto, T., Tomisaka, K., Wada, K., & Yoshida, N. 2008, *PASJ*, 60, 667

Serabyn, E. & Morris, M., 1996, *Nature*, 382, 602

Spaans, M. & Norman, C. A. 1997, *ApJ*, 483, 87

Yusef-Zadeh, F., Hewitt, J. W., Arendt, R. G., Whitney, B., Rieke, G., Wardle, M., Hinz, J. L., Stolovy, S., Lang, C. C., Burton, M. G., & Ramirez, S. 2009, *ApJ*, 702, 178

Wolfire, M. G., Hollenbach, D., McKee, C. F., Tielens, A. G. G. M., & Bakes, E. L. O. 1995, *ApJ*, 443, 152