Resolving the Rise and Fall of Star Formation in Galaxies
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Bar-Driven Star and Star Cluster Formations and Gas Fueling to Galactic Center

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Abstract. In order to study gas evolution in the central region of a barred galaxy, we have performed numerical simulations of gas in the potential of the barred galaxy. We have found that the bar potential produces a gas ring within the central 1 kpc region. In the gas ring, active star and star cluster formations take place. Since the gas ring is dense enough to become self-gravitationally unstable, gas clouds form in the ring. These gas clouds interact gravitationally and collide with the other clouds. Such interaction and collision reduces their angular momentums effectively, and finally gas clouds fall into the galactic center. These processes triggers episodic gas fueling to the galactic center.

Keywords. galaxies: evolution, galaxies: nuclei, galaxies: star formation, method: numerical

1. Introduction

Barred galaxies are generally known to have a large amount of gas in their central kpc region. For examples, in Milky Way, the central region called central molecular zone (CMZ) has rich molecular gas and gas clouds (Morris & Serabyn 1996). Such abundant gas is expected to play important roles in the galactic central evolution. In the central region, active star formations have been observed in some barred galaxies (Benedict et al. 2002). Observations also have implied the existence of candidates of intermediate-mass black holes (IMBHs) in Milky Way (Oka et al. 2017). Gas supply from kpc scale to pc scale would induce growth of a central supermassive black hole (SMBH) or activity of active galactic nuclei (AGN). Thus, understanding of gas evolution in the central region of barred galaxies is crucial for understanding of galaxy formation. Here, we report results of our numerical simulations of barred galaxies.

2. Method

In order to study evolution of gas in the central region of a barred galaxy, we have performed numerical simulations of barred galaxies by using parallel SPH/Nbody code "ASURA" (Saitoh et al. 2008). In our simulations, a wide range of radiative cooling ($10\,\mathrm{K} < T < 10^8\,\mathrm{K}$), star formations from cool and dense gas ($T < 100\,\mathrm{K}$, $n_{\mathrm{H}} > 100\,\mathrm{cm}^{-3}$), and heating from supernovae (SNe) feedback are taken into account, which enables us

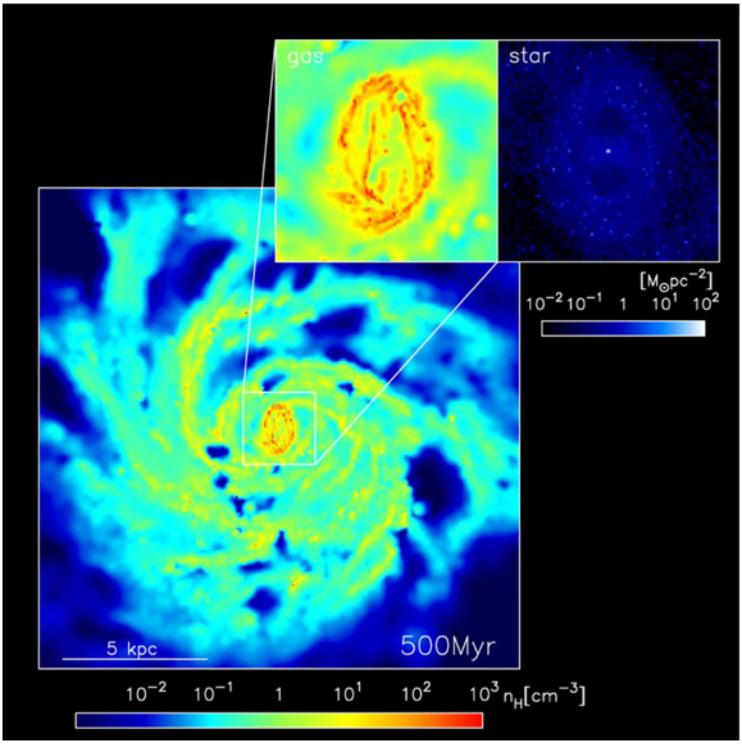

Figure 1. Gas density map at 500 Myr. The upper left and right panels show gas density and surface density of newly formed stars within the central 2 kpc. In our simulations, the coordinate system rotating with the bar potential is used, and the bar is along horizontal direction.

to understand formations of gas clouds (Saitoh et al. 2008) and star and star clusters (Saitoh et al. 2009; Matsui et al. 2012, 2019).

We have simulated gas motion in the external potential of a barred galaxy. The exponential disk with total mass of 3.5×10^{10} $M_\odot$ and scale length of 7 kpc is adopted for the initial gas distribution. Since the number of SPH is 10^6, the mass of a SPH particle is 3.5×10^4 $M_\odot$. A stellar disk, a stellar bulge, a stellar bar, a dark halo, and a central SMBH are given by external potential. The models of the stellar disk, the stellar bulge, and the dark matter halo are Miyamoto-Nagai potential, Plummer model, and NFW profile, respectively. In these models, Milky Way like parameters are adopted (Saitoh et al. 2008; Sofue 2012; Gillessen et al. 2017). The stellar bar potential is given by the quadrupole model (Monari et al. 2016). The bar potential gradually grows from 200 Myr to 500 Myr in order to avoid unnatural reaction of gas.

3. Results

3.1. *Episodic gas fueling to the galactic center*

Figure 1 shows the density map of gas at 500 Myr. In the figure, the bar is along the horizontal direction. The bar potential produces a vertically elongated ring, which is generally called the x-2 ring, with respect to the bar. The size of ring is less than 1 kpc. As the bar potential grows, the gas ring becomes dense. Since the gas ring is dense enough to become self-gravitationally unstable and clumpy during bar growth phase, gas clouds form in the ring.

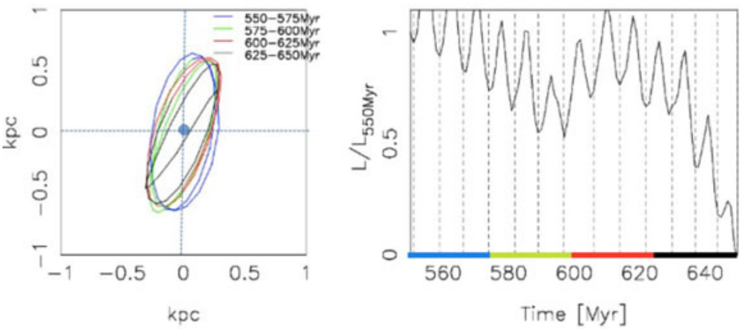

Figure 2. The orbit of one gas cloud (left) and time evolution of the angular momentum of the cloud (right). In the right panel, the dot at the center shows the galactic central SMBH. In the left panel, the vertical dashed lines show the time that the cloud reaches the apocenter.

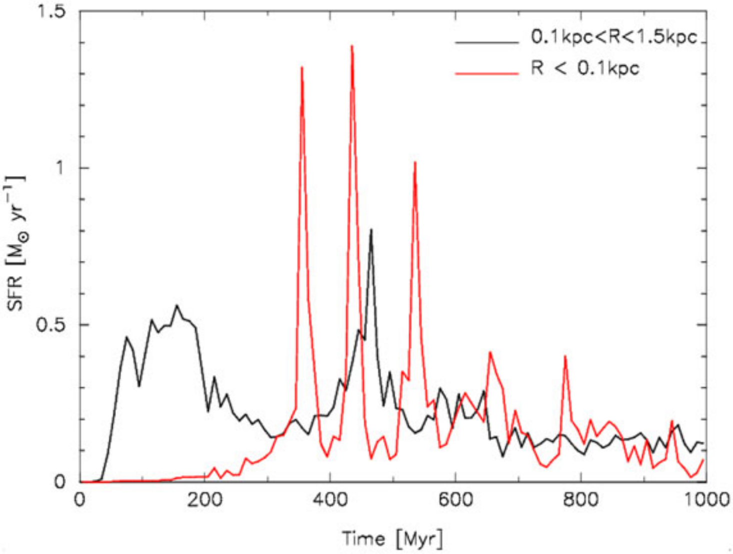

Figure 3. Time dependence of SFR. The black and red lines show SFR at $0.1 \text{ kpc} < R < 1.5$ kpc and $R < 0.1$ kpc, respectively.

In the ring, gravitational interactions and collisions between clouds take place. Due to their interactions and collisions, some gas clouds begin to deviate from the ring. Figure 2 shows the time evolution of the distance from the galactic center (left) and the angular momentum (right) of one deviated cloud. We can see that the cloud finally falls into the galactic center due to the decrease of its angular momentum within a few hundred Myr. This is because the deviated cloud interacts gravitationally and collides with the other clouds, which still rotate on the ring, at the apocenter of the orbits. The interactions and collisions reduce the angular momentum of the cloud effectively. We can also see the short time oscillations of its angular momentum. This is caused by a bar potential.

The falls of gas clouds trigger gas fueling to the galactic center episodically. As a result, mass within the central 10 pc increases by 8×10^7 $M_\odot$ for 500 Myr.

3.2. *Star formations*

Figure 3 shows the time evolution of star formation rate (SFR). Since a large number of gas is collected during the bar growth phase, gas ring becomes dense enough to induce active star formations and increase SFR. After the bar grows, SFR gradually decreases. These results agree with Baba & Kawata (2020). When gas clouds fall into the galactic center, a nuclear starburst takes place. As a result, some peaks of SFR appear.

4. Discussion

In our simulations, some star clusters form in the galactic central region. If runaway collisions of massive stars occur within the cluster, IMBH would form (Portegies Zwart et al. 2004). These clusters might play an important role in IMBH formations observed in CMZ (Oka et al. 2017).

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References

Baba, J., & Kawata, D. 2020, MNRAS, 492, 4500
Benedict, G. F., Howell, D. A., Jørgensen, I., Kenney, J. D. P., & Smith, B. J. 2002, AJ, 123, 1411
Gillessen, S., Plewa, P. M., Eisenhauer, F., et al. 2017, ApJ, 837, 30
Matsui, H., Tanikawa, A., & Saitoh, T. R. 2019, PASJ, 71, 19
Matsui, H., Saitoh, T. R., Makino, J., et al. 2012, ApJ, 746, 26
Monari, G., Famaey, B., Siebert, A., et al. 2016, MNRAS, 461, 3835
Morris, M., & Serabyn, E. 1996, ARA&A, 34, 645
Oka, T., Tsujimoto, S., Iwata, Y., Nomura, M., & Takekawa, S. 2017, Nature Astronomy, 1, 709
Portegies Zwart, S. F., Baumgardt, H., Hut, P., Makino, J., & McMillan, S. L. W. 2004, Nature, 428, 724
Saitoh, T. R., Daisaka, H., Kokubo, E., et al. 2008, PASJ, 60, 667
—. 2009, PASJ, 61, 481
Sofue, Y. 2012, PASJ, 64, 75